Mixed Stand vs Monoculture: A Simulation Study Assessing Growth and Profitability of Norway spruce and Birch in Mixtures and Pure Stands

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Abstract

Picea abies L. Karst (N. spruce) monocultures dominate the forest landscape of southern Sweden due to their suitability for the prevalent site conditions, well-established silviculture, and profitability. However, disturbances such as windthrow, bark beetle damage, and Heterobasidion root rot pose a risk to N.spruce stands' stability. Consequently, recent studies recommend increased tree species diversity in production forests as a form of risk reduction in addition to securing multiple ecosystem services. The natural regeneration potential of birch in southern Sweden makes it a suitable species for establishing mixed stands with N.spruce. However, much research is still required to effectively manage these mixtures and develop silvicultural guidelines.

Inventory data after the first PCT from well-replicated mixed species experiment with naturally regenerated birch and planted N.spruce on scarified soil were used as starting values to project stand development in the Heureka decision support system (StandWise). The experiments were established on highly fertile sites in southern Sweden namely: Hörja, Tagel, and Tönnersjöheden. Two thinning treatments, one aimed at maintaining species proportion (_mix) and another removing the smallest trees of either species (_TFB), were applied to the mixed stands, which had different initial species proportions B2S1 (66% Birch, 33% N.spruce) and B1S2 (33% Birch, 66% N.spruce). In contrast, thinning for pure stands was according to common silviculture for N.spruce and birch monoculture (_mono). Based on the thinning treatments, birch proportion (% basal area), growth (MAI_{max}), and profitability (LEV) of N.spruce-birch stands were assessed in comparison to N.spruce and birch monoculture at final felling.

When _TFB thinning was applied to the mixed stand with a high initial birch proportion, B2S1_TFB, it provided a slightly higher growth and significantly better economy than N.spruce monoculture while retaining a 30% birch proportion. N.spruce dominated mixed stands (B1S2_mix, B1S2_TFB) had similar MAI_{max} and higher LEV than N.spruce monoculture (S_mono) regardless of thinning treatment but resulted in lower birch proportion than the B2S1_TFB. On the other hand, thinning prioritizing initial species proportion was effective in the birch-dominated stand, B2S1_mix. However, the high birch proportion in the B2S1_mix led to trade-offs in stand growth and economic performance. Moreover, birch monoculture (B_mono) was the least productive stand. This study presents viable pathways for managing N.spruce-birch stands in southern Sweden to secure the provision of multiple ecosystem services.

Keywords: N.spruce-birch stands, monoculture, thinning treatment, mixed forest.

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Abbreviations

Birch (B)	Silver birch and downy birch
LEV	Land expectation value
MAI_{max}	Maximum mean annual increment
NFI	National forest inventory
NPV	Net present value
N.spruce (S)	Norway spruce
PCT	Precommercial thinning

1. Introduction

The boreal forest of Northern Europe is dominated by monocultures, especially in Finland and Sweden, where conifer-dominated stand covers more than 70% of the forest area (Forest Europe, 2020). In southern Sweden, *Picea abies* L. Karst (hereinafter named N.spruce) dominates the landscape, while *Pinus sylvestris* L. (hereinafter named pine) is prevalent in the north (Nilsson et al., 2012). Even-aged monocultures of these two conifers have been the norm for decades, with a clear focus on increased wood production and economy (Dahlgren et al., 2021; Lundmark et al., 2013; Yrjölä, 2002). Yet society's demand is changing as forests are expected to provide multiple ecosystem services and timber production (Huuskonen et al., 2021).

An increase in disturbance events such as windstorms and the susceptibility of N.spruce to bark beetle attacks has been a cause for concern, leading to calls for increased species diversity in boreal forests (Seidl et al., 2014). The debate on climate change amplifies the need for increased biodiversity in forest management since forests can contribute significantly to mitigation and adaptation efforts (Coll et al., 2018). There is also a growing bioeconomy based on forest biomass; thus, sustainable, and increased wood production is essential more than ever (Forest Europe, 2020; Gardiner & Moore, 2014; Paré et al., 2011).

Furthermore, FSC certification standards in Sweden require production forests to be managed with the basal area comprising 5 - 10% broadleaves (Holmstrom et al., 2021). To these effects, increasing tree species diversity by including broadleaves in forested landscapes is proposed to deliver multiple ecosystem services (Felton et al., 2016; Felton et al., 2010). The share of mixed forest in Sweden is about 18% of the total forest land area, and similar trends can be observed in other Nordic countries such as Finland and Norway (Huuskonen et al., 2021). While monocultures are viewed as specialized systems optimizing a particular ecosystem service, i.e., timber production, mixed forests are thought to provide a wide range of ecosystem services at average levels (Van der Plas et al., 2016).

Much research has been carried out to assess the benefits of growing mixtures over monocultures in Fennoscandia. Studies by Jansson and Andrén (2003); Lindbladh et al. (2017) showed an increase in bird species richness in managed conifer stands even with a relatively low proportion of broadleaves (<15%) admixed. Mixed forests can provide higher resilience against pathogens if only one species in the mixture is susceptible (Setiawan et al., 2014). Still, a devastating effect may be experienced if the pathogen affects different species within the mixture (Mattila, 2005). An admixture with pine or birch reduces the risk of root rot infection in N.spruce stands, this positive effect is largely based on pine and birch's resistance to *Heterobasidion parviporum* (Lindén & Vollbrecht, 2002; Piri et al., 1990). Bark beetle damage may also be less in N.spruce stands with an increasing proportion of broadleaves (Huuskonen et al., 2021). When a N.spruce stand is windthrown, bark beetle damage can be severe on surviving trees (Komonen et al., 2011; Eriksson et al, 2007). Meanwhile, broadleaves can act as stabilizers in N.spruce stands, reducing windthrow risk and by extension tree death from bark beetle attack (Felton et al., 2016).

The microclimate of streams along riparian forests is improved with an increased proportion of broadleaves (Felton et al., 2016). This benefit is due to increased litterfall and a varying amount of solar radiation reaching the water body (Burrows et al., 2015). Leaf litters of broadleaves decompose faster than the needles of conifers (Johansson, 1995). Kiikkilä et al. (2012) found that a mixture of birch and N.spruce litter resulted in higher decomposition rates. Regarding understorey vegetation, mixtures tend to have higher species diversity which is a combined effect of the tree species in the overstorey (Macdonald & Fenniak, 2007). In a N.spruce-birch stand, a decrease in species richness was found for lichens and bryophytes, while the population of vascular plant increased with a higher proportion of birch (Hedwall et al., 2019). However, the study also noted that stand density has greater influence on understorey species diversity than overstorey composition.

A challenge to managing mixtures in southern Sweden and boreal forests, in general, is increased browsing damage (Milligan and Koricheva, 2013). Silver birch is preferred by moose when compared to downy birch and pine (Månsson et al., 2007). Although silver birch saplings survive moose browsing, tree vitality and timber quality are hampered, affecting the economy of the future stand (Nevalainen et al., 2016). Aesthetically, mixed forests are more interesting to visit due to the variety of species and the probability of better light conditions in the understorey (Olson, 2014; Erikson et al., 2012).

1.1 Mixed Forest Definition

A mixed forest comprises of two or more tree species at any given stage of stand development. For a given tree species in the mixture, its proportion can be quantified with regards to stem density, which is usually the case in young stands. It can also be defined as a proportion of the basal area, crown cover, or volume in more matured stands (Bravo-Oviedo, 2014a).

Mixed stands can be single or multi-layered, and species proportion can change during the rotation depending on site factors, tree species growth rate, disturbances, and management interventions (Puettmann et al., 2015). Here we refer to the mixture at the stand level, focusing on even-aged N.spruce-birch stands. The regeneration is characterized by soil scarification followed by natural regeneration of birch and planting of N.spruce seedlings.

Depending on the country, the threshold for what is regarded as a mixture varies, and the parameters used in defining them. The Swedish national forest inventory (NFI) defines a mixed forest as one where the dominant species comprises not more than 65% of the basal area (Drössler, 2010). While Finnish NFI makes the description based on volume, setting a threshold of 75% for one of the admixed species (Huuskonen et al., 2021).

1.2 Management of N.spruce-Birch Stands

Although mixed forests can provide multiple ecosystem services (Huuskonen et al., 2021; Felton et al., 2016), there is a reluctance to keep N.spruce-birch mixtures over a full rotation in southern Sweden. It is noted that 40% of young forests in Sweden are mixed stands of conifers and broadleaves, but the proportion of broadleaves declines rapidly over the rotation (Fahlvik et al., 2005). Two factors influence this observed decline. First, the admixture of broadleaves is not an active decision by the forest owner (Holmstrom et al., 2015). Secondly, during precommercial thinning (PCT) and commercial thinning, most forest owners thin out the broadleaves, i.e., birch, to favour an even-aged conifer monoculture (Holmstrom et al., 2021). Forest owners' decision to harvest birch during thinning can be ascribed to the negligible timber market for the species in Sweden (Fahlvik et al., 2011) and a general lack of knowledge in managing mixed forests. Currently, there are no established silvicultural guidelines for N.spruce-birch stands in Sweden. There are also uncertainties surrounding the growth, yield, and economy of N.spruce-birch stands compared to N.spruce monocultures. The general trend reported for N.spruce-birch mixtures is a similar or higher growth in young stands compared to N.spruce monocultures with a decline in yield for the mixture later in the rotation (Fahlvik et al., 2011; Agestam et al., 2006; Frivold & Frank, 2002).

Birch is a light-demanding pioneer species with fast growth in its early years, while N.spruce is a shade-tolerant late-successional species with slow initial growth (Frivold & Frank 2002). In the absence of a disturbance, the growth of N.spruce increases steadily, thus outcompeting pioneer species such as birch (Nilsson et al., 2012). Due to the complexity of tree species interaction a lot of uncertainty surrounds the silviculture of mixed boreal forests (Puettmann et al. 2015; Bravo-Oviedo et al., 2014b; Pawson et al. 2013), N.spruce-birch stands inclusive.

The establishment of N.spruce-birch stands in southern Sweden results from the natural regeneration potential of birch (silver birch (B*etula pendula* Roth) and downy birch (*Betula pubescens* Ehrh)) and the planting of N.spruce seedlings after soil scarification (Holmstrom et al., 2016a; Nilsson et al., 2010). Although an experiment by Dahlgren et al. (2021) utilized a clearcut of naturally regenerated birch and N.spruce without soil preparation, this is seldom the practice in Sweden as over 80% of clearcuts are planted with conifers at high density after soil scarification (Dahlgren et al., 2021; Holmstrom et al., 2016a). Natural regeneration of birch is attractive from an economic point of view because it reduces the establishment cost by allowing planting of N.spruce at lower densities (Holmstrom, 2015). However, early financial gains may be hampered by an increased cost of PCT, i.e., if the natural regeneration of birch is very successful due to favourable site conditions (Uotila et al. 2010). When the opposite happens, and the density of birch regeneration is very low, future revenue from the stand is reduced (Holmstrom et al., 2017; Agestam et al., 2005).

Recent studies provide insights on the management of young N.spruce-birch stands in Sweden, stating the importance of treatment timing, height difference and stand density after PCT as essential factors for sustaining the mixture throughout the rotation (Fahlvik et al., 2015; Holmstrom, 2015; Holmstrom et al., 2015; Fahlvik et al., 2005). A decision on the timing of PCT is tricky. After a PCT is carried out usually at 3-5m height, stump sprouts of birch appear, which often needs to be removed before first commercial thinning at extra costs (Hynynen et al., 2010). Since sprouting occurs during the birch seedling/sapling stage, one option is to delay PCT, but this may limit the possibility of selecting future crop trees (Holmstrom, 2015). The practice in Finland is to make an early intervention at 1m height and a second PCT when the stand reaches a height of 3 - 5m (Bataineh et al., 2013).

N.spruce-birch stands tend to have a higher density than N.spruce monocultures (Dahlgren et al., 2021; Pretzsch and Forrester, 2017), but they could also be similar depending on management goals. The height difference between N.spruce and birch after PCT is an essential factor influencing future stand dynamics (Holmstrom et al., 2016a; Fahlvik et al., 2015). Based on Swedish conditions, birch height should be higher than N.spruce, while the opposite holds in Finland (Huuskonen et al., 2021). To keep birch proportions in mixed stands at the time of first commercial thinning (about 13m N.spruce height in Sweden), Fahlvik et al. (2005) suggest that a height advantage of 0.5 – 1m should be prioritized for birch during PCT.

While several experiments have been carried out in young N.spruce-birch stands, knowledge on the management of intermediate and matured stands is based on simulation studies (Dahlgren et al., 2021; Holmstrom et al., 2016b; Fahlvik et al., 2015; Fahlvik et al., 2011; Valkonen & Valsta, 2001). Heureka and Motti are examples of decision support systems employed in boreal forests for long-term projections. Heureka is built for Swedish conditions and the input data for models embedded in the software includes NFI data and long-term experiments (Wikström et al., 2011). The simulation study by Dahlgren et al. (2021) provides some insight in the management of matured N.spruce-birch stands, they note that thinning strategy for mixtures should be different from that of monocultures, i.e., removal or retainment of the desired species during thinning. Using survey data from the Swedish NFI, Holmstrom et al. (2021) found that older N.spruce-birch stands in southern Sweden are managed in a similar way to N.spruce monocultures. Thinning was frequent, with birch taken out in most interventions; this leads to a low proportion of birch basal area with increasing stand age. However, they noted that the decline in birch proportion was not solely based on thinning decisions but also on the slow growth of birch further in the rotation.

1.3 Growth and Economy of N.spruce-Birch Stands

A common way to compare growth between mixed stands and monoculture is by calculating the mean annual increment (MAI) for each stand. Considering the difference in stand composition and growth rate of the individual species, the comparison is usually based on the highest MAI (MAI_{max}) found for both stands (Holmstrom, 2015). For economic evaluation, Net Present Value (NPV) or Land Expectation Value (LEV) can be calculated. LEV can be used to compare the economic performance of forest stands with different rotation ages and management since the estimate considers the same time horizon, repeating similar management starting from bare land until infinity (Jacobsen, 2020). While NPV is employed for stands having the same rotation length.

In the simulation study by Fahlvik et al. (2011), reduced growth was observed in N.spruce-birch stands with increasing birch proportions compared to N.spruce monoculture. This slow growth affected the NPV as the N.spruce monoculture was more profitable. Conversely, Valkonen & Valsta (2001) reported higher NPV in a two-layered N.spruce-birch stand in southern Finland; the birch was used as a shelter for N.spruce and harvested 30 years into the rotation. Growth comparisons in the study by Dahlgren et al. (2021) showed the MAI_{max} for N.spruce-birch stands to be higher than N.spruce monoculture. The starting point of both stands was natural regeneration without any form of soil preparation. However, when the mixture was compared with a planted N.spruce monoculture on scarified soil, growth was higher in the latter. Fahlvik et al. (2015) found that mixtures with birch-pine-N.spruce had similar productivity to N.spruce monoculture, provided the basal area of birch is less than 25%. At the time of first thinning, Fahlvik et al. (2005) reported a higher volume yield in N.spruce-birch stands than in N.spruce monoculture with similar stand density.

1.4 Research Justification and Objectives

The effect of PCT on the management of young N.spruce-birch stands is well studied (Holmstrom et al., 2016a; Fahlvik et al., 2015; Holmstrom, 2015; Holmstrom et al., 2015; Fahlvik et al., 2005), proving to be quite effective in maintaining species proportion when appropriately done. However, little is known about the effect of commercial thinning on the outcome of N.spruce-birch stands. Recent studies by Dahlgren et al. (2021) and Holmstrom et al. (2021) highlight the need for active management to retain birch; continued research is thus needed to advance current knowledge. This study investigates the long-term effect of different commercial thinning treatments on the basal area proportion of birch (birch proportion), growth, and economy of N.spruce-birch stands at final felling. The results obtained here, thus, could contribute to promoting the management of N.spruce-birch stands in southern Sweden for the provision of multiple ecosystem services.

Field trials focused on monocultures are abundant in Sweden, but experiments on mixed forests are generally low. The long-term mixed species experiment established on three sites in southern Sweden provides a rare and unique opportunity to follow the development of N.spruce-birch stands over a full rotation. Here, we use Heureka StandWise to project and compare the development of N.spruce-birch stands having different initial species proportions (from birch dominated to N.spruce dominated), with monocultures of N.spruce and birch along one rotation. We apply two distinct thinning treatments in the N.spruce-birch stands and one in the monoculture stands.

The specific objectives for the present study are:

I. To compare birch proportion in the N.spruce-birch stands with different thinning treatments and initial species proportion.

II. To compare MAI_{max} of the N.spruce-birch stands with N.spruce and birch monoculture

III. To compare the LEV of N.spruce-birch stands with different thinning treatments and initial species proportion.

IV. To compare the LEV of N.spruce-birch stands with N.spruce and birch monoculture.

In line with the objectives of this study, we hypothesize that:

H_1: Birch proportion will decline in all N.spruce-birch stands regardless of the thinning treatments and initial mixture proportions. Based on the reported decline in birch growth over the rotation, with or without management interventions, (Holmstrom et al., 2021), it is expected that the thinning treatment applied is insufficient to maintain the initial proportion of birch until the end of the rotation.

H_2: There is a significant economic loss in N.spruce-birch stands with thinning treatments aimed at maintaining birch proportion. A decrease in growth and yield is associated with an increasing proportion of birch in the stand basal area (Fahlvik et al., 2015). The general recommendation to improve yield is to reduce the proportion of birch in thinning (Huuskonen et al., 2021). With this inverse relationship, we expect the economic cost of retaining birch to be high.

MAI_{max} (H_3) and LEV (H_4) of the N.spruce monoculture is higher than all N.spruce-birch stands. Economic and growth comparisons over a rotation tend to favour N.spruce monoculture over N.spruce-birch stands, especially in scenarios with soil scarification and planting of N.spruce (Dahlgren et al., 2021; Fahlvik et al., 2011). Thus, faster growth and a better economy are expected in the N.spruce monoculture.

2. Material and Methods

2.1 Site and Experimental Design

The data used in this study were from mixed species trials established on three sites in southern Sweden namely Hörja (lat. 56.21^0N, long. 13.59^0E), Tagel (57.04^0N, 14.40^0E), and Tönnersjöheden (56.70^0N, 13.11^0E) (Fig. 1). These experiments were established by the department of Southern Swedish Forest Science and the forest experimental parks in Tönnersjöheden and Asa (www.silvaboreal.com). The aim is to compare growth and the provision of various ecosystem services between the mixtures and monocultures. In the short term it can also be used as a starting point for simulation studies to predict future stand development of the different treatments.

All sites are highly fertile with site index (SIH N.spruce) between 29.5 and 35.5 (Table 1). Soil scarification was carried out on all sites, subsequently genetically improved N.spruce seedlings were planted at a density of about 2000-3000 stems ha^{-1}, but abundant natural regeneration of birch was also present at the start of the experiment. The treatment in first PCT was to create pure stands with monocultures of N.spruce (S) and birch (B); mixed stands with 2/3 birch and 1/3 N.spruce (B2S1) or 1/3 birch and 2/3 N.spruce (B1S2) based on stem-number (Table 1). Three blocks were laid out on each site with the four treatments assigned randomly within each block (3sites x 3blocks x 4 treatments). Plot size of the treatments varied between 800 - 1000m^2. PCT was carried out when the stands reached an average height of about 2 m. Measurements were taken in all plots between 2020 & 2021.

For the mixed treatments B2S1 and B1S2, the height of birch was the same or higher than N.spruce (between 0 – 1.6 m) in Hörja and Tagel, while in Tönnersjöheden, N.spruce had a slight advantage ranging from 0.1 – 0.4 m (Table

1). Stand density did not vary much between Tagel and Tönnersjöheden but the average stand density in Hörja was higher, especially in treatment S which had 4370 stems ha^{-1} (Table 1). The age of the stands in Hörja, Tönnersjöheden and Tagel were 11, 14 and 16 years respectively.

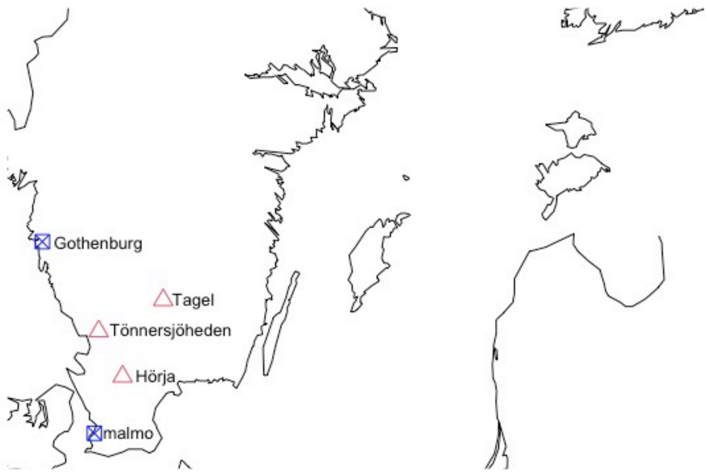

Figure 1. Map showing the three mixed species trial sites, Hörja, Tagel and Tönnersjöheden including major cities in Sweden.

Table 1. Mean values for height (m), stand age (years), stand density (stems ha^{-1}) and site index (m) for the mixed species trials in Hörja, Tagel and Tönnersjöheden based on revisions in 2020/2021. The treatments are N.spruce monoculture (S), birch monoculture (B), 2/3birch, 1/3N.spruce (B2S1), 1/3birch, 2/3N.spruce (B1S2). Values in parenthesis are standard deviation.

		Height (m)		Stand Age	Density	Site Index
Site	**Treatment**	**Birch**	**N.spruce**	**(years)**	**(stem ha^{-1})**	**(m)**
Hörja	S	5.2 (0.1)	5.3 (0.5)	11	4370 (2467)	34.1 (1.0)
	B	7.7 (0.7)	3.7 (0.4)	11	2935 (627)	33.4 (0.6)
	B2S1	7.6 (0.6)	6.0 (0.5)	11	3262 (487)	29.5 (0.6)
	B1S2	7.3 (0.2)	6.2 (0.2)	11	3377 (763)	35.5 (0.5)
Tagel	S	4.2 (2.4)	6.3 (0.7)	16	2015 (172)	32.6 (1.4)
	B	7.7 (0.3)	3.8 (2.2)	16	1893 (129)	31.1 (1.0)
	B2S1	7.4 (0.2)	7.4 (0.1)	16	2152 (171)	33.8 (2.5)
	B1S2	7.5 (0.8)	6.8 (0.4)	16	2044 (136)	33.9 (1.0)
Tönnersjöheden	S	4.3 (2.5)	6.9 (0.4)	14	2417 (391)	34.5(1.0)
	B	6.9 (0.7)	5.7 (3.3)	14	2473 (670)	31.4 (1.1)
	B2S1	6.7 (0.2)	7.1 (0.5)	14	2144 (312)	35.1 (0.8)
	B1S2	7.0 (0.1)	7.1 (0.2)	14	2498 (894)	34.8 (0.6)

2.2 Heureka (StandWise)

Heureka is a multipurpose decision support system developed for long term prediction of growth, timber production, carbon stock, biodiversity, and other variables in Swedish forests. Simulations are made in 5-year time steps called "periods". The Heureka system is composed of basal area growth models, height, ingrowth and mortality functions, habitat suitability models; there is also flexibility as new models can be added to improve predictions (Wikström et al., 2011). Input data for simulations require site (altitude, latitude, site index, vegetation type), stand (age, management history), and tree level (diameter, height, tree species) information. It is possible to designate unmanaged, even-aged, or uneven-aged management to stands. Simulations can be carried out from stand to regional level depending on the goal of the user, available data and Heureka application employed. StandWise (version 2.18.1.0) is used in this study because it is built for analysis at the stand-level. This gives the user flexibility in timing of treatment for each stand to achieve the specified management objective. Treatments such as regeneration, PCT, creation of strip-roads, selective felling, fertilization, final harvest can be simulated in StandWise. Imported data can be viewed in 2D and 3D, with the 2D view users can select trees to be removed in thinning or allow the program to make this decision. When simulations have been made, results can be viewed using tables and/or graphs.

2.2.1 Thinning Treatments

For B2S1 (birch dominated) and B1S2 (N.spruce dominated) stands, two commercial thinning treatments were simulated, one designed to keep the mixture proportions (_mix) and another without consideration for the mixture (_TFB) (Table 2). The difference between _mix and _TFB is that in the later only the smallest trees were removed, there was no preference for retaining either birch or N.spruce. It is possible to evaluate the economic cost of prioritizing the mixture in our thinning treatment by comparing LEV of _mix and _TFB stands. Thinning treatment in the monoculture stands was aimed at keeping pure stands (_mono) which is the traditional management applied to production stands in Sweden. All thinning is from below regardless of the thinning treatment.

Table 2. The three thinning treatments simulated in Heureka StandWise. The _mix and _TFB were applied to N.spruce-birch stands while _mono was applied to birch and N.spruce monoculture.

Thinning Treatment	Stand	Description
_mix	B2S1_mix	Maintain 66% birch, 33% N.spruce
	B1S2_mix	Maintain 33% birch, 66% N.spruce
_TFB	B2S1_TFB	Thin the smallest trees
	B1S2_TFB	Thin the smallest trees
_mono	B_mono	Maintain 100% birch
	S_mono	Maintain 100% N.spruce

2.2.2 Simulation in StandWise

PCT, commercial thinning, and final felling were the only treatments simulated. A second PCT was simulated in stands with high amount of birch stump sprouts since the time of first PCT. During second PCT: 66% of the stem number was prioritized for the dominant species in B2S1 and B1S2 stands respectively following the _mix strategy. 100% stem density was retained for birch (B) and N.spruce (S) stands respectively according to the _mono treatment. There was no _TFB treatment during PCT, thus all mixed stands had the same starting point before commercial thinning. The target stem density after PCT was 2000 stems ha^{-1} for all stands.

Commercial thinning was simulated following established guidelines, B_mono was managed with the recommendations by Hynynen et al. (2010). An intensive first thinning was simulated at dominant height between 13 – 15 m, while second thinning was performed 15 years later. SODRA thinning template was used in simulations for B2S1_mix, B1S2_mix, B2S1_TFB, B1S2_TFB and S_mono stands (Supplementary Fig. 1). First thinning was simulated at a dominant height between 13 – 15 m, while second thinning was performed before the stand dominant height reached 20 m. Since thinning in Heureka can only be made in 5-year periods, thinning in some stands was simulated at 22m height; a risk of this late intervention is increased susceptibility to wind damage. But this was necessary in some stands due to low basal area when dominant height was below 20m. The guidelines by SODRA were created for even-aged monoculture of N.spruce, but it was employed here for mixed stands due to the lack of thinning guidelines for N.spruce-birch stands.

All four treatment plots (Table 1) within each block were regarded as a stand in the simulations, making it a total of 36 stands. Species proportion during commercial thinning was defined by basal area. A maximum of two thinning was carried out in all stands. Thinning intensity was between 25 – 35% basal area depending on the growth of the stand. When performing a thinning in Heureka, it is possible to favor the removal/retainment of birch or N.spruce by changing the Deciduous/conifer settings (Supplementary Fig. 2). This function was employed to maintain species proportion in the B2S1_mix, B1S2_mix, B_mono and S_mono stands by weighting thinning grade on the less desired species. The simulation process required multiple trials to attain the desired species proportion for each stand. Deciduous/Conifer ratio was set to zero in the B2S1_TFB and B1S2_TFB stands. All stands were clear-felled at the end of the rotation. Final felling was simulated for different periods to determine optimal rotation age for each stand based on LEV calculation.

2.3 Analyzed Variables at Final Felling

2.3.1 Basal Area Proportion of Birch (%)

Basal Area proportion of birch at the financially optimal rotation age was calculated for all stands. While it was possible to maintain the species proportion both in PCT (by stem density) and during commercial thinning (by basal area), it is important to see if we can keep birch proportions until the end of the rotation especially in the _mix thinning treatment. This was calculated as %birch of the total BA at the end of the rotation (Eq. 1) for N.spruce-birch stands.

$$\text{Birch Proportion} = (\text{BA birch} / \text{Total BA}) \times 100 \quad (1)$$

2.3.2 Maximum Mean Annual Increment (MAI_{max})

Mean annual increment tells us the average growth of each stand up until a given year. This can be calculated according to Eq. 2, where V_s is standing volume ($m^3ha^{-1}yr^{-1}$) at a given time (t), and V_h is the sum of harvested volume from previous years. Based on the maximum MAI (MAI_{max}) obtained for each stand, the growth performance of stands with different thinning treatments (_mix, _TFB and _mono) (Table 2) was compared.

$$MAI = (V_s + \sum V_h) / t \quad (2)$$

2.3.3 Land Expectation Value and Rotation Age

LEV is one of the measures used in forestry to determine the optimal time for final felling. The age when LEV is maximum is described as the rotation age of a given stand, at this point the forest should be cut to get the best economy. Other considerations exist for determining optimal rotation age such as pointing percentage and minimum legal felling age which is set by the government. A discount rate of 2.5% was used in LEV calculation. Eq.3 is LEV formula, where R_t (SEK) is the net income from final harvest, thinning and cleaning, C_0 (SEK) is establishment cost, t (years) is the age of the stand when treatment was simulated, and r is the discount rate.

$$LEV = \sum R_t\ (1+r)^{-t} - C_0 * (1+r)^{t} / ((1+r)^{t} - 1) \qquad (3)$$

2.3.4 Sensitivity Analysis for Discount Rate (r)

The discount rate used in LEV calculations can determine which management alternative performs best economically. Thus, we used additional discount rates of 1% and 4% to test if the economic ranking of management alternatives obtained by using r = 2.5% will change.

2.3.5 Establishment Costs, Timber Prices, and Forest Operation Costs

Establishment cost varied between stands and is based on the cost of soil scarification and first PCT (4500 SEK) as well as the density of planted N.spruce seedling (5 SEK/seedling). B_mono costs 4500 SEK since natural regeneration of birch was only required while 14500 SEK is invested in the S_mono with 2000 N.spruce stems ha^{-1} planted (Table 3). The birch dominated (B2S1_mix, B2S1_TFB) and N.spruce dominated mixed stands (B1S2_mix, B1S2_TFB) were planted with 600 and 1200 N.spruce seedlings respectively (Table 3). Heureka default values were used for timber assortment prices, harvesting, and cleaning costs.

Table 3. Establishment cost for N.spruce dominated, birch dominated, and monoculture stands. Total cost includes planting, first PCT and soil scarification. Values in parenthesis represent number of planted N.spruce seedling.

Stand	**Planting Cost (SEK)**	**Total Cost (SEK)**
B_mono	0 (0)	4500
S_mono	10000 (2000)	14500
B2S1_mix, B2S1_TFB	3000 (600)	7500
B1S2_mix, B1S2_TFB	6000 (1200)	10500

2.4 Statistical Analysis

The response variables: Birch proportion (% basal area), MAI_{max} (m^3 ha^{-1} yr^{-1}) and LEV (SEK ha^{-1}) were estimated for each treatment (stand), block and site based on the projected values from StandWise. We fitted a linear mixed model using R package (lme) (Bates et al., 2011), to test the significance of the variables studied as follows:

$$Y_{ijklm} = m + A_i + B_j + C_k + a_{ijk} \quad (4)$$

Where m is the general mean, A_i is the effect of site, B_j is the effect of block, C_k is the effect of mixture and thinning treatments, and a_{ijk} is residual error. Y_{ijklm} is the response variable i.e., birch proportion, MAI_{max} or LEV. The A_i and B_j were considered as random effects whereas C_k was considered as fixed effect. When A_i, B_j or C_k was significant in the mixed-model analysis ($p < 0.05$), differences between thinning treatments were evaluated using the post-hoc Tukey test method (Abdi & Williams, 2010) with R package (emmeans) and cld-function. All tests were run in R studio 1.4.1717.

3. Results

There was no significant variation between the results from Horja, Tagel and Tönnersjöheden as indicated by the p-values (Table 4). Meanwhile, the treatments differed significantly (<.0001), explaining the observed variance for the analyzed response variables. Thus, the choice of thinning treatment for different stands during the rotation had a great impact on birch proportion, growth, and economy at final felling. Since there was no difference between the sites, only average site values are shown in the figures further in this section. The figures representing values for each site have been included in Supplementary Fig. 3, 4, 5 and 6.

Table 4. Analysis of variance for birch proportion, maximum mean annual increment, land expectation value and rotation age. Level of significance is $p < 0.05$.

Response Variables	Parameters	F-value	df	P-value
Birch Proportion	site	8.165	1	0.214
	block	0.115	1	0.748
	treatment	331.661	5	<.0001
MAI_{max}	site	0.175	1	0.748
	block	0.08	1	0.789
	treatment	36.387	5	<.0001
LEV	site	0.523	1	0.601
	block	0	1	0.999
	treatment	28.332	5	<.0001
Rotation Age	site	0.188	1	0.740
	block	0.062	1	0.814
	treatment	11.923	5	<.0001

3.1 Birch Proportion in Mixed Stands at Final Felling

The birch dominated B2S1_mix had a significantly higher birch proportion than the B2S1_TFB, it was also possible to keep birch proportion until the end of the rotation in the B2S1_mix by thinning out competing N.spruce (Fig. 2). The decision to remove only the smallest trees in B2S1_TFB reduced birch proportion by 52%, thus creating a N.spruce dominated stand at final felling.

For N.spruce dominated stands B1S2_mix and B1S2_TFB, birch proportion did not vary much between the treatments (Fig. 2). In both treatments, the proportion of birch was lower than the initial state but >20% in the B1S2_mix. The interventions made in the B1S2_mix were not sufficient to maintain birch proportion (1/3birch) until final felling.

The _mix thinning treatment was most effective in the B2S1_mix stand, where 2/3 birch was maintained until final felling while the biggest shift in species proportion is noted in the B2S1_TFB, which was once a birch dominated stand. We now have three N.spruce dominated stands at final felling (B1S2_mix, B1S2_TFB and B2S1_TFB) and one birch dominated stand (B2S1_mix). Notably, it was possible to keep birch in all the N.spruce-birch stands at varying proportions regardless of the thinning treatment.

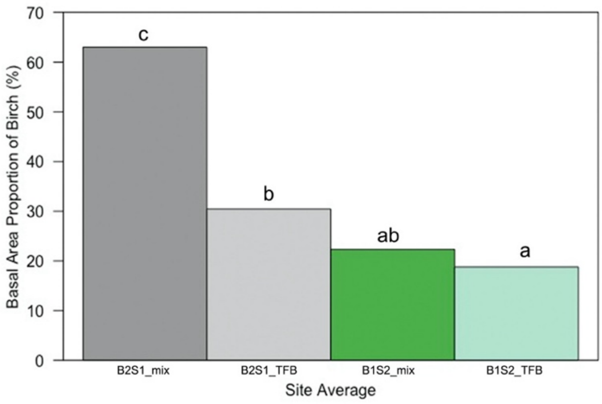

Figure 2. Basal area proportion of birch (%) at final felling for the two thinning treatments _mix and _TFB simulated in Heureka. The treatments were applied in birch dominated (B2S1) and N.spruce dominated (B1S2) stands. The significant difference between treatments is shown on the bar plots. Thinning in _mix prioritized initial species proportion while in _TFB, the smallest trees are removed regardless of the species.

3.2 Growth Performance of N.spruce-Birch stands and Monocultures

The birch dominated stand, B2S1_mix, where birch proportion was maintained until the end of the rotation had a significantly lower growth than other mixed stands (Fig 3). The best growth performance (10.2 $m^3\ ha^{-1}\ yr^{-1}$) was recorded in the

B2S1_TFB stand, but it did not differ much from other N.spruce dominated stands (B1S2_mix and B1S2_TFB).

Growth in the N.spruce monoculture (S_mono) was similar to all N.spruce-birch stands except the birch dominated B2S1_mix which had 14% lower MAI_{max}. Thus, stands with low proportion of birch (≤ 30%) provided the same or slightly better growth, i.e., B2S1_TFB, compared to N.spruce monoculture (Fig 2 & 3). In comparison with birch monoculture (B_mono), all other stands had a significantly higher growth.

A high proportion of birch (> 60%) seems to have a negative effect on stand growth as indicated by the B_mono and B2S1_mix treatments (Fig. 2 & 3). The decision to keep birch proportions during thinning in the N.spruce dominated B1S2_mix stand did not have a negative effect on growth.

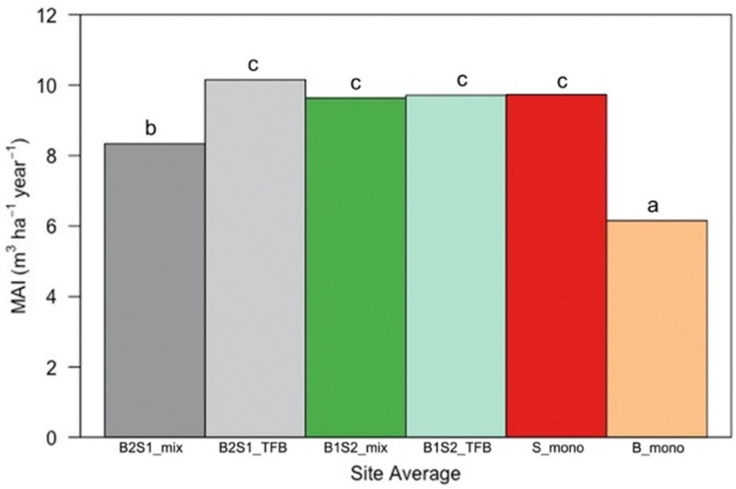

Figure 3. Maximum mean annual increment (m^3 ha^{-1} $year^{-1}$) for the three thinning treatments _mix, _TFB and _mono simulated in Heureka. The _mix and _TFB treatments were applied in birch dominated (B2S1) and N.spruce dominated (B1S2) stands while the _mono was applied in N.spruce (S) and Birch (B) monocultures. The significant difference between treatments is shown on the bar plots. Thinning in (_mix) prioritized initial species proportion, in (_TFB), the smallest trees were removed regardless of the species and in (_mono) pure N.spruce and birch stands were created.

3.3 LEV and Rotation Age Comparison between Treatments

The B2S1_mix had a significantly lower LEV than B2S1_TFB, B1S2_mix, and B1S2_TFB stands (Fig. 4). While trying to maintain a high proportion of birch during thinning, a significant income was lost in comparison with other N.spruce-birch stands. The largest difference was found between B2S1_mix and B2S1_TFB, with the former having an LEV deficit of 35%. Average rotation age for all mixed stand alternatives is 60 years (Fig. 5).

The B2S1_mix is competitive when compared with the S_mono. Although a higher LEV is obtained from the N.spruce monoculture, it is not significantly higher than the birch dominated stand B2S1_mix (Fig. 4). Also, we get the income from the N.spruce monoculture a little later than in the B2S1_mix (Fig. 5). The economy of the N.spruce dominated stands, B1S2_TFB and B1S2_mix, is slightly higher than the S_mono but the difference is not substantial. We get a significantly higher LEV (28%) from the B2S1_TFB than in the S_mono. By choosing to thin only the smallest trees irrespective of the species, the economy and productivity of the previously birch dominated B2S1_TFB stand is greatly improved. Even with low establishment cost, (Table 3) the B_mono provided a significantly lower income than all other stands. The low income is gotten earlier at a rotation age of 53 years (Fig. 5).

It appears that the mixed stands are generally more profitable than the N.spruce monoculture except for B2S1_mix where thinning favored a high birch proportion. Comparing the overall performance of the mixed stands, B2S1_mix had the least growth and economic performance. This observation presents a trade-off between keeping a high proportion of birch and maintaining productivity.

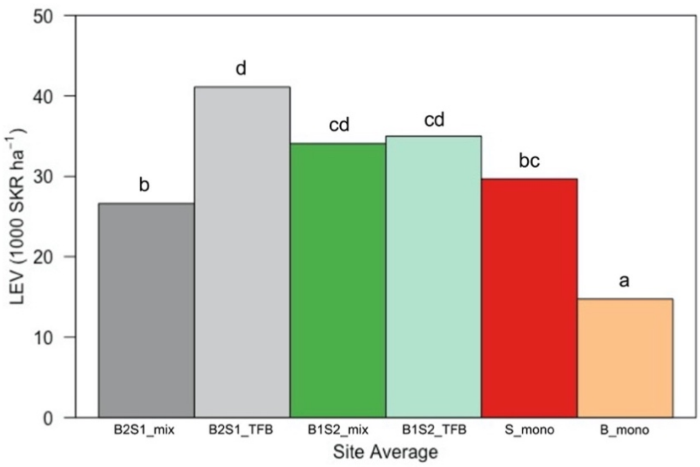

Figure 4. Land expectation value (SEK ha^{-1}) for the three thinning treatments _mix, _TFB and _mono simulated in Heureka at 2.5% interest rate. The _mix and _TFB treatments were applied in birch dominated (B2S1) and N.spruce dominated (B1S2) stands while the _mono was applied in N.spruce (S) and Birch (B) monocultures. The significant difference between treatments is shown on the bar plots. Thinning in (_mix) prioritized initial species proportion, in (_TFB), the smallest trees were removed regardless of the species and in (_mono) pure N.spruce and birch stands were created.

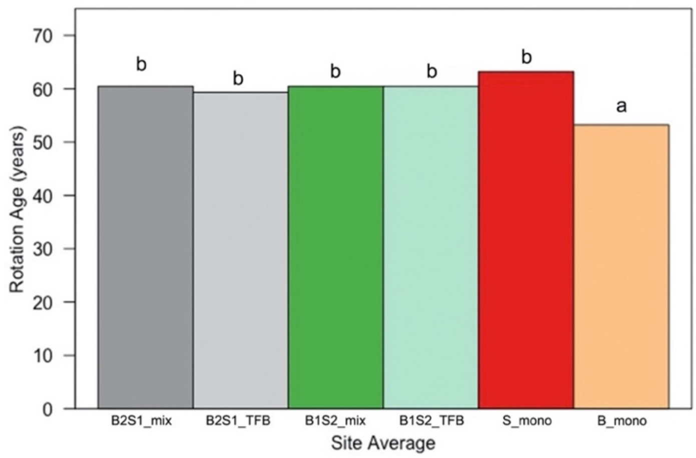

Figure 5. Rotation age (years) for the three thinning treatments _mix, _TFB and _mono simulated in Heureka. The _mix and _TFB treatments were applied in birch dominated (B2S1) and N.spruce dominated (B1S2) stands while the _mono was applied in N.spruce (S) and Birch (B) monocultures. The significant difference between treatments is shown on the bar plots. Thinning in (_mix) prioritized initial species proportion, in (_TFB), the smallest trees were removed regardless of the species and in (_mono) pure N.spruce and birch stands were created.

Table 5. Land expectation value for simulated mixed and monoculture stands in Heureka at 1%, 2.5% and 4% interest rate. B2S1 is birch dominated, B1S2 is N.spruce dominated while S and B are monocultures of N.spruce and birch respectively. Thinning in (_mix) prioritized initial species proportion, in (_TFB), the smallest trees were removed regardless of the species and in (_mono) pure N.spruce and birch stands were created.

	LEV (SEK HA^{-1})		
Stands	**1%**	**2.5%**	**4%**
B2S1_mix	129753	26617	6210
B2S1_TFB	189428	41070	11656
B1S2_mix	172386	34063	6768
B1S2_TFB	175836	34971	7187
S_mono	172049	29701	2329
B_mono	71353	14728	3411

3.4 Economic Performance of Stands based on Interest Rates

In comparison with the 2.5% interest rate used in the LEV calculation, the economic ranking of stands did not change at a low interest rate of 1% (Table 5). However, at an interest rate of 4%, the N.spruce monoculture (S_mono) was less profitable than the birch monoculture (B_mono) and all N.spruce-birch stands. The high initial cost of establishment in the S_mono (Table 3) made it the least attractive investment given a high interest rate.

4. Discussion

4.1 Differences in Stand Thinning Treatments

For the first hypothesis, a decline in birch proportion in all N.spruce-birch stands is refuted. It was possible to maintain species proportion in the birch-dominated stand, B2S1_mix (Fig. 2). Although we applied the same thinning strategy in the B1S2_mix stand, the basal area of N.spruce increased compared to the starting point. Fahlvik et al. (2015) also noted this tendency of N.spruce dominance. In their simulation study, birch proportion decreased in the mixed stands even though a higher thinning grade was employed for pine and N.spruce after the first commercial thinning. The species composition of the mixed stand in their study is similar to B1S2_mix, which is a low initial birch proportion after PCT. N.spruce is a shade-tolerant species that dominate the forest canopy at the latter stages of the rotation (Nilsson et al., 2012); thus, a high N.spruce basal area might create a dense stand unfavorable for the growth of birch, making it difficult to keep them in the mixture. The _mix strategy was more effective in the B2S1_mix stand possibly due to the initial species proportion in favor of birch and the removal of competing co-dominant N.spruce during thinning.

Unsurprisingly, birch proportion declined in the B2S1_TFB, and B1S2_TFB stands as the thinning treatment did not prioritize species proportion. However, the birch proportion in these stands exceeds 10% of stand basal area, surpassing the minimum requirement for managing production stands in southern Sweden according to FSC certification rules (Holmstrom et al., 2021). In a simulation study, Holmstrom et al. (2016b) reported that N.spruce-birch stands with a high density of planted N.spruce (2800 stems ha^{-1}) became N.spruce monoculture at final felling.

This was not the case in our study, because the density of N.spruce was reduced in the mixed stands during the first PCT according to the treatments (B2S1, B1S2).

The second hypothesis is upheld as we observed a substantial economic loss in the B2S1_mix compared to the B2S1_TFB thinning treatment. The _mix thinning treatment implies that we sometimes removed healthy and bigger N.spruce while retaining smaller birches. Also, the thinning grade for N.spruce was usually higher. Fahlvik et al. (2011) noted an 18% increase in the NPV of a N.spruce-birch stand with 50% birch proportion by simulating alternative management in which birch proportion was reduced to 20% in the last commercial thinning. Their finding is in line with our results. Since birch proportion in the B1S2_mix and B1S2_TFB stands was < 25%, N.spruce had a more significant influence on stand profitability. Thus, the B1S2_mix thinning treatment did not provide a significantly lower LEV even though we prioritized birch.

The N.spruce-dominated mixtures had the same or higher growth than N.spruce monoculture (Fig. 3) and a better economy than N.spruce monoculture; thus, the third and fourth hypotheses are rejected. Specifically, the B2S1_TFB with a 30% birch proportion at the end of the rotation had a significantly higher LEV. Possible explanations for this could be the establishment cost, which was higher in the N.spruce monoculture (Table 3), but this effect was not the only explanation for high LEV in B2S1_TFB. The highest MAI_{max} was also recorded in the B2S1_TFB stand even though it had the same starting point as the B2S1_mix, a high density of birch after PCT. Thus, the _TFB thinning treatment made a significant difference. According to this strategy, thinning puts equal weight on N.spruce and birch species, favoring the biggest trees while removing suppressed and small trees of either species. Although thinning from below was also simulated in the _mix and _mono treatments, constraints such as the deciduous/conifer ratio used in Heureka to maintain species proportion led to suboptimal outcomes for LEV and MAI_{max}.

Fahlvik et al. (2015) observed higher growth in N.spruce monoculture than in N.spruce-birch mixtures. Most importantly, they pointed out that mixed plots with a birch proportion lower than 25% provided similar growth to the N.spruce monoculture, while plots with a higher birch proportion accounted for the reduced growth. Higher growth was reported in N.spruce-birch stands than in N.spruce monoculture in the study by Dahlgren et al. (2021); both stands were naturally regenerated. At the start of their thinning treatment, the density of the individual species in the mixed stand was the same, but subsequently, birch was reduced from 1200 to 400 stems ha^{-1}. Our results agree with studies by Dahlgren et al. (2021), Fahlvik et al. (2015), and Fahlvik et al. (2011), which found that it is necessary to reduce birch proportion during commercial thinning to ensure sustainable growth and economy. This finding is exemplified by the massive difference in profitability between B2S1_mix and B2S1_TFB. While they both had a 66% birch proportion after PCT, the B2S1_TFB became the most profitable mixed stand, whereas the opposite can be said for the B2S1_mix.

Fahlvik et al. (2011) reported over 30% decrease in NPV for N.spruce-birch stands with 50% birch proportion compared to N.spruce monoculture, but such significant differences were not observed in this study. The LEV of the N.spruce monoculture was only 10% higher than the birch-dominated stand, B2S1_mix (Fig. 4). Although the diameter at breast height (dbh), timber, and pulpwood proportions for birch and N.spruce were not analyzed in this study, the growth and economic outcome of the mixed stands suggest that birch was growing favorably in the mixture.

4.2 Management Implications and Recommendations

The findings from this study suggest different pathways for managing mature N.spruce-birch stands. One way is to start with a high birch density after PCT, B2S1. Subsequently, commercial thinning should focus on retaining dominant and co-dominant trees regardless of tree species (_TFB thinning). To this effect, the high preference for N.spruce needs reconsideration. Other viable alternatives involve starting with a low birch proportion after PCT, B1S2, and applying either _TFB or _mix thinning. These three management alternatives (B2S1_TFB, B1S2_TFB, B1S2_mix) provided the same or better growth, higher income, and increased tree species diversity than the N.spruce monoculture. The B2S1_TFB might be the more attractive option because starting with a high initial birch proportion could improve stand stability and reduce the risk of bark beetle attack (Huuskonen et al., 2021). A high initial birch density also increases the possibility of keeping birch in the mixture. It is generally better to reduce birch proportion (to 30% or less) further along the rotation to avoid trade-offs between stand productivity and species diversity. One could argue that such N.spruce-birch stands would have more than 65% basal area of N.spruce; thus, they do not meet the description of mixed forests provided by the Swedish NFI. However, the reported growth reduction associated with increasing birch proportion calls for a threshold review for this specific mixture type.

Starting with a high N.spruce density and afterward harvesting it during PCT, as was done in the experiment, is unattractive from a practical and economic point of view; the forest owner is not likely to make this decision. However, such intervention was necessary since the aim is to keep N.spruce-birch stands over the rotation. A more practical option is to plant N.spruce at a lower density and rely on abundant natural regeneration of birch, Holmstrom et al. (2016b) found this to be a viable pathway. The success of this regeneration method will depend on at least two factors. First, the natural regeneration potential of birch on a specific site, which is influenced by distance to the seed source, scarification method, soil moisture, and the extent of soil disturbance (Holmstrom et al., 2016a). The continued practice of retention forestry and the promotion of mixed forests on a landscape level may provide adequate seed trees to establish new N.spruce-birch stands. Secondly, the survival rate of planted N.spruce; low-density planting may allow the possibility of using improved planting material, which is in limited supply (U. Nilsson 2022, personal communication, 11 April). Taking advantage of birch natural regeneration and planting N.spruce at low-density results in lower establishment costs than N.spruce monoculture (Table 3). This reduced payment at the beginning of the rotation has a far-reaching effect on the economic outcome of the final stand especially at high interest rates (Table 5). However, if natural regeneration is unsuccessful, the stands will develop into a low-density N.spruce monoculture. This means future economic losses without improvement in biodiversity.

N.spruce-birch stands could have been more profitable than the estimates in this study if there was a substantial market for birch timber in Sweden. Birch logs were sold as pulpwood, while a higher income was obtained from the sale of N.spruce timber at final felling. This market gap presents future opportunities but is currently another drawback to the management of N.spruce-birch stands. Given that birch was sold only as pulpwood, the average rotation age of birch monoculture (53 years) (Fig. 5) is rather long, and this may negatively impact pulpwood qualities. The relatively long rotation is due to the use of thinning guidelines reported by Hynynen et al. (2010) for birch stands in this study, the guidelines are suited to Finnish conditions. Birch timber market exists in Finland thus, at least two commercial thinning are carried out to improve timber qualities which increase the rotation length. All the stands in this study were established on highly fertile sites (G30 - G36) (Table 1), which improves productivity. Hence, it is expected that growth will be slower, and profitability reduced on poor/medium fertile sites. Also, birch basal area may be higher in N.spruce-birch stands growing on less productive sites. Eko et al. (2008) noted that the yield of N.spruce increases compared to birch with an increasing site index.

Active management of N.spruce-birch stands will increase the area of mixed forests and the share of broadleaves in the boreal biome and Northern Europe in general. We can also expect better light conditions in the understorey leading to increased species diversity and richness. A caveat is that N.spruce-birch stands should be managed to a similar density as N.spruce monoculture, as we have done in this study. Hedwall et al. (2019) noted the importance of stand density on understorey vegetation. Overall, browsing pressure still poses a challenge to managing young N.spruce-birch stands (Månsson et al., 2007), as birch height can be significantly affected (Holmstrom et al., 2016b; Bergquist et al., 2009), which hampers the competitiveness of the species in the mixture.

4.3 Study Limitation and Future Research

This thesis was a simulation study; although models used in Heureka are constructed based on data from practical forestry and field trials in Sweden, these models may not account for stochastic events. Therefore, results from long-term experiments like the one used as input data in this study will be vital. Apart from the variables analyzed here, we could also look at the dbh classes, volume, timber assortment proportions for individual species, and height difference at final felling.

These variables would have provided a better understanding of birch performance in the mixture. The result from the stand with a high initial proportion of birch, B2S1_TFB, should be further investigated on sites with different fertility and soil conditions. Such research together with the findings in this study will provide valuable insights leading to the development of silvicultural guidelines for N.spruce-birch stands in southern Sweden.

5. Conclusion

This thesis analyzed the growth and profitability (**r** 2.5%) of N.spruce-birch stands with varying species proportion (B2S1, B1S2) in comparison with N.spruce (S) and birch (B) monoculture using different thinning strategies (_mix, _TFB, and _mono). In comparison with N.spruce monoculture, growth and economy were found to be the same or even better in N.spruce-birch stands with (30% or less) birch proportion at final felling. The finding above indicates the need to reduce birch basal area further along the rotation. Thinning from below without preference for tree species (_TFB) was the most effective strategy for managing N.spruce-birch stands to improve growth and economy, exemplified by the B2S1_TFB and B1S2_TFB stands. The initial birch proportion was preserved only in the birch-dominated stand, B2S1_mix, leading to trade-offs between species diversity and stand productivity. Although we also prioritized initial species proportion in the B1S2_mix, it remained competitive compared to S_mono, B2S1_TFB and B1S2_TFB stands. Birch monoculture was the least productive and economic option. All N.spruce-birch stands exceed the minimum requirement of broadleaves presence to be included in production forests according to the FSC certification rules for southern Sweden. Benefits of managing N.spruce-birch stands include but are not limited to lower establishment cost, higher biodiversity, improved stability, and increased recreational values. The findings in this study provide valuable insights for managing N.spruce-birch stands through commercial thinning, which is an important step toward developing silvicultural guidelines for this specific mixture in southern Sweden.

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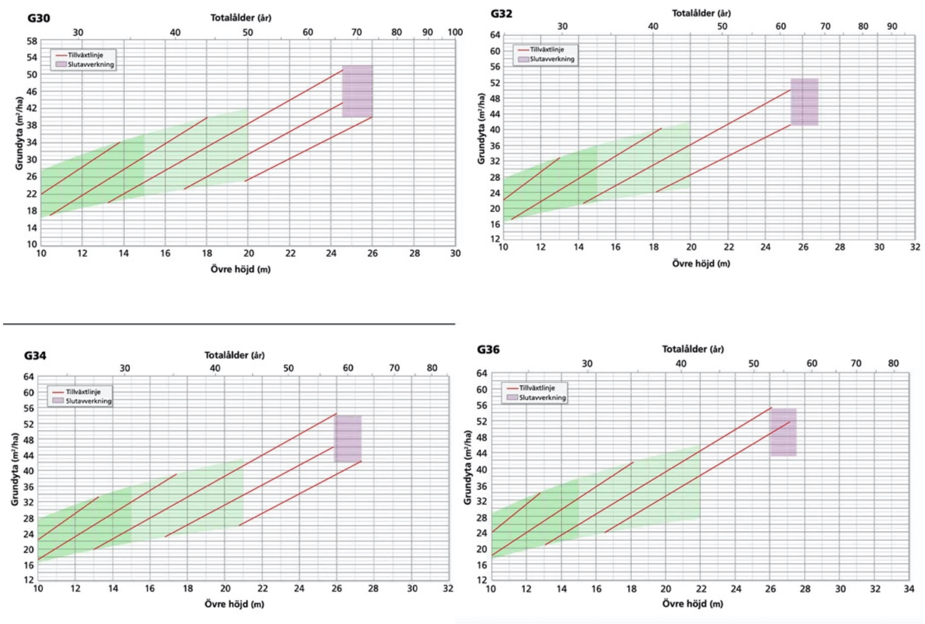
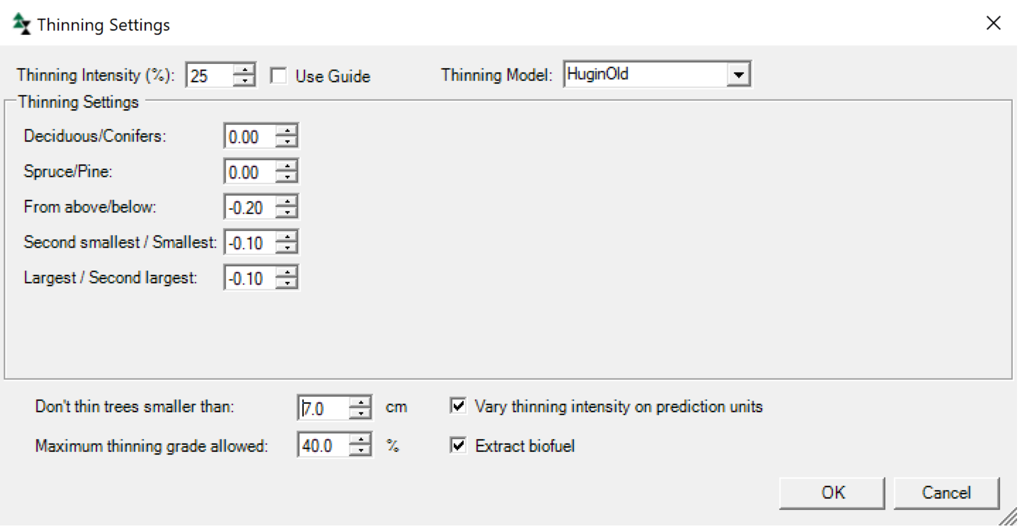
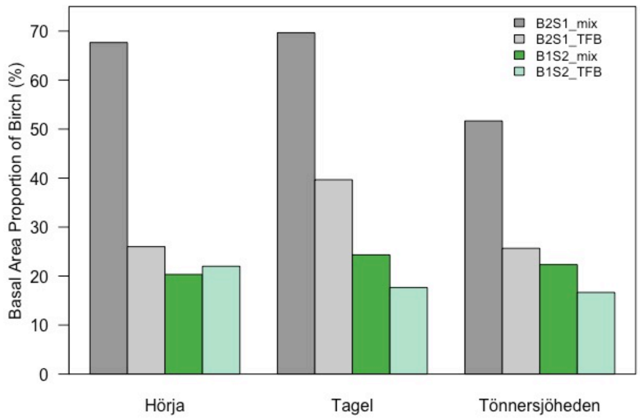
Appendix



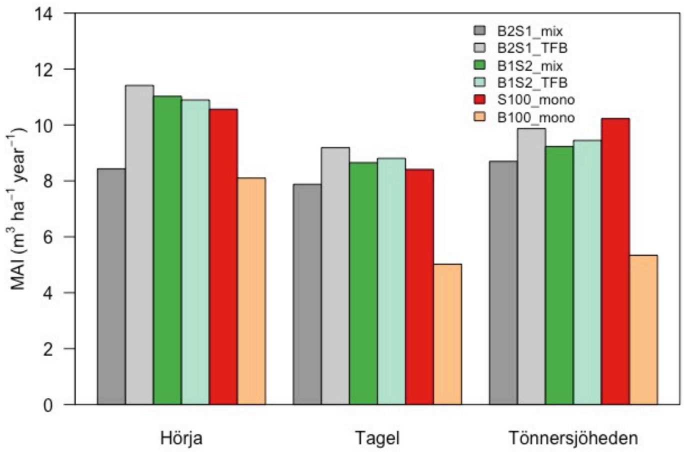
Supplementary Figure 1. Thinning guidelines by SODRA for G28 – G36 sites



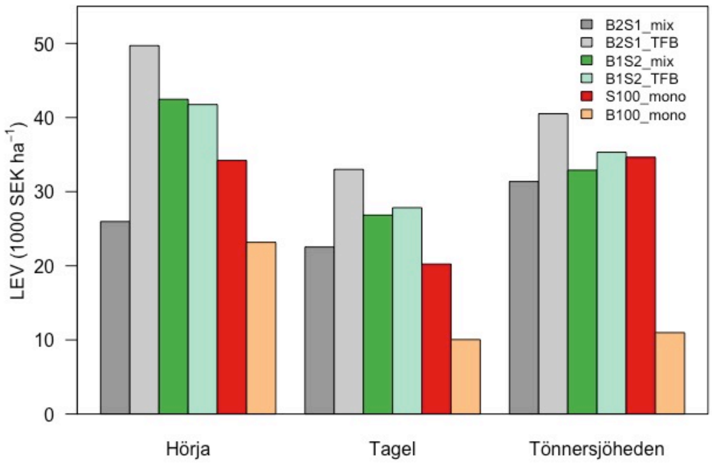
Supplementary Figure 2. The HuginOld thinning model and thinning setting used in Heureka simulations to achieve the three thinning treatments _mix, _TFB and _mono. The _mix and _TFB were applied to N.spruce-birch stands while _mono was applied to birch and N.spruce monoculture.



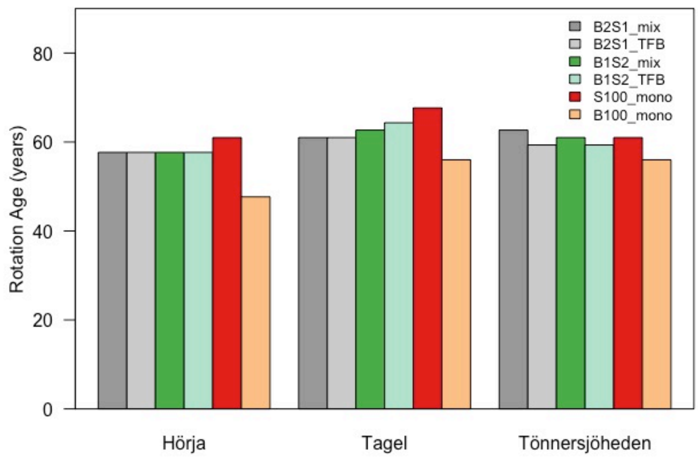
Supplementary Figure 3. Basal area proportion of birch (%) at final felling for the two thinning treatments _mix and _TFB simulated in Heureka. The treatments were applied in birch dominated (B2S1) and N.spruce dominated (B1S2) stands. Thinning in _mix prioritized initial species proportion while in _TFB, the smallest trees are removed regardless of the species.



Supplementary Figure 4. Maximum mean annual increment (m^{3}ha^{-1}year^{-1}) for the three thinning treatments _mix, _TFB and _mono simulated in Heureka. The _mix and _TFB treatments were applied in birch dominated (B2S1) and N.spruce dominated (B1S2) stands while the _mono was applied in N.spruce (S) and Birch (B) monocultures. Thinning in (_mix) prioritized initial species proportion, in (_TFB), the smallest trees were removed regardless of the species and in (_mono) pure N.spruce and birch stands were created.



Supplementary Figure 5. Land expectation value (SKRha^{-1}) for the three thinning treatments _mix, _TFB and _mono simulated in Heureka at 2.5% interest rate. The _mix and _TFB treatments were applied in birch dominated (B2S1) and N.spruce dominated (B1S2) stands while the _mono was applied in N.spruce (S) and Birch (B) monocultures. Thinning in (_mix) prioritized initial species proportion, in (_TFB), the smallest trees were removed regardless of the species and in (_mono) pure N.spruce and birch stands were created.



Supplementary Figure 6. Rotation age (years) for the three thinning treatments _mix, _TFB and _mono simulated in Heureka. The _mix and _TFB treatments were applied in birch dominated (B2S1) and N.spruce dominated (B1S2) stands while the _mono was applied in N.spruce (S) and Birch (B) monocultures. Thinning in (_mix) prioritized initial species proportion, in (_TFB), the smallest trees were removed regardless of the species and in (_mono) pure N.spruce and birch stands were created.

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