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The Environmental Impact of Wool Yarn from Two Norwegian Sheep Breeds: An LCA Study

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Declaration

I, Marie Katelijne Verheule, declare that this thesis is a result of my research investigations and findings. Sources of information other than my own have been acknowledged and a reference list has been appended. This work has not been previously submitted to any other university for award of any type of academic degree.

Signature

Date: 15 May 2023

Preface

To start off this thesis, I would like to show gratitude to all that made this study come together. First of all, I would like to thank my supervisor, Lars Olav Eik, for giving me advice, giving me information on Norwegian sheep farming, helping me collect my data, and giving feedback on my work. Second, I would like to thank my co-supervisors, Hanne Møller, and Muhammad Azher Bhatti. Azher, thank you for providing me with data from your PhD thesis, for giving feedback on my writing and for being a mentor to me. Hanne, I am very grateful for your help during the construction of the LCA and the writing process, especially between your busy schedule. Without all of you, it would have been impossible to carry out this study.

I want to thank Bente Aspeholen Åby for taking the time to help me with the calculations of the feed intake of the sheep and the calculations of the GHG emissions. I would have been lost without you. Thank you to Stine Samsonstuen for showing me how to set up an LCA for sheep production.

I want to thank the farmers for allowing me to interview them and providing me with the necessary data because I know you all have hectic jobs. Thank you to those at the spinnery, who also provided data for me. Due to privacy reasons, I cannot name names but I hope that the people in question know this applies to them.

Lastly, I would like to thank Amund Bratlien for being a translator during my interviews and supporting me throughout the process. I also want to thank my parents who have been a major support, who were always there for me, and who I could call at any moment for a talk and some advice. And to my Belgian and Norwegian friends for supporting and ensuring me that everything would be ok. We made it! I am proud of all of you!

Thank you.

Ås, May 2023

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Abstract

For decades, the clothing industry is one of the most polluting industries. In recent years the clothing industry has been getting more attention due to its unsustainable practices, especially within fast fashion. The transition towards more sustainable business strategies in both social and environmental areas seems to be going slower in the clothing industry than for other large industries (e.g. energy). Recently, there has been bad reflection on the use of wool for clothes because it, supposedly, has a bad impact on the environment. It is here, that the inspiration of this thesis came from. Because of its severe winters, Norway's culture relies heavily on wool clothing and is therefore a perfect setting for this study. The environmental effect of the entire process of making 1820 meters of wool yarn (enough for about one sweater) will be calculated in this thesis using Life Cycle Assessment including wool production and wool spinning. Although the stages of sweater production, use, and disposal would be interesting to investigate, they are outside the scope of this research. A comparison will be made of the production of wool from the two most produced Norwegian sheep breeds; Norwegian White Spæl and Norwegian White Sheep (NWS). To show how much of the impacts from the sheep production is allocated to wool in contrast to meat, economic allocation was used.

The results show that the wool production indeed has a big impact on all impact categories considered. The majority of the effect originate from the production of wool from sheep, which includes enteric fermentation and manure from sheep, production of feed concentrates, grass silage and grazing infield and outfield. The negative effects of the Norwegian White Sheep were greater than those of Spæl in every category except for the risk to biodiversity. The latter results show that sheep production can potentially benefit biodiversity in terms of land occupation from infield and outfield grazing and here NWS could possibly have more positive impact.

The potential total impact of one wool sweater over its whole life cycle was analysed in two separate studies. This shown that wool sweaters, when cared for according to their specific recommendations (e.g. low temperature, air drying, long lifespan, fewer washes, etc.), have a far smaller impact during the usage phase than cotton sweaters, for instance (Laitala et al., 2017; Nolimal, 2018). Wool also fits fairly well into the category of circular products since the recycling of the textiles and clothing is quite easy.

Keywords: Wool, Sheep, LCA, Textile, Fashion, Sustainability, Circularity.

List of abbreviations

GHG:	Greenhouse gasses
GWP:	Global Warming Potential
NWS:	Norwegian White Sheep
LCA:	Life Cycle Assessment
LCI:	Life Cycle Inventory
LCIA:	Life Cycle Impact Assessment
EF:	Environmental Footprint
EU:	European Union
DM:	Dry matter
IWTO:	International Wool Textile Organisation
GE:	Gross Energy
FU:	Feed Unit
DE:	Digestible Energy
PEF:	Product Environmental Footprint
PEFCR:	Product Environmental Footprint Category Rules
FEFAC:	European Compound Feed Manufacturers' Federation
eq.:	equivalent
inc.:	increase
Pt.:	Indicator for soil quality
depriv.:	deprived
PI:	Protein intake
PR:	Protein retained
EF:	Emission Factor (only in Appendix)

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1 Introduction

In the modern world, Norway is a place where one can enjoy a life of relative opulence. We won't have a problem getting our hands on pretty much anything on the market. This is something of which I am also guilty. I make an effort to reduce my impact on the environment, but even so, my carbon footprint is not negligible. It's unfortunate but true that improving our planet's condition, despite our best efforts, isn't always easy. Because of our deeply-grounded consumption-based culture, it can be challenging and even overly expensive to make lifestyle changes that are good for the environment. However, the first step is awareness about the purchases you make.

One way to lessen one's impact on the environment is to be selective about one's clothing purchases. The clothing industry is one of the world's most polluting sectors, responsible for approximately 8-10% of all CO_2 emissions (Filho et al., 2022). Over the past decade, most global product prices have increased. Clothes, on the other hand, are increasing in price at a slower rate than most other goods. These days, most people also don't wait until an item of clothing is completely worn out before discarding it. If current trends continue, the clothing industry's resource consumption will increase to three times that of 2018 by 2050 (Nature Climate Change, 2018). We can only hope that the increased focus on sustainable fashion in recent years signals the start of a new era in the clothing industry.

Buying second-hand clothing is a great way to reduce your personal clothing impact. Even so, many people have a hard time taking the first step into thrift shopping. It's crucial that they, too, learn to reduce the environmental impact of their wardrobe choices. Examining the pros and cons of various fabrics from an ecological standpoint is one approach. That is to say, they can compare the negative effects of producing cotton and wool on the environment. That way, they could select clothing made from materials that caused less harm to the planet. But we could also go beyond that if we wanted to. Those in need of wool clothing may also benefit from knowing the environmental impact of two types of wool.

The environmental impact of Norwegian White Spæl (referred to as Spæl in this study) wool versus Norwegian White Sheep (NWS) wool will be calculated in this study using Life Cycle Analysis (LCA). Both of these sheep breeds are produced in Norway. There has been no previous life-cycle assessment of either wool type's environmental impact. This study can be used to inform wool consumers, but it can also be used to investigate sustainable wool production in Norway. Wool clothes is extremely important in Norway because of its cold and long winters, and it is clear that wool garments have become an important part of Norwegian culture.

The following research questions will be addressed in this study: - What is the current state of the sheep industry in Norway? What are sheep typically raised for?

- What effect does Norwegian White Spæl wool have on climate change, acidification, eutrophication, particulate matter, water use, land use, and biodiversity? What effect does Norwegian White Sheep wool have on climate change, acidification, eutrophication, particulate matter, water use, land use, and biodiversity?
- Which wool type has the greatest impact on climate change, acidification, eutrophication, particulate matter, water use, land use, and biodiversity?
- What are the environmental benefits and drawbacks of wool? What about the environmental benefits and drawbacks of other fashion fabrics in comparison to wool?
- What other differences exist between the production of Norwegian White Sheep and Norwegian White Spæl?

The study's hypothesis is that the environmental impact of Norwegian White Sheep wool is greater than that of Spæl wool across the board.

2 Background

GHG emissions have been increasing since the industrial revolution began in the second half of the 18th century. Many industries are growing, which increases emissions of carbon dioxide (CO_2), methane (CH_4), and dinitrogen monoxide (N_2O). CO_2 is regarded as the most significant greenhouse gas. Despite having a lower Global Warming Potential (GWP) than CH_4 and N_2O, CO_2 has a substantially longer lifetime (>1000 years) than CH_4 (12 years) and N_2O. (121 years). This, combined with the fact that CO_2 is the most widely emitted greenhouse gas, makes carbon dioxide the most important greenhouse gas when discussing climate change (EPA, 2023).

When discussing climate change, one of the most essential industries to consider is the textile and garment industry. This industry accounts for around 8-10% of worldwide carbon emissions (Filho et al., 2022). Aside from GHG emissions, the textile and garment industries use a lot of water. The textile and garment industry's projected water use in 2015 was around 79 billion m^3. Since then, the industry has expanded, thus it is possible that this figure has risen (European Parliament, 2020).

Agriculture is frequently linked to the textile and garment business. Many textiles are manufactured with plant or animal fibers. It is commonly acknowledged that the agricultural industry has a significant impact on climate and the environment, particularly in terms of CH_4 and N_2O emissions. Cotton, hemp, and flax, as well as fibers like wool and feathers from livestock animals, contribute to both agricultural and textile and garment industry emissions. Agriculture for food or textile production has a significant impact on biodiversity and greenhouse gas emissions.

This thesis will focus on fibers derived from livestock, notably wool from sheep. Wool has long been regarded as one of the least sustainable fibers, yet studies show that this is only partly true. Wool is seen as a negative product since it is derived from sheep, which are ruminants and hence contribute significantly to methane emissions. Wool, on the other hand, is one of the most durable fibers for apparel. Wool clothing have a fairly long lifespan and do not require frequent washing (use phase). They are washed using a short wool routine and cold water. Wool is also rather simple to recycle. However, because of the emissions associated with the manufacture of wool, these sustainability considerations are frequently disregarded (Nolimal, 2018; Laitala et al., 2017; Wiedemann et al., 2020).

2.1 Sheep breeds

The global sheep population has reached an all-time high, reaching 1.266 billion heads in 2021. The world's largest growth in sheep head occurred between 2010 and 2019, when demand for sheep meat and meat prices increased (IWTO, 2022). Although the number of heads has been stable since 2020, there has been a modest growth. China has by far the biggest sheep output in the world, accounting for around 15% of the global share, followed by India and Australia, each accounting for approximately 5% of the global sheep population (IWTO, 2022). However, the amount of greasy wool produced by sheep has been decreasing since 2000. There is little to no explanation for why this is happening, but it appears that there are far more resources to be obtained from the global sheep population (IWTO, 2022).

Sheep production began in Norway around 5000-6000 years ago. Farmers valued the sheep because they could fertilize the pasture while grazing. Norway will have 932 841 winterfed sheep in 2022, which will be used to create wool and meat. However, sheep meat production is the primary source of income for sheep farmers in Norway (Blix & Vangen, 2009).

The majority of Norwegian farmers are small and lifestyle farmers who get the majority of their income from off-farm activities. Norway has strong restrictions governing what land can be used for agriculture. Furthermore, several rules make it simpler for farms to be inherited by one of the previous farmers' children, thus they frequently take over their parents' farms to continue their operations (Bondelaget, n.d.; Knutsen, 2020).

These new generations of farmers are usually more conscious of the environmental impact of agriculture and food production and strive to do better. However, inherited farms are increasingly ceasing operations and renting out their agricultural property. This means that farms that are left, typically grow in size because most surplus agricultural land is rented out. In 2018, the average farm had approximately 24.9 ha of farmland while it was up to 14.7 ha in 1999. Approximately 45 percent of the agricultural land was rented (Kildahl, 2020). Norway's livestock production has been relatively consistent throughout the years, despite a decline in the number of livestock farmers. This means that, while animal farms have grown in size over the previous decade or so, they still do not approach industrial scale. The sheep population overtook the cattle population in the early 1980s and has remained relatively stable since, while the cow population has been declining since the late 1990s (Knutsen, 2020).

Despite the fact that there are no farm size limitations in Norway, there are highly strict animal welfare legislation. Below are some rules concerning animal care for small livestock:

> *"It is forbidden to put equipment on the animals other than ear tags, bells, spring harnesses when grazing or equipment used for veterinary medical reasons, unless it can be documented that this is justifiable."* (*Forskrift om velferd for småfe 2005* (FOR)).

> *"Small livestock must be kept on suitable pasture for at least 16 weeks a year, unless climatic or other animal welfare conditions are an obstacle. Small livestock must, when the conditions are right, be given access to outdoor areas also outside the ordinary grazing season. The operation must be adapted to the climatic conditions."* (*Forskrift om velferd for småfe 2005* (FOR)).

As previously indicated, Norwegian farmers are required to allow their sheep to graze for at least 16 weeks during the summer (*Forskrift om velferd for småfe 2005* (FOR)). Depending on where the farm is located, they frequently spend their grazing period in the forest or the mountains. Forest owners usually discuss where the sheep can graze with the farmer and the municipality. They will also be compensated if the sheep (or cattle) cause any harm (*Beitelova 1961* (LOV)).

In Norway, sheep typically mate in November and December, implying that lambing occurs in April and May (Blix & Vangen, 2009). For a few weeks, the sheep and young lambs are kept inside and sometimes outside in a grass meadow near the farm. Then, from June through September, there is a period of outfield grazing. The slaughter season peaks in late September and early October.

In Norway, several distinct breeds are developed. They are classified into two groups: long-tailed sheep such as the Norwegian White Sheep (NWS), Steigar sheep, and Cheviot, and short-tailed sheep such as the Spæl, Old Norwegian Spæl, Old Norwegian sheep, and Norwegian Pels sheep (Blix & Vangen, 2009). There are also a few sheep breeds that are critically endangered, according to the UN Food and Agriculture Organization, such as the Dala sheep and the Rygja sheep. This is primarily due to breeding with other breeds, most commonly the NWS. This thesis will concentrate on NWS and Spæl, namely the white Spæl (Blix & Vangen, 2009).

2.1.1 Norwegian White Sheep (NWS)

The Norwegian White Sheep is a crossbred sheep. NWS was developed by combining Norwegian sheep breeds (Dala, Steigar, and Rygja) with a variety of sheep breeds from the United Kingdom. With 261 404 ewes, it is the most common breed in Norway, accounting for 65.2 percent of the total sheep population (Animalia, 2022). In the year 2000, it was recognized as a breed (Oliveira et al., 2020). Because of so much breeding and crossing over the last few decades, the Norwegian White sheep has a wide range of sheep, but all of them have strong wool, a high growth rate, and superb meat (Jensen, 2013; Klepp, 2009; Bhatti, 2020). NWS are raised for both meat and wool, although meat production is definitely the sheep farmers' primary source of income.

2.1.2 Norwegian White Spæl (Spæl)

Spæl is an old Norwegian breed that consists of coloured Spæl and white Spæl. It is the second most produced breed in Norway with 52 513 ewes accounting for 13% of the whole Norwegian sheep population (9.4% white and 3.6% coloured). There is little to no difference between the coloured and white Spæl except for the colour of their wool (Animalia, 2022). Spæl are produced for their wool and meat, but here too, the meat production accounts for the main source of income for the farmer. The sheep are a slightly smaller than the NWS and have great maternal- and survival instincts. Their wool consists of two layers: the fine bottom hairs and the coarser upper hairs. Spæl wool has great quality and is therefore quite well for making clothing (Klepp, 2009; Jensen, 2013). During this thesis, the main focus will be on white Spæl to be able to compare the wool with the wool from NWS.

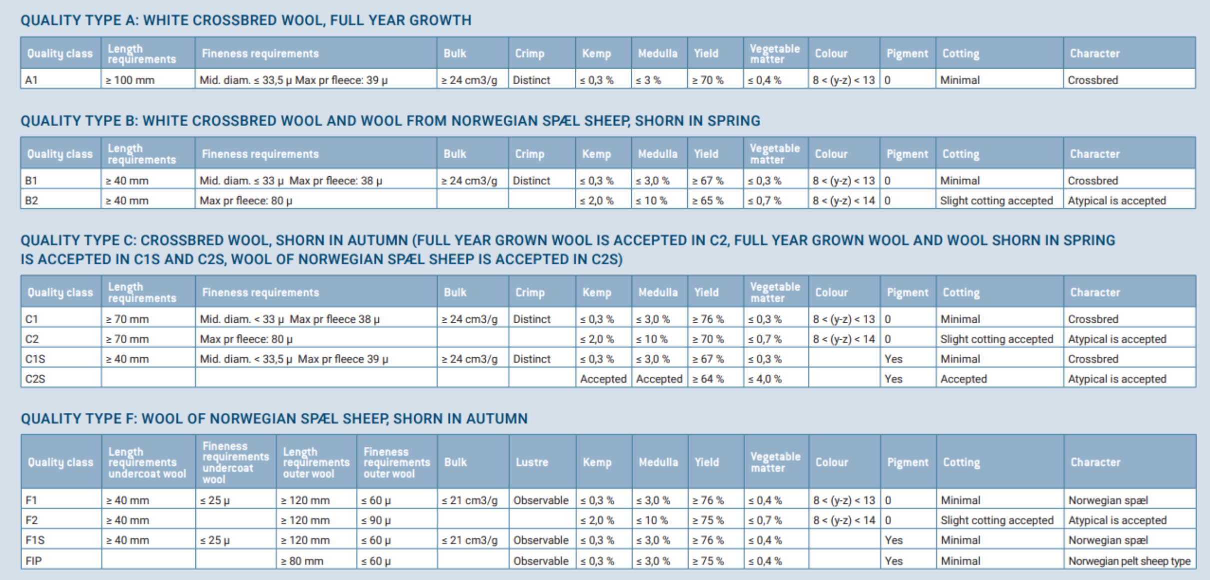
2.2 Wool

Wool is defined as the "the soft, thick hair that grows on the bodies of sheep and some other animals" (Cambridge dictionary, n.d.). Except from sheep, wool can come from goats, rabbits, alpacas, lamas, vicuñas, etc. It can be used for clothing, furniture, textiles, etc. Wool plays a very important part in Norwegian culture. Norwegians are very dependent on wool clothing during their long, harsh winters. They have numerous brands that produce mostly wool garments, like Devold, Dale of Norway, Ulvang, Kari Traa, Oleana, Janus etc. (Hebrok & Klepp, 2013). Sheep wool can be divided into 3 types: merino wool which is known to be very soft, crossbred wool like that of NWS, and landrace wool characterized by fine bottom hairs and coarse upper hairs like the wool of Spæl (Klepp, 2021).

In Norway, most wool comes from sheep and goats. All sheep breeds produced in Norway produce wool while only some goat breeds produce wool. Usually, goat breeds that do produce wool, are produced mainly for that wool such as angora goats and cashmere goats. In Norwegian sheep production, wool is a by-product of the meat industry because meat accounts for the main income of sheep farmers.

2.2.1 Wool standards

In Norway, wool from different breeds is divided into wool standards. These wool standards determine how high the subsidy for the wool will be. Usually, the subsidies and wool standards for coloured wool are lower than for white wool because it is more difficult to use in clothing and textile. The reason for this is that coloured wool needs to be bleached before anything else happens while white does not need bleaching. The wool standards for white crossbred wool (NWS) are from types A, B, or C. The wool standards for white Spæl wool are from types B, C, or F. Figure 1 explains the different wool standard types a little more.



QUALITY TYPE A: WHITE CROSSBRED WOOL, FULL YEAR GROWTH

Quality class	Length requirements	Fineness requirements	Bulk	Crimp	Kemp	Medulla	Yield	Vegetable matter	Colour	Pigment	Cotting	Character
A1	≥ 100 mm	Mid. diam. ≤ 33,5 μ Max pr fleece: 39 μ	≥ 24 cm3/g	Distinct	≤ 0,3 %	≤ 3 %	≥ 70 %	≤ 0,4 %	8 < (y-z) < 13	0	Minimal	Crossbred

QUALITY TYPE B: WHITE CROSSBRED WOOL AND WOOL FROM NORWEGIAN SPÆL SHEEP, SHORN IN SPRING

Quality class	Length requirements	Fineness requirements	Bulk	Crimp	Kemp	Medulla	Yield	Vegetable matter	Colour	Pigment	Cotting	Character
B1	≥ 40 mm	Mid. diam. ≤ 33 μ Max pr fleece: 38 μ	≥ 24 cm3/g	Distinct	≤ 0,3 %	≤ 3,0 %	≥ 67 %	≤ 0,3 %	8 < (y-z) < 13	0	Minimal	Crossbred
B2	≥ 40 mm	Max pr fleece: 80 μ			≤ 2,0 %	≤ 10 %	≥ 65 %	≤ 0,7 %	8 < (y-z) < 14	0	Slight cotting accepted	Atypical is accepted

QUALITY TYPE C: CROSSBRED WOOL, SHORN IN AUTUMN (FULL YEAR GROWN WOOL IS ACCEPTED IN C2, FULL YEAR GROWN WOOL AND WOOL SHORN IN SPRING IS ACCEPTED IN C1S AND C2S, WOOL OF NORWEGIAN SPÆL SHEEP IS ACCEPTED IN C2S)

Quality class	Length requirements	Fineness requirements	Bulk	Crimp	Kemp	Medulla	Yield	Vegetable matter	Colour	Pigment	Cotting	Character
C1	≥ 70 mm	Mid. diam. < 33 μ Max pr fleece 38 μ	≥ 24 cm3/g	Distinct	≤ 0,3 %	≤ 3,0 %	≥ 76 %	≤ 0,3 %	8 < (y-z) < 13	0	Minimal	Crossbred
C2	≥ 70 mm	Max pr fleece: 80 μ			≤ 2,0 %	≤ 10 %	≥ 70 %	≤ 0,7 %	8 < (y-z) < 14	0	Slight cotting accepted	Atypical is accepted
C1S	≥ 40 mm	Mid. diam. < 33,5 μ Max pr fleece 39 μ	≥ 24 cm3/g	Distinct	≤ 0,3 %	≤ 3,0 %	≥ 67 %	≤ 0,3 %		Yes	Minimal	Crossbred
C2S					Accepted	Accepted	≥ 64 %	≤ 4,0 %		Yes	Accepted	Atypical is accepted

QUALITY TYPE F: WOOL OF NORWEGIAN SPÆL SHEEP, SHORN IN AUTUMN

Quality class	Length requirements undercoat wool	Fineness requirements undercoat wool	Length requirements outer wool	Fineness requirements outer wool	Bulk	Lustre	Kemp	Medulla	Yield	Vegetable matter	Colour	Pigment	Cotting	Character
F1	≥ 40 mm	≤ 25 μ	≥ 120 mm	≤ 60 μ	≤ 21 cm3/g	Observable	≤ 0,3 %	≤ 3,0 %	≥ 76 %	≤ 0,4 %	8 < (y-z) < 13	0	Minimal	Norwegian spæl
F2	≥ 40 mm		≥ 120 mm	≤ 90 μ			≤ 2,0 %	≤ 10 %	≥ 75 %	≤ 0,7 %	8 < (y-z) < 14	0	Slight cotting accepted	Atypical is accepted
F1S	≥ 40 mm	≤ 25 μ	≥ 120 mm	≤ 60 μ	≤ 21 cm3/g	Observable	≤ 0,3 %	≤ 3,0 %	≥ 76 %	≤ 0,4 %		Yes	Minimal	Norwegian spæl
FIP			≥ 80 mm	≤ 60 μ		Observable	≤ 0,3 %	≤ 3,0 %	≥ 75 %	≤ 0,4 %		Yes	Minimal	Norwegian pelt sheep type

Figure 1: Norwegian Wool Standards for crossbred wool and Spæl wool (Animalia, 2022)

Each wool standard is associated with a different amount of subsidies. In general, NWS wool is more valuable since it can be used for a variety of purposes like as carpets, clothes, furniture, and so on. It does not imply that the wool is of higher quality. Spæl wool has higher quality, especially when used for clothing, but it is less valuable than NWS wool. Shearing takes place twice a year, once in the autumn and once in the spring. Because spring wool is of lower quality than autumn wool, it is valued less and receives fewer subsidies. Table 1 displays the settlement price from Norilia and subsidy per kilogram of wool in accordance with Norwegian Wool Standards (explained above). Norilia is a daughter company from Nortura (one of Norway's biggest food producers) that handles and buys by-products from the meat- and egg industry. Their settlement price is the price the farmers receive directly from the sales and the subsidies are added through the government.

Table 1: Settlement prices and wool subsidies from 2022 for the relevant Norwegian Wool Standards (*unwashed) (Nortura, 2022)

	Settlement price Norilia (NOK/kg)	**Subsidy (NOK/kg)**	**Amount received by producer (NOK/kg)**
A1*	3.00	54.35	57.35
B1*	1.50	48.35	49.85
B2*	0.00	20.00	20.00
C1*	5.00	54.35	59.35
C2*	0.00	20.00	20.00
C1S*	1.00	31.35	32.35
C2S*	0.00	0.00	0.00
F1*	2.50	48.35	50.85
F2*	0.00	20.00	20.00
F1S*	0.00	31.35	31.35
F1P*	3.00	31.35	34.35

3 Materials and methods

3.1 Introducing Life Cycle Assessment (LCA)

Life Cycle Assessment is a methodology to assess the environmental impact of a part of-, or the whole life cycle of a product or service. These analyses have been an important part of environmental science since the 1990s (Ecochain, 2021). An LCA can be performed on any product and is the most commonly used method for companies, institutions, and organizations to quantify the environmental impact of their products. This methodology addresses all stages of a product's life cycle, from cradle to grave. This means that the process includes resource extraction, transportation, production, retail, distribution, usage, waste, and so forth (NORSUS, 2022). For a wool sweater, the production of sheep for wool, transport of feed and sheep to the slaughterhouse, production of yarn, (transport), production of the sweater, distribution to the store, transport to the closet, usage (e.g.: washing and drying), waste, and recycling would all be included. However, there is also the possibility to access only a part of the life cycle. In this master's thesis, I will use LCA to compare the environmental impact of virgin wool yarn to compare two breeds of Norwegian sheep. This part of the life cycle was chosen for the LCA because there has been little published research done on this specific topic in Norway.

LCA's consist of four steps:

1. Goal and scope definition
2. Life cycle inventory (LCI)
3. Life cycle impact assessment (LCIA)
4. Life cycle interpretation.

The goal and scope outlines the reasons for carrying out the study, the intent of the study, functional unit, etc. The life cycle inventory includes the data collection, and the calculations of the inputs and outputs of the process within the production of a product (European Commission, n.d.). The life cycle impact assessment measures the environmental impact using characterization factors to calculate the impact of an impact category. And lastly, the interpretation of the LCA includes the results and the explanation of what they mean exactly (European Commission, n.d.)

Specific software packages are required to conduct a Life Cycle Assessment study. There is a wide variety of software applications available, with some tailored to certain sectors. The

SimaPro program will be used to examine the environmental impact of wool yarn for this project.

3.2 LCA methodology

3.2.1 Goal and Scope

The primary objective of this LCA is to evaluate the environmental impact of NWS wool and Spæl wool. Consequently, two LCAs will be conducted, with the results compared to provide insights into the preferred wool type for the clothing industry from an environmental standpoint. This information can also guide consumers who wish to reduce their carbon footprint.

3.2.2 Analysis

This study aims to compare the environmental impact of wool yarn obtained from two Norwegian breeds, NWS and Spæl, using the Life Cycle Assessment. The EF method 3.0 as implemented in SimaPro is used as characterization method. This method was developed by the European Commission and adheres to ISO14040, ISO14044 guidelines and the Product Environmental Footprint (PEF) guidelines from the EU (Manfredi et al., 2012; European Commission, n.d.).

3.2.3 Functional unit

The functional unit of this LCA is 1820 meters of yarn from both NWS wool and Spæl wool, approximately the amount of wool needed for an adult sweater (Porter, 2016). The colour of the wool will be the natural "white" colour because data on the chemicals used for colouring were not available.

3.2.4 System boundaries

Figure 2, illustrates the system boundaries of the LCA's from 1820 meters of wool yarn from Spæl and NWS. Within the system boundaries these life cycle stages are included: production of feed and grazing, the enteric fermentation and manure from ewes, young ewes and lambs (including mortality rate for the latter), manure management, wool production, and the spinning process including electricity use, propane combustion and water use. Waste streams like waste from concentrate production, wool waste from yarn production, wastewater from yarn production, etc. are not included inside the system boundaries. The data set acquired from the interviews did not include waste streams. Therefore there was too little data to make assumptions about waste treatment etc. The impact of the building materials of the barn were not included within the system boundaries and are assumed to have little impact, especially after allocating environmental impact to wool (Erzinger et al., 2004). Inhouse greenhouse gas emissions (CH_4 and N_2O) from the sheep, however, are included in the calculations from enteric fermentation and manure. The barn is not heated and the electricity use is very minimal. Therefore they are put outside the system boundaries as well as the electricity use inside the barn are not included either. The transport of the wool to the spinnery to produce 1820 meters of yarn is not included because it is such a small proportion of the wool delivery and will therefore have an insignificant impact.

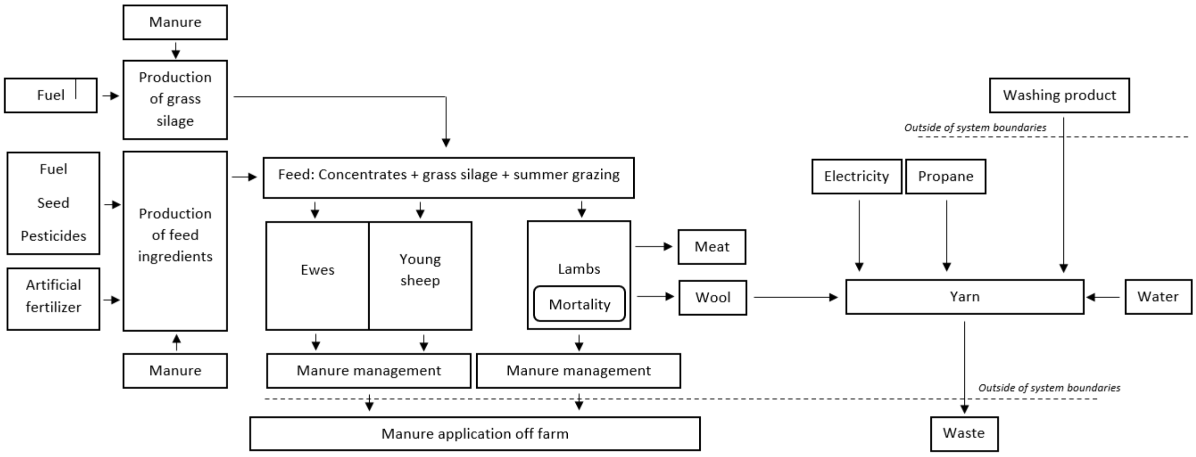


Figure 2: System boundaries for the LCA's from woollen yarn from Spæl and NWS

3.3 Inventory analysis

3.3.1 Data collection and setting

Data for this study were gathered through in-depth interviews with two farmers, one in Viken and the other in Telemark, who both manage Spæl and NWS breeds. Primary data were obtained from "Sauekontrollen," (Sheep Control) a tool used by farmers and government authorities to track sheep output on a farm, county, and national scale. Sheep Control is frequently used in breeding operations (Animalia, 2023). In Telemark, 46.1 percent of sheep farmers engage, whereas 51.5 percent of Viken sheep farmers participate (Animalia, 2022). Interviews with both farmers provided additional information that helped to a better understanding of the breeds' behaviour and the farmers' personal preferences.

Later, the farm in Telemark was chosen as the case study for this examination. Due to its inability to meet specified study criteria, the farm in Viken was judged unsuitable as a representative example. This farm, for example, works with Old Norwegian Spæl, which differs from Norwegian White Spæl in factors such as weight. However, the new data from this farm was still aplicable to the discussion.

During the interview, the following subjects were discussed:

- Number of animals
- Average daily gain of lambs
- Lambing
- Feed concentrates
- Grazing period
- Wool production per year
- Meat production per year
- Earnings from wool and meat production
- Transport
- Experiences with sheep farming

The following data points from the Sheep Control were used in the study:

- Birthweight, spring weight (before release on outfield pasture), autumn weight (after collection from outfield pasture) and carcass weight
- Number of pregnant ewes and young ewes
- Stillborn lambs
- Lambs died before pasture
- Lambs and ewes died or lost on pasture
- Number of lambs and ewes slaughtered, sold and kept
- Dates of weighing

One interview was done with a wool spinnery that was able to provide data on wool spinning. Data gathered during the interview:

- Use of electricity
- Use of washing agents
- Use of propane
- Use of water
- Wool received per year
- Wool spun per year
- Weight losses of the wool during the spinning process

- Kg wool needed for 1820 meters of yarn

Background data, such as feed ingredients, energy, land occupation, and so on, will come from previous studies, as well as data from SimaPro and Nortura databases.

3.3.2 Sheep system

The modelling of the sheep farm system in SimaPro was done according to the Holos model, a Canadian tool to estimate GHG emission from farms through whole farm modelling (Little et al., 2008). Two example farms were made, one for Spæl and one for NWS. Each farm had had 3 different sheep groups: ewes, young ewes and lambs. For the ewes it is at least the second time they bare lambs and for the young ewes it is their first time. In the Spæl farm there were 11 ewes, 2 young ewes and 28 lambs after lambing. In the NWS farm there were also 11 ewes and 2 young ewes. The pregnant ewes and young ewes of NWS were expecting more lambs compared to Spæl which could be seen after examination with ultrasound. However, some of the lambs were stillborn or died before going to pasture. These lambs were not included in any calculations. In the end, NWS had 28 lambs on pasture as well.

3.3.2.1 Feeding

The feed intake of both breeds was calculated using a sheep feeing tool based on a Nortura (2011) study that calculates feed intake for a given group of sheep. Data for the feed requirements (see data collection and setup) were obtained from the farm's Sheep Control in Telemark and are thus confidential. Data approximations are provided. The feeding was separated into multiple times, each with a varied feed demand for the various sheep groups (ewes, young ewes, and lambs):

- Collection from infield pasture until heavily pregnant (from the end of September until the beginning of March)
    - **Feeding** with grass silage and few concentrates
- Heavily pregnant until lambing (from the beginning of March until the end of April)
    - **Feeding** with grass silage and more concentrates
- Lambing until outfield pasture (from the end of April until mid-May)
    - **Feeding** with grass silage and more concentrates
- Grazing outfield (from mid-May until the end of August)

        - **Grazing** on outfield mountainous pasture
    - Grazing infield + final feedings for lambs before slaughter (from the end of August until the end of September)
        - **Grazing** on high quality infield pasture + concentrates for lambs

The length of pregnancy used in the sheep feeding tool was slightly adjusted to 145 days for Spæl and 148 days for NWS (Nortura, 2022). Lambs were fully dependent on milk from birth until pasture. Throughout the outfield pasture time from mid-May until end of August, the lambs become less dependent on milk and more dependent on grazing. On average, the assumption was made that the lambs gained 2/3 of their weight from milk and 1/3 of their weight from grazing (B.Å. Aspeholen, personal communication, April 28, 2023). At the end of August they are fully weaned and their weight gain comes from grazing and concentrates during the final feedings until slaughter time. At this point, the ewes are separated from the lambs. It was assumed that no lambs were outcast or fed by bottle.

NWS is overall heavier than Spæl and therefore needs more feed. An adult NWS ewe weights around 100kg while an adult Spæl ewe weights around 75kg (Fjorlamprosjektet, personal communication, April 12, 2023). Data on the live weight of young ewes was taken from Bhatti (2020).

Data on dry matter (DM), feed units (FU), digestible energy (DE) and protein content of the of the different feeds are listed underneath.

Grass silage:

- 30% DM (Avdem, 2018)
- 0.84 FU/kgDM (Avdem, 2018)
- 61% DE (B.Å. Aspeholen, personal communication, April 28, 2023)
- 0.16 kg protein/kgDM (B.Å. Aspeholen, personal communication, April 28, 2023)

Concentrates

- 88% DM (Avdem, 2018)
- 1.08 FU/kgDM (Avdem, 2018)
- 78% DE (B.Å. Aspeholen, personal communication, April 28, 2023)
- 0.17 kg protein/kgDM (B.Å. Aspeholen, personal communication, April 28, 2023)

Outfield mountainous grazing

- 18% DM (Avdem, 2018)
- 0.92 FU/kgDM (Avdem, 2018)
- 67% DE (B.Å. Aspeholen, personal communication, April 28, 2023)
- 0.15 kg protein/kgDM (B.Å. Aspeholen, personal communication, April 28, 2023)

Infield high quality grazing

- 22% DM (Avdem, 2018)
- 0.95 FU/kgDM (Avdem, 2018)
- 69% DE (B.Å. Aspeholen, personal communication, April 28, 2023)
- 0.22 kg protein/kgDM (B.Å. Aspeholen, personal communication, April 28, 2023).

The amount of feed found in the outfield mountainous area was based on a study from Hofsten et al. (2008) about grazing capacity of outfield pastures and vegetation types in Telemark and a study from Rekdal (2001) about the feed intake of sheep per vegetation type. The first study estimated the vegetation types in Telemark and the forage quality in each vegetation type. They argue that most sheep will be found in the areas with good or very good forage quality. The most common vegetation types with good or very good forage quality are "rishei" and "bilberry-birch forest" (Hofsten et al. 2008). Rishei is a mountainous vegetation type dominated by species such as bilberry, dwarf birch, juniper, wavy hair-grass, grey willow, mountain fern moss, etc (NIBIO, 2022). Bilberry-birch forest is a vegetation type with dominating species like birch, bilberry, wavy hair-grass, mountain fern moss, and crowberry (NIBIO, 2022). In Rekdal (2001), the feed units found in these vegetation types are estimated. For rishei it is approximately 75 kgDM/daa and for bilberry-birch forest approximately 112.5 kgDM/daa (Rekdal, 2001). An average of 94 kgDM/daa or 522.2 kg/daa will be taken for the outfield grazing pastures. The yield from the grass grown at the farm is 500 FU/daa or 2392.3 kg/daa

Figure 4: Rishei (Hofsten, n.d.)

Figure 4: Bilberry-birch forest (Bjørklund, n.d.)

(NIBIO, n.d.). Transport of sheep to pasture and grass silage to the farm is not included in the calculations.

The actual recipe of the feed concentrates could not be obtained from the concentrates' manufacturer. As a result, two recipes from prior experiments were used as a guide. The recipes were compared to the Norwegian concentrates and modified to better suit the Norwegian conditions. In this study, the actual Norwegian recipe was not permitted to be obtained or used. Concentrates were supposed to come from Felleskjøpet's (Norway's largest agricultural product maker) largest feed factory in Trondheim. Concentrate transport was estimated accordingly.

Table 2: Feed recipes from Ognik et al. (2013) and Geß et al. (2020) adapted to Norwegian conditions.

Ingredients	Feed for ewes and young ewes (g/kg)	Feed for lambs (g/kg)
Oats	390	260
Barley	150	380
Rapeseed meal	150	110
Wheat bran	150	90
Dry beet pulp	80	0
Corn gluten meal	0	60
Soybean meal	70	60
Minerals and vitamins (mix)	10	40

3.3.2.2 CH_4 and N_2O emissions from enteric fermentation and manure

Greenhouse gas emissions from sheep were calculated using the Tier 2 methods from IPCC (2006). An overview of the variables and equations used in the calculations of GHG emissions from enteric fermentation and manure from sheep listed in Little et al. (2008) according to the IPCC guidelines for National Greenhouse Gas Inventories (2006), are to be found in the appendix at the end of this thesis. The manure of the sheep is assumed to be applied on pasture since 77% of Norwegian farmers use this method of deposition (Miljødirektoratet, 2022). The following Gross Energy (GE) values were calculated to estimate the GHG emissions from the different sheep groups using the sheep feeding tool from Nortura.

Table 3: Calculated Gross Energy (GE) in take per breed per sheep group.

Sheep groups per breed	Gross Energy (MJ/head/day)
NWS young ewes	25
Spæl young ewes	24

NWS ewes	34
Spæl ewes	29
NWS lambs	15
Spæl lambs	14

3.3.2.3 Wool and meat production

3.3.2.3.1 Allocation

Allocation is used when several products are retrieved from one process. In this case, sheep are produced for wool, and meat. Allocation methods for meat and wool could be biophysical allocation, protein mass allocation or economic allocation (Wiedemann et al., 2015; IWTO, 2016). The method of allocation will affect the results of the LCA on wool (Wiedemann et al., 2015). For this study, economic allocation was applied since income is the main motivation for farmers to keep sheep in Norway. It is the best method to show that wool is a by-product of the sheep meat industry. It means that the environmental impacts of wool and meat will depend on the income of the farmers from wool and meat and allocated accordingly. Only the income from wool and meat are calculated into the allocation which means that the actual profit from wool and meat is much lower.

Income from meat were obtained from personal data from the interviewed farmers and is confidential. For the wool production, general data was used since there is no data on wool production from specific breeds. Lambs produce around 1.2kg of wool (Avdem & Fause, 2015) and ewes produce around 2.5kg of wool (I.A. Boman, personal communication, 11 April, 2023; Animalia, 2022). The young ewes and ewes are shorn twice a year, once in the spring and once in the autumn. Lambs are only shorn in the autumn, usually in the slaughterhouse. Transport of the sheep to the slaughterhouse in Sandefjord is included. Spring wool from NWS is assumed to be from wool standard B1 and spring wool from Spæl is assumed to be from wool standard B2. Autumn wool from NWS is assumed to be from wool standard C1 and autumn wool from Spæl is assumed to be from wool standard F1 (see table 1) (Nortura, 2022). In total the economic allocation for NWS products is 88.4% for meat and 11.6% for wool. The total economic allocation for Spæl products is 90% for meat and 10% for wool.

3.3.3 Spinnery

To produce yarn from wool, the wool needs to be washed, dried, and spun. For this process, electricity, water, washing products, and propane are used. Data from the spinnery is confidential so the actual amounts of electricity, water, propane, washing agents and yarn production per year are not to be exposed. Approximately 0,9kg of wool is needed to produce 0,6kg of yarn (1820 meters). 20% of the weight of the sheep wool is grease and is exposed of when washing the wool. 10% of the wool is wasted but is outside of the system boundaries. The spinning process of Spæl wool and NWS wool is assumed to be the same. There was no data available about the ingredients of the washing products used during the process. Accordingly, washing products were put outside of the system boundaries.

The interviewees from the spinnery explained that the electricity use of spinning with Spæl wool might be a slightly higher than that of NWS wool because it has upper hairs and bottom hairs which requires a slightly more spinning. However, there was no actual data on how big the difference was, so it was assumed that the electricity use of wool spinning from Spæl was the same as NWS wool spinning. The difference would have been minimal anyhow.

3.4 Impact assessment

As previously stated, the impact assessment of this study was conducted using the EF method 3.0. The most important impact categories according to the PEFCR report from 2018 are evaluated during this study (FEFAC, 2018):

- Climate change in kg CO_2 equivalent
- Particulate matter in disease increase
- Acidification in mol H^+ equivalent
- Eutrophication, freshwater in kg P equivalent
- Eutrophication, terrestrial in mol N equivalent
- Land use as soil quality in Pt
- Water use in m^3 depriv.
- Biodiversity in Damage potential

Biodiversity loss is a significant problem when talking about agriculture and therefore deemd important to be included in this study. An impact category for biodiversity has not yet been included in the EF method 3.0 because there has not yet been an agreement on the methods to be used. Therefore, the impact category of biodiversity damage potential according to Koellner & Scholz (2008) was added to the method. This paper identified "characterization factors for the local ecosystem damage potential based on total plant species data and data on threatened plant species" (Koellner & Scholz, 2008). This method was mainly designed using data from Switzerland, but the paper says it can be applied for all of Central Europe. It was assumed to still be relevant for this study in Norway. Numerous papers were considered to be used for the damage potential of biodiversity. Knudsen et al. (2017) and Chaudhary & Brooks (2018) had a very high potential but the vegetation types that were used in these studies did not totally fit the characteristics for the infield grazing on pasture and outfield grazing in the mountains. The results of the LCA will be estimates of the potential biodiversity damage from infield and outfield grazing, silage and concentrate production based on the land occupation. In table 4, the characterization factors are displayed as they are in Koellner & Scholtz (2008). The factor for intensive arable land will be used for land occupation from production of concentrates. The factor for less intensive arable land will be used for land occupation from production of grass silage. The factor for pastures and meadows above 800 meters will be used for the land occupation from outfield grazing in the mountains. And lastly, the factor for organic pastures and meadows will be used for land occupation from infield grazing (fertilized with only manure).

Table 4: Characterization factors for potential species loss per type of crop use (Koellner & Scholz, 2008)

	Characterization factor for potential plant species loss per m²
Intensive arable land	0,74
Less intensive arable land	0,61
Pastures and meadows above 800m	-1,42
Organic pastures and meadows	-0,13

4 Results

4.1 Comparison two types of wool

Table 5 presents a complete comparative analysis of the environmental impacts associated with the production of 1820 meters of two types of yarn, Spæl and NWS. This comparison covers multiple ecological impact categories, including climate change, particulate matter formation, acidification, freshwater eutrophication, land use, water use, and biodiversity.

Climate change: In terms of climate change, the production of NWS yarn contributes a greater volume of greenhouse gas emissions, with 24.2 kilograms of carbon dioxide equivalents (kg CO2 eq), as compared to the 16.7 kg CO2 eq generated by Spæl yarn production. This suggests that NWS yarn manufacturing processes are more carbon-intensive.

Particulate matter: The emission of particulate matter, which is associated with various health effects including diseases, is slightly higher in the case of NWS yarn. The reason behind this, is the production feed, since NWS have higher feed requirements. The disease incidence (Disease inc.) is 1.53×10^{-06} for NWS yarn, a bit higher than the 1.01×10^{-06} associated with Spæl yarn.

Acidification: Acidification potential, measured in moles of hydrogen ion equivalent (mol H^+ eq), is also higher for NWS yarn (0.19) compared to Spæl yarn (0.13), indicating that NWS yarn production may contribute more significantly to the acidification of ecosystems.

Eutrophication, freshwater: Freshwater eutrophication, measured in moles of nitrogen equivalent (mol N eq), is higher for NWS yarn (2.38×10^{-03}) than for Spæl yarn ($1.57 \times 10^{-03).}$ This suggests that NWS yarn production might contribute more to nutrient enrichment in freshwater bodies, potentially leading to harmful algal blooms and other destructive ecological effects.

Eutrophication, terrestrial: Terrestrial eutrophication potential, which was indicated with mol nitrogen equivalent, was also higher for NWS (0.39) than for Spæl (0.26). This could indicate that NWS contributes more to terrestrial eutrophication than Spæl.

Land use: The production of NWS yarn also requires more land resources, as indicated by a higher point (Pt) value of 1222.4 compared to Spæl yarn's 907.3 Pt. This could imply a greater footprint on ecosystems or higher demands on land for cultivation, grazing, infrastructure, or other requirements due to higher feed requirements.

Water use: Water deprivation (m³ depriv.), a measure of water scarcity, shows a marginally higher value for NWS yarn (1.25 m³) compared to Spæl yarn (1.15 m³). This suggests a slightly higher water footprint for NWS yarn, implying potential pressure on local water resources.

Biodiversity: Interestingly, the "Damage potential" on biodiversity is negative for both types of yarn, with a more significant negative value for NWS yarn (-92.4) than for Spæl yarn (-72.9). This is the only impact category where NWS has a smaller impact.

This data suggests that across all examined categories, the production of NWS yarn has a more significant environmental impact than Spæl yarn. However, it is crucial to interpret these findings within the context of the specific conditions, methodologies, and limitations of the study.

Table 5: Total results from the whole life cycle of producing 1820 meters of yarn.

Impact category	Unit	Total impact from Spæl yarn	Total impact from NWS yarn
Climate change	kg CO_2 eq	16.7	24.2
Particulate matter	Disease inc.	1.01×10^{-06}	1.53 x 10-06
Acidification	mol H^+ eq	0.13	0.19
Eutrophication, terrestrial	mol N eq	0.26	0.39
Eutrophication, freshwater	kg P eq	1.57×10^{-03}	2.38×10^{-03}
Land use	Pt	907.3	1222.4
Water use	m³ depriv.	1.15	1.25
Biodiversity	Damage potential	-72.9	-92.4

To detect which yarn, Spæl or NWS, offers a preferred environmental compatibility, we must engage in the comparative analysis. This analysis covers several impact categories, as visually portrayed in Figure 5, which charts the contributions of crucial life stages: feed, enteric fermentation and manure, and spinning to the overall ecological footprint of both yarn types.

The results reveals that NWS yarn obtains a greater environmental impact across all categories, except for one. Its contribution to climate change is notably higher than that of Spæl, presenting a difference of 7.5 kg of CO_2 equivalent. This climatic effect is mainly driven by enteric fermentation and manure, with feed also contributing a modest portion. Importantly, the spinning process exerts minimal influence on the climate change impact.

In the context of particulate matter, NWS yarn's impact on human health slightly exceeds that of Spæl yarn. Moreover, acidification impact is also higher for NWS yarn, with feed production and intake being the most influential life stages. The differential impact in this category amounts to 0.1 mol H^+ equivalent.

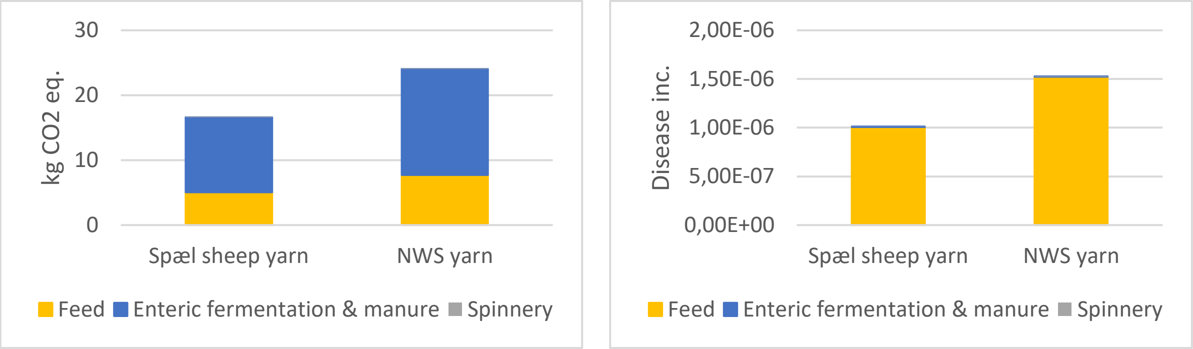
In terms of freshwater eutrophication, the influence of NWS yarn production surpasses that of Spæl yarn, with the differnce being 0.0004 kg P equivalent. Here, too, feed contributes the most significantly. For terrestrial eutrophication, the difference between NWS and Spæl was 0.13 mol N equivalent. Feed contributed the most to this impact category.

Land use, a critical environmental aspect, demonstrates that NWS yarn production requires more resources, with feed once again being the most substantial contributor. The distinct impact on land use between NWS yarn and Spæl yarn is quantified as 315.1 Pt.

Regarding water consumption, NWS yarn's impact surpasses that of Spæl yarn, primarily due to feed, which is the second most significant contributor to water use. The primary driver of water use in yarn production is the spinning process, predominantly due to the need for wool washing before spinning. Notably, the water use from spinning remains consistent for both Spæl and NWS yarn.

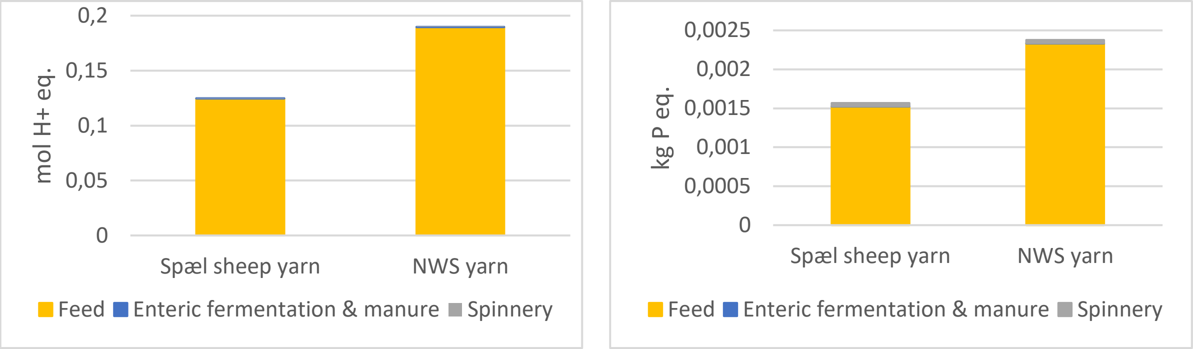
In relation to biodiversity, the potential damage value is negative for both types of yarn, implying that yarn production may potentially enhance plant biodiversity. The influence on biodiversity is less for NWS yarn, suggesting that NWS production might foster biodiversity to a greater extent than Spæl.

In summary, except for biodiversity, NWS yarn demonstrates a greater environmental impact across all categories. The overall ecological footprint of NWS, considering aspects of sheep wool production like enteric fermentation, manure, and feed, is more substantial, rendering it less environmentally friendly compared to Spæl. However, in terms of biodiversity, NWS production may be advantageous due to the requirement for more uncultivated land that might benefit local plant biodiversity during the grazing period.



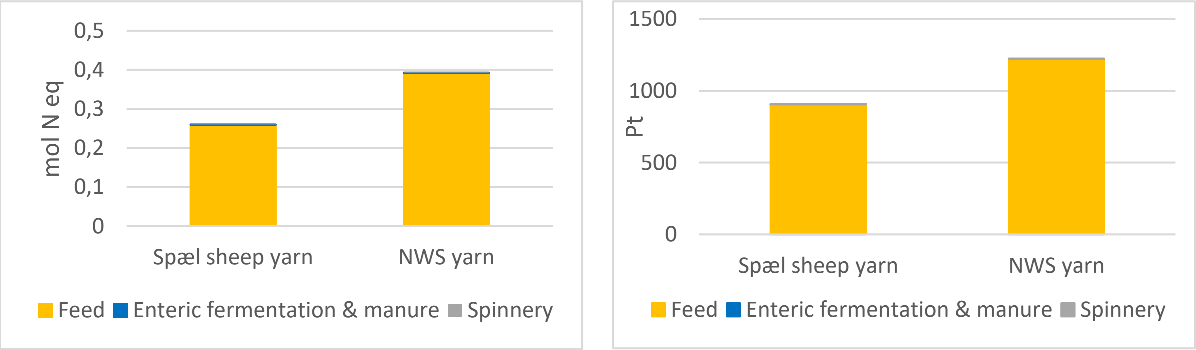
a) Climate change

b) Particulate matter



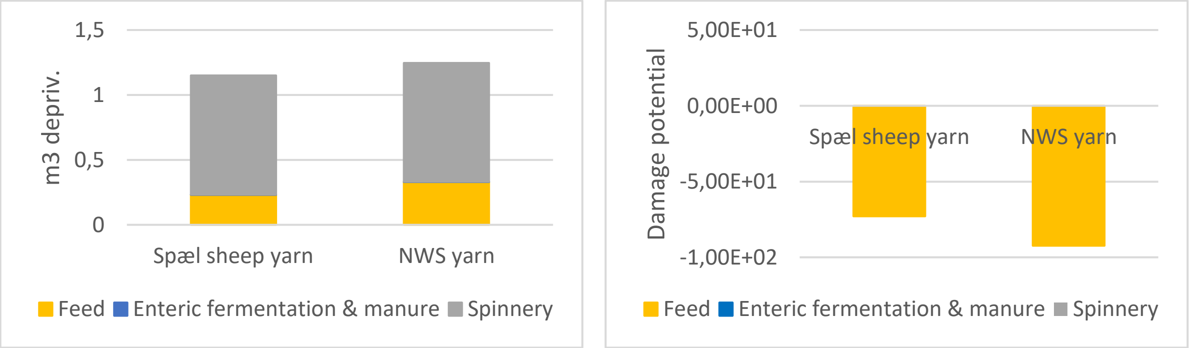
c) Acidification

d) Eutrophication, freshwater



e) Eutrophication, terrestrial

f) Land use



g) Water use

h) Biodiversity

Figure 5: Graphs a)-h): The contributions of the most important life stages (feeding, enteric fermentation and manure, and spinning) of the production of 1820 metres of yarn for all the impact categories comparing NWS and Spæl yarn

4.2 Impact of one ewe

The previous findings show that the overall wool production from sheep has the greatest impact. As a result, a closer look at the results of wool production would be appropriate to illustrate where the most significant influences originate from and which feed elements contribute the most. As a result, two graphs were created to highlight the contribution of one ewe to the various effect categories.

4.2.1 Spæl & NWS

Upon first examination, the most noticeable results apply to climate change. Emissions deriving from enteric fermentation and manure constitute the major contributors to climate change, followed by grass silage, with concentrates and infield grazing causing more honorary impacts.

As for particulate matter, grass silage dominates in terms of impact, while infield grazing and concentrates contribute slightly. Acidification impacts mainly originate from grass silage production, complemented by minor contributions from infield grazing and concentrates production.

In the case of freshwater- and terrestrial eutrophication, the production of grass silage emerges as the principal impactor, with a substantial amount also deriving from the production of concentrates. When assessing land use impacts, a significant proportion can be attributed to outfield grazing in mountainous regions. The remaining land use impacts are divided among grass silage, concentrates, and infield grazing.

The burden of water use primarily appear from concentrate production and grass silage production. Biodiversity impacts present a more nuanced picture. Concentrate production and grass silage production provide positive impacts, signifying potential damage to local plant diversity. In contrast, both outfield and infield grazing demonstrate negative damage potential, contributing to an overall negative value for potential biodiversity damage. This suggests that the land occupation associated with sheep production may, in fact, support biodiversity improvement.

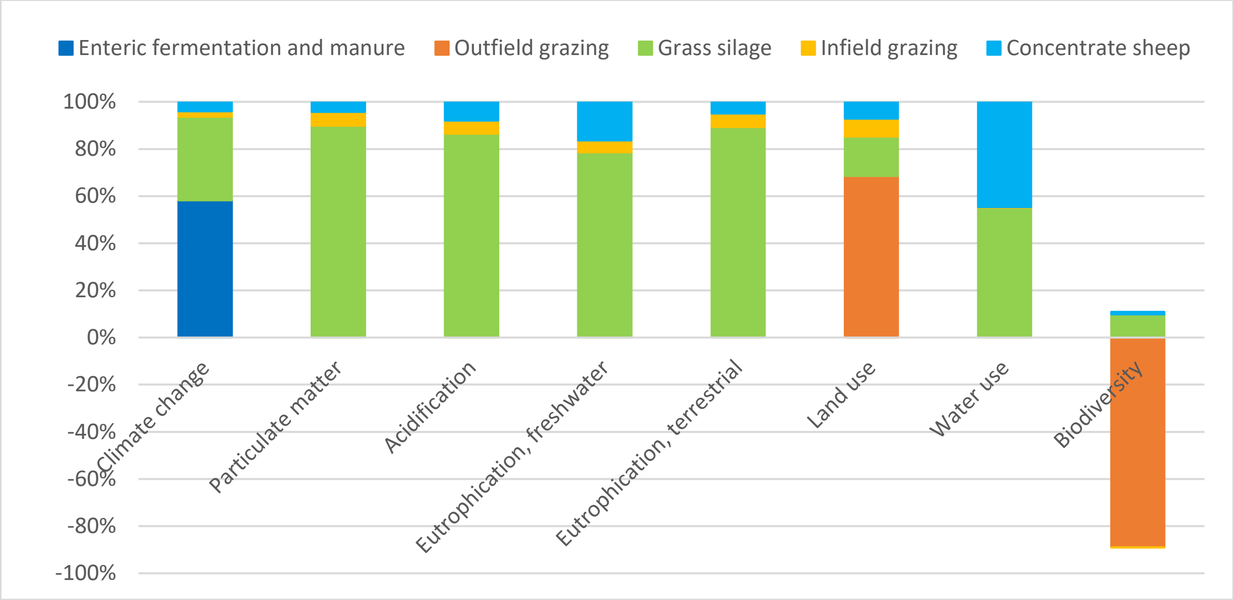


Figure 6: Contribution analysis of the different feeding types for the production of one Spæl ewe for the different impact categories (in percentage)

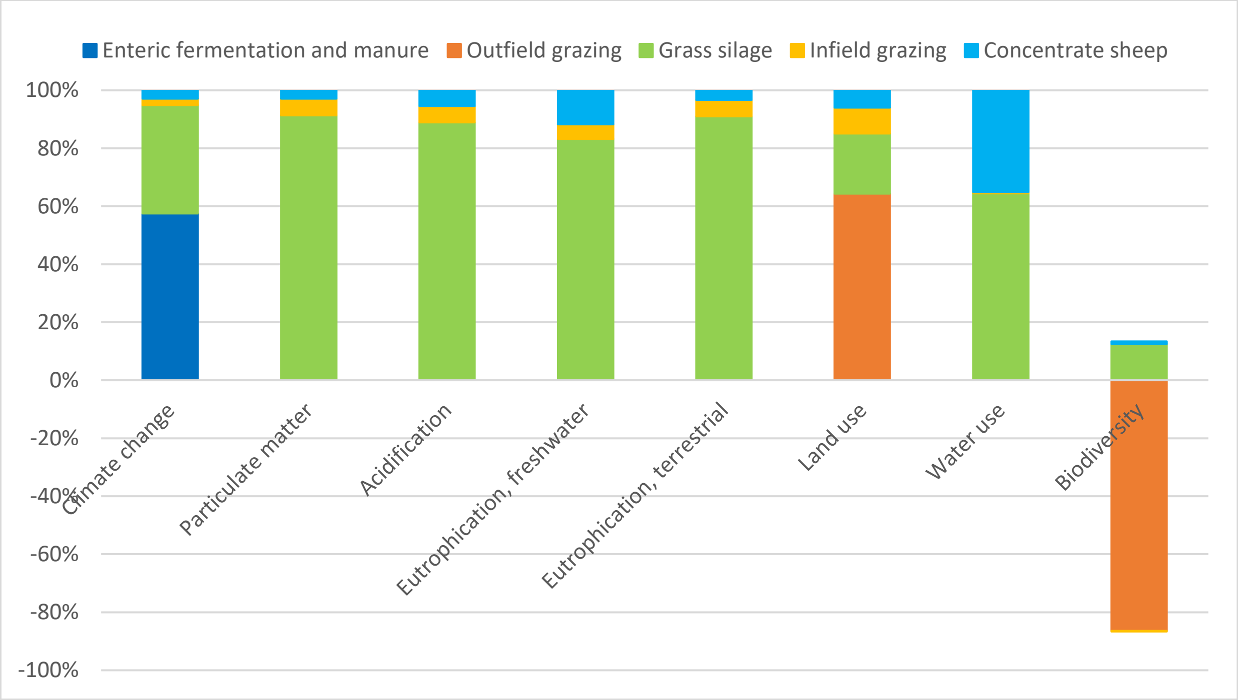


Figure 7: Contribution analysis of the different feeding types for the production of one NWS ewe for the different impact categories (in percentage)

4.3 Feed

4.3.1 Production of concentrates

Figures 8 and 9 portray the contributions of sheep and feed, and accentuate the main impact of feed production on the emission of greenhouse gases associated with wool production. The two primary contributors are concentrates and grass silage, attributable to their intensive processing requirements throughout their life cycles.

Figure 6 provides a dissection of the contribution analysis of 1 kg of feed concentrates. The life cycle stages are divided into fertilizer production, concentrate production, machinery and infrastructure, transport, feed ingredient production, and herbicide and insecticide production. Concentrate production encapsulates electricity usage and heat generation obtained during the merging of various feed ingredients. Machinery and infrastructure include both on-farm and off-farm elements utilized in the production of the feed ingredients. Transport consists of all transportation activities involved in concentrate production, including, for instance, soy transportation from Brazil to Norway. Feed ingredient production entails the growth of crops, the application of fertilizer and manure, and the complete process of drying, cutting, refining, etc., necessary to prepare the feed ingredients for incorporation into the concentrates. Herbicides and insecticides refer to the production thereof.

Generally, feed ingredient production has the biggest influence across all impact categories. For climate change, particulate matter, and acidification, the production of feed ingredients is the most contributing process, followed by machinery and infrastructure, fertilizer production, and transport. With respect to freshwater eutrophication and water usage, feed ingredient production again stands as the major contributor, with fertilizer production and machinery and infrastructure providing lesser contributions. For terrestrial eutrophication, the impact mainly comes from production of feed ingredients but also a substantial amount due to fertilizer production, machinery and infrastructure and transport. Lastly, in the case of land use and biodiversity, the production of feed ingredients is the primary contributor. The production of herbicides and pesticides and concentrate production hold a negligible impact on the overall contribution.

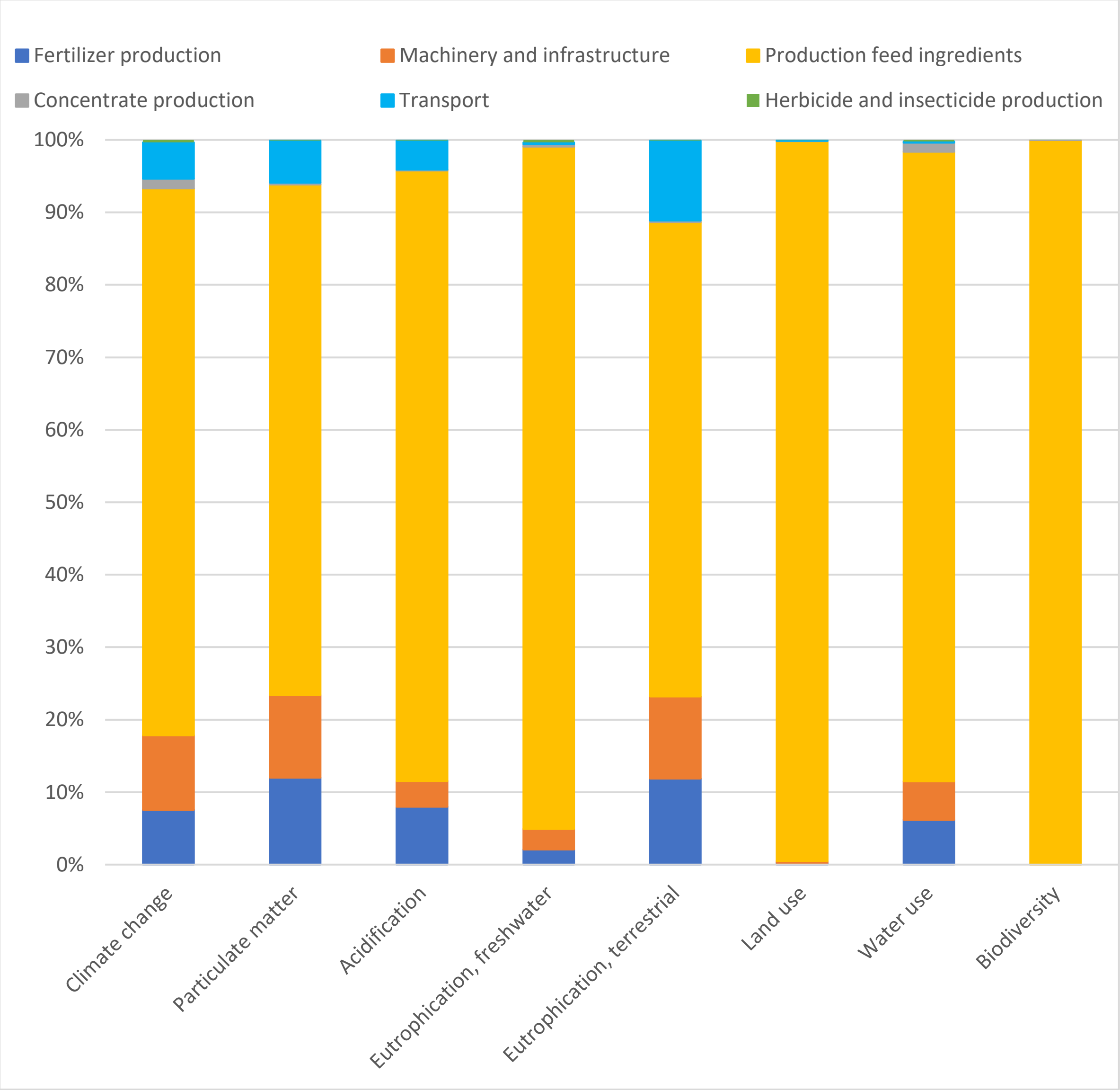


Figure 8: Contribution analysis for the production of 1 kg of feed concentrates for the different impact categories (in percentage)

4.3.2 Production of grass silage

Figure 7 portrays the contribution analysis of 1 kg of grass silage production. The assorted contribution stages include fertilizer production, grass production, machinery and infrastructure, transport, plastic, and herbicide production. Machinery and infrastructure account for all elements required for grass silage production. The category of plastic incorporates the production and utilization of plastic for the silage bales. Grass production covers the fertilization and usage of fields for grass cultivation. Transport primarily involves the transportation of plastic to the farm for silage bale production.

Generally, grass production dominates the impact across nearly all categories. For climate change, grass production contributes most significantly, followed by machinery and infrastructure, fertilizer production, plastic, and transport. Regarding particulate matter, acidification, and freshwater eutrophication, grass production stands as the primary contributor, with supplementary inputs from machinery and infrastructure, fertilizer production, and plastic. With respect for terrestrial eutrophication grass production again stands as the major contributor, with fertilizer production and plastic providing lesser contributions. For land use and biodiversity, grass production remains the primary contributor. Notably, water usage is most affected by plastic production, followed by machinery and infrastructure, and a minor contribution from fertilizer production. The production of herbicides and transport contribute minimally, verging on insignificance, to the total impact across all categories.

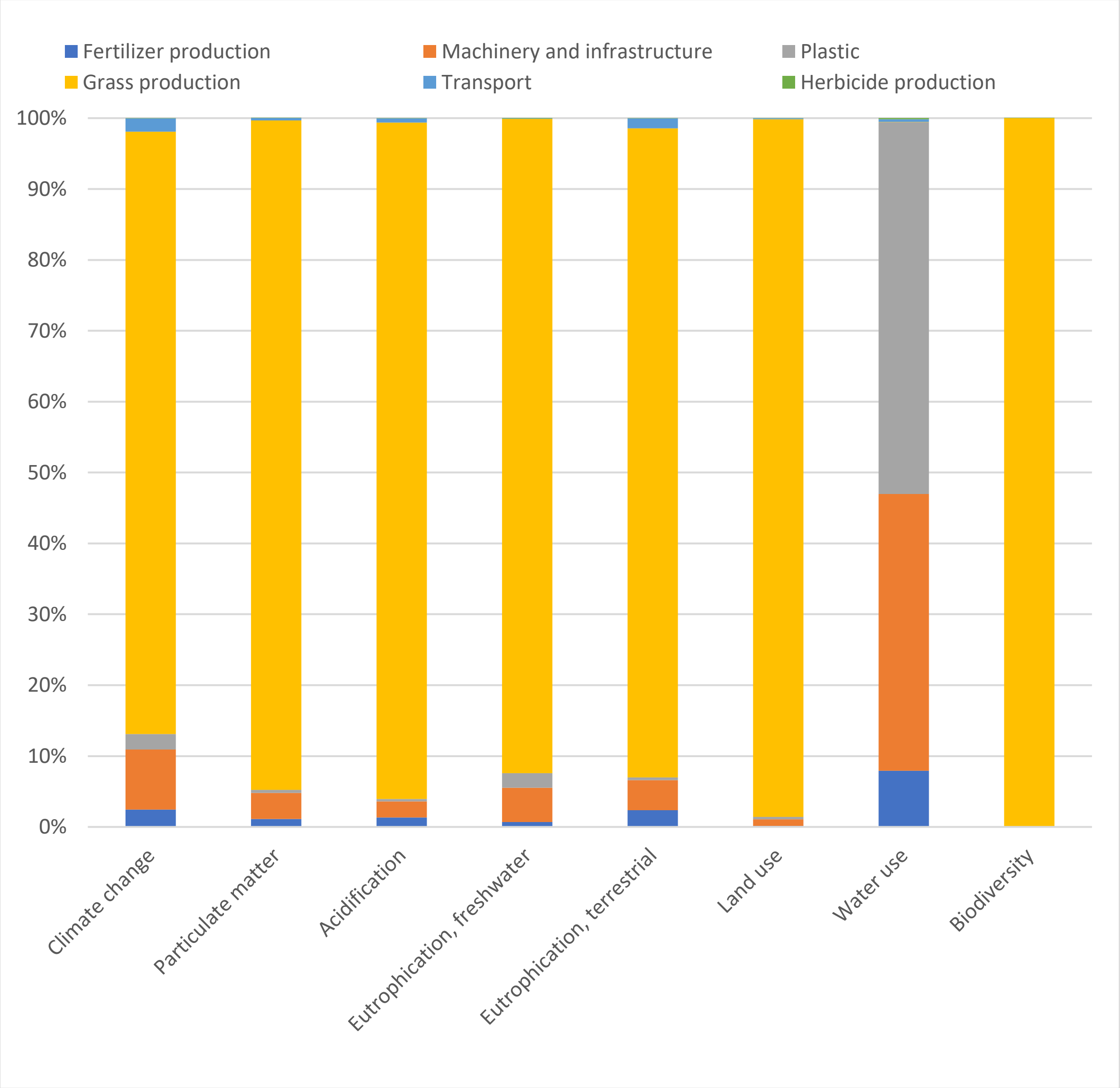


Figure 9: Contribution analysis for the production of 1 kg of grass silage for the different impact categories (in percentage)

5 Discussion

5.1 Environmental impact of yarn

In the results, it became apparent that the yarn from NWS has a higher impact on climate change, particulate matter, acidification, freshwater eutrophication, land use and water use. Whereas NWS yarn scores better for biodiversity. The biggest contributor for all impact categories but one was the wool production (enteric fermentation, manure and feed). Wool and meat are the two commercial products from the Norwegian sheep industry.

The values for climate change are expressed in kg CO_2 equivalent, which shows the contribution to climate change. Clearly, the yarn from both breeds has a high impact on climate change, although the impact from NWS yarn is higher than from Spæl yarn. The spinning process has a slight contribution to the whole impact on climate change. Going deeper into the results, the most significant contributor to climate change are the CH_4 and N_2O emissions from the sheep via enteric fermentation and manure and grass silage (Figures 6 and 7). The impact from enteric fermentation and manure is 598.5 kg CO_2 eq. for NWS and 476.6 kg CO_2 equivalent for Spæl, due to higher feed requirements for NWS. Whereas, the impact from grass silage was 290.9 for Spæl and 388.6 For particulate matter, the results are higher for NWS yarn. The biggest contribution for the results from grass silage come from the production of grass through burning of fossil fuels.

For acidification and freshwater- and terrestrial eutrophication the results are higher for NWS. The results in these impact categories mainly come from the feed production where the production of grass silage and concentrates contributes the most. Here the highest impact came from the production of feed ingredients in the concentrates and the grass production for grass silage due to usage of fossil fuels in the process.

As for land use, most of the impact on soil quality came from the total wool production caused by production of winter feed and grazing as well. Outfield grazing has the most impact because there is generally less food available so the sheep need to range over a larger amount of area to fulfil their feeding needs.

For water use, the most impact came from the spinning process, specifically the washing process of the wool. After the spinner receives the wool from the slaughterhouses or the farms, the wool must be washed because it is still dirty and contains a lot of grease. This is where the biggest impact on water use comes from. The rest of the impact comes from feed and then mainly from the production of grass silage an d the production of concentrates. Water use from the production of concentrates mainly come from the irrigation of the crops. For grass silage it comes from plastic production for the silage bales and the use of machinery and infrastructure. Here as well, Spæl yarn scored a slightly better compared to NWS yarn. Water use might be the least important impact category when it comes to production in Norway, since Norway usually does not have many problems with water scarcity. When comparing to Belgium, my home country, there are often some problems with water scarcity during the summer and therefore, these results might be more significant in Belgium than in Norway.

The impact on biodiversity is the only result that varies from the rest. Here, NWS yarn has a better impact on biodiversity than Spæl yarn. The reason for this is that NWS has higher feed requirements during the outfield grazing and infield grazing period compared to Spæl. The characterization factors for biodiversity in outfield grazing areas and infield grazing areas are negative and therefore have a potential to increase plant biodiversity in the area (Koellner & Scholz, 2008). A reason for this can be because they play a big part in the distribution of seeds through their excreta or because the seeds get stuck on their fleece and fall of later in another area. They also might play a role in containing overgrowth by dominating plant species (Sickel et al., 2021).

To summarise, there are two main reasons as for why the yarn from NWS wool has a higher impact on climate change, particulate matter, acidification, eutrophication, land use and water use compared to the yarn from Spæl wool. The first one is the difference in allocation. The impacts from Spæl production are for 10% allocated to wool while it is 11,6% for NWS. This means that the Spæl wool accounts for less of the impacts from its sheep production compared to NWS. The second reason is because NWS generally needs more feed to maintain its weight of 100kg while Spæl need less feed to maintain its weight of 75kg. This means that the overall GE intake of NWS is higher than Spæl (see table 3). This resulted in NWS sheep generally having higher emissions from enteric fermentation and manure and feed. This also has an effect on the impacts from land use and biodiversity. Because NWS has a higher energy requirement, they need more land to receive enough feed. This means that more land is needed for the production of grass silage and the grazing areas. Since the characterization factors for biodiversity are negative for grazing areas, NWS scores better on biodiversity.

Figures 6 and 7 show specific results of a contribution analyses of the production of one Spæl ewe and one NWS ewe. The graphs look very similar but there are some slight inconsistencies to be explained. There is a small increase in the contribution of concentrates for Spæl compared to NWS. This is because the sheep feeding tool showed that NWS need slightly less concentrates during the period in which they are heavily pregnant. During this period, NWS is able to take most of its energy from grass silage which is also why the contribution of grass silage is higher for NWS for all impact categories compared to Spæl. This is in contradiction to what the interviewed farmers say.

Limitations of the results are the absence of washing agents within the spinning process due to lack of data thereof. The inclusion of washing agents might have given interesting results. The feed recipes can also be seen as a limitation because I was not allowed to receive or use the actual recipe from the Norwegian feed concentrates used by the farmer.

5.2 Biodiversity

To be very clear, the results for biodiversity is in this study calculated solely comes from the impact of land occupation. However, it is important to keep in mind that biodiversity is also very much affected by climate change, acidification, and eutrophication. There has been a lot of research about the effects from climate change on biodiversity. Firstly, climate change is impacted by the emissions of GHG emissions from anthropogenic activities (Nunez et al., 2019; IPCC, 2022). And because those emissions are increasing, climate change is becoming a bigger problem every year. The IPCC came out with its latest report on the impacts and risks of climate change was released in April 2022. An assessment of the impact from climate change on biodiversity was made. It says that because of global warming caused by the GHG emissions there will be more occurrences of extreme weather events which will cause high or very high risks for biodiversity loss (IPCC, 2022). These variabilities make it hard for animals and plants to adapt to their new climate. A next big impact is the rising of the mean temperature in the world. This can affect biodiversity in many different ways. Some of the most affected areas to global warming are alpine regions and arctic regions. They seem to be the most vulnerable to global warming compared to other ecosystems. The reason for this is because the species within alpine- and arctic regions are very adapted to the cold weather. Not many species are able to grow in such places which means that there is not a lot of competition between the species. However, with the mean temperatures rising more and more non-alpine species are able to grow there which can result in the extinction of alpine species and the treeline to move up. This effect has already been observed in many places all around the world (Steinbauer et al., 2018). The same thing happens in arctic regions as well; there the treeline moves more North.

5.3 Differences between Spæl and NWS

In Jensen's master's thesis from 2013, she studies the differences between Spæl and Norwegian White sheep (Jensen, 2013). The main findings strongly correlated to the data received for the interviews in this study. First of all, there is a big difference in the weight of both breeds. Generally, NWS is a lot heavier than Spæl . Even though both breeds are becoming a lot heavier through breeding programs that focus on optimizing the meat production, Spæl have not surpassed NWS in terms of weight. Although the data about the weight from NWS and Spæl date from 2013, the main trend remains valid. They generally need more feed than Spæl to maintain their heavy weight (Jensen, 2013). The Sheep Feeding tool, however, suggested that NWS ewes need less concentrates than Spæl when they are heavily pregnant. This is in contradiction to what the sheep farmers say, and therefore might be a limitation to the study and could result in NWS having even higher impacts. Secondly, NWS have more difficulties giving birth to their lambs than Spæl (Jensen, 2013). They have been bred to produce more than two lambs and give birth to triplets more often than Spæl. This is why NWS have more difficulties with nursing too, because sometimes their milk supply does not cover the needs of all three lambs. On top of that, compared to Spæl , NWS gives birth to more still born lambs. It is clear that giving birth comes naturally to Spæl and that they have better maternal instincts (Jensen, 2013). The farmers in this study claim that the difference is quite noticeable during the lambing season. It is also one of their biggest motivations to keep Spæl even though their meat production is less. The farmer in Viken usually keeps the lambs and ewes that had problems during birth on an infield pasture until they are strong enough to go to the outfield pasture, which would result in more impact from those sheep because this pasture is fertilized with manure. Often there are more NWS grazing on that infield pasture than Spæl. According to the farmers and Jensen (2013), Spæl have better survival instincts when grazing outfield than NWS. They usually form flocks which is a better way to fight off any potential predators. They also like to go into higher altitudes when grazing and eat more tree leaves and shrubs (Steinheim et al., 2006). NWS on the other hand, like to form smaller groups, usually of one ewe and her lambs when grazing on outfield pastures. This is not a very good strategy when it comes to predation protection. While grazing, they prefer to eat more grass-like plants. (Johanssen, 2018). Economically, NWS performs better in terms of winterfed ewes and working hours. This means that they are still economically superior even with the considerable amount of help they need (Jensen, 2013).

In conclusion, the reason why farmers like to keep both breeds at the same time is that NWS needs more help than Spæl. In combination with Spæl, who need less help in most aspects of sheep farming, they earn the most money with the least amount of work. In general, sheep are one of the most rewarding livestock when it comes to working hours for farmers (Jensen, 2013). If we were to calculate the production of the same amount of meat from both breeds, Spæl will probably have more environmental impact compared to NWS as they need to produce more animals for the same amount of meat.

5.4 Wool and other fibres

Nolimal (2018), studied the environmental impact from four different sweaters which yielded very interesting results. She studies the difference between 100% cotton sweater, a 100% wool sweater, a 60% cotton and 40% polyester sweater, and a 100% acrylic sweater. The use phase consisted of 28 washes and tumble dryings except for the wool sweater which was air dried every time (Nolimal, 2018). The data used for the LCA's came from databases like Ecoinvent, GaBi Professional and from previous research. The calculations therefore give a general overview of the sweaters' environmental impact but are not specific to one place. The impact categories used in this study were not completely the same as the ones used in this thesis. The only matching impact categories were climate change, acidification and eutrophication. For all of those categories the wool sweater scored better than the other three sweaters (Nolimal, 2018). The results of the LCA for the impact category of climate change are showed in the graph underneath, retrieved from the paper of Nolimal (2018). This graph shows that the impact from one wool sweater compared to the other sweaters is very low. The production of wool is surprisingly small, especially compared to cotton production. The use phase for all but one sweater had the highest impact on climate change. The impact from the use phase of wool is smaller because wool needs to be air-dried and therefore skips the step of

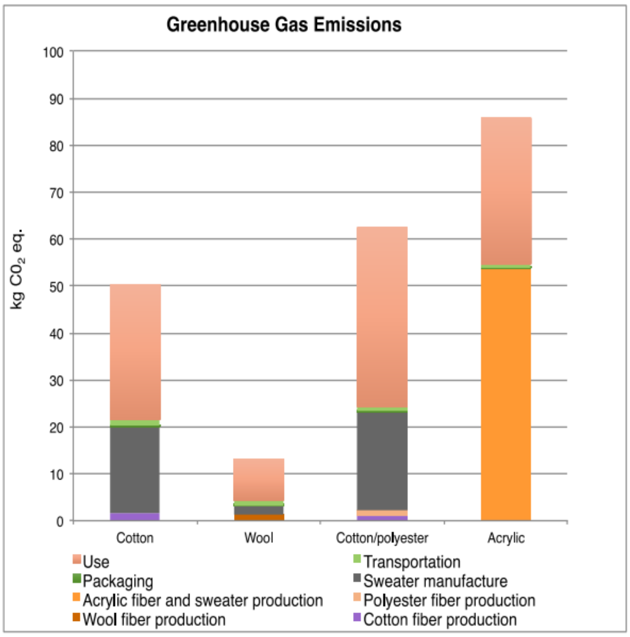


Figure 10: Results from Nolimal (2018) on the impact of four different sweaters on climate change (100% cotton sweater, 100% wool sweater, 40% polyester and 60% cotton sweater, and 100% acrylic sweater)

tumble drying (Nolimal, 2018). The impact from the wool production from sheep is a lot lower than what the results of this thesis showed. This might be because the sweater used in this study was lighter (0.35kg) than the wool for one sweater calculated in this thesis (0.6kg). If we would take half of the amount of CO_2 equivalent calculated in this thesis, the value would be 12.03kg CO_2 equivalent. This is still more than what the study implies but the overall result would still be that the impact from a wool sweater is lower than the other three sweaters.

It can be argued that the use phase of wool clothing can be even less impactful than what Nolimal (2018) suggests because there are a few other things to take into account. Laitala, et al. (2017) made an overview of the use phase of wool clothes compared to clothes from other fabrics, especially cotton. The median washing temperature for wool clothes is lower (25°C) than that the cotton clothes (49.7°C). Calculations were made about the energy use for one wash. On estimation, the electricity use of one wash for wool clothes is 0.56 kWh and the electricity use of one wash for cotton clothes is 1.02 kWh (Laitala, 2017). Secondly, wool clothes are worn more days before being washed. European surveys showed that wool sweaters are worn approximately 10 days before being washed and cotton sweaters approximately 5 days before being washed (Laitala et al., 2017). On average, that means that cotton sweaters are washed twice as much as wool sweaters. Another characteristic is the life span of wool garments. In the study of Laitala et al. (2017), an average life span was taken from multiple surveys mainly conduced in Europe. They concluded that 100% wool garments had an average lifespan of 5.3 years compared to 100% cotton garments with an average lifespan of 3.6 years.

It can be concluded that the use phase of clothing is a very important part of the life cycle of a clothing piece. It is also the life cycle step in which people can make a big difference. In Nolimal (2018), it was very clear that the use of tumble drying has a very big effect on the overall environmental impact. The impact from the electricity use also depends on the location. In Norway, most electricity come from renewable sources and might therefore have lesser impacts compared to China or India where much electricity comes from coal plants. The results lead to believe that if consumers choose to air-dry their clothing it can have a great importance for the environmental performance of their clothing. Also, if they decide to wait until the clothing is dirty or smelly before washing them, it might have a large effect.

Adding the manufacturing of the sweater and the use phase to this thesis to see the environmental impact of the whole life cycle specified to Norway. The use phase, however, will most likely be the same for a sweater from NWS wool and a sweater from Spæl wool. Therefore, there is a possibility of going further with the wool of just one of the breeds.

5.5 Circularity

In terms of circularity, wool clothing can contribute very much to circularity within the clothing industry. Wool is fairly easy to recycle and. Several collection methods can be applied to receive the wool clothing at the end of usage, such as donation, door step collections and take-back schemes (Russel et al., 2016). Once the clothes are collected, they can be recycled. Two main recycling schemes can be practiced; open loop recycling and closed loop recycling (IWTO, 2020; Russel et al., 2016). Within open loop recycling, the wool fibers are used for industrial products such as insulation or matrass padding (IWTO, 2020). Within the closed loop recycling scheme, the wool fibers will be retained to their original state to be used again as a source for yarn and clothing production. Open loop recycling can be seen as downcycling (IWTO, 2020). However, often, wool garments are not fully made out of wool and have other fibers added to the garment. This makes it very difficult to recycle the wool clothing and it is a big limitation (Russel et al., 2016).

6 Conclusion

In an overarching perspective, the yarn production of Norwegian White Sheep (NWS) wool displays the most significant impact on all environmental impact categories, except for one. Typically, wool production constitutes the most substantial contribution to these impact categories. The effects on climate change mainly originate from the emissions associated with enteric fermentation and manure management of the sheep. For particulate matter, acidification, and freshwater eutrophication, the majority of the impact derives from feed production, particularly grass silage and feed concentrates. The impact on land use also stem especially from feed, primarily due to outfield grazing. This is attributed to the lower yields of edible plants in comparison to arable land and infield grazing, requiring more area to satisfy the feed requirements. Interestingly, the water use category is the sole one where the spinning process contributes the most, primarily due to the washing of the wool before spinning. For the biodiversity damage potential category, the results are negative values, suggesting that the land occupation associated with wool yarn production could potentially enhance biodiversity. The results for NWS were less than those of Spæl, which could indicate that NWS may cause a more beneficial effect on biodiversity in terms of land occupation. However, it is vital to remember that the production of wool yarn also contributes to climate change, which in turn, can negatively impact biodiversity.

There are also substantial differences between both breeds that cannot be accurately showed through a Life Cycle Assessment (LCA). Some of the most striking differences lie within maternal instincts. Spæl sheep are demonstrably superior mothers, experiencing fewer complications during lambing and exhibiting more efficient milk production. Spæl sheep also possess stronger survival instincts during the grazing period due to their propensity to form flocks. There are also differences in forage selection on outfield grazing pastures.

According to Nolimal's study (2018), the environmental impact of wool sweaters is less than that of cotton sweaters, positioning wool clothing as a particularly sustainable option in terms of environmental impact. While the production phase of wool is more impactful compared to its cotton counterpart, the usage phase of wool clothing is likely the most environmentally friendly, primarily due to the minimal impact of washing (Nolimal, 2018).

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Appendix

Equations for emissions from enteric fermentation and manure

Variables use for calculations

Variable	Value	Source
Y_m ewes & young ewes	0.065	Little et al., 2008
Y_m lambs	0.045	Little et al., 2008
DE (%) - weighted average		
Young ewes	NWS: 65% SS: 66%	Own calculations
Ewes	NWS: 64% SS: 65%	Own calculations
Lambs	NWS: 68% SS: 68%	Own calculations
B_o	0.19	Little et al., 2008
Ash (%)	8	Little et al., 2008
MCF	0.010	Little et al., 2008
Protein_content (kg/head/day) - weighted average		
Young ewes	NWS: 0.159 SS: 0.160	B.Å. Aspeholen (personal communication, April 28, 2023)
Ewes	NWS: 0.160 SS: 0.159	B.Å. Aspeholen (personal communication, April 28, 2023)
Lambs	NWS: 0.165 SS: 0.165	B.Å. Aspeholen (personal communication, April 28, 2023)
PR	0.10	Little et al., 2008
EF_{direct}	0.01	Little et al., 2008
$Frac_{volatilization}$	0.20	Little et al., 2008

$EF_{volatilization}$	0.01	Little et al., 2008
$Frac_{leach}$	0.22	Miljødirektoratet, 2022
EF_{leach}	0.0075	Little et al., 2008

Then next equations are retrieved from IPCC (2006) and Little, et al. (2008).

Enteric CH_4 emissions

Gross energy

$$GE = kgDM/head/day * 18.45$$

(IPCC, 2006; Little et al., 2008)

GE	Gross energy intake (MJ head^{-1} day^{-1})
18.45	Conversion factor for gross energy per kg of dry matter (MJ kg^{-1})

CH_4 emission

$$CH_{4enteric\_}rate = GE * \frac{Y_m}{55.65}$$

(IPCC, 2006; Little et al., 2008)

$CH_{4enteric\_}rate$	Enteric CH_4 emission rate (kg head^{-1} day^{-1})
Y_m	Methane conversion factor
55.65	Energy content of CH_4 (MJ kg^{-1} CH_4)

$$CH_{4enteric} = CH_{4enteric\ \_}rate * 365days$$

(IPCC, 2006; Little et al., 2008)

$CH_{4enteric}$	Enteric CH_4 emission head/year (kg CH_4)

Manure CH_4 emissions

$$VS = \left[GE * \left(1 - \frac{DE}{100}\right) + (0.04 * GE)\right] * \left(1 - \frac{Ash}{100}\right) * \frac{1}{18.45}$$

(IPCC, 2006; Little et al., 2008)

VS	Volatile solids (kg head^{-1} day^{-1})
GE	Gross energy intake (MJ head^{-1} day^{-1})
DE	Percent digestible energy in feed
Ash	Ash content of manure (%)
18.45	Conversion factor for gross energy per kg of dry matter (MJ kg^{-1})

$$CH_{4manure\_}rate = VS * B_o * MCF * 0.67$$

(IPCC, 2006; Little et al., 2008)

$CH_{4manure\_}rate$	Manure CH_4 emission rate (kg head^{-1} day^{-1})
B_o	Methane producing capacity
MCF	Methane conversion factor
0.67	Conversion factor from volume to mass (kg m^{-3})

$$CH_{4manure} = CH_{4manure\_}rate * 365days$$

(IPCC, 2006; Little et al., 2008)

$CH_{4manure}$	Manure CH_4 emission/head/year (kg CH_4)

Manure N_2O emissions

Nitrogen excretion

$$PI = \frac{GE}{18.45} * protein\_content$$

(IPCC, 2006; Little et al., 2008)

PI	Protein intake (kg head^{-1} day^{-1})
GE	Gross energy intake (MJ head^{-1} day^{-1})
protein_content	Protein content (kg kg^{-1})

$$N_{excretion\_}rate = \frac{PI*(1-PR)}{6.25}$$

(IPCC, 2006; Little et al., 2008)

PR	Protein retained (kg (kg protein intake)$^{-1}$)
$N_{excretion\_rate}$	N excretion rate (kg head^{-1} day^{-1})
6.25	Conversion from dietary protein to dietary N

N_2O emission

Direct emission

$$N_2O - N_{direct\_}rate = N_{excretion\_}rate * EF_{direct}$$

(IPCC, 2006; Little et al., 2008)

$N_2O\text{-}N_{direct\_rate}$	Manure direct N emission rate (kg head^{-1} day^{-1})
EF_{direct}	Emission factor [kg N_2O-N (kg N)$^{-1}$]

$$N_2O - N_{directmanure} = N_2O - N_{direct\_}rate * 365days$$

(IPCC, 2006; Little et al., 2008)

N_2O-Ndirectmanure	Manure direct N emission (kg N_2O-N)

Indirect emission

$$N_2O - N_{volatilization\_}rate = N_{excretion\_}rate * Frac_{volatilization} * EF_{volatization}$$

(IPCC, 2006; Little et al., 2008)

$N_2O\text{-}N_{volatilization\_}rate$	Manure volatilization N emission rate (kg head^{-1} day^{-1})
$Frac_{volatilization}$	Volatilization fraction
$EF_{volatilization}$	Emission factor for volatilization [kg N_2O-N (kg N)$^{-1}$]

$$N_2O - N_{volatilization} = N_2O - N_{volatilization\_}rate * 365days$$

(IPCC, 2006; Little et al., 2008)

N_2O-$N_{volatilization}$	Manure volatilization N emission (kg N_2O-N)

$$N_2O - N_{leaching\_}rate = N_{excretion\_}rate * Frac_{leach} * EF_{leaching}$$

(IPCC, 2006; Little et al., 2008)

N_2O-Nleaching_rate	Manure leaching N emission rate (kg head^{-1} day^{-1})
$Frac_{leach}$	Leaching fraction
$EF_{leaching}$	Emission factor for leaching [kg N_2O-N (kg N)$^{-1}$]

$$N_2O - N_{leaching} = N_2O - N_{leaching\_}rate * 365days$$

(IPCC, 2008; Little et al., 2008)

N_2O-$N_{leaching}$	Manure leaching N emission (kg N_2O-N)

$$N_2O - N_{indirectmanure} = N_2O - N_{volatilization} + N_2O - N_{leaching}$$

(Little et al., 2008)

N_2O-$N_{indirectmanure}$	Manure indirect N emission (kg N_2O-N)

Total emission

$$N_2O - N_{manure} = N_2O - N_{directmanure} + N_2O - N_{indirectmanure}$$

(Little et al., 2008)

N_2O-N_{manure}	Manure N emission (kg N_2O-N)

Conversion from N_2O-N to N_2O

$$N_2O_{manure} = N_2O - N_{manure} * \frac{44}{28}$$

(Little et al., 2008)

44/28	Conversion from N_2O-N to N_2O
Total_N_2O_{manure}	Total manure N_2O emission from sheep (kg N_2O/head/year^{-1})

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