Birch for Future: Yay or Nay?

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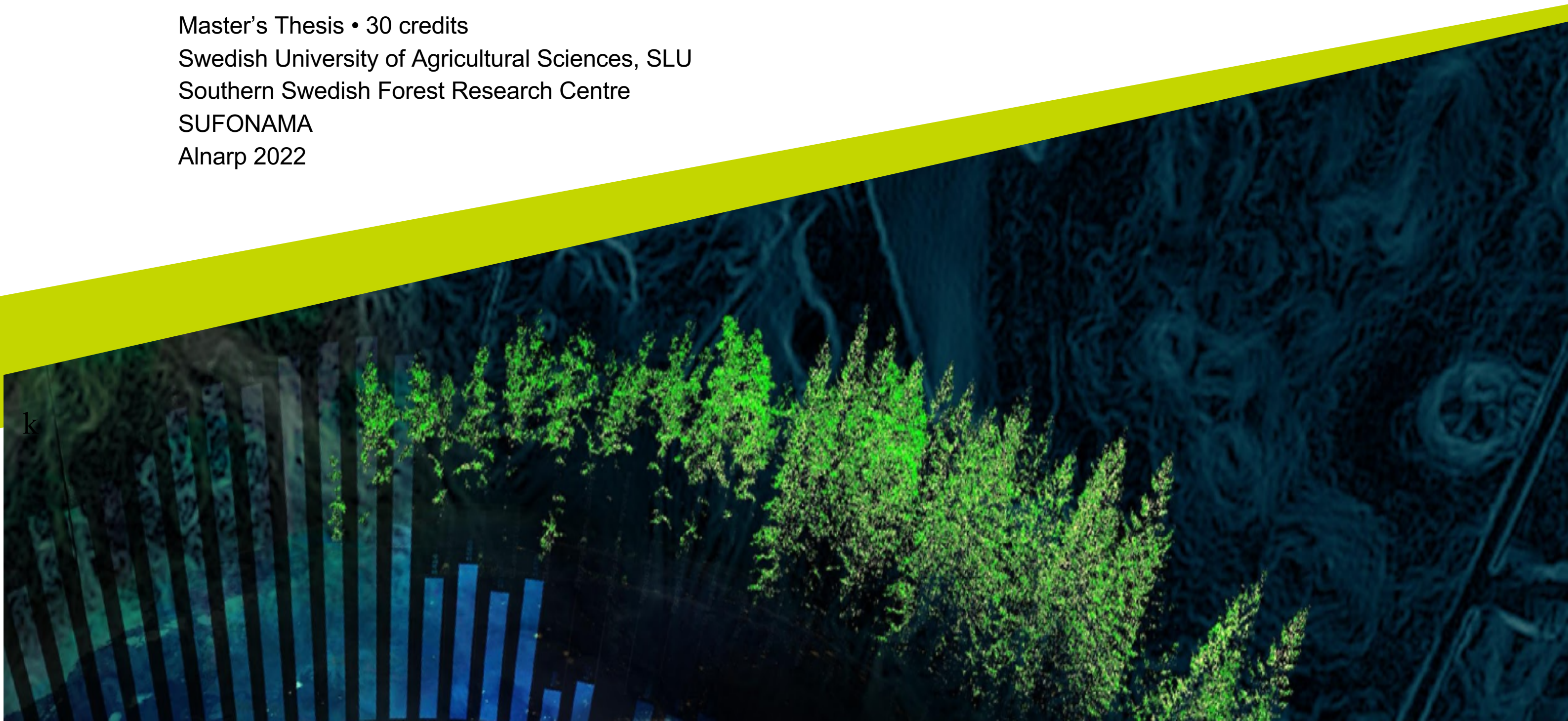

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Abstract

Birch (*Betula pendula* Roth in this study) is a widespread broadleaf species in the Swedish forests. Different birds, saproxylic insects, understorey vascular plants and mycorrhizal fungi are dependent on birch and birch deadwood. The mixture of birch and Norway spruce (*Picea abies* (L.) Karst) in forest stands has been long discussed due to their ecological compatibility and ecosystem services.

In this study, initial data from five different experimental forest stands with planted birch and Norway spruce has been used to simulate the stands until the final felling for management alternatives with varying thinnings and species proportions. The stands had a group mixture of Norway spruce and birch. The basal area development and diameter growth of birch have been compared between treatments. The simulated birch deadwood over time and the net present values of the stands for varying management alternatives have been compared respectively as a biodiversity indicator and economic indicator.

The stands have been simulated with six different management alternatives with one thinning where 10%, 20%, 30%, 40%, 50% and 60% of birch proportion after thinning has been maintained. An unthinned alternative has been simulated as control. No significant loss in productivity (total basal area of birch and Norway spruce) and the economic outcome has been observed in the stands with an increasing proportion of birch. The basal area of birch was the highest in the alternatives with 50% and 60% of birch and was the lowest in the alternatives with 10% and 20% of birch. The post-thinning increase in the basal area of birch has been observed. Due to the thinning response, the basal area of birch in the alternative with 40% of birch had no significant difference from the basal area of birch in the alternatives with 50% and 60% of birch.

The diameter growth of birch was significantly higher in the thinning alternatives when birch was thinned and with increasing thinning intensity (at 10% and 20% of birch proportion), the diameter development of birch was the highest. Therefore, thinning favoured the birch diameter growth. birch deadwood supply significantly increased when birch proportion was higher (40-60%).

The net present values for different treatments with varying birch proportions in this study did not show any significant decrease with the increasing birch proportion. Overall productivity in the stands was not lost with increasing birch proportion in the stand and the revenues earned were profitable. The birch deadwood in the stands with a higher initial proportion of birch was significantly higher. Thus, based on the results from this study, maintaining a higher proportion of birch as a group mixture (> 10%, as required by FSC) in the stands as well as trying out mixtures with birch proportions between 30- 40% can be recommended which will allow increasing the natural value of the forests without losing production and economic value of the forests.

Keywords: Betula pendula Roth*,* Biodiversity, Growth, Simulation, Species Mixture

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Abbreviations

BA	Basal area
DBH	Diameter at breast height
Diameter	Basal area weighted mean diameter (cm)
FSC	Forest Stewardship Council
FF	Final felling
MAI	Mean annual increment
NPV	Net present value
SEK	Swedish Krona
SI	Site Index
Stand	Forest stand

1. Introduction

Sweden is a heavily forested country with 70% of its land area, ranging from hemi-boreal to boreal climates, covered by forests (Felton et al., 2016a). Forests are complex ecosystems that play important roles in providing wood, ecosystem services and climate change mitigation effects (Santaniello et al., 2017). Sweden has a strong forest-based economy. In the production of the industrial roundwood, pulpwood and woodchips Sweden is 6th, 4th and 5th respectively among all the countries (Faostat, 2022). The forest industry is based on even-aged rotational forestry; about half of the forests are owned by small-scale private forest owners (SFA, 2014, Felton et al., 2016a).

Norway spruce (*Picea abies* (L.) Karst.) is the most productive tree species in terms of timber volume production and constitutes about half of the total timber volume production (SFA, 2014, SLU, 2016). The next most common species are Scots pine (*Pinus sylvestris* L.) and silver and downy birch (*Betula pendula* Roth and *Betula pubescens* Ehrh respectively) (SLU, 2016, Lodin et al., 2017). High productivity and low-browsing damage, which results in low establishment costs are some of the reasons why forests owners choose Spruce monoculture over other species (Lindbladh et al., 2014) even though it has low resistance to biotic and abiotic stresses such as bark beetle attack, drought, snow damage and wind throw which are going to increase with climate change and global warming (IPCC, 2007, Kohler et al., 2010, Lodin et al., 2017, Netherer et al., 2019, Faccoli and Bernardinelli, 2014). Another reason for choosing Norway spruce as the main tree species is the knowledge gap in the growth potential of other tree species (Ekö et al., 2008).

Several studies have shown that species mixture in forests has benefits over monocultures in terms of resistance against biotic and abiotic stresses, biodiversity and recreation (Kelty, 2006, Felton et al., 2010, Gamfeldt et al., 2013). The substantial presence of broadleaf and broadleaf deadwood in the forests is important for biodiversity, such as white-backed woodpecker needs ca. 10-20 m^3 ha^{-1} of broadleaf deadwood in the forest (Carlson, 2000, Ranius and Fahrig, 2006, Angelstam et al., 2003). According to Forest Stewardship Council (FSC, 2010), in Sweden, at least 10% of the volume in a forest (5% in northern Sweden) should be broadleaf. Silver birch and downy birch are important broadleaf species in Northern Europe constituting about 10% of the total produced wood volume in Sweden and provide a wider range of habitats than Norway spruce monoculture supporting a species-rich forest ecosystem (Felton et al., 2016b, Felton et al., 2011, Dubois et al., 2020, Hynynen et al., 2009, Götmark et al., 2005). This study will include Norway spruce and silver birch (*Betula pendula* Roth, referred to as birch henceforth unless otherwise specified) as the species of interest in the forest.

1.1. Geographic distribution of birch and its relevance to Swedish Forests:

Birch grows in a wide geographic range from the Atlantic to eastern Siberia (Hultén and Fries, 1986, Hynynen et al., 2009). In a fertile site, it has a similar site requirement as Norway spruce and it grows well in sandy and silty till soil and fine sandy soil with adequate moisture and air content (Hynynen et al., 2009, Hynynen et al., 2011). It is a pioneer species and in Sweden, in clearcuts it regenerates naturally in high densities due to high seed production and long-distance seed dispersal (Götmark et al., 2005, Nilsson et al., 2006, Hynynen et al., 2009). Traditionally in Sweden birch stands are not managed commercially and most of the young trees are usually removed during pre-commercial and commercial thinnings (Götmark et al., 2005, Liziniewicz et al., 2022)

1.2. Birch growth and Management:

According to Hynynen et al. (2009) in the Nordic countries dominant height of birch at 50 years can be up to 30 m and in a good site managed birch can achieve a mean annual increment (MAI) between 6 - 9.3 $m^3ha^{-1}yr^{-1}$. In Sweden MAI of birch can be ca. 10 m^3 ha^{-1} in good sites (Dahlberg et al., 2006). Liziniewicz et al. (2022) found MAI between 6 – 10.5 m^3 ha^{-1} yr^{-1} for genetically improved planted birch in Southern Sweden. The prediction model by Liziniewicz et al. (2022) projected a site index (SI) of 32 m in 31 years using genetically improved birch in the fertile site.

In Sweden, the common regeneration method for birch is natural regeneration (Nilsson et al., 2006) and the stands are not managed to produce timber (Liziniewicz et al., 2022). However, quality birch timber can be produced using good planting material and suitable management (Dubois et al., 2021, Liziniewicz et al., 2022). Birch is very sensitive to the timing of management and does not respond well to thinning if thinning intervention is not done at an optimum time or delayed (Dubois et al., 2021). In the case of naturally regenerated birch pre-commercial thinning (PCT) is required to achieve the target density of 1600-2500 trees ha^{-1} and to select the future crop trees (Holmström, 2015, Hynynen et al., 2009). In Sweden, pre-commercial thinning (PCT) is done when the tree height is 2-4 m and due to sprouting in birch, a second PCT might be required (Holmström et al., 2015). In the case of planted birch PCT is usually not required (Hynynen et al., 2009).

According to Finnish management practice, an established birch stand with a planting density of 1600 trees ha^{-1} should have two thinning interventions with 30-40% of thinning intensity. A first thinning when the trees are 13-15m tall and a second thinning ca. 15 years after the first thinning is recommended (Hynynen et al., 2009). According to the birch self-thinning model by Hynynen (1993), about 600 trees ha^{-1} can reach a diameter at breast height (DBH) of 25 cm. However, Hynynen et al. (2009) suggest the density in a birch plantation after first thinning should be 700-800 trees ha^{-1} and after second thinning it should be 350-400 trees ha^{-1}. The growth of birch culminates between the ages of 30-40 years and after 50-60 years the risk of discoloration and rot increases (Dubois et al., 2021, Hynynen et al., 2009). Birch grows well in fertile sites and growth is poor on infertile sites, for example, a typical pine site is too poor for birch (Hynynen et al., 2009).

1.3. Mixture of birch and Norway spruce:

There are several definitions for a mixed forest. According to Bravo-Oviedo et al. (2014), stands having a different number of tree species where each species affects the growth through inter-specific competition can be referred to as mixed stands. The mixed structure can be determined with the basal area (BA) proportion of two or more tree species present in a stand as well as with stem proportion (Bravo-Oviedo et al., 2014, Drössler et al., 2015, Drössler, 2010). In Sweden, a stand can be defined as mixed if a secondary species constitutes at least 30% of the total BA but this proportion can be adjusted according to the purpose (Drössler, 2010).

Birch and Norway spruce admixture is common in boreal forests in Scandinavia as both species have similar site requirements and ecological compatibility and birch is usually grown for pulpwood production (Hynynen et al., 2011, Stener and Hedenberg, 2003, Liziniewicz et al., 2022). Birch is a pioneer species that has a light requirement and growth pattern with early dominance, which lowers the competition in a Norway spruce-birch mixed stand and as a shade tolerant species Norway spruce can have shelter under birch without being affected negatively (Hynynen et al., 2011, Hynynen et al., 2009). Growth of birch culminates before Norway spruce allowing for better growth of Norway spruce at a later stage (Hynynen et al., 2009, Valkonen and Valsta, 2001). Some studies suggest a small proportion of birch in pure Norway spruce stands can slightly increase the total production than a pure Norway spruce stand (Tham, 1988, Hynynen et al., 2009), however other studies also found a decrease in diameter and production in a Norway spruce-birch admixture with an increasing proportion of birch (Agestam, 1985, Fahlvik et al., 2015).

In southern Sweden the growth of Norway spruce is high and the growth of birch is about 40% and 60 % of Norway spruce in southern Sweden and northern Sweden respectively (Ekö et al., 2008). In a Norway spruce-birch mixed stand Birch requires active management allowing required space for them to grow well and the density, height difference time of thinning intervention are important factors to maintain the mixture (Holmström et al., 2021, Fahlvik et al., 2015, Hynynen et al., 2009). However, as commonly observed in Swedish forests, although birch is predominant at an early developmental stage, during pre-commercial and commercial thinnings most of the birches are removed to allow good growth of Norway spruce which structures the forest as an even-aged monoculture (Fahlvik et al., 2015, Holmström et al., 2021, Felton et al., 2016b, Nilsson et al., 2006). While there is some available knowledge on naturally regenerated birch (Holmström et al., 2021, Holmström et al., 2016, Holmström et al., 2015, Dahlgren Lidman et al., 2021, Fahlvik et al., 2015, Fahlvik et al., 2011), the knowledge on planted birch in Sweden remains scarce.

1.4. Economy and Scope of birch and birch-Norway spruce Mixture:

Net present value (NPV) is an economic evaluation where all the present costs, as well as discounted future costs and revenues, are considered to assess the economic performance of an investment (Žižlavský, 2014). According to the current Swedish market, the NPV of Norway spruce-birch mixed stands is usually lower than Norway spruce monoculture and it decreases with an increasing proportion of birch (Fahlvik et al., 2011, Dahlgren Lidman et al., 2021). In a northern Swedish experiment Dahlgren Lidman et al. (2021) found that at an interest rate of 2% or higher, an unmanaged birch stand is the most economically sound option. According to Knoke et al. (2007) risks and risk preferences are not always included in the economic analysis of mixed stands, which might play role in a lower economic value of mixed stands. However, one Finnish study (Valkonen and Valsta, 2001) shows economic gain in Norway spruce-birch mixture over Norway spruce monoculture.

Currently in Sweden the market demand for birch is mainly as energy wood and pulpwood and the market for birch sawlog is not big (Stener and Hedenberg, 2003, Liziniewicz et al., 2022, Fahlvik et al., 2011, Skogsaktuellt, 2022). In the central and southern parts of Europe birch has been seen as a 'forest weed' for a long time, which is recently changing (Dubois et al., 2020). According to Dubois et al. (2020), there is an emerging market for birch timber and veneer in Western Europe due to its unique timber aesthetics and dense, strong and durable timber similar to beech wood. This might create an export opportunity for birch. Additionally, the renowned wooden furniture chain IKEA uses 18% of birch wood, which is second after Pine wood (Trubins, 2009, Dubois et al., 2020). Changing forest policies, such as certification schemes as FSC, European Union strategy such as Natura 2000 and local government recommendations regarding increasing local broadleaf species for ecological reasons go in favour of birch and might influence the market of birch in the future.

Birch is a source of energy wood and biofuel (Dahlgren Lidman et al., 2021). There are predictions that by 2050 there will be a 50-55% of increased demand for biomass supply for bioenergy production (Börjesson et al., 2017, Lodin et al., 2020). Sweden is one of the leading countries in using bioenergy and most of Sweden's biomass supply for energy production comes from forests (Ericsson et al., 2004). If the biomass demand for bioenergy production increases, birch and birch-mixed forests might have a scope to contribute to this sector in the future.

In a birch and birch mixed stand light penetrates the ground layer in a way that creates a wide range of habitats for various understorey vegetation (Hynynen et al., 2009). Birch trees and deadwood are important habitats for birds, saproxylic insects and mycorrhizal fungi (Felton et al., 2016b, Dubois et al., 2020, Hynynen et al., 2009) and work as a biodiversity indicator (Lassauce et al., 2011, Jonsson et al., 2005, Dubois et al., 2020, Martin et al., 2021). Birch forests and mixed forests with birch have high aesthetic value with great recreational potential as well as better resilience to climate change and its associated risks (Huuskonen et al., 2021, Felton et al., 2016b, Dubois et al., 2020).

1.5. Aims of the Study and Research Hypotheses:

This is a simulation study on five different experimental forest stands, established in typical Norway spruce sites in Sweden where both Norway spruce and birch have been planted. The idea was to see how the presence of birch (more than 10%), and varying birch proportion by different thinning treatments affect the productivity of the forest, the growth of birch, the economy and biodiversity. For this purpose, basal area (BA) and basal area weighted mean diameter (diameter) as growth indicators, birch deadwood as biodiversity indicator and NPV as economic indicator have been chosen. The aims of this study were to observe:

i) If management can favour the growth of birch,
ii) If the overall productivity loss occurs with increased birch proportion in the mixture,
iii) The effect of management on the birch deadwood accumulation,
iv) The economic performance of the different stands with varying managements.

Thus, the hypotheses to test in this study focusing on these aims are:

H_1: Thinning interventions would favour the diameter increase and BA growth of birch.

H_2: It has been hypothesized that the productivity of the stands will decrease with a higher birch proportion in the stand.

H_3: The managements with increased birch proportion in the forest would allow higher birch deadwood volume in the forest.

H_4: The higher birch proportion would cause an economic loss. Thus, the managements favourable for deadwood accumulation would be the least favourable for managements for NPV.

2. Materials

2.1. Data

The data has been collected from the first revision data of 5 different tree species experiments forest stands around Sweden (figure 1). The experiments are part of a nationwide series of tree species comparisons that includes a total of 9 trials at different latitudes of the country with different light and temperature conditions.

The tree experiments in the experiment series include 13 different exotic tree species as well as Norway spruce, Scots pine and birch as references. Both Norway spruce and birch are planted with nursery-grown seedlings (Silvaboreal). For this study, only the plots with Norway spruce and birch have been selected.

For running stand-wise simulations for the five different stands, the sample plots in the stands consisting of birch and Norway spruce had been chosen and all Norway spruce- and birch plots are considered as one stand. This gave the stands a structure of group mixture.

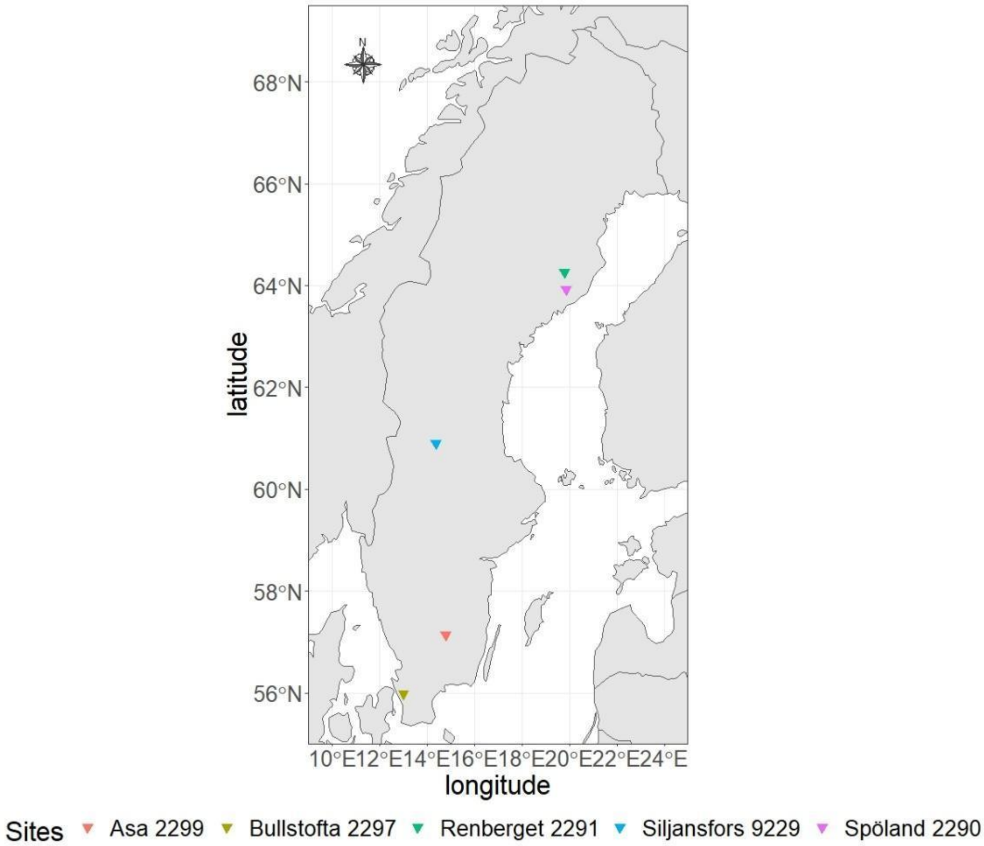


Figure 1. Locations of the experimental sites around Sweden

2.2. Site Description:

For this study, experimental sites Asa, Bullstofta, Renberget, Siljansfors and Spöland have been selected. The experimental sites have been selected so that the data represents both northern and southern geographic conditions. Latitudes below 60° north have been considered south and 60° north and over have been considered north. Experimental sites Asa and Bullstofta are in the geographic south of Sweden and Renberget, Siljansfors and Spöland are in the geographic north (figure 1).

All the sites are fertile Norway spruce sites. Renberget has the lowest SI of G22 and Bullstofta has the highest SI of G36 (Silvaboreal). The stands have been established between 1992 – 1994, except for Siljansfors, which has been established earlier in 1964. But the data that has been used in this study is the first revision data of all the stands, thus tree parameters are comparable.

The soil at Bullstofta and Spöland is arable soil and Asa, Renberget and Siljansfors have been established on podsol soil (Silvaboreal). The sites have been prepared before planting. The annual average temperature is quite diverse in the selected sites, varying between 3-9°C (SMHI, 2020a). Annual precipitation in the selected sites has less variation with a range of 600-800 mm year^{-1} (SMHI, 2020b). Detailed information on the site characteristics has been included in table 1.

Table 1. Description of the selected experimental sites

Experimental Sites	**Asa**	**Bullstofta**	**Spöland**	**Renberget**	**Siljansfors**
Latitude (°N)	57.13	55.98	63.92	64.26	60.90
Longitude (°E)	14.78	13.00	19.86	19.80	14.37
Altitude	200	85	80	300	240
Site Index	G32	G36	G26	G22	G25
Soil Moisture	Mesic	Mesic	Mesic	Mesic	Mesic
Vegetation Type	Thinleaved grass	No field layer	No field layer	Blueberry	No field Layer
Planting (month/year)	Jul/1994	May/1993	Jun/1993	Jun/1992	Oct/1964
Annual Average Temperature (°C)	6 - 7	8 - 9	3 - 4	3-4	4 - 5
Annual Average Precipitation (mm year^{-1})	600 - 800	600 - 800	600 - 800	600-800	600 - 800
Stand Establishment Method	Planting	Planting	Planting	Planting	Planting

Annual average temperature (SMHI, 2020a); annual average precipitation (SMHI, 2020b); Other information – Research plans for experiments: 2290, 2291, 2297, 2299, 9229 (Silvaboreal)

2.3. Stand description:

Birch and Norway spruce in all stands were ca. 19 years, except in Asa where trees were 24 years old. The stands Asa, Renberget and Spöland were mixed in structure with starting BA proportion of birch > 30%. In Bullstofta the BA proportion of birch was < 30% and in Siljansfors it was > 70%. The birch in Bullstofta has undergone thinning once and the stem density in Spöland is lower than the other stands due to mortality. The area of each stand was 1 ha.

Table 2. Description of the selected stands as projected in Standwise software at period 0:

stand	**Height (m)**		**Basal Area (m^2ha^{-1})**		**BA % Birch**	**Density (stem ha^{-1})**		**Mean age**
	Birch	**Spruce**	**Birch**	**Spruce**		**Birch**	**Spruce**	**(year)**
Asa	15,4	11,7	11,0	10,8	50	1064	1117	24
Bullstofta	14,8	11,7	5,4	18,1	23	454	1160	19
Renberget	9,2	4,9	6,3	3,5	65	1101	1234	19
Siljansfors	9,7	3,8	4,6	1,1	81	1068	1034	19
Spöland	10,1	4,8	6,0	4,6	57	623	842	19

3. Methodology

To forecast forest development and plan for forest management Heureka is a suitable simulation software in Sweden (Fahlvik et al., 2015). For this study, Heureka Standwise version 2.18.2 has been used to perform the simulations. Heureka Standwise is software for stand-level simulation of forests based on input data. Various treatments such as cleaning, PCT, thinning, and final felling can be applied. The management options include even-aged, uneven-aged and continuous cover forestry (HeurekaWiki). It is possible to simulate different management alternatives and forest structures using the software as the tree proportion in a forest can be controlled during thinning.

The software can estimate the growth parameters such as basal area weighted mean diameter (referred to as diameter), basal area and basal area weighted mean height. Parameters like carbon stock, deadwood and recreational index can be simulated as well to understand the natural and recreational value. All these parameters can be generated as stand-level means and as individual species-level means depending on the user's need. In this study, the diameter, BA and deadwood volume both at the stand level and at the individual species level have been simulated using Standwise. Moreover, NPV, which has been used as the economic indicator in this study, can be collected from the software. Otherwise, the cashflows and costs can also be retrieved from Standwise. In Standwise the simulations are done as 5-year periods.

3.1. Input data for Heureka Standwise:

For the simulations, the initial stand data has been imported to the Standwise software as treelists. The data was collected as plots from 5 stands which have been used to create the treelist. All the stands had equal proportions of birch and Norway spruce plots. Plot number, plot area, mean age, latitude, altitude, site index, vegetation type and soil moisture type have been used as stand parameters. The sample plot area varied from 370 – 1440 m^2. Species, DBH, height, tree type (sapling, DBH < 4 cm or tree DBH> 4 cm) and stem number have been used as tree parameters. Each stand had an area of 1 ha.

3.2. Simulations:

The stands have been simulated as even-aged stands. Thinning according to the thinning guidelines of Skogskunskap has been applied as treatments. Thinning guideline for birch by Hynynen et al. (2009) has also been consulted to crosscheck the density of birch after thinning.

All the stands have been simulated unthinned and thinned. During thinning the proportion of birch has been varied according to 6 treatment alternatives. Thinning from below has been done using the Hugin system (Lundström and Söderberg, 1996) which is a built-in option in Standwise. Final felling has been done after the stands have reached the minimum final felling age according to the Heureka generated final-felling age for each stand, which follows recommended final-felling age in Sweden. As the birches in the stands are planted, the birch has been final felled together with Norway spruce at the end of the rotation to observe the growth. The stands were too old at period 0 to apply precommercial thinning (PCT). Moreover, the stands were established by planting (table 1). Thus, PCT has not been carried out as a management option. The workflow for the simulations has been shown in figure 2.

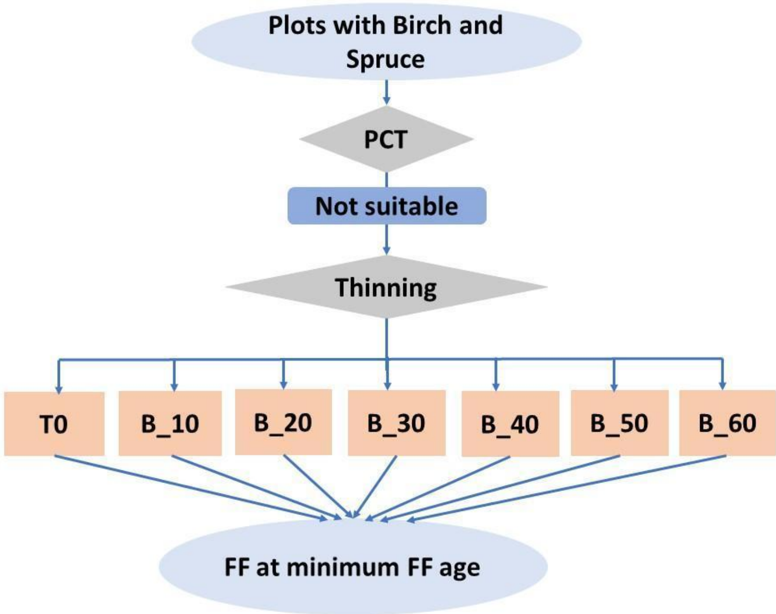


Figure 2. Workflow for the simulations in Heureka.
T0, B_10, B_20, B_30, B_40, B_50, B_60: thinning treatments (table 3).
T0 = Unthinned; B_10, B_20, B_30, B_40, B_50, B_60 = thinned according to thinning guideline (Skogskunskap) and the proportion of birch after thinning has been set to 10%, 20%, 30%, 40%, 50% and 60% respectively.

3.2.1. Management Alternatives:

For all the stands 6 treatment alternatives have been tested. The treatment alternatives are B_10, B_20, B_30, B_40, B_50 and B_60 where the proportion of birch has been maintained 10%, 20%, 30%, 40%, 50% and 60% respectively. This range covers from the 10% broadleaf requirement by FSC (2010) to a substantially large proportion of 60% of birch within the definition of mixed forest. Unthinned management T0 has been done as control. The treatments are described in table 3:

Table 3. Treatment alternatives used in the simulation:

Treatment Description	Proportion of birch after Thinning (%)	Name of the Treatment	Thinning Type
Unthinned	-	T0	Thinning from below
Thinned	10	B_10	
	20	B_20	
	30	B_30	
	40	B_40	
	50	B_50	
	60	B_60	

The thinnings have been carried out before the dominant height of Norway spruce was 20m to reduce wind damage. For birch Hynynen et al. (2009) recommend an intensive first thinning when the dominant height is between 13-15m. However, the height of the birch was between 19-21m at the time of thinning as the simulations are done as a 5-year period and sometimes the thinning has been delayed one period to achieve the required basal area for thinning intervention. Thinning has been done from below removing smaller trees. As the data that has been used is plot-wise measurement data, the treatment alternatives have been applied at the stand level considering a group mixture within the stand.

3.3. Growth estimation:

In Heureka the growth of small stands where the mean stand height is less than 7m is estimated using the functions by Elfving (1982). The height of the individual trees is estimated using the function by Söderberg (1992) and the total height growth is estimated by the top height development curve (Elfving and Nyström, 2010). The height and diameter relationship has been described by Nyström and Söderberg (1987) which is used to estimate the DBH of a single tree (Elfving and Nyström, 2010, Fahlvik et al., 2015). Basal area and DBH development are estimated using the growth functions and height-diameter relationship described by Elfving and Nyström (2010) and validated by Fahlvik et al. (2014). Thinning effect on the BA is estimated by thinning response function by Elfving and Nyström (2010). The deadwood is estimated by the mortality function by Elfving (2014).

3.4. Net present value (NPV):

The NPVs for the stands and different treatments have been calculated according to the following equation:

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t}$$

Where,
R_t = Net revenue at time t,
t = time of the cash flow,
n = number of periods
i = Real discount rate,

Discount rate of 2.5% has been used in the NPV calculation.

3.4.1. Costs and Revenues and Rotation Age in NPV Calculation:

To calculate the NPV the revenue and operational costs of the stands have been collected from Standwise. The software considers the operational costs, costs of soil scarification and regeneration of new stands and the revenues earned from the thinnings and final felling. The revenues have been earned from timber and pulpwood. birchwood has been sold only as pulpwood. Norway spruce wood has been sold both as timber and pulpwood. In NPV calculation the Heureka default pricelist has been used which uses the price of pulpwood and timber by Mellanskog (2013). The rotation age is used in the discounting, rotation length in this study was the legal minimum FF age for each stand in Standwise. In all the stands the rotation age is ca. 60 years except in Asa and Bullstofta where it is 45 years.

The net revenue has been adjusted according to the planting costs for birch and Norway spruce. The total seedlings and seedling number of birch and Norway spruce at the time of planting have been estimated according to the projected stem proportion of birch and Norway spruce (table 2). The cost of each birch and Norway spruce seedling used in the calculation is 6,15 SEK and 5,2 SEK respectively (Södra, 2022) which have been discounted using a discount rate of 2.5% for the year 2013 as the Heureka default pricelist uses the prices from 2013. The stand data that has been used is from established stands thus an additional cost of 4000 SEK ha^{-1} has been assumed to cover any early operational costs.

Table 4. Planting cost of the stands:

Stand	**Establishment cost (SEK ha^{-1})**
Asa	13073
Bullstofta	12759
Renberget	13049
Siljansfors	13105
Spöland	12978

3.5. Statistical analysis:

Analysis of variance (ANOVA) has been done for the projected total BA of Norway spruce and birch (m^2 ha^{-1}), BA of birch (m^2 ha^{-1}), diameter (cm) and deadwood (m^3 ha^{-1} $year^{-1}$) of birch at the end of rotation and NPV of the stands at 2.5% discount rate (SEK ha^1). using the following two-way ANOVA model:

$$y_{ij} = \mu + s_i + t_j + e_{ij}$$

Where,

y_{ij} = variable,

μ = total mean,

s_i = stand effect,

t_j = treatment effect

e_{ij} = random error term

Additionally, the diameter of Norway spruce and birch between different treatments in the mixed stands has been compared using the following model:

$$y_i = \mu + s_i + e_{ij}$$

Where,
y_{ij} = variable,
μ = total mean,
s_i = species

P-value has been obtained for treatments and stands to see the differences between the means of the treatment alternatives and the means of the stands in both groups. If the p-value of the response variable was significant (< 0.05) then the Tukey test was done to see which treatments or stands have a significant difference (Abdi and Williams, 2010). The difference between the means found in the Tukey test has been shown using the letters ‘a’, ‘b’, ‘c’..., where ‘a’ indicates the highest mean, followed by ‘b’ and so on. The analysis has been done using RStudio 2022.2.1.461 (R Development Core Team, 2022).

4. Result

4.1. Statistical analysis of the variables of interest:

The total basal area, basal area of birch, diameter of birch and deadwood of birch were significantly different between treatments and stands. NPV did not show any significant difference among the treatments, but it had significant differences among stands. The results are shown in the table below and will be discussed in the following sections.

Table 5. ANOVA of the total BA at the end of rotation and BA, diameter and deadwood of birch at the end of rotation and NPV of the stands and treatments at 5% confidence limit.

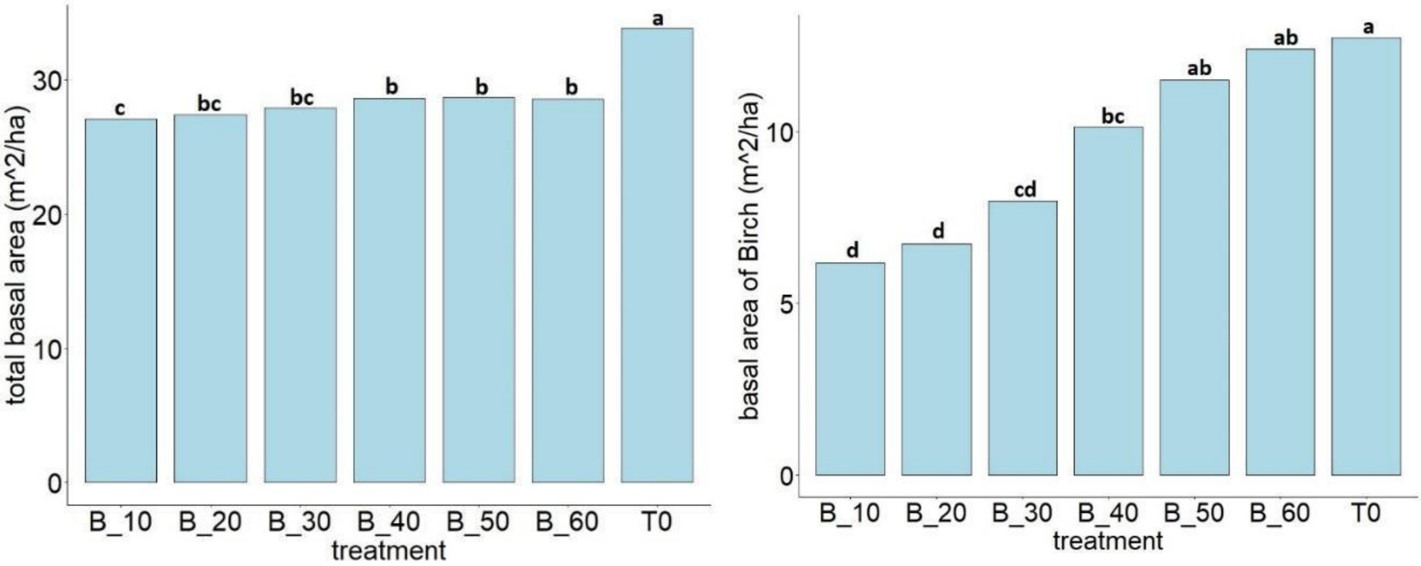
Response Variable	Source of Variance	F-value	df	p-value
Total BA	stand	285.6	4	< 0.05
	treatment	60.3	6	< 0.05
BA (birch)	stand	8.59	4	< 0.05
	treatment	28.65	6	< 0.05
Diameter (birch)	stand	451.2	4	< 0.05
	treatment	27.4	6	< 0.05
Deadwood (birch)	stand	8.77	4	< 0.05
	treatment	14.67	6	< 0.05
NPV	stand	2146.36	4	< 0.05
	treatment	1.89	6	NS

NS = non-significant at 5% confidence limit.

4.2. The basal Area:

The mean total BA was significantly different among treatment alternatives and stands. T0 had a higher total BA than all the other treatment alternatives and B_10 had the lowest total BA. The total BA did not vary significantly in the other alternatives but showed a gradual decrease with the decreasing proportion of birch (figure 3a). Among stands, Spöland and Asa showed the highest mean total basal area which was 32.59 m^2ha^{-1} and 31.63 m^2ha^{-1} respectively, followed by Renberget. Siljansfors had the lowest total BA among all which was 21.91 m^2ha^{-1} (data not shown).

The basal area of birch at the end of the rotation was significantly higher in the T0, B_60, B_50 and B_40 alternatives compared to the B_10 and B_20 alternatives (figure 3b). Among thinning alternatives, B_60 had the highest mean basal area of birch which is 12.4 m^2ha^{-1} and B_10 had the lowest which is 6.2 m^2ha^{-1}. Among the stands, Spöland and Asa had the highest mean basal area of birch and Siljansfors has the lowest (data not shown).



(a) (b)

Figure 3. The basal area in the stands

a) *Mean total basal area at the end of the rotation for different managements in the stands.*

b) *Mean basal area of birch at the end of the rotation.*

T0 = Unthinned; B_10, B_20, B_30, B_40, B_50, B_60 = thinned according to thinning guideline (Skogskunskap) and the proportion of birch after thinning has been set to 10%, 20%, 30%, 40%, 50% and 60% respectively.
'a', 'b', 'c'… = difference between the means. 'a' is the highest mean, followed by 'b' and so on.

4.3. The diameter:

The diameter of the birch at the end of rotation was significantly higher in the B_10 and B_20 than in alternatives with more than 40% birch. With an increasing proportion of birch, the diameter of birch showed a decreasing trend and B_50 and B_60 had a significantly lower birch diameter than B_10 and B_20 (figure 4). T0 had the lowest diameter of birch but was not significantly different from B_50 and B_60. Among stands, Spöland had the highest diameter of birch which was 24.48 cm and Siljansfors had the lowest which was 16.37 cm (data not shown).

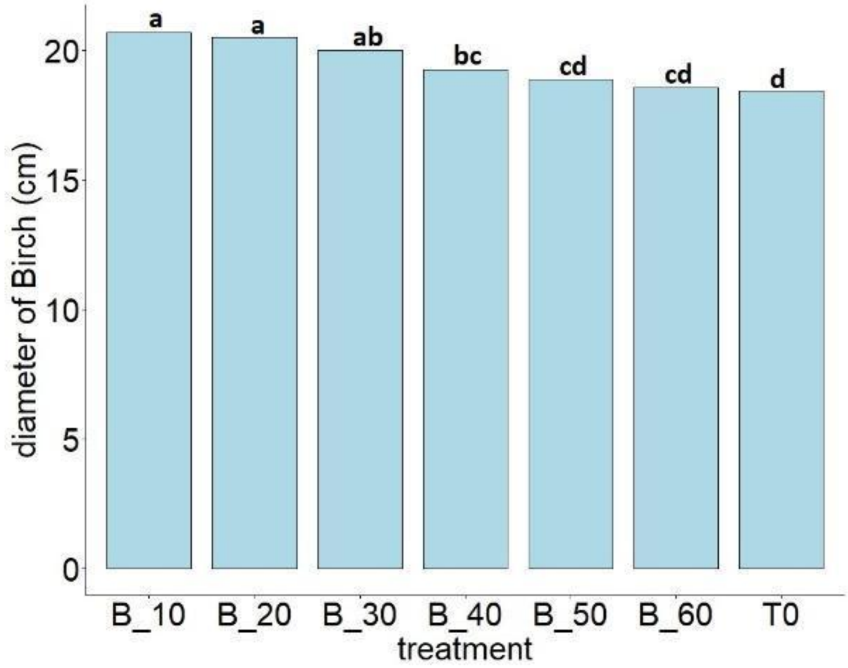


Figure 4. The mean diameter of the harvested birch in the stands after final felling
T0 = Unthinned; B_10, B_20, B_30, B_40, B_50, B_60 = thinned according to thinning guideline (Skogskunskap) and the proportion of birch after thinning has been set to 10%, 20%, 30%, 40%, 50% and 60% respectively.
'a', 'b', 'c'… = difference between the means. 'a' is the highest mean, followed by 'b' and so on.

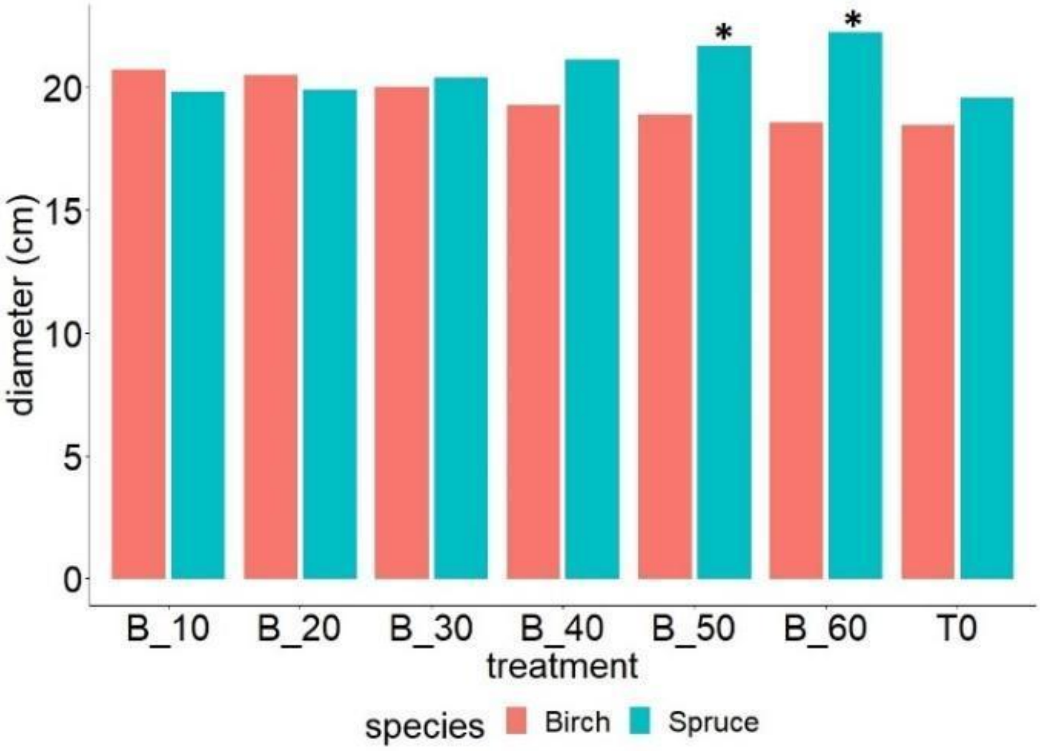


Figure 5. Comparison of the mean diameter of the harvested birch and Norway spruce in the stands
T0 = Unthinned; B_10, B_20, B_30, B_40, B_50, B_60 = thinned according to thinning guideline (Skogskunskap) and the proportion of birch after thinning has been set to 10%, 20%, 30%, 40%, 50% and 60% respectively.
**Significantly different than the other treatments.*

The mean diameter of Norway spruce was significantly larger than the mean diameter of birch in B_50 and B_60. In other thinning treatments, there was no significant difference between Norway spruce and birch (figure 5).

4.4. The deadwood of birch for different managements:

The deadwood of birch was highest for unthinned management (T0) and decreased gradually in the treatment alternatives with decreasing proportion of birch (figure 6). The deadwood of birch in B_60 and B_50 was significantly higher than the deadwood in B_10 and B_20. In the B_40 and B_30 alternatives, the deadwood of birch was lower than B_60 and B_50, but the loss was not significant.

Among stands, Spöland had the highest birch deadwood where the initial proportion of birch was ca. 57% and Bullstofta had the lowest deadwood of birch where the initial proportion of birch was ca. 23% (data not shown).

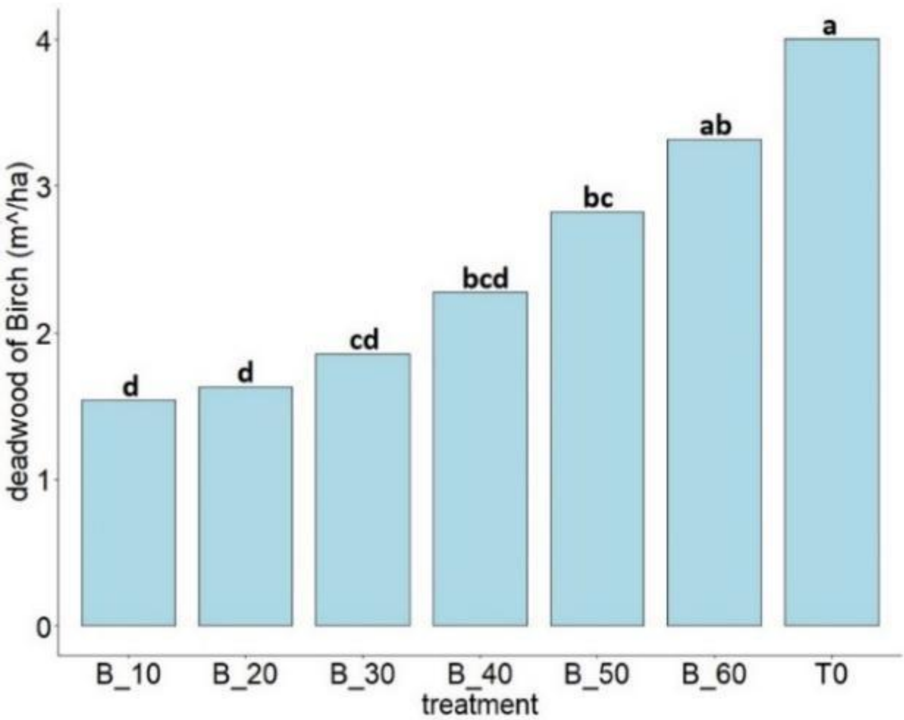


Figure 6. The mean deadwood of birch at the end of the rotation.
T0 = Unthinned; B_10, B_20, B_30, B_40, B_50, B_60 = thinned according to thinning guideline (Skogskunskap) and the proportion of birch after thinning has been set to 10%, 20%, 30%, 40%, 50% and 60% respectively.
'a', 'b', 'c'... = difference between the means. 'a' is the highest mean, followed by 'b' and so on.

4.5. Changes in net present value (NPV) for different proportions of birch:

Revenues came from thinnings and final felling. Norway spruce was the only source of timber and all the birch was sold as pulpwood.

The NPV did not vary much with the different thinning alternatives. The NPV of B_40 is slightly higher and the NPV of T0 is slightly lower than other treatments. However, the differences in NPVs for different treatments do not show any significant difference (figure 7) and no loss of NPV has been observed with an increasing proportion of birch or with management activities applied to the birch.

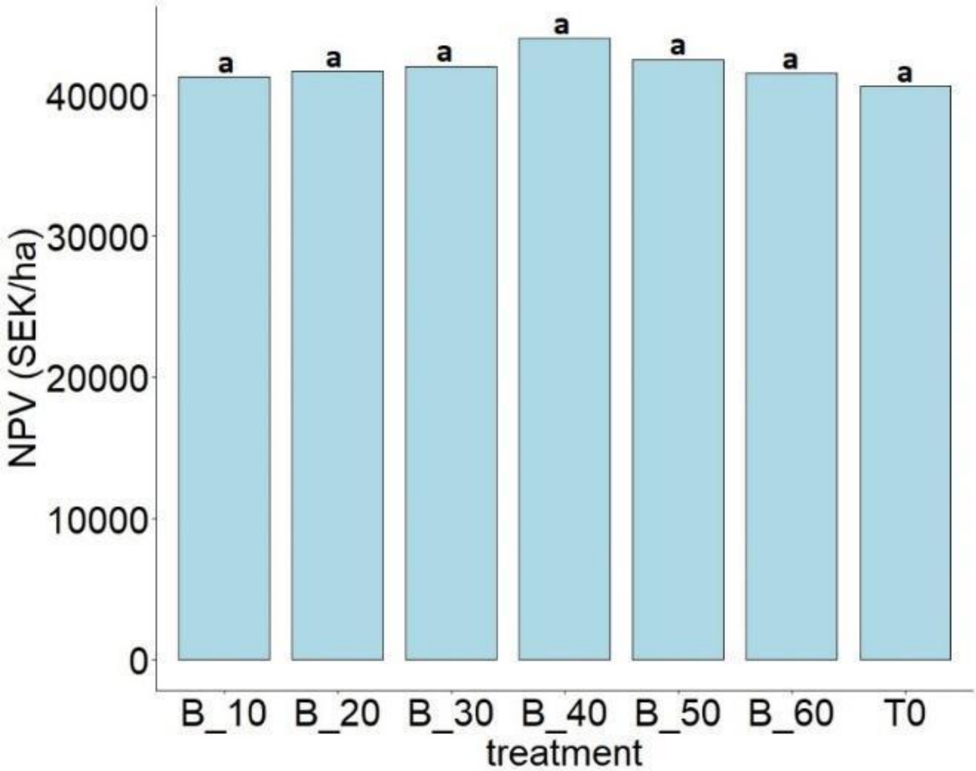


Figure 7. The difference in the mean NPV for different proportions of birch after thinning.
T0 = Unthinned; B_10, B_20, B_30, B_40, B_50, B_60 = thinned according to thinning guideline (Skogskunskap) and the proportion of birch after thinning has been set to 10%, 20%, 30%, 40%, 50% and 60% respectively.
'a', 'b', 'c'… = difference between the means. 'a' is the highest mean, followed by 'b' and so on.

Among stands, Bullstofta has the highest NPV and Siljansfors has the lowest (data not shown).

5. Discussion

5.1. Effect of the treatment alternatives on the growth parameters:

5.1.1. On the basal area:

The basal area of birch at the end of the rotation period was expected to be significantly higher in B_60 as this alternative has the highest proportion of birch (60%). B_60 alternative had significantly higher BA than B_10, B_20 and B_30 alternatives with 10%, 20% and 30% of birch respectively, but the BA in B_40 and B_50 alternatives (40% and 50% of birch respectively) had almost equal development of BA as B_60. This could happen probably because in these alternatives the chosen proportions (40%, 50% and 60%) are not different enough from each other to cause a significant difference. The B_60 and B_50 treatments had no significant difference from the T0 alternative (unthinned). As the proportions were maintained by commercial thinning, in B_60 and B_50 the birch was not thinned very heavily or remained unthinned to maintain the high proportion of birch which gave birch a BA development close to the unthinned alternative in B_60 and B_50 (see appendix 1). In B_10 and B_20, birch was thinned heavily and a large proportion of birch from the stand was removed. Heavy thinning causes very low competition between the trees and is not the optimum situation for vigorous growth (Mäkinen and Isomäki, 2004). This along with a low percentage of remaining trees has probably caused the lowest BA in the B_10 and B_20 alternatives. Additionally, to produce quality timber some competition between trees in the stand is good as it reduces branching and influences the self-pruning of the trees (Höwler et al., 2017). The post-thinning BA increase of birch could be observed in all the alternatives where the birch plots have been thinned (see appendix 1). This response to the thinning will allow post-thinning BA increment due to competition release (Elfving and Nyström, 2010) and income after thinning if birch is planted for timber production in the future. This supports H_1, that the thinning interventions would favour the BA growth of birch. However, due to low thinning removals and less post-thinning increase in BA, B_50 and B_60 alternatives were not the best performing in this study and the BA growth is similar to the T0. Considering both growth response after thinning and percentage of thinning removal, B_40 seemed a better option for the production of birch timber in the future.

Among the stands, the BA of birch in Spöland and Asa was the highest. The initial proportions of birch in these stands were 57% and 50% (table 2) respectively. Although Spöland is situated in the geographic north of Sweden, it was established on a former agricultural land, which along with the high initial proportion of birch might have played a significant role in good growth. Compared to Spöland, Siljansfors, which is established on forest land, has a significantly lower growth of birch even though their geographic condition is similar (table 1). Asa is a fertile site in Southern Sweden (table 2), and the initial proportion of birch is higher as well, which is reflected in the growth of birch in this site. Although Bullstofta is a very fertile site in the same geographic location, it had a lower initial proportion of birch (23%), thus the BA growth was lower than Asa. This indicates that higher initial proportion and thinning interventions, as well as a fertile site, can be favourable to birch growth. However, in Asa, the stand age was higher initially, which might have given it some advantage in the BA growth.

The total BA showed no significant difference among B_20, B_30, B_40, B_50 and B_60 alternatives. Therefore, H_2, that productivity of the stand would decrease with increasing birch proportion is rejected in this study and no trade-off between increasing birch proportion and productivity could be observed. As all the stands have average to high SI (table 1), it is possible that the stand structure with group species mixture could have an influence on the total productivity allowing good growth in the Norway spruce plots. The loss of Norway spruce production due to slightly heavy thinning in the Norway spruce plots in the alternatives with high proportions of birch might not cause any significant loss in growth as the Norway spruce growth in those stands was good and the competition release due to thinning allowed vigorous growth. Additionally, the remaining birch might have helped to maintain the total BA at the end of the rotation. Further studies are required to confirm this outcome and studies with stem mixtures might show different results. Moreover, due to the lower productivity of birch compared to Norway spruce the total BA of the stand might be affected by a higher proportion of birch than the ones used in this study, (Ekö et al., 2008).

In B_10 the total BA was the lowest. In this alternative, birch had been thinned intensively and Norway spruce remained almost unthinned. birch had constituted a substantial proportion initially; thus, intensive removal of birch could have possibly caused a lower total BA in the B_10 alternative.

5.1.2. On the diameter:

In the stands, the mean diameter of birch was significantly higher in the alternatives where birch had been heavily thinned (B_10 and B_20) and it gradually decreased with decreased thinning intensity (figure 5). In B_10 and B_20 alternatives birch had undergone intensive thinning and the diameter development showed a better response in these two alternatives than in all other alternatives. Intensive thinning is favourable to birch diameter growth (Hynynen et al., 2009) and in these two alternatives the birch probably could get more sunlight due to lower density as well as space to grow in diameter, which might have played an important role as birch is a pioneer species (Hynynen et al., 2009, Dubois et al., 2020). Moreover, as thinning has been done from below, more smaller trees have been removed in B_10 and B_20 alternatives than in other alternatives. This probably improved the overall mean diameter in these alternatives due to the remaining larger trees. On the contrary, the diameter growth is the lowest in B_50 and B_60, where it was similar to the T0 alternative. The birch plots were lightly thinned in B_50 and B_60 alternatives, which probably did not allow competition release leading to less available space and inefficient absorption of sunlight and hence less growth in diameter. Additionally, compared to B_10 and B_20, a large number of smaller birch trees remained in the stand in B_50 and B_60, which would also cause a decrease in the mean diameter. Furthermore, the high proportion of birch had been achieved by intensive thinning of Norway spruce (stems of Norway spruce decrease with an increase in birch proportion). The space available by intensive thinning of Norway spruce might have filled up quickly by remaining Norway spruce as all the sites have average to very good SI and the remaining Norway spruce were the larger trees. Therefore, the thinning in the B_50 and B_60 was not very effective for the remaining birch trees. In B_30 and B_40 the birch was thinned and these alternatives showed higher diameter growth than B_50 and B_60. Even though the diameter growth in B_30 and B_40 was slightly lower than in B_10 and B_20, the difference is not significant. Thus, it can be said that the alternatives where the proportion of birch had been achieved by thinning instead of retaining the birch, had a better effect on the diameter growth of birch and this supports the H_1 that thinning interventions would favour birch diameter increase. Therefore, depending on the goal of the forest owner, B_10, B_20 and B_30, B_40 alternatives would be applicable to manage a stand with higher (>10%) birch proportion and produce a better assortment of birch timber. But, the difference in diameter between B_10, B_20 and B_50, B_60 was relatively small. Birch thinning response is sensitive to timing and height (Dubois et al., 2021, Hynynen et al., 2009). In the stands sometimes the thinning had to be delayed one period to achieve the required basal area to perform thinning and in all the stands the birch had height dominance over Norway spruce (table 2). Thus, the diameter growth of birch could have shown a better response to thinnings if the timing of the thinning was at the period when the height of birch was between 13-15 m. Therefore, this needs further studies prioritizing birch thinning and specific birch thinning guidelines to observe the difference. Moreover, the SI and growth conditions among the stands were quite heterogeneous which caused a varying diameter growth in different stands (see appendix 3). Therefore, a study using homogeneous SI and growth conditions will probably capture the difference between each treatment more accurately and might show a higher difference between the alternatives with lower and higher stem densities of birch. Furthermore, these results are from stands with a group-species mixture, thus in a different mixture type, the results could be different.

In all the alternatives the diameter of Norway spruce and birch had no significant differences except in B_50 and B_60 where the diameter of Norway spruce was significantly higher than the diameter of birch (figure 6). In B_50 and B_60 more Norway spruce stems were removed in the alternatives to maintain a higher proportion of birch than the alternatives with birch proportions lower than 50% and 60%. This had probably removed more of the smaller Norway spruce stems in B_50 and B_60, leaving more space for the remaining trees that allowed good growth. The vigorous growth of Norway spruce might have occupied the free space available by intensive thinning. Since the diameter growth of birch was the lowest in these two alternatives (figure 5) along with the better growth of Norway spruce, the diameter of Norway spruce was significantly higher in these two stands. Another reason that the diameter of birch and Norway spruce did not show significant differences in other alternatives could be that the stands had been final-felled right after the minimum legal FF age had been passed. As the growth of birch culminates between 30-40 years and earlier than Norway spruce (Dubois et al., 2020, Valkonen and Valsta, 2001, Hynynen et al., 2009), it is possible that the Norway spruce would grow more surpassing the diameter of birch in all the treatment alternatives if final-felling was delayed. However, this study is focused on birch growth and all the stands had been final-felled well after the culmination period of birch, thus even if the Norway spruce diameter would grow better if the rotation period was longer, that remains out of the scope of this study.

The diameter of birch was the highest in Spöland, followed by Bullstofta and lowest in Siljansfors. Spöland is in the north and Bullstofta is in the south of Sweden. In the north of Sweden, the growth potential of birch is lower than in the south of Sweden (Ekö et al., 2008), thus it would make more sense if all the northern stands had less diameter growth than the southern stands. But both Spöland and Bullstofta were established on former agricultural land, which is very fertile. This could be a reason that the diameter of the birch in these two stands is significantly higher than Asa, Renberget and Siljansfors.

5.2. Effect of the treatment alternatives on birch deadwood:

The birch deadwood was significantly higher in the treatments with higher birch proportions and gradually decreased with the decrease in the proportion of birch (figure 7). This supports H_3, that a higher proportion of birch would allow a higher proportion of birch deadwood in the stands. Among stands the mean deadwood of birch was significantly higher in Spöland, Asa and Renberget, where the initial proportion of birch was high (table 2), as well as the growth of birch, was better (see section 4.2). This indicates that a higher initial proportion of birch along with better growth might influence the birch deadwood accumulation due to self-thinning.

In this study, the production (BA development) and NPV were not affected by increased birch proportion and from the knowledge in previous studies it can be said that the higher biodiversity, such as mycorrhizal fungi, saproxylic insects and broadleaved dependent birds, would occur in the stands with higher birch deadwood (Lassauce et al., 2011, Dubois et al., 2020, Hynynen et al., 2009, Felton et al., 2010, Carlson, 2000, Angelstam et al., 2003, Ranius and Fahrig, 2006). But even with a higher than usual proportion of birch in the stands, the birch deadwood volume found in this study was not high enough in any treatments in any stand to support a wide range of biodiversity (see appendix 2), which is recommended to be ca. 10-20 m^3 ha^{-1} (Ranius and Fahrig, 2006, Angelstam et al., 2003). However, as production was not decreased with a higher proportion of birch, it can be recommended to try management with a higher proportion of birch and observe if that helps to achieve a higher deadwood volume of birch.

5.3. Effect of the treatment alternatives on NPV:

In this study, no treatment alternatives had any significant difference in the NPV. Therefore, the H_4 that the higher birch proportion in forests would result in a loss of NPV cannot be confirmed by this study. The NPV being unaffected by increasing birch proportion contradicts previous findings on the economy of Norway spruce-birch mixture where increasing birch proportions resulted in lower NPV (Dahlgren Lidman et al., 2021, Fahlvik et al., 2011). While it could be found in this study that scenarios with higher birch proportions were favourable to the birch deadwood, no loss of NPV in the scenarios with higher birch proportions could be found. Thus, a trade-off between higher NPV and higher birch deadwood as was assumed in H_4, cannot be concluded by this study.

All the birch wood in the simulation was sold as pulpwood. It can be said that in the treatment alternatives with higher birch proportions, pulpwood volume would be higher which might add to the revenue earned by selling the Norway spruce timber preventing the loss in NPV. Moreover, when a higher birch proportion (50% and 60% in B_50 and B_60) was maintained, the birch was slightly thinned which possibly lowered the thinning cost compared to the alternatives where birch was thinned heavily. Furthermore, Norway spruce was thinned at a higher intensity in the scenarios where a higher birch proportion was maintained. As thinning was done from below, removing smaller trees allowed to earn an earlier pulpwood revenue from Norway spruce in addition to the pulpwood revenue from birch. These two factors have possibly had an impact to prevent NPV loss in the scenarios with higher birch proportions compared to the alternatives with low birch proportions. In the B_40 alternative, the NPV seems slightly higher, but the difference is not significantly different compared to other scenarios. Thus, in terms of NPV, all the alternatives performed the same. However, as mentioned before the mixture type in this study was group mixture. This might cause a different thinning cost than a stem-wise mixture and affect the NPV.

The previous finding by Dahlgren Lidman et al. (2021) that unthinned management of mixed birch forest is the economically viable option for any discount rate higher than 2% is contradicted in this study as the T0 alternative did not have any significantly different NPV than the alternatives with a proportion of birch > 30%. As the SI of the sites is average to high, the production of Norway spruce possibly compensated for the low production of birch thus resulting in good profit even though the birch was managed. Moreover, unlike the study by Dahlgren Lidman et al. (2021), the stands in this study had planting costs for birch. This might have lowered the NPV in T0 to some extent as in this alternative no revenue from thinning was earned and that probably contributed to the similar economic performance even for the alternatives with increasing Birch proportions. Since no loss of NPV occurred in the managed alternatives, it would be possible to manage forests with higher birch proportions depending on the forest owner's goal. In this study birch and Norway spruce was2 final felled together around 60 years on average. But if genetically improved planting material is used, shorter rotation age and higher growth can be expected as suggested by Liziniewicz et al. (2022) to earn an early revenue. The potential to earn profit from selling birch timber could not be assessed in this study due to the current Swedish market structure.

The NPV was highest in Bullstofta followed by Asa. Both these stands are situated in the South of Sweden where the growth of Norway spruce is better and rotation age in these stands was lower than in Renberget, Siljansfors and Spöland. In Renberget, Siljansfors and Spöland the growth is slower and rotation age is longer, which causes a lower yield and late income. Thus, the higher NPV in Asa and Bullstofta was expected due to their higher yield and early income.

5.4. The experimental design and statistical analysis:

The dataset that has been used in this study is from five different experimental forest sites in Sweden. As mentioned in table 1, the sites are not located in the same geographic location. As the geographic range is wide, each experimental site varies from the others in terms of annual temperature and SI (table 1). The initial stem density is somewhat similar in Asa, Renberget and Siljansfors, but in Bullstofta and Spöland the stem density was lower (table 2). This heterogeneity in the stand conditions violates the assumption of random residual error which is essential for a sound statistical analysis to assess the effect of treatments. However, as this study covers stands from a long geographic range, the trends found with the varying treatment alternatives are expected to represent both northern and southern forest stands.

Due to varying SI, some stands, for example, Asa and Bullstofta, had very high growth and lower rotation period than the other stands. Thus, these two stands have very high NPVs and shorter rotation compared to Renberget, Siljansfors and Spöland which are northern stands with longer rotation and lower NPV. As the stands had varying rotation age, land expectation value would give a more accurate economic overview as it evaluates the value of the stands in perpetuity (Straka and Bullard, 1996).

This study has been based on group-species mixture data. Thus, the results would be more applicable to that sort of stands. A similar kind of research should be conducted with stem-wise mixture data to come up with the knowledge and recommendations for stem-wise mixture.

5.5. To birch or not to birch:

As no significant loss of productivity and NPV has been found in this study and a higher proportion of birch increased birch deadwood significantly, keeping a higher proportion of birch in the forest as a group mixture is recommended as a lot of previous studies goes in favour of having a higher proportion of birch in the forest to support biodiversity (Angelstam et al., 2003, Carlson, 2000, Ranius and Fahrig, 2006, Felton et al., 2011, Felton et al., 2022). Increased birch proportion is also recommended to achieve resilience to climate change risks, which includes Norway spruce susceptibility to storm and bark beetle attack (Faccoli and Bernardinelli, 2014, Lodin et al., 2017). However, while in this study the diameter growth and BA increment after thinning show response to the thinning interventions, the profitability potential of planted birch and birch timber remains uncertain as all the birchwood are sold as pulpwood according to the current market demand (Skogsaktuellt, 2022). Planting, applying management and growing birch longer than usual rotation time when the production potential is only pulpwood seems a less attractive option from a production perspective.

The BA and diameter growth of birch showed a response to the thinning interventions when the birch was thinned down to a lower proportion. According to the results in this study, the management activity had a positive effect on the diameter growth of birch, when birch was thinned down to 10-40% from higher proportions. This indicates that if a timber market for birch develops then in similar sites certain proportion of birch as a group mixture (10-40% in this study) could be managed to produce birch logs. Stands having birch more than 30% can be considered a mixed stand (Drössler, 2010), and according to this study 30-40% of birch would be possible to keep in a stand which would give it a mixed structure without losing NPV or productivity.

As this study is based on planted birch data, the establishment cost was higher, and the higher proportion of birch did not cause any significant economic loss. So, if the pulpwood market remains the same, it will still be possible to make a profit from Norway spruce dominated stands with a higher proportion of birch than required by FSC (> 10%) and from Norway spruce-birch mixed stands having 30-40% of birch. The alternatives with higher birch proportions found in this study can possibly have a better economic outcome in the coming future considering the growing bioenergy market in Europe (Börjesson et al., 2017, Lodin et al., 2020), but to confirm this more studies considering the bioenergy scenarios and prices would be required. Additionally, it can be assumed that if naturally regenerated birch with a lower establishment cost is used then the profit might be higher than this study. In the end, from the findings in this study, a higher birch proportion in the forest seems a possible option to produce Norway spruce timber and birch pulpwood and meet both economic and nature conservation goals.

6. Conclusion

The main economic drawback of planting and managing birch as one of the main species is the lack of a birch timber market in Sweden. It is uncertain if a timber market for birchwood would emerge in Sweden in the coming future, which makes it difficult to answer if planted birch could be an economically attractive species choice in the future. However, as analysed in this study, in the pure Norway spruce stands it is possible to keep and manage a higher proportion of birch than required by FSC without losing productivity and revenue. This would support the broadleaf-dependent biodiversity as well. Additionally, the presence of broadleaf will give a resilient forest structure lowering the climate change associated risks of Norway spruce monoculture and increase the natural value of the forest. Thus, in the case of Norway spruce dominated stands, increasing birch proportion in the stand and maintaining a higher than 10% of birch proportion as a group mixture is certainly a recommendation. In the case of the alternatives with a proportion of birch higher than 30%, all the treatment alternatives with different birch proportions were profitable and the diameter growth was better in the alternatives with 30-40% of birch. Therefore, in similar site conditions birch-Norway spruce admixture in groups with a proportion of birch more than 30% is a possibility to try out without risking profit when the goal is to manage a mixed forest with birch and Norway spruce.

7. Reference

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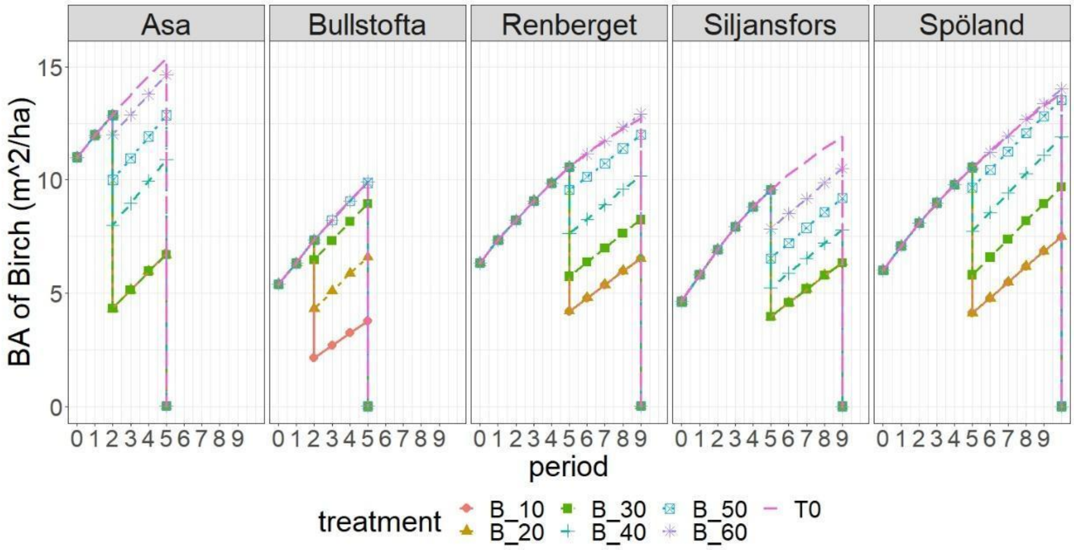
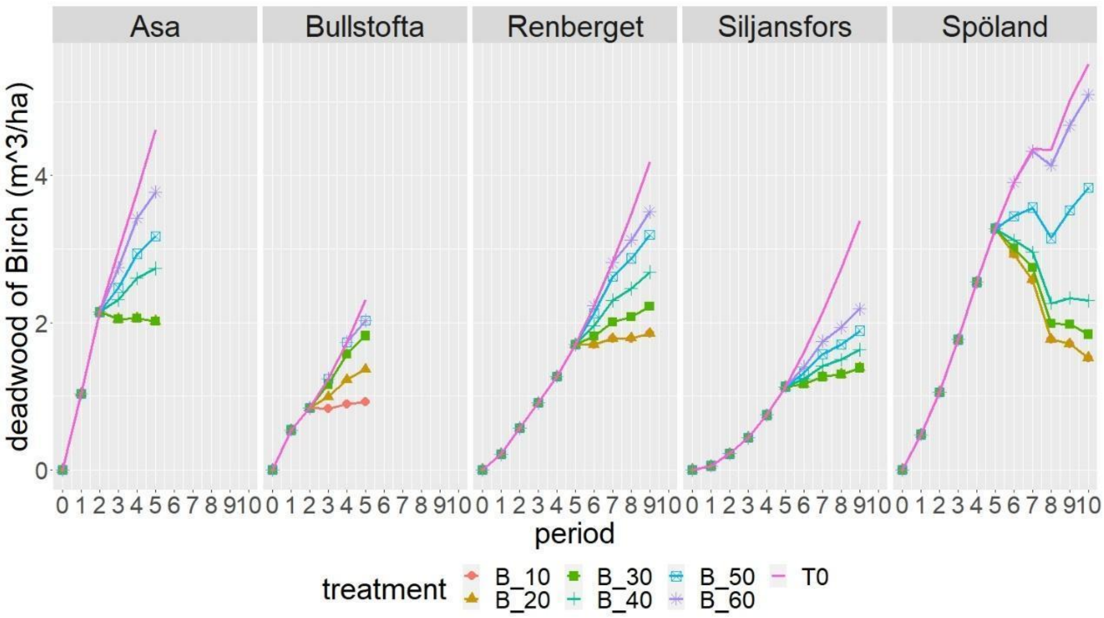
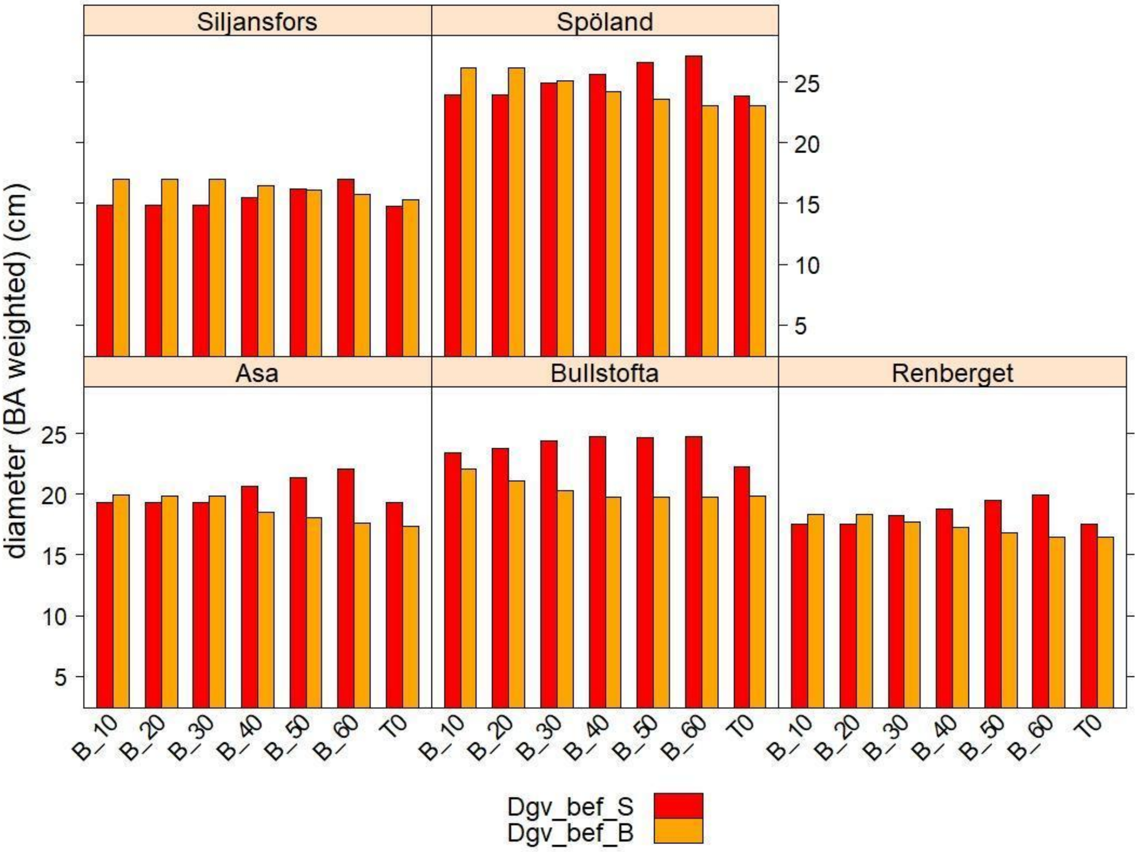
9. Appendix



Appendix 1. Basal area development of birch in individual stands
T0 = Unthinned; B_10, B_20, B_30, B_40, B_50, B_60 = thinned according to thinning guideline (Skogskunskap) and the proportion of birch after thinning has been set to 10%, 20%, 30%, 40%, 50% and 60% respectively.



Appendix 2. Deadwood development of birch in individual stands
T0 = Unthinned; B_10, B_20, B_30, B_40, B_50, B_60 = thinned according to thinning guideline (Skogskunskap) and the proportion of birch after thinning has been set to 10%, 20%, 30%, 40%, 50% and 60% respectively.



Appendix 3. Diameter of birch and Norway spruce in individual stands
T0 = Unthinned; B_10, B_20, B_30, B_40, B_50, B_60 = thinned according to thinning guideline (Skogskunskap) and the proportion of birch after thinning has been set to 10%, 20%, 30%, 40%, 50% and 60% respectively.