Europeiska jordbruksfonden för
landsbygdsutveckling. Europa
investerar i landsbygdsområden

Sustainability Assessment of Swedish Wool

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Funded by: Vinnova
Report number C769
ISBN 978-91-7883-498-3
Edition Only available as PDF for individual printing

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Bakgrund

Den globala textilindustrin står inför omfattande miljöutmaningar såsom klimatförändringar, kemikalieanvändning, vattenbrist och avfallshantering. Ekonomisk tillväxt tillsammans med populationsökningar och förändrade konsumtionsbeteenden, särskilt den s.k. ”fast fashion”-industrin, har bidragit till att världens textilproduktion fördubblats sedan 1970. För att möta miljöutmaningarna behöver textilindustrin förändring inom både produktion och konsumtionsmönster. En förändring som behöver ske inom produktionen är att i högre grad använda, eller snarare återgå till att använda, hållbara råvaror för textil. Ett bra exempel på en sådan råvara är ull. Ull är ett naturligt material som har goda möjligheter att återanvändas, ett sätt att minimera miljöpåverkan.

Efterfrågan på ull stiger i Sverige, dock förses denna efterfrågan huvudsakligen genom import av ull, medan mer än hälften av den ull som produceras i Sverige slängs eller eldas upp. Det kommer sig av att den svenska ullen kommer från djur inom får- och lammköttsproduktionen, där ull är en biprodukt. Dock finns hinder på vägen som behöver hanteras för att stödja utökad användning av svensk ull och stärka expansionen av svensk ullindustri; som kvalitetssäkring, prissättning och infrastruktur för att bearbeta ullen. Det är i detta sammanhang även avgörande att bedöma ullens övergripande hållbarhetspåverkan med lämpliga metoder och ett systemperspektiv, där både miljö-, social och ekonomisk påverkan undersöks. Denna rapport är en del av projektet *The Swedish Wool Intitiative* som drivs av Axfoundation och finansieras av Vinnova och *Ull som resurs 2.0* som drivs av Hushållningssällskapet Halland och finansierats av Jordbruksverket. Den här delrapporten syftar till att granska de metoder som används för att bedöma hållbarheten i svensk ullproduktion idag, baserat på tillgängligt vetenskapligt och icke-vetenskapligt material.

Resultat

Djurhållningen och gårdsrelaterade aktiviteter står för de största utsläppen av växthusgaser inom fårproduktion samt ullprodukter därav, vilket flera oberoende studier visat. Metanutsläpp från djurens matsmältning står tillsammans med metan- och kväveoxidutsläpp från gödselhanteringen för den största klimatpåverkan. Växthuseffekter, försurning och nedbrytning av ozonlagret ingår i fårproduktionens följder. Användning av el och värme i bearbetning av ull står för större delen av ullens klimatpåverkan.

Behandling och hantering av ull kräver typiskt sett stora mängder vatten, men det varierar mellan olika producenter, länder och steg i tillverkningen. Dock är vattenanvändning inom svenskt jordbruk lägre än i andra länder vilket minskar vattenavtrycket för inhemsk foderproduktion. Bearbetning av ull och produktion av textilier inkluderar användning av diverse kemiska ämnen som kan orsaka föroreningar via tvätt, eller påverka människors hälsa genom hudkontakt. Dessa kemikalier och potentiella föroreningar behöver förstås och hanteras för att utveckla textilindustrin i en hållbar riktning, särskilt som få studier på ullproduktionens hållbarhet inkluderar detta perspektiv.

Biodiversitet påverkas på olika sätt av fåruppfödning, både positivt och negativt. Naturbetesmarker bidrar till biologisk mångfald och varierat landskap. Samtidigt finns också en negativ påverkan från insekticider, vattenförorening från åkergödsling och från gödselhantering. I

Sverige tenderar gårdar att tilldela mer mark för bete än för odling av grödor, vilket bidrar till bevarandet av mångsidiga landskap och livsmiljöer. När man jämför konventionella och ekologiska gårdar konstateras att konventionella gårdar förbrukar mer energi, främst relaterat till produktion av foder och syntetiska gödselmedel. När det gäller ullklädesproduktion ägnas en betydande mängd mark åt att skaffa råmaterial, medan energiförbrukningen ökar under bearbetning och tvättning. Genom att förstå dessa varierande effekter på markanvändning och energiförbrukning kan vi identifiera områden för förbättring och implementera mer hållbara metoder inom får-, ull- och klädesproduktionssektorerna. De olika negativa miljöpåverkansfaktorer som beskrivits här bör vara fokusområden för att utveckla hållbar får- och ullproduktion.

Svenska djurskyddsregler är mer strikta än i andra länder, vilket skyddar djur från smärta, främjar naturligt beteende och resulterar i lägre antibiotikaanvändning och färre medicinska ingrepp för djuren. Värdekedjor inom den Europeiska ull- och textilindustrin har identifierats ha färre risker sett till social påverkan jämfört med värdekedjor som lägger mindre fokus på hållbara och etiska metoder i produktionen.

Sammanfattning

Sammanfattningsvis ger denna studie en grundlig analys av hållbarheten för får- och ullproduktion i Sverige och andra länder. På grund av variation i metod och system är det inte helt enkelt att jämföra resultaten från denna studie med annan ullproduktion. Dock tyder resultaten på att svensk ullproduktion kan erbjuda lägre klimatpåverkan och fler positiva effekter jämfört med andra länders ullproduktion. Genom att förstå och utnyttja dessa fördelar kan vi arbeta mot att skapa ett mer hållbart och miljövänligt produktionssystem i landet. Vidare kartlägger denna rapport aktuella metoder och tillgänglig kunskap, vilket lägger grunden för mer detaljerade studier i framtiden och möjliggör för forskare och branschintressenter att bygga vidare på dessa resultat. Framtida forskning om svensk ull bör prioritera aspekter som klimatpåverkan, kemikalieanvändning, biologisk mångfald, resurseffektivitet, djurvälfärd och lönsamhet. En sådan övergripande strategi kommer att bidra till en ännu bättre förståelse av hållbarheten i svensk ullproduktion. Bättre förståelse möjliggör i sin tur informerat beslutsfattande och utveckling av riktade strategier för att förbättra branschens totala miljömässiga, sociala och ekonomiska prestanda.

Summary

This report is written within the Swedish Wool Initiative project, funded by Vinnova. The project aims at increasing the competitiveness for Swedish wool and contributing to a more sustainable and circular textile industry through developing circular products based on discarded Swedish wool. Apart from project leader Axfoundation, project partners include actors from the textile industry, supply chain as well as from research and innovation. The report describes the results of a working package focusing on the sustainability of Swedish wool.

The study aimed at looking into methodological choices applied in sustainability assessments of sheep and wool production, as well as to investigate results of sustainability impact assessments of the production. Based on this, the study aimed to highlight potentially missing aspects in previous assessments as well as to compare the impacts of Swedish production in relation to production in other countries.

For studies assessing wool at farm-gate, a functional unit of per kg of greasy wool was found to be a common choice. Using such functional unit has been criticized for not relating to the function of the fiber which for comparison should be expanded to include its quality and durability. For the reviewed assessments of woolen garments, these were commonly assessed from a cradle to grave perspective, with a functional unit including a definition of a specific weight as well as lifetime, which is preferable as this makes it possible to compare the function of different garments.

Concerning handling multi-functionality of production systems, most studies were found to apply one or several allocation strategies to distribute the environmental burdens between the by-products. The choice of allocation factors was found to vary substantially between the reviewed studies which had large implications on overall results. Studies covering Swedish production were found to apply a low or no allocation to wool, due to the low economic revenues of wool. In comparison, studies covering the production in other countries were found to use higher economic allocation factors. This was explained by a higher level of specialization of wool production in combination with larger extent of wool taken care of, which increase its economic revenues and thus allocation factors.

On comparing the environmental impact categories and indicators recommended by frameworks and the ones currently applied in the literature, large overlaps were found. Overall, all environmental impact categories recommended by the

reviewed frameworks were found to be used in the studied literature, although no single study was found to cover all aspects in either of the frameworks.

The indicators recommended by the studied frameworks were not always applied by the reviewed studies. For example, the impact category of land use and land system change is commonly investigated through assessing overall land use, but is recommended to include indicators on soil health by e.g. the Product Environmental Footprint guidelines.

In the workshop with actors from different parts of the supply-chain of Swedish wool, environmental perspectives given top priority included climate impact, chemical use in production, biodiversity and resource efficiency. Climate impact and resource use were found to be among the most applied indicators in the literature. Chemical use in production and biodiversity were on the other hand rarely assessed. Thus, future studies assessing the environmental sustainability of Swedish wool could ideally include these aspects. Few studies covering social and economic dimensions were found. The participants in the workshop highlighted animal welfare and profitability among top priorities of social and economic perspectives to be included in a sustainability assessment of Swedish wool.

No conclusions could be drawn on the climate impact of Swedish sheep or wool production systems compared to other countries, as the studies vary in analyzed production systems, as well as methodological choices, e.g. regarding the functional units and impact assessment method chosen. However, considering the low allocation factors assigned to Swedish wool in the identified studies, this result in substantially lower climate impact for wool up to farm-gate, compared to the results reported by other studies.

Swedish sheep farming has been highlighted to impact positively on several of the Swedish Environmental Objectives, e.g. through grazing animals sustaining biodiversity conservation of threatened species in Swedish semi-natural pastures. Another often lifted benefit for Swedish agriculture is the potential carbon sequestration due to grass ley production. However, several studies were found to highlight the same attributes to sheep and wool production in other countries worldwide, as the farming systems to a large extent are extensive pastoral-based systems. Regarding other potential benefits often highlighted for Swedish production of sheep and wool, these include animal welfare regulations. On comparing Swedish regulations to legislation and literature for other production countries, potential added values from Swedish production compared to other countries were found, e.g. with regards to use of veterinary antibiotics and medical interventions.

Sammanfattning

Den här rapporten är skriven inom ramen för projektet *The Swedish Wool Initiative*, som finansieras av Vinnova och drivs av Axfoundation. Projektet syftar till att öka svensk ulls konkurrenskraft och att bidra till en mer hållbar och cirkulär textilindustri. I projektet ingår olika aktörer från den svenska industrin och värdekedjan av svensk ull, samt aktörer från forskning och innovation.

Rapporten beskriver resultatet av ett arbetspaket inom projektet som har fokuserat på hållbarheten av svensk ull. Studien har syftat till att ge bakgrund till hur tidigare studier rapporterar kring hållbarheten av ull, dels vad gäller olika metodval som används, dels kring rapporterade resultat av hållbarheten. Baserat på detta lyfts i rapporten potentiella luckor från tidigare studier och pekar på vad som kan tas hänsyn till i framtida studier. Vidare görs en jämförelse mellan rapporterade resultat av svensk produktion och den i andra länder.

I genomgången av tidigare studier som undersöker hållbarheten av ull inom primärproduktionen och till gårdsgrind, fanns att en funktionell enhet per kg vanligtvis används. Att använda en funktionell enhet per kg har dock kritiserats då den inte tar hänsyn till funktionen av fibern. För en mer nyanserad jämförelse mellan olika fibertyper bör den funktionella enheten innehålla ett mått som relaterar till dess kvalitet och slitstyrka. För de studier som undersökte ullplagg användes vanligen en funktionell enhet som inkluderar en specifik vikt på plagget och som relaterar till dess livstid, vilket är att föredra eftersom det möjliggör att funktionen av olika plagg går att jämföra.

De flesta genomgångna studier hanterar allokering av biprodukter med en eller flera allokeringsmetoder för att fördela miljöpåverkan. Val av allokeringsfaktor visade sig variera stort mellan studierna och hade stor inverkan på resultatet. I de studier som rörde svensk lammproduktion allokerades ingen eller en mycket liten del av miljöpåverkan till ullen, på grund av den låga ekonomiska avkastningen för ull jämfört med lammkött och andra biprodukter. I studier som undersöker produktionen i länder såsom Australien och Nya Zeeland var allokeringen till ull betydligt högre. Detta kan förklaras av att en högre grad av specialisering skett mot att tillvarata både ull och kött, vilket ökar ullens ekonomiska värde och därmed de ekonomiska allokeringsfaktorerna.

Stora överlapp hittades i jämförelsen av de miljöpåverkanskategorier och indikatorer som rekommenderas av olika ramverk och de som används i litteraturen. Alla kategorier som rekommenderas av de genomgångna ramverken används i litteraturen, men ingen studie applicerar alla de rekommenderade

aspekterna. Många studier använder också andra indikatorer än de som rekommenderas av ramverken. Till exempel använder studier som undersöker markanvändning och förändrad markanvändning, ofta en indikator som baseras på total markyta, medan ramverk rekommenderar att en koppling görs mellan markanvändningen och dess påverkan på markhälsa.

En workshop hölls under projektet med dess medlemmar, med syftet att undersöka vilka fokusområden en studie av svensk ulls hållbarhet bör ha. Inom miljöpåverkan lyftes klimatpåverkan, användning av kemikalier, biologisk mångfald och resurseffektivitet som nyckelkategorier att ta med i en hållbarhetsanalys. Klimatpåverkan och resursanvändning var två av de kategorier som används mest i den genomgångna litteraturen. Däremot var det få studier som undersökte kemikalieanvändning och biologisk mångfald vilket är viktiga aspekter att ta hänsyn till i framtida studier av den miljömässiga hållbarheten av svensk ull. Det finns i dagsläget få studier som täcker sociala och ekonomiska dimensioner av hållbarhet av ull. Deltagarna på workshopen pekade på djurvälfärd och lönsamhet som prioriterade indikatorer som bör inkluderas i framtida studier av svensk ulls sociala och ekonomiska hållbarhet.

På grund av olika metodval kunde inga slutsatser dras från de svenska studier som undersöker klimatpåverkan av produktionen av lamm, jämfört med studier av produktionen i andra länder. Eftersom allokeringsfaktorerna för den svenska ullen däremot sågs vara betydligt lägre än andra länders produktion får svensk ull i dagsläget ett lägre klimatavtryck jämfört med den ull som produceras i andra länder.

Svensk produktion av får och lamm lyfts ofta som viktig inom flera områden i det svenska miljömålssystemet, till exempel vad gäller betande djur på svenska naturbetesmarker som bidrar till den biologiska mångfalden. Ett annat mervärde som ofta lyfts för det svenska jordbruket och produktionen av får och lamm är potentialen för kolinlagring i odlingen av vallgrödor. I flertalet studier som undersöktes inom projektet lyftes dock liknande aspekter för produktionen i andra länder, och inga slutsatser har kunnat dras om den svenska produktionen kan anses bidra till ökade mervärden i jämförelse med produktionen i andra länder. Vad gäller andra områden pekar resultatet från projektet att den svenska produktionen har potentiella mervärden mot andra länder inom djurhälsa och djurvälfärd, till exempel i fråga om den låga användningen av antibiotika och inom medicinska insatser i produktionen.

1 Introduction

Global textile production is associated with major environmental degradation, e.g. through climate change, chemical use, water scarcity and waste generation. Since 1970, the production has more than doubled globally due to the rising global population and its increased affluence, combined with the 'fast fashion' industry driving the production of less durable clothing (Peters et al., 2019). To reduce the environmental burdens from the sector, profound changes are needed both with regards production and consumption, which includes finding more sustainable textile alternatives (e.g. Sandin et al., 2019a). Within this context, wool has been highlighted as a biobased resource with the potential for circular material use and reduced environmental impacts (Axfoundation, 2021).

Sheep farming in Sweden has traditionally had its primary purpose in producing meat while wool until recently has been considered a low-value product (Svenska Fåravelsförbundet, 2021b). In recent years, the value of wool has increased, leading to a larger share being taken care of on Swedish farms. However, more than 50% of the 1000 tons of annual wool produced in Sweden is still being burnt, destroyed or disposed in other ways. At the same time, around 1650 tons of wool was imported to the Swedish market in 2019 to meet the growing demand for wool in Sweden (Svenska Fåravelsförbundet, 2021b). As such, the Swedish wool industry has large potential to increase its share on both the domestic and international market.

Main challenges of upscaling the use of Swedish wool include lack of sorting and quality assurance making it difficult to justify a higher price compared to imported wool, or fossil-based alternatives and cotton (Axfoundation, 2021). Other challenges include the poor domestic infrastructure for processing wool at a larger scale why Swedish produced wool primarily is shipped to other countries for further refining (Axfoundation, 2021). Moreover, although actors have highlighted Swedish animal farming to have potential environmental benefits compared to other countries (e.g. SBA, 2016), and lifted wool as a more sustainable alternative to synthetic fibers or cotton (e.g. Axfoundation, 2021), research on the sustainability impacts of Swedish wool is limited. Further, standardizations such as the Higg index (SAC, 2019), have claimed wool as having higher environmental impacts than e.g. fossil-based synthetic fibers. However, criticism has been raised against such comparisons having a too narrow sustainability approach including only a few environmental categories and on a global level, not covering site-specific impacts such as water availability or eutrophication. Moreover, the index has been claimed to rely on generalized data from a limited number of studies that may not be representative for global textile manufacturing (Watson and

Wiedemann, 2019). Hence, it is of importance to transparently assess the overall sustainability impacts of wool using appropriate methods. Further, to reduce the risk of burden-shifting between sustainability impacts, it is crucial to apply a systems perspective in a sustainability assessment of wool, including both environmental, social and economic sustainability dimensions.

1.1 Context of the report

This report is written within the Swedish Wool Initiative project, funded by Vinnova (Axfoundation, 2021). This report is the deliverable as a part of a larger project looking into several aspects of Swedish wool production. Contributing to the work with this report is Hushållningssällskapet and their project "*Ull som resurs 2.0 Halland*", founded by the European Agricultural Fund for Rural Development (Hushållningssällskapet, 2022). The project aims to increase Swedish wool's competitiveness and contribute to a more sustainable and circular textile industry by developing circular products based on discarded Swedish wool. Apart from project leader Axfoundation, project partners include actors from the textile industry, supply chain as well as from research and innovation. The report describes the results of a working package focusing on the sustainability of Swedish wool.

1.2 Aim and objective

The aim of the study was to look into methodological choices applied in sustainability assessments of sheep and wool production, as well as to investigate results of sustainability impact assessments of wool and sheep production. Based on this, the study aimed to highlight potentially missing aspects in previous assessments as well as to compare the impacts of Swedish production in relation to production in other countries. The study applied a systems perspective, including environmental, social and economic aspects. The report can be used by actors within the industry and supply chain of wool, as well as in research, when performing a sustainability assessment, as well as for interpreting sustainability assessments and understanding how the results can be used.

1.3 Structure of the report

The remainder of the report is structured as follows: Chapter 2 provides background to global and Swedish wool production, and presents the Life Cycle Sustainability Assessment (LCSA) methodology. Chapter 3 describes the methods used in the project. Chapter 4 and 5 are dedicated to results and discussion.

Firstly, Chapter 4 provides results and discussion on the findings on methodological choices within LCSA of sheep production and wool. Secondly, Chapter 5 presents and discusses the findings regarding sustainability impacts of sheep production and wool.

2 Background

2.1 Wool on the global fiber market

The global fiber market is dominated by fossil-based synthetic fibers with polyester covering 55% of overall market shares. Plant-based fibers is the second biggest fiber group, dominated by cotton with 27% of global market shares. Animal fibers constitute a small part of global market shares, with wool consisting of roughly 1% of the shares (Textile Exchange, 2021). Globally, largest production countries of wool include China and Australia which between 2015-2021 accounted for 20 and 19% of overall production respectively, followed by New Zealand and United Kingdom with 8 and 4% of the global production respectively (FAO, 2023).

2.2 Wool production in Sweden

Sheep has mainly been bred for meat production in Sweden (Svenska Fåravelsförbundet, 2020), resulting in wool being a by-product of low value often wasted (Axfoundation, 2021, Svenska Fåravelsförbundet, 2021b). However, the demand for wool is steadily increasing. Among the highlighted added values of wool, these include the materials' longevity, biodegradability and recyclability (e.g. Filippa K, 2016), as well as it being experienced as a natural product that regulates heat, is renewable and resistant to smell and dirt (Länsstyrelsen Stockholm, 2020).

Swedish wool production comprises a number of breeds of sheep (Figure 1). With a domestic production of little under 1000 tons in 2020, and an import of wool to Sweden from 2017 to 2021 of approximately 3000 tons, leaves the Swedish wool producer with a market share of approximately 25 % (SCB, 2022, Svenska Fåravelsförbundet, 2021b). The overall imports to Sweden between 2017 and 2021 are illustrated in Figure 2[1].

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[1] Here, production and demand consider greasy wool, carded wool, combed wool, and yarn for manufacturing in Sweden or abroad.

The Swedish high-end fashion brands' request for fine quality wool resulted in imported materials of 219 tons of washed raw wool mainly from New Zealand and 1240 tons of carded and spun material from other production countries, with the largest volumes originating from Norway, Peru, Germany and Turkey (Axfoundation, 2021, Svenska Fåravelsförbundet, 2021b). This indicates a significant potential of increased Swedish wool production to satisfy the demand.

However, even if the Swedish wool market is turning to face the national demand of wool fibers, it cannot respond to the requirements by increasingly taking care of the produce. Parts of the import is a consequence of the Swedish wool industry’s lack of infrastructure to prepare the wool (Axfoundation, 2021), resulting in a majority of the raw produce from Sweden being sent abroad for washing, carding and spinning, whereafter it is returned as yarn or cloth for the final production of garments. Washing commonly occurs in European countries such as Belgium, where the price is manifold lower compared to Sweden (SCB, 2022). Hence, there is great potential in developing the quality of Swedish wool by breeding and increasing the possibility for local handling of the raw material.

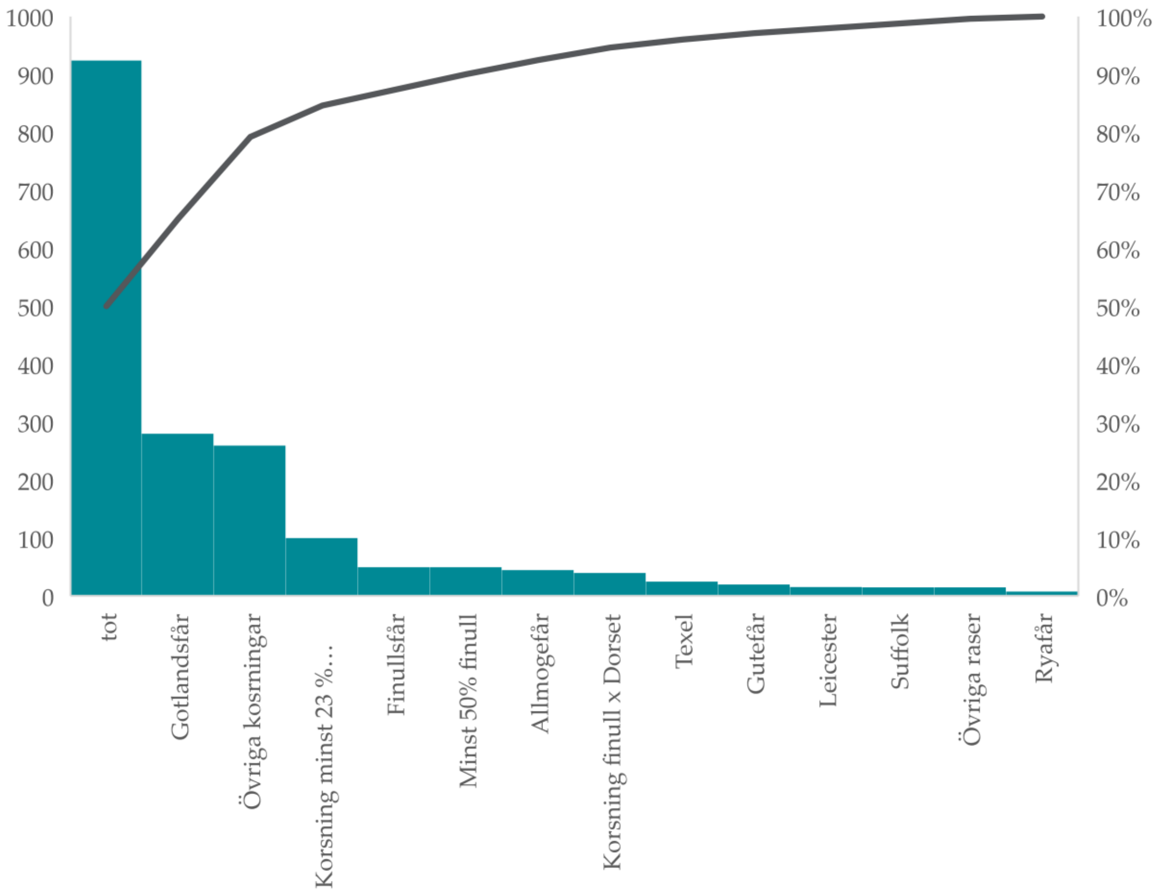

Figure 1: Depiction of Swedish wool production from different breeds of sheep (Svenska Fåravelsförbundet, 2021b).

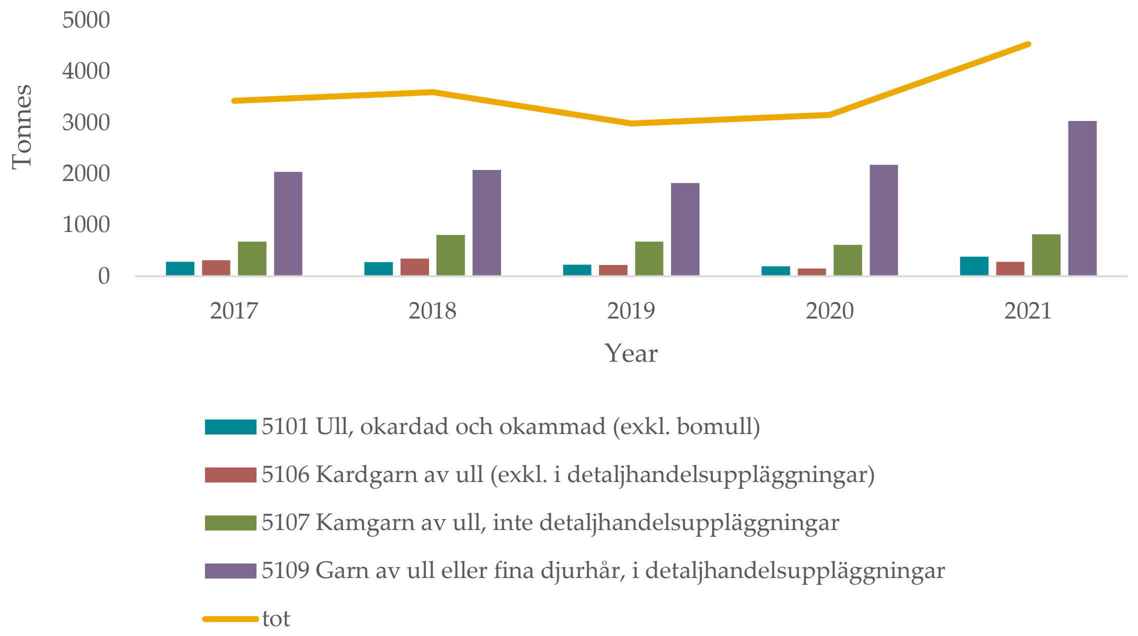

Figure 2: Import of wool to Sweden, data collected compiled for 2017 to 2021 (SCB, 2022).

2.2.1 The supply chain of Swedish wool

When applying life cycle thinking to the value chain of wool production, it can be divided into the activities shown in Figure 3. Wool production implies the breading of sheep, feeding them and maintaining good living conditions required for sheep. It is followed by shearing, which is most commonly done at the farm and mainly requires handcraft and electricity. After shearing follows a first assessment and sorting at the farm. After collecting the raw material, there is a step in sorting it based on quality and classification schemes. The raw material is then sold at a price corresponding to the quality and exported around the world.

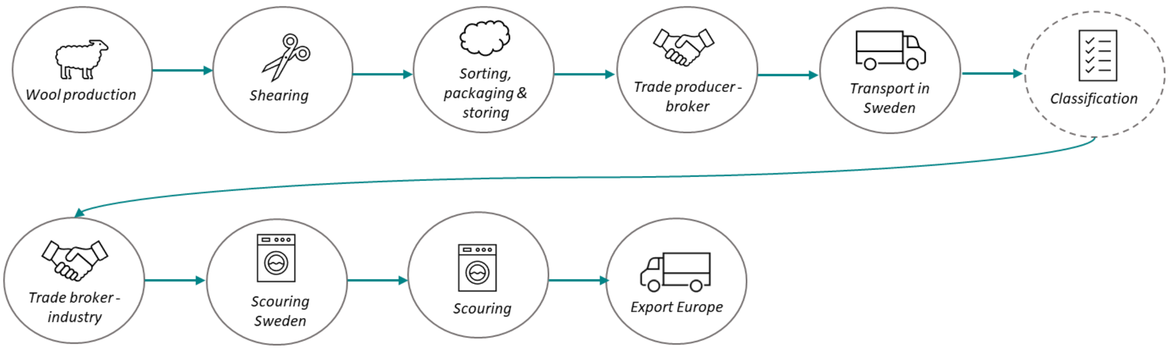

Figure 3. Lifecycle stages for the European wool market.

An overview of what goes into the first step of the primary production of wool is depicted in **Error! Reference source not found.**.

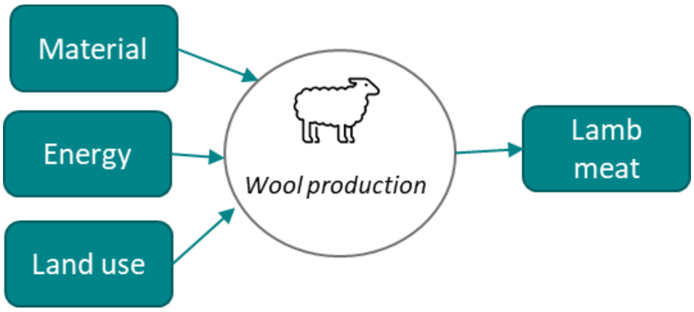

Figure 4: Inputs to breeding sheep in primary production of wool.

2.3 Life Cycle Sustainability Assessment

The concept of sustainable development was defined in the Brundtland report in 1987, and relies on the three pillars of environment, economy and social wellbeing (Brundtland, 1987). The last decades, numerous methods, tools and metrics have been developed to measure and assess the sustainability impacts of products. Life cycle assessment (LCA) is a method to investigate environmental impacts due to resource use and emissions associated with a product over its lifetime. Life cycle costing (LCC) focuses on the aggregated costs associated with the product's life cycle, while social LCA (S-LCA) looks at the social consequences. Together, the three methods of LCA, LCC and S-LCA form a LCSA (e.g. Finkbeiner et al., 2010, Ciroth et al., 2011, Valdivia et al., 2021). Performing a LCSA thus allows for a combined assessment of the three sustainability pillars of environmental, economic and social wellbeing associated with a product, and allows for identification of potential trade-offs between the three dimensions (Ciroth et al., 2011).

2.3.1 Life Cycle Assessment methodology

LCA methodology has been standardized by the International Organization for Standardization, ISO (ISO, 2006a, ISO, 2006b). According to the ISO standards, an LCA consists of the four iterative phases:

- Definition of goal and scope, where one describes the studied product system, the purpose of the study and the methodological choices such as functional unit, system boundaries and allocation procedures (see further Section 2.3.3)
- Life cycle inventory, where one collects data on emissions and resource use related to the studied product system
- Life cycle impact assessment, where one classifies and characterizes inventory data according to their environmental impact

- Interpretation of results, where one evaluates the outcomes of the study and discusses the uncertainty and sensitivity of the results

Apart from the ISO standardizations on LCA methodology, several other standards have been developed including the Product Environmental Footprint (PEF) standard by the European Commission (2021). Based on the PEF, product category rules (PCR) within the PEF (PEFCR) have been developed to guide assessments of the environmental impact of specific products or product groups, including t-shirts (European Commission, n.d.). Furthermore, a PEFCR for apparel and footwear is currently under development (Quantis, 2021). Product category rules have also been established under the International Environmental Performance Declarations (EPD) system (The International EPD System, n.d.-b). No specific PCR has yet been developed for wool but wool is included within PCRs related to animal products, as well as fabrics, yarn and apparel. With regards to other standardization specifically for wool, this is further elaborated upon in Section 2.4.

2.3.2 Social Life Cycle Assessment and Life Cycle Costing methodology

S-LCA and LCC have similar perspectives and aims as LCA and shall follow the principles of ISO 14040 with the four phases stated above in Section 2.3.1 (Valdivia et al., 2021). Guidelines for S-LCA have been developed by UNEP/SETAC (Benoît Norris et al., 2020, UNEP-SETAC, 2009), and by SETAC (2011) for LCC.

2.3.3 Methodological choices within Life Cycle Sustainability Assessment

In the following sections (2.3.3.1-2.3.3.4), some of the key concepts when using LCSA methodology are described.

2.3.3.1 Functional unit

In a LCSA, the 'functional unit' describes the function or the utility of the studied product in a quantitative manner and is the reference to which the inflows and outflows (e.g. emissions and resource use in an LCA) from production are related. With regards to the functional unit in a S-LCA of a product, it is recommended that it includes both a description of the technical and social utility (Benoît Norris et al., 2020, UNEP-SETAC, 2009).

For LCAs studying animal systems such as sheep meat, a functional unit of per kg of meat is often used (e.g. Ahlgren et al., 2022). Similarly, for LCAs assessing the environmental impact of fibres or fabrics, a functional unit of per kg or m^2 may be applied respectively. For example, in the PCRs on yarn and fabrics by the International EPD System (n.d.-b), the functional units of per kg and per m^2 are used respectively. Using a functional unit based on mass or size has however been highlighted to not relate to the function of a fibre which for comparison should be expanded to include its quality and durability (e.g. Watson and Wiedemann, 2019). Rather, if the mass is not related to the function, studies could report findings on lower environmental impact due to minimised mass, but at the expense of durability. Including quality in the functional unit would facilitate demonstrating sustainability benefits of durable fibres, and those with the possibility to be recycled. In Sweden, current market of domestically produced wool mainly include high quality wool while large volumes of wool of lower quality goes to waste. In order to take care of larger volumes of different wool qualities, and to get the appropriate quality of wool for right area of use, a quality assurance framework including a classification system for Swedish wool has been developed by Axfoundation. Future LCSA assessing the sustainability of Swedish wool could investigate the possibilities to apply the quality framework in the functional unit chosen for the study.

Further, to assess the sustainability impacts of a garment, it is possible to assess the impacts per garment, e.g.' one t-shirt', or 'one pair of jeans' (e.g. Sandin et al., 2019b). This is also the required functional unit in the PCRs for apparel by the International EPD System (n.d.-b). However, as different garments provide different functions, it can be preferable to extend the functional unit to include the number of years of serviceable life for the garment (Watson and Wiedemann, 2019). Following the PEFCR for apparel and footwear (Quantis, 2021), a functional unit of 'one day of wear' shall be used, which also allows for studying functional improvements such as benefits of prolonged life time due to e.g. changed consumer behaviour.

2.3.3.2 System boundaries

The 'system boundaries' of a LCSA define the parts of the product system that will be included in the assessment, i.e. which processes or activities are to be included. Ideally, the system boundaries should embrace a cradle to grave perspective, including the extraction of resources, production, further processing, packaging, transportation and end-of-life. However, the boundaries may be modified depending on the aim of the study, available resources, and data limitations, not allowing for an assessment of the entire life cycle.

Performing a full LCSA might result in a more extensive choice of system boundaries than would be the case if applying each technique (LCA, S-LCA or LCC), individually. For example, when performing an LCC, the system boundary would typically include the working hours, cost and prices of a company's staff, or farm for the case of wool production. For a S-LCA, the working hours of the staff and their salaries might be relevant for the scope, while for studying the environmental impact in an LCA, such activities might be less relevant as these do not affect the resource use or emissions (Ciroth et al., 2011).

The PCR for fabrics by the International EPD System states processes' cradle to gate' as mandatory for inclusion, but subsequent processes may be excluded. For the PCRs on yarn and apparel, processes from 'cradle to grave' should be included (The International EPD System, n.d.-b). Following the PEFCR for apparel and clothing (Quantis, 2021), system boundaries shall be applied from 'cradle to cradle', i.e. including raw material production, manufacturing, distribution, use and end-of-life.

The choice of system boundaries can have large implications on the end results, depending on which sustainability category that is studied. Sandin et al. (2019b) showed that 80% of the overall climate impact of the clothing purchased and used by the average Swede is associated with the production stage, while only 3% relates to the washing after use. However, regarding other impact categories and certain garments, the washing might have a substantial impact, e.g. concerning water use and release of microplastics (Watson and Wiedemann, 2019). The washing impacts may also vary widely depending on location (Roos et al., 2017). Thus, exclusion of the use stage may result in burden shifting for fabrics with lower impacts in the production stages, but higher impacts in the use stage (Watson and Wiedemann, 2019).

2.3.3.3 Allocation

Some product systems generate multiple outputs, e.g. a main product and several by-products. In LCSAs, the sustainability impacts in such multi-output production systems are commonly divided, or 'allocated' between the various outputs (Ciroth et al., 2011). With regards to wool, it is produced in sheep production systems delivering a variety of outputs such as meat and skins, as well as hides, offal and blood from slaughter.

The ISO standardization on LCA (ISO, 2006a, ISO, 2006b) states that allocation primarily should be avoided. This could be done either by dividing the multifunction product system into sub-processes and collecting separate data for each sub-processes or expanding the investigated systems until all systems deliver the same functions. As this may not always be feasible, the standard recommends allocation as a second-best option, based on physical relationships between the outputs, e.g. based on mass or energy content of the these. Otherwise, the standard recommends using allocation based on the economic revenues of the outputs. When using economic allocation, allocation factors can preferably be calculated as an average of a longer period if market prices fluctuate.

In the PCRs for yarn and apparel by the International EPD system, allocation according to the steps in the ISO 14040 (2006a) is advocated. With regards to the PCR for fabrics, specific biophysical allocation rules based on protein requirements for the different outputs are required (The International EPD System, n.d.-b). In the PEFCR for apparel and footwear (Quantis, 2021), allocation based on mass or volume is advised for processes throughout the life cycle of the products. The discussion of allocation procedures is relevant when quantitative data is used, while in S-LCA this might not be the case as more qualitative data may be used.

2.3.3.4 Impact categories, indicators and assessment methods

In the impact assessment, the inventories (e.g. the emissions and resource use in an LCA) are classified and characterized according to their impacts. For each impact category, one or several indicators may be applied. Further, to assess the impacts of the collected inventory data, an assessment method is chosen for each indicator.

When performing an LCSA, it is recommended to include all relevant impact categories throughout the life cycle of a product and within all three sustainability perspectives, i.e. including the environmental, social and economical dimensions. By doing so, potential trade-offs between different impact categories can be identified which may help to avoid burden-shifting between the categories (Ciroth et al., 2011, Valdivia et al., 2021).

With regards to environmental LCA, the PEF includes 16 different impact categories (see more in Section 4.2) which are required to be used when following the PEFCR on apparel and clothing (Quantis, 2021). The International EPD system lists 17 required environmental performance indicators which may be extended according to the scope for the EPD (The International EPD System, n.d.-a).

The UNEP-SETAC guidance on S-LCA (Benoît Norris et al., 2020), addresses 6 main impact categories based on a stakeholder approach, i.e. addressing the potential impacts on different social actors such as workers, consumers and children (see more in Section 4.2). Each impact category is further divided into subcategories for which one or several indicators are suggested. For example, the 'Impact on workers' category contains 8 subcategories: child labour, fair salary, working hours and forced labour. Then, for the subcategory of 'child labour', an assessment can be made using the indicators of 'hours of child labour', or 'percentage of child labour in the workforce'.

Regarding LCC, the impact assessment differs from the LCA and S-LCA as the collected inventory data is measured in a specific currency, but does not need to be characterized or weighted according to an impact. Instead, the costs only need to be aggregated by different cost categories (Ciroth et al., 2011).

Several methods may exist for assessing the same indicator. For example, when assessing the impacts of emissions and resource use in an environmental LCA, available assessment methods may consider either global or site-dependent impacts. GHG emissions leading to climate change cause global impacts and are not dependent on site, and methods for assessing climate change are site-independent (Finnveden et al., 2009). On the other hand, water scarcity may vary substantially within a country and it is recommended to assess the impacts of water use by accounting for the availability in a specific watershed (Boulay and Lenoir, 2020). However, there are also methods available for assessments related to impacts of water use on a global or national level, if data on water use on a detailed level is scarce.

Assessment methods also differ in whether they consider impacts on a 'midpoint' or 'endpoint' level (e.g. Finnveden et al., 2009, Benoît Norris et al., 2020). For example, the environmental impacts of fertilizer use in agricultural systems may be evaluated at the midpoint level as eutrophication of marine and terrestrial ecosystems. On an endpoint level, methods may focus on the damage to ecosystems caused by fertilizer use and subsequent eutrophication (Cosme and Hauschild, 2017). Likewise, assessing impacts on workers in a S-LCA on a midpoint level may be carried out by using impact categories related to wage level, while this could be assessed as the standard of living, using an endpoint impact method (Benoît Norris et al., 2020).

When assessing the environmental category of climate change, the impacts of different greenhouse gases (GHGs) are commonly assessed by midpoint modelling using the Global Warming Potential over a 100- year time horizon (GWP_{100}). Using this method, the GHGs are weighted according to their impact on the 'radiative forcing', which is the net change in the energy balance of the Earth system. The impacts of other gases than carbon dioxide (CO_2) are weighted relative to the impact of CO_2, from which the weighted measure CO_2 equivalents (CO_2eq.) is obtained. The impacts of different GHGs can also be evaluated by assessing the GWP over different time horizons or using alternative metrics.

In agricultural systems such as sheep and wool production, methane (CH_4) is an important GHG. Using the GWP_{100} assigns an impact to CH_4 about 27 times higher than CO_2 (Forster et al., 2021). Criticism has been raised on using the GWP metric in general, and particularly for animal production systems, assigning it a higher impact than e.g. virgin polyester or cotton associated with large emissions of fossil-based CO_2 (e.g. Haeggman et al., 2018). While CH_4 is a short-lived GHG which is broken down in the atmosphere after 12 years, CO_2 accumulates in the atmosphere. Therefore, if constant emission levels of CH_4 are generated, emissions and removals will be at approximately a constant level, causing no additional warming over time. On the other hand, constant emissions of CO_2 will lead to additional warming due to the accumulation in the atmosphere. Using the GWP measure over a fixed 100-year time horizon has been criticized for failing to consider the contrasting impacts these gases have on temperature change after 100 years. Using a short time scale such as 100 years of less emphasize the impacts of CH_4 and signal a need of early mitigation of the GHG. Applying a longer time frame instead, signal the necessity of stabilizing temperature change in the longer run, which thus gives smaller value to CH_4 and the focus is then instead on reducing the emissions of CO_2. Alternative metrics have been suggested to better account for differences between GHGs, including the GWP* (Lynch et al., 2020). Instead, using the GWP* gives weight only to additional emissions of short-lived GHGs such as CH_4. Still however, the GWP is recommended to be used in LCA studies, e.g. by the ISO standardization and is the metric of choice in the PEF (European Commission, 2021).

2.4 Frameworks and schemes for assessing environmental information

The demand for sustainable products is increasing, and companies are required to fulfil their responsibility and provide adequate information to their customers on the performance of their products. Certifications can be a great tool to communicate sustainability performance to consumers, contributing to their willingness to pay for and purchase goods. However, in 2019, less than 3% of the wool on the world market had some kind of certification or label in accordance with a standard (Textile Exchange, 2022). Tables 1-2 list the most commonly used frameworks and schemes and some important factors of these, such as their intended function, what part of the value chain they are used for, as well as the sustainability aspects in focus of the frameworks and schemes.

Most frameworks or schemes have a third-party verification and apply some kind of LCA methodology or life cycle thinking to their approach. However, few of them evaluate all three pillars of sustainability. Rather, the focus is often on GHG emissions and for some, the focus is extended to include animal welfare. The main usage of the frameworks and schemes is for communication with consumers, even though a few mention the possibility of improvements in the supply chain.

Frameworks and schemes focusing solely on environmental impacts include the PEF, MADE-BY and EPD. If further social aspects of animal welfare and workers conditions are included in the evaluation for a certifcate, this could potentially benefit the Swedish production as well as other countries production that can withold high standards within the areas reviewed (see further discussion of potential added values of Swedish animal welfare in Section 5.2.5). However, it does not favour wool fibers or other natural fibers prior syntheic ones. Frameworks and schemes including further social aspects include Higg, ZQ, SustainWool, Kerrings and GOTS.

The Higg index has gained critique for scoring natural fibres low in comparison to synthetic, which is partly explained by choices of input data and the scope set up for evaluation (Watson and Wiedemann, 2019). As stated in Section 2.3, the exclusion of the use stage might favour fabrics with lower environmental burden during production but with higher impacts in the use stage.

Further analysis is required to establish the function and usefulness for certifiers, producers and customers of the frameworks and schemes. It would also be important to investigate if the application of the frameworks and schemes improves the sustainability performance in wool production at a larger scale.

Table 1. Summary of methodological choices within frameworks and schemes for textiles and wool.

	Higg index	PEF	MADE-BY	EPD	PCR	ZQ
Launch	2011	2013	2020	1997		2007
Organisation or operation responsible	SAC	EU	MADE-BY	EPD International	EPD International	NZM
Supposed user	Three tools for: products, facility or brand & retail	Any company within the product value chain		Supplier of product or service	Same as EPD	Brands using wool fibers
Function	Communication	Improve own supply chain, comparison, and communication	Ranking and environmental benchmarking of fibers	Communicate environmental performance, improve supply chain	Same as EPD	Establish blueprint for global best practices in wool production
Part of the value chain	Entire value chain	Product or service, entire value chain included	Primary production	Product or service, entire value chain included	Same as EPD	Cradle to gate
Establishing/spread	Available in 100 countries, 21 000 organizations as users			100 000+ published EPDs over all product categories	Same as EPD	Available through contracting to ensure quality, consistency and price stability for brands and growers, mainly New Zealand and Australia but also

						South Africa and Argentina
Focus (sustainability aspects)	Environmental and social performance	Environment	Environment	Environment	Same as EPD	Environmental and social performance, the main focus on ethics
Method (based on other standards or similar)		Follows PEFCR, life cycle-based	Based on LCA data	Full LCA calculation according to corresponding PCR with mainly empirical data gathered by the supplier	The basis for the EPD method	Farmers sign up for the ZQ program, and calculations and data collection is LCA based.
Output	Points, a lower score is considered good	A PEF study provides recommendations on improving the product's environmental impact along its life cycle.	Five classifications—Class A to Class E. Fibers for which not enough data was available to have been listed as Unclassified.	Certification and report of environmental performance	The basis for EPD certification	Certification
Review process	Third-party review	Independent external review		Third-party review	Third-party review	Third-party verification every 3 years

Criteria used	Three different tools with up to 11 environmental and 16 social impact categories	16 environmental impact categories	6 environmental impact categories	5 environmental parameters and 6 resource use parameters. Result from the upstream, core and down stream processes.		

Table 2. Summary of methodological choices within frameworks and schemes for textiles and wool.

	SustainaWool	ZQRX	Textile Exchange's Responsible Wool Standard RWS	Kerings database	Global Organic Textile Standard GOTS
Launch	2015		2016	2017	2002
Organizations behind	AWEX (Australian wool exchange)	NZM	Textile Exchange		Non-profit, self-financed
Supposed user	Farmers/producers		Primary production of wool, contractors and retail	Suppliers who work with brands within the Kering Group	Clothing brands using natural fibres
Function	Benchmark minimum sustainability standards for wool practice in Australia		The global benchmark for animal protection and ag in sheep farming.		Information to consumers
Part of the value chain	Wool production, primary production	Cradle to gate	Cradle to gate		Post-harvest processing (spinning, knitting, weaving, dyeing, and manufacturing)
Establishing/spread	Application in Australia, recognition globally	ZQRX is only available via contracts to ensure quality, consistency and price stability for brands and growers, mainly NZ and Australia	Available on the open auction market or through negotiated NZM contract		12 338 certified facilities

Focus (sustainability aspects)	Environmental and social	"Framework" focus on regenerative mindset, continuous improvement, and net positive outcomes	"Certification" focus on process, requirements, and compliance	Environment and social	Ecological and social
Method (based on other standards or similar)	ISO-certified				
Output	Certification	Certification	Certification		Certification
Review process	Third party (ISO)	Initial assessment completed by NZM Team Quantitative indicators will be calculated and substantiated by third party verification	Third party verification every 3 years		Have a committee with more than 300 reviewers
Criteria used	6 pillars: 1. Sheep health and wellbeing 2. Environmental management & farm facilities 3. Competence & record keeping 4. Wool quality & clip preparation 5. Social responsibility 6. Traceability	ZQ plus regenerative index. ZQRX takes a holistic approach to regenerative agriculture and encompasses 15 key performance indicators across the environment, animals and people		Minimum: the best effort to traceability, Kerings animal welfare standards, respect human rights and social standards in Kerings code of ethics Additional conditions: Achieve traceability, prioritize the use from Kering's Preferred sources, ensure animal welfare practices aligned with Kering Standards, ensure land management and grazing practices are sustainable, use recycled/regenerated when possible	Fibre Requirements Chemical Inputs & Processing Requirements Environmental criteria Traceability

3 Material and methods

3.1 Literature review

To explore the methodological choices and sustainability impacts associated with sheep and wool production, a literature review was conducted using the scientific search engine Scopus, Science Direct and Web of Science in March and April 2022. Apart from the search amongst scientific literature, a complement of grey literature from the project partners and a search in regular search engines complemented the reviewed material. The literature review covered studies from 2011 or more recently. Keywords used in the search were wool, LCA, sustainability, environmental impacts, primary production, lamb, lam meat, mutton and sheep. It was an iterative process to unveil as many studies as possible covering environmental impacts in several lifecycle stages in wool production. The number of scientific articles on wool produce is limited and therefore grew to include those of lamb meat, as wool often is seen as a by-product, and impacts are allocated between the outputs.

Moreover, commonly applied frameworks and guidelines were investigated for the choice of relevant impact categories and indicators in a life cycle sustainability assessment in wool production. This included the Planetary Boundaries (PB) framework (Rockström et al., 2009, Steffen et al., 2015), the European guide for PEF (European Commission, 2021), the United Nations Environmental Programme and Society of Environmental Toxicology and Chemistry (UNEP-SETAC) Life Cycle Initiative guide for social life cycle assessment (UNEP-SETAC S-LCA) (Benoît Norris et al., 2020, UNEP-SETAC, 2009) and the SETAC Environmental Life Cycle Costing guidelines (SETAC, 2011). The frameworks and guidelines were chosen because of their widespread impact and importance in research and policy.

3.2 Open Space workshop

The findings in the literature review (Section 3.1) were complemented by a workshop including 26 participants representing the Swedish textile industry, the supply chain of wool, as well as research and innovation. The aim of the workshop was to capture impact categories and indicators considered important by these actors. The workshop followed an 'Open Space' structure, aiming to generate creativity and informal discussions on a specific theme (Owen, 2008). The idea of such a workshop format is to function without a predestined agenda and organize itself with the workshop participants.

The workshop started with the participants individually generating ideas for indicators and aspects they consider important to include in a sustainability assessment of wool in general, and Swedish wool in particular. The participants were asked to consider both quantitative and qualitive indicators and aspects, and to include environmental, social and economic perspectives. The ideas were posted on a wall and presented for the whole workshop group, and the indicators and aspects were grouped in categories, from which a schedule for group discussion was generated. The participants were divided into smaller groups where each group were assigned a share of the indicators and aspects for a more in-depth discussion. After the group discussions, the ideas from the groups were shared in the whole workshop group. Finalizing the workshop, each participant was given 6 Yes- and 3 No-votes to distribute freely among the indicators and aspects to indicate what they considered important to account for in a sustainability assessment of wool.

4 Methodological choices within Life Cycle Sustainability Assessment of wool

This chapter presents and discusses results on methodological choices within LCSA on wool based on findings in the literature and the workshop with actors from the supply-chain of wool. Section 4.1 focus on choices of functional unit, system boundaries and allocation, while Section 4.2 looks into choices of impact categories, indicators and aspects.

4.1 Functional unit, system boundaries and allocation factors

4.1.1 Findings from the literature review

Table 3 summarizes the findings of methodological choices of studies assessing the sustainability impacts of wool fabric, yarn or garment, including choices of functional unit, system boundaries and allocation factors.

Table 3. Findings from the literature review on methodological choices.

Study	Description of study	Functional unit	System boundaries	Allocation method and factors applied
Ahlgren et al. (2022)	LCA of sheep meat production systems in Sweden, including autumn, winter and spring lamb	1 kg of lamb meat, slaughter weight	Cradle to slaughter house (including energy use at slaughter)	Economic, 5-year average, 76-96% to meat, 0.3-0.7% to wool, 3.7-20% to hides, 3.5-4% to other by-products from slaughter
Bianco et al. (2022)	LCA of recycled wool fiber produced by an Italian textile company	1 kg MWool® (recycled wool fibre)	Cradle to gate (collection of waste wool, processing, transportation, new production)	Circular Footprint Formula (European Commission, 2021)
Geß et al. (2022)	LCA and LCC of lamb meat production systems in Germany, Italy, Portugal, Slovenia, Spain and Turkey, including extensive, semi-extensive, semi-intensive and intensive management	1 kg of lamb meat	Cradle to slaughterhouse	Wool and other non-meat by-products counted as waste. Gain in electricity and energy from waste incineration of waste credited to the overall results.
Wiedemann et al. (2022)	LCA of a recycled wool blend sweater produced in Australia	1 garment (recycled wool blend sweater) over its lifetime, with impacts reported per wear event in Europe	Cradle to grave	Circular Footprint Formula (European Commission, 2021)

Martin and Herlaar (2021)	LCA and S-LCA of sweater production using waste wool	1 mid-weight (600 g) sweater produced from waste wool in the new value chain available for retail	Cradle to gate (collection of waste wool, processing, new production, transportation)	
Geß et al. (2020)	LCA of lamb meat production systems in Italy, including one semi-extensive and one semi-intensive	1 kg of lamb meat	Cradle to slaughterhouse	Wool and other non-meat by-products counted as waste. Gain in electricity and energy from waste incineration of waste credited to the overall results.
Wiedemann et al. (2020)	LCA of a wool sweater	1 garment (unisex, lightweight woollen sweater containing 300 g of fine Merino wool, fibre diameter < 20 μm, which is breathable and odour repellent) used for a single wear event	Cradle to grave	Biophysical (protein mass) allocation between wool and sheep, 71% to meat, 29% to wool. Mass allocation between wool and wool grease separated during scouring, 92% to wool, 8% to wool grease
Sánchez et al. (2018)	Comparative LCA of a wool and a polyester sweater	1 wool sweater with a lifetime of 5 years (0.265 kg)	Cradle to grave	Economic between meat and wool
Cottle and Cowie (2016)	LCA of Australian sheep and wool production, evaluating methods to handle co-product allocation	1 kg of greasy wool at the farm gate	Cradle to farm gate	Allocation between lamb, mutton and wool using 4 different allocation methods (mass, protein mass and economic allocation, as well as system expansion), 35-86% to meat, 14-65% to wool

O'Brien et al. (2016)	LCA of Irish sheep production systems, including lowland and hill farms	1 kg of sheep live weight sold	Cradle to farm gate	Economic allocation between lamb meat, wool and other by-products
Wiedemann et al. (2016)	LCA of three wool types produced in different regions in Australia, evaluating methods to handle co-product allocation	1 kg greasy wool at the farm gate	Cradle to farm gate	Allocation between greasy wool and lamb meat based on biophysical allocation and system expansion, 53-65% to meat, 35-47% to wool
Wiedemann et al. (2015a)	LCA of Australian sheep meat export to the United States	1 kg of retail ready cuts of Australian lamb, at the regional storage centre in the United States	Cradle to regional storage center	Biophysical allocation between sheep and greasy wool, 71% to meat, 29% to wool
Wiedemann et al. (2015b)	LCA of lamb meat produced in Australia	1 kg LW		Allocation between lamb meat and greasy wool based on protein mass allocation
Wiedemann et al. (2015c)	LCA of sheep meat and wool produced in New Zealand, evaluating methods to handle co-product allocation	For lamb meat: 1 kg of LW at the farm gate For wool: 1 kg of greasy wool at the farm gate	Cradle to farm gate	Allocation between sheep meat and wool using 7 different allocation methods (protein requirements, partitioning of digested protein, protein mass allocation, economic allocation, two different system expansion methods), 48-96% to meat, 4-52% to wool

Jones et al. (2014)	LCA of sheep production systems in England and Wale, including lowland, upland and hill farms	1 kg live weight	Cradle to farm gate	Economic, 97.7% to meat, 2.3% to wool
Brock et al. (2013)	LCA of wool produced in Australia	1 kg greasy wool	Cradle to farm gate	Economic allocation, 44% to the culled stock and surplus young ewes sold, 56% to wool
Ripoll-Bosch et al. (2013)	LCA of sheep production in Spain, evaluating multifunctionality of sheep production and ecosystem services	1 kg of lamb meat, slaughter weight	Cradle to farm gate	Economic allocation between lamb meat and ecosystem services (e.g. biodiversity conservation). No allocation to wool due to assumed low value. 54-74% to meat, 26-46% to ecosystem services.
Eady et al. (2012)	LCA of Australian sheep and greasy merino wool, evaluating methods to handle co-product allocation	1 kg greasy merino wool	Cradle to farm gate	Economic and biophysical allocation
Bevilacqua et al. (2011)	LCA of a wool sweater	1 sweater of 100% merino wool, four colours, 2009 winter collection, 264.85 g net weight	Cradle to grave	
Ledgard et al. (2011)	LCA of lamb meat production in New Zealand, exported to United Kingdom	1 kg of processed lamb meat from New Zealand, purchased by a consumer.in the United Kingdom	Cradle to consumer, including cooking and waste	Biophysical and economic allocation (5-year average between lamb, mutton, wool

Wallman et al. (2011)	LCA of Swedish sheep production systems, including conventional production with indoor winter lamb and outdoor spring lamb systems, as well as organic production with outdoor lamb breeding or mixed systems	1 kg lamb meat, carcass weight	Cradle to retail distribution center	Economic, 62% to meat, 38% to hides

For the reviewed studies covering the environmental impacts of wool, the functional unit was for all studies found to be specified with regards to the weight of per kg of wool. Furthermore, all reviewed studies regarding wool specify that the focus is on greasy wool. As discussed in Section 2.3, using a functional unit based on mass or size does not relate to the function of a fibre which for comparison should be expanded to include its quality and durability.

For the woolen garments, all of which were found to be sweaters, the details in the functional unit vary. Many of the studies define a specific weight of the sweater, as well as the lifetime. For example Sánchez et al. (2018) define a functional unit of "1 wool sweater with a lifetime of 5 years", which then is further specified to have a weight of 0.265 kg. Wiedemann et al. (2020) define a functional unit "1 garment, used for a single wear event" which then is further specified to be a unisex, lightweight woollen sweater containing 300 g of fine Merino wool, fibre diameter < 20 μm, which is breathable and odour repellent. As discussed in Section 2.3, the functional unit should preferably include the number of years of serviceable life for the garment to consider the different functions provided by different garments.

With regards to the choice of system boundaries, the reviewed studies focusing on per kg greasy wool were all found to employ a cradle to farm gate perspective. For the woollen garments, system boundaries were in the majority of studies chosen to cover impacts from cradle to grave. For the studies investigating the environmental impacts of garments made of recycled wool, these were found to employ system boundaries from cradle to gate, i.e. from the collection of the waste wool, including processing, transportation as well as the production of the sweater. As discussed in Section 2.3, the system boundaries should ideally include a cradle to grave perspective to avoid burden-shifting between different stages in the life cycle. Wiedemann et al. (2020) argue garment lifetime to be the most influential factor to the environmental impacts of woollen garments, showing the implications on reduced environmental impacts by increasing garment lifetime, as the impacts from wool production and garment manufacturing would be amortized over a longer time period when the lifetime of the garment is extended. Thus, Wiedemann et al. (2020) argue the importance of accounting for the impacts of the use stage.

Concerning handling multi-functionality, most studies applied one or several allocation strategies. The choice of allocation factors varies greatly between the reviewed studies which has large implications on overall results (more elaborated upon in Section 5.1). The allocation factor for wool range between 0.3-0.7% in the study of Swedish lamb meat production by Ahlgren et al. (2022), up to 65% in the study of Australian wool production by Cottle and Cowie (2016), both studies employing economic allocation. A higher level of specialization of wool production in combination with larger extent of wool taken care of, increase its economic revenues and thus the economic allocation factors. While e.g. the ISO standard (ISO 2006a, 2006b) does not recommend economic allocation as a first choice (Section 2.3), it is applied in various of the identified studies and is argued as suitable as it shows the drivers of production. The downside of using economic allocation includes potential large fluctuations in price over years, causing results to vary over time (Wiedemann et al., 2015c). Apart from economic allocation, several of the identified studies applied allocation based on mass, thus distributing the largest share of the sustainability impacts to the heaviest co-product. Another common allocation choice was the one based on protein mass, i.e. mass of protein in wool in relation to that in the live weight of sheep or lamb, applied by e.g. Wiedemann et al. (2015c) who argues allocation based on biological processes to be preferable to economic allocation as these are more stable over time. As discussed in Section 2.3, using biophysical allocation are also the choice in e.g. the PCR for fabrics (The International EPD System, n.d.-b).

4.2 Impact categories, indicators and aspects

4.2.1 Findings from the literature review

4.2.1.1 Environmental impacts

Table 4 summarizes the environmental impact categories and indicators recommended in commonly applied frameworks (including the PB and the PEF) as well as in the literature.

Table 4. Summary of environmental impact categories and indicators recommended in the frameworks of the PB (Steffen et al., 2015, Rockström et al., 2009) and the PEF (European Commission, 2021), as well as those used in the literature.

Main environmental category	Environmental indicator		
	PB	PEF	Literature
Climate change	Atmospheric concentration of carbon dioxide, radiative forcing	Radiative forcing fossil emissions, radiative forcing biogenic emissions, radiative forcing land use change emissions	Greenhouse gas emissions, carbon footprint, global warming, global warming potential (GWP), climate change
Chemical pollution and novel entities	Production of novel entities	Human toxicity cancer, human toxicity non-cancer, freshwater ecotoxicity, ionizing radiation impact on human health	Pesticide use, ionizing radiation, human carcinogenic toxicity, human non-carcinogenic toxicity, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity
Ozone	Stratospheric ozone concentration	Ozone depletion potential, photochemical ozone formation impact on human health	Photochemical ozone creation, photochemical ozone formation, ozone depletion, ozone formation human health, ozone formation terrestrial ecosystems

Air emissions	Atmospheric aerosol loading globally and regionally	Particulate matter impact on human health	Particulate matter, fine particle matter formation
Acidification	Ocean acidification	Acidification	Acidification, terrestrial acidification, acidifying emissions
Eutrophication	Nitrogen emissions globally, phosphorus emissions globally and regionally	Terrestrial eutrophication, freshwater eutrophication, marine eutrophication	Eutrophication, freshwater eutrophication, terrestrial eutrophication, eutrophying emissions
Freshwater use	Blue freshwater consumption globally and at basin level	Blue freshwater consumption	Freshwater use, water use (resource depletion), freshwater consumption, water consumption, water stress, stress-weighted water use
Land use and land system change	Share of forested land to original cover	Land use measured through soil quality index, biotic production, erosion resistance, mechanical filtration and groundwater replenishment	Land use, land occupation, cropland use, cropland occupation, arable pasture land, non-arable pasture land, cultivated land, erosion resistance, mechanical filtration, physiochemical filtration, groundwater replenishment

Biodiversity loss	Extinction rate, biodiversity intactness index		Biodiversity points
Resource use		Resource use of minerals and metals, resource use of fossil fuels	Fossil resource use, mineral and metals resource use, fossil fuel energy demand, depletion of minerals, depletion of fossil fuels, depletion of renewables, mineral resource scarcity, fossil resource scarcity, primary energy use

4.2.1.2 Social impacts

Table 5 summarizes the social impact categories and indicators recommended in the framework of the UNEP-SETAC S-LCA (Benoît Norris et al., 2020, UNEP-SETAC, 2009) as well as those found in the literature.

Table 5. Summary of impact categories and indicators recommended in the UNEP-SETAC LCA framework (UNEP-SETAC, 2009, Benoît Norris et al., 2020) and those used in the literature.

Main social impact category	Social indicator	
	UNEP-SETAC S-LCA	Literature
Impact on workers	Freedom of association and collective bargaining, child labour, fair salary, working hours, forced labour, equal opportunities/discrimination, health and safety, social benefits/social security	Child labor, forced labor, safety measures
Impact on local community	Access to material resources, access to immaterial resources, delocalization and migration, cultural heritage, safe and healthy living conditions, respect of indigenous rights, community engagement, local employment, secure living conditions	
Impact on consumers	Health and safety, feedback mechanism, consumer privacy, transparency, end of life responsibility	

Impact on society	Public commitments to sustainability issues, contribution to economic development, prevention and mitigation of armed conflicts, technology development, corruption	Active involvement of enterprises in corruption and bribery
Impact on other value-chain actors	Fair competition, promoting social responsibility. supplier relationships, respect of intellectual property rights	Social responsibility along the supply chain
Animal welfare		Wool cortisol concentration of lambs

4.2.1.3 Economic impacts

Table 6 summarizes the economic impact categories and indicators found in the SETAC LCC code of practice (SETAC, 2011) and in the literature.

Table 6. Summary of economic impact categories and indicators recommended in the SETAC LCC guidelines (SETAC, 2011) and those used in the literature.

Main economic impact category	UNEP-SETAC LCC	Literature
Life cycle cost	Life cycle cost (revenue and total cost)	Revenue, variable costs, fixed costs, earnings

4.2.2 Results from the workshop

The results from the Open Space workshop are summarized in Table 7, showing the indicators or aspects considered important to include in a sustainability assessment of wool, together with the number of Yes-votes and No-votes for each indicator or aspect. Overall, 24 indicators or aspects were considered of which 12 environmental, 6 social and 6 economic. No-votes were only distributed for three indicators or aspects which included cultivated organic soils, culture and crisis readiness.

Table 7. Indicators and aspects identified in the workshop for inclusion in sustainability assessments of wool, together with results of the voting (Yes/No) indicating which indicators and aspects were considered important.

Indicator or aspect	Yes-votes	No-votes	Belonging to impact category	**Comment by workshop participants**
Animal welfare	14	0	Social	Less use of antibiotics and no mulesing in Swedish production
Traceability	10	0	Social	
Climate impact	9	0	Environmental	
Chemical use in production	8	0	Environmental	Less use of chemicals in Swedish production
Biodiversity	8	0	Environmental	Swedish sheep grazing semi-natural pastures positive for biodiversity, small-scale production common in Sweden may be positive for biodiversity
Resource efficiency	7	0	Environmental	Resource efficient to take care of all wool from current Swedish sheep production
Profitability	7	0	Economic	Important with economic security for sheep and wool farmers, as well as shared responsibility with actors in other parts of the supply chain
Working conditions	5	0	Social	Working conditions generally good in Swedish production
Water scarcity	4	0	Environmental	
Resource efficiency	4	0	Economic	
Regenerating farming practices	3	0	Environmental	Important, but few Swedish sheep farmers are using regenerative farming practices
Land use	3	0	Environmental	Swedish sheep grazing semi-natural pastures positive for biodiversity

Circularity	3	0	Environmental	Important to ensure circular production and consumption, e.g. not using chemicals or other raw materials, ensure good durability of fibers
Living countryside	3	0	Social	Sheep and wool farming may encourage people to live on the countryside
Ecosystem services	2	0	Environmental	
Energy consumption	1	0	Environmental	
Emissions to air	1	0	Environmental	Important to minimize transportation
Local	1	0	Economic	Important to question the term "local" and focus on the fiber and raw material.
Create jobs	1	0	Economic	
True cost	1	0	Economic	Important to include quality of wool, e.g. durability, recyclability, warming
Green policy	1	0	Economic	Expensive to certify wool for small-scale producers
Cultivated organic soils	0	3	Environmental	
Culture	1	4	Social	Sheep farming deeper rooted in other countries than in Sweden. Feeling and sense of culture could be strengthened.
Crisis readiness	1	4	Social	Important with self-sufficiency

4.2.3 Discussion of findings on impact categories, indicators and aspects

4.2.3.1 Environmental impacts

On comparing the environmental impact categories and indicators recommended by frameworks and the ones currently applied in the literature, there are large overlaps. Overall, all environmental impact categories recommended by either the PB framework or the PEF were found to be used in the literature, although no single study was found to cover all aspects in either of the frameworks. Resource use, which is covered in the PEF but not in the PB framework, was found to be applied in several studies. Biodiversity aspects were only found to be represented in one study. The indicator is covered by the PB framework but not included in the PEF. However, biodiversity is partly covered by several of the land use indicators concerning soil health used within the PEF.

With regards to climate change, both the PB framework and the PEF use radiative forcing as a control variable. This indicator is rarely used in the literature, where GHG emissions or GWP are instead commonly applied. Within the impact category of chemical pollution and novel entities, a variety of indicators were found to be used within the literature, e.g. related to pesticide use, or related to impacts on humans and ecosystems due to the application of e.g. pesticides or chemicals. Many studies were found to assess the impact category of land use and land system change, but few use the recommended indicators by the frameworks. Instead, the indicators found in the studies typically relate to e.g. cropland and pasture use.

With regards to the workshop results, environmental perspectives given top priority included climate impact, chemical use in production, biodiversity and resource efficiency. There is a strong overlap between many of the environmental indicators and aspects identified in the workshop, the ones in the PB and PEF frameworks as well as the findings in the literature, e.g. with regards to indicators such as climate impact, chemical use, land use and air emissions. Energy consumption is an indicator brought up by the workshop participants but is currently missing in the PB and PEF frameworks. This indicator was however found to be applied within various of the reviewed studies. Resource use is covered by the PEF and applied in several studies, and was also brought up in the workshop with special focus on efficiency and circularity. Ecosystem services and regenerating framing practices were highlighted by the workshop participants and could be considered to be included within the PEF category of land use regarding the different soil health indicators.

4.2.3.2 Social impacts

Most of the identified studies in the literature focus on environmental impact categories and indicators, whereas social perspectives are more seldom assessed. The UNEP-SETAC S-LCA framework recommends using a variety of indicators, of which only a few are applied in the literature. For example, within impacts on society, the only indicator found to be applied within the literature include corruption and bribery. However, important to notice is that all impact categories and indicators recommended by the UNEP-SETAC S-LCA framework may not be relevant for the context of wool production in general, nor for the case of Swedish wool production.

With regards to the social indicators and aspects considered especially important by the workshop participants, these include animal welfare, traceability and working conditions. Notably, animal welfare is not recommended within the UNEP-SETAC framework, and was only found to be included in one of the studies found in the literature (Geß et al., 2020). Traceability was included within one study, regarding social responsibility along the supply chain (Martin and Herlaar, 2021).

4.2.3.3 Economic impacts

Only one study was found to include indicators regarding economic sustainability impacts (Geß et al., 2022). Concerning the economic indicators and aspects highlighted by the workshop participants, profitability was voted highest followed by resource efficiency.

5 Sustainability impacts of wool

This chapter presents and discusses results on sustainability impacts of sheep production and wool. Section 5.1 is dedicated to the findings in the literature, while Section 5.2 discusses how the production in Sweden compares to other countries.

5.1 Findings from the literature review

5.1.1 Climate impact of sheep and wool production systems

Table A1 summarizes the findings from the literature review on climate impact of sheep and lamb meat production, as well as the impact of wool fabric, yarn or garment.

For the studies investigating sheep or lamb meat, the climate impact was found to range from 3.6 to 18 kg CO2eq./kg live weight, 11 to 42 kg CO2eq./kg slaughter weight and 19 to 57 kg CO2eq./kg of lamb meat. In general, sheep production in more extensive production systems generate higher amount of GHG emissions per kg. In more intensive systems, breeds are generally faster growing, have a higher lambing rate, consume less feed during their life time and emit less due to their shorter life time (e.g. Geß et al., 2020, Geß et al., 2022).

The majority of the GHG emissions associated with sheep production were found to arise from on-farm emissions. For example, Ledgard et al. (2011) found 80% of the emissions associated with lamb production in New Zealand to be associated with the on-farm emissions, while O'Brien et al. (2016) reported figures of up to 87% of overall emissions taking place on the farm. On-farm emissions were found to be dominated by CH_4 due to enteric fermentation of the ruminants as well as emissions of CH_4 and N_2O from manure management (e.g. Wiedemann et al., 2016, Wallman et al., 2011, Brock et al., 2013).

Two studies looking at sheep production in Sweden were identified where the results by Ahlgren et al. (2022) were found to be substantially higher than the study by Wallman et al. (2011). Most of the differences between the two Swedish studies are explained by factors of allocation (discussed in Section 4.1). Both studies employed economic allocation with 62% allocated to meat in Wallman et al. (2011), while Ahlgren et al. (2022) allocated between 76-96% to the meat. As discussed in Ahlgren et al. (2022), applying similar allocation factors in the both studies would have yielded similar results.

Based on the literature findings, the climate impact of virgin wool was found to range from -27 to 36 kg CO_2eq. per kg greasy wool. The negative impact of wool was found in the study by Wiedemann et al. (2015c) when system expansion was applied as allocation method. When excluding the negative results from the case on system expansion, the results range from 8.5 to 36 kg CO_2eq. per kg greasy wool.

The majority of the studies employed one or several methods for allocation between sheep or lamb meat, and by-products of e.g. wool and hides. One study investigated recycled wool, with findings of a climate impact of 0.63 kg CO_2eq. per kg wool (Bianco et al., 2022), thus indicating a substantially lower climate impact than for virgin wool.

Various studies were found looking into the impacts of wool sweaters, with results ranging from 1.9 to 53 kg CO_2eq. per sweater. Interestingly, the climate impact of a sweater using recycled wool was found to be 6.3 kg CO_2eq. per sweater (Martin and Herlaar, 2021), thus indicating a higher impact than for the study by Bevilacqua et al. (2011) on 1.9 kg CO_2eq. per sweater, using virgin wool. However, the study by Bevilacqua et al. (2011) did not include non-CO_2 GHG emissions which explain the lower reported value.

When using a functional unit of per wear of a sweater, the impacts varied between 0.05 to 0.17 kg CO_2eq. per wear, where the lower value was found for a sweater produced with recycled wool (Wiedemann et al., 2022).

As previously mentioned, the majority of the climate impact associated with the life cycle of textiles are in general generated during the production process from fiber to garment, due to the use of electricity and heat (Sandin et al., 2019a). With regards to production of woollen garments however, a larger share may be attributable to wool production. For example, Wiedemann et al. (2020) reported the acquisition of raw materials to account for over half of the overall emissions and processing to about a third of the emissions. In the assessment of a wool sweater by Sánchez et al. (2018), about 80% of the overall climate impact were found to be associated with the production of raw materials, while 19% were linked to the manufacturing stage of the sweater. In the comparison between the wool and the polyester sweater, the authors found that the use stage for the polyester sweater contributed to more than double the emissions of the wool sweater, explained by assumptions on a higher number of washing cycles. However, when studying a wool sweater based on recycled wool, Wiedemann et al. (2022) found that the emissions were dominated by garment manufacturing and the use stage with 54 and 43% of the emissions respectively.

5.1.2 Other environmental impacts of sheep and wool production systems

Various of the identified studies report on land use by sheep, wool or garment production (Table A1). With regards to the studies investigating impacts from sheep production, Ahlgren et al. (2022) report an average land use of 100 m^2/kg CW with large variations between the Swedish production systems with highest land use for winter lamb systems where the lifetime is longer than for systems with spring lamb which are raised intensively in stables. For the most extensive system, land use was double the most intensive system (144 m^2/kg CW compared to 73 m^2/kg CW). Pasture land was found to be dominating overall land use in all systems with grazing on semi-natural pastures ranging between 26 to 59% of overall land use. Land use for production of annual feed crops such as grains and sugar beet contributed to a minor share of overall land use, at maximum 6% in the spring lamb systems. Wallman et al. (2011) made similar findings as Ahlgren et al.

(2022), reporting an average land use of 118 m^2/kg CW, dominated by grasslands and with large variations between the studied farms. Geß et al. (2022) was the only study found where an impact assessment was made using the LANCA® method (Land Use Indicator Value Calculation), based on the PEF. The method compares the current state of land use of an area with a fictitious state of the same area without human interference. Both occupation and transformation of land is considered and their impacts on soil health indicators such as erosion resistance and groundwater replenishment. Geß et al. (2022) found that impacts of land use on soil health are lowest for extensive farming systems. Grazing in high stock numbers may cause changes in vegetation and subsequent soil erosion which may explain the results of the lower impacts by the more extensive systems.

In the study by Wiedemann et al. (2016) substantial variation was found between production systems of wool in different Australian regions. Findings of overall land use per kg wool ranged from 141 m^2 to as much as 9000 m^2, explained by land availability as well as differences in the use of supplementary feed. In all regions, pasture land dominated overall land use whereas cropland use in general made a minor contribution. The findings on lower pasture land use was explained by higher stocking rates compared to the regional average.

When looking at the land occupation in the life cycle of a woollen garment, Wiedemann et al. (2020) found land use at raw material production to be completely dominating the overall land use.

Various of the identified studies investigated resource use from different dimensions, mainly through fossil energy use as well as demand for minerals and metals (Table A1). Wallman et al. (2011) found substantial difference between energy use on conventional and organic farms where the former used almost the double amount of primary energy. This was explained by high input of concentrate feed for indoor rearing on several of the conventional farms, requiring higher energy use. Furthermore, the use of synthetic fertilizer in feed production also explained the differences between the conventional and organic farming systems. Wallman et al. (2011) indicated about half of the total energy use to be associated with feed production. Wiedemann et al. (2016) found on-farm energy use for fuel and electricity to be dominating overall fossil energy demand for wool production in Australia with up to 80% of the emissions, while energy use for supplementary feed constituted a smaller share of the emissions. However, for some systems, energy demand due to high input of fertilizer or pesticide for forage and pasture was observed, which generated higher energy demand.

When looking at the energy use for the life cycle of a woollen garment, Wiedemann et al. (2020) found energy use in wool production to be low compared to the subsequent processes. Processing was found to contribute to up to 60% of overall energy use, followed by the use stage through garment washing and drying with almost 30% of the impacts.

Only three of the identified studies evaluated chemical pollution and novel entities (Table A1). For example, Wallman et al. (2011) looked into the use of pesticides as an indicator of toxicity. Naturally, conventional production was found to cause highest use as pesticides are banned in organic production within the European Union. Wallman et al. (2011) found that, on average, crop cultivation for concentrate feed requires the majority of the pesticide use while the need in Swedish grasslands is low. Apart from on-farm pesticide use for crop production, chemicals may be used on sheep to avoid insect bites and parasites. Furthermore, chemicals are also present throughout other parts of the life cycle of textiles such as in dyes and bleaches for processing (Quantis, 2018). These aspects were however rarely evaluated in the reviewed studies.

Textile production impacts on eutrophication by use of nitrogen and phosphorus compounds in fertilizers, as well as emissions from manure management in e.g. sheep production for wool. Various studies in the identified literature reviewed eutrophication impacts (Table A1), where e.g. Wallman et al. (2011) found nitrogen leaching from feed cultivation being the most important contributor to eutrophication from sheep production. Similar findings were reported by Ahlgren et al. (2022) when evaluating eutrophying emissions from lamb meat production. Ahlgren et al. (2022) highlighted feed production as the most important contributor to the emissions, while emissions from permanent pastures being small. For nitrate emissions, small differences were found between the farms while differences were more pronounced for ammonia emissions. Ammonia emissions were found to be linked to manure management systems, with lowest emissions for autumn lamb and highest for winter lamb systems. Geß et al. (2022) reported highest eutrophication impact from intensively managed farms as more extensive farms use a larger area per sheep which thus can take up more nutrients and reduce the eutrophication potential.

Apart from contributing to eutrophication, ammonia is one of the dominating sources to acidification, for which manure management in agriculture is a main source (SEPA, 2022a). Several of the identified studies reported impacts related to acidification (Table A1). O'Brien et al. (2016) report up to 96% of the impacts being linked to ammonia emissions on farm, due to manure management and fertilizer application. Wallman et al. (2011) and Geß et al. (2022) report the emissions profile being lower in more extensive system as smaller amounts of NH_3 may be emitted from manure left on pasture than in stables, due to infiltration into the soil and lower temperature than in bedding systems in stables.

Food production has been highlighted as responsible for the major share of the increase in atmospheric nitrous oxide (N_2O), mainly due to the use of synthetic fertilizers and manure management. Apart from contributing to global warming, N_2O cause impacts on ozone depletion and the gas is currently the most important ozone-depleting gas (SEPA, 2022b). Only three studies were found to report on impacts related to ozone, using indicators of e.g. ozone depletion as well as ozone formation (Table A1). As the studies focus on three different outputs (lamb meat, virgin wool sweater and recycled wool) the results are not comparable. With regards to ozone formation, all three studies use different characterization models for emissions. For example, Wallman et al. (2011) report ozone formation in emissions of C_2H_4-equivalents with findings indicating CH_4 from enteric fermentation dominating the emissions profile with up to 95% of overall emissions. No clear difference was seen between different production systems. Concerning ozone depletion, Wallman et al. (2011) report results in kg of chlorofluorocarbon compounds (CFCs) for which energy-related emissions dominate the results. However, as CFCs are currently being phased out due to e.g. European legislation (SEPA, 2022b), results would probably differ if instead including emissions of N_2O. This would probably favor extensive farms, as well as those with organic practices, due to less use of concentrate feed and synthetic fertilizers. However, for sheep and wool production outside of Europe, the emissions profiles might differ with higher emissions of CFCs.

Textile production requires energy input and transports, generating air emissions and particulate matter. In general, clothes produced in countries with an electricity mix based on coal or diesel production may have caused higher share of air emissions than production taking place in countries with a ‘cleaner’ energy mix (Haeggman et al., 2018). Of the reviewed studies, only two were found to look into the impacts of air emissions, evaluating the particulate matter formation of recycled wool (Bianco et al., 2022, Sánchez et al., 2018). No conclusion can be drawn based on the results reported by these studies.

With regards to impacts on biodiversity, only one study was found directly assessing the impacts on sheep production on biodiversity (Ahlgren et al., 2022). Other environmental impact categories have indirect effects on biodiversity, e.g. habitat loss due to land system change, or emissions of pollutants to air, water and land. Current methods used within LCA (e.g. Chaudhary and Brooks, 2018) assess biodiversity regarding the potential negative impact from antrophogenic land use. In the study by Ahlgren et al. (2022), biodiversity is assessed with a point system to include positive effects of biodiversity from grazing of semi-natural pastures in Sweden. Thus, increased land use lead to increased points, i.e. is considered positive for biodiversity, but at different scales depending on the land use type such as whether production includes grazing on semi-natural pastures, or production of annual crops. In conclusion, Ahlgren et al. (2022) report highest points for sheep production in systems with a high grazing area per kg slaughter weight. In another study by Ripoll-Bosch et al. (2013), biodiversity is taken into consideration indirectly by allocating the overall emissions of sheep production between sheep meat and ecosystem services such as biodiversity conservation through grazing.

Freshwater use and impacts due to the use was found to be evaluated in various studies (Table A1). Indicators included overall freshwater consumption measured in m^3 or litre of water per functional unit, as well as water stress caused by the water consumption. Due to methodological differences in the impact methods and functional units chosen, no conclusions can be drawn from the identified studies. Wiedemann et al. (2015b) and Wiedemann et al. (2016) report highest water use in sheep production to be associated with losses from farm water supply systems with up to 85% of overall water use, while livestock drinking water having minor contributions.

In an LCA of a woollen garment by Wiedemann et al. (2020), freshwater consumption was found to be highest for the wool production, with about 65% of the overall consumption. However, when assessing the water stress caused by the use, impacts associated with freshwater use were found to be spread more equally between wool production, processing and garment care, which can be explained by differences in water availability in different production regions of the garment.

5.1.3 Social and economic impacts of sheep production systems and their outputs

Among the identified studies, few were found to analyze social or economic impacts (Table A2). Geß et al. (2020) was the only study found to assess animal welfare, which was carried out by using an indicator of wool cortisol concentration identifying chronic stress detection. The results on cortisol concentration were found to differ between the systems, where the lambs reared in more extensive systems were identified with substantially lower levels than lambs raised in continental systems.

In another study by Geß et al. (2022), the life cycle costs of sheep production were analyzed. The production system with highest revenue was found to be a system with high lambing efficiency and with highest lamb meat price. In contrast, the lowest income was found for an extensive system. For the indicator of fixed costs, the highest costs were found for a system with higher wages for employed shepherds.

Martin and Herlaar (2021) evaluated the social impacts associated with the supply-chain of a recycled wool sweater, looking at different impact categories such as impact on workers with indicators on child labour and forced labour. The results from the S-LCA indicates large social risks (i.e. 'medium risk hours') regarding shipping between production sites in Europe as well as manufacturing facilities for the wool garments. Overall, supply chains involving European producers were found to be associated with fewer risks than other types of supply chains that did not prioritizing sustainability or ethical practices in their production processes.

5.2 Discussion on sustainability of Swedish production of sheep and wool

5.2.1 Climate impact

Of the identified studies on sheep production, two of the studies focused on production in Sweden (Ahlgren et al., 2022; Wallman et al., 2011). The results by Ahlgren et al. (2022) were found to be in the upper part of the overall results of the analyzed studies while the results by Wallman et al. (2011) are in the lower to the middle part. However, no conclusions can be drawn on the climate impact of Swedish sheep production systems compared to other countries, as the studies vary in analyzed production systems, as well as methodological choices, e.g. regarding the functional units, impact assessment method chosen, or whether including carbon sequestration and emissions from organic soils.

With regards to wool production however, applying the economic allocation factors suggested by Ahlgren et al. (2022) (0.3-0.7% of overall impacts of the production system) would result in a substantially lower climate impact for wool up to farm-gate, compared to the results reported by other studies. Considering the climate impact of life cycle of woollen garments, Wiedemann et al. (2020) reported the acquisition of raw materials to account for over half of the overall emissions and processing to about a third of the emissions in the context of Australia. No studies were found investigating the impacts of Swedish garment production with virgin wool. However, considering the low climate impact from Swedish electricity mix (Sandgren and Nilsson, 2021), it is possible that the climate impact of garments produced in Sweden could generate lower GHG emissions than countries with a higher emission intensity.

5.2.2 Land use, land-system change and biodiversity

Swedish sheep farming has been highlighted to impact positively regarding several of the Swedish Environmental Objectives, including "A rich diversity of plant and animal life" and "A varied agricultural landscape"[2]. Grazing animals have been identified as important for biodiversity conservation of threatened species through maintenance of Swedish semi-natural pastures (SBA, 2023). A large share of Swedish sheep farming take place on semi-natural pastures and between 10-15% of the pastures have been estimated to be grazed by sheep (SBA, 2021).

Swedish sheep production has been reported to be dominated by production on temporary grassland on arable land as well as semi-natural grassland (Wallman et al., 2011). Temporary grasslands are cultivated on about one third of Swedish arable land (SBA, 2021) and often include cultivation of ley grass, which are perennial crops that may favor sequestration of carbon, as well as contribute to improved soil health. Carbon storage also takes place in pastures and is stimulated by grazing (e.g. SLU, 2022). Including soil carbon changes in LCA studies of ruminants has been pointed out as important due to the potential of decreased overall climate impact of the production systems (e.g. Stanley et al., 2018, Mogensen et al., 2015, Pelletier et al., 2010).

Apart from biodiversity conservation, semi-natural grassland areas have been highlighted as important for resource efficiency as these are unsuitable for other purposes such as cropping. Thus, while other farm animals such as pigs and poultry generally are fed crops that could be used for human consumption directly, ruminants such as sheep can utilize feed sources that cannot be utilized by nonruminants and humans (e.g. Röös et al., 2016, van Zanten et al., 2018). Based on this, LCA studies using overall land use or cropland use as indicator for measuring impacts of land use and land system change have been criticised for being too simplistic in their metric. Rather, it has been highlighted that the studies should ideally be expanded to include aspects on e.g. resource-efficiency (e.g. Haeggman et al., 2018).

In summary, Swedish sheep production has been highlighted as potentially important for carbon sequestration in grass ley, biodiversity conservation through maintenance of semi-natural pastures as well as resource-efficiency with regards to utilizing pastures unsuitable for other purposes. However, several studies have

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[2] The Swedish Environmental Objectives steer Sweden's environmental policy work, more information available at http://www.swedishepa.se/Documents/publikationer6400/978-91-620-8620-6.pdf

highlighted the same attributes to sheep production in other countries worldwide. For example, Ripoll-Bosch et al. (2013) report on the positive aspects with regards to promotion of ecosystem services by different sheep production systems in Spain, such as biodiversity conservation through grazing. Ledgard et al. (2011) report sheep farming in United Kingdom and New Zealand to take place on long-term perennial grasslands in upland and hill areas. Additionally, an increase has been seen in sheep farming on extensive steeper grassland areas in New Zealand. Similar to semi-natural grasslands in Sweden, grazing of sheep on these pastoral areas has been reported as a resource efficient as the areas are unsuitable for e.g. cropping. Australia is one of the biggest wool producers globally (FAO, 2023) with a production based on the Merino sheep bread. With regards to sheep production on Ireland, O'Brien et al. (2016) report the majority of producers to allow grazing throughout most of the year. Lowland farms dominate the production with about 85% of the overall farming. Similarly to New Zealand, the production in Australia and Ireland is to a large extent based on grazing, and in some regions supported by supplementary feeding during periods of feed deficiencies (Wiedemann et al., 2016, O'Brien et al., 2016).

5.2.3 Energy use

With regards to energy use in Swedish production compared to other production countries, Wallman et al. (2011) reported sheep farming in Sweden to require a higher input than production in e.g. New Zealand and Australia. This was explained by the use of harvested feed for half of the year which requires higher energy input than e.g. production in countries with extensive pastoral-based systems for a larger or all part of the year. Regarding fossil energy demands however, it is likely that Swedish production shows added values compared to other production countries where a larger share of the energy mix is based on fossil fuels.

5.2.4 Freshwater use

Due to methodological differences in the impact methods and functional units chosen, no conclusions could be drawn on differences between freshwater use or impacts e.g. on water stress from the identified studies. In general, freshwater consumption has been reported to be low for Swedish agriculture (Mekonnen and Hoekstra, 2012, Mekonnen and Hoekstra, 2011). In a study by Moberg et al. (2020), the freshwater consumption of sheep meat was compiled for Sweden and main production countries to the Swedish market of lamb meat. The results showed that Swedish sheep meat had lower freshwater use than meat from e.g. Ireland and New Zealand, as well as the global average. On comparing water stress related impacts from freshwater consumption, Sweden generally shows low scores compared to other countries in more dry or arid regions (e.g. Boulay et al., 2018). As such, it is likely that freshwater impacts are lower in Swedish production of sheep and wool than production countries in warmer regions. For woollen garments, the impacts depend on the production sites chosen for further processing of the wool and manufacturing.

5.2.5 Animal welfare

Animal welfare was only found to be assessed in the study by Geß et al. (2020), looking into wool cortisol concentration to identify chronic stress detection. Swedish animal welfare regulations have been highlighted by the industry and actors to have potential benefits compared to other countries (SBA, 2016), and was considered especially important by the workshop participants.

Swedish animal regulation aims to both protect animals from unnecessary pain as well as give the animals the conditions to behave naturally (SFS 2018:1192). Further, Swedish animal farming aims to have a preventive animal health care in order to avoid diseases and for a low use of antibiotics. In general, outbreaks of common diseases such as Scrapie and Maedi visna are rare on Swedish sheep farms (SBA, 2016).

Sweden is continuously reported in top of lowest sales of veterinary antibiotics in the European Union (EMA, 2022)[3]. Use is only allowed for treatment of sick animals while preventive use for e.g. growth promoting has since long been prohibited in Swedish animal farming (SVA, 2021). With regards to other countries within the European Union, the use of veterinary antibiotics in a routinely or preventive manner was banned in 2022, with the main argument of decrease spreading of bacteria resistant to antibiotics (SVT, 2022). According to the Swedish Meat Guide (WWF, 2022), the use of antibiotics in non-European countries such as New Zealand is low.

Considering the use of chemicals to avoid insect bites and parasites, Swedish legislation (SFS 2018:1192) does not allow to spray or bath the sheep in chemicals or pesticides. This practice has however been reported to be common in countries outside of the Nordics (Svenska Fåravelsförbundet, 2021a).

According to Swedish legislation (SFS 2009:302), medical interventions may only be carried out if considered necessary by veterinary reasons. Castration of male lambs is however excluded from this, if carried out by a veterinarian and under

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[3] The reporting does not differ between animal types and report overall sales for food-producing animals, including e.g. cattle, pigs and chickens.

anesthesia. Swedish legislation also requires anesthesia of animals during slaughtering, including religious slaughtering such as halal (SJVFS 2020:22). In several countries both within and outside of the European Union, dispense may be given for religious slaughter and slaughtering may be carried out without anesthesia (European Commission, 2009).

The surgical process to remove skin folds on the rear of the sheep to prevent fly attacks, i.e. 'mulesing', is prohibited in Sweden (SJVFS 2015:31). The procedure has been common on the Merino sheep breed but has been banned in other large production countries such as New Zealand (Farm Online, 2018). However, mulesing is still a legal procedure in production countries such as Ireland (WWF, 2022), as well as in Australia where the latter may involve the procedure being carried out without anesthesia (Australian Wool Innovation Limited, 2022).

6 Conclusions

This study aimed at looking into methodological choices applied in sustainability assessments of sheep and wool production, as well as to investigate results of sustainability impact assessments of the production. Based on this, the study aimed to highlight potentially missing aspects in previous assessments as well as to compare the impacts of Swedish production in relation to production in other countries.

For studies assessing wool at farm-gate, a functional unit of per kg of greasy wool was found to be a common choice. Using such functional unit has been criticized for not relating to the function of the fiber which for comparison should be expanded to include its quality and durability. For the reviewed assessments of woolen garments, these were commonly assessed from a cradle to grave perspective, with a functional unit including a definition of a specific weight as well as lifetime, which is preferable as this makes it possible to compare the function of different garments.

Concerning handling multi-functionality of production systems, most studies were found to apply one or several allocation strategies to distribute the environmental burdens between the by-products. The choice of allocation factors was found to vary substantially between the reviewed studies which had large implications on overall results. Studies covering Swedish production were found to apply a low or no allocation to wool, due to the low economic revenues of wool. In comparison, studies covering the production in other countries were found to use higher economic allocation factors. This was explained by a higher level of specialization of wool production in combination with larger extent of wool taken care of, which increase its economic revenues and thus allocation factors.

On comparing the environmental impact categories and indicators recommended by frameworks and the ones currently applied in the literature, large overlaps were found. Overall, all environmental impact categories recommended by the reviewed frameworks were found to be used in the studied literature, although no single study was found to cover all aspects in either of the frameworks.

The indicators recommended by the studied frameworks were not always applied by the reviewed studies. For example, the impact category of land use and land system change is commonly investigated through assessing overall land use, but is recommended to include indicators on soil health by e.g. the Product Environmental Footprint guidelines. This would however require site-specific data, which may not always be available.

In the workshop with actors from different parts of the supply-chain of Swedish wool, environmental perspectives given top priority included climate impact, chemical use in production, biodiversity and resource efficiency. Climate impact and resource use were found to be among the most applied indicators in the literature. Chemical use in production and biodiversity were on the other hand rarely assessed. Thus, future studies assessing the environmental sustainability of Swedish wool could ideally include these aspects.

Few studies covering social and economic dimensions were found. The participants in the workshop highlighted animal welfare and profitability among top priorities of social and economic perspectives to be included in a sustainability assessment of Swedish wool.

No conclusions could be drawn on the climate impact of Swedish sheep or wool production systems compared to other countries, as the studies vary in analyzed production systems, as well as methodological choices, e.g. regarding the functional units and impact assessment method chosen. However, considering the low allocation factors assigned to Swedish wool in the identified studies, this result in substantially lower climate impact for wool up to farm-gate, compared to the results reported by other studies.

Swedish sheep farming has been highlighted to impact positively on several of the Swedish Environmental Objectives, e.g. through grazing animals sustaining biodiversity conservation of threatened species in Swedish semi-natural pastures. Another often lifted benefit for Swedish agriculture is the potential carbon sequestration due to grass ley production. However, several studies were found to highlight the same attributes to sheep and wool production in other countries worldwide, as the farming systems to a large extent are extensive pastoral-based systems.

Regarding other potential benefits often highlighted for Swedish production of sheep and wool, these include animal welfare regulations. On comparing Swedish regulations to legislation and literature for other production countries, potential added values from Swedish production compared to other countries were found, e.g. with regards to use of veterinary antibiotics and medical interventions.

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Appendix 1

Table A1. Environmental impacts of sheep and lamb meat, wool fabric, yarn and garment based on the literature review.

Study and functional unit	Climate impact	Land use and land system change	Chemical pollution and novel entities	Ozone	Air emissions	Acidification	Eutrophication	Freshwater use	Biodiversity loss	Resource use
Ahlgren et al. (2022) Per kg slaughter weight	31-42 kg CO$_2$eq.	Land use: 73-144 m^2				Acidifying emissions: 0.14-0.26 kg NH$_3$-N	Eutrophying emissions: 0.05-0.07 kg NO$_3$-N		Contribution to biodiversity through grazing: 39-84 points	
Bianco et al. (2022) Per kg wool	0.63 kg CO$_2$eq.	Land use: 3.0 Pt	Eco-toxicity, freshwater 6.3 CTUeq.	Ozone depletion: 1.1×10^{-7} kg CFC11eq. Photochemical ozone formation 6.4×10^{-3} kg NMVOCeq.	Particulate matter 3.5×10^{-8} disease inc.	Acidification: 8.3×10^{-3} mol H$^+$eq.	Freshwater eutrophication: 6.2×10^{-5} kg Peq. Terrestrial eutrophication: 2.4×10^{-2} mol Neq.	Freshwater use: 9.3×10^{-2} m^3 deprived		Fossil resource use: 8.4 MJ Minerals and metals resource use: 3.3 ×

										10^{-3} kg Sbeq.
Geß et al. (2022) Per kg of lamb meat	33-57 kg CO_2eq.	Erosion resistance: 0.5-18 t/area Mechanical filtration: 0-15 cm×m^2/day Physiochemical filtration: 0-1.2×10^9 (cmol×m^2)/m^2 Groundwater replenishment: -7×10^5 – 1.5×10^6 (mm×m^2)/area				Acidification: 0.08-0.15 kg SO_2eq.	Eutrophication: 0.43-1.4 kg PO_4^-eq.			
Wiedemann et al. (2022) Per wear	0.05 kg CO_2eq.							Water stress: 0.58 L H_2Oeq.		Fossil energy demand: 0.63 MJ

								Freshwater consumption: 0.95 L		
Martin and Herlaar (2021) Per sweater	6.3 kg CO_2eq.					Acidification: 0.03 Mole H^+eq.	Freshwater eutrophication: 0.005 kg Peq.	Water use (resource depletion): 0.02 m^3		Resource depletion of mineral, fossils and renewables: 7×10^5 kg Sbeq.
Geß et al. (2020) Per kg of lamb meat	51-55 kg CO_2eq.					Acidification: 0.12-0.15 kg SO_2eq.	Eutrophication: 0.43-1.4 kg PO_4^-eq.			
Wiedemann et al. (2020) Per wear	0.17 kg CO_2eq.									

Sánchez et al. (2018) Per sweater	53 kg CO_2eq.	Land use: 44 m^2a crop eq.	Terrestrial ecotoxicity: 0.009 kg 1.4-DCBeq. Freshwater ecotoxicity: 0.79 kg 1.4-DCBeq. Marine ecotoxicity: 1.0 kg 1.4-DCBeq. Human carcinogenic toxicity: 1.3 kg 1.4-DCBeq. Human non-carcinogenic toxicity: 655 kg 1.4-DCBeq.	Ozone depletion: 3.1 × 10-4 kg CFC11eq. Ozone formation, human health: 0.05 kg NO_xeq. Ozone formation, terrestrial ecosystems: 0.05 kg NO_x eq.	Fine particulate matter formation: 0.025 kg $PM_{2.5}$ eq.	Terrestrial acidification: 0.59 kg SO_2eq.	Freshwater eutrophication: 0.03 kg Peq.	Water consumption: 0.93 m^3		Mineral resource scarcity: 0.04 kg Cueq. Fossil resource scarcity: 4.5 kg oil eq.

			Ionizing radiation: 0.89- kBq Co-60 eq.							
Cottle and Cowie (2016) Per kg lamb and mutton live weight Per kg greasy wool	3.6-8.5 kg CO_2eq. 8.5-36 kg CO_2eq.									
O'Brien et al. (2016) Per kg live weight	9.7-14 kg CO_2eq.	Land occupation: 15-128 m^2				Acidification: 0.08-0.15 kg SO_2eq.	Eutrophication: 0.04-0.06 kg PO_4^-eq.			

Wiedemann et al. (2016) Per kg greasy wool	15-30 kg CO_2eq.	Cropland use: 0.01-68 m^2 Arable pasture land: 71-116 m^2 Non-arable pasture land: 62-12 156 m^2						Freshwater consumption: 145-518 L		Fossil fuel energy demand: 3.8-29 MJ
Wiedemann et al. (2015a) Per kg of retail ready cuts	16 kg CO_2eq.	Cropland occupation: 2.5 m^2						Freshwater consumption: 464 L Stress-weighted water use: 169 L H_2Oeq.		Fossil fuel energy demand: 28 MJ
Wiedemann et al. (2015b) Per kg live weight	6.1-7.3 kg CO_2eq.	Cropland occupation: 0.2-2.0 m^2						Freshwater consumption: 58-239 L Stress-weighted water use:		Fossil fuel energy demand: 2.5-7.0 MJ

								2.9-138 L H_2Oeq.		
Wiedemann et al. (2015c) Per kg live weight Per kg greasy wool	4-10 kg CO_2eq. -27-38 kg CO_2eq.	Cultivated land: 0.01-14 m^2/year 0.007-2.0 m^2/year								Fossil fuel energy demand: -5–30 MJ
Jones et al. (2014) Per kg live weight	11-18 kg CO_2eq.									
Brock et al. (2013) Per kg greasy wool	25 kg CO_2eq.									

Ripoll-Bosch et al. (2013) Per kg slaughter weight	28-39 kg CO_2eq.									
Eady et al. (2012) Per kg greasy wool	27-36 kg CO_2eq.									
Bevilacqua et al. (2011) Per sweater	1.9 kg CO_2eq.									
Ledgard et al. (2011) Per kg of lamb meat	19 kg CO_2eq.									

Wallman et al. (2011) Per kg slaughter weight	11-25 kg CO_2eq.	Land use: 30-390 (mean 118) m^2	Pesticide use: 0.2-0.9 (mean 0.5) g active substance	Photochemical ozone creation: 0.002-0.004 kg C_2H_4eq. Ozone depletion: 0.06-0.21 (mean 0.17) kg CFC11		Acidification: 0.06-0.19 (mean 0.12) kg SO_2eq.	Eutrophication: 0.04-0.13 kg (mean 0.07) PO_4^-eq.			Primary energy use: 36 MJ

Table A2. Social and economic impacts of sheep and lamb meat, wool fabric, yarn and garment based on the literature review. MRH = Medium risk hours.

Study and functional unit	Impacts on society	Impacts on workers	Impacts on other value-chain actors	Animal welfare	Life cycle cost
Geß et al. (2022) Per ewe					Revenue: 77-244 € Variable costs: 13-263 € Fixed costs: 0-325 € Earnings: -489-231 €
Martin and Herlaar (2021) Per sweater	Active involvement of enterprises in corruption and bribery: 35 MRH	Child labour: 10 MRH Goods produced by forced labour: 4.8 MRH Safety measures: 37 MRH	Social responsibility along the supply chain: 470 MRH		
Geß et al. (2020) Per mg				Wool cortisol concentration of lambs: 1.59 - 41.65 pg	

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