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Forest growth under future climate change in the context of bioenergy – case studies of combined heat and power plants in Sweden

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Master thesis, 30 credits, in *Geomatics*

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Abstract

The pressure to achieve net-zero emissions has pushed for new technologies including carbon capture and storage (CCS) based on the combustion of biomass (BECCS). While bioenergy is a relatively mature industry in Sweden, the addition of CCS may increase the demand for local biomass. Furthermore, previous studies on the potential of BECCS in Sweden have not considered the impacts of climate change of future forest growth.

This thesis aims to fill in the gaps of future forest growth under warming climate, specifically under the context of BECCS being implemented in Swedish industry. Three combined heat and power (CHP) plants were selected for a case study. It was assumed that these plants will source forest residues from Swedish forest as their major fuel.

The dynamic vegetation model LPJ-GUESS was applied to simulate current and future forest growth under changing climates. It was found that standing volume could increase approximately 30% in Northern and Central Sweden, which could be beneficial to the CHP plants there. But the outlook for Southern Sweden was less positive, with smaller increase of standing volume for pine trees and potentially up to 10% decrease of standing volume for spruce trees. This suggests that an alternative fuel may be desired for CHP plants in Southern Sweden.

The potential negative impacts of removing forest residues were also discussed. It was suggested that comprehensive, thorough investigation be performed before moving ahead with sourcing forest residues to ensure the sustainability of such alternative is well-maintained.

Keywords: Physical geography, climate change, ecosystem modelling, LPJ-GUESS, BECCS

List of Abbreviations

BECCS	Carbon capture and storage based on the combustion of biomass
BEFs	Biomass expansion factors
CCS	Carbon capture and storage
CO_2	Carbon dioxide
CHP	Combined heat and power
FAO	Food and Agriculture Organization of the United Nations
FSC	Forest Stewardship Council
GPP	Gross primary productivity
IPCC	Intergovernmental Panel on Climate Change
NPP	Net primary production
PEFC	Programme for the Endorsement of Forest Certification
PFTs	Plant functional types
RCP	Representative concentration pathway
SMHI	Swedish Meteorological and Hydrological Institute
SNFI	Swedish National Forest Inventory

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1 Introduction

1.1 Background

Following the commencement of the Paris Agreement in 2016, the Swedish Parliament adopted a new climate policy framework in 2017 (Swedish Environmental Protection Agency, n.d.). The goal is that Sweden should achieve net-zero greenhouse gas emissions by 2045 at the latest, and to attain net negative emissions thereafter. To achieve this, national emissions level must be at least 85 per cent lower in 2045 than in 1990. Remaining reductions and negative emissions shall be realised through supplementary measures including increased uptake of carbon dioxide (CO_2) by forests as the result of additional measures, verified emission reductions carried out outside the Swedish borders; and carbon capture and storage (CCS) based on the combustion of biomass (BECCS) (Swedish Environmental Protection Agency, n.d.).

As suggested by its name, BECCS involves the use of bioenergy and CCS technology. Without CCS, atmospheric CO_2 that was captured by plants during photosynthesis will be released back into the atmosphere when the biomass is converted to bioenergy through direct or indirect combustion. On the contrary, BECCS technology captures the CO_2 emission in the conversion process and subsequently inject them into geological formations for long-term storage, thereby preventing the CO_2 from re-enter the atmosphere in the short term (Fajardy et al., 2019).

There has been great interest and thorough studies regarding the deployment of BECCS within Sweden's industry, and the potential of BECCS in Sweden is proven to be substantial, where the highest estimation reaches 23 $MtCO_2$ per year, corresponding to more than 50% of total CO_2 emissions in Sweden (Johnsson et al., 2020; Karlsson et al., 2021; Karlsson, 2022; Zetterberg et al., 2021). However, BECCS is not currently economical due to high capture, transport and storage costs (Johnsson et al., 2020). As such, the Swedish Energy Agency has proposed a reverse auction system to support its implementation, with the goal of removing 2 million tons of biogenic emissions per year. The Swedish authority will subsidise the winning tender through the reverse auction system, who operates BECCS with the lowest cost. The first auction is set to take place in 2023 and the storage of carbon dioxide shall begin by 2025.

1.2 Problem Statement

Given the stance and proposed regulations by the Swedish authorities, as well as the strong support from Swedish industries, there is a possibility that BECCS will be in-use in the near future. Although the current potential of implementing BECCS within Sweden's industry is proven to be substantial, the potential impact of future climate change on forest growth in Sweden and thus the availability of domestic biomass for BECCS is uncertain.

1.3 Aim and Research Questions

The main goal of this study is to understand the impact of future climate change on the forest growth in Sweden, specifically in the context of BECCS being deployed in Swedish industry. The focus would be on forest residue, which would otherwise be left at site, to lower the social and environmental risks of using bioenergy (IEA Bioenergy, 2009).

The research questions are thus:

- What is the existing capacity of locally-sourced forest biomass for bioenergy use in Sweden?
- How will climate change affect future forest growth rate and thus the potential of locally-sourced forest biomass for bioenergy use in Sweden?

2 Theoretical Background

2.1 Sweden’s Forest and Forest Industry

Sweden has a large expanse of forests - around 70% of Sweden’s land area are covered by forest land (Swedish University of Agricultural Sciences, 2022a). The large amount of forest plays a vital role in mitigating climate change by acting as a carbon sink through CO_2 sequestration, providing renewable energy and alternatives to fossil-based products, as well as maintaining biodiversity, and contributes to the public’s recreational and cultural values (Intergovernmental Panel on Climate Change, 2007).

Apart from its environmental and social benefits, Swedish forests make up a large part of the country’s economy. More than 80% of the forest land are productive (Swedish University of Agricultural Sciences, 2022a), and the forest industry accounts for a significant proportion of employment, exports, turnover, and value added in the country's industry. It was estimated by Statistics Sweden that forest-based products accounted for 10% of Sweden's total goods exports in 2021, with a gross value of 16.5 million euro (Statistics Sweden, 2022).

Both obligatory legislation and voluntary certificates aims for a sustainable forest industry in Sweden. The Forestry Act mandates that forests must be managed sustainably for ecological, economic, and social objectives. For example, forest owner must restock the land after harvesting, and considerations must be given to reindeer husbandry in relevant areas. On the other hand, the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC) provide a framework and voluntary certification for sustainable forest management that includes standards for biodiversity conservation, water and soil protection, and workers' rights. However, environmentalists have criticised the forest management in Sweden to be unsustainable mainly due to the clear-cutting and monoculture approach (Hoffner, 2011; Naturskyddsföreningen, 2023). Furthermore, Sweden hosts a substantial amount of Europe’s primary forests, which are crucial for forest biodiversity and climate change mitigation (Sabatini et al., 2021). Yet, it was evident that these forests were logged and converted to plantations in the past 20 years, which could be detrimental to biodiversity, climate change mitigation, and cultural values (Ahlström et al., 2022). Although the sustainability of Swedish forest management approach is not a focus of this study, it is important that any implementation of BECCS in Swedish forests to take into account this broader context.

2.2 Bioenergy and Forest Residue

Bioenergy is a form of renewable energy that is produced by converting biomass, such as plants or organic waste, into useful energy (IEA Bioenergy, 2009). It is one of the oldest forms of energy used by humans, with the use of fire dating back to prehistoric times. Today, the majority of bioenergy utilised globally is still in the form of 'mundane bioenergy', as defined by Chatti et al. (2017). This refers to the burning of wood and crop residue cooking or heating purposes, which is mostly used in rural areas and developing countries. The minority, which Chatti et al. (2017) called 'modern bioenergy', are using biofuels as alternative fuels for automobiles or aircraft, or using biomass instead of coal or oil to generate power. This study focuses on the latter - using biomass for power generation.

Bioenergy is often regarded as a sustainable alternative since biomass is renewable (Gosalvez, 2021). On top of that, bioenergy is presumed to be carbon neutral, as plants naturally take up carbon during their growth (Johnson, 2009). However, Johnson (2009) pointed out that this presumption is inaccurate when considering the entire life cycle of bioenergy. Harvesting biomass for bioenergy purposes leads to a reduction in carbon stock both in vegetation and soils, and land use changes from natural vegetation to crop lands result in emissions, potentially making biofuels carbon positive (Fargione et al., 2008). Additionally, concerns regarding food security were also raised by scientists, as energy crops might take up arable land that were used for food crops (IEA Bioenergy, 2009).

To fully realize the potential of bioenergy in reducing the carbon footprint of energy production, it is crucial to implement appropriate safeguards and regulatory measures. The International Energy Agency (IEA) (2009) highlighted in their report the need for technological development and regulatory measures to promote sustainable bioenergy that uses residues and wastes to lower environmental and social risks. One of such solution is to utilise forest residue, which is the by-product of forest management activities such as thinning and final felling and are usually left at site otherwise (f3 Innovation Cluster for Sustainable Biofuels, 2014). The most commonly-used form of forest residue is currently tops and branches cut off during final felling. They are usually left in the clearing to dry-off and to allow needles – a good source of forest nutrient - to fall off so as to avoid nutrient depletion, which also complies to the legal requirement of not removing all residues. The dried tops and branches could then be used as fuel.

A number of combined heat and power (CHP) plants in Sweden have been utilising forest residue as their feedstocks to some extent for years. The most notable example is Fortum Värme in Stockholm, where forest residues and wood wastes serve as its principal feedstocks (IEA Bioenergy, 2018). Other examples of energy provider which includes forest residue in their energy mix are Skellefteå Kraft, Söderenergi, Umeå Energi and Vattenfall (Skellefteå Kraft, n.d.; Söderenergi, 2023b; Umeå Energi, 2022; Vattenfall, n.d.-b). This study looks into the potential usage of forestry residues by CHP plants in Sweden. The European Commission's Joint Research Centre (Camia et al., 2020) defined three main types of forest residues in their report:

- Fine Woody Debris (including slash – tops and branches)
- Coarse Woody Debris (including snags, standing dead trees, and high stumps)
- Low-stumps

They also pointed out small logs without commercial value, for example those harvested during pre-commercial thinning or during cleaning operations, which are not considered in their report. Stems salvages after disturbances such as fire or diseases are also another example of forest residues that could be used for bioenergy production

In this study, however, forest residue is confined to slash resulting from final felling (clear-cutting), as it is the most common fuel currently used by Swedish CHP plants. Residues from thinning is not common currently due to mainly due to difficulty of transporting the trees out of the forest without damaging the remaining trees (f3 Innovation Cluster for Sustainable Biofuels, 2014). Stumps are also mostly left in the forest after final felling, and currently make up a minimal portion of forest fuels (Swedish Energy Agency, 2022).

By harnessing forest residues as an energy source, additional land use is not required, and no competition with food crops for resources is involved. Yet, it is worth noting that the removal of deadwood for bioenergy production will have implications for biodiversity and soil carbon stocks (Camia et al., 2020). Forest residues are vital resources for saproxylic species such as decomposers, fungi, and bacteria. They play a crucial role in breaking down woody material and cycling nutrients back to the soil. Forest residues also provides nesting sites for insects, birds, and mammals, and serves as a substrate for the growth of lichens and mosses. Removing forest residue could disrupt important ecological functions such as nutrient cycling, carbon storage, and habitat provision. Moreover, the operations involved in collecting and removing logging residues can result in the extraction or damage of other ecologically valuable dead wood. As such, careful consideration of the entire life cycle and safeguards against all potential challenges are essential to ensure the sustainability of bioenergy.

2.3 BECCS and its Development in Sweden

Since 2009, bioenergy overtook oil and became the dominating energy source in Sweden (Swebio, n.d.). This shift can be attributed to the widespread use of biomass as fuel by district heating companies, as well as the adoption of biomass as the primary energy source by forest-based industries. In 2017, the 23 largest pulp mills and 15 largest CHP plants in Sweden combined emitted more than 30 million tonnes of CO_2 (Swedish Energy Agency, 2021). Notably, 98% of the emissions from pulp mills and 75% of the emissions from cogeneration plants are biogenic, emphasising the great potential of adopting BECCS technology in Swedish industries as suggested by recent researches (Johnsson et al., 2020; Karlsson et al., 2021; Karlsson, 2022; Zetterberg et al., 2021).

As mentioned, BECCS involves the integration of bioenergy and CCS technology, where the captured CO_2 would theoretically be stored in geological formations for permanent removal, leading to negative emissions (Fajardy et al., 2019). This is in contrast to the temporary storage that occurs in biomass, which ranges from several seasons for leaf tissue and fine roots to several centuries for long-living wood (Keenan, 2018). While carbon can also be stored in soil for millennia, BECCS is more valuable to industries and decision makers as it provides the possibility to generate negative emissions and has the dual benefit of producing energy while capturing carbon (Fajardy et al., 2019). However, scientists have pointed out the risk of leakage, which leads to CO_2 re-entering the atmosphere (Johnson, 2009). Yet, Lyngfelt et al. (2019) refuted that the benefits of negative emissions brought by BECCS still outweigh the damage caused by allowing the CO_2 to be emitted and remain in the atmosphere.

Apart from the aforementioned policies and regulations, the development of BECCS has also received significant support from the industry. Several Swedish energy companies, including Stockholm Exergi and Vattenfall, have initiated research projects on implementing BECCS in their facilities (Beccs Stockholm, n.d.; Vattenfall, n.d.-a). In addition, numerous stakeholders are collaborating in a joint project aimed at establishing a large-scale BECCS project in the Nordic region (IVL Swedish Environmental Research Institute, 2022). This industry-driven momentum highlights the growing interest and potential for BECCS as a viable solution for reaching the ambitious national climate goals.

2.4 Ecosystem Modelling and LPJ-GUESS Model

A model is a simplified representation of the reality used to help solving complex problems by predicting outcomes or simulating scenarios under specified constraints (Jørgensen & Bendoricchio, 2001). Models can take many forms, such as physical prototypes, mathematical equations, computer simulations, drawings and maps, etc. They seldom contain all details of the reality, but rather include the necessary information for solving each problem at hand.

Ecosystem models are computer models attempting to simulate the interactions within and between ecosystems (Geary et al., 2020). Scientists use ecosystem models to understand the ecosystem components and interactions, predict future scenarios, and aid decision-making by assessing diverse management approaches, in various applications. However, the reliability of models depends on the quality and quantity of data used to train them, as well as the assumptions made during construction. Therefore, careful consideration should be taken when selecting an ecosystem model to satisfy specific research requirements and reflect important characteristics of the concerned system.

The dynamic vegetation model, Lund-Potsdam-Jena General Ecosystem Simulator, or hereinafter referred to as the LPJ-GUESS model (Smith et al., 2014), could project regional and global vegetation growth with user-input variations including plant age and species, carbon, water, and nitrogen cycle processes, land use, climate conditions, forest management strategy and more (Lindeskog et al., 2021). Outputs from the model includes vegetation composition and cover that describe major species or plant functional types (PFTs), net primary production (NPP), vegetation carbon density, etc. (Smith et al., 2014). The model simulates the dynamics of terrestrial vegetation and soils that are controlled by climatic conditions, soil physical properties and land-use inputs on a regional or global scale. It operates on a grid system where users could define the size of the grid cells and the number of patches within each grid cell. The grid system allows the model to represent the spatial variability of environmental conditions across the landscape while the use of patches – a homogeneous unit of land with a unique combination of environmental conditions, such as climate, soil type, and vegetation cover (Smith et al., 2014) – allows the model to capture the heterogeneity of environmental conditions across the landscape and to simulate the effects of local-scale processes on ecosystem dynamics. Within each patch, the model simulates the interactions between the vegetation and the environment, including the exchange of energy, water, and carbon, and the transfer of water and nutrients between the vegetation and soil. The simulation combines daily time steps such as photosynthesis, and yearly time steps such as mortality and biomass growth allocation to mimics the dynamic processes of the ecosystem (Lindeskog et al., 2021). It provides a prediction to future vegetation outlook and insights into the effects of variabilities such as climate variables and land use change, which are useful in assessing the feasibility and capacity of implementing BECCS technology.

2.5 Predictions of Future Climate and Forest Growth

According to the Intergovernmental Panel on Climate Change (IPCC), some degree of global warming and climate change is unavoidable in the coming decades even with the most stringent policies and rapid emissions reduction (Intergovernmental Panel on Climate Change, 2021). In order to understand and anticipate the impacts of climate change, the IPCC modelled multiple scenarios of global future climate change based on different emissions reduction pathways. Similarly, the Swedish Meteorological and Hydrological Institute (SMHI) built on the IPCC's Fifth Assessment Report (AR5) to produce detailed predictions on Sweden's future climate (Swedish Meteorological and Hydrological Institute, 2015), highlighting the increase of air temperature and average rainfall throughout the country, especially in Northern Sweden. This could impact the ecosystem services and forest production of the nation. The SMHI predicted future climate based on two time periods: 2021-2050 and 2069-2099. In this study, the first time period was considered.

Lagergren & Jönsson (2017) used the LPJ-GUESS model to investigate the effects of future climate change and different management approaches on Sweden's forest production. The study found that while warming temperatures and an extended growing season generally increased productivity and thus resulted in increased forest harvest levels. These effects were less pronounced in the north, possibly due to a decrease in incoming radiation in the particular climate scenario data used. The simulations also showed that a warmer climate would lead to a shift from boreal coniferous forest to nemoral broad-leafed trees across the country. Such changes could potentially impact the viability of BECCS from forest residue.

3 Methodology

3.1 Terminology

This section aims to provide an overview to some terminologies used within this study.

3.1.1 Standing volume

This metric is used throughout the study. It is given by $m^3\ ha^{-1}$ and represents the volume of the tree that is above ground. More details on how this metric was used and deduced are provided in Section 3.4.

It is important to note that within this study, when standing volume is mentioned, it is confined to the standing volume at the final harvest. All volume that was previously removed due to thinnings were excluded, as only the forest residue from final harvest is currently widely in-use by the forest industry in Sweden, as mentioned in Section 2.2 (Swedish Energy Agency, 2022).

3.1.2 Normalised standing volume/biomass

This metric will be used in Section 4. As the rotation time differs between each location, the standing volume and biomass at the final harvest of each location are normalised to give the abstraction from final harvests over a fixed period of 100 years to eliminate the bias caused by the differences in rotation time. This provides a fair comparison of achievable return from each site within the same time period.

3.1.3 Overall productivity

This metric will be used in Section 4.2.2. It is represented by summing up the removed biomass from thinnings and the biomass at final harvest. These 2 figures were given by total $kg\ C\ m^{-2}$ and added up to provide a comparison of the productivity between different tree species during an entire rotation.

3.1.4 Accumulated average of proportion of tree species

This metric will be used in Section 4.3.3 to assess the impacts of climate change on spruce and pine in mixed-stands. The ratio between spruce and pine trees were summarised for each year. The accumulated average for a given age n was then calculated by the below formula, where x_i represents the proportion of spruce trees at each age i:

$$accumulated\ average\ at\ age\ n = \left(\sum_{i=1}^{n} x_i\right)/n$$

For example, if the proportion of spruce trees at year 1 to 5 are 30%, 31%, 32%, 33%, 35% respectively, the accumulated average for the forest at age 5 will be:

$$\frac{30\% + 31\% + 32\% + 33\% + 35\%}{5} = 32.2\%$$

The accumulated average at each age instead of the proportion at that specific age was used due to the fact the pine and spruce were thinned at different time, meaning that the proportion could fluctuates greatly if the individual proportion was shown.

3.2 Model and Software

3.2.1 LPJ-GUESS model and Environmental Forcing Data

In this study, the number of patches within each 0.5° × 0.5° grid cell was set to 150. Furthermore, the model used in this study started with a 500-year spin-up period from the year 1400 to 1900 where the entire ecosystem including soil carbon, nitrogen, and vegetation was gradually built up from bare land. Additionally, the forest management module was used to simulate the growth of managed forests in Sweden with user-defined parameters such as tree species, rotation period, as well as thinning strength and timing in relation to rotation period (Lindeskog, 2021).

The model required a number of environmental forcing data, including temperature, precipitation, short-wave radiation, atmospheric CO_2 concentration, soil nitrogen deposition, and soil property.

The monthly climate data used in this study was provided by the CRUNCEP version 7 dataset (Viovy, 2018), while atmospheric CO_2 concentration came from the Global Carbon Project (Le Quéré et al., 2018). A pre-industrial value of 2kg N ha^{-1} $year^{-1}$ was used during the spin-up period of the model. Monthly values of nitrogen deposition at 10-year intervals based on Lamarque et al. (2011) were used for the period 1850 to 2009. It was assumed that nitrogen deposition rates remained similar to the period 2000-2009 after the year 2009. Soil data used in this study originated from the WISE Soil Property Databases (ISRIC – World Soil Information, n.d.), where soil property was determined with the definitions of the Food and Agriculture Organization of the United Nations (FAO).

As the climate data only covered up to the year 2015, this is the latest year where simulations for the current (historical) climate could be run. For the future scenarios, the climate was defined by using the historical climate data from the same dataset during the period 1986-2015 as a baseline, and adding the future climate change for the period 2021-2050 as predicted by the Swedish Meteorological and Hydrological

Institute (SMHI) (2015). The climate anomalies were additive monthly values on top of the detrended recycled time series of historical climate. The simulations targeting future climates were simplified scenarios designed with reference to what the SMHI (2015) had reported. Climate models from the IPCC were considered but not adopted due to their large variability and resulting uncertainties. Temperature and precipitation change in Sweden for the period 2021-2050 were predicted by SMHI under RCP (Representative Concentration Pathway) 4.5 and 8.5, as chosen for analysis in SMHI's report. Atmospheric CO_2 concentrations are corresponding values to the RCPs (Intergovernmental Panel on Climate Change, 2013). Other environmental forcing data including soil property and soil nitrogen were assumed to be constant. More details for the future scenarios are described in Section 3.6.

3.2.2 Software Used

Observational data, model evaluation and model simulation results were processed with the software Excel (Microsoft Corporation, 2019) and R (R Core Team, 2022).

The Geographic Information System QGIS (QGIS Development Team, 2022) was used for producing visualisations and calculating study areas.

3.3 Scope of Study

3.3.1 Case Study Sites

Three combined CHP plants in different regions of Sweden were selected as case study sites. These plants already use forest residues or wood wastes as at least part of their feedstocks, therefore there are no technical difficulties in making use of forest residue. The location and capacity of each plant are listed in Table 3.1 below. As explained in Section 3.1, the focus of this study is on slash resulting from final felling (clear-cutting).

Table 3.1 Selected CHP plants as case study sites (Sysav, n.d.; Söderenergi, 2023a; Umeå Energi, 2022)

Plant name	Location (City, County,)	Coordinates (Longitude, Latutude)	Average Annual Production[1] (GWh)
Sysav Avfallsförbränning	Malmö, Skåne	13.04009736°, 55.6325578°	1,650
Söderenergi Igelsta	Södertälje, Stockholm	17.66372034°, 59.17749692°	1,950
Umeå Energi Dåva 1 and 2	Umeå, Västerbotten	20.40747381°, 63.87576637°	1,054[2]

3.3.2 Study Area

Forests within a 75km radius around each selected CHP plant were investigated for their potential provision of forest residue. This decision is based on the findings from Karlsson et al (2021), which showed that a 75km radius is the maximum radius that allows cost-effective road transport and limited competition for the same resource with other industries.

To match the study area with the grids of the LPJ-GUESS model, the selected CHP plants were first plotted into a map created with the Geographic Information System QGIS (QGIS Development Team, 2022). Buffers with a 75km radius were then drawn around each plant. After that, a grid system with intervals of 0.5° was added to the map to match the grids of the model. The area of the buffers was then compared to the grid system and to select grids with more than half of their area covered by the buffer. Grids without a forest stand due to the lack of soil and climate data were however excluded. Figure 3.1 below shows the location of each CHP plant and its corresponding capturing zone. Note that formally protected areas were excluded in later calculations of the potential provision of bioenergy. The layer was provided by the Swedish Environmental Protection Agency and is identical to the one used in the Forest data 2022 report (Swedish University of Agricultural Sciences, 2022a). A complete list of grids taken for consideration in this study can be found in Appendix I.

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[1] Including heat and electricity

[2] Total of Dåva 1 and 2; Umeå Energi only reports plants capacity but not annual production, the figure listed in the table is therefore calculated based on the assumption that the plants have the same amount of production hours as Söderenergi Igelsta.

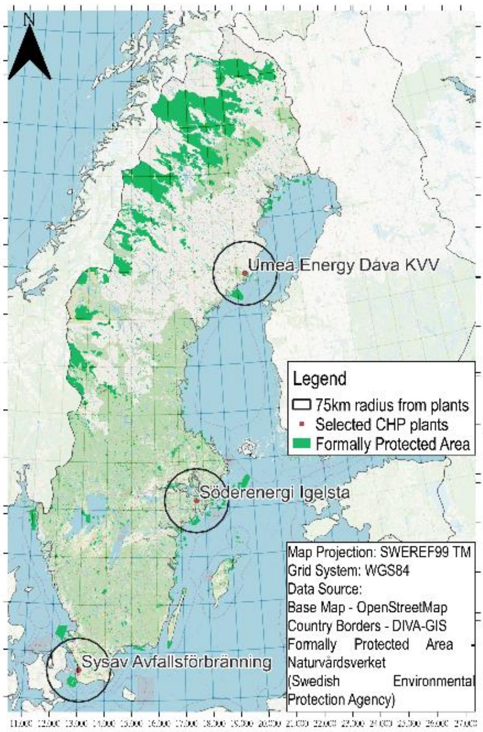

Figure 3.1 Location of selected CHP plants and their corresponding capturing zone.

3.3.3 Forest Species

The study was focused on monoculture and mixed-culture forests formed by Norway spruce (*Picea abies* L. Karst) and Scots pine (*Pinus sylvestris* L.), which were referred to as spruce and pine respectively in this report. That is, the three types of forests being studied were spruce monoculture, pine monoculture, and spruce and pine mixed-culture. Together, they represented around 80% of productive forest land across Sweden (Swedish University of Agricultural Sciences, 2022a). Birches (*Betula* L.), another major tree species in Sweden, were left out due to their relatively small proportion within productive forest land.

3.4 Model Evaluation

3.4.1 Forest Observational Data

Simulation outcomes from the LPJ-GUESS model were compared to observational data for evaluation. The Swedish National Forest Inventory (SNFI) provides sample plot data for the period between 2007 and 2021 (Swedish National Forest Inventory, 2022) with information including detailed location, tree species, stem volume and other parameters for each plot, which is suitable for such usage. One point to note is that stems below 0.5m height were not inventoried (Swedish University of Agricultural Sciences, 2022b).

The number of plots available for each forest type in each study location is summarised in Table 3.2 below.

Table 3.2 Total number of plots available for each forest type in each study location

Location	Forest Type	Total number of plots
Malmö	Pine monoculture	15
	Spruce monoculture	82
	Spruce and pine mixed-culture	30
Södertälje	Pine monoculture	45
	Spruce monoculture	96
	Spruce and pine mixed-culture	131
Umeå	Pine monoculture	13
	Spruce monoculture	24
	Spruce and pine mixed-culture	63

3.4.2 Evaluation Site and Simulations

Plots of observational data were assigned to 0.5° grid cells and the grid cell with the most amount of data in each location was taken for detailed evaluation. A complete list of grids taken for detailed evaluation can be found in Appendix II.

The observational data was extracted and separated to match the three targeted forest types in this study. Stand age, observation year, and standing volume were the major parameters concerned. The data were grouped into 10-year age classes (0-9, 10-19, 20-29, 30-39, 40-49, 50-59, 60-69, 70-79, 80-89, 90-99, 100-109, 110-119) but the oldest 2 classes were only included for the grid in Umeå, where stand rotations are prolonged due to the colder climate in Northern Sweden (Bergkvist, 2023). After that, the median standing age and observation year was calculated for each age class. A simulation was then run for each class based on this information. The forest was initiated at a year that leads to the median stand age at the median year to simulate a managed forest. For example, if a plot has a median standing age of 15 in the year 2010, the forest will be clear-cut followed by a plantation in the year 1995. Thinning treatments were also applied to the simulated stands. The specific volume removal percentages and timings for monocultures are shown in Table 3.3 below, which are typical even-aged management approaches in Sweden during the 20th century (Bergkvist, 2023). As for the mixed-cultures, the automated wood harvest option was selected in the model for convenience. It is based on Reineke's self-thinning rule, which governs the relationship between the density of trees the number of stems and the quadratic mean diameter of the stand (Lindeskog et al., 2021). This auto-thinning approach is considered the optimal scenario where total productivity is maximised. The thinning approach may not be completely accurate but could nonetheless provide an estimation of forest growth.

Table 3.3 Forest management treatments applied to simulated monoculture stands (Bergkvist et al, 2023)

Location	Forest Type	Forest Management Treatment					
		Rotation Period (year)	Pre-commercial Thinning	First Thinning	Second Thinning	Third Thinning	Forth Thinning
Malmö	Pine monoculture	100	15% at 9 years	35% at 21 years	30% at 36 years	25% at 54 years	25% at 72 years
Södertälje		100	15% at 9 years	35% at 24 years	30% at 39 years	25% at 60 years	25% at 81 years
Umeå		120	15% at 12 years	30% at 27 years	25% at 60 years	20% at 69 years	
Malmö	Spruce monoculture	100	10% at 6 years	20% at 18 years	15% at 30 years		
Södertälje		100	10% at 9 years	25% at 24 years	20% at 36 years		
Umeå		120	15% at 12 years	25% at 33 years	20% at 42 years		

The model produced total carbon in live vegetation biomass (kg C m^{-2}) as an output. To convert this into standing volume (m^3 ha^{-1}) as reported by the SNFI, a carbon content of 0.5g C/g dry matter was assumed (Intergovernmental Panel on Climate Change, 2007) and age-class specific biomass expansion factors (BEFs), available in Appendix III, were then applied (Lehtonen et al., 2004). BEFs (B_i) are given by:

$$B_i = \frac{w_i}{v}$$

where W_i is the dry weight of tree component I and V is stem volume.

The results from the simulations were then grouped in the same way as the observational data to compare the standing volumes.

Although the observational data covers up to year 2021, there was no resulting median year falling after year 2015, thus the constraint of the climate data input was not an issue in this context.

3.5 Estimating Existing Availability of Forest Biomass

3.5.1 Simulating forest growth

To understand the existing energy potential using locally-sourced forest residue, simulation results based on the same environmental forcing data and thinning approaches in Section 3.4 with a harvest year in 2015 were investigated. The age of final clear-cut harvesting was set to be the mean age at the time of final felling as reported in the Forest Data 2022 report (Swedish University of Agricultural Sciences, 2022a), as indicated in Table 3.4 below. Note that this age of harvest may not accurately reflect the rotation period in reality due to the limitation of the available data. As the reported age was merely the average age of all harvested trees, some older trees from forests that were previously not managed may have skewed the average to a higher figure. This issue will be further discussed in Section 5.7 and 5.8.

Table 3.4 Age of harvest in simulations for estimating existing availability of forest biomass

Location	Age (year)
Malmö	86
Södertälje	98
Umeå	122

Although the latest year with available simulation results was 2015 due to the constraint of climate data, it was still reasonably recent to be considered as a representation of existing availability.

3.5.2 Scaling up the total standing volume

The simulation results were converted into standing volume (m^3 ha^{-1}) with the method outlined in Section 3.4.2. The total standing volume of each study site was estimated by scaling up the per-hectare standing volume to the total volume within the study area. An effective area was deduced by removing non-land area and formally protected area from the study area layer in QGIS. Figure 3.2 below is a flow chart built with graphical modeler in QGIS that handles the above process.

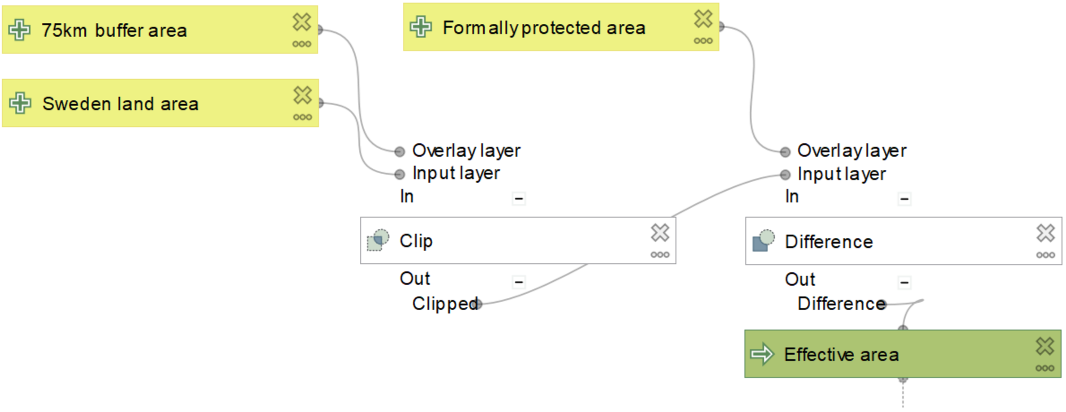

Figure 3.2 Flow chart of calculating effective area to scaling up standing volume for the estimation of existing availability of forest biomass

This land area was then multiplied by the standing volume with the proportion of each forest type (Appendix IV) to estimate the total standing volume for each study site. In this study, it was assumed that the mixed conifer forest only contains pine and spruce although a small portion of lodgepole pine was reported. Experts at each study site shall be able to calculate the amount of forest residue available from the total standing volume at harvest, and thus the energy potential for their operation. The conversion of biomass to energy potential was not included in this study as many assumptions would be required, which may not fit the individual specifications at each plant.

Depending on the location of the study sites, the total land area used for calculation varies. This figure could be found in Appendix IV.

3.6 Estimating Future Availability of Forest Biomass

As mentioned in Section 3.2.1, future climate was defined by using the historical climate during the period 1986-2015 as a baseline, and adding the future climate change for the period 2021-2050 in 2 RCP scenarios. Such changes were on a monthly basis, as were the predictions made by SMHI. Temperature was expected to increase throughout the year in most scenarios, except one month (April) in Malmö where temperature was expected to decrease by 0.36°C under both RCP 4.5 and 8.5 scenarios. The predicted temperature change increases with latitude – Umeå shows a greatest temperature increase among all 3 locations with a year-round average increase of 2.25°C (Table 3.5). Moreover, the temperature increase was predicted to be the highest in May and June across all locations and RCP scenarios. As for precipitation, it was predicted to increase during winter months and decrease during summer months in general. In terms of the difference between the 2 RCP scenarios, Malmö and

Södertälje showed almost identical temperature and precipitation change under the 2 scenarios; whereas Umeå was exposed to greater temperature and precipitation change under RCP 8.5 scenario.

In this study, a fixed climate approach was used to investigate the effects of a changing climate, meaning that the fixed average climate for each of the period was used to represent the entire period. This approach could simulate forest growth purely under each fixed climate. Existing forests would experience both the baseline and the future climate; therefore, their growth could be estimated by comparing the growth of different fixed climates. The simulation was run for 150 years with forest stands first established from bare ground.

Apart from the environmental forcing data mentioned in Section 3.2.1, forest management approach was also included for future scenarios. This was assumed to be unchanged in the future, i.e., they are kept the same as in Section 3.4. The scenarios simulated are summarised in Table 3.5.

The fixed climate assumption has its advantages against using a specific transient scenario. It offers simplicity and controlled conditions by eliminating complex climate variabilities and dynamics. It also makes it easier to establish a baseline for comparing ecosystem responses to a different climate. The results produced with a fixed climate approach are also more generic and easier to interpret. Since the model assumes a consistent climate, the outputs can be generalized to broader contexts and provide insights that are more readily understandable. However, it must be understood that a fixed climate is an artificial approach. The fluctuations of climate are ignored such that the interactions and feedback between climate and ecosystems may be oversimplified, potentially leading to unrealistic results. Nonetheless, it provides a straightforward way to predict forest responses to future climate change needed in this study.

Table 3.5 List of simulations based on future climate scenarios

Location	Tree species	RCP	Temperature change (year-round average)	Atmospheric CO_2 (ppm)	Precipitation (year-round average)
Malmö	Spruce monoculture	4.5	+1.25°C	486.5	+10%
	Pine monoculture	4.5	+1.25°C	486.5	+10%
	Spruce monoculture	8.5	+1.25°C	540.5	+10%
	Pine monoculture	8.5	+1.25°C	540.5	+10%
	Spruce and pine mixed-culture	4.5	+1.25°C	486.5	+10%
	Spruce and pine mixed-culture	8.5	+1.25°C	540.5	+10%
Södertälje	Spruce monoculture	4.5	+1.75°C	486.5	+10%
	Pine monoculture	4.5	+1.75°C	486.5	+10%
	Spruce monoculture	8.5	+2.25°C	540.5	+10%
	Pine monoculture	8.5	+2.25°C	540.5	+10%
	Spruce and pine mixed-culture	4.5	+1.75°C	486.5	+10%
	Spruce and pine mixed-culture	8.5	+2.25°C	540.5	+10%
Umeå	Spruce monoculture	4.5	+2.25°C	486.5	+14%
	Pine monoculture	4.5	+2.25°C	486.5	+14%
	Spruce monoculture	8.5	+2.25°C	540.5	+14%
	Pine monoculture	8.5	+2.25°C	540.5	+14%
	Spruce and pine mixed-culture	4.5	+2.25°C	486.5	+14%
	Spruce and pine mixed-culture	8.5	+2.25°C	540.5	+14%

The resulting standing volume was scaled up with the same approach outlined in Section 3.5.2.

4 Results

4.1 Model Evaluation

The results presented in Figure 4.1 depict the comparison between observed and simulated data for various locations and growth scenarios. Overall, the simulated results align reasonably well with the observed values, indicating a satisfactory performance of the model. However, it is important to note that certain locations exhibit discrepancies, particularly in specific age groups. Notably, the observational data for pine monoculture and mixed-culture in Malmö and Umeå are discontinuous and incomplete, limiting the fairness of the comparison between observation and simulation. Plots for these cases can be found in Appendix V.

For spruce monoculture, Malmö and Södertälje have a substantial amount of observational data. The splines show a similar pattern, with standing volume peaking in the middle of the tree's lifetime and subsequently decreasing. In contrast, the simulated standing volume steadily increases with tree age, resulting in an underestimation during the middle of the tree's lifetime compared to the observations. Umeå, on the other hand, exhibits a different spline shape. While the simulated results fall within the range of observed values, there is a slight overestimation. Both observed and simulated splines closely follow each other in age groups with continuous data but diverge in the oldest age groups, where observed standing volume declines while simulated standing volume continues to increase.

In the case of pine monoculture, simulations consistently overestimate standing volume across all locations and age groups. While there are some discrepancies between observed and simulated values, most of the simulated results fall within the range of observed values at Södertälje, where there was sufficient observed data.

Regarding spruce and pine mixed-culture, simulations tend to overestimate standing volume across all locations and age groups, largely exceeding the range of observed values. The results for Södertälje and Umeå exhibit similar patterns, with both observed and simulated standing volume steadily increasing with stand age. In Umeå, larger gaps are observed in the oldest age group, likely attributed to the limited amount of available data.

In summary, the model generally performs well in comparison to the data for most locations and parts of the growth curve. However, certain discrepancies exist, particularly in specific locations and/or age groups where data availability is limited.

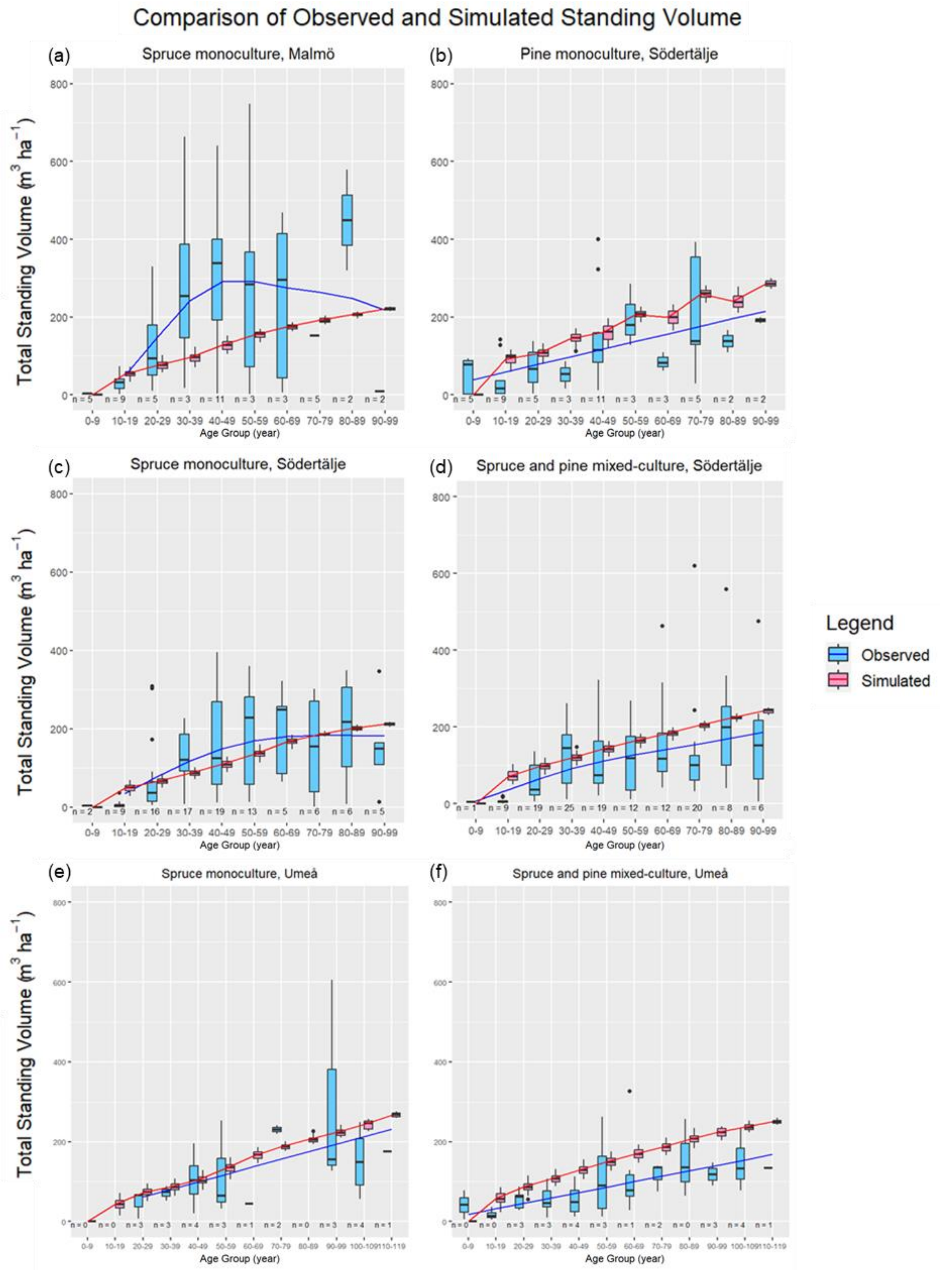

Figure 4.1 (a) to (f) Box and whisker plots for comparing observed and simulated data of different forest stands at different locations; plots were smoothed with a spline function solely for visual interpretation; n = number of observations

4.2 Existing Potential

4.2.1 Total standing volume

The per hectare standing volume of each forest type at the age of harvest is shown in Table 4.1 below. Generally, a longer rotation gives more standing volume. Pine trees in mixed-stands are an exception, where the longest rotation in Umeå resulted in almost the same standing volume as the much shorter rotation in Malmö. The results in Table 4.1 are consistent with those from Section 4.1. For instance, pine appeared to produce more biomass than spruce at the same age (Figure 4.1b and 4.1c); and the resulting per hectare standing volume for different species and location are also similar to the corresponding figure simulated in Section 4.1.

Table 4.1 Per hectare standing volume under historical climate by forest type at harvest age; note, all figures presented in this section and Section 4.3.1 are mean values across all grids within the same region.

Location	Harvest age (year)	Spruce monoculture ($m^3 ha^{-1}$)	Pine monoculture ($m^3 ha^{-1}$)	Spruce in mixed-culture ($m^3 ha^{-1}$)	Pine in mixed-culture ($m^3 ha^{-1}$)
Malmö	86	190.20	280.66	49.31	162.27
Södertälje	98	215.10	309.95	56.73	186.96
Umeå	122	271.16	353.11	93.14	163.19

The normalised figures (definition provided in Section 3.1) shown in Table 4.2 allow a fair comparison of achievable return from each site within the same time period. Malmö and Södertälje have fairly similar figures, whereas Umeå has higher possible yield for spruce in mixed-culture but lower for pine (both monoculture and mixed-culture) compared to the other sites.

Table 4.2 Per hectare standing volume under historical climate by forest type, normalised

Location	Spruce monoculture ($m^3 ha^{-1} 100yr^{-1}$)	Pine monoculture ($m^3 ha^{-1} 100yr^{-1}$)	Spruce in mixed-culture ($m^3 ha^{-1} 100yr^{-1}$)	Pine in mixed-culture ($m^3 ha^{-1} 100yr^{-1}$)
Malmö	221.16	326.35	57.34	188.69
Södertälje	219.49	316.28	57.89	190.78
Umeå	222.26	289.43	76.34	133.76

The scaled-up total standing volume at harvest age is summarised in Table 4.3 below. The total standing volume was calculated based on the mean volume at harvest age across all grids at each location. It was assumed that the entire region has forests established in the same year, which is most likely not the case in reality. Nonetheless, this total figure serves as a reference for an overall biomass potential in each region. Note that the standing volume was grouped by species, meaning that the total standing volume from monoculture and mixed-cultures are added up based on the tree species. The ratio of spruce to pine in mixed-cultures for each location is available in Appendix VI. Malmö has significantly lower standing volume of pine due to the smaller total area and low proportion of pine monoculture forests in the region (Appendix VI). On the other hand, the higher proportion of pine forests (both mono- and mixed-culture) in Södertälje and Umeå is reflected by the higher provision of total standing volume. A significantly older harvest age also led to greater standing volume at Umeå.

Table 4.3 Total standing volume under historical climate by species at harvest age

Location	Harvest age (year)	Total standing volume of spruce (million m^3)	Total standing volume of pine (million m^3)
Malmö	86	48.44	22.78
Södertälje	98	59.68	129.27
Umeå	122	57.89	164.36

4.2.2 Overall productivity

Although it was assumed that forest residues from thinning are not utilised, the overall productivity (definition provided in Section 3.1) was considered to provide a comparison of the productivity between different tree species during an entire rotation (Table 4.4).

Consistent to the figures above, pine trees were able to produce significantly more biomass under the same period than spruce. This is further discussed in Section 5.2.2.

Table 4.4 Biomass produced from final harvest and thinning

Location	Spruce monoculture (kg C m^{-2})	Pine monoculture (kg C m^{-2})	Spruce in mixed-culture (kg C m^{-2})	Pine in mixed-culture (kg C m^{-2})
Malmö	8.64	20.53	3.95	16.57
Södertälje	15.12	25.20	6.37	19.96
Umeå	11.40	16.52	6.95	14.24

When considering the normalised values (Table 4.5), it appears that spruce stands in Malmö shows a lower productivity than in Södertälje, counter to what was shown in Table 4.2 where these 2 sites have similar standing volume. This could be attributed to the lower removal rates during thinning at Malmö.

The lower productivity of pine at Umeå, both in monoculture and mixed-culture, echoes its lower standing volume as shown in Table 4.2. Lower thinning rates and frequency could attribute to the lower total productivity. On the other hand, spruce trees produced less biomass than those in Södertälje despite higher removal rates during thinning, contrary to what was found previously.

Table 4.5 Biomass produced from final harvest and thinning, normalised

Location	Spruce monoculture (kg C m^{-2} $100yr^{-1}$)	Pine monoculture (kg C m^{-2} $100yr^{-1}$)	Spruce in mixed-culture (kg C m^{-2} $100yr^{-1}$)	Pine in mixed-culture (kg C m^{-2} $100yr^{-1}$)
Malmö	10.05	23.87	4.59	19.27
Södertälje	15.43	25.71	6.50	20.37
Umeå	9.34	13.54	5.70	11.67

4.2.3 Growth of forest stands under historical climate

The simulated standing volume across all grids at each location were plotted against stand age to visualise the growth of forest. The solid line represents the mean standing volume, while the grey window represents the range of the simulated standing volume. Note plots start at different year for different location to simulate a harvest age in year 2015.

From Figure 4.2 below, it can be seen that the range of standing volume is much larger in Malmö than the other 2 locations, despite it having the least number of grids. This is further discussed in Section 5.2.1.

It was also found that the auto-thinning in mixed-culture resulting in much more frequent thinning than that specified in other simulations. To understand the effect of the auto-thinning on productivity, the simulations for monocultures were re-run with the auto-thinning option. It was found that under the auto-thinning option, the resulting total standing volume at the harvest age could be approximately 6 to 15% less than that in stands with defined thinning (Appendix VII).

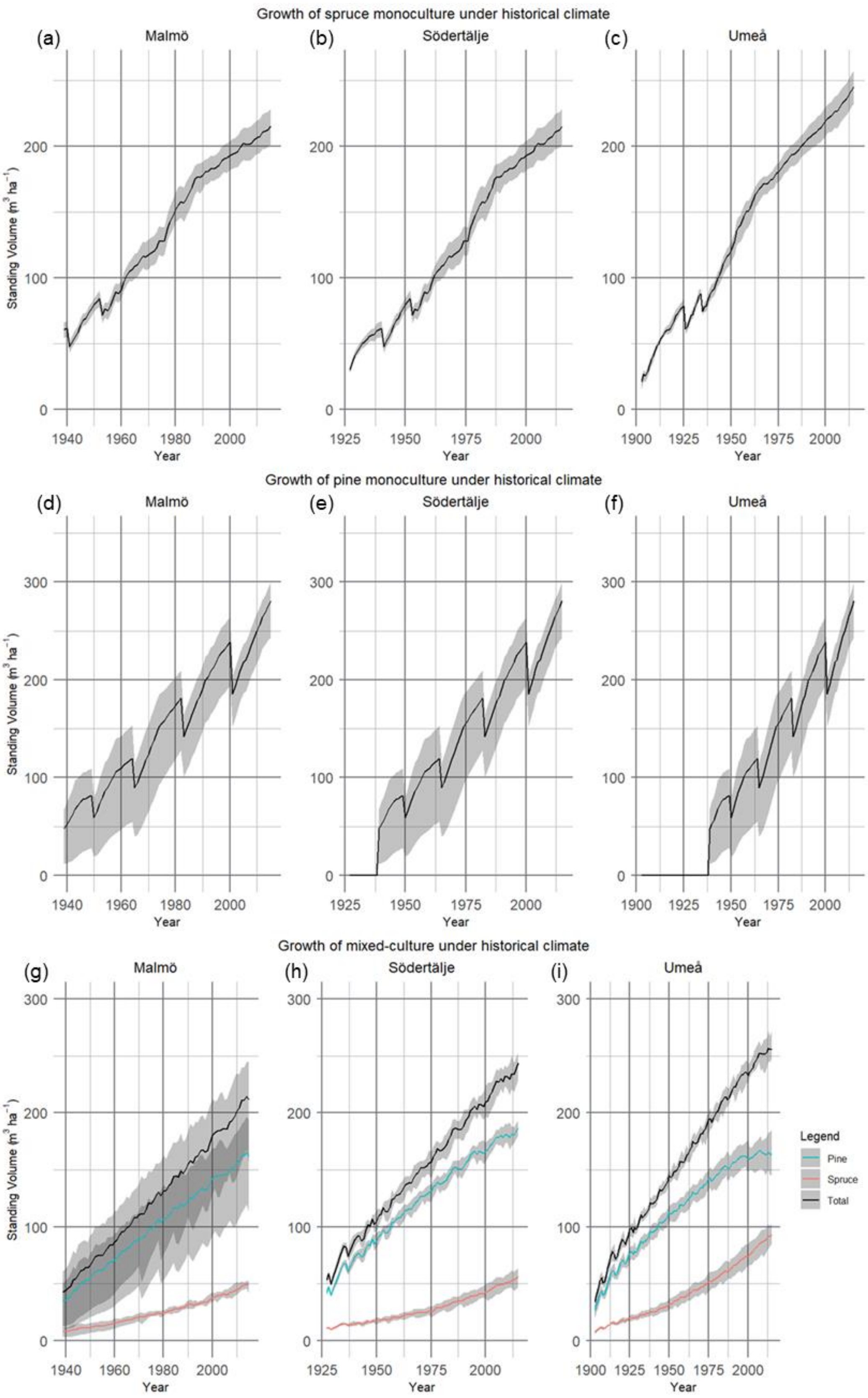

Figure 4.2 (a) to (i) Growth curves of different forest stands in different locations under historical climate; note differences in y-axis across forest type; note that the definition of BEFs meant that there is no standing volume before the age of 10, thus all curves start from age 10

4.3 Future Potential

4.3.1 Total standing volume

Assuming the same harvest age as to current practice is maintained, the total standing volume and its percentage difference to existing provision under historical climate is summarised in Table 4.6 below. The result for the baseline scenario is included to indicate the representability of a fixed climate to the actual historical climate. It was also assumed that the proportion of each forest type (Swedish University of Agricultural Sciences, 2022a) remained unchanged in the future scenarios when scaling-up the per hectare mean volume to total standing volume. The per hectare figures broken down by forest types is available in Appendix VIII.

The results are based on the assumption that the forest stand experienced a constant climate in their entire life-time. Whereas in reality, existing forest stands would have experienced climate under the baseline scenario and likely a warming climate (RCP scenarios) in the future. This means that older stands that are planted before 2015 would have a growth pattern more aligned with the baseline scenario, whereas younger stands and future stands would show a growth pattern between that of the baseline and the future fixed climate scenarios.

In general, the simulation result showed that warming temperature and increased precipitation led to higher productivity, agreeing with the findings of Lagergren & Jönsson (2017). Lagergren & Jönsson (2017) also found that the increase is less pronounced in the north of Sweden. However, it was found here that the increase of pine was more obvious in the north of Sweden, with up to 30% more biomass. The increase of spruce was however only less than 2% in the same region.

Table 4.6 Total standing volume under 3 climate scenarios by species at harvest age

Location	Harvest age (year)	Scenario	Spruce (million m^3)	Difference to existing provision based on historical climate (%)	Pine (million m^3)	Difference to existing provision based on historical climate (%)
Malmö	86	Baseline	57.21	+18.10	26.09	+14.55
		RCP 4.5	43.53	-10.13	26.73	+17.34
		RCP 8.5	43.63	-9.93	27.97	+22.80
Södertälje	98	Baseline	68.48	+14.74	141.19	+9.22
		RCP 4.5	77.56	+29.97	159.35	+23.27
		RCP 8.5	80.96	+35.66	163.26	+26.29
Umeå	122	Baseline	56.29	+1.68	185.05	+12.59
		RCP 4.5	64.00	+1.91	214.50	+30.51
		RCP 8.5	66.36	+1.98	218.66	+33.03

4.3.2 Growth of forest stands under changing climate

The mean simulated standing volume across all grids at each location were plotted against stand age to visualise the growth of forest under different climate scenarios.

As mentioned, simulation result showed that warming temperature and increased precipitation generally led to larger standing volume. The baseline scenario usually resulted in the lowest productivity and the RCP 8.5 scenario usually led to the highest productivity. This increase is mostly seen throughout the whole rotation period of forest stands, and the older the stands are, the more noticeable the increase is. Note that the temperature and precipitation change are very similar in the two RCP scenarios at Södertälje and Umeå, thus the corresponding growth curves at those locations are also similar. Figure 4.3 below can be taken as an example. Forests at Södertälje and Umeå showed similar responses (Appendix IX). Note that the definition of BEFs meant that there is no standing volume before the age of 10, thus all curves start from 10 years age.

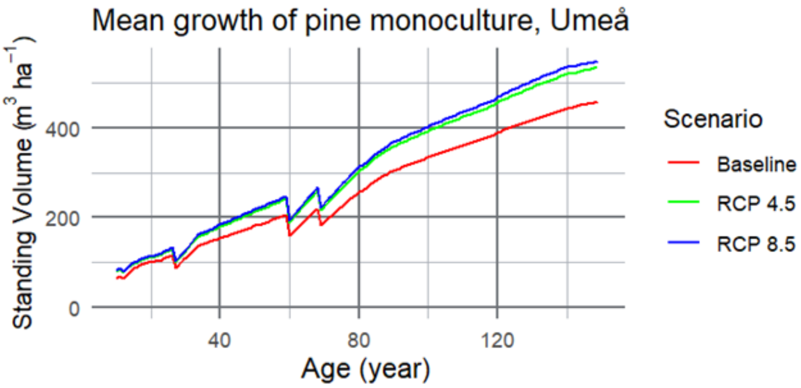

Figure 4.3 Growth curves of pine monoculture in Umeå under 3 climate scenarios

Forest stands in Malmö, however, showed a different pattern than the other 2 locations, where the baseline scenario does not always show the lowest productivity.

Figure 4.4 below visualises the growth of pine monoculture at Malmö. The baseline scenario showed the highest standing volume among all scenarios before the third thinning (54 years), and the RCP 4.5 scenario showed the lowest standing volume during the same period. Between the third and fourth thinning (72 years), the standing volume from RCP 8.5 scenario overtook the baseline scenario, while the RCP 4.5 scenario remained the lowest volume. It was only after the fourth thinning that the patterns began to follow the development at the other locations, where the baseline scenario resulted in the lowest productivity and the RCP 8.5 scenario led to the highest productivity.

Spruce monoculture in Malmö showed yet another pattern. The curve from the baseline scenario is consistently higher than the two RCP scenarios, and there is a huge gap between them until the age of 110. After that, the curves began to come closer to each other, but the baseline still resulted in the highest productivity. The possible cause of the forest stands in Malmö behaving differently to those in the other 2 regions is discussed in Section 5.3.2.

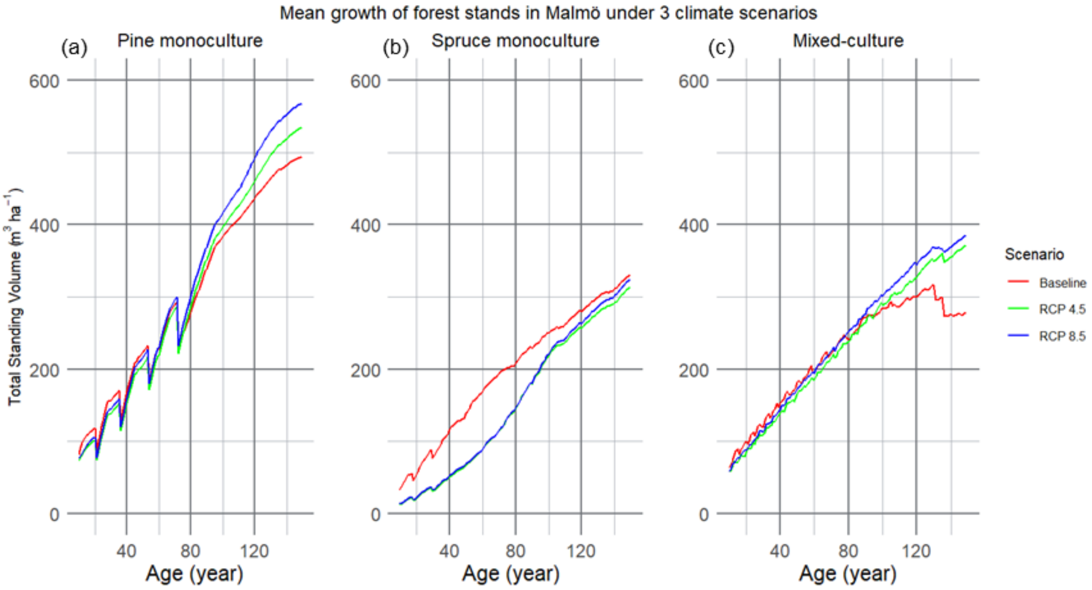

Figure 4.4 (a) to (c) Growth curves of different forest stand in Malmö under 3 climate scenarios

The overall growth of mixed-culture at Malmö displays a similar pattern to that of pine monoculture in Umeå - the baseline scenario resulted in the highest productivity at younger age but the lowest productivity in older age (Figure 4.3 & 4.4). However, a different pattern was revealed when the plots were broken down by species within the mixed-stand. Figure 4.5 below shows that the spruce trees in mixed stand behaved similar to forests in Södertälje and Umeå (Figure 4.3; Appendix IX), where the baseline scenario resulted in the lowest productivity and the RCP 8.5 scenario led to the highest productivity. This increase is seen throughout the whole life time of forest stands, and the older the stands are, the more noticeable the increase is. This is opposite to what happened in the spruce monoculture in the region, where warming temperature led to a decrease in productivity.

Another noticeable outcome from Figure 4.5 is that the rate of increase in standing volume slows down earlier in the baseline scenario than the future climate scenarios, suggesting that the rotation period could be extended under future climate change.

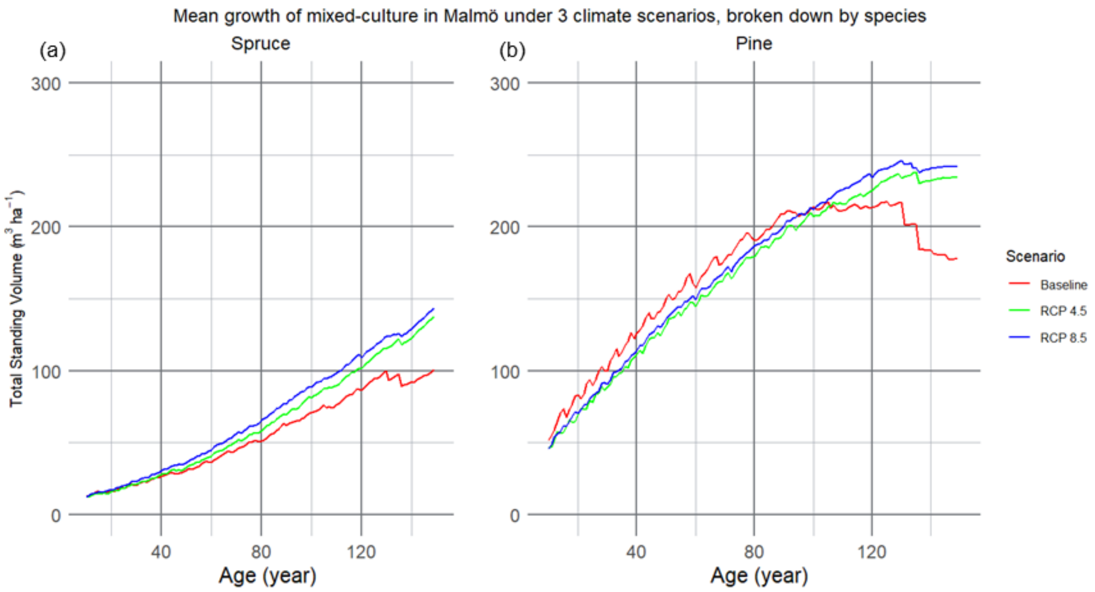

Figure 4.5 Growth curves of (a) spruce and (b) pine tree species in mixed-culture at Malmö under 3 climate scenarios

The simulations for monocultures were re-ran with the auto-thinning option, as in Section 4.2.2. Forests managed with an auto-thinning option show a decrease in after approximately 120 years in all three locations, similar to what the mixed-forest has shown in Figure 4.4 above. In contrast, the increase of standing volume typically continues beyond the 150 years simulation for forests managed with defined thinning option. Indicating that this seemingly shorter life-time was not caused by the forest type, but rather the auto-thinning option. This also suggests that the drop in standing volume found in Figure 4.4 above might not be truly reflecting the reality, as the mixed-cultures were simulated with the auto-thinning option.

Consistent with the findings in Section 4.2.2, the available biomass at the harvest age under an auto-thinning option is significantly lower than that from a defined thinning management. The percentage difference ranges from approximately 4% to 21% (Appendix X). However, there is no clear correlation between the percentage difference and the climate scenario.

As mentioned previously, forests in Malmö showed different patterns to the other locations under future climate – future climate does not always lead to higher productivity as in other locations. To understand its possible cause, the gross primary productivity (GPP) and total respiration of forest in Malmö were investigated, where the difference between GPP and total respiration represents net primary productivity (NPP) and could reflect forest growth.

Refer to Figure 4.6 below, the GPP and total respiration of pine monoculture at Malmö under the baseline and both future climate scenarios all increased rapidly in early age (before 10), but the baseline scenario led to a higher initial value. However, the GPP and total respiration in the baseline scenario starts to decrease at around the age of 30, before the third thinning. On the other hand, GPP and total respiration under the future climate scenarios continues to increase steadily at the same age and catches up with that in the baseline scenario, explaining the crossover of standing volume between the third and fourth thinning found in Figure 4.4. The GPP and total respiration under the future climate scenarios continues to increase after that, while those under the baseline scenario shows a bigger drop at around age 60, after the fourth thinning. As respiration decreases less than GPP, and NPP is the difference between these two, the productivity in the baseline scenario is lower than that in the future scenarios, which was reflected in the standing volume shown in Figure 4.4.

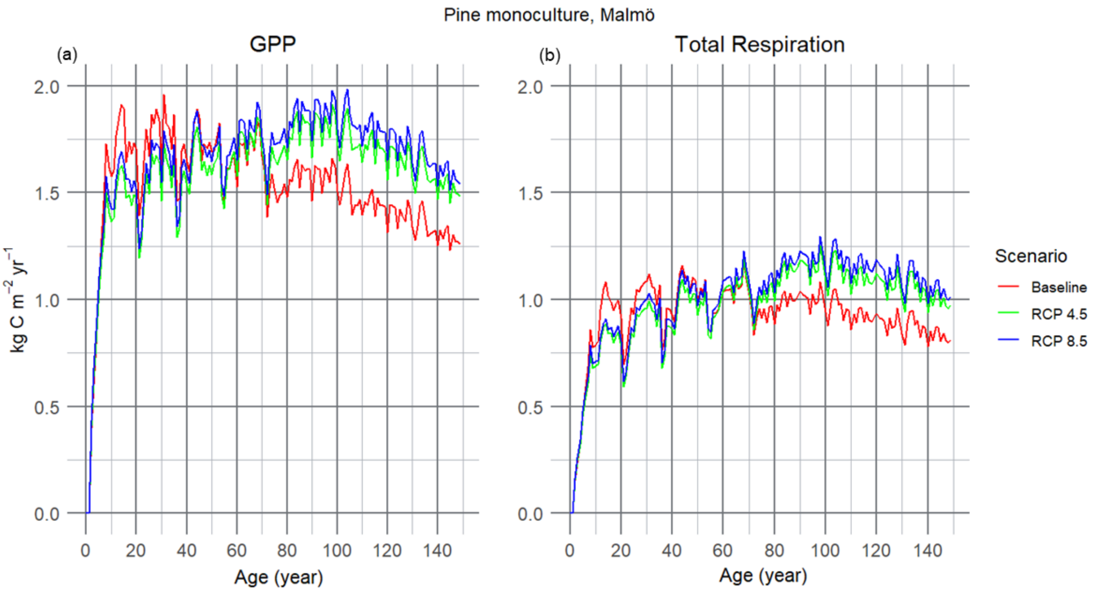

Figure 4.6 (a) GPP (gross primary productivity) and (b) total respiration of pine monoculture at Malmö under 3 climate scenarios

From Figure 4.7 below, it can be seen that both the GPP and total respiration of spruce monoculture under the baseline scenario were rather stable. They increased rapidly in early age (before 20 years), then rose with a lower rate of increase till the age of 80 until they stabilised. On the other hand, GPP and total respiration of stands under future climate scenarios did not increase rapidly, but rather steadily climbed up until the age of around 110, then stabilised.

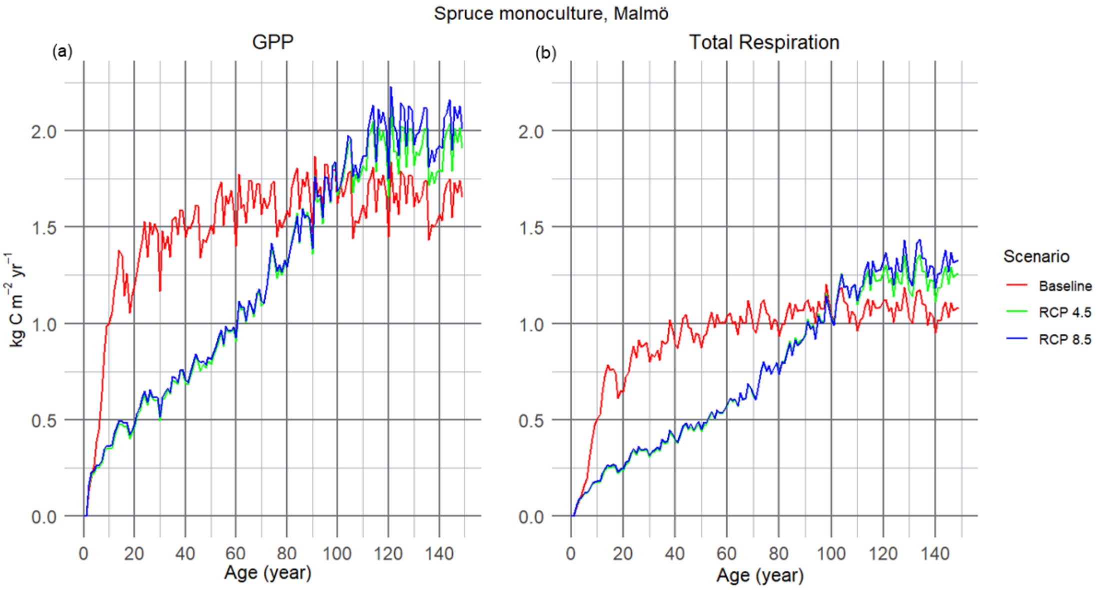

Figure 4.7 (a) GPP (gross primary productivity) and (b) total respiration of spruce monoculture at Malmö under 3 climate scenarios

The pattern of GPP and total respiration of pine in mixed-culture (Figure 4.8) is partly similar to that in pine monoculture, where the baseline scenario shows higher initial productivity. However, the drop in productivity was more significantly in the mixed-culture, and the future climate scenarios started the decrease at around the same age as the baseline scenario, unlike in monoculture where the decrease happened at later age for future climate. The dramatic dip in productivity in the baseline scenario was also reflected in the drop of standing volume (Figure 4.4).

The pattern of GPP and total respiration of spruce in mixed-culture clearly shows that the productivity increases in future climate scenarios (Figure 4.8), echoing the increased standing volume shown in Figure 4.4.

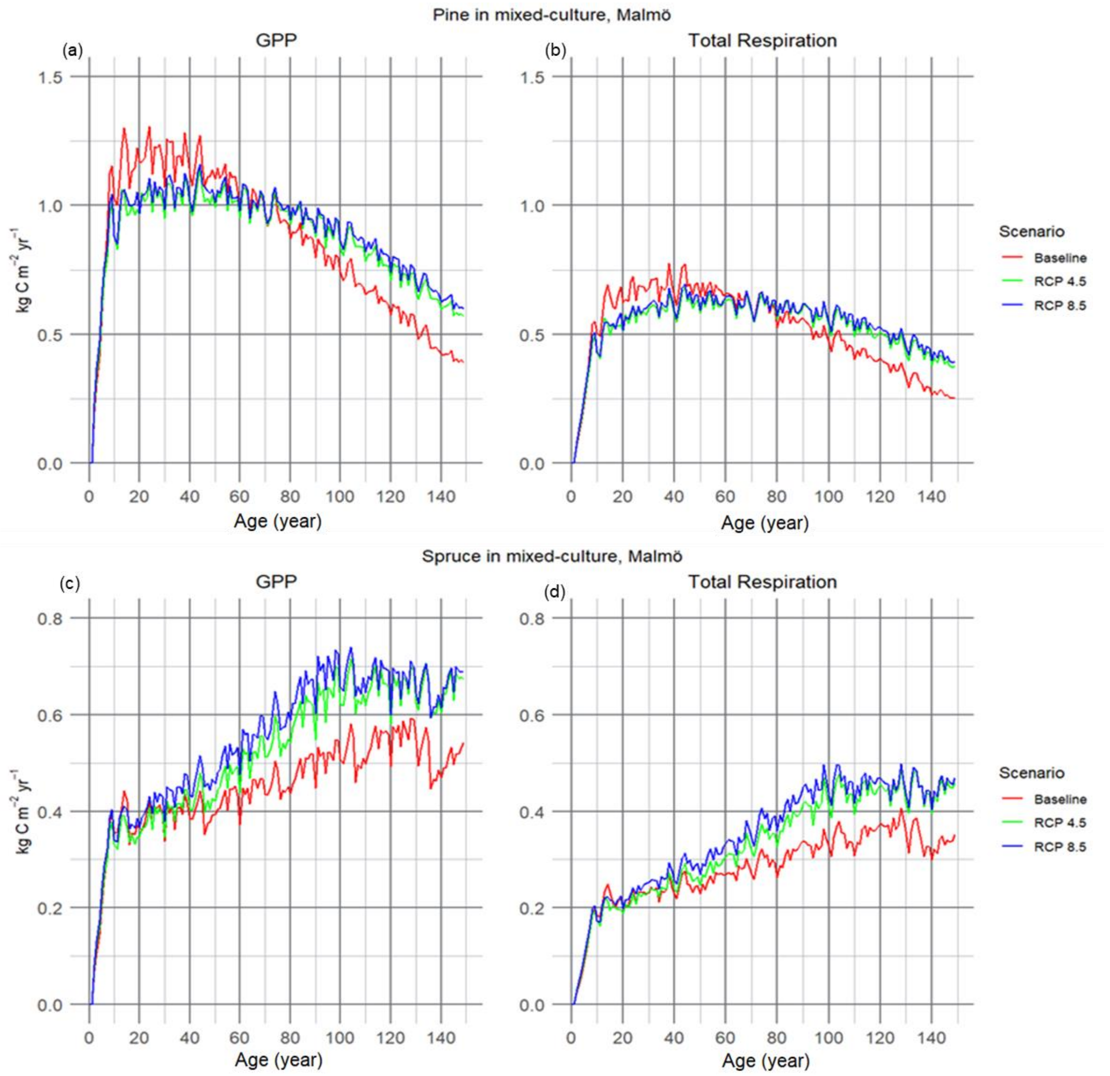

Figure 4.8 (a) GPP (gross primary productivity) and (b) total respiration of pine tree species in mixed-culture at Malmö under 3 climate scenarios; (c) GPP (gross primary productivity) and (d) total respiration of pine tree species in mixed-culture at Malmö under 3 climate scenarios

4.3.3 Species replacement in mixed-culture under changing climate

To understand the impacts on spruce and pine in mixed-stands, the accumulated average (definition provided in Section 3.1) of the proportion of spruce was plotted. Additionally, as it was assumed that the mixed-stands only contain spruce and pine, the graphs could also be read as the proportion of pine.

Refer to Figure 4.6 below, it can be seen that the proportion of spruce increases with latitude in the baseline scenario. The warming future climate scenarios also consistently increased the share of spruce in mixed-culture among all locations, with the greatest increase shown in Malmö. Although an increase of spruce share indicates a decrease of pine share, it does not necessarily mean that the productivity of pine decreased. For instance, Södertälje and Umeå had shown an increase in standing volume of both species in mixed-stand. A decrease of standing volume of pine under RCP 4.5 and 8.5 scenarios was only found in Malmö, as shown in Figure 4.5.

Another trend that is consistent across regions is how the curves were shaped. The accumulated average share of spruce started to drop in the beginning, reaching a minimum at around age 60 to 80, then increases until the end of cycle. The implications of these observations are discussed in Section 5.4.

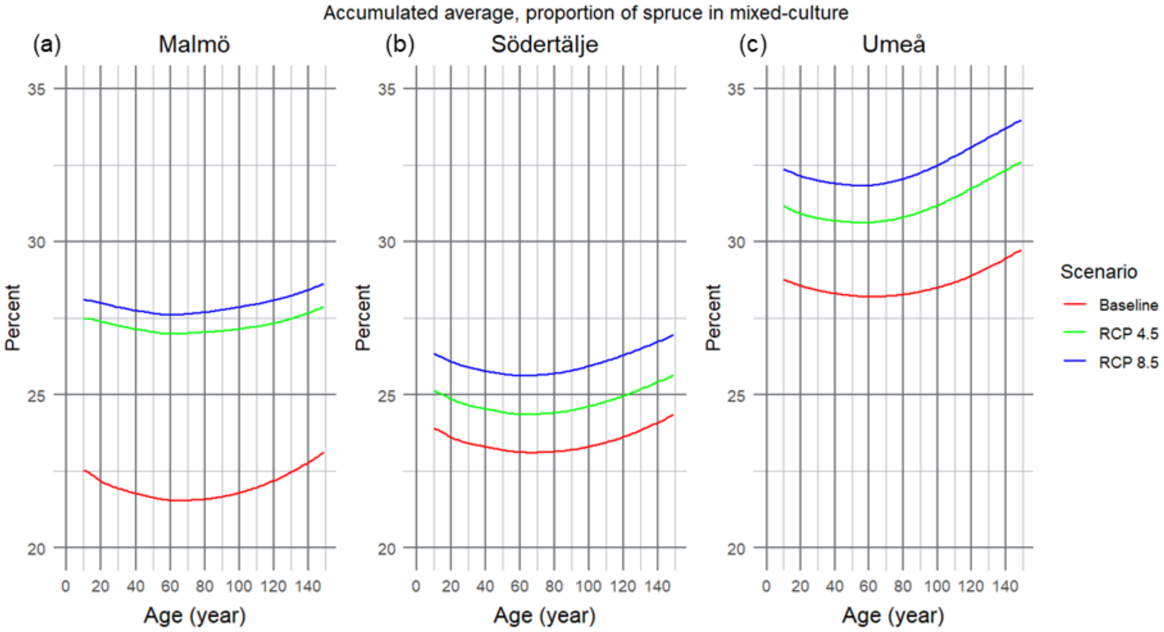

Figure 4.9 Accumulated average of proportion of spruce in mixed-culture under 3 climate scenarios at (a) Malmö, (b) Södertälje and (c) Umeå

5 Discussion

5.1 Reliability of Model

The finding in Section 4.1 where the amount of observational data correlates with the degree of fit between the plots was expected as a larger dataset can better represent the population and reduce the influence from variability and random error. It was also noted that the youngest and oldest age groups had fewer observational data than the middle age groups. For the youngest age group, it could be due to the minimum requirement for a tree to be inventoried, which resulted in less observations for the youngest age groups; for the oldest age group, it is likely due to the fact that trees are harvested at earlier age, therefore resulting in fewer old stands. It could also be a bias arising from the sample plot data, which were collected on temporary sample plots instead of permanent sample plots, although it is unclear what the difference was.

Spruce monoculture in Malmö shown a greater discrepancy between simulated values and observed values compared to other forest stands and location (Figure 4.1). Yet it was also seen that the range of observed data there was larger, indicating that the spatial variability was larger, which may have affected the accuracy of the simulation.

Regarding the overestimation of standing volume of pine monoculture by the simulations, one possible cause might stem from industry practice. G. Vulturius (personal communication, April 14, 2023) shared that pine is planted more often by forest owner due to a higher biomass potential, often despite less favourable land conditions. This could lead to a systematic bias when comparing actual and simulated standing volume, as pine are on average planted on less favourable land conditions than spruce, and thus show a less-optimal productivity than that under simulations. The same could apply to mixed-culture, where simulated values were also an overestimation across all locations. Another reason could be a different ratio of pine to spruce in real-life, which may influence the dynamics between the species and thus their growth.

Other uncertainties associated such as parameter estimation and model structure were not further investigated. However, the model has been extensively evaluated for its performance on simulating forest growth and has shown satisfactory accuracy (Bergquist et al., 2023; Lindeskog et al., 2021; Smith et al., 2014). The evaluation in this study also proved that it generally gives reliable results. However, the confidence level does decrease for further findings from simulation in sites and culture where the amount of observational data limited the accuracy of simulations

5.2 Provision of Bioenergy with Existing Forest Residue Potential

5.2.1 Existing potential

The total standing volume given in Section 4.2.1 could be converted to energy potential for each study site, and to understand if existing biomass is sufficient to provide for their production. The provision in Malmö is significantly lower than the other regions due to the location of the site, as most of the captured area within the 75km radius is the sea. The provision could be increased with the capturing radius, but the cost implications was not considered in this study. Although forest productivity is lower in Umeå (Table 4.2), the total standing volume at the end of rotation was the greatest due to the large forest coverage in the region (Table 4.3). However, the prolonged rotation period in Northern Sweden also meant that there are fewer forests ready for harvest each year compared to the South, reflected by a lower figure in annual felling (Swedish University of Agricultural Sciences, 2022a). Therefore, the actual potential might be lower than the value given in Table 4.3.

It is important to note that the competition with other operators was not considered in this study. Even if the provided figures showed that the provision is sufficient, it may not be the case in reality if there are more operators in the region sourcing from the same forests. This may be a greater concern for Sysav Avfallsförbränning, as Karlsson et al (2021) mentioned in their study that the competition for forest residue is particularly higher in southern Sweden. However, it is worth noting that Sysav Avfallsförbränning currently rely mainly on municipal solid waste, and forest residue is only a very small portion of its feedstock. The high competition may explain their business decision of not focusing on forest residue, or could reinforce this decision, provided that the sourcing of municipal solid waste and their other feed stock is stable.

Another finding related to Sysav Avfallsförbränning is that the range of simulated standing volume is greater in Malmö than the other two locations (Figure 4.2). This indicates that the spatial variability in growing conditions in the region is larger, suggesting that using the mean growth across all grids may not be the best representation. For instance, the number of soil types among different grids were higher in Malmö than in the other two locations. Therefore, a grid-level study could be beneficial for an in-depth investigation targeting specifically to this site.

5.2.2 Difference in productivity between species

In Section 4.2.2 and 4.2.3, it was evident that pine trees have a higher productivity than spruce under the same conditions. This could reinforce the industry practice mentioned in Section 5.1, where pine is often preferred over spruce due to its higher biomass potential. For the CHP plants operators, this means that they would likely be sourcing more forest residue from pine trees. This has limited impacts on their operation due to the slight difference of energy content in spruce and pine, which is further discussed in Section 5.4.

5.3 Forest Productivity under Changing Climate

5.3.1 Future potential

The results in Section 4.3.1 showed a mainly positive outlook when considering solely on the provision of biomass. Most location and forest stand showed more than 20% increase in biomass under future climate scenario, suggesting that a warming climate could be beneficial to forest growth. However, what was not considered in this study was that a more severe climate change is likely to induce stricter decarbonisation legislation, thus higher competition for alternatives including biomass and forest residue, as mentioned in Karlsson et al (2021). The benefit of increased biomass provision due to a warming climate could be cancelled out by the heightened competition caused also by climate change.

The large percentage differences in total biomass provision between the fixed average baseline scenario and the actual historical climate scenario at Malmö and Södertälje suggest that existing forests are not yet in equilibrium with the current climate. Older forests that were planted in the 20th century - those that are ready for harvest recently - experienced a lower temperature and level of CO_2 in their early ages (Intergovernmental Panel on Climate Change, 2021), therefore the productivity would be lower in their earlier age. It could be expected that younger forest stands would show higher productivity compared to the older forests at the corresponding age due to more favourable conditions in recent decades, such that the biomass provision in the future would also be higher, even if future climate change is well mitigated and temperature rise is kept minimal.

5.3.2 Response of forest growth to climate change

In general, the simulation result showed that warming temperature and increased precipitation led to higher productivity, agreeing with the findings of Lagergren & Jönsson (2017). Lagergren & Jönsson (2017) also found that the increase is less pronounced in the north of Sweden. The increase of spruce found in this study agrees with the literature, with only less than 2% increase at Umeå. However, it was found here that the increase of pine was more obvious in the north of Sweden, with up to 30% more biomass. The reason of such discrepancies is however hard to draw, since Lagergren & Jönsson (2017) used a climate model with solar radiation also changing, which was not the case in this study.

In Malmö and Södertälje, the only major difference between the two RCP scenarios was atmospheric CO_2 concentration, whereas the temperature and precipitation change only varies very slightly on the monthly scale as mentioned in Section 3.6. It can be seen from Section 4.3.1 and 4.3.2 that the change in biomass did not differ much among the two RCP scenarios, suggesting that increased atmospheric CO_2 has limited impact on tree growth, but that temperature and precipitation has stronger effect on biomass growth.

Regarding the inconsistency of forest response in Malmö compared to the other 2 locations, the graphs showing GPP and total respiration (Figures 4.6 – 4.8) might be able to explain some patterns. Figures 4.4, 4.6 and the described patterns (Section 4.3.2) suggests that future climate is less favourable for the growth of pine initially, but the growth could catch up with current conditions at a later stage and even produce greater amount of biomass at the current harvest age. Similarly, Figure 4.4 and 4.7 revealed that productivity under future climate scenarios could not catch up with the baseline scenario before it stabilised, indicating that future climate is less favourable for the growth of spruce initially, but the growth could catch up with current conditions at a later stage. However, unlike pine monoculture, the growth of spruce could only catch up at a much later age, more than doubled the current harvest age. This implies that the rotation period must be extended if the same level of biomass is required and may potentially reduce the available provision each year, same as the case in Northern Sweden. As for the mixed-culture in Malmö, the pattern of GPP and total respiration clearly shows that the productivity increases immediately for spruce and in later stage for pine under future climate scenarios (Figure 4.8), echoing the increased standing volume shown in Figure 4.4.

As the forest stands were simulated with the same set of environmental conditions as their counterparts in monoculture, it is likely that the competition between the two species contributed to a different behaviour when compared to monocultures. The decrease of standing volume of pine in future climate scenarios, although minimal, also suggested that future climate is particularly unfavourable for pine in Malmö, as this is the only location where pine volume decreases.

5.4 Species change

Results from Section 4.3.3 have shown that spruce is gradually replacing pine in all study areas, despite an increased productivity of both species. This suggests that the changing climate is becoming more favourable for spruce and less favourable for pine in mixed-cultures of these 2 species. Combined with an increased popularity of spruce planting among forest owners due to improved initial growth and higher productivity in fertile land (Zhang, 2012), it is possible to see a larger switch from pine to spruce.

Aniszewska & Gendek (2014) have tested the heat of combustion and calorific value of the dry weight of the cones and wood of several species. It was found that Norway Spruce has a slightly higher heat of combustion and calorific value than Scots Pine. But due to the very slight difference in heat of combustion and calorific value, it is suggested that the species displacement should not be taken as a sign of increase in energy potential. Although the species displacement due to climate change would not be a major concern for the energy industry, it might be a concern for the wood and paper industry, as there could be major differences between the timber quality of the two species. This is however out of the scope of this study.

5.5 Impacts of removing forest residues

Although fuelling bioenergy with forest residues can be a low-carbon alternative to fossil fuels without the concerns of land use change and food security, it is important to consider the implications on soil organic carbon and biodiversity due to removal of deadwood (Camia et al., 2020).

Forest residue plays a crucial role of forest ecosystems and are vital to forest health (Zhou et el., 2007). During its decomposition, forest residue releases carbon, nitrogen, phosphorus and other nutrients, thus maintaining the material flow, energy flow and nutrient cycling in forest ecosystems. Furthermore, forest residues are vital resources for saproxylic species such as decomposers, fungi, and bacteria. They play a crucial role in breaking down woody material and cycling nutrients back to the soil (Camia et al., 2020). Therefore, the removal of forest residue eliminates a substantial source of nutrients and carbon source of the forest floor, potentially deteriorating forest health over time.

A study done by Johnson et al. (2002) has found that the removal of forest residue could have long-term impact to regenerative forests and soil carbon pools. In their study, some study sites with forest residue removed after a harvest shown less regenerative biomass and lower soil carbon. This suggests that the removal of forest residue which led to decreased carbon and nutrient input into the soil could negatively affect the overall productivity and health of the forest ecosystem in the long run. Thiffault et al. (2011) also concluded that residues removal might have a worse impact in boreal stands, which should be a major concern for the Swedish forestry sector.

The decline in soil carbon stock due to the removal of forest residues also has implications to the mitigation of climate change and net-zero targets. Forests are a natural carbon sinks as they absorb and store CO_2 from the atmosphere through photosynthesis. Forest residues are part of the forest carbon pool and contribute to the carbon sequestration process by storing carbon for extended periods. Removing forest residue for energy purposes releases the stored carbon and thus reduces the potential carbon sequestration capacity of forests. Although the released carbon is supposed to be captured and stored permanently through a BECCS facility, it is unclear if such storage is actually permanent and leak-proof, and thus outweigh the benefits of natural carbon sinks such as forests.

In addition, forest residues also act as a habitat for insects, birds, and mammals, apart from providing nutrients to saproxylic species such as fungi, lichens and mosses. Moreover, the operations involved in collecting and removing logging residues can result in the extraction or damage of other ecologically valuable dead wood, further decreasing the availability of resources and habitats (Camia et al., 2020). Stokland et al. (2012) emphasised the importance of dead wood for maintaining biodiversity within forest ecosystems. They highlighted that saproxylic species are particularly vulnerable to the removal of forest residue such that the loss of dead wood as a habitat and food resource can result in declines or even extinctions of saproxylic organisms, as well as other species that depend on them for food or habitat. This loss of biodiversity can have far-reaching consequences, impacting the overall health and functioning of forest ecosystems.

Due to the many potential detrimental impacts caused by removing forest residue, comprehensive studies must be conducted before the implementation of BECCS and sustainable management practices must be applied to preserve forest ecosystems and to ensure the sustainability of bioenergy.

5.6 Implications of BECCS

A major motivation for this study was the increased interest in BECCS. Although industry and governmental support seem promising, and the future outlook of forest growth was proven to be positive, the energy penalty of BECCS facilities must not be ignored. CO_2 captured from the combustion process are usually liquefied for storage purpose, and is likely to be the case in the Swedish industry due to the established sea transportation network (Karlsson et al., 2021). However, the liquefaction of CO_2 requires extra energy, thereby resulting in an energy penalty, meaning that more energy is needed to run the facility than is generated by the bioenergy produced.

Technological advancement such as improved conversion efficiency, utilising waste heat, and developing more efficient and cost-effective carbon capture technologies are some possible ways to reduce the energy penalty associated with CO_2 capture and storage (Quiggin, 2021). Yet at the moment, Quiggin (2021) suggested that a BECCS facility could either increase the load factor of the facility, or to decrease power efficiency in order to maintain the same level of power production and a high volume of captured CO_2. Increasing the load factor means that the facility would be operational and generating power for more hours in a year, therefore producing more energy. And the reason to decrease power efficiency in exchange of higher CO_2 capture volume at a same level of energy production is that BECCS facilities often has a CO_2 capture target to meet, which is usually tied to the national net-zero targets. However, it is important to understand that a lower power efficiency would result in higher energy consumption, reduced overall system efficiency, and increased biomass demand, posing adverse environmental and economic implications (Quiggin, 2021). In any case, both approaches would significantly increase the demand for fuel, thus could cancel out the benefit of increased biomass provision in the future. Therefore, the selected CHP plants must consider this energy penalty before implementing BECCS in their facilities.

5.7 Source of errors

A potential major source of error in estimating the standing volume is associated with the thinning options in the model. As mentioned in Section 4.2.2 and 4.3.3, auto-thinning always led to less biomass at harvest, with a percentage difference ranging from 4-20% in monocultures. As the mixed-culture was purely simulated with the auto-thinning option, this might mean that the standing volume of such forest stands could be up to 20% less than what they could be with a defined thinning option. However, due to the complexity of a mixed-culture, the auto-thinning setting was considered the best possible option in this study. In addition, considering the smaller proportion of mixed-culture forests (Appendix IV), this error has a smaller impact than if a similar error was associated with the monocultures.

It is also important to note that the defined thinning forest management treatments (Table 3.3) was reported to be the typical practice in Sweden during the 20th century. It is possible that it differs from current practices. Therefore, the results may not accurately reflect the current availability. Yet, the management approach adopted in this study was taken from recent research (Bergkvist, 2023), which is the best available information. Similarly, the adopted age of harvest may not accurately reflect actual rotation period and harvest age in reality, as mentioned in Section 3.5.1. This may have affected the resulting estimation of biomass availability. Yet this is the best available information that could be located in the public domain.

Several errors may have been associated with the calculations of scaling-up the biomass potential. To start with, the total area was only excluding formally protected areas, but no other land use such as crop land or urban area were excluded. These areas are not productive forest land. Therefore, the total figures given in Section 4.2.1 is likely an overestimation. Considering productive forest area outside formally protected areas covers 40% of Sweden's total area, it is possible that the overestimation is relatively large. However, the per hectare figure were provided for more accurate calculation. If the exact area of productive forest land which are the sourcing location of the study sites are known, relevant personnel in those sites could easily calculate a more accurate figure for their own use.

Another potential error is rising from the future climate scenarios. In this study, only temperature, precipitation, and atmospheric CO_2 concentration was changed, while all other variables such as solar radiation and soil carbon were kept constant. This is less likely to be the case in the future, thus could be a potential source of error. However, as mentioned in Section 3.6, comprehensive climate models used by the IPCC also poses great uncertainties as it is sometimes difficult to determine all the variables used in each individual models. Therefore, using such models does not necessary improve accuracies. As such, using simplified scenarios should be satisfactory in this study.

5.8 Limitations

There were some unanswered questions in this study, which should be considered as part of the limitations in this study. For instance, the underlying reason of different response to climate change of forest stands in Malmö was not clear. The driving force of species displacement was also not investigated in-depth. All of these unanswered questions could be a stand-alone research topic on its own.

In relation to the previous point, the model outputs for Malmö were often unexpected. For instance, the pattern in shown in Figure 4.5 and 4.7 were abnormal compared to that in other locations. the pattern may be caused by the difference between the climate in different locations, or could potentially be caused by behaviour of the model. As the model was not calibrated in detail to every location, it is expected that it would not perform with outstanding precision in all locations. However, it was proven to be satisfactory reliable, as mentioned in Section 5.1.

Some other aspects not considered in this study may also bring valuable new inputs within relevant topics. For instance, only two tree species were considered in this study, but many other species such as birch, oak and beech do exist, despite making up a smaller portion of all forest area. Residues from all of the other forest could provide extra biomass that were not considered in this study.

Additionally, this study mainly focused on slash from the final harvest stage due to current industry practice, as explained in Section 2.2 and 3.1. Other forest residues in other stage of the rotation, such as slash from thinnings, were not considered as part of the fuel source. Although not currently adopted, such residues may also be considered as fuel source in the future.

In terms of future scenarios, although it was found that warming temperature facilitates forest productivity, extreme events, such as droughts, flood, bark beetle outbreak etc., associated with climate change were not investigated. It is possible that these extreme events and disruptions could worsen future biomass provision, and should be taken into account.

Another important consideration that was overlooked in this study is the potential pressure exerted on Swedish forests as the use of BECCS becomes more widespread and the demand for forest biomass increases. As highlighted in Section 3.5.1, the current mean age at the time of final felling, as reported in the Forest Data 2022 report by the Swedish University of Agricultural Sciences (2022a), may have been skewed by older trees from natural forests that have now been converted to managed forests. This has implications not only for biomass estimation, as mentioned in Section 5.7, but also for the issue discussed in Section 2.1, where the conversion of many primary forests in Sweden to managed forests has taken place.

Given the already rapid rate of conversion (Ahlström et al., 2022), it is crucial to consider the potential consequences of increased demand for forest biomass due to the implementation of BECCS. There is a risk that this heightened demand could pose further harm to the natural environment. Primary forests hold immense value for forest biodiversity and climate change mitigation (Sabatini et al., 2021), and therefore, the decision to convert primary forests to managed forests solely to meet the increased biomass demand must be carefully evaluated. It is essential to ensure that sustainability remains at the forefront and that the long-term health and integrity of existing forests are not compromised in the pursuit of a "sustainable alternative."

6 Conclusions

The LPJ-GUESS model was able to estimate the existing capacity of locally-sourced forest residue in Sweden, providing important insights for CHP plant operators to evaluate the energy potential from forest residue based on the different figures provided in this study. Results showed that the capacity of locally-sourced forest biomass for Swedish industries ranges from 70 million m^3 in the south to 221 million m^3 in the north. The higher capacity in Northern Sweden was due to the larger area of forests in the region. However, the figure of actual available biomass must be adjusted by each CHP plant operators according to the specifications of their own facilities, thereby providing a more accurate result.

Regarding future scenarios under different degrees of climate change, the results were generally positive for bioenergy alone, as the forest stands mostly responded with higher productivity, meaning the available forest residue would be more than current. Umeå Energi might benefit the most with heightened productivity, with around 30% increase of standing volume was found in all forest stands at Umeå, which also made up the highest proportion of productive forest land in the region. However, the future might be less favourable for Sysav Avfallsförbränning, the plant in Malmö, due to the smaller increase of productivity found in pine monoculture and mixed-culture, and even a potential 10% decrease of standing volume of spruce monoculture. But considering that the current feedstock of Sysav Avfallsförbränning mostly consists of municipal solid waste, the decrease in forest residue supply might not be a big business concern.

With BECCS joining the scene, it became uncertain whether or not the increased productivity could outweigh the energy penalty associated with the capture and storage of CO_2. Other negative impacts that could potentially be caused by the removal of forest residue including the loss of soil carbon and nutrients must also be thoroughly investigated before any decision-making to ensure that the natural carbon stocks are not disturbed in exchange for an artificial carbon stock that has not yet been proven to be certainly efficient.

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Appendices

Appendix I Grid List for Study Area

The dynamic vegetation model that was used in this study – the Lund-Potsdam-Jena General Ecosystem Simulator - or the LPJ-GUESS model (Smith et al., 2014) operates on a grid system. Table A1 below listed the grids that were considered in this study. They cover 3 different locations, each corresponding to a case study site in this study.

Table A 1 Grids taken for considerations in this study

Location	Longitude	Latitude
Malmö	12.75	55.75
	12.75	56.25
	13.25	55.75
	13.25	56.25
	13.75	55.75
	14.25	55.75
Södertälje	16.75	58.75
	16.75	59.25
	17.25	58.75
	17.25	59.25
	17.25	59.75
	17.75	59.25
	17.75	59.75
	18.25	59.25
	18.25	59.75
Umeå	19.25	63.75
	19.25	64.25
	19.75	63.75
	19.75	64.25
	20.25	63.75
	20.25	64.25
	20.75	64.25
	21.25	64.25

Appendix II Grid List for Model Evaluation

There were a relatively large number of grids shown in Appendix I. Only one grid was selected for each location during the model evaluation stage (Section 3.4), which were shown in Table A2 below. The simulation results from each grid were compared with corresponding observational results provided by the Swedish National Forest Inventory (SNFI) (2022).

Table A 2 Grids taken for detailed assessment during model evaluation stage

Location	Longitude	Latitude
Malmö	13.25	56.25
Södertälje	18.25	59.75
Umeå	19.25	63.75

Appendix III Biomass Expansion Factors

Table A3 provides the biomass expansion factors (BEFs) mentioned in Section 3.4.2. The BEFs were used to convert model output of total carbon in live vegetation biomass (kg C m^{-2}) to standing volume (m^3 ha^{-1}) for direct comparison to figures reported by the SNFI.

Table A 3 Biomass Expansion Factors (kg m^{-3}) used for converting model output of total carbon in live vegetation biomass (kg C m^{-2}) to standing volume (m^3 ha^{-1}) (Lehtonen et al., 2004)

Age of Stand (year)	Scots Pine	Norway Spruce
0-9	0	0
10-19	697	862
20-29	705	860
30-39	710	840
40-49	702	820
50-59	701	816
60-69	710	791
70-79	708	784
80-89	707	777
90-99	704	782
100-109	703	784
110-119	698	782
120-129	698	782
130-139	698	782
140-	690	788

Appendix IV Figures Used for Scaling-up Standing Volume

Appendix IV provides figures mentioned in Section 3.5.2. Table A4 provides the effective area at each location that was used to scale-up the standing volume from a single grid resulted from the LPJ-GUESS model. By scaling-up the standing volume, an estimation of the availability of biomass for each study site within its capturing zone is available. The effective area was also multiplied by the proportion of each forest type to provide a more accurate figure based on trees species in each location. The proportion of each forest type at each location are listed in Table A5.

Table A 4 Effective area at each location used to scale-up standing volume from a single grid

Location	Area (ha)
Malmö	738,985
Södertälje	1,158,413
Umeå	916,191

Table A 5 Productive forest area outside formally protected areas by forest types (Swedish University of Agricultural Sciences, 2022a)

Location	Corresponding County	Pine (%)	Spruce (%)	Mixed conifer (%)
Malmö	Skåne	9.9	34.3	2.5
Södertälje	Stockholm	28.2	22.8	17.3
Umeå	Västerbotten	47	21.3	13.5

Appendix V Supplementary Plots for Section 4.1

Appendix V provides supplementary plots for Section 4.1. They correspond to Figure 4.1 in the Section, which provided a comparison between observed and simulated data for various locations and forest stands. Figures A1 to A3 in Appendix V were however not included in Section 4.1 due to the discontinuous and incomplete observational data, which limited the fairness of the comparison between observation and simulation.

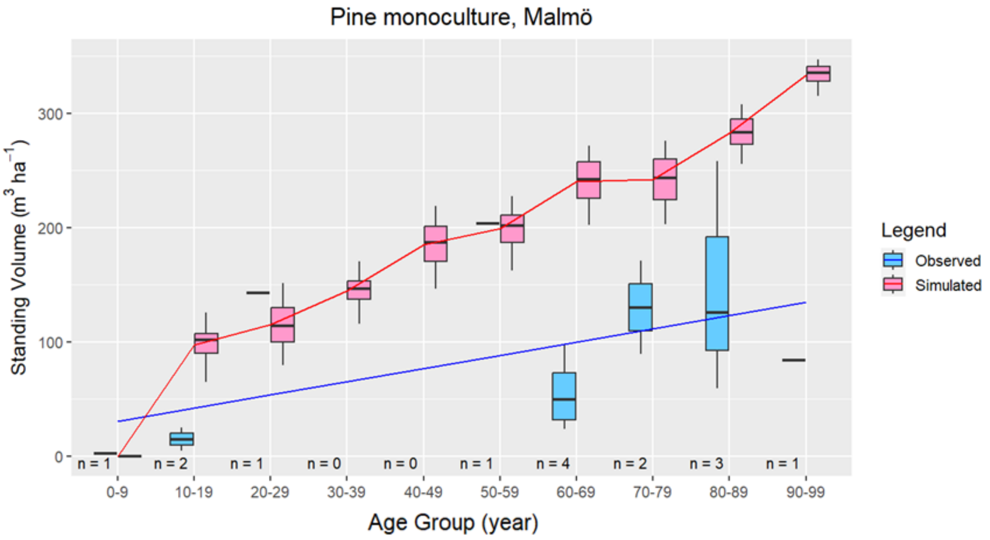

Figure A 1 Box and whisker plots for comparing observed and simulated data of pine monoculture at Malmö

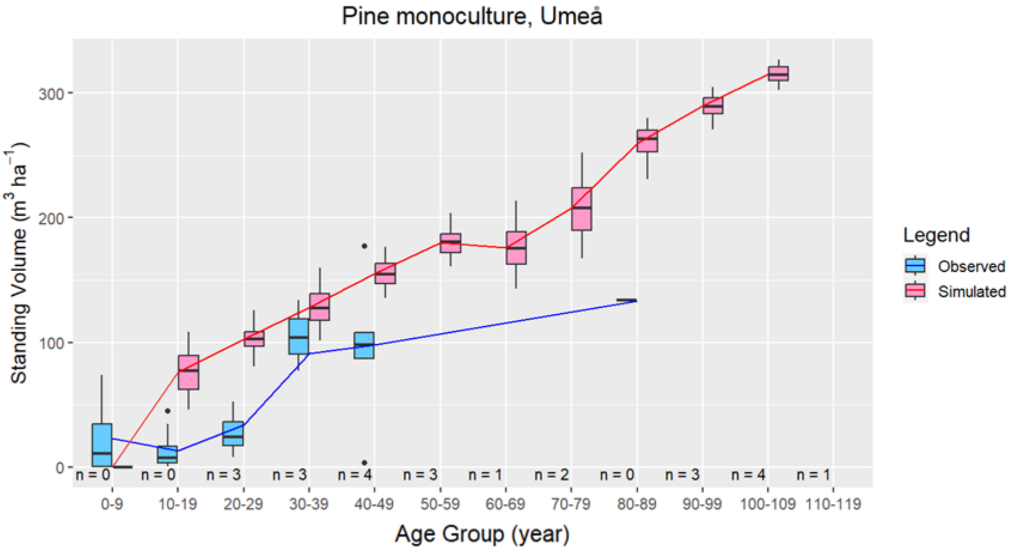

Figure A 2 Box and whisker plots for comparing observed and simulated data of pine monoculture at Umeå

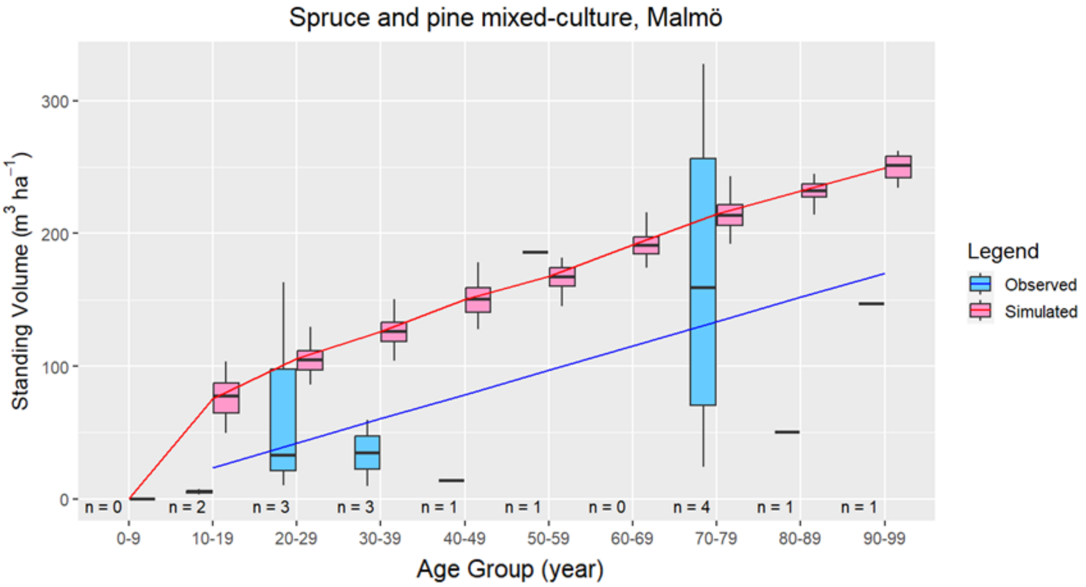

Figure A 3 Box and whisker plots for comparing observed and simulated data of spruce and pine mixed-culture at Malmö

Appendix VI Ratio of Spruce to Pine

Table A6 provides the ratio of spruce and pine species in different location at their corresponding harvest age under historical climate. These figures were used in Section 4.2.1 to estimate the existing total standing volume at each location.

Table A 6 Ratio of spruce to pine at harvest age under historical climate

Location	Pine (%)	Spruce (%)
Malmö	25.0	75.0
Södertälje	25.2	74.8
Umeå	39.0	61.0

Appendix VII Existing Standing Volume Simulated with Auto-thinning

In the study, a defined thinning option was used for monoculture stands, while an auto-thinning option was used for mixed culture stands. It was found in Section 4.2.3 that the auto-thinning in mixed-culture resulted in much more frequent thinning than that specified in other simulations. The simulations for monocultures were therefore re-ran with the auto-thinning option to investigate the effect of the auto-thinning option on productivity. The results are provided in Table A7 below.

Table A 7 Per hectare standing volume under historical climate by forest type at harvest age, simulated with auto-thinning option

Location	Harvest age (year)	Spruce monoculture (m^3 ha^{-1})	Difference to standing volume from defined-thinning (%)	Pine monoculture (m^3 ha^{-1})	Difference to standing volume from defined-thinning (%)
Malmö	86	190.20	-6.15	264.04	-5.92
Södertälje	98	215.10	-10.37	274.42	-11.46
Umeå	122	271.16	-10.51	301.22	-14.70

Appendix VIII Per Hectare Standing Volume, Future Scenarios

Appendix VIII supplements Table 4.6 in Section 4.3.1 by providing a per hectare standing volume (Table A8) instead of the scaled-up total standing volume. The figures were also normalised (Table A9) to provide a fair comparison across species similar to the approach in Section 4.2.1.

Table A 8 Per hectare standing volume under climate scenarios by forest type at harvest age

Location	Scenario	Harvest age (year)	Total standing volume of spruce monoculture (m^3 ha^{-1})	Total standing volume of pine monoculture (m^3 ha^{-1})	Total standing volume of spruce in mixed-culture (m^3 ha^{-1})	Total standing volume of pine in mixed-culture (m^3 ha^{-1})
Malmö	Baseline	86	224.73	317.55	58.30	200.11
	RCP 4.5		170.49	330.10	66.26	188.75
	RCP 8.5		170.64	346.60	73.80	195.19
Södertälje	Baseline	98	245.87	340.43	69.06	201.00
	RCP 4.5		275.78	386.98	85.79	226.57
	RCP 8.5		285.52	401.55	94.24	226.67
Umeå	Baseline	122	262.79	396.58	108.88	183.86
	RCP 4.5		293.48	465.08	133.51	194.21
	RCP 8.5		302.00	477.04	140.15	187.18

Table A 9 Per hectare standing volume under climate scenarios by forest type, normalised

Location	Scenario	Standing volume of spruce monoculture (m^3 ha^{-1} $100yr^{-1}$)	Standing volume of pine monoculture (m^3 ha^{-1} $100yr^{-1}$)	Standing volume of spruce in mixed-culture (m^3 ha^{-1} $100yr^{-1}$)	Standing volume of pine in mixed-culture (m^3 ha^{-1} $100yr^{-1}$)
Malmö	Baseline	261.31	369.24	67.79	232.69
	RCP 4.5	198.24	383.84	77.05	219.48
	RCP 8.5	198.42	403.02	85.81	226.97
Södertälje	Baseline	250.89	347.38	70.47	205.10
	RCP 4.5	281.41	394.88	87.54	231.19
	RCP 8.5	291.35	409.74	96.16	231.30
Umeå	Baseline	215.40	325.07	89.25	150.70
	RCP 4.5	240.56	381.21	109.43	159.19
	RCP 8.5	247.54	391.02	114.88	153.43

Appendix IX Supplementary Plots for Section 4.3.2

Figures A4 to A8 in this appendix serve the same purpose as Figures 4.3 and 4.4 to visualise the growth of forest under different climate scenarios. These plots were however not included in Section 4.3.2 due to the high similarities to Figure 4.3, so as to reduce repetition.

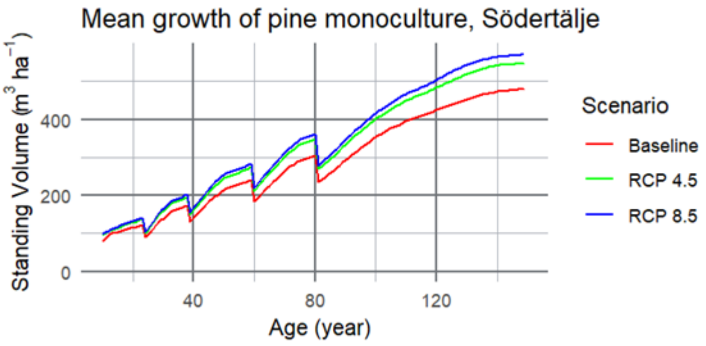

Figure A 4 Growth curves of pine monoculture in Södertälje under 3 climate scenarios

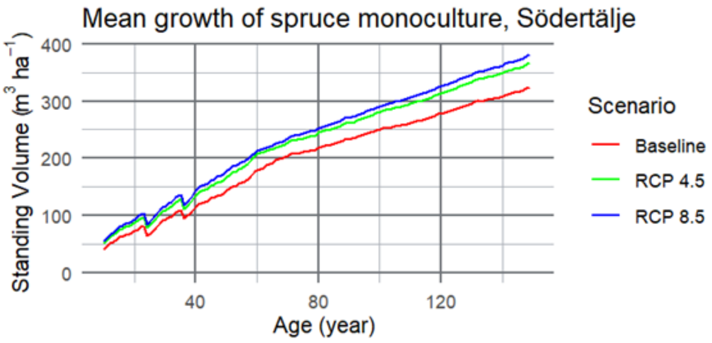

Figure A 5 Growth curves of spruce monoculture in Södertälje under 3 climate scenarios

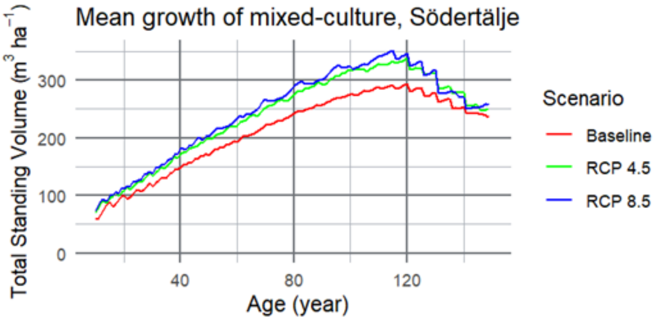

Figure A 6 Growth curves of spruce and pine mixed-culture in Södertälje under 3 climate scenarios

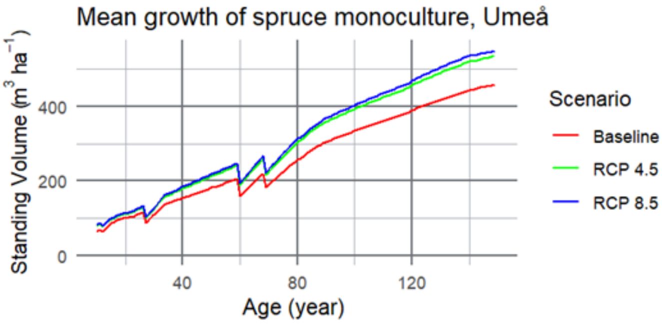

Figure A 7 Growth curves of spruce monoculture in Umeå under 3 climate scenarios

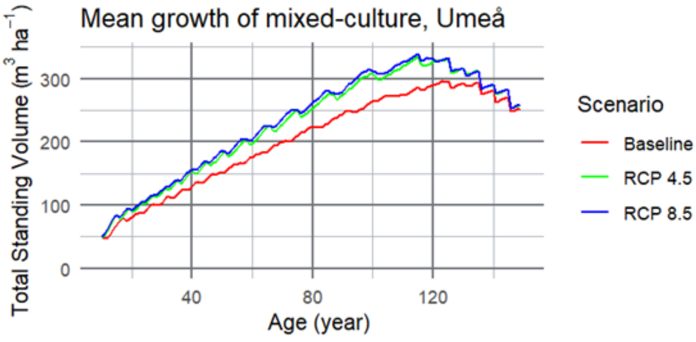

Figure A 8 Growth curves of spruce and pine mixed-culture in Umeå under 3 climate scenarios

Appendix X Future Standing Volume Simulated with Auto-thinning

Similar to Appendix VII, this appendix provides the result of running simulations for monocultures with an auto-thinning option. But the results provided in this appendix were simulated under climate scenarios instead of historical climate as in Appendix VII.

Table A 10 Per hectare standing volume under future climate scenarios by forest type at harvest age, simulated with auto-thinning option

Location	**Scenario**	**Harvest age (year)**	**Spruce monoculture (m^3 ha^{-1})**	**Difference to standing volume from defined-thinning (%)**	**Pine monoculture (m^3 ha^{-1})**	**Difference to standing volume from defined-thinning (%)**
Malmö	Baseline	86	191.39	-14.84	282.10	-11.16
	RCP 4.5		133.58	-21.65	279.47	-15.34
	RCP 8.5		134.61	-21.11	299.51	-13.59
Södertälje	Baseline	98	210.70	-14.30	315.03	-7.46
	RCP 4.5		239.43	-13.18	361.32	-6.63
	RCP 8.5		253.94	-11.06	374.36	-6.77
Umeå	Baseline	122	245.36	-6.63	345.60	-12.86
	RCP 4.5		280.64	-4.38	406.47	-12.60
	RCP 8.5		291.25	-3.56	419.31	-12.10

Appendix XI References

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