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Thinning strategies impact the productivity, perpetuity and profitability of mixed stands

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ABSTRACT
In southern Sweden, there is possibility for growing spruce-birch mixed stands. However, the required knowledge to manage these stands effectively, i.e. optimal thinning strategies, is limited. Thus, we utilized data from young mixed-forest experiments in southern Sweden to simulate different thinning strategies. Moreover, we compared results from the mixed stands to spruce and birch monocultures. The regeneration was characterized by soil scarification, natural regeneration of birch and high-density planting of Norway spruce seedlings. Pre-commercial thinning (PCT) was carried out to create spruce-dominated mixed stands, birch-dominated mixed stands, and spruce and birch monocultures. The first commercial thinning strategy in the mixed stands was to retain the initial mixture proportions until final felling, while the other was thinning from below, which prioritized removal of the smallest trees of either species. At the end of the rotation, similar growth (9.6–10.2 m^3 ha^{-1} yr^{-1}) and better economy (ca. 13–28% more) was observed in spruce-dominated mixed stands compared to spruce monoculture. It was possible with the appropriate thinning strategy to maintain birch proportion in the mixed stand when the initial stand at PCT is birch-dominated. However, tradeoff exists between retaining a high birch basal area, sustaining productivity and obtaining a good economy.

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KEYWORDS
Spruce; birch; simulation; heureka; growth; economy

Introduction

Today, most of the regenerations in Sweden have the potential to become mixed forest stands (Drossler 2010; Fahlvik et al. 2015). In southern Sweden, the prevalent practice of soil scarification prior to planting of Norway spruce seedlings (*Picea abies* L.Karst) promotes natural regeneration of birch species (*Betula pendula* Roth and *Betula pubescens* Ehrh (Ara et al. 2022b; Ara et al. 2022a; Holmström et al. 2016a; Nilsson et al. 2006)). Thus, creating opportunities for establishing Norway spruce (hereafter named spruce) and birch mixed stands. Forest stewardship council (FSC) certification in Sweden provides an incentive to grow these mixed stands rather than conventional spruce monocultures, and hence, mature conifer stands need to be managed with the basal area comprising 5–10% broadleaves (FSC 2020). Furthermore, with the susceptibility of spruce monoculture to disturbances, such as windstorms (Ikonen et al. 2017; Schütz et al. 2006) and bark beetle attacks (Nardi et al. 2022; Marini et al. 2017; Seidl et al. 2007), there might be a need to seek forest management alternatives. Tree species diversification could be a good management option for risk reduction in production forests (Bravo-Oviedo et al. 2014; Seidl et al. 2014). Moreover, conifer forests with broadleaf admixture can be expected to deliver other vital ecosystem services (Huuskonen et al. 2021; Lindbladh et al. 2017; van der Plas et al. 2016; Felton et al. 2016; Jansson and Andrén 2012).

Expertise in the management of spruce monoculture stands is widespread within the boreal region due to long-term innovations in research and practice (Uotila 2017; Bergh et al. 2014; Niinimäki et al. 2012; Bergh et al. 2005). Conversely, knowledge about spruce-birch mixed stands is developing (Aldea et al. 2023; Agestam et al. 2006). Given the complexity of tree species interaction, uncertainty surrounds the silviculture of mixed boreal forests (Bravo-Oviedo et al. 2014; Puettmann et al. 2015; Pawson et al. 2013). There are no established silvicultural guidelines for spruce-birch mixed stands in Sweden. Current practice focuses on securing planted spruce and cutting naturally regenerated birch during pre-commercial thinning (PCT) and first commercial thinning (Fahlvik et al. 2015; Ara et al. 2022a; Holmström et al. 2021).

Early results from young mixed-species experiments in southern Sweden indicate similar yields in spruce-birch mixed stands and spruce monoculture (Fahlvik et al. 2011), while in south-eastern Norway, young mixed stands provided higher growth (Frivold and Frank 2010). Furthermore, stand density management is crucial to retaining the mixed stand until final felling, and birch sprout control is vital for sustaining young mixed stands' productivity (Holmström et al. 2016a). There is a general lack of mature spruce-birch

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This article has been corrected with minor changes. These changes do not impact the academic content of the article.

mixed stand experiments in Sweden. However, data from young stands have been used in simulation studies to evaluate the productivity, profitability and perpetuity of the mixed stands over a full rotation (Fahlvik et al. 2015; Ara et al. 2022a; Fahlvik et al. 2011; Dahlgren Lidman et al. 2021; Holmström et al. 2016b). In Sweden, the Heureka decision support system is widely used for growth simulations and the performance of its basal area growth models has been evaluated in general (Fahlvik et al. 2014) and specifically for mixed stands (Aldea et al. 2023).

Sustaining spruce-birch mixed stands until final felling requires planting spruce at lower densities (i.e. ≤1600 stems ha^{-1}) or removal of planted spruce in PCT (Ara et al. 2022a; Holmström et al. 2016b). In comparison with spruce monoculture, lower volume growth and yield have been reported for mature spruce-birch mixed stands (Dahlgren Lidman et al. 2021); and this effect increased with higher birch proportions (Fahlvik et al. 2015; Fahlvik et al. 2011). Ara et al. (2022b) observed marginal economic gains from growing spruce monocultures compared to mixed stands with equal stem proportions of spruce and birch. Meanwhile, Fahlvik et al. (2011) reported an inverse relationship between economy and birch proportion in spruce-birch mixed stands. Their research emphasizes the need to reduce birch proportions in mixed stands further in the rotation to have a comparable income with spruce monoculture.

Management priority in the highlighted studies above has been on applying the best PCT strategies for creating spruce-birch mixed stands, except for (Dahlgren Lidman et al. 2021). Although PCT is necessary for altering stand structure and creating spruce-birch mixed stands (Fahlvik et al. 2015; Ara et al. 2022b), active management may be required in mature stands to retain birch throughout the rotation (Holmström et al. 2016b; Holmström et al. 2021). Analysis of the Swedish National Forest Inventory (NFI) data showed a decline in birch basal area in spruce-birch mixed stands with increasing stand age and density (Holmström et al. 2021). Birch is a light-demanding pioneer species with fast growth in its early years, while spruce is a shade-tolerant late-successional species with slow initial growth (Frivold and Frank 2010). In the absence of a disturbance, i.e. thinning, the growth of spruce increases steadily, eventually outperforming birch (Huuskonen et al. 2022; Nilsson et al. 2012). Thus, it becomes imperative to find thinning strategies that ensure the perpetuity of spruce-birch mixed stand coupled with the provision of multiple ecosystem services.

Within this study, the mixed stands are single-storeyed stem-wise mixture of spruce and birch. The threshold for what is a mixture varies (Johansson 2003), the Swedish NFI describes a mixed stand as one where the basal area of the dominant species is not more than 65% (Drossler 2010) but another study in Fennoscandia used 75% as a limit for mixed stands (Lee et al. 2023).

The objective of this simulation study is to investigate the effect of different thinning strategies on the basal area proportion of birch (% birch BA), volume growth expressed as maximum mean annual increment (MAImax), and economy expressed as land-expectation value (LEV) of spruce-birch mixed stands at final felling and compare their outcomes with spruce and birch monocultures. We intend to provide answers to the following questions:

Can the spruce-birch mixed stands produce the same growth (MAImax) compared to spruce monoculture by finding optimal thinning strategies?

Is it possible with thinning to maintain birch basal area proportion (% birch BA) from first commercial thinning until final felling?

Are there significant economic losses by applying a thinning strategy that prioritizes the initial species proportion of birch in the mixed stands?

Materials and methods

Site and experimental design

The data used in this study is from mixed species trials established on three sites in southern Sweden namely Hörja (lat. 56.21°N, long. 13.59°E), Tagel (57.04°N, 14.40°E), and Tönnersjöheden (56.70°N, 13.11°E) (Figure 1). All sites are of high productivity with site index (SIH spruce 100 years, Elfving 2010) between 29.5 and 35.5 m (Table 1). Soil scarification was carried out on all sites, subsequently, genetically improved spruce seedlings were planted at a density of about 2000–3000 stems ha^{-1}, and abundant natural regeneration of birch was also present at the time of spruce planting (Holmström et al. 2016b).

The experimental treatments in the first PCT were to create four unique stands; monocultures of spruce (S) and birch (B), mixed stands with 66%birch and 33% spruce (B2S1) or 33% birch and 66% spruce (B1S2), defined by stem-number (Table 1). Three blocks were established on each site with the four treatments assigned randomly within each block (3 sites × 3 blocks × 4 treatments). Plot size of the treatments

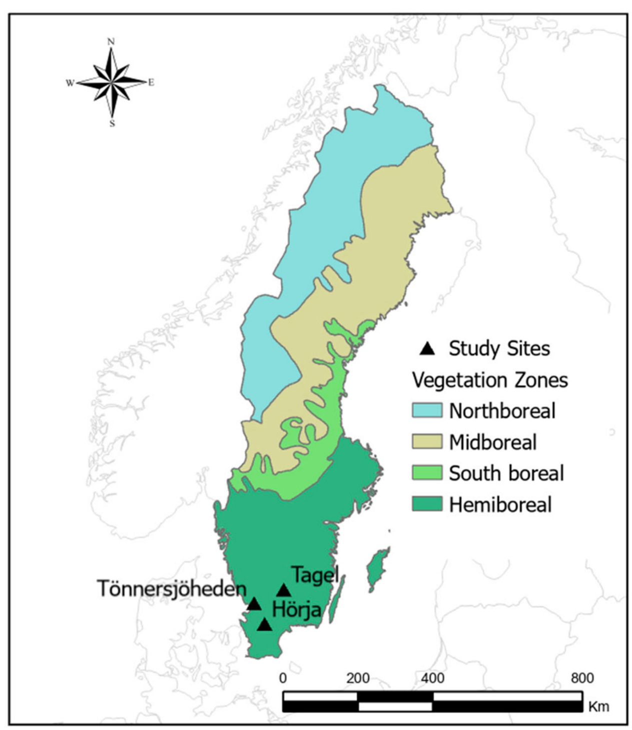

Figure 1. Map showing the three mixed species trial sites; Hörja, Tagel and Tönnersjöheden including vegetation zones in Sweden.

Table 1. Mean values for height (±sd), stand age, stand density (±sd) and site index (SIH spruce, 100 years) (±sd) for the mixed species trials in Hörja, Tagel and Tönnersjöheden based on revisions in 2020/2021. The treatments are spruce monoculture (S), birch monoculture (B), 66% birch, 33% spruce (B2S1), 33% birch, 66% spruce (B1S2).

Site	Treatment	Height (m)		Stand Age (years)	Density (stem ha^{-1})	Site Index (m)
		Birch	Spruce			
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

varied between 800 and 2500 m^2. PCT was carried out when spruce reached an average height of about 2 m. Tree height and diameter were recorded in all plots directly after PCT and two and four years after PCT. Input data in our simulation is from the measurements taken four years after PCT, which was carried out in 2020–2021. For the mixed treatments B2S1 and B1S2, the height of birch four years after PCT was the same or higher than spruce (between 0 and 1.6 m) in Hörja and Tagel, while in Tönnersjöheden, spruce had a slight height advantage ranging from 0.1 to 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 an average of 4370 stems ha^{-1} (Table 1). The stand age in Hörja, Tönnersjöheden and Tagel were 11, 14 and 16 years, respectively, at the beginning of the simulations.

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, and the system is composed of basal area growth models, height, ingrowth and mortality functions, and habitat suitability models (Wikström et al. 2011). Input data for simulations require site (altitude, latitude, site index, vegetation type), stand (age, density, management history), and tree level (diameter, height, tree species) information. Heureka StandWise (version 2.18.1.0) was used in this study because it is built for analysis at the stand-level and because the StandWise software gives the user flexibility in timing of treatment for each stand to achieve the specified management objective.

Thinning strategies and simulations in StandWise

PCT, commercial thinning, and final felling were simulated in StandWise. A second PCT was simulated in most stands to remove birch stump sprouts that developed after the first PCT. Based on stem number; 66% of saplings were prioritized for the dominant species in B2S1 and B1S2 stands respectively while 100% birch and spruce were retained in the respective monocultures. The target stem density after PCT was 2000 stems ha^{-1} for all stands.

Two commercial thinning strategies were simulated in the birch (B2S1) and spruce-dominated (B1S2) mixed stands (Table 2). The first thinning strategy, named with the suffix "_mix", was designed to maintain the initial mixture proportions following the experimental design with varying thinning form (thinning from below or above) depending on tree-species stand-structure. The second strategy, "_TFB", did not prioritize the initial mixture proportions (Table 2). The difference between "_mix" and "_TFB" was that in the latter, thinning was done from below with no aim at retaining either birch or spruce. Thinning in the birch (B) and spruce (S) monocultures were done from below aimed at keeping pure stands (_mono), representing the business as-usual approach.

Commercial thinning was simulated following established guidelines. Birch monoculture (B_mono) was managed with the recommendations of Hynynen et al. (2009). Intensive first thinning was simulated at a dominant height between 13 and 15 m, while second thinning was performed 15 years later. SODRA thinning template was used in simulations for mixed stands (B2S1_mix, B1S2_mix, B2S1_TFB, and B1S2_TFB) and spruce monoculture (S_mono) (Figure A1). The first thinning was simulated at a dominant height between 13 and 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 22 m height; a risk of this late intervention in practical forestry is increased stand susceptibility to wind damage. Nevertheless, this late thinning simulation was necessary in some stands due to low basal area when dominant height was below 20 m. The guidelines by SODRA were created for even-aged monoculture of spruce, but it was employed here also for mixed stands due to the lack of thinning guidelines for spruce-birch stands.

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

Thinning Strategies	Stands	Description
_mix	B2S1_mix	Maintain 66% birch, 33% spruce
	B1S2_mix	Maintain 33% birch, 66% spruce
_TFB	B2S1_TFB	Thin the smallest trees
	B1S2_TFB	Thin the smallest trees
_mono	B_mono	Maintain 100% birch
	S_mono	Maintain 100% spruce

All four treatments (Table 1) within each block were regarded as a stand in the simulations, resulting in a total of 36 stands. Species proportion during commercial thinning was defined by basal area. A maximum of two thinnings was carried out in all stands. Thinning intensity varied between 25 and 35% of basal area, depending on the growth of the stand. When performing a thinning in Heureka, it is possible to favor the removal and retainment of birch or spruce by changing the Deciduous/Conifer settings of the HuginOld thinning model. 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, which ensures that thinning is equally weighted on birch and spruce. All stands were clear-felled at the end of the simulation which was defined as the age when land expectation value (LEV) reached its maximum.

Development of measured and projected heights

Height development from both measured data and Heureka projections was plotted for visual inspection before the start of thinning simulations (Figure 2). There was an overall good fit between measured and simulated heights and spruce tends to overtop birch towards mid-rotation.

Analyzed variables at final felling

Maximum mean annual increment (MAI_{max}). Mean annual increment shows the average growth of each stand up until a given year. This was calculated according to Equation (1), 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.

$$MAI = (V_s + \sum \cdot V_h)/\ t \qquad (1)$$

Basal area proportion of birch (%). Basal Area proportion of birch at the economic optimal rotation age was evaluated for spruce-birch stands to determine change in species proportion since the second PCT. This was calculated as percentage birch of the total BA at the end of the rotation (Equation (2)).

$$\text{Birch Proportion} = (\text{BA birch} \ / \ \text{Total BA}) \times 100 \qquad (2)$$

Land expectation value (LEV) and sensitivity analysis. LEV is one of the measures used in forestry to determine the optimal time for final harvest. The age when LEV is maximum is described as the economic optimal rotation age of a given stand (Straka and Bullard 1996). A reference interest rate of 2.5% was used in LEV calculation. Equation (3) shows 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

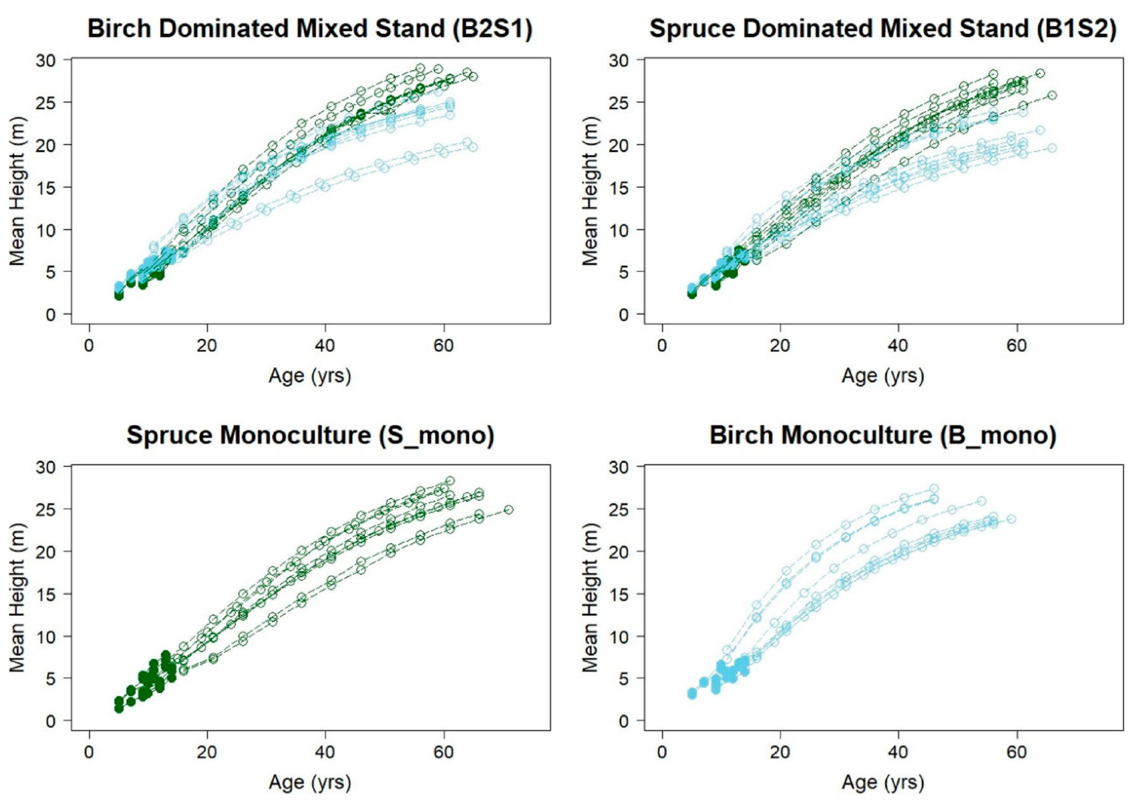

Figure 2. Mean stand height of treatment plots over time. Filled dots represent measured heights after PCT while open dots are height projections from Heureka's 5-year simulation periods. Dark curve is spruce, light curve is birch.

was simulated, and r is the interest rate.

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

The interest rate used in LEV calculations can determine which management alternative performs best economically. Thus, we did a sensitivity analysis based on interest rates of 1% and 4% to test if the economic ranking of management alternatives obtained by using r = 2.5% will change. Establishment cost varied between stands based on the number of spruce seedlings to be planted (5 SEK/seedling) as well as the cost of soil scarification and first PCT (4500 SEKha^{-1}). B_mono costs 4500 SEK ha^{-1} since natural regeneration of birch was only required while 14,500 SEKha^{-1} was invested in the S_mono with 2000 spruce stems ha^{-1} planted (Table 3). The birch dominated (B2S1_mix, B2S1_TFB) and spruce dominated mixed stands (B1S2_mix, B1S2_TFB) were planted with 600 and 1200 spruce seedlings respectively (Table 3). Heureka default values were used for timber assortment prices, harvesting, and cleaning costs.

Statistical analysis

The response variables, i.e. 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:

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

where m is the general mean, S_i is the effect of site, B_j is the effect of block, T_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 S_i and B_j were considered as random effects whereas T_k was considered as fixed effect. When S_i, B_j or T_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 and Williams 2010) with R package (emmeans). All tests were run in R software (R version 4.2.0). Results from the analysis are in the Appendix section (Table A1).

Results

Growth comparisons

Based on the full rotation simulations the mixed stands having lower proportion of birch (≤ 30%) at final felling, i.e. B1S2_mix, B1S2_TFB, B2S1_TFB, provided comparable growth to the spruce monoculture (Figure 3 and Table 4).

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

Stands	Planting Cost (SEK ha^{-1})	Total Cost (SEK ha^{-1})
B_mono	0 (0)	4500
S_mono	10,000 (2000)	14,500
B2S1_mix, B2S1_TFB	3000 (600)	7500
B1S2_mix, B1S2_TFB	6000 (1200)	10,500

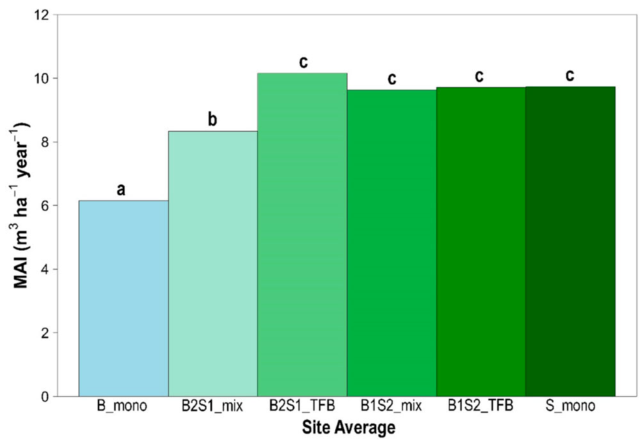

Figure 3. Maximum mean annual increment (m^3 ha^{-1} year^{-1}) for the three thinning treatments _mix, _TFB and _mono simulated in Heureka. The _mix and _TFB treatments were applied in birch dominated (B2S1) and spruce dominated (B1S2) stands while the _mono was applied in spruce (S) and birch (B) monocultures.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

Only the birch dominated mixture, B2S1_mix, had significantly lower MAI_{max}. (14% lower compared to spruce monoculture). In comparison with birch monoculture (B_mono), all other stands had significantly better growth.

Within the mixtures, the birch dominated stand, B2S1_mix, where high birch proportions (63%) was maintained until final felling had a significantly lower growth than spruce dominated stands (Figure 3). The best growth performance (10.2 m^3 ha^{-1} yr^{-1}) was recorded in the B2S1_TFB stand, which was initially birch dominated but it did not differ significantly from other spruce dominated mixed stands (B1S2_mix and B1S2_TFB).

A high proportion of birch (>60%) caused significant reduction in stand growth as indicated in the B_mono and B2S1_mix stands (Figure 3 and Table 4). The decision to maintain the initial birch proportions (33%) in spruce dominated, B1S2_mix stands, did not have a negative effect on growth.

Birch proportions in the mixed stands

It was only possible to maintain a high birch proportion until the end of the rotation by thinning out competing spruce B2S1_mix (Table 4). The B2S1_mix stand had a significantly higher birch proportion than the B2S1_TFB stand, even though they were both birch dominated mixed stands at the start of our simulations. Thinning from below in

Table 4. Stand basal area (m^{2}ha^{-1}) and proportion of birch (%) in the mixed stands at final felling. B2S1 represents initially birch dominated stands while B1S2 is initially spruce dominated stand. The _mix thinning is a simulation where the initial species proportion was prioritized, _TFB was simulated to remove small trees of either species in the mixture. Values in parenthesis represent significant differences.

Stands	Basal Area (m^2 ha^{-1})	Birch Proportion (%)
B2S1_mix	32.8 ± 2.2	63 (c)
B2S1_TFB	38.7 ± 2.7	30 (b)
B1S2_mix	37.7 ± 2.8	22 (ab)
B1S2_TFB	37.4 ± 2.9	19 (a)

B2S1_TFB reduced birch proportion by 52%, thus creating a spruce dominated stand at final felling.

For spruce dominated stands B1S2_mix and B1S2_TFB, birch proportion did not vary much between the simulation strategies (Table 4). In both, the proportion of birch was lower than the initial state, and thinning interventions made in the B1S2_mix were not sufficient to maintain initial birch proportion (33%) until final felling.

The "_mix" thinning treatment was most effective in the B2S1_mix stand, where 63% birch was maintained until final felling while the biggest shift in species proportion is noted in the B2S1_TFB, which started as a birch dominated stand but ended as a spruce-dominated stand. We ended up with three spruce dominated mixed stands at final felling (B1S2_mix, B1S2_TFB and B2S1_TFB) and one birch dominated mixed stand (B2S1_mix). Notably, it was possible to keep birch in all the spruce-birch mixed stands at varying proportions regardless of the thinning treatment.

Economic outcomes

Maintaining high birch proportions, led to substantial economic loss. The B2S1_mix had a significantly lower LEV than B2S1_TFB, B1S2_mix, and B1S2_TFB stands (Figure 4). The largest difference in economic performance was found between B2S1_mix and B2S1_TFB, with the latter having a 35% higher LEV. The average rotation age based on maximum LEV was 60 years for all mixed stands and spruce monoculture (Figure 5).

The B2S1_mix was competitive when compared with the S_mono. Although a higher LEV was obtained for the spruce monoculture, the difference was small and not significant (Figure 4). The economy of the spruce dominated mixed stands, B1S2_TFB and B1S2_mix, was slightly higher than the S_mono but the difference was not significant. LEV of B2S1_TFB was significantly higher (28%) 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 were significantly improved. Even with lower establishment cost, the B_mono provided significantly lower economy than all other stands and the rotation length was also shorter (Figure 5).

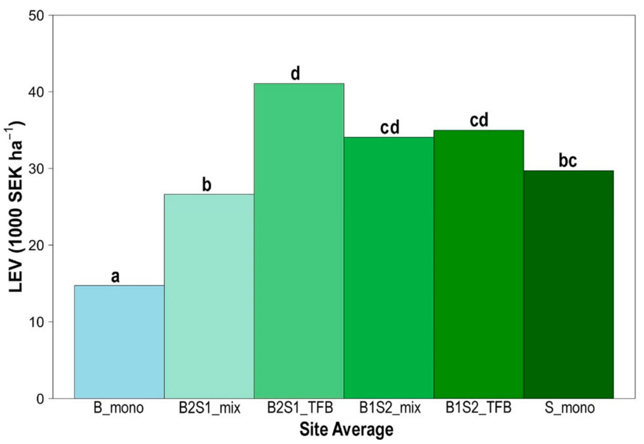

Figure 4. Land expectation value (SEK ha^{-1}) for the three thinning treatments _mix, _TFB and _mono simulated in Heureka at 2.5% interest rate. The _mix and _TFB treatments were applied in birch dominated (B2S1) and spruce dominated (B1S2) stands while the _mono was applied in spruce (S) and birch (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 spruce and birch stands were created.

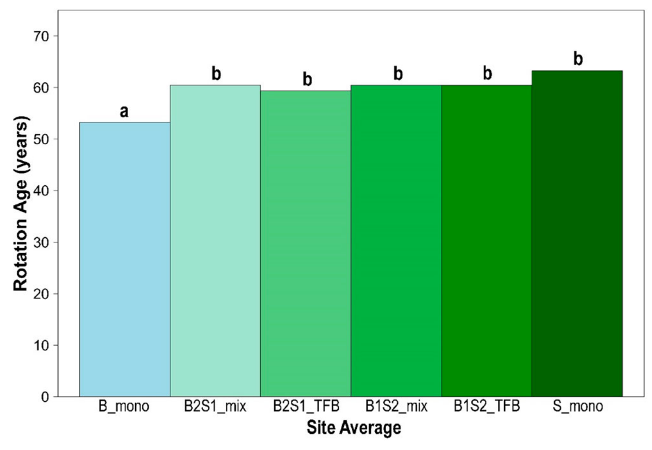

Figure 5. Rotation age (years) for the three thinning treatments _mix, _TFB and _mono simulated in Heureka. The _mix and _TFB treatments were applied in birch dominated (B2S1) and spruce dominated (B1S2) stands while the _mono was applied in spruce (S) and birch (B) monocultures. The significant difference 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 spruce and birch stands were created.

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 lower interest rate of 1% (Table 5). However, at an interest rate of 4%, the spruce monoculture (S_mono) was less profitable than the birch monoculture (B_mono) and all spruce-birch mixed stands.

Discussion

Overall, the growth performance of spruce dominated mixed stands were comparable with spruce monoculture. However, it was not possible to maintain a high birch proportion in the mixed stands while sustaining growth and profitability. Moreover, birch monoculture had the least growth and lowest economy.

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 spruce dominated while S and B are monocultures of 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 spruce and birch stands were created.

Stands	LEV (SEK ha^{-1})		
	1%	2.5%	4%
B2S1_mix	129,753	26,617	6210
B2S1_TFB	189,428	41,070	11,656
B1S2_mix	172,386	34,063	6768
B1S2_TFB	175,836	34,971	7187
S_mono	172,049	29,701	2329
B_mono	71,353	14,728	3411

MAI and thinning strategies

At the end of the rotation, there was only a statistically significant difference in volume growth between the birch dominated mixed stand, spruce monoculture and birch monoculture; whereas, MAI in spruce dominated mixed stands was comparable to the spruce monoculture. Conversely, in a previous simulation study by Fahlvik et al. (2011), the mean annual increment of spruce monoculture was found to be higher than all spruce-birch mixed stands. However, in line with our findings, they noted that reducing birch proportion over time increased volume growth in the mixed stands. Fahlvik et al. (2015) observed higher growth in spruce monoculture than in spruce-pine-birch mixed stands. Notably, their results showed that mixed plots with a birch proportion lower than 25% provided similar growth to the spruce monoculture, while plots with a higher birch proportion accounted for the reduced growth. Dahlgren Lidman et al. (2021) reported lower yields in spruce-birch mixed stands compared to planted spruce monoculture, but the mixed stand in their simulation study was composed of naturally regenerated spruce and birch.

Thinning from below increased production in birch dominated mixed stands compared to thinnings aiming at retaining the initial species proportions. Consequently, a good management option for maintaining the growth of spruce-birch mixed stands is to thin out smaller trees of both species (_TFB). The positive effect of this thinning strategy on stand growth is obvious from the difference in stand productivity between B2S1_TFB and B2S1_mix (Figure 3). In the latter, the _mix thinning strategy was focused on maintaining the initially high birch proportions, which meant removing better performing spruce trees to favor less competitive birch trees. However, applying the _mix thinning strategy in spruce dominated mixed stands (B1S2_mix), did not have a negative impact on growth. Thus, retaining birch when its basal area proportion in the mixed stand is low (≤30%), is also a good management option.

Retaining birch proportions

Based on the results, the possibility of maintaining birch proportion in the spruce-birch mixed stands is largely dependent on the species composition before thinning. In the birch dominated stand, the high initial birch proportion was retained. Whereas, birch declined in the spruce dominated mixed stand. It is generally better to reduce birch proportion further along the rotation to avoid tradeoffs between productivity and species diversity at the stand level. If the aim is to promote spruce-birch mixed stand over a full rotation, planting spruce at higher densities might be unsuitable. An earlier study by Holmström et al. (2016b) noted the tendency for high-density spruce-birch mixed stands growing on productive sites to evolve into spruce monoculture. One reason for planting spruce at relatively high densities might be the need to secure the future stand in the case of unsuccessful birch natural regeneration. Nevertheless, given the right conditions, birch natural regeneration is usually abundant in southern Sweden (Ara et al. 2022b; Ara et al. 2022a; Nilsson et al. 2006). The regeneration study by Holmström et al. (2016a) gives insight into the factors influencing natural regeneration potential of birch, i.e. distance to seed source, soil scarification method, soil moisture and the extent of soil disturbance. Even when the intention is to promote spruce monocultures in the establishment phase, studies have shown that young forests evolve into spruce dominated mixed stands with a broadleaf admixture (mostly birch) (Ara et al. 2021; Holmström et al. 2019). Thus, the potential for growing spruce-birch mixed stands exists.

Economy

There is a clear tradeoff between having a good economy and retaining high basal area of naturally regenerated birch. LEV of birch dominated stands was much lower than spruce dominated stands. In our economic calculations, birch is only sold as pulpwood while spruce is sold as timber at a higher price which impacts revenue of birch dominated mixed stands. Nevertheless, the birch dominated stand is the only mixture that meets the criteria set by the Swedish NFI regarding what is considered a mixed stand. Notably, all mixed stands meet the minimum criteria set by the FSC, that conifer stands should be managed with at least 5–10% basal area of broadleaves. The spruce monoculture was more profitable than the birch monoculture (Figure 4). The poor economy from the pure birch stands could be attributed to lower growth performance of naturally occurring birch compared to genetically improved spruce seedlings. The better economic performance of spruce dominated mixed stands in this study is in contrast with previous findings where spruce monoculture had the same or slightly better LEV (Ara et al. 2022a) and much higher net present value (NPV) (Fahlvik et al. 2011). In the establishment costs, we take into account that mixed stands will be planted with lower number of spruce seedlings compared to spruce monoculture, which positively impacted the economy of the mixed stands.

Conclusions

This study shows that with an appropriate thinning strategy, and the intention to establish mixtures from the beginning of the rotation, it is possible to grow productive and profitable spruce-birch mixed stands over a full rotation. However, birch proportion in the mixed stands needs to be reduced further along the rotation to minimize tradeoffs between productivity, profitability and tree species diversity. Thus, we provide alternative management options to spruce monoculture on sites having the potential for successful natural regeneration of birch in southern Sweden.

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Data availability statement

The data used in this study is open access and can be found on www.silvaboreal.com. The unique ID for Hörja is 13,736, Tagel is 10,491 and Tönnersjöheden 8257, 8261, 8262.

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Appendix

Table A1. 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

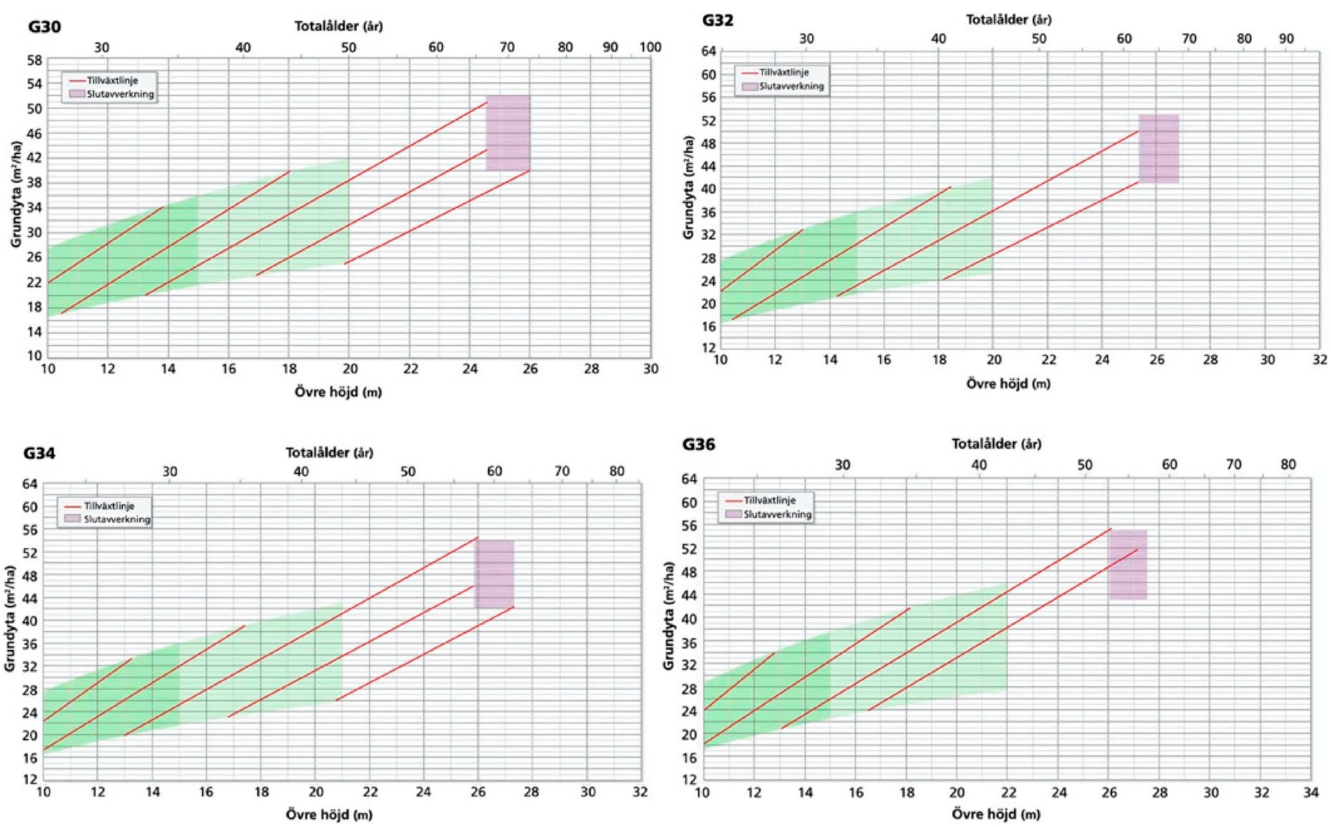

Figure A1. Thinning guidelines by SODRA for G28 – G36 sites.