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Wool Production

Systematic review of Life Cycle Assessment studies

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Abstract

Wool is often being marketed as sustainable. However, when looking at LCA studies, results can be significantly different from one study to another and wool sometimes shows higher impacts than other fabrics. Based on a comprehensive literature review, this thesis aims at understanding the key environmental impacts of wool production and assessing the influence of main methodological choices on wool LCA results. In particular, the choice of the scope, allocation method and further considerations on water consumption and land use indicators have a great significance on the results of the studies. In order to provide with a fair representation of wool environmental impacts, the whole life-cycle should be taken into account, and methodological choices, such as the scope definition and allocation methods are to be clearly stated. The current tools that are the most widely used in the textile industry to rank fibres according to their sustainability performance are not suitable for wool due to unresolved methodological issues. Indeed, the impact categories that are taken into account in those tools are disadvantageous for wool compared to other alternative fibres, especially regarding water consumption and land use. This thesis also explores the construction of a single score based on the eco-costs of environmental impacts as a more suitable option to build a representative tool.

Key words: Life cycle analysis, LCA, wool, systematic review

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1. Introduction

1.1. Context

The textile industry represents a substantial proportion of the global environmental burden. It has been estimated that clothing is responsible for more than 3% of the global anthropogenic CO_2 emissions. (Quantis, 2018) Fiber production is increasing and represents 100 million tonnes per year (The Fiber Year Consulting, 2017).

Environmental impacts occur in different stages of the fiber production, including agricultural steps (animal grazing) and industrial processes (spinning, weaving, sewing, dying, etc.). Textile production requires large amounts of water and energy (Laitala et al, 2018) and it has been estimated that 20% to 35% of all primary source microplastics in the marine environment are caused by synthetic clothing (Eunomia, 2016). Regarding natural fabrics, the production requires land occupation, which could have been used for food production. Greenhouse gas emissions from the cattle grazing is another issue when considering wool production (Aiama et al, 2016).

There is a growing pressure of manufacturers and consumers on sustainability performance of the textile industry. In addition to some regulations related to use of harmful chemicals such as REACH in EU (European Parliament, 2013), there is a trend in the fashion industry to develop sustainable clothing in order to meet the new requirements of the stakeholders. Several labels have been introduced in order to certify the sustainable production of the products, such as EU ecolabel (European Commissions, 2018), but are still quite unused in the textile industry which commonly label products based on their fiber content (Lehmann et al, 2018).

Tools for enabling sustainability comparisons of products have also been developed. Two of the most commonly used tools for the textile industry are the Higg Materials Sustainability Index (Sustainable Apparel Coalition, 2012) and the Environmental Benchmark forFibres (Made-by, 2009). Those tools assess the impact of different fibres from a cradle-to-gate perspective, based on differences in production. While wool is often being marketed as sustainable, it is poorly graded by those tools. Indeed, wool is ranked E (worst category) by the Environmental Benchmark for Fibres (Made-by, 2009). However, those tools are criticised as their methodological choices are disadvantageous for wool. For instance, the scope of Made-by's methodology prevents to take into account the better performance of wool over the use phase compared to alternative textiles. (Laitala et al, 2018).

1.2. Aim and objectives

This study aims at reviewing the existing LCA studies on wool and understanding the key environmental impacts of the wool production. This study also aims at assessing what are the key methodological choices that affect the results of the LCA and thus key elements to look at in order to correctly interpret the results of studies on the life cycle environmental impacts of wool production.

This thesis will highlight correlations between methodological choices and the results of the studies. Those elements should be carefully considered by stakeholders, such as textile manufacturers, in order to be able to interpret correctly the results of the studies and to understand why some studies are not comparable. Those analysis will also be used as a ground to make recommendations for further LCA studies of wool, for instance by underlining what scope should be considered and what modeling choices should be evaluated in a sensitivity analysis.

Lastly, this thesis will discuss methodological aspects that influence the perceived performance of wool compared to other fabrics and explore a new methodology to build a single score indicator that would be more representative than the current ones.

In order to reach the aim of this study, this thesis sets out to answer the following questions:

- RQ1: What methodological choices in modelling the life cycle of wool textile have a significant impact on the results?
- RQ2: What recommendations could be identified in order to correctly interpret wool LCA results?
- RQ3: What methodological aspects should be considered when comparing wool to other textiles in order to give a fair representation of wool?
- RQ4: How to build a representative single score to assess the sustainability performance of different fabrics?

2. Background

Global wool production

According to the FAO, the majority of the 2,1 million tonnes of wool produced annually is concentrated in few countries. The below lists the top twelve countries ranked on clean wool production. Those twelve countries account for close to 70% of the global greasy wool production (i.e. wool before scouring process) and about 40% of the total sheep population. The global leading producer of clean wool is Australia and is the main exporter. Indeed, about 50% of the exported clean wool volume in 2012 was produced in Australia. New Zealand is another major producer of high-quality fine wool. China is one of the main wool processing countries. China was responsible for about one third of the total wool spinning and weaving on 2012 and was accounting for around 30% of wool imports. Italy, the United Kingdom, India and Pakistan are also part of the main wool processing countries. (FAO, 2014).

Table 1: Top 12 countries ranked for clean wool production (FAO, 2014)

Country	Sheep (1000 head)	Greasy wool (t)	Clean wool equivalent (t)
Australia	74 700	374 157	245 073
China	139 600	400 057	177 697
New Zealand	31 263	167 900	127 830
Russia	20 767	51 502	28 750
Iran	48 750	61 897	27 854
Sudan	52 428	55 221	27 611
Turkey	25 032	49 542	24 771
Uruguay	7 350	32 500	24 050
South Africa	24 391	40 621	24 040
Kazakhstan	15 200	39 600	23 176
Turkmenistan	14 000	38 333	22 825
United Kingdom	32 215	34 000	22 780
Total world	1 110 647	1 999 284	1 109 433

Life-cycle Assessment

Life-cycle assessment (LCA) is a method developed in the 1980s and used to assess environmental impacts of products, processes or services. The concept of life-cycle thinking is increasingly used in both public and private sectors globally. (ILCD Handbook, 2010)

Full LCA includes all stages of the lifecycle from raw material extraction, materials processing, manufacture, transport, use, repair and maintenance, recycling, and end-of-life (“cradle-to-grave” analysis). Product LCA is measuring the impacts of one unit, called the functional unit, which is defined by the qualitative service delivered within a given period of time.

LCA provides an internationally accepted method to help decision making and is commonly used for:

- Understanding the impacts of supply chains and identify hotspots in order to drive continuous improvement (standalone LCA)
- Enabling comparisons with of alternative products, processes or services (comparative LCA) in order to influence stakeholders’ choice.

The LCA methodology is standardised at the international level by the standards ISO14040 and ISO 14044 (2006).

Guidelines and standards have been developed in order to limit uncertainties and bias due to modelling choices. General guidance for application of the LCA approach is set out in ISO 14044 (2006), covering all steps from goal and scope definition, through data collection, inventory analysis and impact assessment. According to the ISO 14044 (2006), the life-cycle assessment consists of 4 phases:

1. Goal and scope definition: the first stage of LCA is to define the goal and scope of the study. The goal must clearly state the reasons for carrying out the study as well as the intended application and audience to whom the results are to be communicated. The functional unit and system boundaries are key elements to carefully define during this phase of the life cycle assessment.

2. Life cycle inventory: the life cycle inventory involves the collection and processing of data to be used in the life cycle assessment. This stage is often the most time-consuming part of an LCA study. Data quality has to comply with the ISO 140140 (2006) requirements as well as with the system boundaries that has been defined in the previous stage.

3. Life cycle impact assessment: this phase aims at understanding and evaluating the potential environmental impact of a system (ISO 14044, 2006). Inventories of resources consumed and emissions are assessed in terms of impacts, using indicators for human health, natural environment and natural resources.

   According to the ISO 14044 (2006), to steps are mandatory in a life cycle impact assessment: the selection of impact categories and their characterisation. Indeed, the life cycle impact assessment is based on selected impact categories, i.e. potential environmental impacts relevant to the study (e.g. resources consumption, emissions into water, emissions to air, etc.). The impacts of each resource consumed or emission are quantitatively assessed and are characterised (i.e. a characterisation factor is applied) in order add up all the contributions of an impact category. The ISO14044 (2006) also defines optional steps for the life cycle impact assessment that are the normalisation of the impact scores with a common reference and the weighting of the different impact categories (i.e. raking of the impacts according to their relative importance).

4. Interpretation: in this stage, the results of the life cycle impact assessment are interpreted and discussed.

The life cycle assessment relies on important concepts that have to be carefully defined (JRC, 2010):

- Functional unit: The functional unit provides a reference to which inputs and outputs are related. It has to define and quantify the intended functions of the product of service system. The functional unit has to be measurable. The clear definition of the functional unit is crucial in order to ensure the comparability between LCA results.
- System boundaries: The system boundaries definition is an important step of the LCA in order to guide data collection in order to be representative of the purpose of the study. The following boundaries can be considered: technological, spatial and temporal boundaries.
- Allocation methods: Many processes produce more than one output (product or service). In this case, an allocation method has to be defined in order divide or partition the burdens among the useful outputs.

More specific guidelines have also been published for LCA studies on small ruminants (sheep and goats) (LEAP, 2015) and for textiles (BSI, 2014), with an emphasis on the application challenges of wool fibre production.

LCA is commonly used in the industrial sector for manufactured products. Although this tool is also appropriate for agricultural commodities such as food and fibre production, there are significant difficulties in applying it to complex and dynamic biological systems. There are still some unresolved issues for accurately reflecting the environmental impacts of agricultural products. Those issues need to be tackled in order to enable fair comparisons of natural commodities with alternative natural or man-made products (for instance comparison of wool and synthetic fibres). (Henry, 2012)

Life-cycle of wool

The Figure 1 below presents a simplified overview of the main stages of a wool apparel life-cycle, from the greasy wool primary production at the farm until the end-of-life of wool products.

The primary production is characterised by the sheep grazing at the farm and leads to the production of greasy wool, i.e. wool directly after being cut off from a sheep. The greasy wool is then sent to primary processing including:

- Scouring, i.e. process of cleaning the greasy wool either simply in a warm bath or using detergent of chemicals.
- Spinning of wool to produce woollen yarn.

There are further processes such as knitting, weaving and dyeing before the manufacturing stage of wool products. Then the use phase of wool products includes all the maintenance and cleaning of the wool. Eventually, at the end-of-life, the products are either reused, recycled or sent to disposal. (IWTO, 2015)

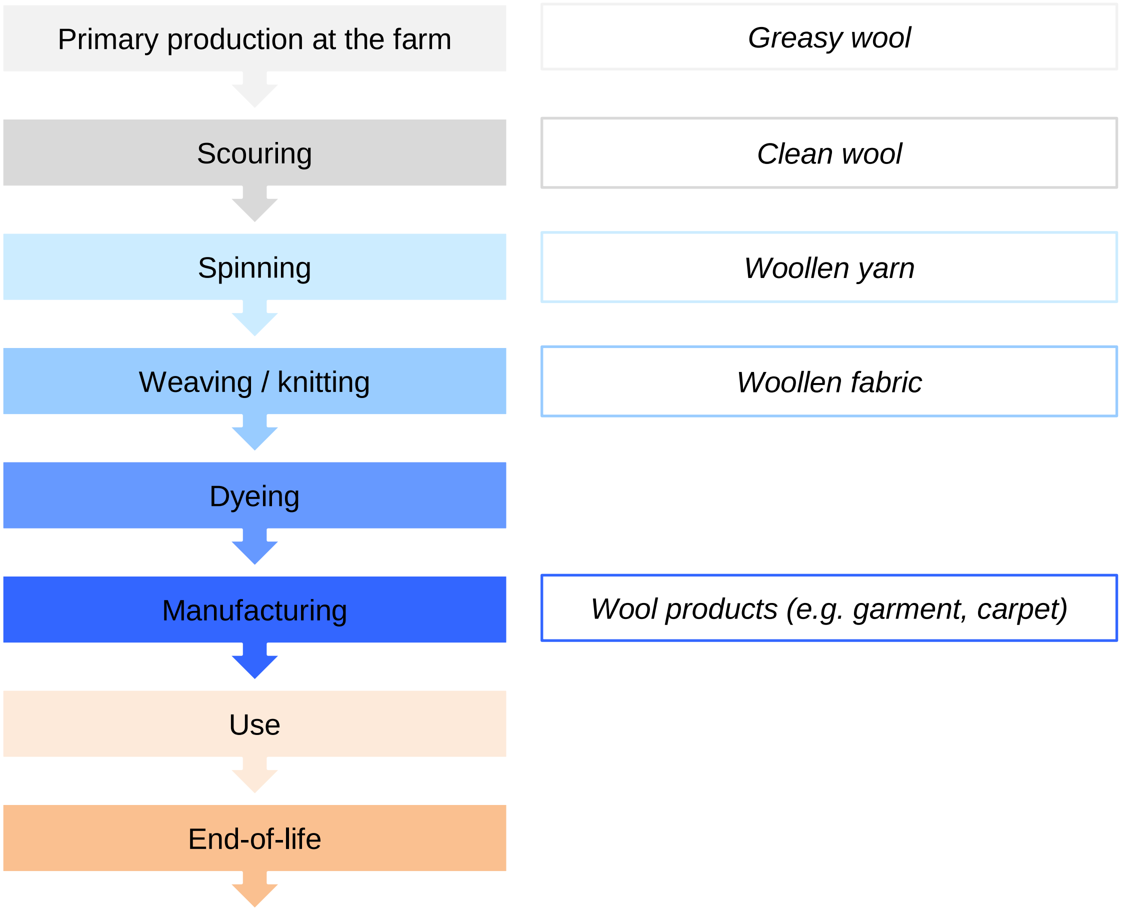

Figure 1: Simplified diagram of stages in the life cycle of wool apparel (adapted from IWTO, 2015)

<u>Focus on allocation for wool LCA:</u>

Sheep production systems have a number of co-products aside to the wool supply chain. The different co-products associated with wool production make wool LCA methodology challenging in order to allocate the burdens. the following examples can be considered among the wool co-products (Henri, 2011):

- Sheep meat
- Manure
- Hides, offal, blood, etc. from slaughters

Those co-products can differ from one farm to another and can also vary according to season and market prices, such as the numbers of sheep for slaughter for instance. Moreover, many sheep farms have mixed production on the same property so that inputs have to be divided between agricultural products (such as fertilizers between cattle and crops)

The ISO standard 14044:2006 is providing guidelines in order to handle co-products in LCA and recommendations on allocation methods:

- Allocation should be avoided as much as possible, by adjusting the system boundaries or using a system expansion method.
- If allocation cannot be avoided, inputs and outputs should be partitioned according to biophysical relationships (for instance weight).
- Allocation based on the economic value of products can be considered when the other methods cannot be used, even though it is the least preferred of the three alternatives.

The IWTO (2016) also recommend an approach based on biophysical properties of wool and its co-products, with a protein allocation or protein mass allocation (PMA).

Existing tools to assess and compare the sustainability of fabrics

The two most widely used tools are the Environmental Benchmark for Fibres (Made-by, 2009) and the Higg Material Sustainability Index (Sustainable Apparel Coalition, 2012).

- The Environmental Benchmark for Fibres compares the environmental impacts of 28 fibres of the garment industry. This benchmark ranks the fibres based on six impact categories that are greenhouse gas emissions, human toxicity, eco-toxicity, energy, water and land use. A score is attributed to each fibre as well as a classification (from Class A to Class E). This tool takes into account environmental impacts from cradle to the raw fiber production, which means that the manufacturing process, use phase and end-of-life stages are excluded. (Made-by, 2009)
- The Higg Material Sustainability Index has been developed by the Sustainable Apparel Coalition in order to enable brands, retailers and other stakeholders to measure and rank a product according to its sustainability performance. It also enables to compare the environmental performance of different materials. The Higg Material Sustainability Index assesses cradle-to-gate impacts for one kilogram of material, from the extraction or production of raw materials, through the manufacturing and finishing stages (i.e. when the material is ready to be assembled into a final product). The impact categories that are considered in this tool are: the global warming, eutrophication, water scarcity, abiotic resource depletion and chemistry. There are 80 materials and more than 400 production processes currently available in the tool. (Sustainable Apparel Coalition, 2012).

3. Methods

The research questions RQ1, RQ2 and RQ3 were answered based on a comprehensive and systematic literature review of wool LCA.

A systematic review is a structured evaluation of the literature with the goal of answering a specific research question with an exhaustive synthesis of the best available evidence. Generally published to share these results with a wide audience for consideration and implementation. After defining a structured question to guide the review, the second step is to perform a thorough search of the literature for relevant papers. (Zumsteg et al, 2012)

LCA studies of wool were selected based on search terms such as “life cycle”, “wool production”, “wool environmental impacts” or “wool LCA”. Publications have been searched in French or English. The databases used were mainly the KTH library search engine and Google Scholar. Other papers have been found by examining all the references from the first wool LCA studies reviewed.

The time period was limited to studies published not before 2005 in order to have the more up-to-date considerations. No restriction on the geographical area was considered, but the studies were looked in priority for the top producing countries, in order to have the greatest geographical representation.

This comprehensive literature review of wool LCA studies is covering different methodological aspects, including:

- The goal and scope
- The functional unit definition
- The system boundaries
- The data inventory
- The impact categories
- The allocation methods

Based on this literature review, a meta-analysis was performed, i.e. the melding of data from multiple studies and use of synergy of information to answer questions that could not be answered with existing individual studies. This meta-analysis enables to combine information and to answer the research questions, find correlations between methodological choices and results and highlight recommendations for correctly interpret results of wool LCA studies.

In order to answer the research question RQ4, a method based on eco-costs have been investigated to build a representative single score, based on the Solvay Sustainable Portfolio Management Guide (2007). Calculations have been performed based on extrapolated data from the Ecoinvent database (2018) for three types of fibres: wool, cotton and viscose. The three types of fibres have been selected in order to be representative of the different types of fabrics: natural fiber from animal origin, natural fiber from vegetal origin and synthetic fiber respectively. The eco-costs for the different environmental impacts have been taken from the Solvay Sustainable Portfolio Management Guide whenever possible or from other literature sources otherwise.

4. Results and analysis of systematic review

4.1. Presentation of the reviewed LCA studies

This thesis provides a comprehensive review of 13 wool LCA studies. Those studies were found to have different goals, such as enhancing the global knowledge about wool impacts, producing average assessments to compare wool with alternative fabrics (such as synthetic fibres of recycled wool) or looking at specific wool supply chains. Depending on their goals, studies result in specific scope, methodology, data requirements and results. Studies also differ in the impact categories that are considered. The 13 LCA studies are representative of a wide range of supply chains and production countries. Some of the studies are assessing wool impacts at a global level while some others are looking into specific countries in Europe (UK, Italy, and Netherlands), the United States, Australia and New Zealand. Moreover, different wool products (fibres, clothing, carpet, insulation) are also considered. The 13 reviewed LCA studies are presented in the Table 2.

It seems difficult to identify a trend in the environmental impacts of wool from the literature reviews. The diversity of wool supply chains, farming practices, geographical and climatic local conditions, as well as some unresolved methodological issues results in a very wide range of studies that cannot be compared easily. Moreover, data quality is also a significant comparison element to take into account while looking at the different LCA studies, as some assessments consider very specific and local data while some others uses regional or global datasets.

This comprehensive literature review examines the scope of existing LCA studies and the critical methodological assumptions affecting the conclusions.

Table 2: Presentation of the 13 reviewed wool LCA studies

Study	Reference	Country	Product	Goal	System boundaries	Functional unit	Impact categories	Allocation method for co-products	Data inventory and quality
Resource use and greenhouse gas emissions from three wool production regions in Australia	Wiedemann et al (2016)	Australia	Fibre	Assess the environmental impact and resource use in the 3 wool production regions as a basis for more detailed full supply chain analysis Contribute to methodological enhancement	Cradle to farm gate	1 kg of greasy wool at the farm gate	Resource use: energy, water and land use GHG emissions (including emissions and removal associated with LU and dLUC)	- protein mass allocation (PMA) method - system expansion process used for comparison (using the average of two scenarios where live weight resulted in avoided live weight production from either an alternative meat sheep or from beef cattle production)	- 10 case study farms via site visits, interviews and a survey of each farm in 2012-13 - 2 regional datasets - The specialist sheep farm dataset including many farms, different regions and covering five years from 2006 to 2010.
Environmental benchmark for fibres	Made-by (2009)	Global	Fibre	Develop a tool to compare the impact of different fibres	Cradle to farm gate	1kg of fibre ready to be spun	GHG, Eco Toxicity and Human Toxicity, Energy, water, land use	Allocation between wool and meat, but the method is not detailed	- Public data coming from more than 150 references. - world average data - some regionally data when global average are not available
LCA of Wool apparel	PE Inter-national Sustainable Performance (2015)	Australia	Clothing	Identify hotspots in the wool supply chain Contribute to methodological enhancement	Cradle to grave	1 pair of socks (70% wool content) and 1 long-sleeved garment (100% wool)	Global Warming Potential (GWP); primary energy demand (PED) and freshwater consumption	- Protein required for wool and meat, using the method of CSIRO (2007) following protocols of LEAP (2014) and Wiedemann et al. (2014) - Mass of protein - Mass - Economic	- Primary data from 27 merino farms based in New Zealand was assessed - National data for use and end-of-life phases - Upstream processes from GaBi Databases (2013)
Greenhouse gas emissions profile for 1 kg of wool produced in the Yass Region, New South Wales	Brock et al (2013)	Australia	Fibre	Determine environmental impacts of 19-micron wool produced in the Yass Region	Cradle to farm gate	1 kg of greasy 19-micron merino wool, modelled for the soil type and weather conditions at Yass	GHG	Gross economic value	- Regional and historical data for soil and pasture from a at'Kia Ora'Bookham, near Yass - Yass weather data from the Specialised Information for Land Owners

Technical report of product's life cycle assessment known as "mechanical wool"	Riccadonna and Bruschi (2015)	Italy	Fibre	Compare the environmental impacts of regenerated wool and virgin wool	Cradle to farm gate	1 kg of regenerated wool	Global Warming Potential, Ozone depletion, Abiotic depletion, Natural land transformation, human toxicity, freshwater eco-toxicity, Particulate / smog caused by emissions of inorganic substance; ionising radiation; Photo-chemical Ozone formation; eutro-phication terrestrial; freshwater and marine eutrophi-cation; water depletion: acidification; Cumulative Energy Demand	Allocation process based on the mass criterion.	- Specific data for energy and raw materials consumptions - SimaPro databases
Resource Use and Greenhouse Gas Emissions from Two Wool Production Systems in Australia	Wiedemann et al (2012)	Australia	Fibre	Investigate the resource use and greenhouse gas emissions from an Australian wool production	Cradle to farm gate	1 kg of greasy wool at the farm gate	GHG	A comparison of mass allocation, economic allocation and system expansion methods is performed between three products: wool, lamb and mutton	Inventory data collected from farmer records, interviews and site visits.
Lifecycle environmental impact assessment of textiles	Van de Vreede and Sevenster (2010)	Nether-lands	Fibre	Compare wool with alternative textiles	Cradle to grave	1 kg wool	Climate change, Fossil depletion, Agricultural land occupation	Environmental impacts have been allocated to the various outputs on the basis of economic value	Average European or even global production data from Ecoinvent database

Application of life cycle assessment to sheep production systems	Wiedemann et al (2015)	UK, Australia, New Zealand	Fibre	Investigate alternative approaches for handling co-production of wool and live weight	Cradle to farm gate	1 kg of greasy wool at the farm gate	Global Warming Potential; cumulative fossil energy demand and land occupation.	Seven methods were applied: - 3 biophysical allocation methods based on protein requirements - protein mass allocation (PMA) - economic allocation - 2 system expansion (SE) methods.	Data from 4 case studies based on survey data collected over the years 2009 to 2012, from farms representative of major agro-ecological zones, with different sheep production systems and breeds
Life Cycle Assessment: New Zeland Merino Industry	Barber and. Pellow (2006)	New Zeland	Clothing	Establish baseline data on merino wool's overall environmental impacts. Identify improvement areas.	Cradle to distribution	1 tonne of dry wool top 1 tonne of greasy wool	Energy use, carbon emissions	- Farm inputs and top making stages inputs are allocated based on the weight of the economic outputs of wool and co-products: (approximately 25% of the total output weight is attributed to wool). - Beyond the farm gate all transport was allocated to wool.	- The primary data was collected directly from farmers, processors and one wool top maker - Background data came from published sources
Does Use Matter? Comparison of Environmental Impacts of Clothing Based on Fiber Type	Laitala et al (2018)	Global	Clothing	Compare the use phase of wool and alternative textiles clothing	Use phase	Clothe use during a given period of time	Energy, water, CO_2	N/A	Global online survey of 467 adult respondents across seven countries: Australia, China, Italy, Japan, South Korea, UK and USA
Life Cycle Assessments of Natural Fibre Insulation	Murphy (2008)	UK	Insulation	Assess environmental impacts of wool insulation and identify improvement areas	Cradle to grave	Insulation of a one square metre 'unit' area within the 'cold roof' space of a house	Abiotic resource depletion; Global warming (GWP100); Ozone depletion; Human toxicity; Ecotoxicity; Photochemical oxidant creation; Acidification; Eutrophication	Economic allocation basis	Detailed information on the processing stages was obtained in consultation with the NFI manufacturers and their suppliers. Cradle-to-gate datasets supplied by the manufacturers were also used.

The life cycle assessment of energy and carbon emissions on wool and nylon carpets in the United States	Sim and Prabhu (2018)	United States	Carpet	Compare wool carpets with alternative fibres	Cradle to grave	Production of 0.09 square meter of a carpet tile	Energy, Carbon	N/A	Data from similar studies, data bases
EcoInvent Wool production	EcoInvent dataset (2018)	US	Fibre	N/A	Cradle to farm gate	1 kg of greasy wool	GHG emissions, human toxicity, ecotoxicity, human health, ecosystem quality, resources (including water)	System expansion	US statistics and data from NREL and other databases

4.1.1. Goal and scope

As highlighted in the table below, the 13 reviewed LCA studies can be grouped into three main different goal categories:

1. Assess hotspots and improvement areas for a specific supply chain, usually from specific local and farms data.
2. Allow comparison between wool products and alternative textiles, relying on some national data or statistics.
3. Improve methodological unresolved issues.

Only a few LCA studies have considered the whole wool life cycle. Most of the reviewed studies have analysed only a partial life-cycle, often from cradle-to-farm gate. Approximately half (54%) of the reviewed studies have studied the greasy wool at the farm gate, thus excluding further production processes and transportation and well as the use and end-of-life stages.

Table 3: Life cycle stages included in LCA studies reviewed in this thesis

Study	Country	Farm	Yarn	Distribution	Use	Disposal
		Fiber				
Wiedemann et al (2016)	Australia					
Made-by (2009)	Global					
Brock et al (2013)	Australia					
Riccadonna and Bruschi (2015)	Italy					
Wiedemann et al (2012)	Australia					
Wiedemann et al (2015)	UK, Australia, New Zealand					
EcoInvent dataset (2018)	US					
Van de Vreede and Sevenster (2010)	Netherlands					
		Clothing, insulation, carpet				
Barber and Pellow (2006)	New Zealand					
Laitala et al (2018)	Global					
PE International Sustainable Performance (2015)	Australia					
Murphy (2008)	UK					
Sim and Prabhu (2018)	United States					

The choice of system boundaries can influence significantly the results of the wool LCA analysis, in particular when looking at comparative LCA studies. As an example, the Higg Materials Sustainability Index (Sustainable Apparel Coalition, 2012) and the Environmental Benchmark for Fibres (Made-by, 2009) are widely used tool to compare environmental impacts of textiles and both of those tools use data from production and exclude use phase. The results from the environmental benchmark for fibres (Made-by, 2009) rank wool within the worst of all fibre categories compared to cotton, synthetic fibres or recycled wool. However, this study was only taking into account impacts from cradle-to-farm gate, thus including all impacts from sheep grazing (enteric methane emissions, land occupation, etc.) and excluding the use phase where wool shows some advantages compared to other textiles. Indeed, when use is excluded, major environmental impacts are omitted, such as the spread of micro plastics (Laitala et al, 2018). Focusing only on the on-farm emissions is also excluding considerations such as product life spans. Regarding the garment industry, differences in dying and washing methods and frequency are also not taken into account, thus displaying only a partial picture of the environmental impacts of the different textiles. For instance, wool requires less energy and chemicals than cotton to be kept clean. Therefore, cradle-to-grave assessments should rather be considered **for comparisons between alternative fibres or textiles. Otherwise, all the assumptions on the life cycle stages should be clearly documented in order to enable stakeholders to accurately interpret the conclusions.**

4.1.2. Functional unit

Defining the functional unit is one of the key steps of the LCA. It should describe the system and its intended functions. (ISO 14040, 2006). The further steps of a life-cycle assessment will be based on the functional unit definition, so it is primordial to clearly define it, in order to be able to collect the relevant data and make relevant assumptions during the life-cycle inventory.

For all the reviewed cradle-to-gate studies, a certain weight of greasy wool (1 kg) is considered as the functional unit. While some studies are very specific in the functional unit definition, such as “1 kg of greasy 19-micron merino wool, modelled for the soil type at Bookham and weather conditions at Yass, from a self-replacing flock of 53 kg mature weight, at a stocking rate of 13.2 dry sheep equivalents (DSE)/ha.” (Brocket al, 2013), other studies consider a more vague functional unit.

Studies looking at one specific wool commodity (clothing, carpet, insulation) are considering a functional unit representative of one wool product, for instance “one pair of socks” or “0.09 square meter of a carpet tile”.

The choice of the functional unit should be aligned with the audience and goal of the study. Therefore, two different functional units are considered in the New Zealander study (Barber and Pellow, 2006) in order to ensure that different audiences could relate to the functional unit and ensure that the on-farm results of the study can be used on its own.

If the functional unit is poorly defined, then the ability to evaluate studies and compare them may be compromised. Moreover, it may result in the misinterpretation of the results if the functional unit is not clearly defined enough. In a wool LCA, the wool should at least be described as greasy or clean. Indeed, it will imply that some additional steps are taken into account in the scope of the assessment. Moreover, when considering wool products, such as one par of sleeves, the wool weight should be specified in order to be able to quantify the wool content.

4.1.3. Data inventory and data quality

Wool LCA studies should also take into account the quality and representativeness of data. When relevant regional data are not available for natural fibres such as wool, it is primordial to be careful when interpreting results and making comparisons. (IWTO, 2016)

An important stage of the life cycle of a wool product is the use phase. However, there are few statistics on that, as depends on individual habits from the consumers. The IWTO states that the wool products' use patterns, such as the frequency and mode of cleaning and drying, as well as the life-time of the products have a significant impact on the environmental burden evaluation for wool. Only a few surveys and research projects provide evidence of the advantages of wool in the use, recycling and disposal phases (IWTO, 2016). As a result, many apparel and textile LCA studies have used units such as one garment or one kilogram of textile or fiber. When included, the use phase has often been assumed to be the same across all types of fabrics, regardless of fiber specificities, the quality of the product or its purpose (socks or long-sleeves garment). Similarly, the disposal destination is assumed to be landfill for all garments, without assessing it the product is suitable for recycling or if it is reused. (Laitala et al, 2018).

A major source of uncertainty in assessments of the environmental impacts of wool is data quality (IWTO, 2016). It is a major challenge to collect representative data for wool and it requires time and money investments in order to build and manage such data sets. Examples of challenges related to wool data collection are listed below:

- Sheep farming covers a very wide range of geographical areas with specific soil types and climatic conditions, as well as farm different practices and technologies for processing and manufacture. Therefore, is necessary to collect specific on-farm data. (Henry, 2013)
- Production and processes data have commercial sensitivity and some data such as weather conditions or market prices have a great variability. Thus, this is important to collect local and temporarily relevant data.
- For the use phase (washing and drying) and end-of-life of clothing products, data depends on human practices relating to purchase, care and disposal of products, which can vary significantly from one person to another and according to regions, cultural, social and economic circumstances. Reliable data are therefore sometimes very difficult to obtain and remain uncertain. (Henry, 2013)

Therefore, this is a great challenge to collect representative data for a specific wool system. This is why it is important to perform a sensitivity analysis to assess the uncertainties, especially when it comes to special or temporal variability or regarding the sensitivity of some methodological choices on the results of the LCA. (Björklund, 2007).

The reviewed LCA studies use a wide range of different data sources and quality. For instance, the Environmental Benchmark for Fibres (Made-by, 2009) aiming at comparing wool impacts with other textiles, rely on public and worldwide data. Besides, studies looking at the impacts of a specific wool supply chain are using data collected directly from farmers, through interviews or site visits. Most of the reviewed LCAs were found to use average data, without considering seasonal variations, for instance in weather conditions, for simplification reasons.

One example of very detailed and robust data inventory is from the study of Wiedemann et al (2016) which relies on 10 case study farms via site visits, interviews and a survey of each farm in 2012 and 2013. Two regional datasets are also used, as well as a specialist sheep farm dataset including 71 farms in 3 different regions and covering five years from 2006 to 2013. Five years of data were used in order to account for inter-annual variation as a result of seasonal variation, following recommendations from LEAP (2014). Land occupation was also divided into use of arable and non-arable land resources.

It is primordial to ensure that the temporal and geographical representativity of the data are relevant and to perform a sensitivity analysis in order to assess the uncertainties related to data quality. For instance, knowledge and innovation relating to chemicals and their toxicity have developed over recent decades and major changes have occurred. As a result, studies and results from studies in the 1990's may not be relevant any longer (IWTO, 2016).

4.1.4. Impact categories

This thesis will mostly focus on four impact categories which are taken into account in most of the reviewed LCA studies. Those impact categories are presented and described (ILCD Handbook, 2010) in the Table 4.

Table 4: Presentation of the main impact categories considered in the LCA studies

Impact category	Description	Unit
Energy use	This impact category assesses the cumulative energy demand of a product. This is a measure of the total amount of energy consumed (fuel energy) and incorporated into product (feedstock energy). It includes both fossil and renewable energies. This impact category is expressed in total energy inputs (MJ) per functional unit.	MJ
GHG emissions	This impact category is an estimate of the contribution of the functional unit to global warming potential (GWP) in kg of CO_2e equivalent per functional unit. All greenhouse gases are considered with their specific global warming potentials. This takes into account carbon emissions due to fossil fuels, methane from animal grazing or nitrous oxide from manure and fertilisers.	kgCO_2e
Water consumption	The traditional classification of water use in LCAs is a measure of the gross amount of water extracted from the natural environment in litres (L) per functional unit. However, this approach is being challenged as more comprehensive considerations take into account the level of water stress in the different regions (stress-weighted water footprint). The water stress index is the evaluation of the exposure of water users to water stress in different regions. It represents the ratio of	L

	total withdrawals to total renewable supply in a given area. A higher water stress rating means that more water users are competing for limited water supplies. (WRI, 2013).	
Land use	The impact category land use is intended to represent the damage to ecosystems associated with human land occupation over a certain period of time. It is expressed in m2/year.	m^2/yr

Other indicators such as eutrophication or natural resources depletion are also taken into account in a few studies:

- The eutrophication is the enrichment of a water body with minerals and nutrients (nitrogen and phosphorous) which induce excessive growth of plants and algae. (ILCD Handbook, 2010)
- The natural resource depletion is the consumption of mineral, fossil and non-renewable resources. This indicator provides information on the depletion of materials more than on the impact caused by their extraction. (ILCD Handbook, 2010)

4.2. LCA results and impact of methodological choices

In this section, the results of the wool LCA studies will be presented and discussed for the four most frequent impact categories considered in the reviewed studies:

- Greenhouse gas emissions
- Energy consumption
- Water consumption
- Land use

It can be complex to interpret results from LCA studies due to the number of methodological factors that can affect the outcomes. Some illustrative examples are included below and discussed in order highlight the limitations and challenges of attempting to make comparisons. From the systematic literature review, the most significant methodological choices affecting the results – and that will discussed and exemplified in the following sections – are:

- The **system boundaries** definition: it has an impact on different impact categories, especially:
    - the inclusion or exclusion of the **use phase**, that has a significant impact on water and energy impact categories,
    - the consideration of a **water stress index** for the water impact category and
    - the consideration of **carbon sequestration in the biomass** for the Global warming category.

- The **allocation methods** for co-products: this has an influence on all the impact categories:

In the reviewed LCA, different allocation methods are applied in order to allocate the environmental impact between wool and meat. When the other types of co-products are sometimes mentioned, they are never taken into account in the studies, as they are less significant and have less value than meat.

- 2 of the studies have not taken into account the allocation of co-product
- 1 has not detailed the methodology
- 5 studies have considered a method based on a biophysical allocation

Economic allocation is a quite common applied methodology (in 7 of the reviewed studies), although this method of allocation is the less recommended by the IWTO and ISO standard.

As it will be highlighted in the following parts, the results of the reviewed **LCA studies are difficult to interpret and compare due to the number of methodological factor and data considerations that can affect the outcomes**. Some illustrative examples are included below.

4.2.1. Greenhouse gas emissions

The major contribution to the greenhouse gas emissions of wool products is generally enteric methane. Methane, which is produced in the digestive process of ruminant animals is a strong greenhouse gas, having a global warming potential of 28 on a 100-year time frame (GWP100), i.e. a unit mass of methane causes 28 times the radiative forcing as the same mass of carbon dioxide (IPCC, 2014). Emissions of methane from waste (defection and urine) and nitrous oxide from waste and fertiliser applications are also significant sources of on-farm greenhouse gas emissions. Carbon sequestration in vegetation and soils is generally not included in LCA studies. Fossil fuel CO_2 emissions from electricity and transport are the main sources of greenhouse gas emissions from the processing and use phases of wool products as well as contributing to on-farm emissions.

- Cradle to farm gate studies:

In cradle-to-farm gate LCA studies, the total GHG emissions vary in quite a large range of values. For instance, according to Wiedemann (2016), between 20,1 and 21,3 kgCO_2e are emitted to produce 1 kg of greasy wool. This result was obtained using a protein mass allocation method from the studied Australian farms' data.

In another study in the Yass region (Brock et al, 2013), the total greenhouse gas emissions amount to 24.9 kg CO_2e/kg of greasy wool considering a gross economic allocation based on the market price and farm output for each commodity in which 56% of the emissions are to be attributed to the wool production.

However, **those results are very sensitive to the allocation method**. Indeed, some of the studies are assessing the sensitivity of the results according to the chosen allocation method. For instance, the study by Wiedemann et al (2015) is investigating seven different allocation methods, that are presented below in the Table 5. A sensitivity analysis has been performed in order to assess the influence of the allocation method on the results in four different case studies: one in the UK, one in New Zealand, and two in Australia.

Table 5: Presentation of the seven allocation methods from the study by Wiedemann et al (2015)

Types of allocation methods	Allocation method description
Biophysical Allocation methods based on the partitioning of digested protein (3 methods)	The allocation to wool and sheep meat is based on the fraction of protein required for wool or meat divided by total utilised digestible protein. Three alternative methods have been investigated and differ on the allocation of the maintenance requirements.
Protein mass Allocation (1 method)	The protein content of greasy wool was estimated from the protein content of clean wool on a dry matter basis and ratio of clean wool to greasy wool. The protein content of live weight was assumed to be 18%.
Economic Allocation method (1 method)	The allocation is based on the economic value for greasy wool and live weight, averaged for more than 2 years.
System Expansion methods (2 methods)	The system expansion methods were assuming avoided products systems being beef cattle or sheep on the same farm.

The study highlights that considerable differences between the results can be observed according to the choice of the allocation method (Wiedemann et al, 2015). It has been found that allocating impacts on the basis of protein mass resulted in a higher allocation of impacts to wool compared to other allocation methods because of the high protein density of wool. The allocation method based on economic consideration shows very different results in the four case studies, as it depends on the quality of wool that is produced. Indeed, the wool quality has a significant impact on the price of the wool whereas the live weigh price remains almost the same. For instance, this allocation method results in high allocation of the environmental burdens to wool for the two case studies in Australia which are producing fine Merino wool but allocates lower burdens in the two case studies which are producing lower quality wool.

Even though the results are very different depending on the region, climate and allocation method, the repartition of the impact are quite similar between the studies, as highlighted in the Figure 2. The greenhouse gas emissions are dominated by the direct on-farm methane emissions (around 80%), followed by nitrous oxide emitted from animal wastes and only a small percentage of total emissions are due to the farm inputs, such as fertilizer and energy consumption.

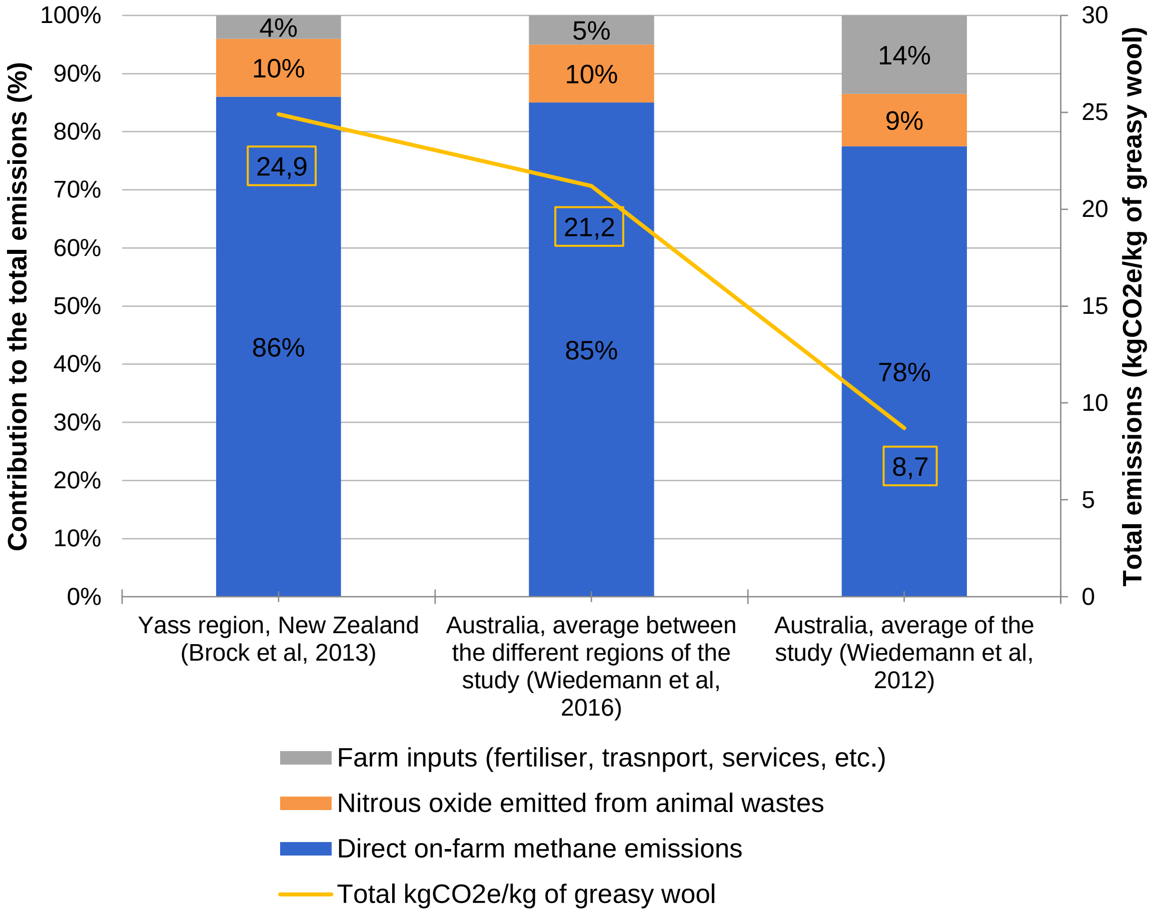

Figure 2: Comparison of the total GHG emissions and repartition of the emission sources for three cradle-to-farm gate studies

- Cradle-to-grave studies:

In studies looking at the whole life-cycle of wool clothing, the dyeing and finishing stages have a considerable impact. Yarn production is also significant due to the use of fossil-based energy. For wool carpet, the share related to the wool processing is much lower. Indeed, unlike cradle-to-farm gate studies, the repartition of the greenhouse gas emissions from the different sources is quite different between the reviewed studies. This is highlighted in the Figure 3 below. End-of-life and transportation stages are negligible in all the cradle-to-grave studies.

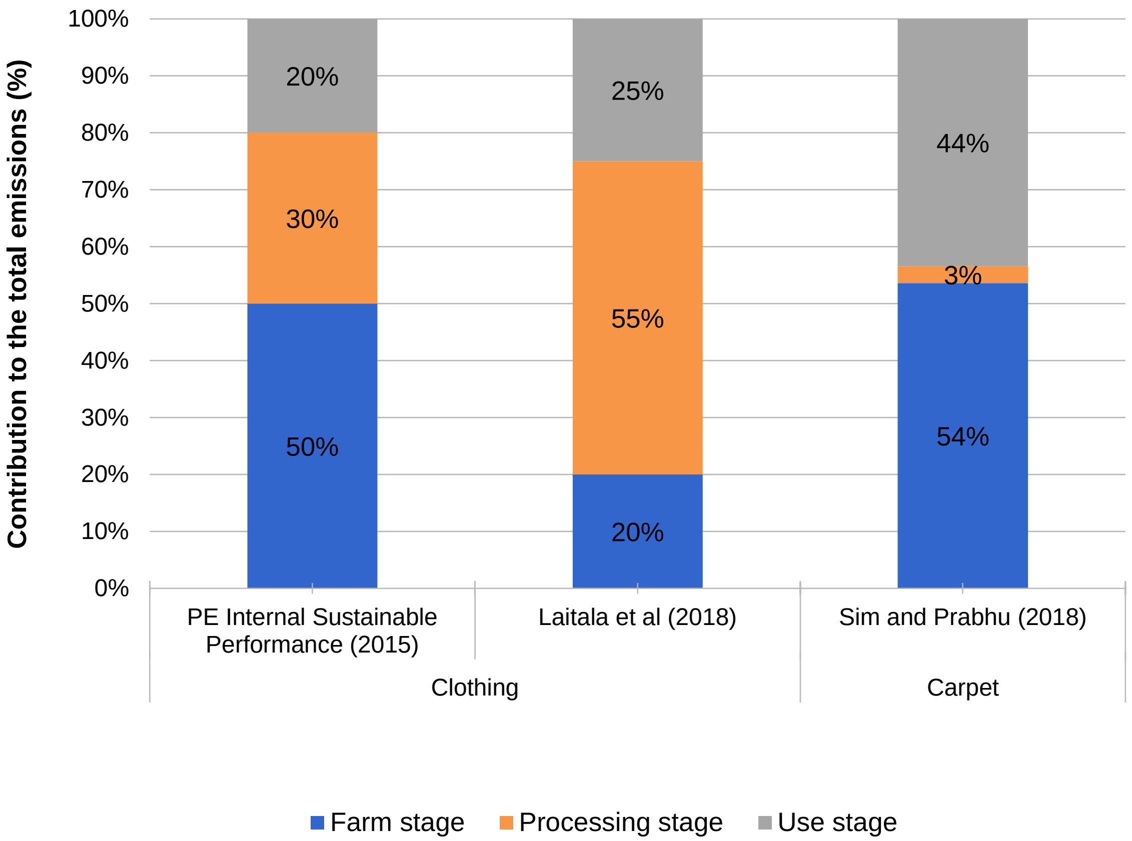

Figure 3: Repartition of the greenhouse gas emissions for cradle-to-grave LCA studies

In the cradle-to-grave LCA study performed by PE International Sustainable Performance (2015) on wool socks and garment, results show that approximately half of the total greenhouse gas emissions are due to the farm stage. One third due to the processing stage and around 20% is linked to the use stage.

In the cradle to grave study on wool clothing by Laitala et al (2018), the farming stage represents a much smaller share of the total greenhouse gas emissions. The results of the study show that the processing phases are the most significant. The dyeing and finishing stages show the highest impact, contributing to 36% of total greenhouse gas emissions. The yarn preparation amounts to 28% of the greenhouse gas impacts because of the energy intensive processes and high dependence on fossil-based energy.

Besides, the results of the cradle to grave LCA of a wool carpet (Sim and Prabhu, 2018) show that the raw material production and use stages contribute to the largest amount of carbon emissions among the other life cycle stages. The carpet use stage contributes 40% of the total carbon emissions and the raw material production stage amounts to 55% of the carbon emissions.

4.2.2. Energy use

- Cradle to farm gate studies:

The Australian cradle-to-fam gate study by Wiedemann et al (2016) shows that purchased inputs, such as fertilizers and pesticide, represent a significant share of the energy consumption of wool, with only 12% associated with direct farm energy demand. The total energy demand ranges between 12 to 22 MJ/kg of greasy wool according to the geographical zone, due to the difference in grazing intensity. The highest energy consumption was observed in the western wheat-sheep zone (WSZ) where fertiliser and pesticide inputs associated with pasture were higher. Fertiliser input was lower in the extensive management systems used in the southern pastoral zone (SPZ), resulting in lower energy demand. The Table 6 below presents the results of the Australian study by Wiedemann et al (2016) for the different impact categories.

Table 6: Results of the study by Wiedemann et al (2016) in 3 different zones in Australia

Impact per kg of greasy wool in the 3 zones	Western Wheat Sheep Zone (WSZ)	Southern Pastoral Zone (SPZ)	High Rainfall Zone (NSW)
Greenhouse gas emissions (kgCO_2e)	20	20	21
Carbon stored in land/soils (kgCO_2e)	0 to -0,1 (stock)	+0,1 (emissions)	-1,9 to -0,7 (stock)
Non-renewable energy consumption (MJ)	22	12	16
Water consumption (L)	394	380	204
Land occupation (m^2)	406	9006	224

- Cradle to grave studies:

Besides, the cradle to grave LCA of a wool carpet (Sim and Prabhu, 2018) indicates that the carpet use stage consumes a large amount of energy contributing 69% of the total energy consumption and the raw material production stage represents 18% of the total energy consumption.

Table 7: Energy consumption for a wool carpet and a nylon carpet (Sim and Prabhu, 2018)

Energy consumption for 0.09 square meter of a carpet tile	Wool carpet	Nylon carpet
Raw material production (MJ)	3,74 (18%)	17,57 (69%)
Use phase (MJ)	14,13 (69%)	6,22 (24%)
Others (carpet tile production, installation, transportation, etc.) (MJ)	2,55 (13%)	1,73 (7%)
Total (MJ)	**20,42 (100%)**	**25,52 (100%)**

System boundaries (use phase):

As is has been highlighted in the part 4.1.1, more than 60% of the reviewed studies do not take into account the use phase in the LCA, whereas it represents a significant share of the energy consumption in a whole life-cycle assessment. Washing and drying are responsible for approximately one-third of the primary energy consumption and half of the water consumption on the life cycle of a wool product (Henri, 2015).

Indeed, on the cradle-to-grave study of wool socks and garment (PE International Sustainable Performance, 2015), the results show that processing and use phases are responsible for the bigger impacts and on-farm needs contribute only to approximately 12% of the total energy consumption. This is due to the fact that wool processing is energy intensive and that the use phase accounts for all the washings of the wool products over their lifetime. As a result, the use phase represents up to one third of the energy consumption over the life cycle of the both the socks and garments products.

Besides, **even though it represents a significant share of the energy impact on the life cycle of the wool garment, excluding the use phase in the scope of a study prevents to take into consideration the better performance wool use phase compared to alternative textiles.** As highlighted in the study by Laitala et al (2018), the use phase of wool shows better impacts than other textiles, especially due to the following features:

- Machine washing at low temperature
- Drying in the open or in low temperature machine
- Longer lifetime than other textile fibers (2-10 years compared to 2-3 years)

However, the use phase is difficult to assess as it depends on many factors that are difficult to assess such as cultural or personal habits. Considering the uncertainty regarding energy consumption in the use phase, further research is required in order to better take this into account in wool LCA studies.

4.2.3. Water consumption

Out of the 13 reviewed LCA studies, only five have considered the water consumption impact indicator in their assessment (3 cradle-to-farm gate studies and 2 cradle-to-grave study).

- Cradle to farm gate studies:

On-farm water consumption depends on the farming and climatic conditions, as shown in the Australian study by Wiedemann (2016) and highlighted in the Table 6 au-dessus. At the farm gate, fresh water consumption ranged from 204 L/kg of greasy wool in the High Rainfall Zone (NRZ) to 394 L in the Western Wheat Sheep Zone (WSZ). This difference relies primarily due to the different climate conditions (Wiedemann et al, 2016). The great majority (around 70% in average) of the water consumption is due to drinking water supply losses in all the scenarios. Only 10% to 20% is related to livestock drinking and a few percentages to other minor water inputs. The water consumption from the Ecoinvent database is in the same range of values and amounts to 364 L/kg of greasy wool.

System boundaries (water stress index):

Some studies are taking into account the water stress index of the region in order to provide with a more comprehensive overview of the real impact of the water use on a region. Indeed, the water stress index represents the ratio of total withdrawals compared to the total renewable supply in a given area. It is a measure of the competitive usage of water in a specific area, in percentage. As a result, a higher percentage is representative of a higher competition for using a limited amount of water supplies (WRI, 2013).

The water stress index is a relevant data to assess in this context, as the water consumption on farm is quite significant. However, as it is highlighted in different studies, the water stress index of the studied areas is low (around 1,5%), as there are few alternative usages for the water. It is linked to the fact that most of the grazing area are non-arable land, as discussed in the section 4.2.4.

As presented above, the study by Wiedemann et al (2016) showed that the total water consumption ranges between 204 to 394 L/kg of greasy wool in the different zones in Australia. However, this water consumption is weighted to 74,6 L H20e in the worst-case scenario using the water stress index. Interestingly, stress-weighted water use follows the opposite trend as water consumption due to the different levels of water stress across the regions. (Wiedemann, 2016), as highlighted in the Table 8 and Figure 4 below.

Table 8: Water and stress-weighted water consumption in three zones in Australia (Wiedemann et al, 2016)

	Western Wheat Sheep Zone (WSZ)	Southern Pastoral Zone (SPZ)	High Rainfall Zone (NSW)
Water consumption (L)	394	380	204
Water stress Index (%)	1,2%	1,7%	1,1%
Stress-weighted water consumption (L H_2Oe)	21,5	11,0	74,6

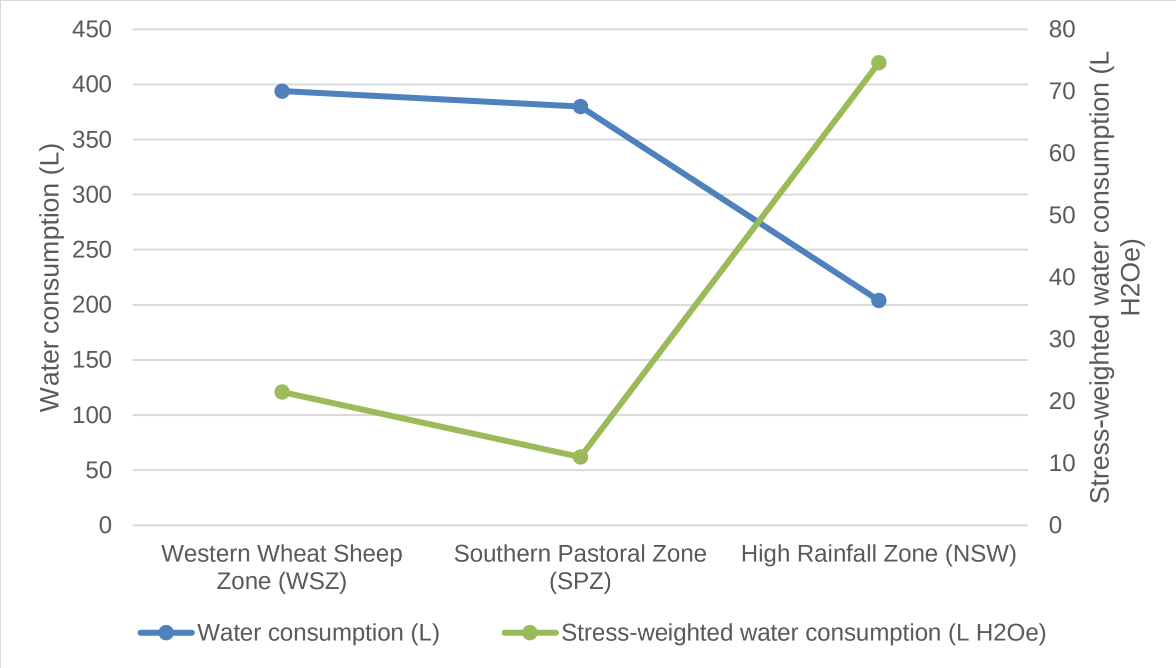

Figure 4: Water and stress-weighted water consumption in 3 zones in Australia (Wiedemann et al, 2016)

- Cradle to grave studies:

The same consideration as for the energy consumption is applicable to water consumption regarding the cradle to grave LCA studies on wool.

System boundaries (use phase):

Only two studies have considered the water impact on a whole life-cycle assessment. However, as highlighted by the of the PE International Sustainable Performance study (2015) on the cradle-to-grave LCA of wool clothing, most of the water is consumed during the use phase: 58%-74% for the wool socks and 44%-60% for the wool garment.

However, the use phase is difficult to assess as it depends on many factors that are difficult to assess such as cultural or personal habits. Considering the uncertainty regarding water consumption in the use phase, further research is required in order to better take this into account in wool LCA studies.

4.2.4. Land use

Less than half of the reviewed LCA studies have assessed the impact of wool on land use. This impact category is taken into account in very different ways, which are not all very representative of a real impact on wool on soils, in terms of biodiversity or occupation against potential alternative usages. Indeed, in some LCA data, such as the Ecoinvent database (2018) or the Environmental Benchmark for Fibres (Made-by, 2009), land use is considered as the area needed for producing the wool at the farm stage (yield, in hectare). According to the Dutch study (Van de Vreede and Sevenster, 2010), land use is not really an environmental impact but rather an intervention. Some other studies are assessing this impact category by taking into account further considerations. For instance:

- by sub-categorising different types of land (on-farm crop land, arable land for pasture and non-arable land) in order to assess whether or not the land could have had an alternative usage (Wiedemann et al, 2015)
- by assessing the damage to ecosystems, i.e. the loss of biodiversity associated with the effects of human land occupation over a certain period of time (Van de Vreede and Sevenster, 2010)
- by assessing the change of carbon stocks in the soils (Wiedemann et al, 2016)

Other sophisticated models exist and are recommended by different organizations but have not been used in the reviewed wool LCA studies.

There are frequently insufficient data on historic land use and when data do exist, large uncertainties remain in the attribution of land changes to natural (such as drought) or anthropogenic (over-grazing for instance) causes (Henri, 2015). Besides, the land occupation varies very significantly between the studies, as it depends on the wide variety of land management practices between individual farmers. The Table 9 summarises the total land occupation in the different geographical zones as well as the percentages of the land occupation that are arable and non-arable. In all the studies where the share of arable land occupation has been assessed, the results show that the great majority (70% to 100%) of the land use for sheep grazing is non-arable and thus that there are few competing land use activities for this land.

Table 9: Land occupation impact from the reviewed LCA studies

Land impact on different geographical zones	Wiedemann et al (2016)			Wiedemann et al (2015)		Van de Vreede and Sevenster (2010)	Ecoinvent (2018)
	Australia Western Wheat Sheep Zone (WSZ)	**Australia** Southern Pastoral Zone (SPZ)	**Australia** High Rainfall Zone (NSW)	**United Kingdom**	**New Zealand**	**Netherlands**	**United States**
Land occupation (m²)	406	9006	224	*Not displayed in the study*	*Not displayed in the study*	126	86,9
Arable land occupation (%)	30%	0%	5%	5%	12%	*Not assessed*	*Not assessed*
Non-arable land occupation (%)	70%	100%	95%	95%	88%	*Not assessed*	*Not assessed*

Furthermore, in some regions, there is evidence of the long-term sustainability associated with the good management practices and that sheep grazing over large areas in extensive production systems does not result into a negative environmental impact. For instance, some positive impacts of the grazing could be the prevention of weed invasions, damage by feral animals or loss of biodiversity through uncontrolled wildfires. (IWTO, 2016).

In a study of sheep systems in Spain, (Ripoll-Bosch et al, 2013), it has been demonstrated that the benefits of sheep to ecosystem services were significant in extensive mid-high altitude natural or semi-natural areas. Those ecosystem services are for instance the conservation of biodiversity and landscapes.

System boundaries: Land use and carbon sequestration modelling

Only one of the studies has measured the impact of grazing on the carbon stocks in the soils. As described above, many studies only consider land occupation as a yield (in hectares of square meters per kg of fibre), which is not correlated with real environmental impacts. Indeed, the study by Wiedemann et al (2016) shows that in some regions, according to the type of land and climate conditions, the grazing results in the sequestration of carbon in the soil, i.e. some negative carbon emissions, which was highlighted in the Table 6. This means that in some case, the sheep grazing could have some positive impacts.

Furthermore, the ISO standard for quantification of the carbon footprint of a product (ISO 1406, 2018) states that when they are significant, the greenhouse gas emissions and removals resulting from direct land use change have to be assessed in accordance with the goal and scope of the study and should be included in the product carbon footprint. The IPCC provides with internationally recognized methods to do so, such as the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).

5. Application to build a representative single score

As it has been highlighted in the section 4, to have a fair representation of wool, it is necessary to consider the whole life-cycle of the product. Moreover, it is recommended by to allocate the burdens between wool and live weight using a physical allocation method (IWTO, 2016).

For the impact categories, water consumption and land use should be elaborated in order to be more representative of the real impacts of wool on the environment.

Table 10: Extrapolation of Ecoinvent impact categories for three types of fibres (Ecoinvent, 2018)

Extrapolated impact categories for 3 types of fibres	Wool	Cotton	Viscose
GHG (kgCO2e)	56,3	53,0	53,6
Energy input (MJ)	32	75,9	46,3
Stressed-water input (L H_2Oe)	105,1	482,9	221,3
Weighted land use (m2 arable/year)	17,4	8,4	0

The Table 10 above presents an extrapolation of Ecoinvent data (Ecoinvent, 2018) for three types of fibres cotton, viscose and wool in order to take into account the recommendations stated in the section 4.2. Those extrapolations consist in rough hypothesis:

- Water input is weighted using a water stress index factor of 1,5%, which is the average water stress index on the different regions studied in the study by Wiedemann et al (2016).
- Energy and water inputs are extrapolated in order to take into account the use phase, considering that it represents half of the impacts for wool and that the use phase is twice as important as wool for cotton and viscose due to worse management patterns.
- Land use is weighted considering that only 20% of the land use for textile production is arable.

In order to provide with simple and comprehensive results that could be used by the textile industry, the Made-by benchmark (2009) or the Higg index (2012) are rating the environmental impacts of textiles and consolidating them into one single score. This also enable to compare the sustainability performance of the different fibres. The Table 11 above presents the weighting factors used in the Made-by tool. The impact categories human toxicity and eco-toxicity are not displayed as this thesis does not focus on those aspects. Greenhouse gas emissions, human toxicity and eco-toxicity are weighted with a 20% factor while the energy input, water input and land use impact categories are weighted with a 13,33% factor. Those weighting factors do not rely on specific scientific considerations

Table 11: Weighting factors of the Made-by Environmental Benchmark for Fibres for the studied impact categories (2009)

Made-by weighting factors	Unit	Weight
GHG	$kgCO_2eq/kg$ fiber	20%
Energy input	MJ/kg fiber	13,33%
Water input	L/kg fiber	13,33%
Land use	ha/kg fiber	13,33%

According to the Figure 5, the water consumption is predominant in the single score for the three types of fibres considered. There is no scientific explanation of those weighting factors on the Environmental Benchmark for Fibres (Made-by, 2009).

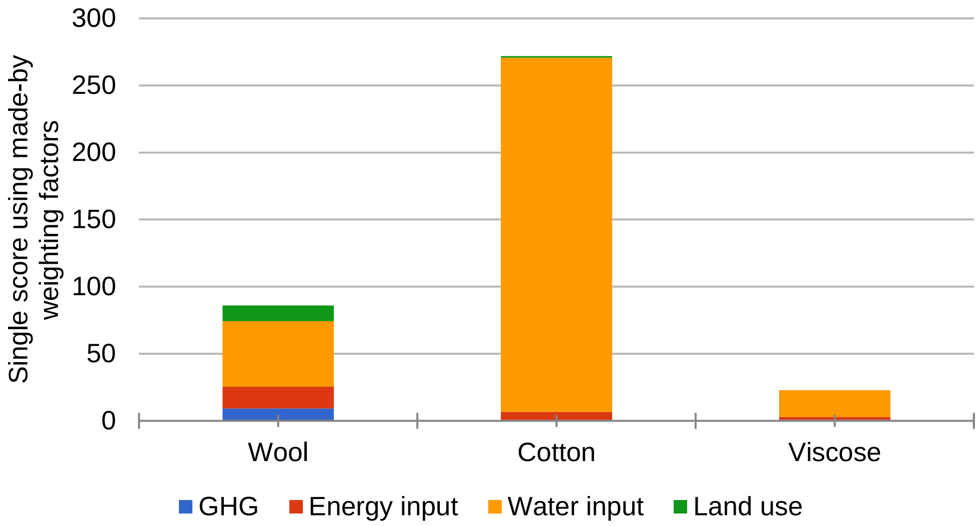

Figure 5: Single score results using Made-by weighting factors on Ecoinvent data for 3 types of fibres on the selected impact categories

Eco costs

The eco-costs are a measure that express the cost of an environmental impact on the basis of prevention of that impact. Those are the costs which should be made in order to reduce the environmental burdens in our world to a level which is in line with the carrying capacity of our earth (Vogtländer and Mester, 2009). Monetarizing the environmental impacts of textile production enables to find a common measure for all the different impact categories and thus to establish a new single score methodology. This could be done based on the eco-costs the different impacts on energy, GHG emissions, water and land use. Eco-costs are an interesting measure for building a single score methodology, as it allows to qualify the environmental impacts and to put them into perspective considering their cost for society. Monetarizing the environmental impacts also provides with a measure that would be more easily understood by companies and help decision makers realize the potential business impact corresponding to the environmental burdens. The Table 11 below presents a set of eco-costs available in the literature.

Other methods could have been investigated, such as the definition of weighting factors based the mitigation costs (i.e. the cost of repairing the damages) or by consulting/performing a poll on the population to assess what are the impacts that people consider as the most important.

Table 12: Example of eco-costs in the literature for energy, greenhouse gas emissions, water and land use

Impact category (unit)	Eco-costs	Source
Water (€/L)	0,001	Solvay SPM Eco-costs (2007)
Land use (€/m2/yr)	0,096	De Groot et al. (2012), converted in € (2007 rate)
CO2 (€/kg CO2e)	0,075	Solvay SPM Eco-costs (2007)
Energy (€/MJ)	0,018	Solvay SPM Eco-costs (2007)

The Figure 6 is a rough trial to build a single score for wool based on the eco-costs presented in the Table 12 and wool impacts from the Ecoinvent database and comparison with the single score methodology of the Made-by benchmark (2009). Using this methodology on the extrapolated impact categories data for wool, cotton and viscose, the three fibres types result in having a more similar single score result, dominated by the greenhouse gas emissions contribution. This is shown in the Figure 7 below.

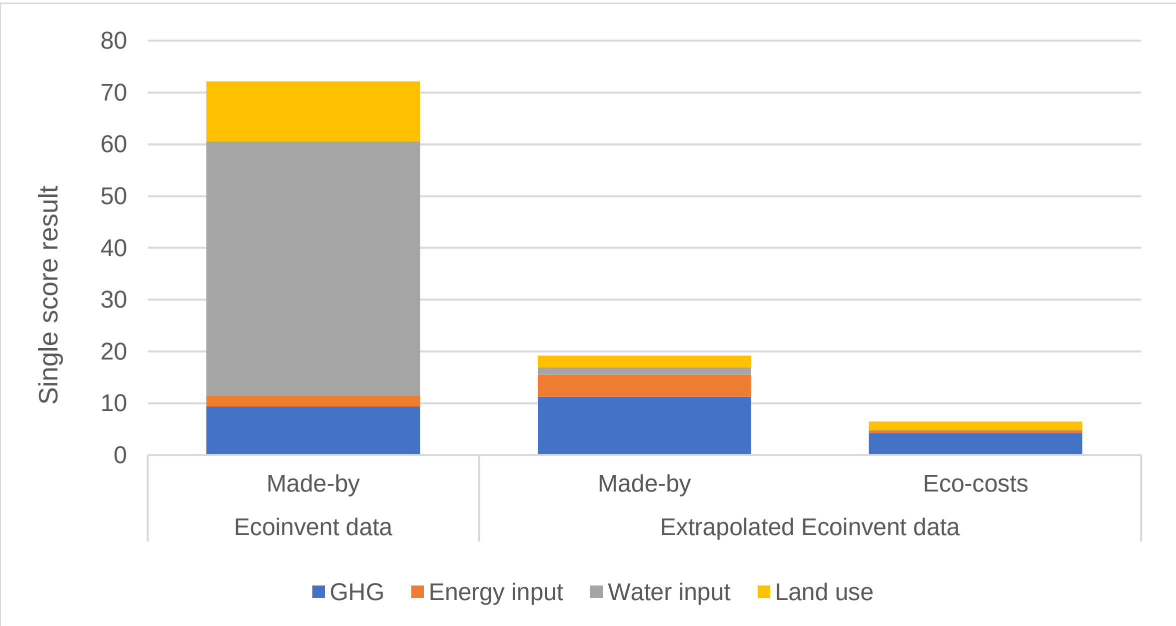

Figure 6: Single score for wool based on eco-costs compared to weighting factors from the Made-by benchmark methodology

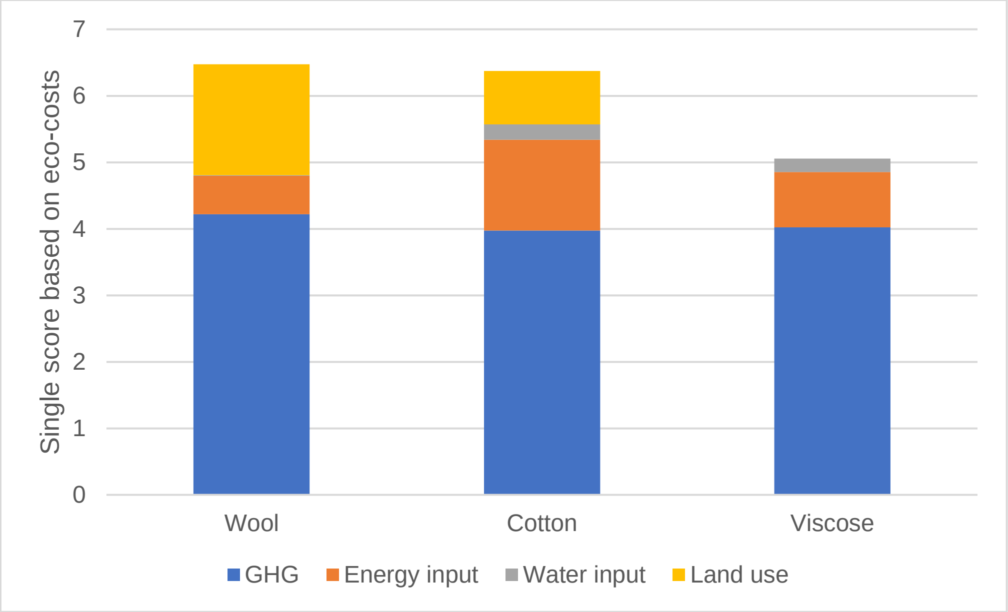

Figure 7: Single score for cotton, viscose and wool based on Ecoinvent extrapolated impact indicators and eco-costs methodology

6. Discussion and conclusion

6.1. Key methodological choices and impacts on the results

- Cradle-to-grave assessments should rather be considered to enable comparisons between alternative fibres or textiles. Otherwise, all the assumptions on the life cycle stages should be clearly documented in order to enable stakeholders to accurately interpret the conclusions.
- It is primordial to ensure that the temporal and geographical representativity of the data are relevant and to perform a sensitivity analysis in order to assess the uncertainties related to data quality.
- At least, the greenhouse gas emission, energy consumption, water consumption and land use impact categories have to be taken into account in the life cycle impact assessment for wool products.
- The system boundaries definition has an impact on different impact categories, especially:
    - the inclusion of the use phase has a significant impact on water and energy impact categories. Even though it represents a significant share of the energy and water impacts on the life cycle of a wool garment, excluding the use phase in the scope of a study prevents to take into consideration the better performance wool use phase compared to alternative textiles.
    - the consideration of a water stress index for the water impact category shows that there is few competitive alternative water usages in the studied areas.
    - the consideration of carbon sequestration in the biomass for the global warming category shows that sheep grazing results sometimes in negative carbon emissions.
- The allocation method for co-products affects all impact categories, so it is primordial to clearly describe the allocation method used and to perform a sensitivity analysis

6.2. Main issues when comparing wool to other textiles

Wool LCA results depend on many methodological and data uncertainties that have to be assessed in a sensitivity analysis

Uncertainties due to methodological choices, especially allocation procedures, have to be carefully evaluated thought sensitivity analysis. Whenever specific data for wool production are not available, uncertainties should also be assessed.

The incomplete scope in the ranking tools is disadvantageous for wool

As it has been highlighted, the most widely used tools to assess the environmental impact of textiles are Made-by and Higg MSI. Those tools are taking into account the on-farm stage but are excluding the use phase and end-of-life stages. However, wool products show a better performance than alternative fibres on those life-cycle stages because of their longer life-time and maintenance patterns (frequency of cleaning, cold water programs, natural drying).

In order to have a fair representation of wool and especially for being able to compare the environmental impact with other fibres, the whole life-cycle of products should be taken into account, as well as the differences in life-time, quality, maintenance patterns, etc.

Morevover, those ranking tools are considering a single score indicator for which the weighting factors are questionable and not clearly motivated.

Wool get a poor score in some of the impact categories due to indicators that are not fully representative of the environmental burden of wool products

Some impact categories, such as water input and land use, can be criticised as they do no really measure the environmental impact of the wool production but are rather an inventory. Indeed, as it has been discussed, more relevant indicators would be the stress-weighted water consumption and a more refined model for the land use (for instance assessing ecosystem services, carbon sequestration in the soils or at least the share of arable land out of the total land use).

Indeed, the IWTO (2016) states that the land occupation, which is often assessed simply as the area of land used and used in some tools ranking fibres or textiles, is large compared to other fibres especially in pastoral regions. However, most land for wool production is non-arable and only a small share is arable land and could be used to feed crops or support wider farm management. Some case studies have shown that grazing can improve the biodiversity and provide valuable stewardship of large natural areas where extensive grazing is the only practical and economically viable productive use.

6.3. Recommendations for building a representative single score indicator

In order to build a more representative single indicator to compare the sustainability performance of textiles, some impact categories have to be adjusted. For instance, water consumption should not be considered only as a volume of water but should rather take into account the water-stress index of the production regions. Land use should not be considered only as a yield. Different models and methodologies are being developed (e.g. soil organic matter, ecosystem services, etc.) to elaborate this indicator.

Moreover, in order to build a fair single score, the weighting factors have to be scientifically justified, for instance through consultation of experts, or by finding a common measure between all the impact categories. This could be done based on the eco-costs the different impacts related to energy use, GHG emissions, water consumption and land use.

This should be further investigated in order to build a single indicator that would give a fair overview of the sustainability performance of fibres and textiles and enable comparisons between them.

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