Biodiversity Impact Assessment of Logging Residue Removal

Applying the Biodiversity Potential Method to Kraftringen’s Logging Residue Fuel

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Master thesis

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Abstract

The negative impact on biodiversity from land use is attracting increasing attention. The urgent need to mitigate biodiversity loss calls for comprehensive methods to assess the biodiversity impact of products and services. Life Cycle Assessment (LCA) represents a widely used tool to support decision making, but the inclusion of biodiversity impact in LCA remains under development. This master thesis uses LCA in an attempt support decision making concerning biodiversity impact related to the use of logging residues in southernmost Sweden.

The study adopts an LCA method based on the conditions for forest biodiversity to assess the biodiversity impact related to logging residue (tops and branches) removal. Through a literature review and interviews with five experts on forest ecology, the study identifies five pivotal components for sustaining regional forest biodiversity: old trees, a diversity of native species, high volumes of dead wood, limited acidity and heterogeneous structures. The first three components are subsequently translated to measurable management parameters. In turn, the parameters are combined to form a regionally specific biodiversity impact model. The model is applied in a case study involving the local energy producer Kraftringen and a sample of seven forest owners. Ultimately, the biodiversity impact per kWh produced heat is calculated for the removal of logging residues from 12 separate forest plots.

The results highlight that the biodiversity impact related to removing logging residues is dependent on the availability of other dead wood. Specifically, if high volumes of other dead wood are present, the biodiversity impact arising from the removal of logging residues decreases. The study suggests that the biodiversity impact can be mitigated by limiting the area subjected to logging residue removal and preserving coarse branches of native trees in areas where little other dead wood is available. Through the study, retaining coarse logging residues from native tree species emerges as the most consistent approach to mitigate biodiversity impact related to logging residue removal. A key contribution from the work is the development of a quantitative framework to support decision making concerning the biodiversity impact of forest management activities. The developed model can serve as a practical tool for energy producers and forest owners aiming to assess the biodiversity impact related to logging residue removal in southernmost Sweden.

The study reveals significant challenges related to collecting reliable data on forest management parameters, which affects the comparability of the results. This underlines the need for standardised data collection methods. Recommendations for further development also include a more detailed differentiation between logging residues from different tree species, as well as an adaptation of the model to a larger spatial scale.

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Contents

Nomenclature

Biodiversity	The variety of life in all its forms, including species diversity, genetic diversity, and ecosystem diversity
Biodiversity attribute	A structural component of a plot of land which is important for sustaining local biodiversity
Biodiversity potential	A value based measurement of the conditions for biodiversity
Logging residues	The leftover materials, specifically tops and branches, which remain in the forest after the harvesting of timber.
Management parameter	A contributing component to biodiversity potential which is measurable and related to land management
Quality change	The change in land quality from a biodiversity perspective
Rotation time	The time period between two final fellings in forestry
Stand	A restricted area constituting a single management unit in forestry

Acronyms

BP	Biodiversity Potential
CHP	Combined Heat and Power
CWD	Coarse Woody Debris
FWD	Fine Woody Debris
FU	Functional Unit
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LRR	Logging Residue Removal
SFA	Swedish Forestry Agency

1 Introduction

The loss of biodiversity has gained increased attention in past years, and is now highlighted as one of the main global challenges (IPBES, 2019). In the context of the European Union (EU), efforts to mitigate the loss of biodiversity has so far failed to curb the trend (EEA, 2020). This applies to the EU in general and to its forests, representing the largest terrestrial ecosystem within the union and covering more than a third of its land area (Forest Europe, 2020). Although the forested area within the EU has increased in recent decades (Forest Europe, 2020), the conservation status of the habitats contained within these forests represent a cause of concern. For example, 84% of forest habitats are classified as in a poor or bad state from a conservation perspective (EEA, 2020). The dominant pressure on the majority of these forest habitats is identified as forestry (EEA, 2020).

Simultaneous to the concern for biodiversity loss, the demand for forest products continues to rise. This demand is fuelled by expectations that woody biomass will play a crucial role in the transition away from fossil fuels (Swedish Forestry Agency, 2022; Fossilfritt Sverige, 2021), with a wide range of possible applications. In the energy sector, residual products from the forestry industry contribute to the mix of renewable energy sources. Looking ahead, the increased use of woody biomass for energy purposes highlights logging residues left on the forest floor after felling trees as an area of unfulfilled potential (Camia et al., 2021).

The urgent need to support forest biodiversity while simultaneously supplying biomass for the energy transition underscores the necessity for a comprehensive tool to assess the impact on biodiversity related to forestry products, including logging residues. In this context, Life Cycle Assessment (LCA) represents a widely used method for evaluating the environmental performance of a product. However, its application in assessing biodiversity impact is still developing, with numerous methods available (Damiani et al., 2023). Given the complexity of biodiversity itself, some methods propose using biodiversity indicators related to land management instead. One such approach is suggested by Lindner et al. (2021), which focuses on landscape attributes indicative of ideal conditions for biodiversity. Labelled the Biodiversity Potential (BP) method, this approach relates biodiversity impact to a number of land management parameters.

This study develops a regionally specific model to assess the biodiversity impact of forestry products on biodiversity, based on Lindner et al. (2021). The model is applied in an LCA-based case study of logging residue fuels supplied by forest owners in southernmost Sweden, involving the local energy producer Kraftringen Energi and forest membership organisation Södra Skogsägarna.

1.1 Objective and scope

The aim of this master thesis is to quantify the biodiversity impact of logging residue removal from an LCA perspective. Moreover, the thesis sets out to provide a contribution to the development of biodiversity impact assessment of forest products within LCA. Included in the aim is also to contribute with conclusions on the usefulness of such assessments for forest owners and energy companies using logging residue fuels.

The scope of the study is limited to applying the BP-method to assess biodiversity impact in the region of Scania, Sweden. In detail, the study covers Kraftringen's use of logging residue fuels in the company's production of district heating, for which Södra Skogsägarna constitute one of the main suppliers of the biomass. The study is designed to be available to decision makers and devoted stakeholders, both in the energy and forestry sectors, including forest owners. From the perspective of south Swedish conditions for forestry and forest biodiversity, the focal research questions are:

- How can a conditions based approach to assess biodiversity impact be applied to consider the biodiversity impact of removing logging residues?
- Which management parameters are relevant for assessing biodiversity impact related to logging residue removal?
- What further developments are required to improve the usefulness of the assessment from an energy company perspective?

1.2 Stakeholders

1.2.1 Kraftringen Energi

Kraftringen Energi is a local producer and distributor of energy in southwestern Scania. The company operates a regional grid of district heating, where the most important production unit is the combined heat and power (CHP) plant Örtoftaverket. The input fuel to the CHP plant is composed of recycled wood and forest fuels, which provide 50% of the energy supply each. In turn, the forest fuels are composed of woodchips (mainly logging residues), bark and sawdust (Pettersson, Björnsson, 2019). In total, the CHP plant converts 310 000 tons of biomass each year, providing a yearly contribution of 600 GWh to the district heating grid (Pettersson, Björnsson, 2019). The generated heat is approximately equivalent to the need of 35 000 villas in the municipalities of Lomma, Lund and Eslöv. In addition to heat, the production generates electricity at a early extent of 100-200 GWh (Kraftringen Energi AB, 2014).

1.2.2 Södra Skogsägarna

Södra Skogsägarna respresents 52 000 forest owners in southern Sweden, making them the largest forest ownership organisation in the country. The company is involved throughout the value chain of forest products, with branches stretching from forest management through the processing and pulp industries of the forestry sector. The forests of Södra Skogägarna's members contribute with an important supply of logging residues to Kraftringen's CHP plant. Between the years 2022 to 2023, Södra Skogsägarna was the single largest supplier of forest fuel to Örtoftaverket, providing 10% of the entire fuel supply (Kraftringen Energi AB, 2023). The fuel provided by Södra Skogsägarna was entirely composed of logging residues originating from different forest owners in the region, with the average delivery distance to Örtoftaverket being 59 km (F. Allemog, Sales director bioenergy at Södra Skogsägarna, personal communication, January 29, 2024).

1.3 Disposition

The master thesis report is structured around three main components: literature study, model development and case study application. The components build on each other and together constitute the results of the master thesis. The three components and their relations are covered and put into context over the seven chapters of the report. The structure of this master thesis is as follows:

The introduction chapter outlines the purpose and context of the thesis, presenting the research questions and the involved stakeholders. Following this, the methods chapter details the approach and methodology employed throughout the study.

In the literature study, a comprehensive background on the interconnected issues of forestry, biodiversity, and bioenergy is provided, with a particular focus on the European and Swedish contexts. This chapter also introduces the concept of Life Cycle Assessment (LCA), emphasising biodiversity impact in LCA and the biodiversity potential method.

The model development chapter elaborates on the creation of a region-specific biodiversity impact model. This is followed by a case study chapter, which applies the model and explores Kraftringen's district heating production from an LCA perspective. This chapter covers the goal and scope, life cycle inventory, and life cycle impact assessment of the LCA, detailing the collection of inventory data for the model and presenting the biodiversity impact of logging residue removal.

The discussion chapter investigates the main findings of the study, which are summarised in the conclusion chapter. The conclusion offers recommendations on interpreting the results, highlighting their relevance and utility for an energy company utilising logging residue fuels.

2 Method

The first component of the master thesis is a broad literature study on the most relevant tangential topics of the research questions. In essence, the literature study provides a background and a foundation for the two remaining components: the model development and its application in a case study. Regarding the model development, a regionally specific model to assess the biodiversity impact of forestry products on biodiversity is developed. Subsequently, representing the third and final component, the model is applied in an LCA-based case study of logging residue fuels supplied by forest owners in southernmost Sweden, involving stakeholders Kraftringen Energi and Södra Skogsägarna. Along the path from the initial literature study, via the model development, to the case study, the master thesis narrows down and becomes increasingly specific (Figure 1). Beyond the case study, the discussion and conclusion serves to once again place the study in a wider context.

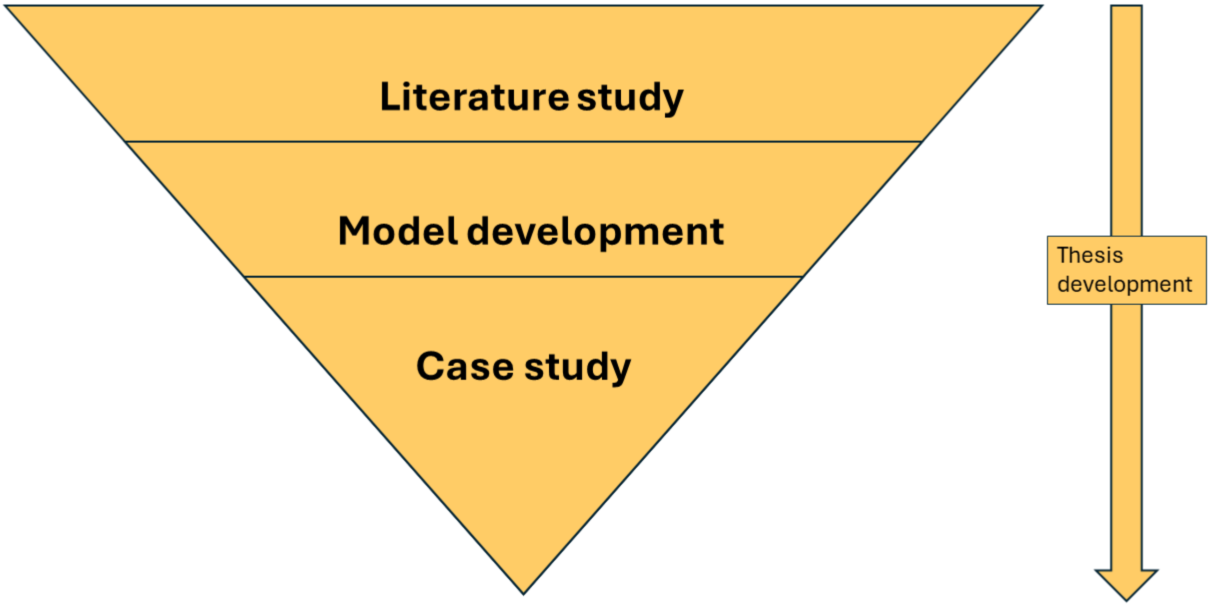

Figure 1: Graphical presentation of the three main components in the thesis approach, illustrating how the thesis narrows down from an initial literature review and subsequent regional biodiversity impact model for forest products to a specific case study of logging residue fuels. The case study is followed by a discussion, which serves to broaden the scope once again.

2.1 Literature study

The literature study was approached with the aim to establish a comprehensive background on the importance of logging residues for forest biodiversity, as well as on the general inclusion of biodiversity in LCA. As the literature study spanned a wide range of subjects, a specific structure of approach was not defined. Nevertheless, a selection of publications can be put forward as keystones, providing a foundation for the literature study as a whole. Foremost, this applies to the Joint Research Centre's assessment of woody biomass for energy production (Camia et al., 2021), investigating a thresholds for a sustainable use of logging residues within the European Union. Moreover, this applies to the review articles on the incorporation of biodiversity in LCA by Crenna et al. (2020) and Damiani et al. (2023).

2.2 Model development

The development of a regionally specific model to quantify biodiversity impact from forest management was based on the model architecture of Lindner et al. (2021). The approach follows a series of steps, starting from defining model parameters based on biodiversity expert interviews of semi-structured character. Biodiversity expert selection was based on the initial literature study as well as specific recommendations from other experts within the field of science. Expert opinion guided the construction of mathematical relations between parameters and biodiversity, as well as the relation between parameters. The model development was an iterative process, where the final model was verified by experts prior to its application in the case study.

2.3 Case study

Inventory data corresponding to the model parameters was collected through structured interviews with forest owners and consequently suppliers of logging residues. The structured interviews were based on a questionnaire designed to include the most relevant parameters for biodiversity in Baltic Mixed Forests, as defined by experts in the model development phase. In addition, questions were designed to capture data on logging residue removal. Data collection included sending the questionnaire along with a statement of purpose to participants and thereafter scheduling an oral interview session. The interview constituted an opportunity to address uncertainties and to make sure the interviewee had understood the questions correctly. The questionnaire used for inventory data collection is attached in Appendix 3.

The selection of interviewees was based on the contacts supplied through Kraftringen and Södra Skogsägarna, with no influence from the author on the distribution and profiles of the respondents. The selection was biased towards forest owners who were expected to have detailed insight in the management of their forest. Södra Skogsägarna provided 6 respondents, with 1 additional respondent being supplied through Kraftringen.

The data supplied by forest owners was used as input data in the model and subsequently translated to LCA-based results. The incorporation of the biodiversity impact assessment of logging residue removal into the LCA framework was conducted based on an Environmental Product Declaration (EPD) produced by the company (Kraftringen Energi AB, 2022). The EPD disclosed environmental impact from the company's district heating grid, corresponding to the functional unit *1 kWh of hot water produced and distributed to a customer*. Additionally, the case study follows the disposition of an LCA as defined by the International Organization of Standardization (ISO), with components goal & scope, LCI and LCIA (International Organization of Standardization, 2006). The interpretation component is covered by the discussion in Chapter 6, under the assumption that it would not influence the content.

3 Literature study

Assessing the biodiversity impact of logging residue removal connects the topics of forestry, forest ecology and LCA. To provide a comprehensive background to these topics, a literature review was conducted as a foundation for the report. The chapter begins with presenting perspectives on logging residues as a product stream in Swedish forestry and its role as fuel in the energy sector. Subsequently, the impact on biodiversity following logging residue removal is investigated in detail from a Scanian perspective. Finally, LCA is presented with a focus on biodiversity impact assessment and it's development within LCA.

3.1 Forestry and logging residues

The harvest of trees, or logging, in a generic Swedish forest generates three main product streams. Healthy stems are divided between timber and pulpwood, while the third product stream is made up of forest fuel. The main fraction of forest fuel originates from tops and branches (Swedish Energy Agency, 2024) which are removed from the stem during the logging process (Figure 2). Along with the stumps left on the ground, tops and branches constitute the so called logging residues (Egnell, 2013). However, as stumps currently are not targeted in the harvest of logging residues (Swedish Forestry Agency, 2022), the term logging residues from here on refers exclusively to tops and branches separated from the stem during logging.

Figure 2: Logging residue tops and branches from deciduous trees (left) and spruce (right) (Own photos).

Logging residues are tightly linked to the concepts of rotation time and stand, which also provide a foundation for assessment. The production cycle covers the time period, known as rotation time, between two final fellings on a managed plot of forest. As a fundamental unit in forestry, these plots are referred to as stands, a term used to indicate an area where forest conditions are relatively homogeneous. In practice, the stand constitutes a single management unit (Swedish Forestry Agency, 2012).

The removal of logging residues in Sweden is restricted by law, which in turn is complemented by general recommendations from the Swedish Forestry Agency (SFA). Legislation declares that forest owners are imposed to report all removal of logging residues as well as take compensatory measures following such removal. Compensatory measures are defined as the recycling of mineral nutrients (ashes), which is required in most cases to sustain the long term nutrient balance and buffering capacity of the soil. Recommendations complementing the legislation include avoiding the removal of logging residues in forests with high biological values and leaving 20% of the volume on the stand as a substrate for biodiversity (Swedish Forestry Agency, 2019).

In addition to legislative objectives, the extraction level of logging residues is influenced by technical constraints. Logging residues are commonly used as substrate for heavy machinery on wet soils, excluding them from extraction. Furthermore, twigs and other finer fractions are infallibly left on the stand even if targeted for extraction (Johannesson et al., 2023). These technical constraints generally limit the removal of logging residues to a maximum of 80% of the generated volume (Eliasson, Nilsson, 2015). In summary, removing logging residues from a stand is not synonymous to extracting every single branch.

3.2 The use of logging residues

No forest is planted or managed for the purpose of harvesting logging residues, but they are in demand in the energy sector (Camia et al., 2021). Wood-based fuels constitute an integral part in the effort to transform the energy supply within the European Union away from fossil fuels and towards renewable sources. Of the 17% of gross energy consumption in the EU made up of renewable energy in 2016, woody biomass comprised 35% of the share (Camia et al., 2021). Consequently, approximately 6% of all energy consumed in the EU originates from forests. In Sweden, the relative importance of wood based fuels is significantly higher. Wood based fuels constitute two thirds of the energy supplied from bio-fuels nationwide, corresponding to 20% of the national energy supply (Börjesson, Björnsson, 2024; Swedish Energy Agency, 2023).

As the EU and Sweden strive for climate neutrality, a further increase in demand is expected for bio-fuels in general and wood-based fuels in particular. A special emphasis on the role of logging residues in this transition is put forward by the Joint Research Centre (JRC) in their report *The use of woody biomass for energy production in the EU* (Camia et al., 2021). To meet the increased demand of forest resources for bio-energy, the authors highlight two responses in terms of forest management practice to enable an increased extraction of biomass from forests. Firstly, an increased removal of logging residues and secondly, afforestation of currently non-forested land. While both measures are relevant in a south Swedish scope, this study focuses on the response based on logging residues.

From a Swedish perspective, the use of logging residues is not novel. The area of use is currently restricted to energy purposes, where logging residues constitute a well integrated fuel in combined heat and power (CHP) plants (Johannesson et al., 2023;Lindholm et al., 2010), providing a supply of energy to the developed district heating grid. While prices on logging residues and the related extraction levels spiked in 2013 at 10.6 TWh, the extraction level then fell before high energy prices in recent years spurred an new increase in demand. In 2022, the extraction of logging residues reached 9.7 TWh, corresponding to 7% of the energy input from of biofuels nationwide (Swedish Energy Agency, 2024). Several publications point toward an increase in the demand and extraction of logging residues in future decades (Pandey, Erbaugh, 2024;Camia et al., 2021). However, the extent of this increase is surrounded by uncertainty, not least as the profitability of extraction is strongly influenced by fluctuating prices on the energy market (Johannesson et al., 2023). Additional limitations to extraction might also be posed due to increased concern for biodiversity, which can influence both the area available for logging and management measures such as logging residue removal (Pandey, Erbaugh, 2024;Börjesson, 2021).

As extraction is assessed to continue and potentially increase, attempts have been made to assess a sustainable level of logging residue removal. Such a threshold is assessed to be located at removal on 50% of the felled area, considering the risks related to acidification, nutrient loss and biodiversity loss, with acidification as the limiting factor (de Jong et al., 2017). Realising this level of extraction nationwide is predicted to correspond to an additional 16-18 TWh per year in 2030 (Börjesson, 2021), representing a three fold increase in extraction.

Between the years 2017-2021, logging residues were harvested on 33% of the logged area in Sweden (SLU, 2023). However, these numbers are highly dependent on geographical location, as extent was significantly higher at 64% in southern Sweden (SLU, 2023). An unfulfilled extraction potential is assessed to remain in all parts of the country, despite regionally exceeding of the 50% defined as a sustainability threshold for the removal of logging residues (de Jong et al., 2017). This conclusion is motivated by the influence of regional factors on the sustainability threshold (Johannesson et al., 2023; Swedish Forestry Agency, 2022).

3.3 Biodiversity aspects of logging residue removal

The impact from forest management on biodiversity must be assessed to comprehensively evaluate the environmental performance of a forest product. As countries nationwide commit to restore degraded ecosystems and protect 30% of terrestrial areas through the Kunming-Montreal Protocol (Convention on Biological Diversity, n.d.), only 14% of forest habitats within EU sustain a favourable conservation status (EEA, 2020).

From a biodiversity perspective, logging residues primarily serve as a substrate for saproxylic (dead wood-dependent) organisms (Bouget et al., 2012;Jonsell et al., 2007). In forests managed for the purpose of biomass production, logging residues contribute with a significant share of the available dead wood (Ranius et al., 2018), a habitat widely regarded as one of the most important for supporting forest biodiversity (Parajuli, Markwith, 2023;Müller, Bütler, 2010). However, logging residues cannot serve as a substitute for the full variety of dead wood which a more natural forest exhibit, where a variation in size, age and arrangement all constitute important elements for supporting forest biodiversity (Vítková et al., 2018;de Jong, Dahlberg, 2017;Kraus, Krumm, 2013;Brunet et al., 2010).

From a European perspective, Camia et al. (2021) underline that any impact following the removal of logging residues is dependent on locally defined landscape thresholds, both in the case of coniferous and deciduous forests. Since logging residues constitute a common and widely used habitat in areas of intensive forestry, extensive removal of logging residues can have negative impact on several communities of species which today are viewed as less interesting from a conservation perspective, risking an eventual decline of the species within these communities (Ranius et al., 2018;Hiron et al., 2017;Felton et al., 2016).

Several attempts have been made to assess the specific importance of logging residues for biodiversity in Sweden, but most studies have been focused on coniferous forests in the central and northern parts of the country (Hiron et al., 2017; Eggers et al., 2020). Although logging residues provide important habitat for a multitude of species on a landscape scale in these regions, these species are typically generalists without current concern from a conservation perspective (de Jong, Dahlberg, 2017). The work of de Jong, Dahlberg (2017) indicates that logging residues from coniferous trees can be extracted with limited impact on biodiversity, up to certain intensity levels, since logging residues primarily provide habitat for more common and generalist species. However, the authors underline that the impact on species of conservation interest (SCI) is difficult to assess, due to the lack of landscape scale studies and the inherent scarceness of these species (de Jong, Dahlberg, 2017). A threshold in terms of harvest intensity after which significant impact on biodiversity can be expected requires further investigation and will likely differ depending on the species concerned (Johansson et al., 2016). Nonetheless, workshop conclusions presented by de Jong et al. (2017) state that collecting logging residues on 60% of the logged area should have no significant impact on biodiversity. This assessment includes assuming the extraction of logging residues does not exceed 70% of the total volume on the stand, due to technical constraints. The contribution from logging residues to biodiversity is potentially more significant in deciduous forests (de Jong, Dahlberg, 2017). For instance, several red-listed species of dead wood dependent insects have been found on logging residues from oak (*Quercus robur*) in southern Sweden (Jonsell et al., 2007; Nordén et al., 2004).

In summary, the impact on biodiversity following the removal of logging residues can vary both depending on the amount and character of the extracted wood. Apart from considering from what tree species the dead wood originates, a widely used differentiation of dead wood follows a division based on diameter:

- Fine Woody Debris (FWD), including most tops and branches
- Coarse Woody Debris (CWD), including snags, standing dead trees and high-stumps.

Although no official definition exists for FWD and CWD, several studies refer to FWD as all fractions with a diameter below 7-10 cm and CWD as all fractions with a diameter above 7-10 cm (Vítková et al., 2018; Bouget et al., 2012; Siitonen, 2001). In general, CWD is assessed to be the more important fraction from a biodiversity perspective, not least as they take longer to decompose and therefore provide habitat for a longer period of time (Vítková et al., 2018).

Although a specific diameter threshold is not defined, Camia et al. (2021) embrace the differentiation between FWD and CWD in their assessment of biodiversity impact of logging residue removal. Their synthesis conclude that the extraction of CWD should be avoided under all conditions. On the contrary, removal of FWD is associated with low or no risk as long as the extraction levels are below local or regional landscape thresholds. As such, biodiversity impact related to the removal of logging residues includes two components. Firstly, the removal of coarse branches should be avoided. Secondly, the overall removal levels should be below landscape thresholds. These findings are valid for both deciduous and coniferous forests, although removal of coniferous residues exhibit the lowest amount of controversy due to lower affinity of SCI to coniferous FWD compared to deciduous FWD (de Jong, Dahlberg, 2017; Nordén et al., 2004). Efforts of defoliation before removal are not considered to be of pivotal importance for biodiversity, although it does have a significant effect on nutrient recycling (de Jong et al., 2017).

3.3.1 Regional characteristics

Assessing both biodiversity and forestry must consider the influence of geography. While forestry and forest management bear similarities between southern and northern Sweden, there are distinct regional differences. In Scania, a notable difference compared to the most other regions of Sweden is the increased presence of broad-leaved deciduous tree species, complementing the nationally widespread coniferous species (SLU, 2023). While the broad-leaved deciduous forest cover less than 1% of the national productive forest area, it supports approximately 50% of the nationally red-listed species, generating interest from a conservation perspective (Hannerz, Simonsson, 2023;SLU, 2023).

The regional characteristics of biodiversity highlights the significance of the spatial scale when assessing biodiversity impact. While country level impact might be desirable to facilitate applicability, country limits are often poor indicators of biodiversity changes (Crenna et al., 2020). For example, de Jong, Dahlberg (2017) suggests the contribution to biodiversity from logging residues can be expected to differ between southern and northern Sweden with regard to differences in tree species composition. Therefore, assessing biodiversity impact has to account for regional differences in biodiversity, with one possible approach being a division into ecologically comprehensive units. Such a division based on the concept of ecoregions divides Sweden into three separate sections, each with different ecosystem characteristics. According to this differentiation, the region of Scania in southernmost Sweden, which is the focus of this thesis, is assigned to the ecoregion Baltic Mixed Forests (Olson et al., 2001). Typically, Baltic Mixed Forests are characterised by deciduous broadleaved species such as beech (*Fagus sylvatica*, Figure 3) and oak (*Q. robur*). Nevertheless, Norway spruce (Picea abies) represents the most common tree species in managed forests (SLU, 2023) within the region.

Figure 3: Managed beech forest in southeastern Scania (left) and managed spruce forest in northern Scania (right) (Own photos).

3.4 Life Cycle Assessment

The increased global concern for environmental issues pronounces the necessity for comprehensive tools to assess the environmental impact related to products and services. Life Cycle Assessment (LCA) emerges as a pivotal methodology in this regard, offering a systematic framework to evaluate environmental performance (International Organization of Standardization, 2006). LCA can be utilised to facilitate informed decision-making by providing a holistic understanding of the environmental burdens associated with a particular product or process (International Organization of Standardization, 2006). In particular, LCA is a useful tool to facilitate decisions between different products based on environmental performance (Weidema et al., 2004). A central component to the application of LCA is the functional unit, which provides a comparable way to express environmental impact. The functional unit is the reference to which all other data is normalised, contributing with a foundation for comparing environmental impact between different products or decisions (Weidema et al., 2004).

Conducting an LCA of a product is an iterative process comprised of four steps (International Organization of Standardization, 2006), starting with defining the 1) goal and scope of the study. Subsequently, data on material flows and emissions are collected and assigned to specific process steps of the product life cycle. This stage is known as the 2) Life Cycle Inventory (LCI). Following the collection of inventory data, the 3) Life Cycle Impact Assessment (LCIA) includes assigning the data to environmental impact categories. Environmental impact can be assigned to a variety of different impact categories, with examples including global warming and biodiversity loss. Furthermore, the third stage evaluates the extent of the environmental impact and relates it to established impact metrics, known as the category indicators. As a final step, the LCA is concluded by 4) interpretation. The fourth step interacts with all three previous stages and evaluates the performance and robustness of the LCA, including the results and their relevance. An overview of the LCA methodology is presented in Figure

4.

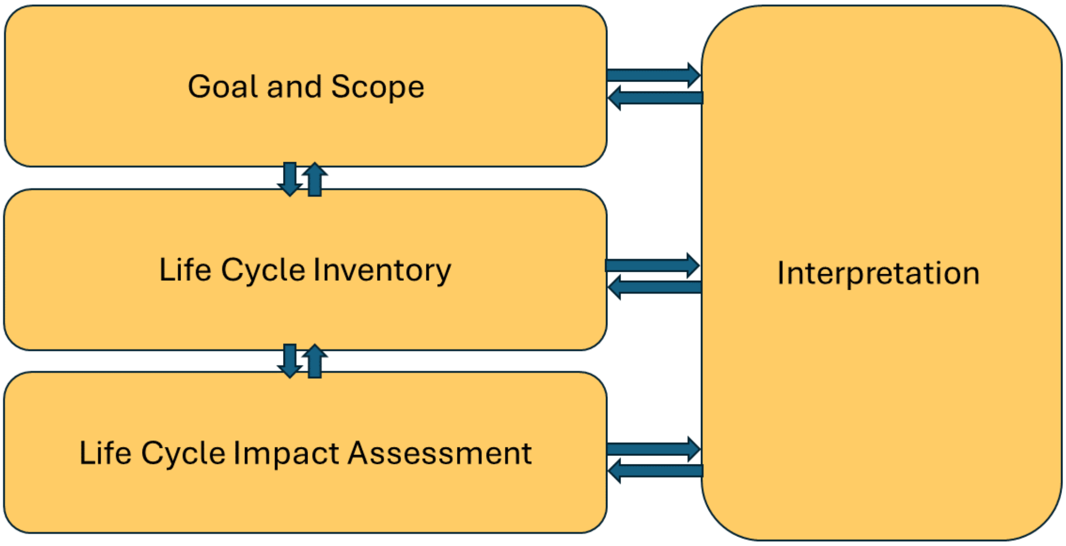

Figure 4: General representation of the LCA methodology, adopted from Lamperti Tornaghi et al. (2018).

3.4.1 Biodiversity in LCA

Evaluating the impact on biodiversity from forestry products is crucial for accurately assessing their environmental performance (Camia et al., 2021; Bouget et al., 2012). Despite this importance, several studies stress that significant challenges persist in comprehensively assessing this impact from a Life Cycle Assessment (LCA) perspective (Côté et al., 2021; Myllyviita et al., 2019). Efforts to incorporate biodiversity into LCA have been ongoing for more than 20 years (Winter et al., 2017), but nevertheless the field remains under development. Numerous approaches are available, but the work of Damiani et al. (2023) indicate that none so far is able to consider all the relevant aspects of biodiversity impact.

Comprehensively assessing biodiversity impact in LCA is difficult for several reasons. One primary challenge is related to the complex nature of biodiversity itself (Crenna et al., 2020). As defined by the Convention on Biological Diversity, biodiversity can be subdivided into several components or levels, including genetic diversity within species, species diversity and diversity of ecosystems (United Nations, 1992). While all levels are important when considering the impact on biodiversity, the lack of data makes it difficult to consider biodiversity in its entirety (Winter et al., 2017). Furthermore, the spatial scale provides a challenge, as comparisons of global value chain products must consider and compare regional aspects of biodiversity (Winter et al., 2017; Koellner et al., 2012). Another major challenge is the definition of a reference state for biodiversity, which can be used a baseline for assessing biodiversity impact. An initial interpretation of this concept predominantly focused on a human-free situation (Vrasdonk et al., 2019). However, there are several examples of ecosystems with high conservation value that are strongly influenced by human activities. Against this background, a reference state based on conditions at re-naturalisation gain more support today (Vrasdonk et al., 2019).

In terms of a metric for biodiversity impact in LCA, an approach based on species richness is the most widely used (Damiani et al., 2023). Predominately, this approach considers the potentially disappeared fraction (PDF) of species, used by e.g. Scherer et al. (2023), to assess biodiversity impact. However, such an approach typically only addresses one aspect of biodiversity, focusing on impacts on a species diversity level. Furthermore, an approach based on species diversity faces issues related to obtaining data for all taxonomic groups of the wide set of organisms contributing to biodiversity (Damiani et al., 2023).

The main alternative to species richness is conditions based assessment (Myllyviita et al., 2019). Such an approach considers biodiversity in terms of the conditions under which a certain biodiversity level can be expected. For example, Michelsen (2008) used a set of indicators related to forest management to consider biodiversity impact from forestry. An approach based on the conditions for biodiversity moves away from empirical biodiversity measurements, but is nonetheless a widely used approach to estimate biodiversity (Gao et al., 2015). In essence, a conditions based approach is not restricted to one level of biodiversity but instead aims to consider biodiversity as a whole (Lindner et al., 2021). Furthermore, such a method is flexible regarding the availability of data, which is beneficial when collecting data on finer spatial levels, e.g. from individual forest owners. Acquiring primary data on species richness for a particular stand or property is typically challenging, while obtaining data on structural attributes related to forest management is more straightforward, as was exemplified by Matsson et al. (2022).

3.4.2 The biodiversity potential method

This study adopts one of the conditions based methods, described by Lindner et al. (2021) and here referred to as the biodiversity potential (BP) method. The BP method is based on the work of Michelsen (2008), and builds on the premise that conditions for biodiversity on all levels are met when a plot of land exhibit certain attributes or characteristics. In essence, the BP method uses the degree of deviation from the ideal conditions for biodiversity as a metric for biodiversity impact. Earlier versions of the BP-method have been applied to case studies investigating biodiversity impact of forest products in northern Europe (Myllyviita et al., 2019; Lindqvist et al., 2016). In these studies, conditions for biodiversity were defined for specific ecoregions and biodiversity impact was calculated based on the impact from forestry on these conditions.

A distinct difference between the BP method and most other approaches is the use of a continuous scale for biodiversity impact (Lindner et al., 2021). Usually, land management is assigned to predefined land use intensity classes. For example, Scherer et al. (2023) and Chaudhary, Brooks (2018) distinguish between minimal, light and intense land use when quantifying biodiversity impact. In contrast, the BP method considers land management continuously from minimal intensity to maximal intensity. The continuous approach enables high resolution assessment, allowing for a differentiation between forest properties that would otherwise be assigned to the same predefined land use intensity class.

Like most LCA-based methods to assess biodiversity impact, the BP method is based on the framework provided by the United Nations Environment Programme Society of Environmental Toxicology and Chemistry (UNEP-SETAC) (Koellner et al., 2013) for land use impact within LCA. The framework states that all land use activities will influence the land quality (Q), as stated by Milà i Canals et al. (2007). The impact on Q can be expressed as the difference between land quality within current land use and land quality at a reference state Q_{ref}, forming the quality change parameter ΔQ. In addition to the quality change parameter, the framework suggests that impact from land use also include the time duration (Δt) and area affected (A) (Koellner et al., 2013). The three parameters ΔQ, t and A provide a basis for calculating biodiversity impact, according to Equation 1:

$$Biodiversity\ \ impact = \Delta Q \cdot A \cdot t \tag{1}$$

The connection between biodiversity and the BP method is limited to the ΔQ, which from here on refers to quality change from a biodiversity perspective. The quality aspect relates to the conditions for biodiversity, or the BP. The use of the BP method involves the use or development of a BP model, which connects BP to parameters of quantitative character.

The management parameters constitute the building blocks of the BP model for biodiversity impact. Each singular parameter (x_i) provides a contribution y_i to BP, with the generic contribution of a parameter expressed as a function $y_i(x_i)$ (Equation 2). In the model, each parameter is normalised to the interval [0,1], where $y_i(x_i) = 1$ corresponds to fully achieved biodiversity potential, i.e Q_{ref}. Plotting the biodiversity contribution function generates the so called contribution curve, which visualises the relation between parameter and biodiversity potential contribution.

$$y_i = \gamma + \epsilon e^{-\frac{|(x_i^{\delta} - \beta)^{\alpha}|}{2\sigma^{\alpha}}} \tag{2}$$

The variables γ, ϵ, δ, β, α and σ of Equation 2 are altered to manipulate the contribution curve to better describe the relation between a parameter and its contribution to BP. The contribution curves aim to describe how land management influences biodiversity. In the context of forestry, this can be exemplified by the impact on biodiversity related to increasing the volume of dead wood in the forest(Lindner et al., 2021; Myllyviita et al., 2019;Lindqvist et al., 2016). Establishing the mathematical relation between a management parameter and the biodiversity contribution is often complicated due to the lack of empirical data, which is why expert consultation is pivotal when designing the contribution curves.

Parameters x_i can provide an independent contribution to the biodiversity potential, but their contribution can also be strongly related to the contribution from other parameters. In the case of dependent parameters, the model uses a set of operators to provide the mathematical relation (Table 1). Where two or more parameters are dependent on each other to provide their respective biodiversity contribution, the AND operator is used. On the contrary, where the contribution of one parameter can be replaced by another, the OR operator is used. The operators can be classified as either STRICT or SOFT, depending on the degree of interaction. The soft operators include the variable p which determines the degree of interaction, with the *soft* bearing increased resemblance to the *strict* as $p \rightarrow \infty$.

Each parameter is assigned a contribution weight, since all parameters and their contributions are not necessarily equally important for biodiversity. The contribution weight is determined by weighting factors z_g. As a final step, the parameters are combined to form a BP field function (Equation 3). In coherence with the individual parameters, the multivariate BP field function is normalised to the interval [0,1], meaning the sum of all weighting factors z_g must be equal to 1.

$$BP = \sum_{g=1}^{k} z_g \cdot y_{ij}(x_i, x_j)_g \tag{3}$$

Table 1: Summary of operator functionality describing the relation between two dependent parameters x_A and x_B, according to (Lindner et al. (2021)).

Operator	Use scenario	Mathematical relation
Strict AND	Both parameters required in a favourable interval to reach high biodiversity contribution. The contribution from one parameter cannot replace the other.	$y_{AB}(x_A, x_B) = y_A(x_A) \cdot y_B(x_B)$
Soft AND	Both variables required in a favourable interval to reach high biodiversity contribution, but they can replace each other to a limited extent.	$y_{AB}(x_A, x_B) = 1 - \sqrt[p]{\frac{1}{2}[(1 - y_A(x_A))^p + (1 - y_B(x_B))^p]}$
Strict OR	One of the parameters required in a favourable interval to reach high biodiversity contribution. The contribution from one parameter can replace the other.	$y_{AB}(x_A, x_B) = y_A(x_A) + y_B(x_B) - y_A(x_A) \cdot y_B(x_B)$
Soft OR	One of the parameters required in a favourable interval to reach high biodiversity contribution, but they are not entirely interchangeable.	$y_{AB}(x_A, x_B) = \sqrt[p]{\frac{1}{2}[y_A(x_A)^p + y_B(x_B)^p]}$

In summary, the BP model uses an unspecified number of parameter values combining to one BP value, ranging between 0 and 1. The BP value indicates to conditions for biodiversity, with a higher value indicating better conditions for biodiversity. The maximum BP value (BP = 1) corresponding to ideal conditions for biodiversity. In the attempt to describe the ideal conditions for biodiversity, the BP field function reconnects to Q_{ref}, where the reference state from a biodiversity perspective corresponds to the fully achieved biodiversity potential (BP = 1). The quality of the current land use from a biodiversity perspective can be labelled Q_i, which corresponds to the actual BP. The unfulfilled biodiversity potential can then be calculated as the difference between the current biodiversity potential and the ideal conditions for biodiversity (Equation 4). This difference captures the impact on biodiversity potential of the current land management, in relation to the reference state. This can be interpreted as the biodiversity quality change (ΔQ) as a consequence of land use.

$$\Delta Q_i = Q_{ref} - Q_i = 1 - BP_i \tag{4}$$

Calculating ΔQ according to Equation 4 results in a quality change corresponding to the unfulfilled biodiversity potential under current land use. Relating ΔQ to areatime (A and t) subsequently represents the biodiversity impact. An overview of the mathematical architecture of the BP method is provided in Figure 5. The model architecture is designed to be ecoregion specific, and while comparable within the same ecoregion, comparisons of BP and ΔQ across different ecoregions requires ecoregion specific factors.

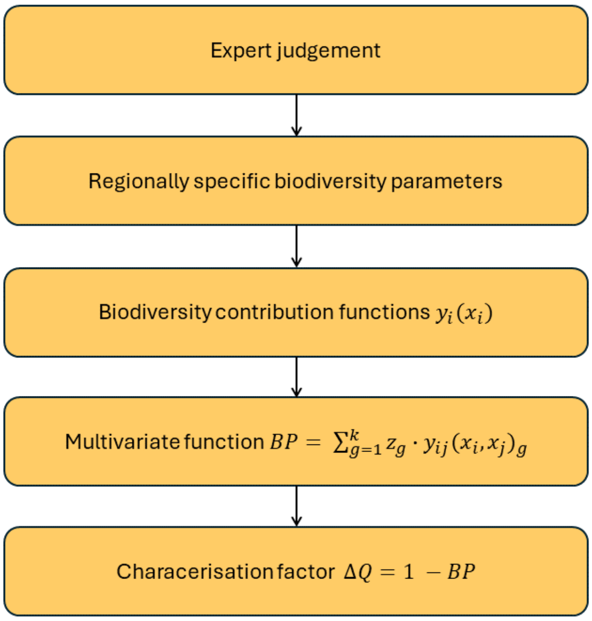

Figure 5: Overview of the model described by Lindner et al. (2021)

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4 Model Development

In this chapter, the development of a regionally specific BP model is described, starting from establishing the most significant attributes for biodiversity in the ecoregion Baltic Mixed Forests. Subsequently, management parameters related to these attributes are defined, along with their inherent relations and corresponding operators. Furthermore, the mathematical relation between parameters and their contribution to BP is defined through the development of parameter specific contribution curves. Finally, biodiversity contribution are weighted to determine their relative relevance for BP. Together, these steps enable the calculation of a BP related to forest management.

The process of developing the model relies entirely on experts on forest ecology and biodiversity. Expert judgement provides the foundation for establishing the most important attributes for biodiversity in the ecoregion, as well as for developing quantitative parameters for these attributes. All decisions made during the model development were either recommended or supported by experts. Expert selection was based on Swedish authors contributing to articles encountered in the literature review, in accordance with the recommendations of Lindner et al. (2021). In addition to the literature review, specific recommendations from researches contributed to broaden the distribution of expert profiles. Specifically, expert selection targeted a distribution of expert profiles and fields of expertise. In total, seven experts where asked to participate in the project, out of which five accepted the invitation and participated in interviews (Table 2).

Table 2: Experts contributing to the development of the model and their affiliation.

Name	Organisation	Expertise
Jörg Brunet	Swedish University of Agricultural Sciences	Ecology of temperate broadleaf forests
Lena Gustavsson	Swedish University of Agricultural sciences	Forest conservation
Mats Jonsell	Swedish University of Agricutural Sciences	Saproxylic insects
Anders Dahlberg	Swedish University of Agricutural Sciences	Fungi
Lars Salomon	Ekologigruppen	Epiphytic lichens

Interviews were conducted with a semi-structured approach, where the set of interview questions was based on the suggestion provided by Lindner et al. (2021) to describe the biodiversity of the ecoregion:

1. What is the typical biodiversity of forests in southern Sweden?
2. Which human activities threaten the biodiversity of forests in southern Sweden?
3. Which attributes within a plot indicates high and low biodiversity, respectively?
4. How can the state of biodiversity be qualitatively related to human activities on a plot level?
5. How can the state of biodiversity be quantitatively related to human activities on a plot level?
6. Are the management parameters related to biodiversity independent of each other?
7. Which is the fraction that each parameter contribute to biodiversity in relation to biodiversity as a whole?
8. (a) In an actively managed forest, what is the contribution to biodiversity from logging residues?

(b) In terms of significance for biodiversity, how important are logging residues in relation to other dead wood?

The interviews were based on the spatial scale of a stand, rather than on landscape level. While assessment of biodiversity impact can be argued to be relevant predominately on a landscape scale (Ranius et al., 2018), an assessment on stand level provides a better foundation for data collection from individual forest owners. Furthermore, stand level studies are valuable, as a limited biodiversity impact on stand level also implies a limited impact on landscape level (Ranius et al., 2018). To validate the information obtained through the expert consultation, experts were asked if they knew of anyone whom would disagree with their opinion. Based on expert opinion, spruce (*P. abies*) was classified as an exotic species in the ecoregion.

4.1 Biodiversity attributes

The interviews resulted in the identification of five main attributes contributing to forest biodiversity in the ecoregion:

- The presence of trees older than 150 years
- A diversity of regionally native tree species
- Limited acidity
- High volumes and diversity of dead wood
- The presence of heterogeneous structures or disturbances, creating a variety of microhabitats

Management activities were assessed to have a significant influence on only three of the five attributes. In consequence, the attributes limited acidity and heterogeneity were omitted from the model. The three remaining attributes where subdivided into quantitative management parameters, generating a total of eight management parameters.

4.2 Management parameters

The management parameters relate forestry to the attributes of ecoregion specific biodiversity. One management parameter was related to old trees, two parameters were related to tree species diversity and five parameters were related to dead wood. The first attribute, the presence of old trees, was measured by the number of trees aged 150 years or older per hectare. The second attribute, diversity of native tree species, was measured by the number of tree species per hectare, combined with a limited area cover of exotic tree species. Finally, the biodiversity contribution from dead wood was subdivided into three management parameters based on diameter classes. All classes were measured in volume per hectare. The two finer classes follows the differentiation between FWD and CWD, while a third class was added to account for coarse stems of large dead trees:

- Class 1: Diameter >50 cm
- Class 2: Diameter 10-50 cm
- Class 3: Diameter <10 cm

Logging residues from native tree species were judged by experts to provide a contribution to biodiversity in terms of dead wood. Therefore, two management parameters related to retained logging residues were added.

The first targeted the volume per hectare of retained CWD logging residues (>10 cm in diameter) from native tree species, while the other targeted the area fraction (%) of logging residue removal. The eight management parameters and their unit ranges are presented in Table 3.

Table 3: The eight management parameters, including their unit and the parameter range.

Parameter	Unit	Range
Number of old trees	1/ha	0-30
Tree species diversity	1/ha	0-10
Exotic species	% area	0-100
Dead wood class 1	m^3/ha	0-20
Dead wood class 2	m^3/ha	0-20
CWD Logging residues	m^3/ha	0-20
Dead wood class 3	m^3/ha	0-20
Removal area fraction	% logged area	0-100

The biodiversity contribution from each of the eight management parameters was described by a contribution curve. Guided by expert opinion, contribution curves were drawn by the author and subsequently reviewed by professor Jörg Brunet. In example, the contribution curve for old trees specify that approximately 25 old trees/ha are required to reach the full biodiversity contribution from this specific management parameter (Figure 6). The variables building the biodiversity contribution functions are presented in further detail in Appendix 1 and each of the contribution curves are presented individually in Appendix 2.

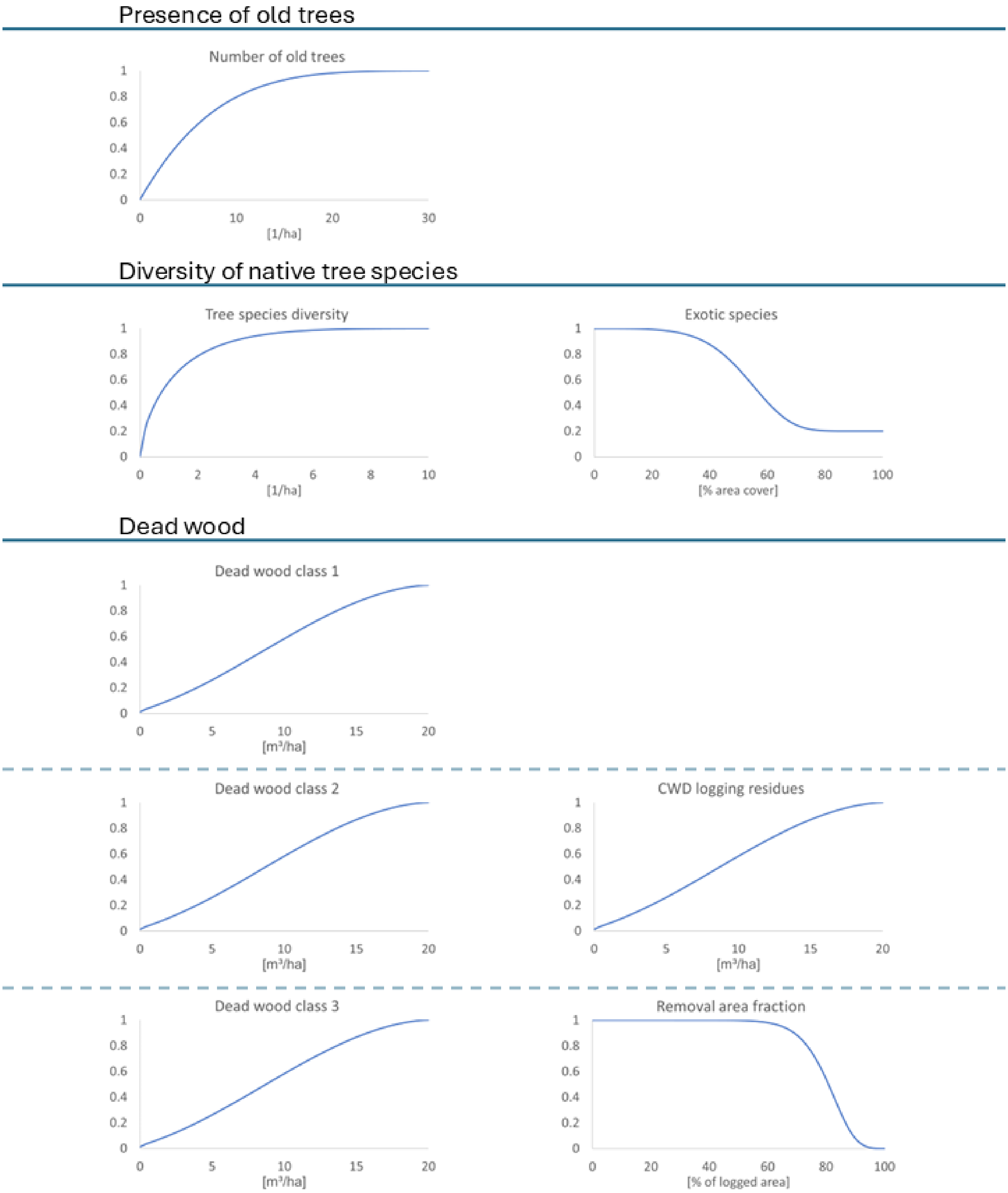

Figure 6: Contribution curves of the management parameters. The x-axis is the specific metric to quantify the management parameter, while the y-axis in all figures is the biodiversity contribution in the interval [0,1].

4.3 Parameter relationships

Relations of dependence are present where more than one management parameter is related to the same biodiversity attribute. Experts agreed that a diversity of native tree species needed to be combined with a limited area cover of exotic tree species to reach the full biodiversity potential. Accordingly, the parameters number of tree species and limited area cover of exotic tree species formed a common biodiversity contribution, corresponding to a *strict AND*-operator defining the relation between the two parameters. In terms of dead wood, native logging residues were judged to be able to replace some naturally occurring dead wood of similar coarseness. Effectively, retaining logging residues coarser than 10 cm in diameter is considered roughly as good as retaining other CWD below 50 cm in diameter. With regard to logging residues finer than 10 cm in diameter, setting aside a fraction of the felled area from logging residue removal was considered roughly as good as retaining other FWD. Accordingly, the relation between logging residues and dead wood of classes 2 and 3 is described by a *soft OR*-operator. Since no logging residues reach a diameter of 50 cm, class 1 dead wood was considered unrelated to logging residue removal.

Five independent biodiversity contributions emerged following the establishment of parameter relationships. These were the number of old trees, tree species diversity and dead wood classes 1,2 and 3. The area cover of exotic species was covered by the tree species diversity contribution, while CWD logging residues and removal area fraction was covered by dead wood classes 2 and 3, respectively.

4.4 Contribution weight

Each of the five biodiversity contributions was assigned a contribution weight. The presence and quantity of trees older than 150 years was identified by experts as the single most important contribution and assigned a contribution weight of 40% of the total biodiversity potential. Divided equally between the two remaining attributes, native tree species diversity and dead wood was assigned a contribution weight of 30% each. In turn, the contribution weight of dead wood was divided between the subcategories. 15% was assigned to class 1 (>50 cm), while 10 % was assigned to the contribution from class 2 (10-50 cm) or coarse logging residues. The remaining 5% were assigned to class 3 (<10 cm) or area fraction of logging residue removal.

4.5 BP model

The final model (Figure 7) was reviewed and accepted by Jörg Brunet and Thomas Ranius, both professors at the Swedish University of Agricultural Sciences. The BP model represent the eight management parameters and their contributions to BP.

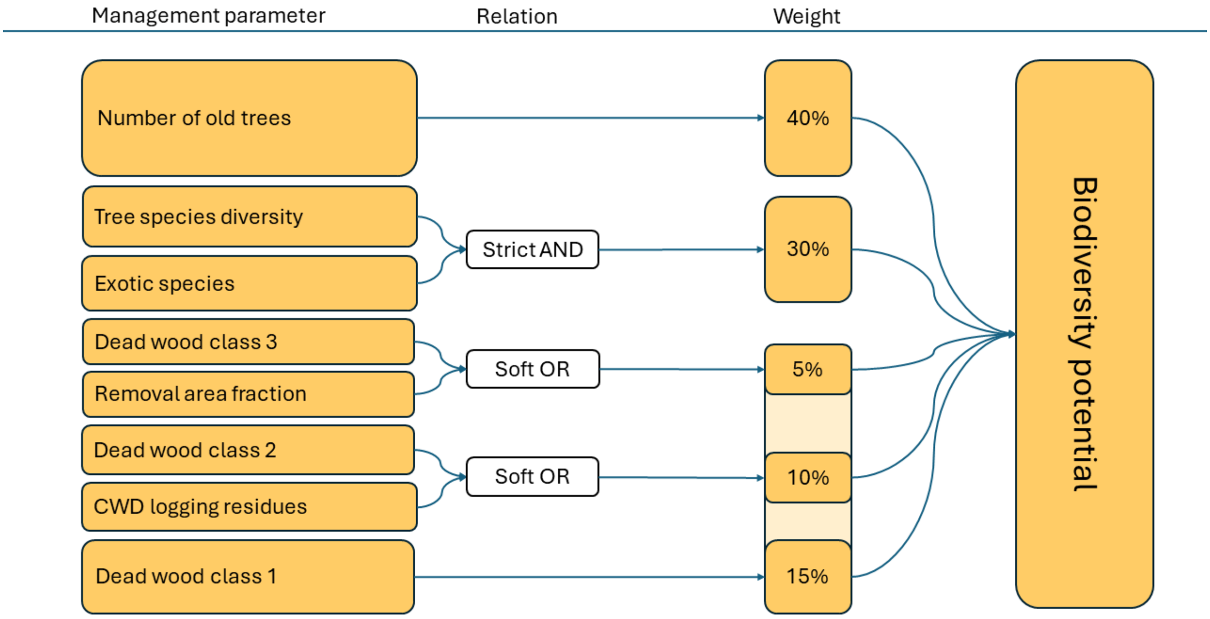

Figure 7: Biodiversity parameters and their contribution to biodiversity as a whole.

5 Case study

In the following chapter, the use of logging residue fuels at Kraftringens CHP plant Örtoftaverket is described and evaluated from an LCA perspective. The case study includes the application of the developed BP model to calculate the biodiversity impact related to the removal of logging residues. The case study is based on the framework of ISO 14044:2006 (International Organization of Standardization, 2006) as a basis for the assessment. Essentially, the case study follows the same methodology as was used in the Environmental Product Declaration (EPD) on Kraftringens district heating (Kraftringen Energi AB, 2022), based on the Product Category Rules (PCR) for the production of hot water and electricity (Lundmark, McGowan, 2021).

Seven forest owners or managers contributed with inventory data to the case study. The contribution from forest properties extends to 12 stands where logging residues were harvested, since several properties provided data for more than one stand. Each of the 12 stands can be viewed as a separate case study, investigating the biodiversity impact related to the removal of logging residues from the specific stand. Logging residues from each single stand are assessed to represent a realistic contribution to the input fuel to Örtoftaverket. However, these contributions represent only a small fraction of the total fuel delivered to Örtoftaverket.

5.1 Goal and scope

The goal of the case study is to quantify the impact on biodiversity related to the removal of logging residues. The study aims to investigate differences in biodiversity impact between logging residues from different stands and from different suppliers. Furthermore, the study investigates to what extent forest owners can supply quantitative information relevant for biodiversity impact assessment of forestry products. The scope of the study is limited to site specific conditions at Örtoftaverket, located in southwestern Scania. The study is based on site specific fuel data covering the production year 1 August 2022 to 31 of July 2023.

5.1.1 Functional unit

District heating is the studied product, with the functional unit being *1 kWh of hot water produced and thereafter distributed to a customer*.

5.1.2 System description

During the production year of 2022 to 2023. fuelwood, including logging residues, comprised one third of the total energy input to Örtoftaverket. In turn, logging residues are subdivided into a variety of fuel classes based on tree species and from what part of the tree the residues originate (Figure 8). Some classes of logging residues are not specified in detail and simply referred to as "logging residues" or "part of tree". In essence, assigning logging residues to a specific fuel class is equivalent to assigning them an energy content.

Different supplies of fuels are mixed at the fuel landing to generate a fuel mix with a desired energy content. Fuel arriving at the plant is weighed and sampled for water content, which forms the basis for the fuel mix. However, the water content of the fuel does not affect the final energy output of the plant, since flue gas condensation recovers the energy required for vaporisation of the water (O. Bengtsson, fuel technician at Örtoftaverket, personal communication, January 22. 2024).

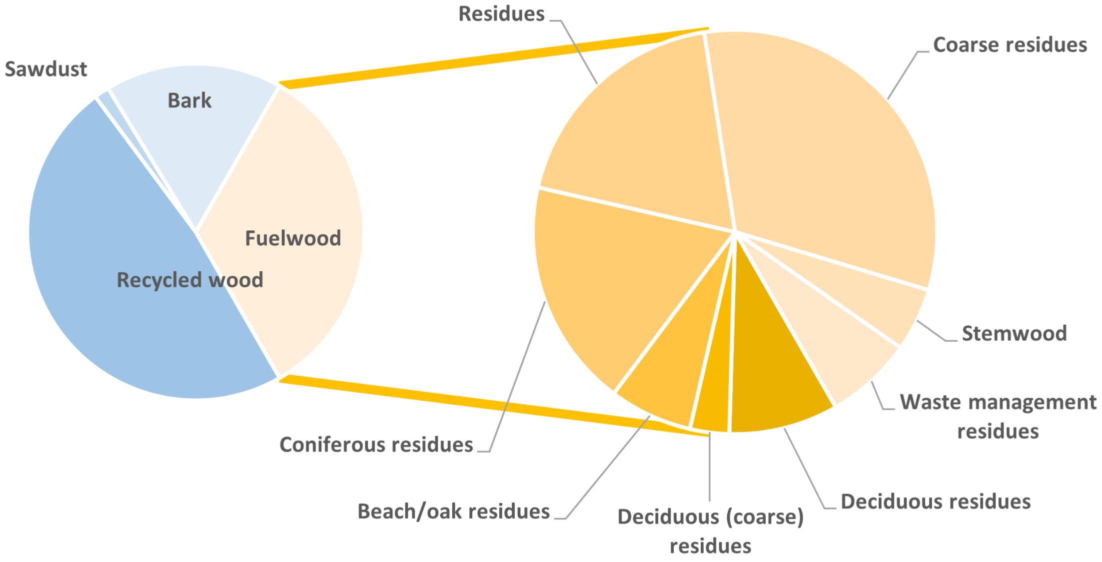

Figure 8: Fuel mix with detail on fuelwood as input fuel to Örtofta CHP plant during the production year 2022 to 2023

The life cycle stages related to the removal of logging residues are located upstream of the CHP plant. The first defined process step is forestry, which in reality is comprised of a multitude of management activities. Forestry generates several product streams and logging residues constitute only a fraction of the produced fuelwood. Essentially, forestry include all the management activities related to the plantation, management and logging operation of the forest. Three unit processes are specific for the removal of logging residues, and are therefore highlighted here. Firstly, logging residues left on the stand after final felling are forwarded to a nearby road. Secondly, a mobile chipper converts logging residues to logging residue woodchips. The third and final step represents the transport of logging residue woodchips to Örtoftaverket.

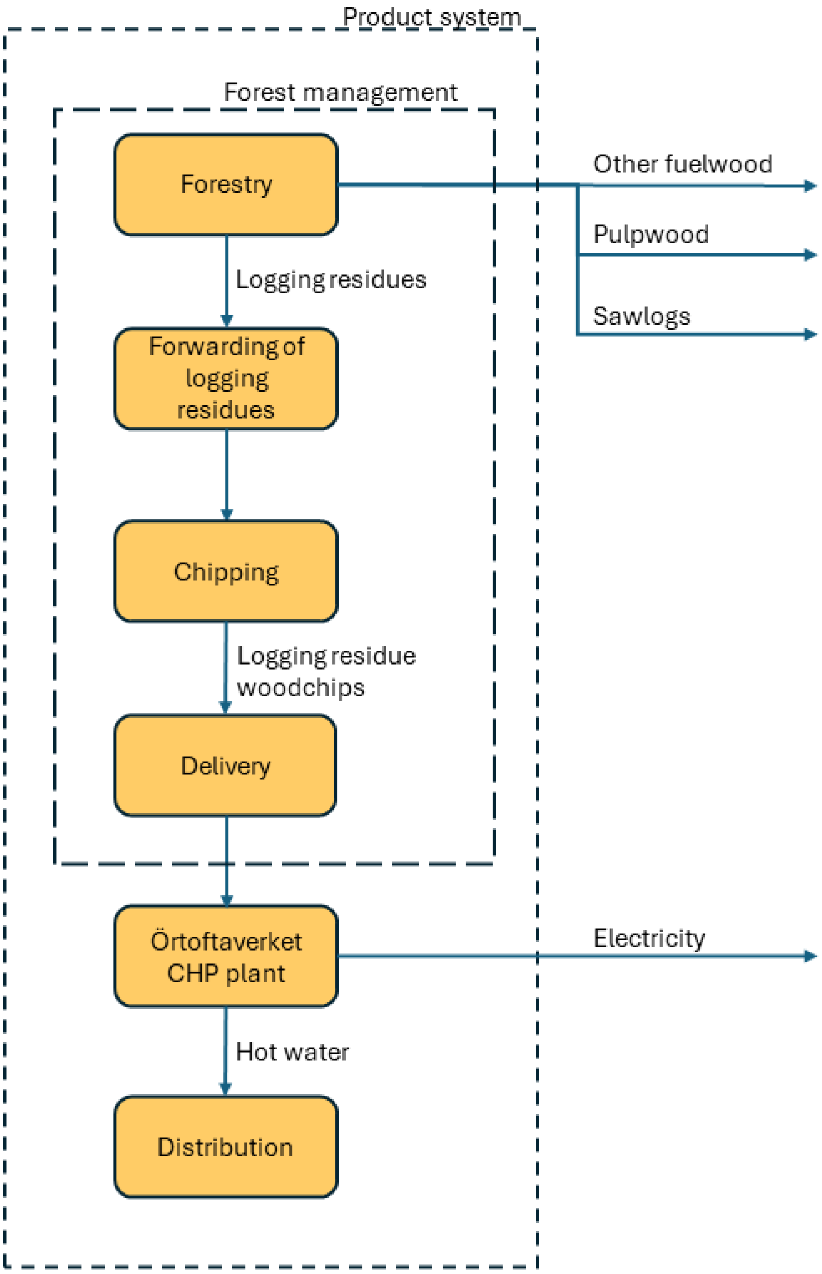

Figure 9: Process flow chart of the product system. The wood produced in forestry is divided between the three main streams sawlogs, pulpwood and fuelwood. Logging residues is a subcategory of fuelwood.

5.1.3 System boundaries and delimitations

While process steps across the entire life cycle of the product can be associated with biodiversity impact, this study focuses on the removal of the logging residues. The study uses forest management as the only studied process step. Doing so, the study merges all the process steps located upstream of Örtoftaverket, including forwarding, chipping and delivery of logging residues.

The system boundaries imply that the considered biodiversity impact is limited to a restricted fraction of the fuel and a marginal part of the life cycle of the product. Furthermore, it only considers logging residues as a habitat in terms of its contribution to biodiversity potential. Accordingly, no biodiversity impact is considered related to the usage of heavy machinery required to extract the logging residues. No formal cut-off criteria were defined as part of the study.

The study can be classified as "cradle to gate". The cradle is shared with the overall product system and the gate refers to the fence of Örtoftaverket. According to Lundmark, McGowan (2021), the cradle is defined as the moment when resource flows cross the border between nature and the product system. From a viewpoint of biodiversity, this can be considered the moment when biodiversity potential deviate from the reference state Q_{ref}. In this case study, materials enter the product system and when they cross the boundary between nature and the managed forest, e.g. when carbon dioxide is sequestered as biomass in growing trees or when nutrients are extracted from the ground through tree roots.

5.1.4 Allocation

Allocation of environmental impact between products is one way of handling multi output processes. In the studied product system, process steps with more than one output product is present on two occasions. Firstly, forest management generates more product streams than logging residues and secondly, the energy conversion process within the CHP plant generates both district heating and electricity. Allocation between the product streams of the forest management cycle is avoided by separating the removal of logging residues from other management processes and product streams. Nonetheless, impact is allocated between district heating and electricity according to the *Alternative Generation Method* (Lundmark, McGowan, 2021). In accordance with the model, 52% of the environmental impact was associated with heat production and the remaining 48% with the production of electricity.

5.1.5 Environmental impact assessment

The study is limited to the impact on biodiversity, which is sole environmental impact category to be assessed in the LCIA. The impact characterisation model is based on the BP-method and follows the methodology described by Lindner et al. (2021), with the category indicator expressed as the quality change proportional to the areatime per kWh (Table 4).

Table 4: Overview of LCIA approach.

Impact category	Biodiversity
Characterisation model	Lindner et al., 2021
Characterisation factor	Quality change (ΔQ)
Category indicator	$\Delta Q \cdot \text{year} \cdot m^2$

The quality change is obtained through comparing the biodiversity potential on the stand before and after the removal of logging residues. Before the removal of logging residues, the removal area is considered below landscape thresholds for biodiversity impact.

5.1.6 Limitations and key assumptions

- Flue gas condensation at Örtofta allows for an efficiency above 100% in relation to the net calorific value of the fuel. Since flue gas condensation is assumed to eliminate the influence from fuel water content, all logging residues are considered equal in terms of efficiency. Therefore, for simplicity, the CHP plant efficiency is assumed to be 100% for all logging residues.
- Impact from upstream infrastructure is not included.
- The assessment is only applicable to the additional impact on biodiversity from the removal of logging residues. Therefore, it is not representative of the biodiversity impact of the product (district heating). A full assessment of biodiversity impact would require an inclusion of more life cycle stages.
- Logging residues are often considered a residual product (Lundmark, McGowan, 2021) and therefore burden-free of environmental impact. However, including logging residues as a by-product can be motivated with regard to their increased economic value and concern from a biodiversity perspective.
- The results of the study are regionally specific and cannot be compared across regions or countries without further development.

5.1.7 Data sources

Data collection is conducted through structured interviews with suppliers of logging residues. 12 separate stands, spread out over 7 properties, with logging residue removal contributed to the inventory data. According to the tree species dominating the stand where logging residues were harvested, each supply is assigned to a fuel class. The fuel class is the foundation for assigning an energy content of the logging residues, with generic data on energy content being supplied through Kraftringen. In essence, each of the 12 stands constitute a case study of it's own. The properties are labelled A-G and the stand is specified by the name of the the dominating tree species.

5.1.8 Data quality

All input data can be considered primary data, collected for site-specific conditions. Respondents were asked to answer the questions based on the current situation on their forest property. When forest management measures were concerned, including logging and harvest of logging residues, respondents were asked to answer according to how they would perform the measure if it was to be performed today. No measures were taken to validate the collected data.

5.2 Life Cycle Inventory

All inventory data contributing to the study was assigned to the forest management process step. This process step represents merging all activities upstream of Örtoftaverket. Inventory data is collected for forest management as a whole, but distinguishes between logging residues and other forestry products to avoid allocation. Nevertheless, allocation is necessary to distinguish between the two products district heating and electricity in the process step *CHP plant*.

The path from the forestry to delivery of logging residue woodchips follows the dry-stacked method, presented in further detail below. Although alternatives occur, this represents the most frequently used method to harvest logging residues in Swedish forestry (Nilsson, 2020, Egnell, 2013). Inventory data related to logging residues was collected in the unit cubic meter loose measure of logging residue wood chips (m^3l), which is a metric of chipped fuelwood.

5.2.1 Forestry

The first process step is the forestry. Forestry incorporates numerous activities, with examples including the planting of trees and logging at the end of the rotation time. When logging residues are to be extracted, the logging operation is so called fuel adapted, with logging residues being left piled on the stand. Inventory data is presented in Tables 5, 6 and 7. The parameters including logging residues are stand specific and connected to tree species, while all other parameters reflect forestry on a property level. Each stand is specified by property (A-G) and the dominating tree species.

Table 5: Inventory data on management parameters, suppliers A-B. The parameter value is represented by x, while y is the corresponding biodiversity contribution in the interval [0,1]

Management parameter	**Metrics**	**A: Spruce**	**A: Beech**	**B: Spruce**	**B: Beech**
Old trees	x [1/ha]	0.00	0.00	0.00	0.00
	y	0.00	0.00	0.00	0.00
Tree species diversity	x [1/ha]	3.00	3.00	2.00	2.00
	y	0.89	0.89	0.79	0.79
Exotic species	x [% area]	62.00	62.00	38.00	38.00
	y	0.38	0.38	0.90	0.90
Deadwood >50 cm	x [m^3/ha]	0.20	0.20	0.04	0.04
	y	0.03	0.03	0.02	0.02
Deadwood 10-50 cm	x [m^3/ha]	1.00	1.00	0.98	0.98
	y	0.06	0.06	0.06	0.06
Remaining logging residues >10 cm	x [m^3l/ha]	0.00	3.75	0.00	20.00
	y	0.01	0.19	0.01	1.00
Total logging residues >10 cm	x [m^3l/ha]	0.00	18.75	0.00	80.00
	y	0.01	0.99	0.01	1.00
Deadwood <10 cm	x [m^3/ha]	0.50	0.50	0.98	0.98
	y	0.04	0.04	0.06	0.06
Area of logging residue removal	x [% logged area]	100.00	100.00	100.00	100.00
	y	0.00	0.00	0.00	0.00

Table 6: Inventory data for forest management, suppliers C-D. The parameter value is represented by x, while y is the corresponding biodiversity contribution in the interval [0,1].

Management parameter	Metrics	C: Spruce	C: Pine	D: Spruce	D: Beech/oak
Old trees	x [1/ha]	0.00	0.00	0.08	0.08
	y	0.00	0.00	0.02	0.02
Tree species diversity	x [1/ha]	7.00	7.00	3.00	3.00
	y	0.99	0.99	0.89	0.89
Exotic species	x [% area]	31.00	31.00	45.00	45.00
	y	0.96	0.96	0.79	0.79
Deadwood >50 cm	x [m^3/ha]	0.00	0.00	1.00	1.00
	y	0.01	0.01	0.06	0.06
Deadwood 10-50 cm	x [m^3/ha]	0.50	0.50	3.00	3.00
	y	0.04	0.04	0.15	0.15
Remaining logging residues >10 cm	x [m^3l/ha]	0.00	5.00	0.00	16.67
	y	0.01	0.26	0.01	0.93
Total logging residues >10 cm	x [m^3l/ha]	0.00	25.00	0.00	166.67
	y	0.01	1.00	0.01	1.00
Deadwood <10 cm	x [m^3/ha]	0.50	0.50	1.00	1.00
	y	0.04	0.04	0.06	0.06
Area of logging residue removal	x [% logged area]	80.00	70.00	100.00	100.00
	y	0.54	0.88	0.00	0.00

Table 7: Inventory data on management parameters, suppliers E-G. The parameter value is represented by x, while y is the corresponding biodiversity contribution in the interval [0,1].

Management parameter	**Metrics**	**E: Spruce**	**F: Spruce**	**F: Pine**	**G: Spruce**
Old trees	x [1/ha]	0.50	1.00	1.00	1.00
	y	0.07	0.13	0.13	0.13
Tree species diversity	x [1/ha]	6.00	6.00	6.00	6.00
	y	0.99	0.99	0.99	0.99
Exotic species	x [% area]	54.00	32.00	32.00	85.45
	y	0.58	0.95	0.95	0.20
Deadwood >50 cm	x [m^3/ha]	1.00	0.00	0.00	0.00
	y	0.06	0.01	0.01	0.01
Deadwood 10-50 cm	x [m^3/ha]	0.80	0.00	0.00	3.00
	y	0.05	0.01	0.01	0.15
Remaining logging residues >10 cm	x [m^3l/ha]	0.00	0.00	19.44	0.00
	y	0.01	0.01	1.00	0.01
Total logging residues >10 cm	x [m^3l/ha]	0.00	0.00	194.44	0.00
	y	0.01	0.01	1.00	0.01
Deadwood <10 cm	x [m^3/ha]	0.20	0.00	0.00	0.00
	y	0.03	0.01	0.01	0.01
Area of logging residue removal	x [% logged area]	80.00	60.00	60.00	75.00
	y	0.54	0.98	0.98	0.75

In addition to data related to management parameters of the BP-model, data is collected on energy content and yield of logging residues, as well as on rotation time of the forest stand. Inventory data on the parameters not related to the BP-model is necessary to relate the biodiversity impact to the functional unit. The energy content of the logging residues is influenced by the tree species, resulting in different fuel classes. The two fuel classes relevant for the inventory data was coniferous residues and beech/oak residues. Each of the 12 supplies is assigned to a fuel class based on the tree species dominating the specific stand. The fuel class provides the basis for determining the energy content, with generic data provided by Kraftringen (Table 8). In contrast, inventory data on rotation time and volume yield is collected from the forest owners. The effective yield of logging residues vary between tree species, with generic numbers stretching from 75 m^3l/ha for pine (*Pinus sylvestris*) to 300 m^3l/ha for beech (*F. sylvatica*). Data on water content is not collected with regard to the flue gas condensation at Örtoftaverket.

Table 8: Energy content of different classes of logging residues.

Tree species	Beech	Oak	Spruce	Pine
Fuel class	Beech/oak residues		Coniferous residues	
Energy content [MWh/m^3l]	1.05	1.05	0.88	0.88

Inventory data on fuel class related energy content, volume yield and rotation time is used to calculate the land use parameter. The land use parameter represents the area required to generate 1 kWh of logging residues during one year, in terms of [$ha/kWh/year$]. Generic energy content, related to tree species and fuel class, is presented in Table 8. The inventory data required to arrive at land use for each of the supplies of logging residues is presented in Tables 9 and 10.

Table 9: Inventory data related to land use, suppliers A-C. The final row represents the land use per functional unit, after allocation.

Plot	A: Spruce	A: Beech	B: Spruce	B: Beech	C: Spruce	C: Pine
Energy content [MWh/m^3l]	0.88	1.05	0.88	1.05	0.88	0.88
Volume yield [m^3l/ha]	120	300	170	300	120	70
Rotation time [years]	60	100	55	110	55	70
[ha/m^3]	8.33E-03	3.33E-03	5.88E-03	3.33E-03	8.33E-03	1.43E-02
[ha/MWh]	9.51E-03	3.18E-03	6.71E-03	3.18E-03	9.51E-03	1.63E-02
[ha/kWh]	9.51E-06	3.18E-06	6.71E-06	3.18E-06	9.51E-06	1.63E-05
Land use [ha/kWh/year]	5.70E-04	3.18E-04	3.69E-04	3.50E-04	5.23E-04	1.14E-03
Land use [m^2/kWh/year]	5.70	3.18	3.69	3.50	5.23	11.41
Land use per FU [m^2/kWh/year]	3.02	1.68	1.96	1.85	2.77	6.05

Table 10: Inventory data related to land use, suppliers D-G. The final row represents the land use per functional unit, after allocation.

Plot	D: Spruce	D: Beech/oak	E: Spruce	F: Spruce	F: Pine	G: Spruce
Energy content [MWh/m^3l]	0.88	1.05	0.88	0.88	0.88	0.88
Volume yield [m^3l/ha]	100	315	200	200	250	80
Rotation time [years]	55	120	45	60	50	65
[ha/m^3]	1.00E-02	3.17E-03	5.00E-03	5.00E-03	4.00E-03	1.25E-02
[ha/MWh]	1.14E-02	3.03E-03	5.70E-03	5.70E-03	4.56E-03	1.43E-02
[ha/kWh]	1.14E-05	3.03E-06	5.70E-06	5.70E-06	4.56E-06	1.43E-05
Land use [ha/kWh/year]	6.27E-04	3.63E-04	2.57E-04	3.42E-04	2.28E-04	9.27E-04
Land use [m^2/kWh/year]	6.27	3.63	2.57	3.42	2.28	9.27
Land use per FU [m^2/kWh/year]	3.33	1.93	1.36	1.81	1.21	4.91

5.2.2 Forwarding of logging residues

Following the logging operation, the logging residues are left to dry and defoliate on the stand before they are transported with a forwarder to larger piles, usually at the side of the nearest road.

5.2.3 Chipping

A mobile chipper converts piled residues stored at the roadside to wood chips.

5.2.4 Delivery

Chipped logging residues are transported directly from the roadside to the Örtoftaverket CHP plant.

5.2.5 Örtoftaverket CHP plant

Logging residue woodchips delivered to Örtoftaverket are included in the fuel mix. The production at the energy conversion plant generates both hot water and electricity, which is why allocation is necessary between the two products. Allocation according to the alternative generation method (Lundmark, McGowan, 2021) means 52% of the fuel energy content is allocated to the production of hot water. Accordingly, 52% of the land area required to produce 1 kWh of logging residues is connected to the district heating system . No losses are included in the energy transition from logging residues to hot water of the district heating grid. Furthermore, variation in moisture content between logging residue supplies is assumed to have no impact on the efficiency.

5.3 Life cycle impact assessment

Following the collection of inventory data, biodiversity impact is calculated through three calculation steps. Firstly, BP of forest management as a whole is calculated, according to the BP model. BP is the sum of the five contributions in Tables 11 - 13. Secondly, the quality change (ΔQ) as a consequence of logging residue removal is calculated. The quality change is calculated through comparing the BP of a logging residue removal scenario to a no logging residue removal scenario. As such, the additional quality change generated by the removal of logging residues can be determined as the difference between the two BP values (Tables 11 - 13). In the final step, ΔQ, which represents the characterisation factor, is connected to land use. The final step relates quality change to the functional unit.

Table 11: Biodiversity contributions, BP and ΔQ for properties A-B. Logging residue removal (LRR) is included in the contributions from dead wood classes 1 and 2, according to the BP model.

	A: Spruce		**A: Beech**		**B: Spruce**		**B: Beech**	
	LRR	No LRR	LRR	No LRR	LRR	No LRR	LRR	No LRR
Presence of old trees	0.00		0.00		0.00		0.00	
Tree species diversity	0.10		0.10		0.21		0.21	
Dead wood class 1	0.00		0.00		0.00		0.00	
Dead wood class 2	0.01	0.01	0.02	0.09	0.01	0.01	0.09	0.09
Dead wood class 3	0.00	0.04	0.00	0.04	0.00	0.04	0.00	0.04
BP	0.11	0.16	0.13	0.24	0.22	0.27	0.31	0.35
ΔQ	0.04		0.11		0.04		0.04	

Table 12: Biodiversity contributions, BP and ΔQ for properties D-C. Logging residue removal (LRR) is included in the contributions from dead wood classes 1 and 2, according to the BP model.

	D: Spruce		**D: Beech/Oak**		**C: Spruce**		**C: Pine**	
	LRR	No LRR	LRR	No LRR	LRR	No LRR	LRR	No LRR
Number of old trees	0.01		0.01		0.00		0.00	
Tree species diversity	0.21		0.21		0.29		0.29	
Dead wood class 1	0.01		0.01		0.00		0.00	
Dead wood class 2	0.01	0.01	0.08	0.09	0.00	0.00	0.02	0.09
Dead wood class 3	0.00	0.04	0.00	0.04	0.02	0.04	0.04	0.04
BP	0.24	0.28	0.31	0.36	0.32	0.34	0.35	0.42
ΔQ	0.04		0.05		0.02		0.07	

Table 13: Biodiversity contributions, BP and ΔQ for properties E-G. Logging residue removal (LRR) is included in the contributions from dead wood classes 1 and 2, according to the BP model.

	E: Spruce		**F: Spruce**		**F: Pine**		**G: Spruce**	
	LRR	No LRR	LRR	No LRR	LRR	No LRR	LRR	No LRR
Presence of old trees	0.03		0.05		0.05		0.05	
Tree species diversity	0.17		0.28		0.28		0.06	
Dead wood class 1	0.01		0.00		0.00		0.00	
Dead wood class 2	0.00	0.00	0.00	0.00	0.09	0.09	0.01	0.01
Dead wood class 3	0.02	0.04	0.04	0.04	0.04	0.04	0.03	0.04
BP	0.24	0.26	0.38	0.38	0.47	0.47	0.16	0.17
ΔQ	0.02		0.00		0.00		0.01	

5.3.1 Biodiversity potential

The BP model output is the biodiversity potential of each stand. The BP reflects forest management, including the removal of logging residues. In Figure 10, the BP results are presented for suppliers A-G, with species name indicating the tree species dominating the specific stand where logging residues were removed. Although results exhibit a large variability between properties, the BP of beech dominated stands is consistently higher than that of spruce stands from the same property (Figure 10).

5.3.2 Quality change

A comparison of two scenarios constitute the basis for a subsequent assessment of quality change (ΔQ) related to logging residue removal. The first scenario is identical to the one used to calculate BP in Figure 10, hence including logging residue removal. The alternative scenario represents leaving all logging residues on the stand. A comparison of the BP of the two scenarios according to Equation 5 reveals the ΔQ of removing the logging residues from the stand.

$$\Delta Q = BP_{no\ LRR} - BP_{LRR} \tag{5}$$

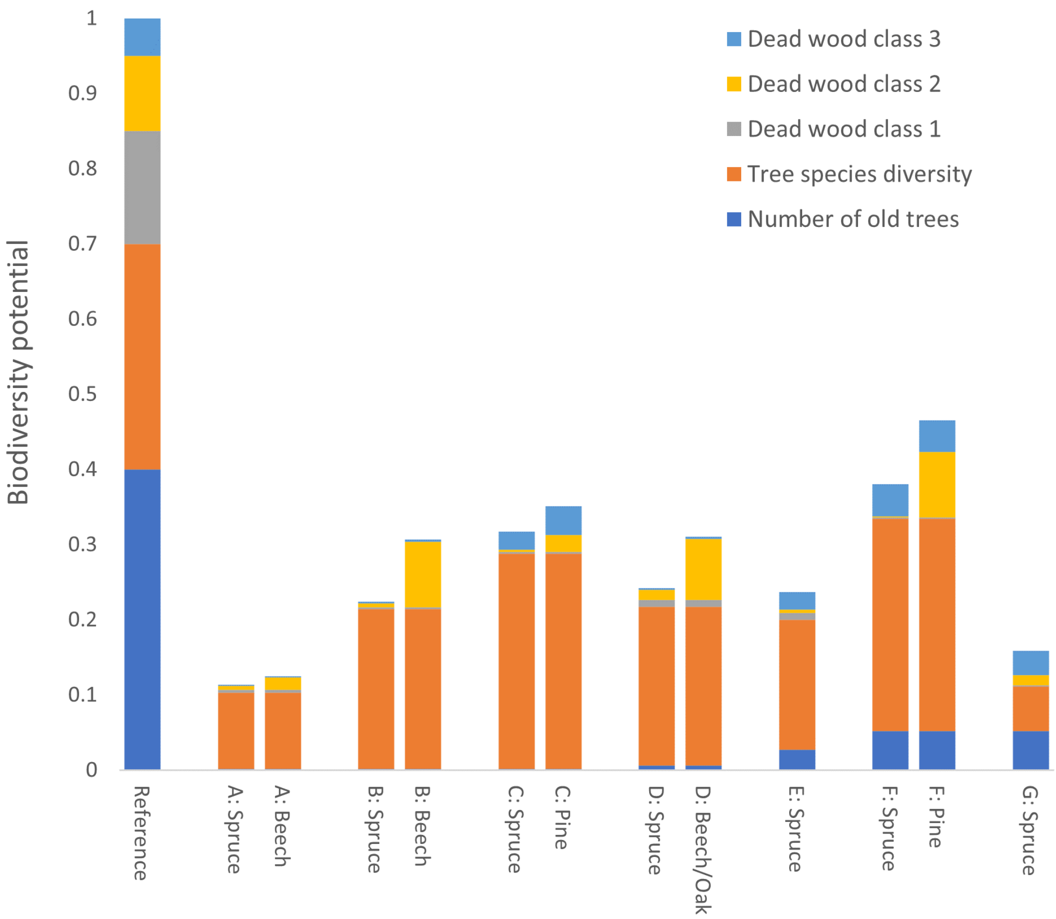

Figure 10: The five contributions and biodiversity potential (BP) for different stands of suppliers A-E. For comparison, the reference state, corresponding to Q_{ref} is displayed to the left in the figure.

The ΔQ from each stand is presented in Figure 11. Consistently, ΔQ remains below 10% of the reference state biodiversity potential ($_{ref}$) and is for some stands entirely absent. However, the proportion to which logging residues contribute to the actual BP of the stand can be as large as 50%, as displayed on property A. A comparison between stands on the same property reveal that spruce stands exhibit a lower ΔQ than neighbouring beech or pine stands.

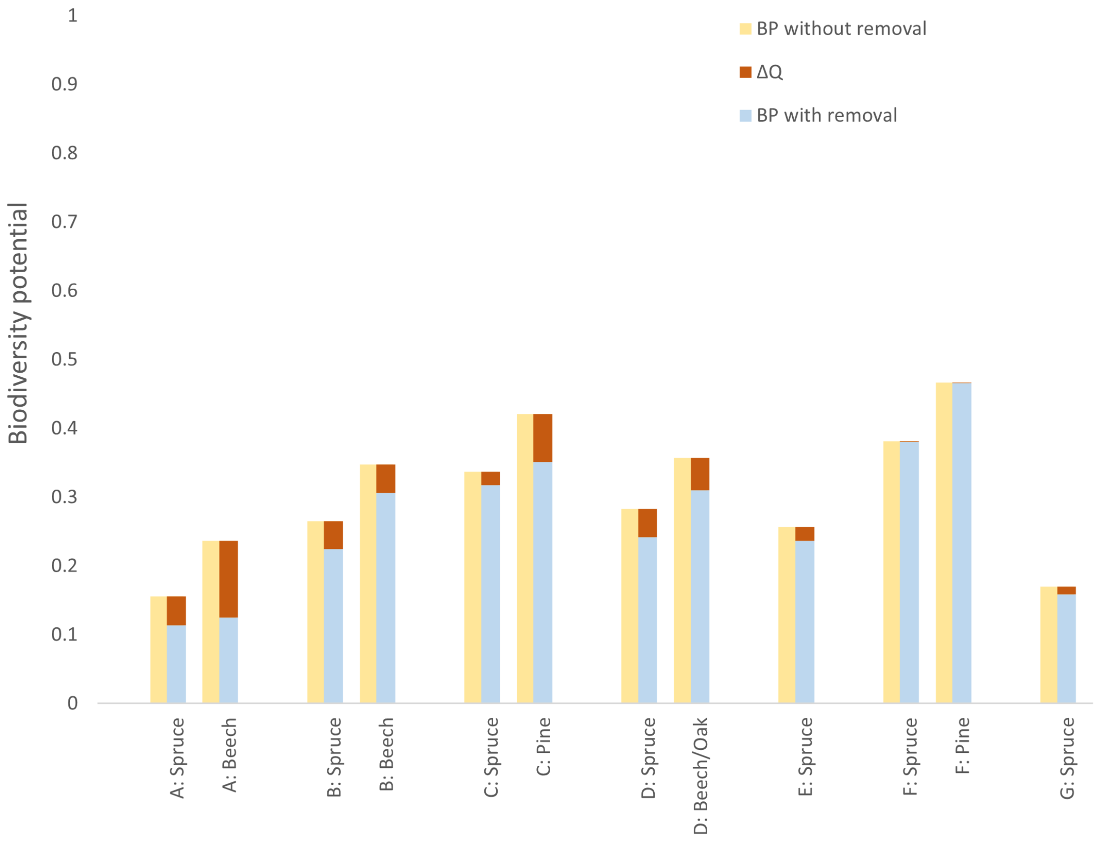

Figure 11: Biodiversity potential of different plots with and without logging residue removal. The red column illustrates the additional contribution to BP from logging residues, corresponding to (ΔQ).

5.3.3 Biodiversity impact

The quality change must be related to the functional unit to connect biodiversity impact to the studied product. The BP and ΔQ provides an indication of how forest management impacts biodiversity, but does not represent the biodiversity impact of district heating. For example, it does not take yield and energy content of the logging residues into account. Relating the biodiversity impact to these factors and by extension to the functional unit is conducted through calculating the category indicator results (Equation 6).

$$Bidiversity\ impact = \Delta Q \cdot Land\ use \tag{6}$$

The category indicator results are to be interpreted as the product of the quality change and the area required to produce 1 kWh of logging residues during one year, presented in the unit $\Delta Q \cdot year \cdot ha/kWh$ (Figure 12). The category indicator results are synonymous to the biodiversity impact per functional unit. As a consequence of a low yield of tops and branches, pine (*P. sylvestris*) residues from property C has the highest impact per functional unit. However, pine residues can also be associated with no biodiversity impact, as illustrated by the results from property F. In this case, the absent biodiversity impact is explained by a (ΔQ)-value of 0 for the stand specific removal of logging residues.

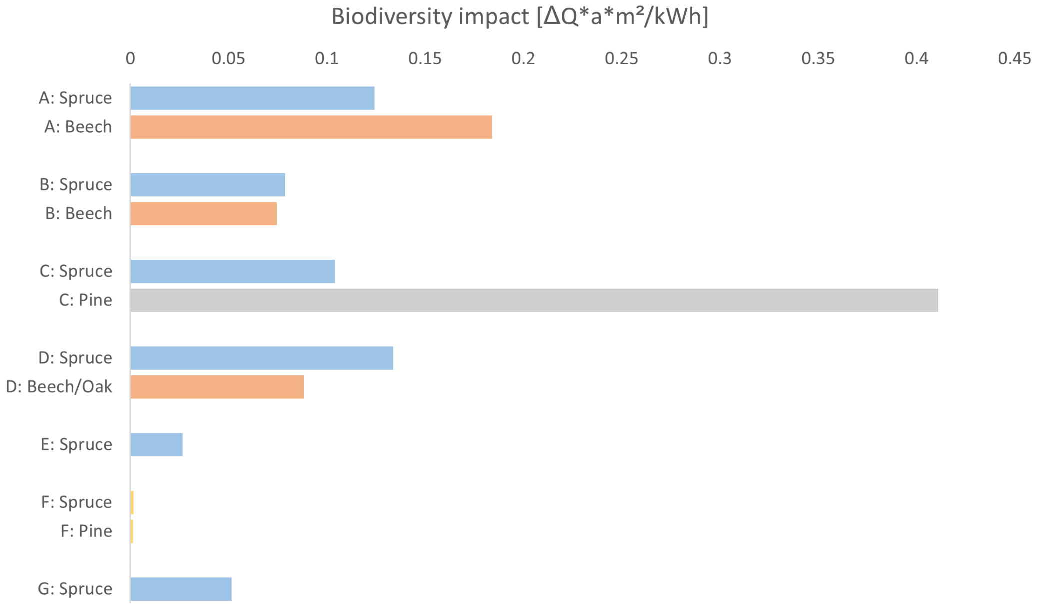

Figure 12: Biodiversity impact per functional unit. Blue represents spruce stands, orange represents beech stands and grey represents pine stands.

5.3.4 Sensitivity analysis

While the model builds on a vast number of assumptions, one of the more controversial is arguably the classification of Norway spruce (*P. abies*) as non-native in the model. Although a nationally native species, spruce is exotic to most parts of Scania and judged by experts to provide as little contribution to biodiversity as any exotic conifer. However, in the far north of the region we approach the natural distribution of the species, which in consequence should increase its contribution to biodiversity. To investigate the consequences of classifying spruce as a native species, spruce stands were subject to a sensitivity analysis. The analysis compares classifying spruce as an exotic and native species, respectively (Figure 13). According to Figure 13, classifying spruce as native will generate an increased ΔQ in some stands, but have a limited impact on other stands. The variability between stands is correlated to the amount of logging residues above 10 cm in diameter. For example, stands on property C and G contain significant volumes of this fraction, which generates an increase in ΔQ if these residues are classified as native. In contrast, other stands are assessed to contain only finer residues. The fine logging residues will not provide an additional contribution to biodiversity if classed as native.

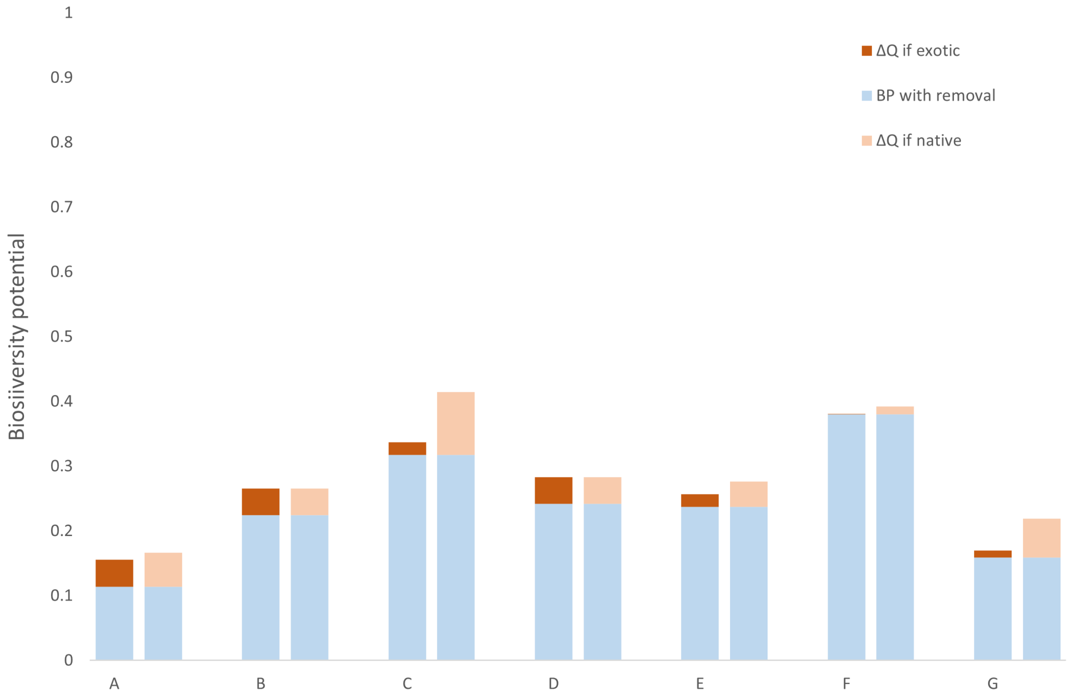

Figure 13: Comparison of two scenarios of ΔQ assessing the assumption to classify spruce as an exotic species in the region

The biodiversity impact per functional unit considers more parameters than just the quality change from a biodiversity perspective, as it also includes the productivity in terms of energy. The productivity can be subdivided into the factors yield [m^3l/ha] at final felling, energy content [kWh/m^3l] of the logging residues and rotation time. To investigate how these factors affect the category indicator results in comparison to ΔQ, a sensitivity analysis was conducted for spruce and beech stands, respectively. The sensitivity analysis uses the median within each category as a baseline and considers the full variation within each parameter in the data. The sensitivity analysis also considers the "combined" parameter, consisting of all parameters except ΔQ.

For both spruce and beech, ΔQ is the parameter with the largest variation and hence associated with the largest influence on the category indicator results (Figure 14). However, the parameters not directly related to biodiversity can also have a strong influence on the biodiversity impact category indicator results.

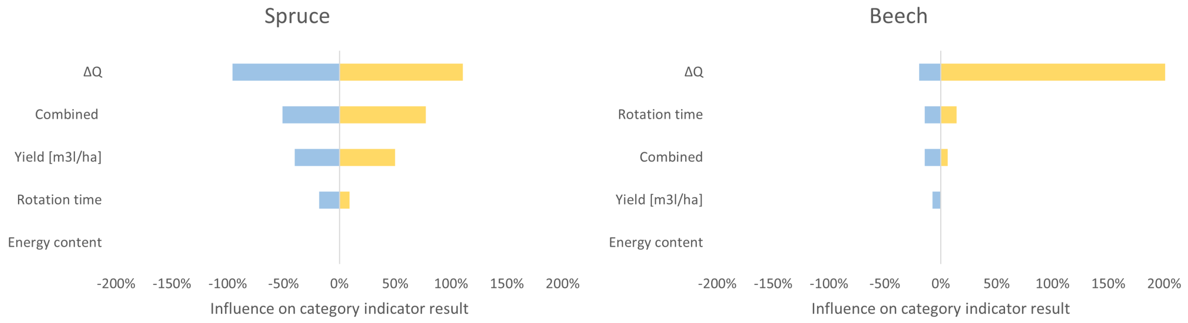

Figure 14: Sensitivity analysis displaying how parameter variability influences category indicator results.

Trees older than 150 years are largely absent from the properties participating in this study. In consequence, the biodiversity contribution from old trees was consistently low in the BP results (Figure 10). This is significant with reference to old trees being the single most important parameter, representing 40% of the BP. Nevertheless, all participating properties reported areas set aside for conservation purposes, implying areas are present where trees will be retained to complete their natural life cycle. However, as these conservation measures were mainly taken in recent years, the trees here are yet to reach an age of 150 years. Thus, there remains a time gap before the model will recognise their contribution from a biodiversity perspective. To account for how biodiversity potential will develop as a consequence of these conservation measures, data was also collected from four suppliers (D-G) on the number of trees expected to become 150 years old (Figure 15). This represents a possible approach to recognise management efforts aiming to improve biodiversity, which would otherwise be invisible in the model. The comparison in Figure 15 presents an increased BP on all properties in the projected future scenario.

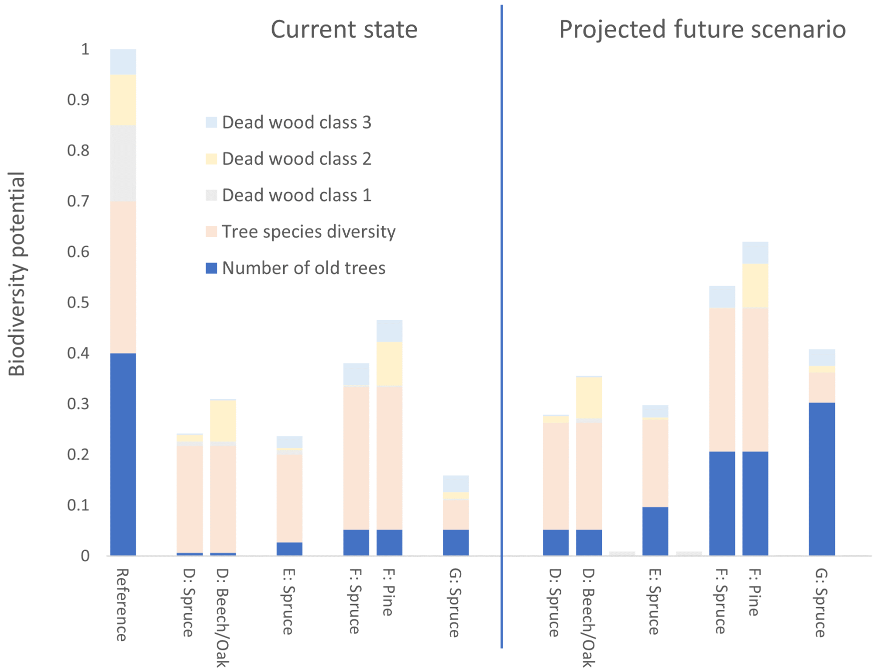

Figure 15: Evaluating the future contribution from land set aside for conservation purposes. On the left is the original BP, while the left illustrates the scenario where trees set aside from forestry are allowed to age until they reach the "old trees" category. Data only available for suppliers D-G.

6 Discussion

The focal points of the discussion are the model development and the case study application. In its entirety, the study represents an attempt to connect biodiversity potential, forest management and district heating from a Scanian perspective. The potential for further development is large, with reference to numerous issues arising along the development of the master thesis. The discussion chapter aims to highlight the most significant of these issues and provide suggestions on how they may be considered. The disposition of the discussion follows the development from inventory data collection to the calculation of biodiversity impact per functional unit. Each step contains it's own set of assumptions and limitations. The discussion assesses these steps separately before considering the model and its application as a whole.

6.1 Data collection and quality

Collecting inventory data on management parameters through interviews with forest owners revealed considerable uncertainties. Interviewed forest owners stated that they made coarse assumptions throughout, but most prominently regarding dead wood volumes. The risk for issues related to data quality was not insignificant considering approach and method, where the biodiversity potential model was developed with respect to the biodiversity attributes as defined by experts, without thoroughly considering the ability of forest owners to provide the input data. Nonetheless, forest owners contributing to the study were initially assessed to be well informed in terms of forest management on their respective properties. In fact, they were selected based on the notion that they would be able to contribute to the inventory data. As such, these forest owners may not be representative, which means the average forest owner would possibly struggle even more with providing inventory data.

Comparing results between different suppliers of logging residues must consider that the data is based on coarse assumptions. Comparing between forest owners is difficult since the inventory data is influenced by the individual approach to estimate management parameter data. Stands where the data was supplied by the same forest owner provide a more promising basis for comparing the results of this study. When collecting data on two stands from the same forest owner, it is expected that there is greater consistency in the assumptions. In consequence, comparisons between logging residues in this study are advised to be restricted to the same property.

The issues related to data quality highlight the need to improve the method of acquiring inventory data. One possible approach to improve data quality is adapting the model to the ability of the supplier, selecting management parameters which are documented or more simple to estimate than e.g. dead wood volumes. In essence, this requires a simplification of the model which risks compromising model accuracy. An alternative is to pursuit other or complementary methods of collecting the inventory data. The development of comprehensive methods to collect data on structural components, like dead wood, are highlighted in emerging EU policy. Such development could significantly facilitate the collection of quality data on management parameters. Data on e.g. dead wood and tree species composition is also available through national monitoring programs (National Forest Inventory), but not on the spatial level of individual forest owners.

6.2 Biodiversity potential

The BP reveal the conditions for biodiversity in relation to the reference state. Moreover, it visualises the impact on the biodiversity potential from forest management as a whole. This impact is illustrated by the difference between the BP of each of the stands and the reference BP. The modelled BP show that tree species diversity dominates the biodiversity contribution on all properties (A-G). In contrast, biodiversity contributions from old trees and dead wood above 50 cm in diameter are largely absent on most properties.

Comparing between stands on the same property show that beech and pine dominated stands maintain a higher BP than neighbouring spruce stands. From a logging residues perspective, this is significant as the difference is mainly constituted by a contribution from coarse (CWD) branches remaining on the stand after logging residue removal. As beech and other deciduous trees naturally have coarser branches than spruce, the logging residues of beech contain a larger amount of branches of this quality. Although most of these coarse branches are removed when the logging residues are harvested, some remain on the forest floor, providing a contribution to the biodiversity potential. On the contrary, the logging residues left on spruce stands do not contribute to the biodiversity potential, since spruce is classified as an exotic species.

6.3 Quality change

The impact on biodiversity potential from the removal of logging residues is captured in the model by ΔQ. In contrast to BP, the ΔQ relates exclusively to logging residues. Removing the logging residues can result in an increased ΔQ according to two possible pathways. Firstly, it can represent reducing the amount of native CWD in a dead wood poor environment. Secondly, removing logging residues on a large fraction of the logged area risks exceeding landscape removal thresholds for FWD.

The calculated values consistently show a larger ΔQ on beech dominated stands compared to spruce dominated counterparts. In the latter case, the exotic logging residues of spruce provide no contribution to biodiversity. Accordingly, the removal of these residues has a low influence on the quality of the stand from a biodiversity perspective (BP). In contrast to spruce logging residues, the beech logging residues are assessed to provide an important contribution to biodiversity in a context with little other dead wood available. Consequently, the removal of beech logging residues has a relatively high impact on BP in the model output. In summary, the relation between BP and ΔQ resembles an inversely proportional interaction. This relation is illustrated by beech dominated stands performing better than spruce dominated counterparts in terms of BP, but simultaneously exhibiting higher ΔQ resulting from the removal of the logging residues.

6.4 Biodiversity impact

The category indicator ($\Delta Q \cdot m^2 \cdot a/kWh$) represents the biodiversity impact per functional unit. Generally, the biodiversity impact is higher for logging residues which exhibit low ΔQ, high yield (volume/area at final felling) and high energy content. Logging residues from stands dominated by spruce and beech display comparable biodiversity impact per functional unit, despite significant differences regarding the factors influencing the category indicator. In terms forest management, beech is associated with long rotation times, but generates large volumes of logging residues at final felling due its coarse branches. On the contrary, spruce generates lower volumes of logging residues at final felling, but is associated with a short rotation time; only half that of a generic beech stand. As a result, spruce compensate for its low yield at final felling by rapid growth. While this illustrates how tree species characteristics influence biodiversity impact, it is also notable how pine stands risks performing poorly in terms of biodiversity impact per functional unit. In general, pine is associated with an intermediate rotation time and low volume yields of logging residues at final felling. Accordingly, pine stands require large areas to produce a kWh of pine logging residues during one year, generating a high biodiversity impact per functional unit.

The sensitivity analysis in Figure 14 aims to investigate which of the factors affecting biodiversity impact has the largest impact on the category indicator results. While ΔQ comes out as the parameter with the largest variability, the other parameters can have a significant impact on the biodiversity impact as well. In the case of spruce, the sensitivity analysis shows that the variation in volume yield of logging residues can affect the category indicator results by a factor of two. In summary, factors not directly related to the biodiversity potential can have a large impact in the biodiversity impact per functional unit, potentially doubling it.

6.5 Model performance

The obtained category indicator results pose questions regarding the validity of the LCA results. In particular, this applies to whether pine residues are disproportionately punished by the method of calculating the biodiversity impact. While ΔQ of removing pine residues from property C (*C: pine*) in Figure 11 is similar to that of other logging residues, the pine residues exhibit the largest biodiversity impact in the study sample. The high biodiversity impact can be attributed to the low yield of pine logging residues. This high biodiversity impact is inconsistent with the qualitative expert assessment and the initial literature study, which rather indicated that logging residues from oak and beech should be the most significant from a biodiversity perspective. As such, the high biodiversity impact of pine residues from property C exposes an intrinsic challenge of interpreting the LCA results. The calculated biodiversity impact per kWh is not necessarily consistent with expert opinion on which logging residues should be preserved to promote biodiversity, but rather serves to identify how the function can be produced with least possible impact.

The participating experts consistently pointed out that logging residues can replace a restricted fraction of naturally occurring dead wood, although opinions differed on the extent of this fraction. In terms of quality from a biodiversity perspective, coarse residues from oak, beech and other deciduous trees were put forward as the most valuable. In particular coarse logging residues (CWD) from these tree species should be the target for measures to improve forest biodiversity related to retaining logging residues, according to both expert opinion and the initial literature study. In the model, CWD logging residues from all native tree species are valued equally. This decision increases flexibility and does not discriminate between differing property conditions. For example, properties best suited for pine can reach as high biodiversity potential as properties more suited for deciduous forest within the current model. Nonetheless, the fact that logging residues from deciduous species are not highlighted in the model can be viewed as contradictory to most expert opinions. Therefore, investigating a further differentiation between logging residues from different native tree species is recommended in a further development of the model.

Although all experts considered logging residues to significantly contribute to the BP, they preferred other management measures over logging residue retention when the goal is to enhance conditions for forest biodiversity. Predominantly, the highlighted measures were the retention of old trees and dead wood of large diameter. The expert verdict constitute the basis for assigning logging residues a low contribution weight (<15%) in the BP model. A larger contribution weight is assigned to the most significant parameter, the amount of old trees.

Assigning the biodiversity contributions a specific contribution weight is surrounded by a significant degree of uncertainty. Experts were generally reluctant to pinpoint an exact weight percentage, with regard to the lack of empirical data. Furthermore, the issue related to assigning logging residues (deadwood class 1 and 2) a specific contribution weight relates to one of the main risks associated with applying the model in a case study, namely a disproportional inclusion of parameters relevant for the industrial branch in question (Lindner et al., 2021). Hence, there is a risk that logging residues are assigned a disproportional significance from a biodiversity perspective, since they are the outspoken focus of the study. This significance could be manifested through a disproportionately large contribution weight of dead wood classes incorporating logging residues. As indicated, no expert promoted logging residues as high quality habitat from a biodiversity perspective. Moreover, large uncertainties remain related to assessing logging residues as a substitute for other dead wood. Nevertheless, their inclusion in this assessment of biodiversity impact is justified by their large contribution to the available dead wood in managed forests, while simultaneously being subject to an increased demand for extraction. In summary, the biodiversity impact results of this study can be considered conservative. This conservatism arises from the recognition of a potential bias, where parameter weights might disproportionately emphasise the biodiversity contribution from logging residues.

6.6 Spruce as an exotic conifer

The classification of spruce as an exotic species constitutes another influential outcome of the expert contributions. The decision is the primary explanation to the limited ΔQ following the removal of spruce residues. However, it is not the only explanation, as spruce residues are also naturally poor in the coarse fractions which are considered more important from a biodiversity perspective. In turn, this is explained by spruce having fine branches in comparison to most deciduous tree species. The sensitivity analysis in Figure 13 investigates the consequences of classifying spruce as an exotic species, and exhibits an variable result. While some stand values of ΔQ are unaffected in the sensitivity analysis, others show a significant increase. The variation in the sensitivity analysis is directly correlated to the amount of coarse logging residues generated during final felling. As such, the result is strongly influenced by the supplier's estimate of the volume of CWD branches in the logging residues. For example, suppliers C and G reported a significant outtake of coarse logging residues from their spruce stands. In consequence, the ΔQ of suppliers C and G would increase by a factor of five if their spruce residues were to be classified as native (Figure 13), by extension increasing the biodiversity impact of these residues by a factor of five. In summary, the classification of spruce as an exotic species can be significant for the biodiversity impact related to the logging residues. The classification's consequences illustrate an issue related to the spatial scale of biodiversity impact assessment, as some experts argue that spruce could be considered native in the northern part of the ecoregion.

6.7 Comparison to previous work

In a addition to the method proposal by Lindner et al. (2021), earlier versions of the method was applied to case studies by Myllyviita et al. (2019) and Lindqvist et al. (2016). Each of these three publications developed their own set of indicators. Despite geographical proximity, and at least adjacent ecoregions, the parameters differ significantly.

The choice of management parameters in comparison to previous studies underscore the normative character of the BP-method. The management parameters used in this study are different to Lindner et al. (2021), except in the case of tree species diversity. The difference could be explained by the different ecoregions, but is likely also influenced by expert preferences. The inconsistency in model parameters is further underlined by Lindqvist et al. (2016), which applies a version of the BP method to forestry in the ecoregion Baltic mixed forests, but uses a different approach in terms of management parameters. For example, while pH is omitted from the model in this study due to its limited connection to forest management, Lindqvist et al. (2016) incorporates pH as a management parameter. This discrepancy highlights the influence of how a concept such as management parameter is interpreted. As such, the wording and approach during expert consultation must be stressed as an element of pivotal importance. Furthermore, it is important to emphasise that the calculated BP is a normative value rather than a measurement of biodiversity.

Protected land area is not included as a management parameter in this study, but was used by Lindner et al. (2021). While protected areas are usually mentioned related to the preservation of biodiversity, this entity is not strictly represented in the BP model used in this study. Forest owners applying the model to their properties might therefore experience that the conservation measures they incorporate in their management are not properly reflected by the model output. Specifically, this is true for land set aside for conservation purposes, a measure widely incorporated in certified forestry and present on all properties participating in this study. The reason behind not including protected areas in the model of this study is that no participating experts highlighted it as a good proxy for biodiversity. Experts rather focused on physical attributes in the forest, which were argued to be more strongly connected to actual biodiversity. Nonetheless, the management parameter "number of old trees" can be viewed as a substitute for protected area, as it indicates the continuity typically connected to such conservation efforts. While conservation zones are present on all properties participating in the study, many were established in recent years and consequently do not yet contain any trees old enough to contribute to the biodiversity potential. Nevertheless, this implies that the biodiversity potential of many forest properties will increase with time, without additional management, as trees within areas set aside for conservation purposes age. Eventually, these trees will contribute to the biodiversity potential through the "old trees" management parameter. A management parameter focused on old retention trees can motivated with regard to its strong connection to forest biodiversity. Alternatively, focusing on protected areas could be argued to be more in line with policy strategies to mitigate biodiversity loss.

6.8 Implications for stakeholders

The study contributes with relevant information for stakeholders in two main ways. Firstly, it can provide guidance on how to manage the extraction of logging residues from a biodiversity perspective according the BP model. Secondly, it provides a basis for comparing different logging residues based on their impact on biodiversity per functional unit.

From a stakeholder point of view, it is important to emphasise that the reference state (Q_{ref}), corresponding to fully reached biodiversity potential, represents the ideal state considering biodiversity only. Exactly which level of biodiversity potential is desirable on a managed property is not considered in this work. Hence, there is no clear threshold which corresponds to an acceptable impact on biodiversity.

Applying the model suggests that the most effective measure to increase BP is to preserve retention trees rather than preserving logging residues. Although one cannot directly replace the other, three such retention trees per hectare would contribute as much to the BP as leaving all logging residues after final felling. An increased biodiversity contribution from other management parameters, according to this example, will have implications for the relative impact from logging residue removal. With the total BP of the stand increasing, the proportion to which logging residue removal contribute to the remaining unfulfilled BP will increase.

The management aspects considered in the BP model highlight that the biodiversity impact related to logging residue removal is influenced by the type of logging residue removed and the available amount of other dead wood. From a management perspective, there is a larger quality change related to extracting logging residues from pine and beech stands compared to spruce stands in Scania. However, stands dominated by the latter are connected to a lower biodiversity potential considering forest management as a whole. Thus, biodiversity may benefit from converting a spruce stand where you preserve logging residues to a beech stand where logging residue removal is incorporated in the forest management. Where logging residue removal takes place, the model output illustrates that the biodiversity impact can be compensated by other management measures. Specifically, this applies to increasing the available volumes of other dead wood.

The model can be used to identify pathways to minimise the impact on biodiversity related to logging residue removal. One example includes a set of two management measures, consisting of firstly sustaining high amounts of native CWD, replacing coarse logging residues. Secondly, setting aside 30% of the logged area from logging residue removal will ensure that extraction levels of fine logging residues do not exceed landscape thresholds. According to expert opinion, the area set aside should target the most important tree species for regional biodiversity, such as beech and oak. Reducing the quality change according to e.g. the pathway described above will effectively reduce the impact per functional unit, as illustrated in the case of property F.

Comparing different supplies of logging residues per functional unit does not single out a specific category of residues which is to be avoided when extracting logging residues. While pine residues stand out with large biodiversity impact on one property, a second is associated with no biodiversity impact. The case study highlights retaining coarse branches from native trees as a consistent approach to reduce biodiversity impact from an LCA perspective, rather than avoiding logging residue removal from specific tree species.

From the perspective of an energy company such as Kraftringen, the model provides a quantitative framework to reduce biodiversity impact. It can be used to minimise the risk of extensive biodiversity impact related to the production of district heating and quantifies the measures required to do so. A strength of the developed model is its flexibility in terms of management measures, as it incorporates several measures which can reduce the impact on biodiversity related to logging residue removal. These measures include retaining CWD logging residues of native tree species, increasing the volume of other dead wood and limiting the area of logging residue removal. The continuous scale for biodiversity potential (between 0 and 1) means that also marginal efforts to improve the conditions for biodiversity will be reflected in the LCA results.

Other dead wood is considered to be able to compensate for the removal of logging residues, but this finding should not be interpreted to encourage logging residue removal in forests with high conservation values. High volumes of dead wood is considered one of the most important indicator of high conservation values in forest ecosystems. Therefore, the biodiversity impact from removing logging residues in a forest with high conservation values could be considered limited, as these forests typically contain enough dead wood to compensate for a removal of logging residues. Such an interpretation is however questionable and contradictory to the recommendations from the SFA, which suggest avoiding logging residue removal in areas with high conservation values. In summary, the study encourages retaining CWD in production forests to compensate for logging residue removal, but discourages logging residue removal in forests with high conservation values.

6.9 Further development

Developing the model to better capture which residues generated in forestry should be targeted for extraction is one suggestion for improvement. In such further development, the model should be adopted to highlight spruce residues as a target for extraction. Moreover, a more detailed distinction between different native tree species should be investigated. In addition, the model would ideally capture that logging residue removal should be avoided in areas with high conservation values, as well as in close proximity of such areas.

More complex interactions between forest management and biodiversity risk being omitted from the model. In this study, the foremost example is probably that the full variety of dead wood is condensed to three diameter classes, excluding factors such as tree species, position and decomposition stage. Furthermore, the issue of simplification relates to the exclusion of landscape heterogeneity from the model. This decision was based on the view, as indicated by experts, that this attribute is mainly affected by topography, hydrology and other site conditions. However, as was also indicated by experts, there are several management efforts that can increase the degree of heterogeneity in a forest landscape, with examples including patch logging and restoring natural hydrology. A suggestion for further development of the model is to consider these aspects more thoroughly,

As a consequence of adding more management parameters in a future development of the model, the contribution from logging residues to biodiversity potential would likely decrease. Suggestions for additional management parameters include measurements related to hydrology or other structural components increasing heterogeneity. With regard to the normalisation of the model, the biodiversity potential can never exceed 1. Thus, adding more independent parameters would require reducing the contribution weight of one or more currently used parameters. In this scenario, a lower biodiversity contribution from logging residues is a possible outcome. This outlook further underlines the conservative results in terms of currently modelled biodiversity impact related to logging residue removal.

In its current state, the model and case study are limited to the specific conditions surrounding Örtoftaverket and the ecoregion Baltic mixed forests. Thus, the results are not comparable beyond the regional level. In order to increase the spatial scale and compare between logging residues from different ecoregions, further development is necessary. Such a development can be motivated with regard to the relevance of biodiversity impact and woody biomass for energy purposes in a wider European context.

7 Conclusion

The master thesis provides an approach to quantify the biodiversity impact related to the removal of logging residues utilised as fuel for the production of district heating. It does so through developing a model for biodiversity impact assessment, based on the most important components to sustain biodiversity in the ecoregion Baltic mixed forests. Five biodiversity attributes are identified as pivotal to support regional forest biodiversity: old trees, a diversity of native species, high volumes of dead wood, limited acidity and heterogeneous structures. The first three attributes are translated to measurable management parameters.

The management parameters are combined to form a regional biodiversity impact model. The model considers the coarseness of logging residues and from what tree species the logging residues originate. The study relates the biodiversity impact of logging residue removal to three distinct management parameters. These include the amount of retained logging residues above 10 cm in diameter, the areal extent of logging residue removal and the available volumes of other dead wood.

The study represents a practical tool for investigating the biodiversity performance of logging residue fuels. The study shows that biodiversity impact related to logging residue removal is limited in relation to other management parameters, such as preserving old trees. Nevertheless, the impact on biodiversity from logging residue removal can readily be decreased through two management parameters. The first is limiting the area which is subject to logging residue removal and the second is leaving coarse branches from native trees in forests which otherwise exhibit low volumes of dead wood. If high volumes of other dead wood are present, the biodiversity impact arising from the removal of logging residues decreases.

From the perspective of an energy company using logging residue fuel, guidance on which tree species to target would be practically useful. However, based on the comparison of 12 separate stands in southern Sweden, the results from this study does not highlight the dominating tree species as a good indicator for biodiversity impact. Due to the large number of parameters and variables affecting the result, tree species alone does not determine biodiversity impact per functional unit. Therefore, the case study highlights retaining coarse branches from native trees as a consistent approach to reduce biodiversity impact from an LCA perspective, rather than avoiding logging residue removal from stands with specific tree species. In order to improve its usefulness, the approach and model can be further developed to provide better guidance on which logging residues to target for extraction. Furthermore, the comparability of the study can be increased through improving data quality as well as developing the method to be applicable on a larger spatial scale.

The case study comprises a small sample limited to seven suppliers of logging residues and one specific CHP plant, but applying the BP method in a forest owner based case study nonetheless reveal significant difficulties related to collecting satisfactory data on dead wood volumes on a property level. The issues related to data collection has implications for the comparability of the study. Primarily, the comparability issue is connected to the interview nature of data collection. As a result, the need for harmonised methods for the collection of data on dead wood and other parameters important for biodiversity is underlined in this study.

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Appendix 1

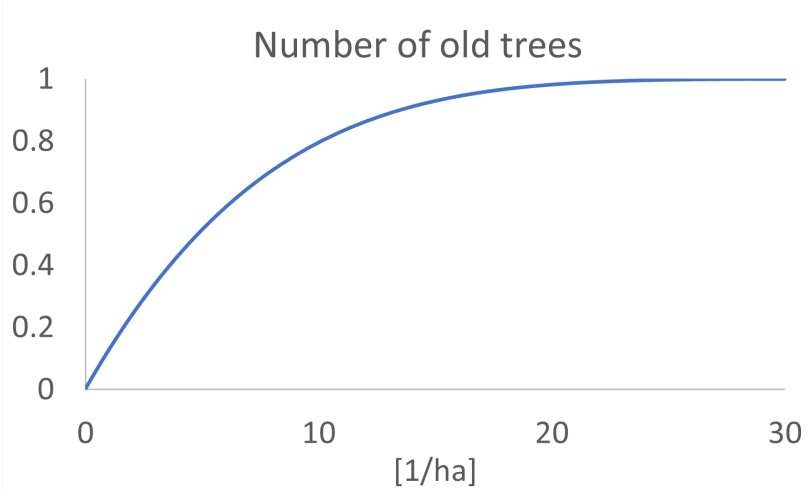
Variables related to biodiversity contribution functions for the management parameters.

Attribute	Parameter	α	β	γ	δ	ϵ	σ	Relation	Weight	p-value
Species diversity	Tree diversity	5	1.2	-9	0.7	10	1.64	Strict AND	0.3	
	Exotic species	6	0	0.2	1	0.8	0.6			
Old trees	No. old trees	5	1.2	-9	1	10	1.64		0.4	
Deadwood 1	Deadwood frac. 1 (>50 cm)	1.7	1	0	0.5	1	0.28		0.15	
Deadwood 2	Deadwood frac. 2 (10-50 cm)	1.7	1	0	0.5	1	0.28	Soft OR	0.1	5
	CWD	1.7	1	0	0.5	1	0.28			
Deadwood 3	Deadwood frac. 3 (<10 cm)	1.7	1	0	0.5	1	0.28	Soft OR	0.05	5
	Area of removal	9	0	0	0.5	1	0.75			

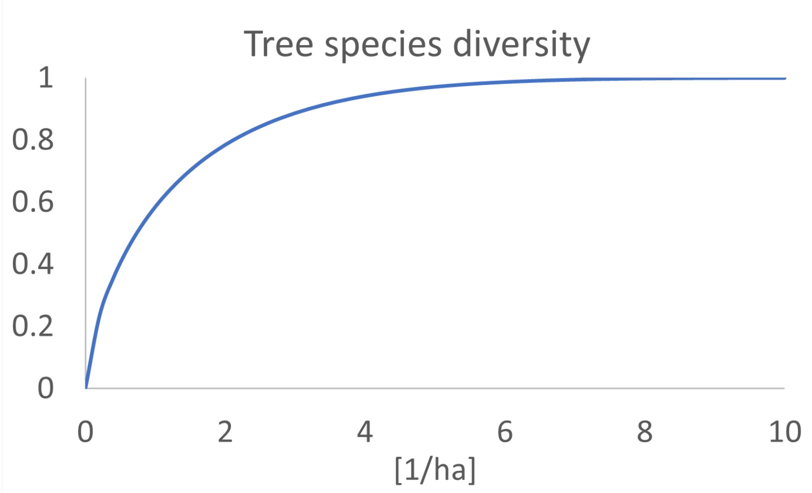
Appendix 2

Appendix 2 presents all of the contribution curves in further detail.

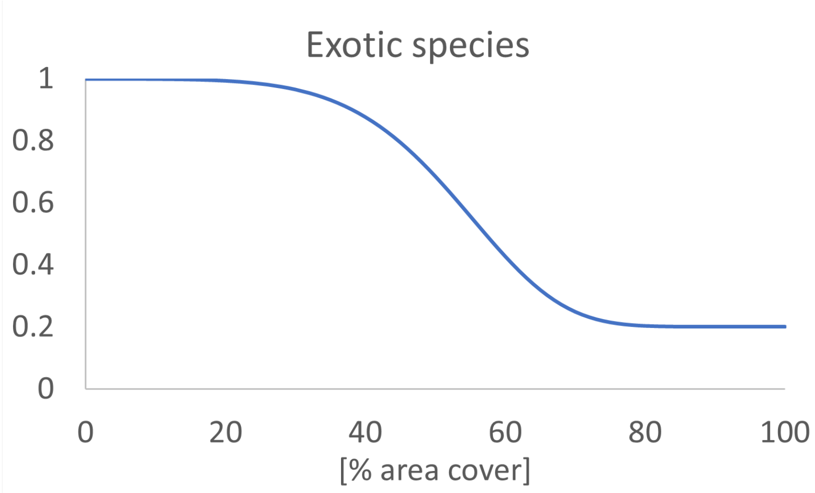
Trees older than 150 years



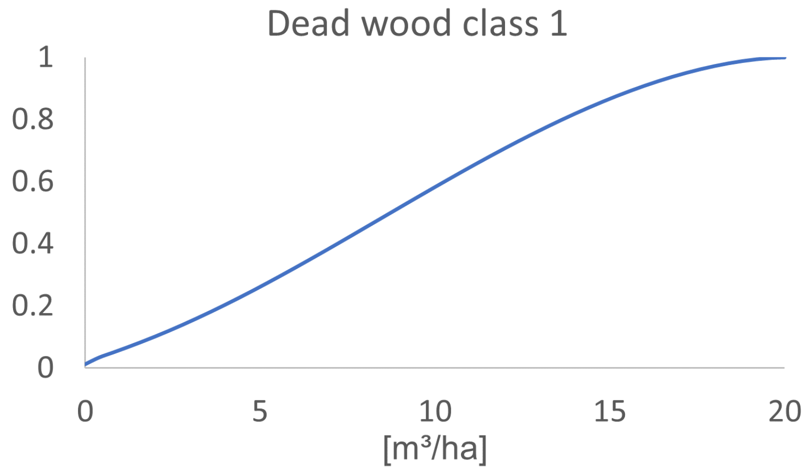
Tree species diversity



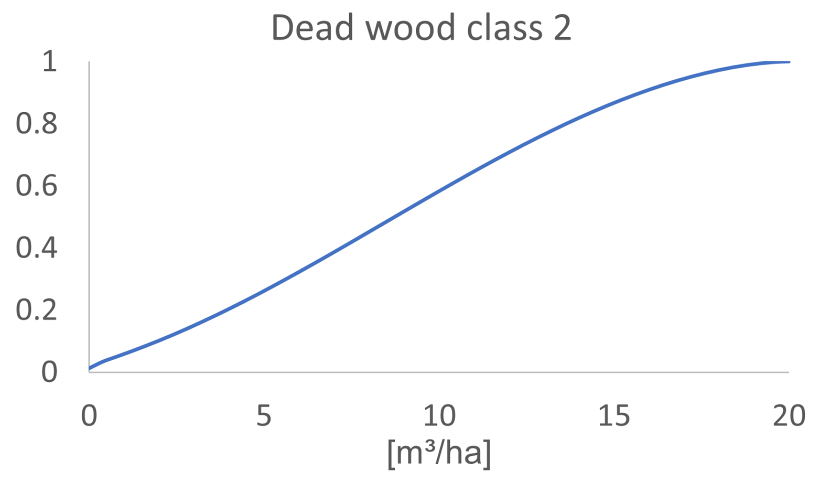
Area fraction of exotic tree species



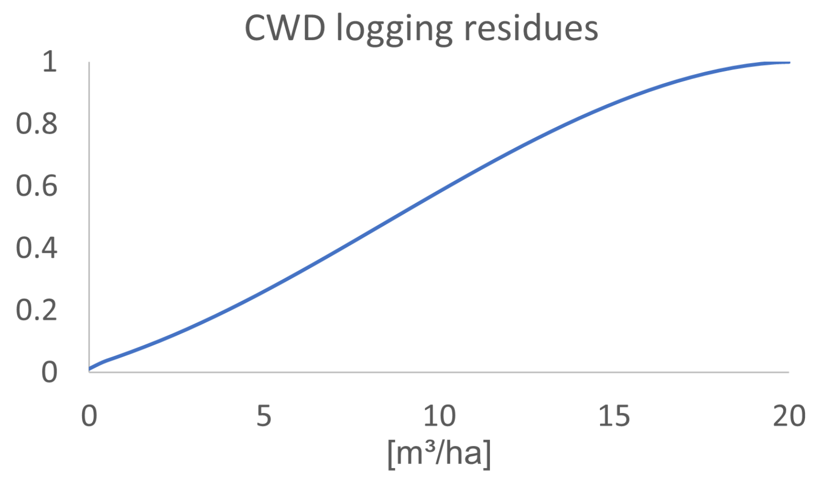
Dead wood class 1 (>50 cm)



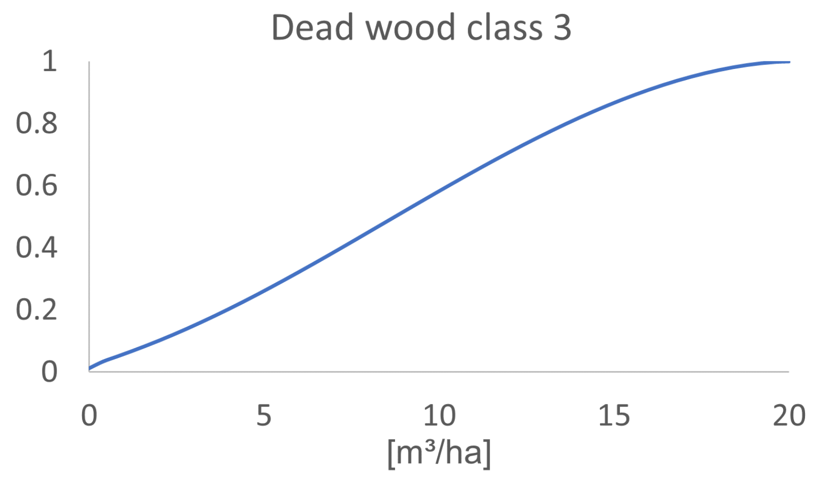
Dead wood class 2 (10-50 cm)



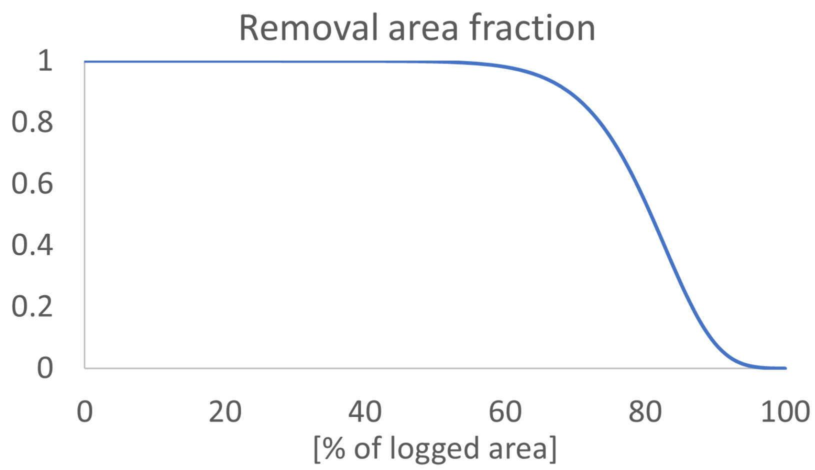
CWD Logging residues (>10 cm)



Dead wood class 3 (<10 cm)



Area fraction of logging residue removal



Appendix 3

Appendix 3 contains the questionnaire presented to forest owners in order to obtain data on all the management parameters. Questions which were part of the original questionnaire but were excluded from the final model were also excluded from the appendix. The appendix version has been translated from Swedish to English.

Part A Here are some general questions about your forest property.

1. How many hectares of forest are there on your property?
2. Where is your forest property located? Answer with the nearest town.
3. What are the dominant tree species on your property? Answer with % area.
4. On what proportion of the harvested area is the extraction of logging residues done in conjunction with final felling?

Part B Here are questions based on your entire forest property.

1. Tree species on your property
    (a) What is the average variation of tree species within a stand in the forest on your property? Answer in number of tree species/ha.
    (b) What is the proportion of spruce on your property? Answer in % area.
    (c) What is the proportion of exotic tree species on your property? Answer in % area.
2. Age structure
    (a) How many trees are 150 years old or older? Answer in number/ha.

3. Dead wood including logging residues
    (a) How much dead wood is there on your property? Answer in cubic meters/ha.
    (b) What proportion of the dead wood has a diameter of at least 50 cm? Answer in % volume.
    (c) What proportion of the dead wood has a diameter in the range of 10-50 cm? Answer in % volume.
    (d) What proportion of the dead wood has a diameter under 10 cm? Answer in % volume.

Part C Here are some questions where you refer to a hypothetical or actual final felling of an average stand on your forest property. If you have a large variation between the stands, you are welcome to provide information for several stands. For example, one with spruce and one with beech.

1. What tree species dominate the stand?

2. What is the rotation period for the stand?

3. What is the total extraction of branches and tops? Answer in cubic meters loose measure/ha.

4. What is the extraction of branches and tops in relation to the amount created during harvesting? Answer in % volume.

5. What proportion of the branches and tops consists of coarser branches and tops (diameter at least 10 cm)? Answer in cubic meters loose measure/ha.

6. What is the extraction of coarser branches and tops (diameter at least 10 cm) in relation to the amount created during harvesting? Answer in % volume.