Production of Biomethanol from Renewable Resources

A Life Cycle Assessment with Incorporation of Biodiversity

Master's thesis in Industrial Ecology

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Cover: Biomethanol production facility in Mönsterås, Sweden. Retrieved from (Södra, n.d-b)

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Abstract

There is growing interest in society for mitigating climate change and sustaining biodiversity. It becomes more and more important for society and companies to produce sustainable products that has a low environmental impact. Renewable resources from the forest is being presented as a more sustainable option to fossil resources and is playing an important role in for example EU's future strategies to achieve climate neutrality. It is of importance to produce these forest resources in a sustainable way and assessing the environmental performance is an important tool to achieve a sustainable production. One big stakeholder regarding products made from renewable forest resources in the south of Sweden is the forestry industry group *Södra Skogsägarna Ekonomisk Förening*, which recently installed a new production facility at their paper pulp mill in Mönsterås to be able to utilize the by-product biomethanol.

This project aimed at investigating how the production of Södras biomethanol impacts the environment and this was achieved by performing an attributional cradle to gate LCA. The purpose was also to investigate how the biomethanol production impacts biodiversity and what type of methods for assessing biodiversity that can be used and included in the LCA. To assess the impact on biodiversity, two methods were used. A method developed by Chaudhary et al., (2015) was used for assessing biodiversity on a species level and another method by Lindner et al., (2021) was used for an ecosystem perspective.

The results showed an environmental impact from the production of biomethanol. Especially the results from the impact category of global warming potential (GWP) was lower compared to fossil-based methanols. The methods for including biodiversity in LCA were concluded to have both advantages and disadvantages in assessing the biodiversity impact of Södra's biomethanol production. The results regarding biodiversity showed an impact of the same magnitude as comparative data from scientific articles using the same methods, but the results were difficult to analyse due to the methods not being widely used in similar LCA's.

Keywords: Life Cycle Assessment, Biodiversity, Biodiversity in LCA, Forestry, Biomethanol, Methanol, Renewable resources.

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Linnéa Rydin, Gothenburg, June 2022
Victoria Svensson, Gothenburg, June 2022

List of Abbreviations

Below is the list of acronyms and abbreviations that have been used throughout this thesis, listed in alphabetical order:

BD	Biodiversity Damage
BI	Biodiversity Impact
CBD	Convention on Biological Diversity
CF	Characterization Factor
EEA	European Environment Agency
EF	Ecoregion Factor
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IUCN	International Union for Conservation of Nature
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
m^3sub	Solid volume under bark
m^3fo	Forest cubic meters of living trees excluding branches and roots
PDF	Potentially Disappeared Fraction
PSL	Predicted Species Lost
SETAC	The Society of Environmental Toxicology and Chemistry
Södra	Södra Skogsägarna Ekonomisk Förening
UNEP	United Nations Environment Program
WWF	World Wildlife Fund

Contents

List of Figures

List of Tables

1
Introduction

Since the 1800s, human activity has had long-term effects on global temperature and weather patterns, which also is known as climate change. The main drivers behind it are anthropogenic use of fossil resources such as coal, oil, and gas (United Nations, n.d-b). Not only are anthropogenic activities leading to global warming, but it is also causing loss of biodiversity. Increased demand for resources, land use, urbanization, etc. are examples of activities that are affecting biodiversity. Biodiversity is defined as "the variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems." (CBD, 1992). The consequences of climate change, such as alternated precipitation patterns, increased land and surface temperatures, increased extreme weather events, etc, are also affecting biodiversity (IPCC et al., 2002).

Society is now trying to mitigate climate change by switching energy systems, from fossil to renewable resources. A growing number of countries are committed to achieving net-zero emissions by 2050 and approximately half of the emission cuts must be achieved by 2030 to keep global warming under 1.5°C (United Nations, n.d-b). The European Union has also set high goals for the future regarding energy use and emissions of greenhouse gases. For instance, the EU has adopted a target of using 32% renewable energy by 2030. Biomass is of great importance for the EU to be able to achieve these targets. With a share of 60%, biomass is the main source of renewable energy. Furthermore, forestry generates the main source of biomass in the EU and the Scandinavian countries consume the most bioenergy per capita. Bioenergy has great potential to reduce the use of fossil energy and play a key role in achieving the European targets (Marios et al., 2019). However, the production of bioenergy must be sustainable and efficient without causing loss of biodiversity or deforestation (Marios et al., 2019). Monitoring and assessing the sustainability performance of bioenergy production is therefore of great importance. One useful tool to perform this is Life Cycle Assessment (LCA). This tool maps the potential environmental impacts of products during the life cycle of the product. LCA is an effective tool to measure various environmental aspects such as climate change, acidification, human toxicity, etc., but due to data scarcity and methodological limitations the aspect of biodiversity is rarely included in standard LCA (Vrasdonk, 2020).

Today, about 30% of the Earth's land surface is covered by forests. However, humans have been harvesting forests and transforming them into other types of land such as agricultural land for the past 8000 years. About half of the forests on Earth have been cleared up by humans. Since 1850, deforestation has been responsible for 30% of the

CO_2 emissions (Melillo, 2021). Local climate can also be affected by forests since trees are releasing moisture that leads to reduced air temperature around them. Forests play an important role in maintaining the climate balance globally by removing CO_2 from the atmosphere and storing it in the biosphere. This is also important to mitigate climate change. It is estimated that forests remove an average of 2 billion metric tons of CO_2 annually. Sustainable forestry is thus important in the future to address climate change (Melillo, 2021). Not only are forests important from a climate perspective, but also from a biodiversity perspective. Plants, animals, and microorganisms are relying on forests for providing habitats. Forests are biologically rich systems that are important for biodiversity but also for humans since they are providing different ecosystem services such as recreation and CO_2 uptake as mentioned earlier (FAO & UNEP, 2020).

This project is a collaboration with Chalmers University of Technology and the large Swedish forestry industry group called *Södra Skogsägarna ekonomisk förening*, also named in this report with the abbreviation *Södra*. Södra's main purpose is to refine the 52.000 forest owners' raw material into renewable, climate-smart products. The business ranges from pulp and wood products to renewable energy and dissolving pulp, which are sold to an international market. Södra is the first in the world to produce fossil-free biomethanol in their new manufacturing facility that was inaugurated in 2020. This biomethanol can be used as a substitute for fossil-based methanol and also as a material to produce other chemicals. Methanol is often used as fuel or to produce fuels such as biodiesel and one possible consumer of this type of fuel is the marine industry (Södra, n.d-b). Sustainability and biodiversity are important topics to Södra and the company is interested in assessing how its product is performing in these aspects. Especially how to account for their biodiversity impact and how it can be quantified to fit their operations in the best possible way with current methods. The company strives to improve its environmental performance, and demands are also increasing from society, customers and other stakeholders. Södra is therefore interested in life cycle assessment of their product, to be able to find potential areas that can be improved.

1.1 Purpose

The purpose of the project is to investigate how Södra's production of biomethanol from renewable resources impacts the environment. The purpose is also to investigate the impact on biodiversity from the biomethanol production; how it can be determined with the current basis of knowledge at Södra and also be included in a life cycle assessment (LCA). Lastly, the purpose is additionally to contribute to the research about how biodiversity can be included in life cycle assessments.

The following problem formulations will be used for the project.

- How does the production of biomethanol from Södra impact the environment?
  - How can biodiversity be included in life cycle assessments of biomethanol?
  - How is biodiversity affected by the biomethanol production from Södra?

1.2 Delimitations

The majority of the delimitations can be applied to both the project as a whole and the LCA. First of all, the LCA is of attributional character and the scope is cradle to gate. The considered processes, data and material consumption for the pulp and biomethanol production is limited to the processes at Södra Cell Mönsterås since it is the only one of Södra's production facilities that produces biomethanol. Moreover, the geographical area for forestry is Sweden and the origin of wood as raw material is thus limited to Sweden. Normally a small share of wood is also imported from the Baltic states and Poland. The forestry activities made by Södra, how they conduct forestry and measurements taken for biodiversity are only considered and used in order to evaluate the environmental impact of the biomethanol production. They are not further examined and no suggestions for improvement are considered in this project. The assessment of biodiversity is limited to the impacts that occurs during forestry.

1.3 Report structure

The next section of the report, section 2, includes some background information for the project where more detail is given on the topics of biodiversity, LCA, and biodiversity in LCA. Next, section 3 is a case description where the production process of both biomethanol and fossil-based methanol is explained. Furthermore, this section also gives a brief description of forestry and biodiversity measurements at Södra.

In the following section 4, the methodology of the project is presented. This sections gives a descriptions of how the life cycle assessment was performed and how biodiversity was included in the LCA. This is followed by the results in section 5. This section presents the result for the LCA and biodiversity assessment and also includes an analysis of the results. The following section of the report, section 6, presents a discussion of the results of the report and methods used to receive the results. Finally, conclusions are presented in section 7.

2
Background

This section includes some background information on the project and it covers the importance and causes of loss of biodiversity, how an LCA can be performed and how biodiversity can be included in LCA.

2.1 Biodiversity

Assessing and working with biodiversity requires setting a definition of it. The Convention of Biological Diversity (CBD) from the UN defines biodiversity in the original convention from 1992 as "the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems." (CBD, 1992). IPBES compresses the definition to "the diversity within species, between species and of ecosystems"(IPBES et al., 2019). And the World Wildlife Fund state that biodiversity is the variety of all living things (Hancock, n.d). Biodiversity can thus be measured on all three levels of genetic, species and ecosystem. However, the genetic biodiversity is very complex to measure and therefore it is more common to evaluate biodiversity on a species and ecosystem level (Vrasdonk, 2020). It also exist other ways of categorizing biodiversity. For example, biodiversity is by Noss (1990) divided into four categories: regional landscape (spatial complexity of regions), community-ecosystem (populations of some or all species coexisting at a site), population-species and genetic (Noss, 1990).

2.1.1 Importance of biodiversity and biodiversity loss

The human influence on nature is so severe that many scientists now describe that the world is entering a new geological epoch, called the Anthropocene. As a consequence of this is biodiversity now declining at the fastest rate in human history (Geisen et al., 2019). A serious decline in many species globally has been detected. For example, according to the living planet index by WWF that tracks the abundance of species, a loss of 68% has been noticed for vertebrate species between 1970 and 2016 (WWF et al., 2020). It is further estimated that 25% of the species on Earth might become extinct. Humans are dependent on nature for providing goods and services and these contributions are vital for the survival of human beings and having good quality of life (IPBES et al., 2019).

Biodiversity is life on Earth since it is necessary in order for ecosystems to provide a large variety of goods and services that are important to humans and nature such as freshwater, food, pollination, climate mitigation, etc. (WWF et al., 2020). Humans have developed substitutes for some of the services nature provides. For example, freshwater can be produced either by ecosystems that filter out pollutants, or produced by man-made water facilities. On the other hand, a number of services are irreplaceable due to financial or technical aspects. Pollination is one service that corresponds to a large economical value that is hard to replace (WWF et al., 2020).

Drivers of biodiversity loss can be both direct and indirect. The most dominating direct drivers for biodiversity loss are land use, exploitation of species, climate change, pollution, and invasive species. These direct drivers are caused by a range of indirect drivers such as rising human population and consumption and production patterns. Mitigation of biodiversity loss needs to address both the direct and indirect drivers to be effective (IPBES et al., 2019). Unless actions are taken to stop the biodiversity loss, approximately 1 million species face extinction, according to IPBES (IPBES et al., 2019).

2.1.2 Biodiversity in forests

Forests are one of the areas that are being highlighted as an important area to manage sustainable in order to increase biodiversity (IPBES et al., 2019). Ecosystems provide shelter and habitats for living organisms and so does also ecosystems in the forest. 69% of the surface of Sweden is covered by forests. Annually there is an expansion of forest area in Sweden. However, this expansion declined by 1% from the year 2000 to 2015. In the same time period, there has also been a 19% rise in forest areas protected by Swedish law (Centralbyrån, 2020). IPBES points out that actions are made to, for example, increase the amount of forest area in the world but that there are actions that are more and less favourable for biodiversity. For example, increasing protected areas might be better than planting monocultures even if the amount of land with forest is increasing in both cases (IPBES et al., 2019). One important condition for biodiversity in forests is the amount of dead wood that is left behind after harvesting forests. A high amount of dead wood indicates favourable conditions for rich biodiversity (SLU, 2021). Other examples of conditions important for biodiversity in forests are availability of old trees and that there is range of different tree species in the forest (EEA, 2016).

On a national level in Sweden, modern forestry and agriculture have the greatest impact on biodiversity (SLU, 2020). The multilateral treaty, Convention of Biological Diversity (CBD), agreed in 2010 to a strategic plan regarding biodiversity for 2011-2020. This plan included the so-called Aichi Biodiversity Targets and these targets were evaluated by the Swedish environmental protection agency and WWF in 2021. It was concluded that even if the consideration of environmental problems in forestry has increased, it is not enough to properly hinder the loss of biodiversity (The Swedish Society for Nature Conservation, 2021). A similar conclusion was drawn by the Swedish Environmental Protection Agency regarding the national target of sustainable forests when it was evaluated in 2022. It is reported that a variety of actions are made but that it takes a long time for changes to be seen. Even if the protected areas within productive forestry areas and the amount of dead wood have increased, it is stated that the current implemented actions are not enough to meet the national targets for a sustainable forest, including the status of biodiversity as an ecosystem service in Sweden (The Swedish Environmental Protection Agency, 2022).

2.1.3 Measuring biodiversity

When conducting environmental analyses indicators are used to describe the state and/or progress of a system and the environment. An indicator can be defined as "An environmental indicator is a parameter, or a value derived from parameters, that points to, provides information about, and/or describes the state of the environment, and has a significance extending beyond that directly associated with any given parametric value. The term may encompass indicators of environmental pressures, conditions, and responses." (OECD, 2001).

Since biodiversity is a highly considered topic internationally, there are many international organizations and policy-making institutions that are constructing indicators of biodiversity. Indicators that are used by the United Nations in the sustainable development goal concerning life on land, goal 15, are mainly the amount and coverage of protected areas, a red list index, and implemented legislation and policy frameworks to promote biodiversity (United Nations, n.d-a). The red list index by the International Union for Conservation of Nature (IUCN) shows trends for extinction risk for species, and governments often uses this list to track their progress for goals related to reducing biodiversity loss (IUCN, n.d). To evaluate the Aichi targets, several biodiversity indicators were used such as the living planet index, area of forest under sustainable management certification, ecological footprint, and forest area as a percentage of total land area (Convention on Biological Diversity, 2016). Additionally, the European Union has recently presented "EU Biodiversity strategy for 2030" with the aim to begin a recovery of biodiversity by 2030. Included in this strategy are a number of goals called "EU Nature Restoration Plan", which for example consist of reversing the decline of pollinators, reducing the number of red list species threatened by invasive alien species, having positive trends in the conservation status of habitats and species and plant three billion new trees (European Commission, 2020).

There are a number of challenges and issues connected to the selection and establishment of biodiversity indicators. At present, there are few indicators that capture the state of biodiversity and some to also describe the condition of soil, land, and water systems (IPBES et al., 2019). Moreover, there are indicators related to different levels of biodiversity. In one research study that analyzed how biodiversity is viewed in LCA by Winter et al., 119 indicators related to biodiversity were found. Out of these, 4% were related to genetic diversity, 40% to species diversity, and 35% to ecosystem diversity. The remaining indicators could not be related to any specific level of biodiversity, they could for example be assessing public awareness (Winter et al., 2017).

2.2 Life cycle assessment

Life cycle assessment (LCA) enables the assessment of a product along its life cycle from the cradle (raw materials) to the grave (disposal) and to analyze its environmental impact along the way. The assessment also gives room for interpretation of the obtained results (Bauman & Tillman, 2004). The International Organization of Standardization (ISO) has a standard that covers the framework and methodology of LCA called ISO14040:2006. An overview of the LCA methodology can be seen in figure 2.1 and it includes goal and scope, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), interpretation, and reporting of results (International Organization of Standardization, 2006).

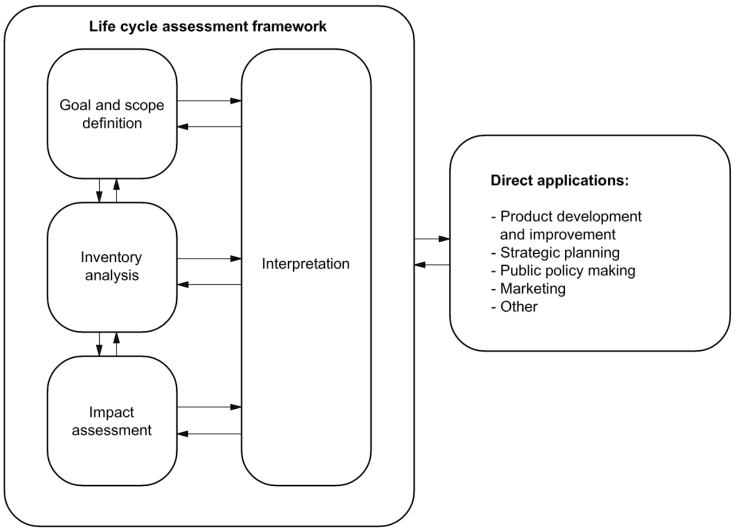

Figure 2.1: Overview of the LCA process (International Organization of Standardization, 2006)

The first step of an LCA is the goal and scope. It aims to define the reason for carrying out the study, the system boundaries and the functional unit. The second step of an LCA is the inventory analysis (LCI) where data about all the environmental inputs and outputs are collected. An important methodological choice that has to be made in the LCI, especially for a paper pulp mill with multiple outputs, is allocation method (Hermansson et al., 2020). Here it is decided how much of the product's life cycle and connective processes are accounted for and how environmental loads are divided within the system boundaries. The partitioning can be made with consideration to physical relationships such as mass, or through other types of relationships when physical ones are inappropriate, for example economic relationships (Bauman & Tillman, 2004). Additionally, combinations of physical components can be used. For example a mass-energy allocation. Depending on the choices made for allocation such as time frame and type of allocation, the results and environmental contribution of the studied product varies more or less (Hermansson et al., 2020). The third step is the life cycle impact assessment (LCIA) where the potential environmental impact is evaluated. Methods such as eco-indicator 99, CLM, and ReCiPe include some of the most commonly used categories for assessment of environmental impact. These are global warming, land use, ozone depletion, toxicity, acidification, and eutrophication (Aitor P. Acero, 2016). However, limitations of characteristics may exist due to unestablished relationships (Bauman & Tillman, 2004). In the fourth and final step of the LCA, interpretation, the results of the previous phases are evaluated in relation to the goal and scope. The described process is also iterative (Bauman & Tillman, 2004).

2.2.1 Biodiversity in LCA

Inclusion of biodiversity in LCA is a complex issue and research has been conducted in the area for over 20 years (Winter et al., 2017). Even if studies have been made, there is still lack of methods, data, and consensus about how to deal with the problem. As mentioned earlier in 2.1.3, 119 indicators related to biodiversity were found in the study by Winter et al. (2017) and it was concluded that 42 of these indicators are useful in LCA. Even though less than half of the total amount of indicators were shown to be relevant for LCA, 42 indicators are still a big number which can lead to confusion about what indicator to use. A collection of methods and indicators from Michelsen and Lindner (2015) indicate a dominance of indicators targeting ecosystem scarcity and vulnerability together with species diversity, richness and endangered species.

Choosing suitable indicators and methods to account for biodiversity in LCA is challenging and there are a number of factors that should be considered. First of all, it can be seen as important to have adequate selection criteria, for example that the indicators should be representative of an impact category in LCA (Winter et al., 2017). It could also be relevant to look at how biodiversity is addressed in conservation strategies and policies so the indicators are useful (Vrasdonk, 2020). Moreover, biodiversity can be viewed at different levels (genetic, species and ecosystem) and there are a different number of indicators and challenges for each perspective. A species perspective is challenging due to the extensive amount of data that needs to be produced, the unknown population size that originally were present in the ecosystem and how this measurement affects the bigger picture of an ecosystem, just to mention a few challenges (Michelsen & Lindner, 2015). Measurements on an ecosystem level also come with challenges. One challenge being the same as for species diversity according to Michelsen and Lindner (2015); how to refer to the natural state and how to account for the often occurring non-linear relationships. The choice between these two perspectives also raises the question about the measurement of the relative or functional diversity where species diversity is the first one och ecosystem the latter. The functionality of an ecosystem might not be as affected if other species in the ecosystem can cover up for the lost ones and it is difficult to exactly predict how an ecosystem is affected by biodiversity loss. It can be seen as preferable though to act with precaution since the mechanisms of ecosystems and biodiversity are not entirely proven (Michelsen & Lindner, 2015). There are additionally multiple factors contributing to biodiversity loss and it is desirable to include as many as possible. However, it is difficult to know to what extent different actions are affecting biodiversity loss (Vrasdonk, 2020).

An additional challenge for inclusion of biodiversity in LCA is the choice of reference state. It is often referred to the natural state of the ecosystem before human intervention and applied to for example species conservation, harvest rate and land use (Vrasdonk et al., 2019). Lindner et. al, (2021) point out that landscapes such as heaths and meadows can be man made and still have a high level of biodiversity, even if the current state is not the natural one. Vradsdonk (2019) further state that the reference state do not have to be in the past but rather refer to a future goal of preservation. This would allow a more comprehensible approach to societal targets.

Land use and land-use change are the main drivers of biodiversity loss and addressing land use impacts on biodiversity in LCA are therefore of great importance. When assessing land use impacts on biodiversity, two classes of land use is often used: *occupation* and *transformation*. Land occupation refers to a land area that is used for a specific human-controlled purpose. Land transformation refers to an area of land that is significantly changed to serve a new purpose, for example transforming forest into arable land (Milà i Canals et al., 2007).

2.2.1.1 Biodiversity on a species level

Although substantial effort has been made to develop a specific impact indicator to assess biodiversity in LCA, no definite consensus has been reached. For more information about what indicators and methods that are available for inclusion of biodivisity in LCA see the scientific review by Winter et al., (2017). One method recommended by the United Nations Environment Programme (UNEP) and The Society of Environmental Toxicology and Chemistry (SETAC) which consists of thousands of experts in LCA, chemistry, and toxicology. UNEP and SETAC have together developed a global guidance for Life Cycle Impact Assessment indicators. In this guide, UNEP/SETAC Life Cycle Initiative presents the current guidelines on how to incorporate biodiversity in LCA. After a comprehensive analysis of existing models, workshops, and expert opinions on the matter, one appropriate indicator was chosen (Frischknecht & Jolliet, 2016). The selected indicator was developed by Chaudhary et al. (2015) and is called *biodiversity damage (BD)* and it uses a model called *Countryside SAR Model*. The indicator shows the effect of land occupation on regional species loss. It represents the loss of species that would have been living on the specific affected land area, the global threat level for the species, and also the relative abundance of the species in the ecoregion. An ecoregion is an area of land or water where similar natural communities, species, and conditions exist (WWF, 2012). Five taxonomic groups are covered in the BD indicator: amphibians, birds, mammals, reptiles, and vascular plants. Six land use types are also covered in the indicator: intensive forestry, extensive forestry, annual crops, permanent crops, pasture, and urban land. In these categories, there are three management types each. See table 2.1 for a description of the different management types related to forestry.

Table 2.1: Presentation of land use types for forestry with corresponding management types for the model of biodiversity damage in PDF/functional unit (Chaudhary et al., 2015).

Land use	Management type	Description
Managed (logged) forest	Minimal use	Forests managed with minimal use techniques designed to minimize impacts on biodiversity
	Light use	Forests where only selected commercially valuable trees are harvested at a time such that the disturbance is not enough to markedly change the nature of ecosystem.
	Intensive use	Forests with extractive use, with either even-aged stands and clear-cut patches. The disturbance is severe enough to change the nature of the ecosystem.
Plantation forest	Minimal use	Extensively managed or mixed timber plantations in which native understorey and/or other native tree species are tolerated, which are not treated with pesticide or fertiliser, and which have not been recently (<20 years) clear-felled.
	Light use	Monoculture timber plantations of mixed age with no recent (<20 years) clear-felling.
	Intensive use	Monoculture timber plantations with similarly aged trees or timber plantations with extensive recent (<20 years) clear-felling.

As can be seen in equation 2.1, the biodiversity damage is calculated by using the characterization factor [PDF/m^2] as either the country's or ecoregion's average land occupation, or transformation, and dividing it by the average yield in functional unit/m^2. In equation 2.1 g is species group (mammals, birds, amphibians, reptiles, and plants), i is land use type and c is management type. There has been a lack of consensus regarding which CFs should be used (Chaudhary & Brooks, 2018), but UNEP/SETAC Life Cycle Initiative recommends using the CFs calculated by Chaudhary et al. (2015) (Frischknecht & Jolliet, 2016).

$$BD_{global,g} = \frac{CF_{global,g,i,c}}{Y_{i,c}} \tag{2.1}$$

2.2.1.2 Biodiversity on an ecosystem level

One method that can be used on an ecosystem level is developed by Lindner et al. (2021). For more information about other methods we refer to the scientific review made by Winter et al., (2017). This method is based on previous knowledge about land use impact where the biodiversity quality is altered due to occupation or transformation for a specific area and time which then is compared with a reference state. The final biodiversity impact (BI) is calculated according to equation 2.2. A lower value indicates a low impact and a higher value indicates high biodiversity impact.

$$BI = EF * (1 - BP) \tag{2.2}$$

In the equation is EF the ecoregion factor that includes the area of the ecoregion combined with the "species richness, endemic species richness, and conservation status" (Lindner et al., 2021). BP is the biodiversity potential which is given by contribution from experts' opinions. Expert's in biodiversity and biology are consulted to both select relevant parameters for biodiversity potential and to explain the contribution function (see equation 2.3) for the selected parameters. According to Lindner et al. (2021), the parameters should preferable both be descriptive and of management character. The contribution function should with help from the experts be altered to fit the parameter's impact on biodiversity potential.

$$y_i(x_i) = e^{-0.5(x_i-k)/l)^r} \tag{2.3}$$

By changing the constants k, l and r, the appearance of the contribution function is changed and the goal is to receive a look that resembles the indicator's (x_i) contribution to biodiversity (y_i), according to the expert's qualitative description. The contribution has a value between 0 and 1. All the contribution functions are then weighted and combined in equation 2.4

$$BP = 1/n * (y_1(x_1) + y_2(x_2) + y_3(x_3)... + y_n(x_n)) \tag{2.4}$$

to receive the biodiversity potential function, BP, for the studied ecoregion (Lindner et al., 2021).

3
Case description

3.1 Methanol

Methanol, CH_3OH, can be used and produced in many different ways. It can be used to synthesize other chemical compounds, most importantly formaldehyde, plastics, paint, and fuel. Historically, methanol has been produced industrially from coal but is nowadays mostly produced from natural gas. (Pirola et al., 2018).

3.1.1 Production of biomethanol at Södra

In 2020, Södra started to produce commercial biomethanol by taking advantage of one of the residual products from the pulp mill. The production facility located in Mönsterås in the south of Sweden is mainly producing paper pulp from wood. Biomethanol was previously used to produce heat and energy in the factory, but can now be purified and sold (Södra, n.d-b).

Biomethanol from Södra is produced from renewable forest resources. An overview of the production process of biomethanol at the mill in Mönsterås can be seen in figure 3.1. Since biomethanol is a by-product, the production is dependent on the pulp production, which is the main product of the production facility. For this pulp production, Södra uses a sulphate process, also called kraft pulping. In this process is wood dissolved by chemicals and cellulose is extracted from the wood by dissolving the lignin that binds it together. The chemicals are reused and can be fed into the process again (Södra, n.d-b).

The first step in the kraft pulping process at Södra is cooking of wood chips at high pressure with a solution of chemicals and water called "white liquor". Chemicals such as sodium sulfide and sodium hydroxide are used to separate the components in the wood and break down the lignin to create the pulp. A condensate, black liquor, is created from the coocking process and biomethanol is one of its components. The pulp is then taken to pulp washers to separate the product from the black liquor. The washed pulp is then taken through a bleaching process that uses chemicals such as oxygen and hydrogen peroxide. After bleaching, the pulp is dried and it is then cut and packed for transportation (Södra, n.d.). After separation of the condensate black liquor from the pulp, it goes through a purification and evaporation plant that includes a chemical recovery process. Raw biomethanol is one of the created products which after the purification process is transformed into biomethanol with a quality that can be used for commercial purposes

(Södra, n.d-c). The production of biomethanol is dependent on the production process of the pulp. Approximately 10kg of biomethanol can be produced for each ton of pulp and around 5250 tons of biomethanol can optimally be produced yearly according to Södra (Södra, n.d-c). During 2021, the production of biomethanol was 3300 ton (Södra, 2022), which was due to planned production stops and optimization of the production process.

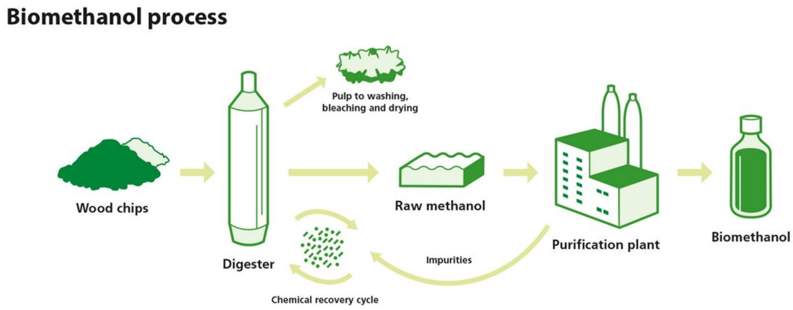

Figure 3.1: Simplified overview of the production process for biomethanol at the pulp production mill in Mönsterås (Södra, n.d-b)

3.1.2 Production of fossil based methanol

To put Södra's production of biomethanol in perspective, this paragraph presents an overview of how fossil methanol can be produced from fossil resources which is the most common way of methanol production.

Most of the produced methanol is made from fossil resources, including coal and natural gas, with the latter being the most common way of production as mentioned earlier (Pirola et al., 2018). Natural gas is a fossil resource that has been formed during millions of years beneath the earth's surface and methane is the biggest component of it. The gas is produced by drilling deep holes into natural gas deposits (EIA, 2021). Methanol production from natural gas is based on three steps. The first one is production of synthetis gas, which is a mixture of hydrogen, carbon monoxide and carbon dioxide. The second step involves converting the synthetis gas into methanol, which is performed by having high pressure and high temperature. See equation 3.1 and 3.2 for the chemical reactions involved in the second step. The last and third step is distillation of the methanol to purify it (Pirola et al., 2018).

$$CO + 2H_2 <=> CH_3OH \tag{3.1}$$

$$CO_2 + 3H_2 <=> CH_3OH + H_2O \tag{3.2}$$

3.2 Forestry and biodiversity measurements at Södra

This report does not consider the forestry activities at Södra other than using data to calculate the environmental impact of biomethanol production. However, the following sections will give brief information about it to put the production of biomethanol into perspective of forestry. Biodiversity measurements at Södra are mainly based on semi-structured interviews with the ecologist Klara Joelsson and complete interviews can be found in appendix A.

3.2.1 Description of forestry at Södra

The total area of forest that Södra's members own is 2.7 million hectares and in 2021 the harvesting rate was 6,8 m^3fo per hectare (Södra, 2022). Södra consists of 52,000 forest owners (Södra, 2022) and the majority have a plan of how to manage the area of forest. It includes descriptions of the condition of the forest and specific areas of it, natural values in the forest, goals for the forest and recommendations of forestry management (Södra, n.d-a). This action plan can be made in dialogue with or without Södra. Södra is annually performing several forestry activities related to managing the forest, if the forest owner wish so. More specifically the forestry activities include soil preparation, brushing and cleaning of trees, nutrition return, planting, thinning, rejuvenation felling, logging residue removal, chipping of logging residue (branches, etc.), ditching, and protective ditching. These activities are mostly performed by machinery or by hand. (Södra, 2020). The majority of Södra's forest owners are certified according to either FSC or PEFC which set a standard on how the forest should be managed (Södra, 2020). Södra is also obligated to follow the environmental act that regulate how forests should be managed. It is for example regulated by law when to perform rejuvenation felling and harvesting (Joelsson, 2022-03-24), (Skogsstyrelsen, 2020).

3.2.2 Biodiversity measurements at Södra

Biodiversity is a topic that Södra is considering in their use and management of the forest. They are according to Swedish law, the environmental act (Skogsstyrelsen, 2020) and the environmental code (of Sweden, 2015), obligated to consider biodiversity and for example certain species that are red listed (Sveriges-Riksdag, 2007), (Joelsson, 2022-03-24). Certifications that is a part of Södra's forestry, PEFC and FSC, (Södra, 2020) also lists overall actions to take with regard to biodiversity (Program for the Endorsement of Forest Certification, 2017), (Forrest Stewardship Council, 2020). Included in the Swedish PEFC certification is for example to have sustainable and responsible forestry, plan for a long-term use of the forest, have a plan for how to use and manage the forest and taking areas with high natural values into consideration. Biodiversity is mentioned in a few areas, for example, in relation to keeping a share of dead wood, areas with high natural values that should be regarded, protecting soil and water and favour deciduous trees (Program for the Endorsement of Forest Certification, 2017). Swedish FSC claims that sustainable forestry should maintain biodiversity and ecosystem services and that profitability should not compromise resources or ecosystems. They are also mentioning the assessment of key biotopes and vulnerable species and managing the forest in a way that decreases the loss of biodiversity (Forrest Stewardship Council, 2020).

Södra is mainly interested in the ecosystem perspective of biodiversity. Keeping records of specific species is not made other than using species as proxy to estimate the biodiversity. The species perspective is thought to be a complex matter since it is expensive and time consuming to keep record of every single specie and it is not entirely established which species to measure for a good representation of biodiversity, according to the ecologist Klara Joelsson at Södra (2022). Their data source for species is mainly the Swedish University of Agricultural Sciences, SLU. It is however in her belief that there will be a greater focus on species in the future and that it is necessary for Södra and the forestry industry to become more detailed in their work and collect more data on the matter. Södra does not provide their own data for any type of indicator in their work with biodiversity. Neither for a genetic, species or ecosystem perspective. They rather performs a number of actions to create prerequisites for biodiversity on an ecosystem perspective. Södra considers biodiversity by taking actions that are to minimize the negative impact on biodiversity. Protecting a minimum 5% of the land on each forest property owned by Södra's members, leaving branches and dead wood when thinning out are examples of this. Another measurement that Joelsson mentions as important is what type of tree species that is planted since it sets the foundations for the forest. It is important to evaluate the soil and environment to know which types of trees that will thrive best. Not only will this, according to Södra, give better prerequisites for biodiversity, but will also give a higher yield of wood (Taylor et al., 2020) and bind more carbon (Vesterdal et al., 2013) (Södra, 2020). It is also crucial to have a mix of tree species (EEA, 2016), a combination of conifer and deciduous trees, but planting of invasive species is strictly regulated. The most relevant and interesting indicators according to Joelsson are thus preventive measurements, indicators in a bigger perspective and how Södra's actions directly impact the biodiversity in their forests, and they are also keen on developing their own indicators for future measurements and assessment of biodiversity.

4
Method

An attributional life cycle assessment was conducted to assess the environmental impact of the production of biomethanol. Incorporation of biodiversity in the LCA was performed using one method that covers biodiversity on a species level and one considering biodiversity on an ecosystem level.

4.1 Life cycle assessment

This section describes how the LCA in this project was conducted of which the majority was made in the software openLCA. Including goal and scope, life cycle inventory analysis, and life cycle impact assessment.

4.1.1 Goal and scope

The goal of the LCA study was, as mentioned in section 1.1, to establish the environmental impact of the biomethanol produced by Södra Cell Mönsterås and to including biodiversity as an impact category. The performed LCA was of the type attributional and was intended to be used by Södra to identify hotspots in their production processes, get an understanding of the environmental impact of their biomethanol and also to identify the possibilities of addressing their impact on biodiversity in the future.

4.1.1.1 Functional unit

The functional unit was 1kg produced biomethanol.

4.1.1.2 System boundaries and allocation

Some boundaries that previously were described in section 1.2 were applied to the LCA as well. The geographical boundaries for forestry was restricted to Sweden and only the processes for pulp and biomethanol production at Södra Cell Mönsterås were considered. The scope for the LCA was set to cradle to gate. The environmental impact of the use phase of biomethanol was thus not addressed. The seedlings were not included in the system. After consultation with Södra it was decided to exclude those since they have no essential impact according to previous assessments made by Södra.

The processes included in the foreground system were the pulp mill, the biomethanol purification, forestry activities, and transportation. Since biomethanol is a by-product, the whole paper pulp production was therefore included in the LCA. The internal electricity production, the recycling of chemicals, and the water purification of the wastewater from the mill were not included in the modeling. This since the pulp mill was seen as a black box and only inputs and outputs were considered. Included in the background system was production and transportation of chemicals and fuels and production of purchased electricity.

The used allocation method was economic allocation.

4.1.1.3 Main data sources

The software used for the LCA was openLCA version 1.11.0 with the database ecoinvent version 3.8. The data that was received from ecoinvent, mostly for the background system, was modelled using market activity with European averages and global averages. Apart from using data from ecoinvent, internal data from Södra was gathered in terms of both reports regarding resources used in the different production steps and informal interviews with employees at Södra.

4.1.1.4 Target audience

Stakeholders that can find the results of this project interesting is Södra, its members and forest owners, researchers in the field of both biodiversity and LCA, other companies producing products from the forest, policy makers in the field of forestry and other individuals that might be interested.

4.1.2 Life cycle inventory analysis

The life cycle inventory analysis (LCIA) was divided into four separate steps; forestry activities, transportation, pulp production and biomethanol purification. Data used in the life cycle assessment were mainly provided by Södra. Some of the data used in the LCA is confidential and can therefore not be presented in this report. Figure 4.1 represents an overview of the production process including all necessary steps from plantation of new trees to the finished product as well as the main inputs and outputs. The forestry activities are included in the purple box and the processes in the pulp mill can be seen in the orange box. The purified biomethanol that is the functional unit in this report is indicated in pink.

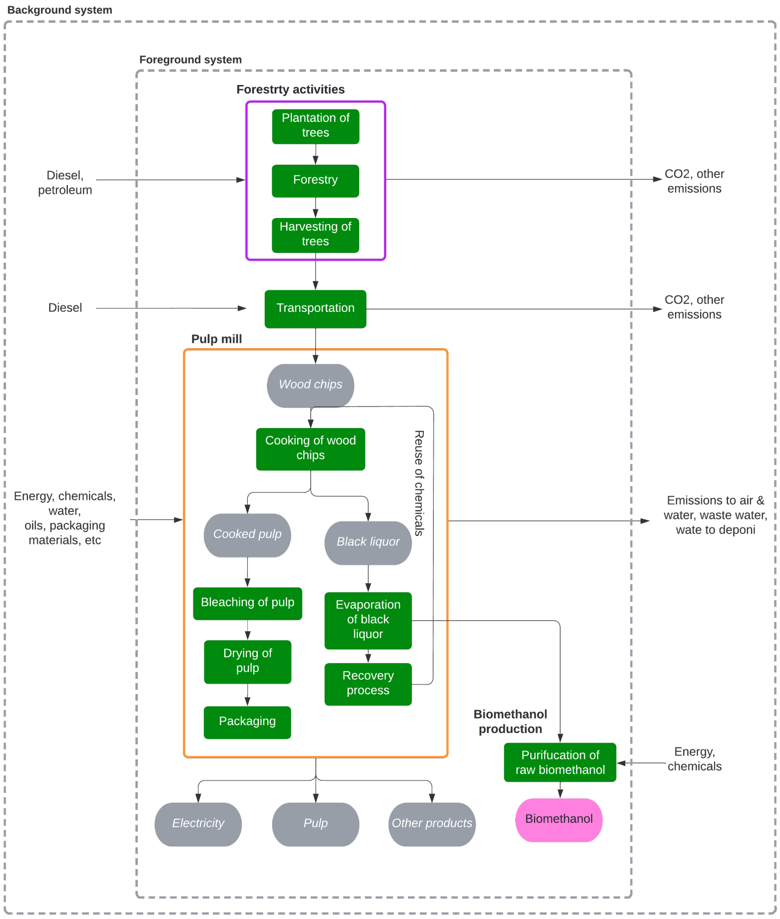

Figure 4.1: Constructed flow chart of the production process included in the LCA of biomethanol from cradle to gate.

4.1.2.1 Forestry activities

The first step in the life cycle inventory analysis was forestry activities and included all necessary steps in Södra's forestry. These are soil preparation, clearing of trees, nutrition return, planting, brushing and cleaning of trees, thinning, rejuvenation felling, logging residue removal, chipping of logging residue (branches, etc.), ditching, and protective ditching. To perform these forestry activities, machinery that uses diesel and petroleum as fuel is needed. The data for the fuel used for this step in the process was provided by Södra. The harvested trees are grown in the southern part of Sweden where Södra has its main area of forest production. Data used for this step was the total amount of diesel and petroleum used during the year 2021. In table 4.1 the inputs and their corresponding amount for the step of forestry activities are presented.

4.1.2.2 Transportation of forest raw material

The second process in the system is transportation of the harvested forest raw material from the forest to the production facility in Mönsterås. Three types of transportation of

Table 4.1: Resources used in the first production step *forestry activities* for 1kg of produced biomethanol

Flow	**Amount**	**Unit (/kg biomethanol)**
Diesel	2.07585E-05	m^3
Petroleum	4.015E-07	m^3
Occupation	0.055857266	ha*year

the forest raw material to the mill are used; timber truck, wood chips truck and by boat. The transportation by timber truck and wood chips truck was assumed to be of the same vehicle class, EURO 5, and was grouped together in the model. Transportation of forest raw material by boat was modeled as inland waterways with the boat type barge. An average distance for all transportation ways for 1 m^3sub was used. Conifer was mostly transported by truck and deciduous trees by boat. Se table 4.2 for more details. Notable is also that even if the wood raw material was assumed to come from Swedish forests only, the used transportation distances include all type of transport. Even import from the Baltic states and Poland. The data for this second production step was provided by Södra and uses average distances for the year 2021.

Table 4.2: Resources used in the second production step *transportation of forest raw material* for 1kg of produced biomethanol

Flow	**Amount**	**Unit (/kg biomethanol)**
Transportation by timber and wood chips truck for conifer trees	1.28382E-07	km/m^3sub
Transportation by timber and wood chips truck for deciduous trees	1.27291E-07	km/m^3sub
Transportation by boat for conifer trees	1.44263E-08	km/m^3sub
Transportation by boat for deciduous trees	1.68024E-07	km/m^3sub

4.1.2.3 Pulp production

The pulp production was modeled as a "black box", where inputs and outputs are accounted for without knowledge of its internal processes and workings. Therefore, only flows that could be considered as an input or an output were included in the model and thus were the internal electricity production, production of fuels that were used internally and recycling of chemicals excluded.

Data for this third production step were provided by Södra and were from the year 2021. In addition to the main input of harvested forest raw material , pulp production requires several different chemicals, oils and energy sources. Included in the model was also the transportation of the used chemicals to the pulp production facility in Mönsterås. This transportation was calculated according to data provided by Södra and included an average distance the chemicals were transported by truck, train and boat. Inputs used in small amounts were considered to not have a significant impact on the production process and were therefore not included in the model. Instead, the principal focus were put on the main inputs and outputs that were used in large amounts and therefore considered to have a large impact on the results of the LCA. Some chemicals and solutions that could not be found in the database ecoinvent version 3.8 were also excluded. These were chemicals used in the pulping process for different purposes, of confidentiality reason these may not be presented here. One specific chemical that cannot be named due to confidentiality, were assumed to be similar and have similar production processes to another already excising chemical in ecoinvent and were thus included in the model. All chemicals that are transported to the production facility, even the ones that could not be found in ecoinvent, were included in the transportation of chemicals.

The considered outputs from the mill were emissions from the production, waste, waste water and products such as pulp, biomethanol, electricity, lime mud, raw tall oil and turpentine. All the included inputs and outputs can be seen in table 4.3. Note that due to confidentiality reasons, some inputs/outputs and specific amounts cannot be presented.

Table 4.3: Inputs and outputs in the third production step *pulp production* for 1kg of produced biomethanol. Due to confidentiality reasons, not all flows can be presented. The flows are calculated using economic allocation.

Flow	**Amount**	**Unit (/kg biomethanol)**
Inputs		
Conifer wood	2.708795649	kg
Deciduous wood	0.467230115	kg
Total chemicals	0.19	kg
Bale wire	0.00231791	kg
Water	0.026372292	m^3
Bought electricity	0.0172061	kWh
Other inputs	confidential	
Outputs		
Waste		
Waste to recycling	0.029111839	kg
Toxic waste	0.000690909	kg
Emissions to air		
Sulfur dioxide	0.000367811	kg
Nitrogen oxides (NOX)	0.001117737	kg
Nitrous oxide (N_2O)	3.50354E-05	kg
Methane	4.23091E-05	kg
Non-methane volatile organic compounds (NMVOC)	0.001179322	kg
Carbon dioxide, fossil	0.01409658	kg
Carbon dioxide, biogenic	2.106975673	kg
Emissions to water		
Waste water	0.0263068	m3
Total organic carbon (TOC)	0.002680387	kg
Biochemical oxygen demand (BOD5)	0.000152143	kg
Suspended solids	0.000264887	kg
Total nitrogen	6.31606E-05	kg
Total phosphorus	3.63689E-06	kg
Products		
Raw biomethanol	1	kg
Other products		

4.1.2.4 Biomethanol purification

During the pulp production, raw biomethanol is produced as a by-product which is then purified to biomethanol. To refine this raw biomethanol and remove pollutants, the product is taken through a purification process at the same production area as the pulp mill in Mönsterås. This facility was in similarity with the previous production step modeled as a black box. Raw biomethanol, chemicals and electricity were the main inputs in this step and the output was purified biomethanol. See table 4.4 for a detailed description of the flows. Data was provided by Södra and were from the year 2021.

Table 4.4: Resources used in the fourth production step *biomethanol purification* for 1 kg of biomethanol

Flow	**Amount**	**Unit (/kg biomethanol)**
Input		
Electricity	confidential	MWh
Other fuels and chemicals	confidential	
Water	confidential	m^3
Output		
Purified biomethanol	1	kg

4.2 Life cycle impact assessment

The chosen impact categories in the LCIA were climate change, acidification, eutrophication, ecotoxicity, land use, and biodiversity. See table 4.5 for an overview of the chosen impact categories. The LCIA was made in openLCA with ReCiPe 2016 midpoint (H) as method for climate change, acidification, eutrophication, eco-toxicity and land use. The (H) in the ReCiPe method stands for *Hierarchist* and represents one of three cultural perspective of which leads to a set of choices in regard to time, future technology, etc. This chosen (H) perspective is considered the default model and is often encountered in scientific models and with a time horizon of 100 years (PRé, n.d.). In order to receive GWP_{bio} under the category climate change was IPCC 2013 GWP 100a (inkl. CO_2 uptake) used. For biodiversity was the methods by (Chaudhary et al., 2015) and (Lindner et al., 2021) used as previously described in section 4.4.

Table 4.5: Selected impact categories for the impact assessment with corresponding LCIA method and contributing flows

Impact category	**LCIA method**	**Contributing flows**
Climate Change	ReCiPe 2016 midpoint (H), IPCC 2013 GWP 100a	CO_2, CH4, NOx
Terrestrial acidification	ReCiPe 2016 midpoint (H)	SO2, NOx, SO_3
Freshwater eutrophication	ReCiPe 2016 midpoint (H)	P
Terrestrial ecotoxicity	ReCiPe 2016 midpoint (H)	C, Zn, Ni, Sb, Pb
Land use	ReCiPe 2016 midpoint (H)	Area, time (Occupation)
Biodiversity	(Chaudhary et al., 2015), (Lindner et al., 2021)	Proxy species, proxy measurements for biodiversity

4.3 Comparison with fossil methanol

It was of interest to compare the obtained impact assessment results for the biomethanol with methanols produced from fossil resources. Therefore, a literature review was made to find already performed LCAs on fossil methanols. The main requirement was to find an LCA with the scope of cradle-to-gate and simular system boundaries. It was also preferred to find an LCA where the methanol was produced from natural gas.

4.4 Biodiversity

The data used for inclusion of biodiversity in LCA was mainly collected from literature and informal interviews with the sustainability strategist Eva Gustafsson at Södra. Informal interviews with the ecologist Klara Joelsson at Södra were also held to gather information about Södra's work with biodiversity. Substantial data was also gathered from The Swedish National Forest Inventory (SLU, 2021).

After a literature review regarding inclusion of biodiversity, the most suitable methods were chosen to be included in the project. The chosen methods were based on several criteria. Including that the methods should be able to use the data that was available in the project, that they included biodiversity in LCA and that they are well known and recommended in the scientific community. As mentioned in section 2.2.1.1, the method by Chaudhary et al., 2015 is recommended to be used in an LCA by the UNEP/SETAC Life Cycle Initiative and this method was also used in this project. To evaluate biodiversity on an ecosystem level, the method by Lindner et al., 2021 was chosen and applied.

4.4.1 Biodiversity on a species level

The first step of using the method by Chaudhary et al., 2015 was to identify which land-use types that were relevant for the project. The chosen land-use types were managed forests and plantation forests. It was also chosen to include the different categories of minimal, light and intense use in these land-use types. These choices were based on the fact that the method would be evaluated, to see if the difference in forestry management would be reflected in the results. Moreover, the relevant ecoregion was identified as "sarmatic mixed forests" with the ecoregion code PA0436 (Olwero, 2013). From this ecoregion, characterization factors [PDF/m^2] were gathered from the supplementary information in the article by Chaudhary and Brooks, 2018 that includes the newest available CFs. These CFs are presented in table 4.6. To calculate the average yield in $functional$ $unit/m^2$, data for the year 2021 was provided by Södra of the total amount of produced biomethanol, annual harvest rate, and the total volume of incoming forest raw material to the production facility in Mönsterås. The calculated value for the average yield was 0.0005689 kg biomethanol/m^2. Due to confidentiality reasons the data used to calculate the yield cannot be presented. The calculated yield and the collected CFs, for both the identified ecoregion and country (Sweden), were then used with equation 2.1 to calculate the global potential impacts on biodiversity from land occupation. Below in equation 4.1 is an example of calculation of BD with the use of the CF from Sarmatic mixed forests for managed forest with intense use.

$$BD_{global,g} = \frac{1.52 * 10^{-14}[PDF/m^2]}{0.0005689[kg/m^2]} = 2.68 * 10^{-11}[PDF/kg] \quad (4.1)$$

Table 4.6: Characterization factors (CF) [PDF/m^2] from the aggregated proxy species for the different forest management types. Gathered from the supplementary information in the article by Chaudhary and Brooks, 2018. NaN represents a CF that is not available in the data from Chaudhary.

Ecoregion/Country	**Management type**	**CF** (Potential disappearance fraction PDF/m^2)
Sarmatic mixed forests	Managed forest: Intense use	1.52 E-14
Sarmatic mixed forests	Managed forest: Light use	NaN
Sarmatic mixed forests	Managed forest: Minimal use	NaN
Sarmatic mixed forests	Plantation forest: Intense use	1.55 E-14
Sarmatic mixed forests	Plantation forest: Lightuse	1.54 E-14
Sarmatic mixed forests	Plantation forest: Minimal use	1.54 E-14
Sweden	Managed forest: Intense use	1.21 E-14
Sweden	Managed forest: Light use	0
Sweden	Managed forest: Minimal use	0
Sweden	Plantation forest: Intense use	1.23 E-14
Sweden	Plantation forest: Lightuse	1.22 E-14
Sweden	Plantation forest: Minimal use	1.22 E-14

4.4.2 Biodiversity on an ecosystem level

The method from Lindner et al., (2021) is described in this section. A Finnish study from Myllyviita et al. (2019) that had applied the same method was used as reference. The indicators and impact functions from the Finnish study were used as a foundation when contacting the ecologist Klara Joelsson at Södra. Through a semi-structured interview, the indicators and impact functions from the Finnish study from 2019, as well as the method in general, was evaluated by Klara Joelsson. She also discussed how applicable the method was to the forests of Södra's members in the southern part of Sweden. It was decided to use the indicators called age structure, amount of dead wood and tree species diversity and it was assumed that the impact functions on biodiversity from the study by Myllyviita et al. (2019) could be straight on applied to this project. Data for the indicators were collected from The Swedish National Forest Inventory, SLU (2021) for the geographical area Götaland in Sweden that includes Södra´s forests. For age structure was a value of 100 years chosen which translated to a normalized value of 0.25. This since the scale of age structure was between 0 and 400 years. 9.1 m^3/ha was chosen for amount of dead wood in productive forests in southern Sweden which translated to a normalized value of 0.09. Lastly, the existence of the four listed species in the Finnish study in Södras forests gave the index value of 4.5 and the normalized value of 1. See table 4.7 for a complete collection of values. The data was then used as input in the impact functions (equation 4.2) which can be seen in equation 4.3 (age structure), 4.4 (amount of dead wood) and 4.5 (tree species diversity) for the three biodiversity indicators below. The results from this were then used in equation 4.6 to receive the biodiversity potential function seen in equation 4.7 below. The biodiversity impact was then calculated according to equation 4.8. and 4.9 which gave a final value of 0.14 as biodiversity impact. The value of EF was 0.212 for the ecoregion PA0436 (Lindner et al., 2019).

Table 4.7: The chosen indicators with their real values from (SLU, 2021) used in the method for inclusion of biodiversity on an ecosystem level. The normalized values (x) and the parameter values for *k*, *l* and *r* are from (Myllyviita et al., 2019).

Biodiversity indicator	**Real value (SLU, 2021)**	**Normalized value (x)**	**k**	**l**	**r**
Age structure (y_1)	100 years	0.25	0.85	0.4	6
Amount of dead wood (y_2)	9.1 m^3	0.09	0.9	0.55	6
Tree species diversity (y_3)	4.5 No.	1	0.99	0.35	4

$$\boldsymbol{y_i(x_i) = e^{-0.5(x_i-k)/l)^r}} \tag{4.2}$$

$$y_1(0.25) = e^{-0.5(0.25-0.85)/0.4)^6} = 0.00336 \tag{4.3}$$

$$y_2(0.09) = e^{-0.5(0.09-0.9)/0.55)^6} = 0.0061 \tag{4.4}$$

$$y_3(1) = e^{-0.5(1-0.99)/0.35)^4} = 0.999 \tag{4.5}$$

$$\boldsymbol{BP = 1/n * (y_1(x_1) + y_2(x_2) + y_3(x_3)... + y_n(x_n))} \tag{4.6}$$

$$BP = 1/3 * (0.00336 + 0.0061 + 0.999) = 0.336 \tag{4.7}$$

$$\boldsymbol{BI = EF * (1 - BP)} \tag{4.8}$$

$$BI = 0.212 * (1 - 0.336) = 0.14 \tag{4.9}$$

5 Results and analysis

In the following chapter, the results of the project are presented. First, the results from the performed LCA are presented in section 5.1. Included in this section from 5.1.1 to 5.1.6 is specific results from the LCA performed in the software openLCA regarding the different impact categories: climate change, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, and land use. Results from the literature review regarding comparative data for fossil methanol production are presented in 5.1.2. Lastly, results from the LCA regarding biodiversity on species and ecosystem level that were calculated with the methods by Chaudhary et al., 2015 and Lindner et al., 2021 are presented in section 5.1.7 and 5.1.8.

5.1 Life cycle impact assessment

This section presents the results from the performed LCIA with usage of Recipe 2016 Midpoint(H) for GWP_{100} and IPCC 2013 specifically for GWP_{bio}. In table 5.1 below can the values of the impact categories climate change, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxisity and land use be seen. This will be followed by separate sections for each impact category.

Table 5.1: Results of LCIA. Environmental impact per 1kg of produced biomethanol

Impact category	Value	Unit
Climate change (GWP_{100})	0.395	kg CO_2-eq
Climate change (GWP_{bio})	2.127	kg CO_2-eq
Terrestrial acidification	0.00363	kg SO_2-eq
Freshwater eutrophication	0.00012	kg P-eq
Terrestial ecotoxicity	3.377	kg 1,4 DCB
Land use	167.59	m^2*yr annual crop land

5.1.1 Climate change

The contributions to the impact category climate change (GWP_{100} [CO_2-eq]) is presented in figure 5.1. The category of pulp production is the biggest contributor. Followed by forestry activities , transportation and biomethanol purification.

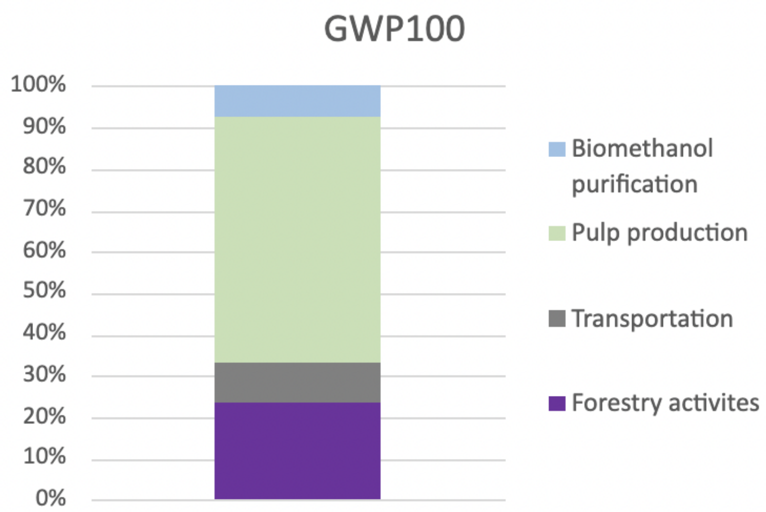

Figure 5.1: Contribution analysis on the total global warming potential divided on the four production steps of biomethanol.

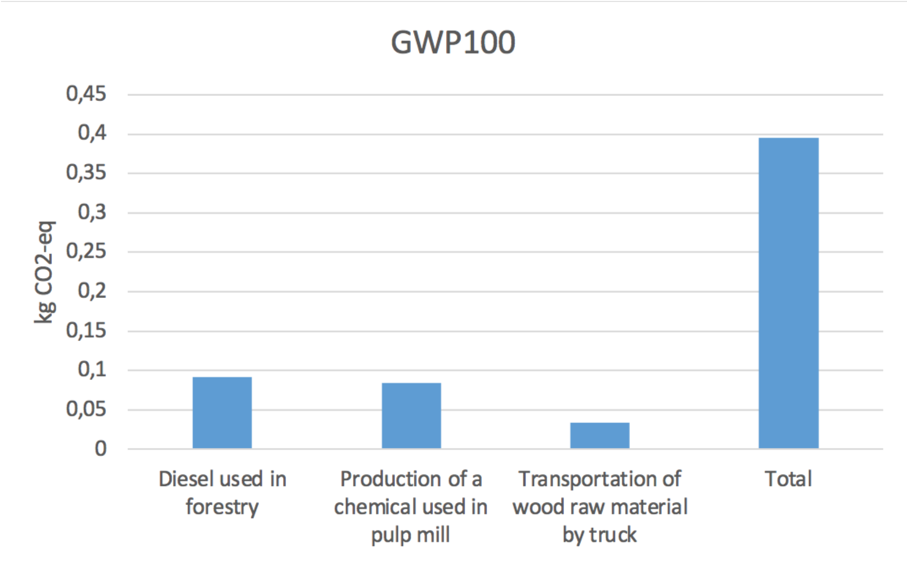

Figure 5.2: Three examples of single processes that has a high contribution to the global warming potential. The chemical presented in the figure cannot be named due to confidentiality. The total value is per 1 kg of produced biomethanol.

As described in section 4.1.2.3, the pulp production step involves several emission outputs, see table 4.3. It also involves inputs of energy sources, several different chemicals, transportation of these chemicals and other types of processes that do not take place directly at the production facility. In figure 5.2 it can be seen that production of a specific chemical that is confidential used in the pulp mill is one of the largest single contributor to GWP_{100}. Since biomethanol only is a by-product and the LCA was performed with an economic allocation, the produced biomethanol only accounts for a small fraction of the inputs/outputs related to this step. However, even though economic allocation is applied, the pulp production is the largest contributor to the GWP_{100}. Depending on the use of the biomethanol (fuel, basic chemical etc.), different allocation methods such as energy allocation could also be considered.

The second largest contributing production step is forestry activities and as can be seen in table 4.1, this step involves the use of diesel and petroleum which is fossil-based products that when used emits greenhouse gases which thus explains the high CO_2-eq impact. Figure 5.2 also shows that diesel used in forestry activities is one of the largest single processes that contributes to the GWP_{100}.

Transportation and production of biomethanol, see figure 5.1, are the production steps that have the smallest contribution to GWP_{100}. In figure 5.2 it can be seen that transportation of forest raw material by truck is one of the single processes that has a high impact.

One aspect of the GWP_{100} that also can be observed is the GWP_{bio}. It has a value of 2.127 kg CO_2-eq compared to 0.395 kg CO_2-eq for the fossil GWP_{100}. Chemically there is no difference between a CO_2 molecule released from a fossil or bio-based source, but depending of time perspective and management of the bio-based sources (The Swedish Environmental Protection Agency, n.d) it is interesting to separate the GWP:s. If the bio-based resource is being managed in a sustainable way, the biogenic carbon can be captured from the atmosphere and recirculated in the carbon cycle. Compared to the fossil-based one, which is not connected to a cycle that captures CO_2 as fast (The Swedish Environmental Protection Agency, n.d). It is therefore positive that the GWP_{bio} is bigger than the fossil GWP_{100} since the majority of the released CO_2 emissions can be a part of the biogenic carbon cycle. It is also relevant to separate the emissions when comparing it with a fossil-based alternative since the two values then are compared within the same carbon cycle.

5.1.2 Comparative data for fossil methanol production

Presented in table 5.2 are values of GWP_{100} for four different fossil-based methanols collected from literature. The presented methanols are produced from natural gas in various areas in the world and are all cradle-to-gate. They are named as A, B, C and D.

Table 5.2: Data regarding production of fossil-based methanol collected from literature.

Source	Name	**Production process**	**Impact category**	**Value**	**Unit**
(Kajaste et al., 2018)	A	Natural gas extracted in Norway. Transportation to production facility in Sweden (648km). Norweigan and Swedish average mix of electricity used. (Cradle-to-gate)	Climate change (GWP)	0.462	kg CO_2-eq
(Kajaste et al., 2018)	B	Natural gas extracted in Algeria. Transportation to production facility in Germany. (Cradle-to-gate)	Climate change (GWP)	0.873-0.881	kg CO_2-eq
(Puig-Gamero et al., 2021)	C	Natural gas extraction in Russia. Transportation to methanol production facility in Spain. Including natural gas reforming, syngas purification and methanol synthesis. (Cradle-to-gate)	Climate change (GWP)	8.74	kg CO_2-eq
(Jingying et al., 2018)	D	Natural gas extracted in China. Including natural gas extraction, fine desulfurization, steam reforming, methanol synthesis and distillation. (Cradle-to-gate, attributional, use of CLM 2001)	Climate change (GWP)	0.915	kg CO_2-eq

The calculated GWP_{100} is 0.395 CO_2-eq per 1 kg of Södra's production of biomethanol. This result can be compared to the methanols produced with fossil resources in table 5.2. It can be concluded that the environmental impact of producing 1 kg of Södra's biomethanol, regarding the impact category climate change, is lower than all the presented comparative data for fossil methanols. Since the production of Södra's biomethanol uses renewable forest resources that absorbs carbon dioxide during its growth, as energy, this is a result that could be expected when comparing to fossil-based methanols. Methanol A is the fossil-based methanol with the lowest impact on climate change. This methanol is extracted in Norway and then transported a relatively short distance to Sweden for further refining. Both the short transport distance and the fact that Norway and Sweden often have renewable energy sources for their electricity production may explain why methanol A has the lowest GWP of the presented fossil-based methanols. However, methanol A has still 17% higher impact compared to Södra's biomethanol production. Furthermore, methanol B and D have similar GWP values, around 0.9 CO_2-eq corresponding to 130% higher GWP than the calculated value for Södra's biomethanol. One possible reason for this is that the production process is located in geographical areas that may have electricity produced from fossil resources, which results in more greenhouse gas emissions. Another reason could be that the transportation distance is long, which also results in higher environmental impact. Methanol C has a significantly higher GWP than the other fossil-based methanols and the calculated value for biomethanol. Compared to Södra's biomethanol, alternative C has a 2200% higher GWP. According to the research study, the high GWP is caused by GHG emissions, energy consumption and heat releases (Puig-Gamero et al., 2021).

To summarize, there are comparative fossil based methanols that have a significantly larger GWP than the biomethanol produced from Södra, and some fossil based ones that are more similar. However, it can be concluded that the GWP for the biomethanol produced from Södra has a lower value compared to all fossil based ones in this project. Important to have in mind is again that these are assessments made of cradle to gate and if the use phase were included the results would likely be different.

5.1.3 Terrestrial acidification

The results for terrestrial acidification [SO_2-eq] as an impact category can be seen in figure 5.3. The largest contributing production step is biomethanol purification and in figure 5.4 it can be seen that production of confidential chemicals is one of the largest single contributing processes to the impact category terrestrial acidification. Here it can also be noted that use of diesel in forestry activities has an impact. Furthermore, figure 5.3 also shows that pulp production is the second largest contributing production step. This is an expected result due to the emissions from the pulp mill that were presented in table 4.3. It should also be mentioned that a total value of 0.00363 kg SO_2-eq is viewed as relatively low compared to the other categories.

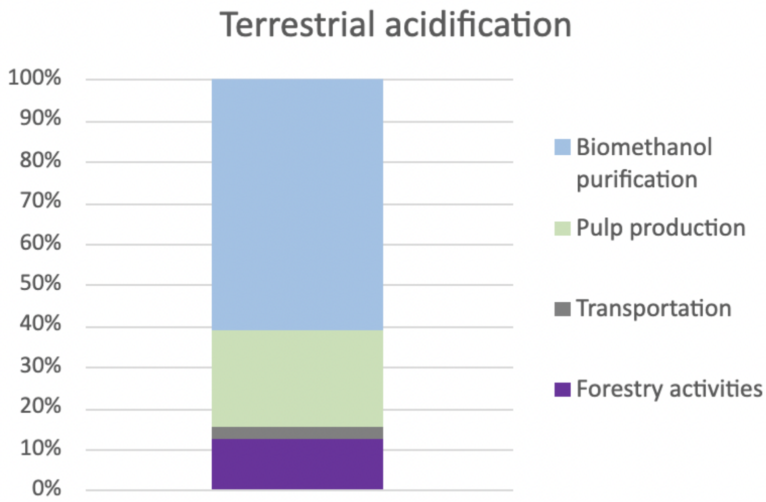

Figure 5.3: Contribution analysis of the terrestrial acidification from the four production steps for biomethanol.

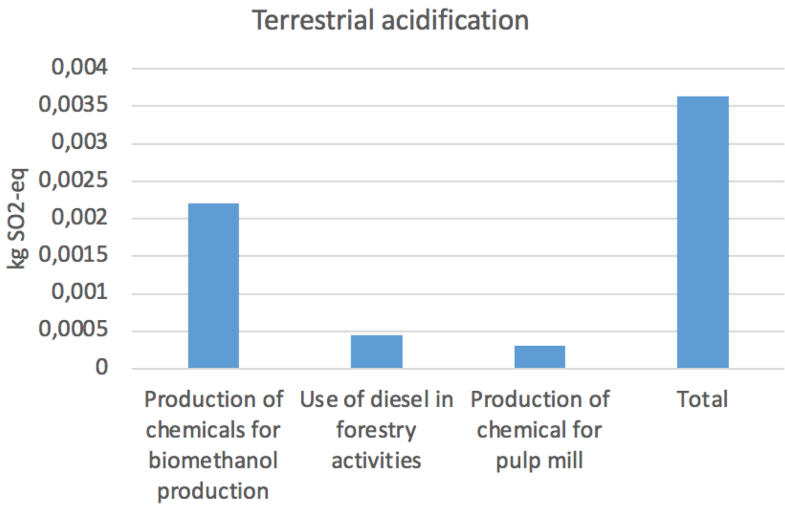

Figure 5.4: Three examples of single processes that has a high contribution to the terrestrial acidification. The chemicals presented in the figure cannot be named due to confidentiality. The total value is per 1 kg of produced biomethanol.

5.1.4 Freshwater eutrophication

Results for the impact category freshwater eutrophication [P-eq] can be seen in figure 5.5 below. The largest contributing production step is pulp production, which is a reasonable result since it is in this production step that wastewater containing nitrogen and phosphorus is an output. In figure 5.6 it can also be seen that production of two different confidential chemicals are large single contributing processes to this impact category. Furthermore, figure 5.5 also shows that forestry activities is the second largest contributing production step. As for the acidification impact result, the eutrophication impact result of 0.00012 kg P-eq can be seen as relatively low compared to the other categories.

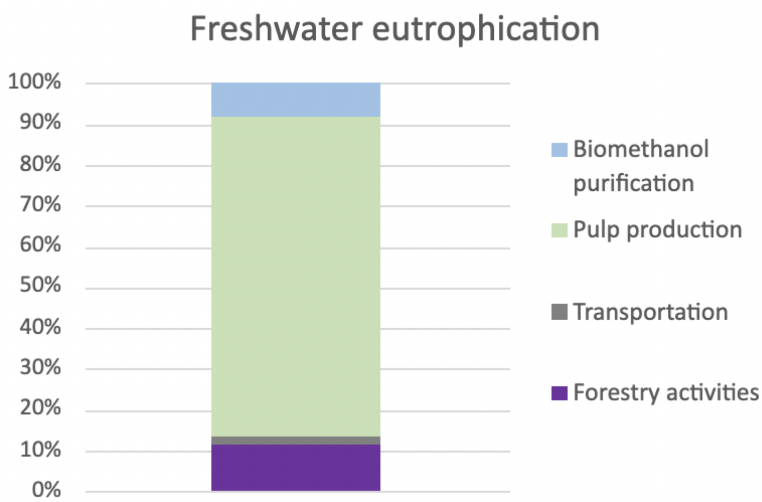

Figure 5.5: Contribution analysis of freshwater eutrophication from the four production steps for biomethanol.

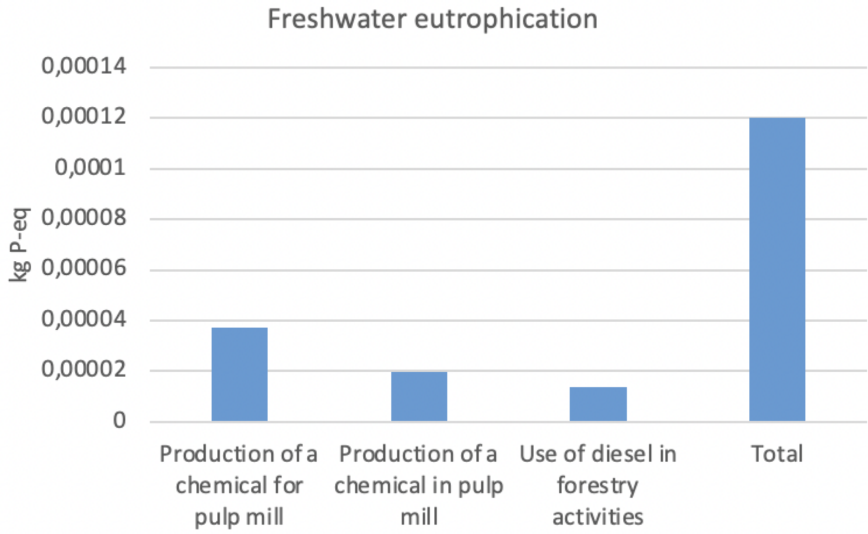

Figure 5.6: Three examples of single processes that has a high contribution to the freshwater eutrophication. The chemicals presented in the figure cannot be named due to confidentiality. The total value is per 1 kg of produced biomethanol.

5.1.5 Terrestrial ecotoxicity

Results for the impact category terrestrial ecotoxicity [1,4DCB] can be seen in figure 5.7 below. It can be seen that biomethanol purification, pulp production and transportation are the biggest contributing production steps and that they have similar contribution to the final impact. A total value of 3.377 kg 1,4 DCB is high compared to the other values obtained from the LCIA and it is suggested that the reason for this is due to the choice of flows and processes in openLCA. It could be the case that processes in the background system are prominent.

Analyzing the results of terrestrial ecotoxicity, and also the other results from the LCIA, further it can be noted that the biggest contributors to eutrophication, toxicity, and to some extent acidification, are activities performed in the background system that Södra has less direct influence on. Reoccurring processes are for example production of chemicals, which are produced by other companies that Södra can influence less. Even if these types of activities are present in the background system, they are still influencing the life cycle of the biomethanol and need to be considered. It can also give an indication on what products, services and decisions that Södra should consider in order to decrease the environmental impact of the biomethanol further. Although, it should also be considered that the processes present in the background system can be more or less valid since the system has been modeled with data from a database and therefore not represents the real system perfectly. This is the case especially for the terrestrial ecotoxicity as mentioned before, but it should be considered for acidification and eutrophication as well.

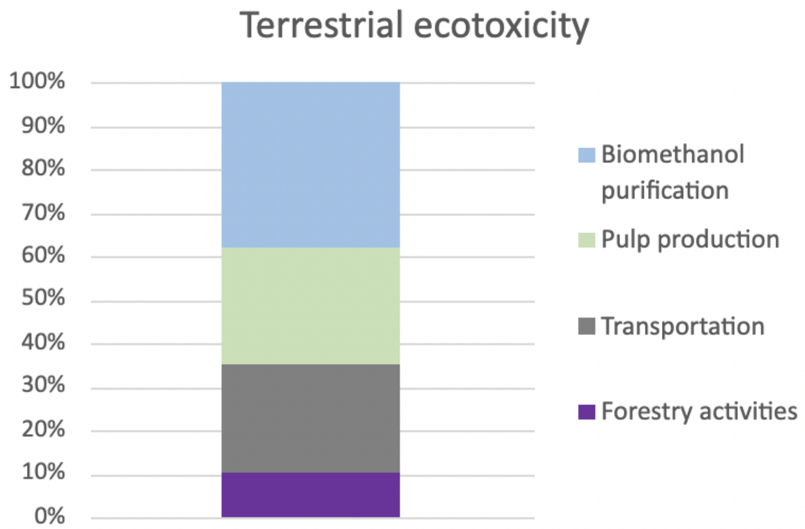

Figure 5.7: Contribution analysis of terrestial ecotoxicity from the four production steps for biomethanol.

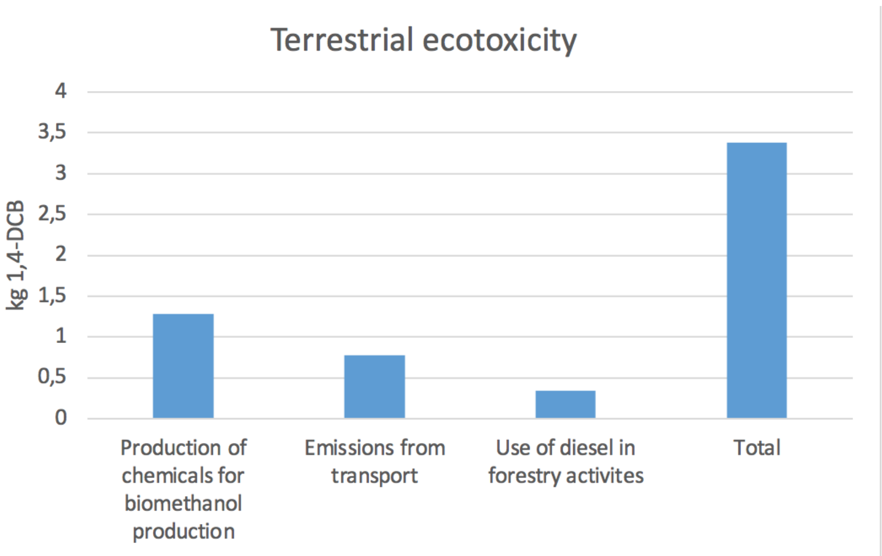

Figure 5.8: Three examples of single processes that has a high contribution to the terrestial ecotoxicity. The chemicals presented in the figure cannot be named due to confidentiality.

5.1.6 Land use

The biggest land use impact (see fig 5.9) is in the process of forestry activities. Since forestry activities is the only production step included in the delimitations that involves land use, this result was expected. Land use is one of the activities that has the highest impact on biodiversity as described in 2.1.1. It is difficult to draw conclusions about how great the biodiversity impact from this indicator is, a part from that a high value for land use is likely to have a larger impact on biodiversity.

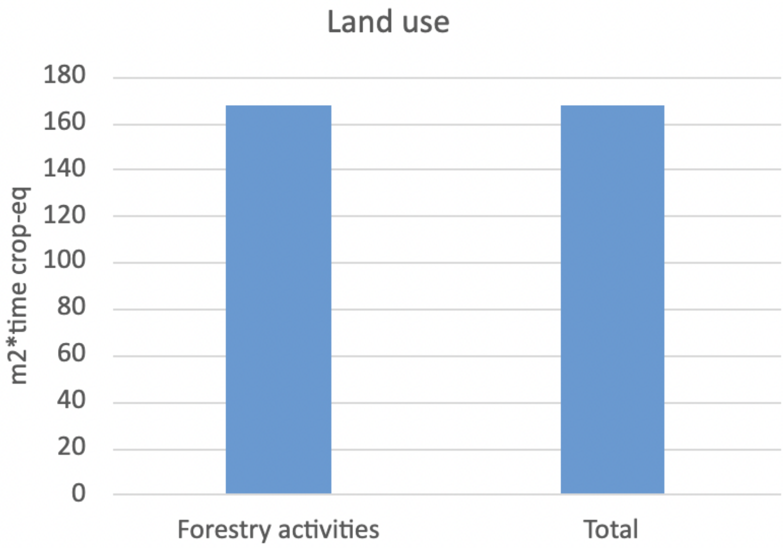

Figure 5.9: Land use for biomethanol showing how the impact is distributed

5.1.7 Biodiversity on a species level

The method from Chaudhary et al., 2015 with the biodiversity damage indicator, gave the results seen in table 5.3. There are two types of forest management with three different intensities of use presented. These are considered for both the ecoregion PA0436 and the country Sweden. Since Södra operates in forests in the southern part of Sweden it can be proposed that the ecoregion is more realistic to use since it covers the geographical area of interest in more detail. Although, it is also notable that the impact is smaller when country specific CF's are used. It is evident that even if the different management types, managed and plantation forest, are very different, the CF's and BD are not that different. Why this is the case is difficult to explain with the analysis made in this project. Even if the difference in BD is minor, the BD for plantation forest is higher. It is expected that the management type plantation forests has higher values and higher impact on biodiversity since this type of management changes the natural conditions to a greater extent compared to managed forests.

Table 5.3: Calculated biodiversity damage due to 1 kg of biomethanol sourced from different forest management types. [Unit - Biodiversity Damage [PDF/kg produced biomethanol]. NaN represents that CFs was not available in the data from Chaudhary and therefore the BD could not be calculated.

Ecoregion/Country	Management type	BD
Sarmatic mixed forests	Managed forest: Intense use	2.68E-11
Sarmatic mixed forests	Managed forest: Light use	NaN
Sarmatic mixed forests	Managed forest: Minimal use	NaN
Sarmatic mixed forests	Plantation forest: Intense use	2.73E-11
Sarmatic mixed forests	Plantation forest: Light use	2.71E-11
Sarmatic mixed forests	Plantation forest: Minimal use	2.71E-11
Sweden	Managed forest: Intense use	2.12E-11
Sweden	Managed forest: Light use	0
Sweden	Managed forest: Minimal use	0
Sweden	Plantation forest: Intense use	2.15E-11
Sweden	Plantation forest: Light use	2.15E-11
Sweden	Plantation forest: Minimal use	2.14E-11

To be able to put the calculated values on biodiversity damage for biomethanol in some perspective, figure 5.10 presents data calculated in the same way for 1 m^3 wood sourced from four different management types in India. Even though the functional unit and ecoregion for this comparative data differ from the biomethanol conditions, this gives valuable possibility to relate the calculated BD to something. However, this comparison should be considered of high uncertainty. From this data it can be seen that the BD ranges from 75 E-10 (plantation) to 1 E-10 (minimal use managed forests) for the Indian example. With the differences between the indian example and this project taken in consideration, it can be seen that the values obtained of BD for production of 1 kg biomethanol are of similar magnitude and hence what can be expected. It can be noted in fig 5.10 that the results for BD has a larger variation for the indian example compared to the results in table 5.3. Since the yield is constant in the calculation of BD, it is likely that the CFs for the geographical areas impacts these results. Perhaps the ecoregion and the corresponding CFs used in the indian example varies to a greater extent compared to this project.

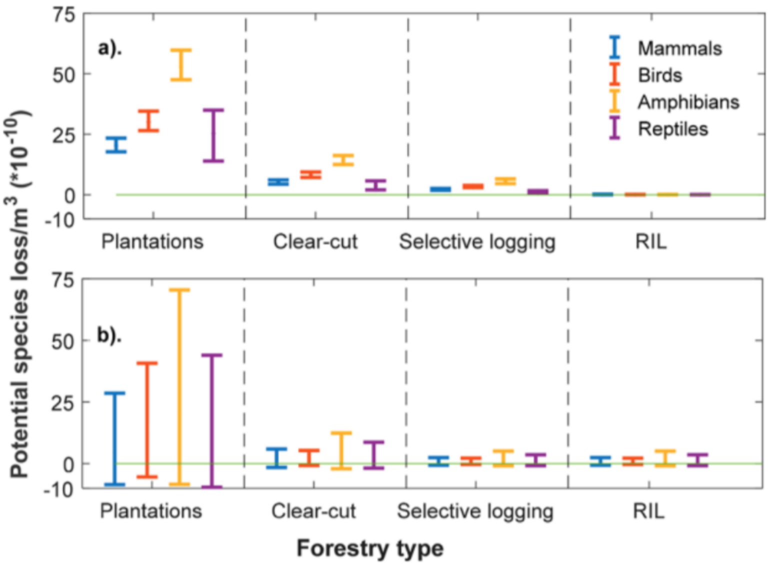

Figure 5.10: Comparative data for biodiversity assessment on a species level from the method by (Chaudhary & Brooks, 2018). The values are calculated for 1 m^3 wood sourced from four different management types in India. The management types were intense use plantation (plantations), intense use managed forests (clear-cut), light use managed forest (selective logging) and minimal use managed forests (RIL). Example **a)** is calculated with CFs from (Chaudhary & Brooks, 2018) and is the example of relevance. **b)** uses an older set of CFs from (Chaudhary et al., 2015) that is of lower relevance to this project.

5.1.8 Biodiversity on an ecosystem level

The results regarding biodiversity impacts on an ecosystem level from using the method by Lindner et al. (2021) is presented in table 5.4. A low value indicates a low impact on biodiversity and a high value indicates high impact. The BP function is constructed in a way that it ranges between 0 and 1. The BP is dependent on the value for the ecoregion factor (EF) which indicates that the highest value that BI can take is 0.212, if BP reaches 0 and EF is constant at 0.212 (BI=EF(1-BP)). The calculated BI for biomethanol of 0.141 and BP of 0.336 can therefore be seen as an impact on biodiversity and that there is room for improvement to decrease the biodiversity impact. It must however be noted that this value is not specifically calculated for just production of biomethanol. Instead since the method uses indicators for biodiversity that applies to the geographical area that Södra has forests, it applies to Södra's forestry in general. Thus it can be concluded that the forestry at Södra as a whole, that includes the forestry for the forest raw material used to produce biomethanol, has a biodiversity impact of 0.14 according to this method.

In table 5.5, comparative data for biodiversity impact on forestry in Finland is presented. This study was used as a reference in this project and uses the same biodiversity indicators (age structure, amount of dead wood and tree species diversity). Depending on method choices, the comparative data varies between 0.014-0.169 in the Finnish study (Myllyviita et al., 2019). The calculated value for biomethanol is around 0.14 and has a similar biodiversity impact to the Finnish study. Since the geographical area of southern Finland and southern Sweden is relatively close and similar, this result is reasonable.

Table 5.4: Results of biodiversity on an ecosystem level for production of biomethanol

Biodiversity potential (calculated with equation 2.4)	0.336
Biodiversity impact (calculated with equation 2.2)	0.141

Table 5.5: Comparative data for biodiversity assessment on an ecosystem level from the method by (Lindner et al., 2021) used in the article from (Myllyviita et al., 2019)

Biodiversity impact for southern Finland	0.041-0.169

6
Discussion

6.1 How does the production of biomethanol from Södra impact the environment?

From the results of the LCA it can be seen that the production of biomethanol has an environmental impact and GWP is the most interesting one. The GWP_{100} is lower compared to all the fossil-based methanols. Much can be discussed about the GWP_{100}, for example how the biogenic carbon dioxide emissions should be accounted for. However, the division of emissions and results from this project with GWP_{100} as 0.395 kg CO_2-eq and GWP_{bio} as 2.127 kg CO_2-eq are relevant to use as they are recommended to use for environmental product declarations for forestry products for example. No other impact categories than GWP_{100} could be compared with fossil-based methanols, but something could possibly be hypothetically said about land use. It can be suggested that the land use of the biomethanol would be larger than a fossil-based methanol due to the extensive use of land that forestry naturally use. Lastly, both acidification and eutrophication have low values compared to the other impact categories.

When discussing the results, it is of importance to take the software into consideration. From the analysis in 5.1.5, the background system was presented as a contributor to the environmental impact shown in the categories terrestrial acidification, freshwater eutrophication and terrestrial ecotoxicity. This implies that a large part of the environmental impact of Södra's biomethanol comes from activities that Södra purchases from other companies and are not producing at their own production facilities. This gives Södra a smaller possibility to control and affect these activities. It must also be noted that the background system is a consequence of using the software openLCA and the database ecoinvent version 3.8. Since processes in the software rarely were related specifically to Sweden, average processes in Europe and globally were mostly used. This can influence the results to not be as true to reality as they could and it is important to consider. For example, data for the production of chemicals that Södra uses are general production data for Europe and globally, which can have an effect on the result since it is not certain that Södra's specific suppliers have the exact same processes and data in their production. Södra's specific suppliers could potentially have better or worse production processes compared with the data from ecoinvent version 3.8. It is believed that this, in combination with the selection of flows in ecoinvent, could be contributing to some uncertainties in the results especially for ecotoxicity as described in the analysis (see section 5.1.5).

One methodological choice that may have affected the outcome of the LCA is that the production steps of pulp production and biomethanol purification were modelled as black boxes in openLCA. This resulted in an overview of the production process of Södra's biomethanol but also a detailed understanding of the relevant inputs/outputs. However, this is just an interpretation of the system and does not give an exact picture of the production. There exist other alternatives regarding how to model a production process and these can give a more detailed picture of internal processes at a production facility and how much impact each of these processes should be accounted for. However, the main goal of this project was to investigate the total environmental impact of biomethanol production and not analysing each process individually at the production facility. Therefore it was decided that using the black boxing technique was the most relevant methodological choice.

Other sources of error in relation to the performed LCA exists. For example, one chemical used in pulp production could not be found in ecoinvent version 3.8 and instead a similar chemical was used. The chemical that could be found in the software was assumed to have a similar chemical structure and thus production process. This assumption could have an impact on the performed LCA and must therefore be mentioned as a possible source of error. However, we assume that the impact is relatively insignificant as the amount of this chemical was relatively low compared to other inputs. Other sources of error can be that some inputs in the pulp production could not be found in ecoinvent and no similar products could be found. These inputs were therefore excluded from the LCA, which may have an impact on the result. The inputs in question were however of a small amount and are thus assumed to have a low total impact on the result.

It is difficult to give clear recommendations to Södra if they would like to reduce the already low environmental impact of biomethanol further. However, since the background system is a large contributor, one recommendation for Södra is to evaluate their suppliers and see if there exist similar products with lower environmental impact. Another recommendation that regards their production activities is to investigate if the step of forestry activities can be performed with machinery that has a lower demand for fossil fuel or investigate if there is machinery available that might be powered by electricity.

6.2 How can biodiversity be included in life cycle assessment of biomethanol and how is biodiversity affected by the biomethanol production from Södra?

Measuring and assessing biodiversity is a continuous research still under development. As described in section 2.1.3, there are many ways of measuring biodiversity. Different large organizations such as the EU and the UN uses a range of different indicators, and the indicators can differ between the organizations as well. It can therefore be difficult to navigate around which indicators that are good to use and how they should be measured.

Including biodiversity in LCA is an even more complex issue. To get a good picture of biodiversity it is necessary to include multiple factors that are difficult to quantify and know to what extent they interact, and the fact that this is still not entirely established makes it difficult to include it in models. There are several developed methods for this purpose, as mentioned in 2.2.1, but scientific consensus has still not been reached. The recommended method by the UNEP/SETAC Life Cycle Initiative is the method by Chaudhary et al., 2015 that assesses biodiversity on a species level. For companies that uses land and thus potentially affect biodiversity, like Södra for example, it is important to have measurements to use and in this case implement in LCA. In this project, the method by Chaudhary et al. and the method developed by Lindner et al., 2021 that is related to biodiversity on an ecosystem level were used. There are several ways of categorizing biodiversity, but from the perspective of biodiversity on a genetic, species and ecosystem level, two out of three levels of biodiversity were in this way assessed in the project. However, the genetic perspective was not included, due to the fact that it could not be assessed within the scope of this study.

The method by Chaudhary et al., (2015) is a useful method that is relatively easy to use, since the characterization factors (CF) are provided from the supplementary material in the scientific article by Chaudhary et.al (2018) and yield is often quite uncomplicated to calculate. To include this method in a LCA is fully possible and relatively simple. This method is also the current recommended method to use according to the UNEP/SETAC Life Cycle Initiative, which gives it a high scientific credibility. Furthermore, the method is very comprehensive and can give specific data about many different species, depending on what the user think is interesting. In addition to this, the method uses the geographical areas ecoregions and countries, which results in data relevant for different projects. As with all methods, there are disadvantages also with this method. One disadvantage is that the method only assess biodiversity on a species level and leaves out the perspective of genetic and ecosystem. The species level can be very relevant and interesting, but Södra is more interested in biodiversity on a higher level such as ecosystem. Although this species perspective is difficult to draw conclusions from at the moment since the results are difficult to put in perspective due to the fact that Södra is not measuring population sizes of species in their forests. It is also Södra's belief that it will have a bigger place in the discussion of biodiversity in the future (Joelsson, 2022-03-24). Moreover, it can be discussed how much the forest management has effect on the results. As mentioned in the analysis, it can be seen in table 5.3 that the numbers for managed forests and plantation forests are not that different, even if the type of management is different and should be different from a biodiversity perspective. It can however be concluded that there are values present in the method for the management type closest to the one that Södra is using, managed forest: intense use, which is positive for a future implementation. Another disadvantage is that the calculated value for biodiversity damage that results from using the method is hard to put in perspective. Currently the method is not widely used in LCAs and therefore it is hard to find scientific resources that is suitable to compare values with. It should also be stressed that even if there are possibilities for future use, biodiversity is declining rapidly every year and it could therefore be better to use a method and to take actions for biodiversity than to not do anything at all. The more the method is used and developed, the better it will probably become and it will also be easier to put the results in perspective.

For the method on ecosystem level based on Lindner et al. (2021) can both advantages and disadvantages be found that could influence the results and application of it. One of the great advantages is that it covers a broader level of biodiversity impact compared to the other one. This is what Södra at least currently is interested in since it captures their work for biodiversity better (Joelsson, 2022-03-24). Since the method includes expert opinions and indicators specific for the area that is being studied it is adjustable to fit the user. Use of experts also gives the method scientific credibility. In this project only one expert, Klara Joelsson, from Södra was consulted which is important to have in mind when looking at the results. On one hand does she have in-depth knowledge of Södra's members forests and the work that Södra does for biodiversity. It is also positive for future implementation of the method if she can use and evaluate it. On the other hand can she be considered as biased. However, experts in the previous conducted study for Finnish forestry was used indirectly since, which increases the scientific credibility in this project. The use of the ecosystem method in this project was based on the finnish study and the impacts, impact functions, constants for the functions and normalized values where directly taken from it. Even if the data used from the Finnish study were said to be reliable and suitable, it might have been beneficial to add an additional impact or tweak the functions to fit the conditions in the ecoregion of Södra's members forests. The values collected and used in the method are additionally taken from the Swedish University of Agricultural Sciences for the area of Götaland in Sweden. Even if use of data from a non-biased source is positive in this case, it can also be seen as a disadvantage for future use of the model and the accuracy of the results. Data directly from Södra that is known to represent their members forests might be preferred. Although this is costly and time consuming, it could possibly be preferred to at least have some indication of the state of Södra's members forests. With this in mind, it is estimated that the potentially biased judgement from Joelsson does not affect the results greatly but it is still worth mentioning.

Disadvantages for this method as a whole could further be the reference situation that is used to set what perfect biodiversity is. It can be discussed what type of landscape in what time that is representative for the best form of biodiversity. Since already created biodiversity potential functions were used in this project, no further research of using reference states could be made. This is however an important issue to have in mind and it is something that likely will be up for discussion in the future use of methods for assessing biodiversity. This and the limited knowledge about when an action or indicators start to have effect on an ecosystem is seen as the greatest disadvantages from Joelsson's perspective for future use (Joelsson, 2022-05-16).

7 Conclusion

It can be concluded that the cradle to gate processes of biomethanol from Södra has lower environmental impact compared to selected fossil based methanols in terms of GWP_{100}. It is also evident from the result that some environmental impacts from Södra's biomethanol come from the background system and that the database that has been used could have an impact on the results.

Although inclusion of biodiversity in LCA is a complex issue, there exist available methods that make it possible to assess biodiversity in LCA. In this project two methods were used and it can be concluded that both methods can be used by Södra. However, the method of measuring biodiversity on an ecosystem level might be more preferable, mainly due to Södra's dominating work for impacts on a broader level for biodiversity. The results from the biodiversity assessment showed values of a reasonable magnitude compared to other scientific resources. It also showed that there is an impact on biodiversity from the biomethanol production which can be expected due to occupation of land during forestry. Nonetheless, at present it is difficult to put the results in perspective and say if the results are good or bad and what can be done to decrease the impact. Therefore it is essential to continue the research on how biodiversity can be accounted for and included in LCA. Moreover, to get a better and more precise assessment of biodiversity impact of the biomethanol production it could be beneficial for Södra to furhter develop the work with measuring their own biodiversity indicators. Biodiversity loss is and will continue to be an urgent matter and even if the methods available today need to be developed further, it is a good start to use them compared to excluding impacts on biodiversity.

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A

Appendix 1

A.1 Material from semi-structured interviews with Klara Joelsson at Södra

A.1.1 Semi-structured interview with Klara Joelsson at Södra 2022-03-24

The sentences showed in **bold** are questions asked by Linnéa Rydin and Victoria Svensson. The rest are answers by Klara Joelsson. The interview was held over zoom and in Swedish.

Do you want to tell us a little about how Södra thinks about biodiversity and how you work with it? How do you do to preserve biodiversity?
What is meant by biodiversity, question of definition. You can see it on a small scale; which species grow in a specific place. Södra works at a higher scale. Populations do not have to be everywhere. 5% must be preserved and protected on each property. General consideration taken: good environmental consideration, you should save a certain amount, you should provide some conditions. It used to burn a lot and the landscape became relatively open and you could imitate the natural landscape after a fire.
Södra have a report where they describe forestry and where they also include how the natural environments in their regions.

Forest nature conservation regions in southern Sweden: on a higher scale. Broken down Götaland in different regions. How to optimize? Green infrastructure: the county administrative board works with certain routes and has invested extra resources there.

Do you have any assessments of how much impact on biodiversity all steps from planting to felling have?
Complex question, and it's also very expensive. That cutting-edge competence is only available at SLU. The species do not care which company makes alterations in the forest. Södra is biased in the matter. However, they follow up on what they are told to do. Indirectly checks the parameters. Södra is certified in 3 different systems. There they check if they reach the requirements.

Do you make any inventories of species or anything similar?
No they do no inventory. Complex question. You can look at proxy for species. Look

at what we know about the ecology of species, how they can be grouped and then make deficiency analyzes. Looking at species is something that is coming in the future, but how to measure it? It is difficult! Should you measure all species, species that are especially important, species that there are few of and that you have to protect, etc.? According to standard routes, there is a little data inventory of species, but a big share of that work is also non-profit. Bird watchers, animals that you see, etc., but it does not cover all species.

Do you look more closely at any indicator? Species loss or ecosystem health?
There is no good indicator currently. Södra want to develop their own in the future. Pines covered in sunlight for example.

What will be the effect of Södras actions? This is something they want to continue to look at and which is largely a research issue

Are there any legal requirements for you that relate to biodiversity? Have you experienced expectations/requirements from customers regarding biodiversity?
The Forest Conservation Act, section 30. What types of considerations should be taken into account gives a great deal of freedom under responsibility. It brings up a bit about the endangered and red-listed species, consideration should be given so that species can survive Environmental Code, Chapter 12, Section 6. Species protection practice ("Artskyddsförordningen") Applies the laws to know what kind of consideration they should take.

Expectations from customers are becoming more and more specific. Is there a specific person at Södra who answers on questions about how they manage the forestry. Customers think that forestry is sometimes more important than how the product is!

Have some species that you can have as indicators of which forest you have, check how much of the species there is and after that you can adjust the consideration and possibly talk to some association about this to protect the species and the forest.

In our work, we plan to make an estimate of PSL as this is a measure that is recommended to do in connection with LCA. We have also thought about how to make an estimate of biodiversity at an ecosystem level. We have also read about methods that use a zero level, an original ecosystem, as a reference and then take it further from there. How do you feel about this?
On a global scale, they may be okay, but using them in a narrower region, they are not so specific that they give a good assessment. Södra want to measure the preventive measures! Must be able to capture a change at an early stage.

How much energy and maintenance work is required during a year to maintain the forest?
Plantation lays the foundation. Important where to plant the plants and where not to plant them. Do not plant spruce against a field edge for example.
After a few years, you make a clearing, thin out so they grow better. There are require-

ment saying that a certain proportion of the trees should be deciduous trees, in the past deciduous trees were removed. Some trees also self-injure so you check what the situation is like now, remove plants where you do not want them, leave the deciduous trees that are important. Ensures that there is a diversity of trees that are important for pollinators, food for animals. You often have different zones, that in one place you have a little more spruce and in another place another type of tree. Thinning = what you take goes into the pulp mill, right? Often do thinning twice. It is important to not destroy the soil and ground and take care of the values and trees that exist, are there natural value trees, etc.?

Certifications often have higher requirements than the laws.

How long can the trees grow before felling?
60-120 years. Depends on the soil, how fast it grows. Usually 80-90 years. Spruce grows faster. Is regulated by law.

When you plant new trees, are you only tree species you are interested in felling in the future, or do you also take into account what nature looked like before and plant different types of trees?
You have to look at the conditions of the ground. Some types of soil is very bad for spruce. If the soil is dried out in the summer, the spruce don't thrive. The landowner decides what to plant. Foreign woods are tightly regulated.

A.1.2 Semi-structured interview with Klara Joelsson at Södra 2022-05-16

The sentences showed in **bold** are questions asked by Linnéa Rydin and Victoria Svensson. The rest are answers by Klara Joelsson. The interview was held over zoom and in Swedish.

What weaknesses do you see with the method on a ecosystem perspective from Södra's perspective?
Mathematics is very black and white, biology not so much. Questions that you need to ask yourself are; When does an indicator start to take effect? You do not really know that! What is your reference? What type of landscape should you start from? What does 100% biodiversity really mean?

What strengths do you see with this method from Södra's perspective?
Dead wood is very important. You can distinguish between large dead wood and dead wood. 20 cubic meters per hectare is according to a Swedish study where it is starting to have an effect. Age is also important. Continuity is more often more important. If it has been a certain forest for a very long time, it is significant. Age is a pretty good proxy for continuity. The graph (graph from the contribution function $y_i(x_i)$) feels quite important.

Proportion of deciduous trees: Not a good graph! You can check what has been the mix in the area before? What percentage had you had before? Deciduous trees have often declined in forestry. Easier to grow straight twig-free conifers. Is often positive to bring in a lot of deciduous trees. Only if you have 10-20% deciduous trees, you get other species = positive for biodiversity. Wood species mixture is positive for biodiversity.

Large and old retention trees: Is basically a good indicator because it indicates that old trees have been left standing. 40 cm is quite large. Are not two things that are correlated. Old trees do not always have to be rough. Age is more important. 100 is quite young. 120-130 years.

Tree species: Is a better indicator to use. You have to adapt to your landscape. The species are just right!

How do you view the Finnish study we sent you? Is it applicable to Södra's forests? Are the factors used in that study also relevant for Södra's forests?
Dead wood and large dead wood (> 10cm), you have to take both into account and it depends on which products you do it. Natural forests have more dead wood (which is the case in the Finnish study) which can be a difference from southern forests

What factors do you consider to be most important to look at when it comes to biological diversity in Södra's forests in southern Sweden?
Dead wood, felling size, mixture of tree species, age

From a perspective as an ecologist at Södra, what method for quantifying biological diversity can you imagine being best suited for your business? One that is based on species loss or expert opinions on how biodiversity is affected by various factors?

Clarify clearly what we are looking at with biodiversity. Write clearly that there will be some form of forestry regardless of whether Södra produces any biomethanol or not.

Measuring biodiversity depends on which scale you look at and we look at our ecoregion.

The method: What is missing in the method are values linked to the cultural landscape. Where there is diversity, it is linked to the country's flora. Light entry into the forest or type of clearings would be good to have. The forest is getting darker and darker, because we have removed disturbances such as fires and that we have reduced the number of grazing animals in the forest. The species that need the light dislikes this and it is not included in the method. Södra would like to find proxies to be able to follow species, etc., but she believes that research is needed. What benefits and what benefits? What does this do for species?

The question of light: Södra measures the amount of nature conservation care or restaureing. This applies to the amount that is not used for forestry, is included in the allocation of forest that is not felled.

None of the methods are perfect. Can be a way to make an opinion.

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