Growth of Silver birch (*Betula pendula*) & Downy birch (*Betula pubescens*) established in four different initial densities on one site in central Sweden

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Abstract

Nowadays, there is an increased demand for timber resources and more sustainable forest management, starting from the establishment phase of the forest, e.g., planting. Depending on the management goals, number of seedlings planted and thus initial spacing can be adjusted in order not to waste resources. However, there is very little existing knowledge on how different initial spacing arrangements in both Silver birch (*Betula pendula*) and Downy birch (*Betula pubescens*) would affect the further development of a stand, with this study being one of the few that comprises such a research question.

The main objective of this study was to test different initial square spacings in Silver birch and Downy birch stands and compare their growth dynamics and long-term production. Long-term production of the different treatments was assessed by using the new basal area functions developed for genetically improved birch. In addition, an economic assessment of full rotation projections was done based on standard management. To do the above-mentioned analysis, long-term observational data was compiled, and additional data collected from one growth trial located in central Sweden, in which both birch species were planted in four different square spacings. Besides the above-mentioned simulations, statistical analyses (one-way Anova) were carried out to test the effect of initial spacing on different growth parameters.

Statistical analysis revealed that initial spacing had a significant effect on diameter development and height of the living crown for both species and Gini index for Downy birch. Full rotation simulations revealed that the best results in terms of production/economy for both species were achieved from initial spacing of 1.8x1.8 m. The optimal rotation of the 1.8 x 1.8 m treatment was determined to be 48 years for Silver birch and 49 years Downy birch for timber and pulpwood as the main goal respectively. An evident observation that was not tested was the superior growth of Silver birch compared to its counterpart – Downy birch, which was also reflected in the considerably higher production/growth (MAI) (7.13 m^3 ha^{-1} $year^{-1}$ to 6.63 m^3 ha^{-1} $year^{-1}$) and better economy (LEV for timber), 34077 SEK compared to 26576 SEK.

Keywords: Betula pendula, *Betula pubescens*, plantation, initial spacing, simulation, management.

Table of contents

List of tables

List of figures

Abbreviations

AMD	Arithmetic mean diameter
BA	Basal area
DBH	Diameter at breast-height
H	Height
Hdom	Dominant height
HLC	Height of the living crown
LEV	Land expectation value
MAI	Mean annual increment
NPV	Net present value
PCT	Pre-commercial thinning
QMD	Quadratic mean diameter
SEK	Swedish krona
V	Volume

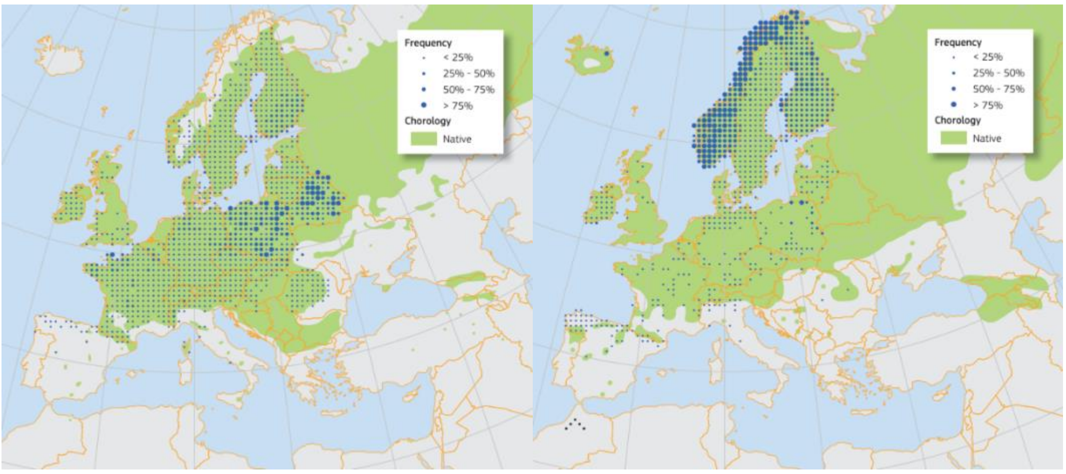
Introduction

1.1 Birch: Distribution, habitat, characteristics

Silver birch (*Betula pendula*) and Downy birch (*Betula pubescens*) are two closely related species of deciduous trees that are widely distributed throughout parts of North America and Eurasia. Both are pioneer species commonly known as birch trees. They are valued for their rapid growth, attractive bark, and ecological benefits (Beck et al., 2016; Dubois et al., 2020).

Silver birch, also known as the Warty birch, is a slender tree with distinctive white bark that peels in papery strips. It is native to Europe (Fig. 1a) and parts of Asia and is often found in open woodlands, heaths, and other well-drained habitats. The tree can grow tall and has a broad, pyramid-shaped crown. Silver birch is known for its graceful appearance and is often used in landscaping and ornamental gardens (Beck et al., 2016; Hynynen et al., 2010).

Downy birch, also known as the Moor birch or White birch is a shorter and more compact tree than Silver birch. It is native to northern Europe (Fig. 1b) and parts of Asia and is commonly found in wetlands, bogs, and other moist habitats. Unlike Silver birch, the bark of Downy birch is dark and fissured, and its leaves are hairy and more rounded. Downy birch is an important source of timber and is often used for making furniture, paper, and other products (Beck et al., 2016; Hynynen et al., 2010).



a) b)

Figure 1. Map of Silver birch (a) and Downy birch (b) distribution and frequency in Europe (Beck et al., 2016).

While Silver birch and Downy birch have slightly different distributions and habitats, they are both ecologically and economically important species in their respective regions. Both trees also have cultural and symbolic significance, with Silver birch often associated with purity and renewal, and Downy birch with resilience and adaptability. Both species have several shared characteristics. They are early succession trees due to their abundant seed production and dispersal, adaptability to a range of soil types and shade intolerance. In addition, both species are also known for their ability to grow in places where no other tree would grow (Beck et al., 2016; Niemste et al., 2008).

In Sweden, Silver birch and Downy birch are important species in the country's forest ecosystem. The popularity of these trees is growing due to the possibility to have improved planting stock from breeding programmes, thus economic importance could also be on the rise, but the lack of the whole supply chain starting from seed production to operational sawmills limits the popularity among forest owners. In Sweden, the two species are often found growing together in mixed species stands, with Downy birch being more common in northern Sweden and Silver birch being more common in southern Sweden (Liziniewicz et al., 2022).

1.2 Growth

The growth of Silver birch and Downy birch is influenced by various environmental factors, such as soil moisture, temperature, and nutrient availability. For example, Silver birch has been found to have higher diameter growth in well-drained soils, while Downy birch has higher growth rates in wetter soils (Niemste et al., 2008).

Silver birch and Downy birch are both fast-growing deciduous trees that can reach a height of up to 20-30 meters. Both species have a typical growth pattern characteristic of broadleaved trees. Owing to their rapid growth, on good fertility sites the trees can reach 25 m in height in 30 years while on poor fertility sites, it plummets to around 6 m in 30 years (Cameron, 1996).

In an optimally managed monoculture birch can reach the height growth culmination at an age of 10-20 years, whereas volume culminates ca 5 years later. The relatively fast growth continues until the age of 40-50, thereafter it declines similarly for height and volume. Diameter growth can reach up to 3-4 mm in fertile growing conditions/fertile sites, however, diameter growth is under a strong influence of initial stand density and the subsequent stand management (Bērziņa et al., 2018; Hynynen et al., 2010).

In Scandinavian operational forestry, the rotation age of birch stands normally is around 30-60 years. In the wild, birch trees can reach up to an age of 90 (100) years. However, this is well beyond the species growth climax as well as at this age birch trees are significantly more susceptible to decay and fungi (Bērziņa et al., 2018).

Both Silver birch and Downy birch are adaptable and can grow in a range of soil types, including sandy, loamy, and clay soils. However, both species prefer well-drained soils and can suffer from waterlogging or drought stress if the soil is too wet or too dry respectively (Hynynen et al., 2010).

1.3 Establishment and management

Thorough care of a stand during the establishment phase is important to enhance the growth and survival of the newly planted seedlings as well as secure a potentially better future development of a stand as a whole. Common practices of the aforementioned include among other things proper soil preparation (depending on the site properties), correct choice of the planting stock (for better growth), and quality planting. Additional silvicultural treatments like weed control, fencing and fertilization can be done to increase the success rate of seedlings reaching the post-establishment phase (Dubois et al., 2020; Hynynen et al., 2010; Niemste et al., 2008).

Natural regeneration of birch is a popular, easy, and cheap method to establish a birch stand owing to birch being a pioneer species. When successfully regenerated, natural birch stands normally are dense (~10000 seedlings per ha), which improves the tree's technical quality as well as in case of a disturbance occurs, there are enough trees left in the stand to choose from. However, pre-commercial thinning cost at age 6 would be significantly higher due to large removal to reach around

1600-2500 seedlings per ha. This method is not ideal to afforest former agricultural land. Planting of birch might be more expensive, but it allows to use genetically superior planting material obtained from breeding programmes. Use of genetically improved material outweighs the high regeneration costs, owing to superior growth and better tree physical qualities of improved birch. Finally, yet importantly, is the choice of a proper planting design (e.g., initial density and special arrangement of the seedlings) which most often is going to be a choice based on the forest management goals (Hynynen et al., 2010; Liziniewicz et al., 2022; Niemste et al., 2008).

In terms of management, thinning and pruning can be done to improve the growth and health of the remaining birch trees. Thinning involves removing some of the trees to reduce competition and promote growth, while pruning can help shape the tree and remove any damaged or diseased branches while also increasing potential future quality. To reach the desired goal appropriate thinning regime is required depending on the stand density (Hynynen et al., 2010; Niemste et al., 2008).

1.3.1 Initial planting density

The planting density of Silver birch and Downy birch can have a significant impact on tree growth, survival, and stand development. The optimal planting density depends on several factors, including site conditions, management objectives, and tree characteristics.

In general, higher planting densities can result in higher total production and better quality, because the branches stay small and natural pruning is high and early. But it may also increase competition for resources such as water, nutrients, and light, thus affecting tree vitality. Keeping the stand dense is only necessary until the first 5-6 metres are branchless to gain higher quality (Niemste et al., 2008).

Moreover, high-density stands fill the available growing space faster, leading to earlier competition between tree crowns. Reduction of a tree´s crown would also lead to a reduction of the tree’s leaf area or in other words, it would lead to a reduction of foliage area that absorbs solar radiation, thus slowing down growth (Goude, 2021). As a rule of thumb, a tree´s live part of the crown should be 50% of the tree´s height, thereby sustaining optimal growth. To maintain trees´ crowns to an appropriate height, suitable thinning regime is necessary (Niemste et al., 2008).

In less dense plantations, there are more available resources per tree, thus reducing competition and promoting better individual tree growth while also large spaces between plants will promote diameter growth. However, it may also result in lower early stand production and development (Hynynen et al., 2010; Niemste et al., 2008)

In 1995, Niemistö determined that at a stand density of 4000-5000 trees ha^{-1}, volume increment was the highest. At the same time, the highest diameter growth was recorded at densities of 1000 trees ha^{-1}. When taking into account both volume and diameter increments planting of 2500 trees ha^{-1} showed the best result as the golden mean (Niemistö, 1995).

In 2008, Niemste reported that the optimal planting density for Silver birch is 1600 trees ha^{-1} (square spacing of 2.5 m). According to the author, denser stands (>2000 trees ha^{-1}) would result in straighter stems and smaller branch diameters, however, an additional, late and expensive PCT would be required (Niemste et al., 2008).

Research conducted in Latvia argues that planting densities above 5000 trees ha^{-1} (Spacing > 1x1 m between seedlings and 2x2 m between rows) of birch is economically beneficial for energy production. However, when the management goal is high-quality timber production, birch should be planted at densities of 1500-3000 trees ha^{-1} (Daugaviete et al., 2017; Daugaviete et al., 2011; Liepiņš et al., 2013).

1.4 Competition and resources

Depending on the initial stand density the competition for resources such as water, nutrients, and light can significantly affect the growth and development of Silver birch and Downy birch. Understanding how these species compete for resources can help to avoid making suboptimal management decisions.

Competition for available water can be particularly important in areas with limited water availability, such as dry or drought-prone regions. Studies have shown that Silver birch and Downy birch can have different water use strategies, with Silver birch having a deeper root system and greater water uptake from deeper soil layers, while Downy birch relies more on surface soil moisture (Hytönen et al., 2014). This can affect how these species compete for water and their ability to withstand drought conditions.

Competition for nutrients is also important for Silver birch and Downy birch, as these species have different nutrient requirements and uptake strategies. For example, Silver birch is more efficient at taking up nitrogen from the soil, while Downy birch is better adapted to nutrient-poor soils (Beck et al., 2016; Hytönen et al., 2014). This can influence how these species compete for nutrients as well as their response to fertilization.

Available light and the competition for it is another important factor affecting the growth and development of Silver birch and Downy birch. These species have different light requirements, with Silver birch being more shade tolerant than Downy birch (Beck et al., 2016; Hynynen et al., 2010). This can influence how these species compete for light and their ability to establish and grow in different forest types.

1.5 Aims of the thesis

There is need to understand how initial spacing can influence birch growth and economic viability, which is important for optimizing forest management practices and decision making. This study provides the insights into relationship between initial spacing, tree growth, and economic prospects while addressing a significant aspect of managing birch stands in central Sweden. Research questions:

1. How does the initial spacing of Silver birch and Downy birch trees affect their growth parameters?

2. How do different initial spacings impact the long-term growth and economic outcomes for Silver birch and Downy birch?

The core of the thesis was to compare and evaluate the effect of initial spacing on the different growth parameters of Silver birch and Downy birch planted on one site in central Sweden. To compliment that, assessment of economy and growth of full stand rotations was done by simulating future outcomes. For the simulations standard birch management regime was used. Given this, the main aims were:

1. Compare growth between different initial spacing treatments for both Silver birch and Downy birch.

2. Simulate full rotation projections for both species and asses the long-term growth and economy of the different scenarios.

Materials and Methods

2.1 Study area

The experiment is located inland, in a village called Skäddarbo, Sala municipality, ca 90 km NW from Uppsala (Fig. 2). The experimental plots were established on agricultural land owned among the rest of the estate by a private landowner and was later named “Skräddarbo Lövskog”.

The area is located some distance away from the Baltic Sea, thus Sala region has a humid continental climate, but is also influenced by maritime winds. The winters are moderate compared to the same latitude inland weather. The average annual temperature is 6.6℃ and annual rainfall is around 661 mm (SMHI, 2021).

The soil in the area is mostly till and peat with bedrock that is composed of granodiorite and granite (Sjödin, 2016).

Figure 2. Location of the study site in Sweden: Norrby Skräddarbo, 733 92 Sala.

2.2 Experimental design

The experiment was established in the year 1989, by planting Silver birch and Downy birch in four different spacing treatments, replicated four times. The whole area, including the experiment, was protected from browsing by setting up an electric fence. For Silver birch plants of Finnish origin were used, whereas for Downy birch planting material germinated from local seed sources was used.

In each of the 32 plots (Fig. 3), 100 trees were planted by using one of four different treatments. The four treatments were:

- 1.3m x 1.3m with and initial density of 5917 seedlings ha^{-1}
- 1.5m x 1.5m with and initial density of 4444 seedlings ha^{-1}
- 1.8m x 1.8m with and initial density of 3086 seedlings ha^{-1}
- 2.6m x 2.6m with and initial density of 1497 seedlings ha^{-1}

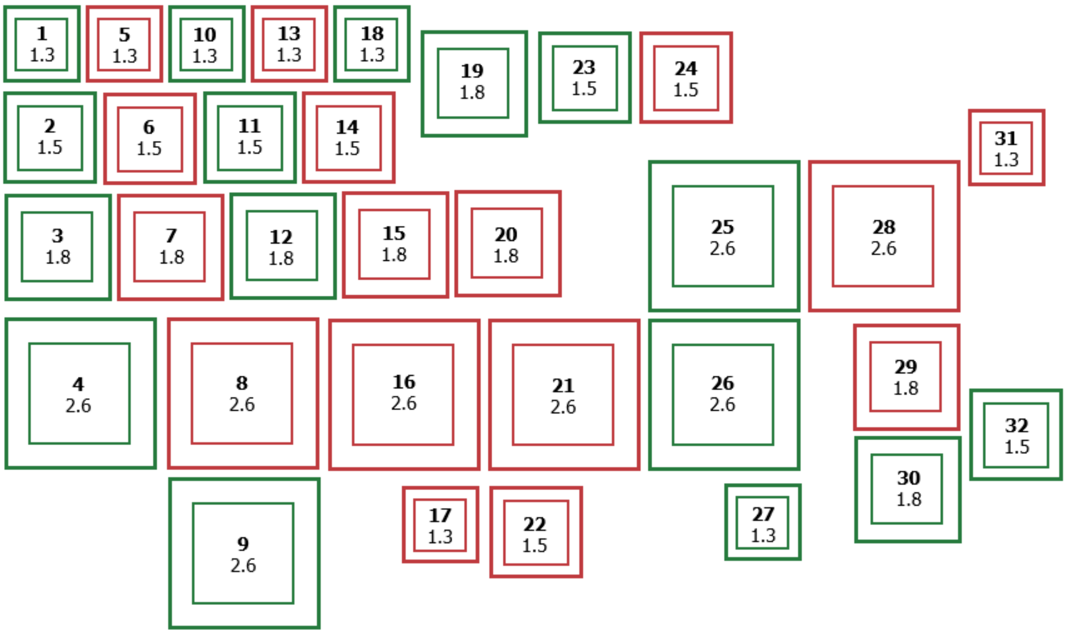


Figure 3. Position of plots: Bold number in the plot represents the numbering and the one underneath represents the planting treatment used. The green colour represents Silver birch and red Downy birch. The space between the inner and outer square represents the outer tree line that is excluded from data analysis due to the edge effect.

In each plot the seedlings were planted in the same "snake-shaped" sequence (Fig. 4). The two outer lines of every plot are considered as buffer rows and therefore were excluded from any data analysis – to avoid the edge effect.

1	2	3	4	5	6	7	8	9	10
20	19	18	17	16	15	14	13	12	11
21	22	23	24	25	26	27	28	29	30
40	39	38	37	36	35	34	33	32	31
41	42	43	44	45	46	47	48	49	50
60	59	58	57	56	55	54	53	52	51
61	62	63	64	65	66	67	68	69	70
80	79	78	77	76	75	74	73	72	71
81	82	83	84	85	86	87	88	89	90
100	99	98	97	96	95	94	93	92	91

Figure 4. Tree sequence with their numbering in the plot.

Noteworthy, all treatments except the 2.6x2.6 m spacing treatments, have undergone a thinning of unspecified intensity in 2005, thus affecting the growth of certain plots. No data on thinnings was recovered, thus making it impossible to estimate total production of the plots thinned as well as making it difficult to compare certain parameters between the different spacing treatments. Also, recently plot nr. 31 was cut down entirely (year 2021).

2.3 Data collection

Both, measurements of tree height and diameter have been collected annually from the year 2005 up to 2022, except for the year 2021. Tree diameters were measured using a calliper. The measurements were done cross-sectionally at the breast height measuring from two directions (N; W). Tree height as well as the height of the living crown (only for year 2022) was measured using a Haglöf Vertex IV hypsometer.

2.4 Estimation of basal area and volume

Basal area is a key variable when describing growth as well as the density of a stand. To calculate the basal area of every individual tree, the following formula was applied:

$$BA = \frac{\pi \times DBH^2}{40000} \quad (1)$$

where BA – basal area; DBH – diameter at breast height.

To calculate individual tree volume a function developed for birch was used (Brandel, 1990):

$$v = \frac{10^a \times D^b \times (D + 20.0)^c \times H^d \times (H - 1.3)^e}{1000} \quad (2)$$

where v – volume; H – tree height; D – diameter; and coefficients – *a* (-0.84627), *b* (2.23818), *c* (-1.06930), *d* (6.02015), *e* (-4.51472) which are estimated specifically for birch.

2.5 Statistical analysis and other calculations

For this thesis, a one-way ANOVA (Analysis of Variance) statistical test was used to analyse the differences between the means of the different treatments. The variables tested were arithmetic mean diameter (AMD), quadratic mean diameter (QMD), dominant height as well as the height of the living crown (HLC) and GINI index (heterogeneity within the diameter distribution). Anova assumptions (e.g., normality, homogeneity) were also checked, and if needed, a square root or logarithmic transformation of the dependent variable was used. Afterwards a post-hoc (TukeyC) test was done after the Anova test. The statistical analysis as well as other calculations were done using R (R core Team 2023).

2.6 Simulations for further stand development

The simulations were applied to each species and treatment (8 simulations) to get further stand development. Different functions were used to acquire the results about basal area, volume, and the economy of the stands by using estimated input data (Table 1). All simulations were carried out using R (R core Team 2023).

The chosen management for stand development consisted of two thinnings. The first thinning was set to year 20 (right at the beginning of the simulation period), while the second thinning was set to year 30. The two thinnings were carried out with an intensity of 35% and 30% respectively.

Table 1. Stand initial data for full rotation projections.

Sim.nr.	Spacing	Species	Age	BA ha^{-1}	H_{dom}	N ha^{-1}
1	1.3×1.3	SB	19	10,9	13	2056
2	1.3×1.3	DB	18	9,8	11,3	1891
3	1.5×1.5	SB	19	10,5	13,5	1790
4	1.5×1.5	DB	18	8,4	11,2	1481
5	1.8×1.8	SB	19	10,9	14,1	1372
6	1.8×1.8	DB	18	9,5	12	1587
7	2.6×2.6	SB	19	8,7	12,9	1233
8	2.6×2.6	DB	18	5,6	11	1109

Note: BA – basal area, H_{dom} – Dominat (top) height, N – number of trees, SB – Silver birch, DB – Downy birch.

2.6.1 Development functions

To acquire the data about full rotations four functions were used. Firstly, a site index (SI) function was used (Fig. 5, a). In order to estimate site index of a every plot, dominant height and age of a plot was used. Dominant height (height of the three thickest trees in the plot) was determined from the data of 2005. Since the data consisted of diameter measurements, an accurate estimate of basal area was achieved by using the function found in the 2.4 section, see Fig. 5, b. Afterwards, by using all the estimated input data (Table 1) in the basal area development function (Fig. 5, c), it was possible to estimate/simulate basal area throughout the whole rotation period. Finally, in order to obtain volume over the simulated period, a volume function (Fig. 5,d) was used (Liziniewicz et al., 2022). All the models/functions and the step-by-step use of them can be seen in Figure 5.

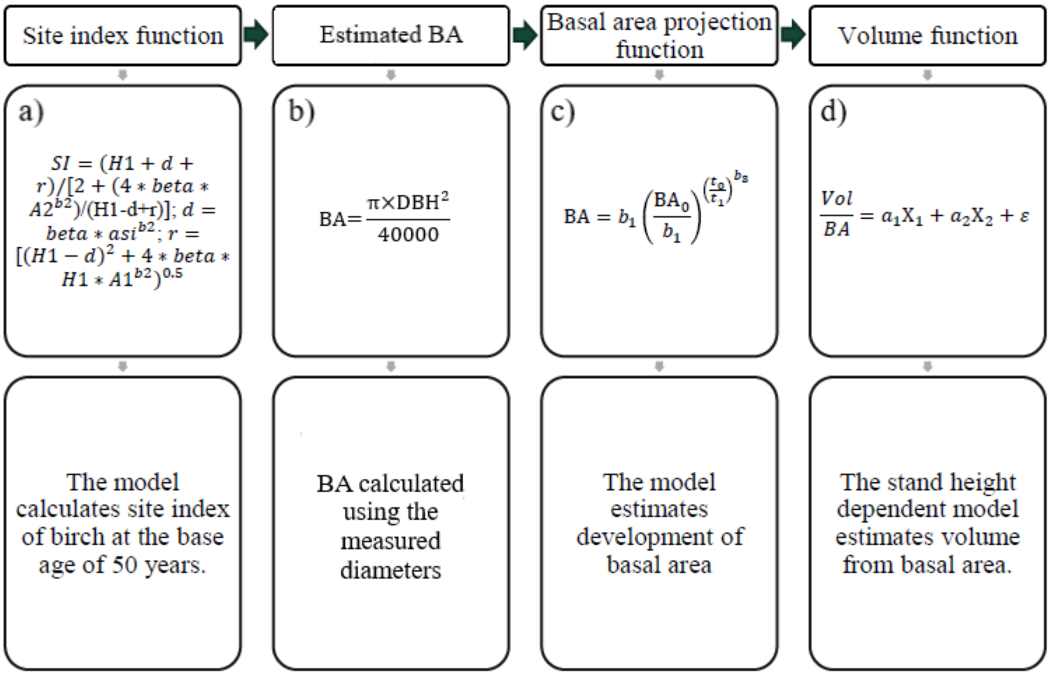


Figure 5. A schematic diagram of functions for a full rotation projection for the stands. Adapted from (Tuvikene, 2021); Modified.

2.7 Economic analysis

To calculate Land Expectation Value (LEV), Net Present Value (NPV) is needed. This considers the costs and benefits throughout the project. The calculation is done according to this equation:

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \tag{3}$$

where n – number of periods; t – time of the cash flow; R_t – net revenue at time t; i –discount rate.

In the NPV calculation discount rate of 2.5% was used.

LEV was calculated with the following equation:

$$LEV = NPV \times \frac{(1+i)^U}{(1+i)^U - 1} \tag{4}$$

where i – discount rate; u – rotation age.

Results

3.1 Effect of spacing

Statistical analysis showed that for Silver birch initial spacing affects the QMD (p=0.000134) and HLC (p=0.00975) more than for Downy birch - QMD (p= 0.0335) and HLC (p=0.0121). However, the GINI index was shown to be significant only for Downy birch (p=0.016). The other tested parameters were affected by spacing but not enough to be significant. The statistical analysis results are found in Table 2.

Table 2. Statistical test results.

Response variable	Species	Treatment	α	Mean	p-value	Groups
QMD	SB	1.3x1.3	0.05	14.19	0.000134 ***	b
		1.5x1.5		15.39		b
		1.8x1.8		17.70		a
		2.6x2.6		17.66		a
QMD	DB	1.3x1.3	0.05	13.59	0.0335 *	b
		1.5x1.5		14.69		ab
		1.8x1.8		15.22		ab
		2.6x2.6		16.07		a
BA	SB	1.3x1.3	0.05	11.47	0.323	a
		1.5x1.5		10.62		a
		1.8x1.8		10.57		a
		2.6x2.6		10.05		a
BA	DB	1.3x1.3	0.05	9.13	0.207	a
		1.5x1.5		8.92		a
		1.8x1.8		9.72		a
		2.6x2.6		7.40		a
V	SB	1.3x1.3	0.05	112.55	0.882	a
		1.5x1.5		109.07		a
		1.8x1.8		110.53		a
		2.6x2.6		104.49		a
V	DB	1.3x1.3	0.05	78.78	0.128	a
		1.5x1.5		76.60		a
		1.8x1.8		83.37		a
		2.6x2.6		59.70		a

Note: SB – Silver birch, DB – Downy birch, H_{dom} (m) – Dominat (top) height, QMD (cm) – quadratic mean diameter, BA (m^2) – basal area, HLC (m) – height of the living crown.

Continuation of Table 2

Response variable	Species	Treatment	α	Mean	p-value	Letter display
H_{dom}	SB	1.3x1.3	0.05	21.58	0.263	a
		1.5x1.5		22.02		a
		1.8x1.8		23.30		a
		2.6x2.6		23.60		a
H_{dom}	DB	1.3x1.3	0.05	18.67	0.653	a
		1.5x1.5		19.15		a
		1.8x1.8		19.47		a
		2.6x2.6		19.10		a
HLC	SB	1.3x1.3	0.05	6.98	0.00975 **	b
		1.5x1.5		7.55		ab
		1.8x1.8		8.83		a
		2.6x2.6		9.05		a
HLC	DB	1.3x1.3	0.05	6.00	0.0121 *	b
		1.5x1.5		7.05		ab
		1.8x1.8		7.42		ab
		2.6x2.6		8.57		a
Gini	SB	1.3x1.3	0.05	0.13	0.365	a
		1.5x1.5		0.12		a
		1.8x1.8		0.09		a
		2.6x2.6		0.11		a
Gini	DB	1.3x1.3	0.05	0.11	0.016 *	ab
		1.5x1.5		0.12		ab
		1.8x1.8		0.09		b
		2.6x2.6		0.13		a

Note: SB – Silver birch, DB – Downy birch, H_{dom} (m) – Dominat (top) height, QMD (cm) – quadratic mean diameter, BA (m^2) – basal area, HLC (m) – height of the living crown.

3.1.1 Dominant height

For Silver birch the difference between the dominant height (Fig. 6) of densest spacing treatment 1.3x1.3 m (21.6 m) and dominant height of sparsest spacing treatment 2.6x2.6 m (23.6 m) is only 2 m while having upward trend from 1.3x.1.3 m to 2.6x2.6 m spacing treatment. For Downy birch the difference between the dominant height of densest spacing treatment 1.3x1.3 m (18.7 m) and dominant height of sparsest spacing treatment 2.6x2.6 m (19.1 m) is only 0.4 m while having upward trend from 1.3x.1.3 m to 1.8x1.8 m spacing treatment and then a small decrease for treatment 2.6x2.6 m. The only noticeable difference is between Downy birch and Silver birch due to their respective differences in growth characteristics, but it was not tested statistically.

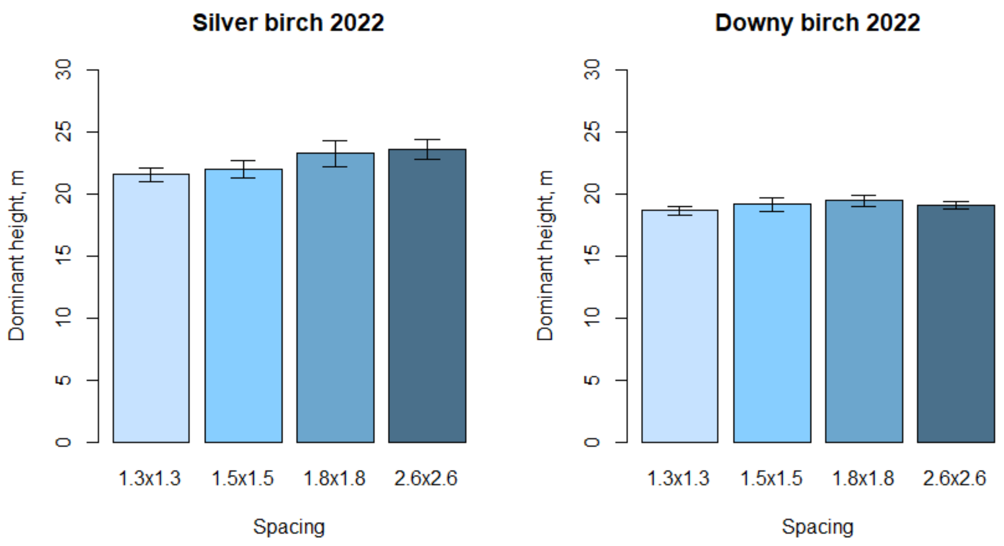


Figure 6. Dominant height differences for Silver birch and Downy birch in different spacing treatments in year 2022.

3.1.2 Diameter development

Wider initial spacing proved to have a considerable effect on QMD, with the spacing treatments 1.8x1.8 and 2.6x2.6 delivering the highest QMD (~16 cm for Downy birch, ~18 cm for Silver birch). Spacing of 1.5x1.5 showed medium QMD (~14.4 cm for Downy birch, ~15.2 cm for Silver birch) growth throughout the years while the spacing of 1.3x1.3 shows the smallest QMD (~13.7 cm for Downy birch, ~14.2 cm for Silver birch) development through the years. The QMD difference in the last revision between the smallest and the largest spacing treatment for Downy birch is 1.8 cm while for Silver birch it is 2.1 cm. Downy birch has shown a slightly smaller QMD growth overall compared to Silver birch what could be explained by differences in the species characteristics.

When it comes to the effect of different treatments on the structure of a stand, the Gini index revealed that structure was affected by spacing treatment but only for Downy birch, thus this species has more irregular diameter distribution within the stand which could be described as a species characteristic, but no further tests were made to determine that.

Figure 7. QMD development over time in different spacing treatments for Silver birch and Downy birch.

3.1.3 Volume and basal area

The basal area was insignificantly ($p>0.05$) affected by initial spacing, but the biggest variation of basal area was seen in the Downy birch plots (2.3 m^2) while in the Silver birch plots the variations and differences in basal area in each spacing is smaller (1.4 m^2). Basal area of Downy birch in spacing 1.8x1.8 m is bigger than the previous smaller spacing of 1.5x1.5 m which is bigger than the last smallest spacing of 1.3x1.3 m, but in Silver birch plots this trend is opposite. The differences in volume (Fig. 8) are small and initial spacing has an insignificant effect ($p>0.05$). The only difference is between the two species is due to their growth characteristics which was apparent but was statistically not tested.

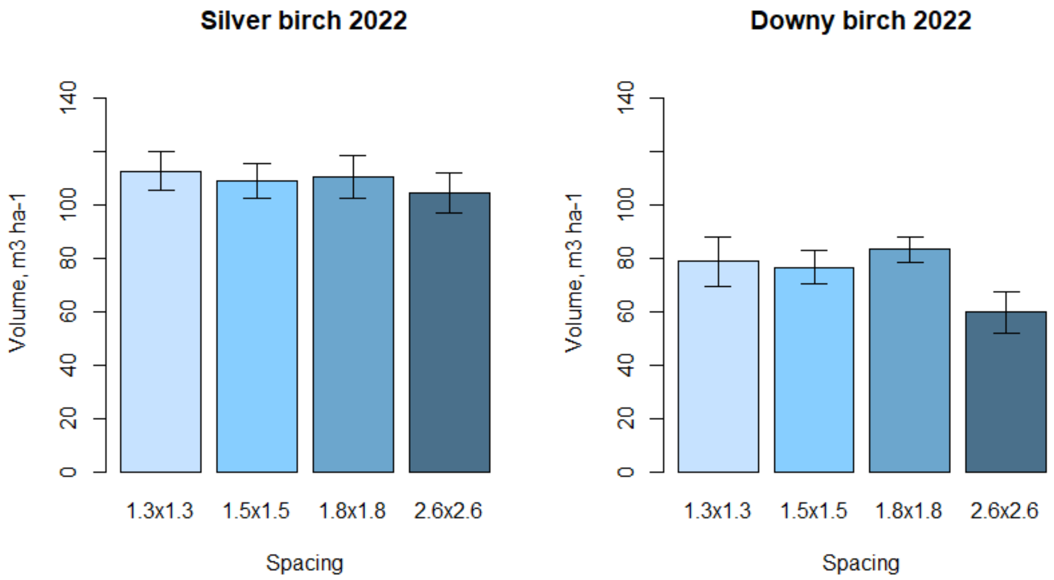


Figure 8. Volume per hectare depending on spacing for Downy and Silver birch in year 2022.

3.1.4 Height of the living crown

With larger initial spacing the height of the living crown (HLC) for Silver birch increased by 2.1 m and for Downy birch increased by 2.6 m (Fig. 9). Silver birch mean values ranged from 7 m for the 1.3x1.3 m spacing treatment to 9.1 m for the 2.6x2.6 m spacing treatment. Mean values of HLC for Downy birch ranged from 6 m for the 1.3x1.3 m spacing treatment to 8.6 m for the 2.6x2.6 m spacing treatment. The largest variation in terms of the HLC could be seen in spacing 2.6x2.6 m for Downy birch (from 7.4 m up to 10.3 m) and in spacing treatment 1.8x1.8 m for Silver birch (from 8 m up to 10.4 m).

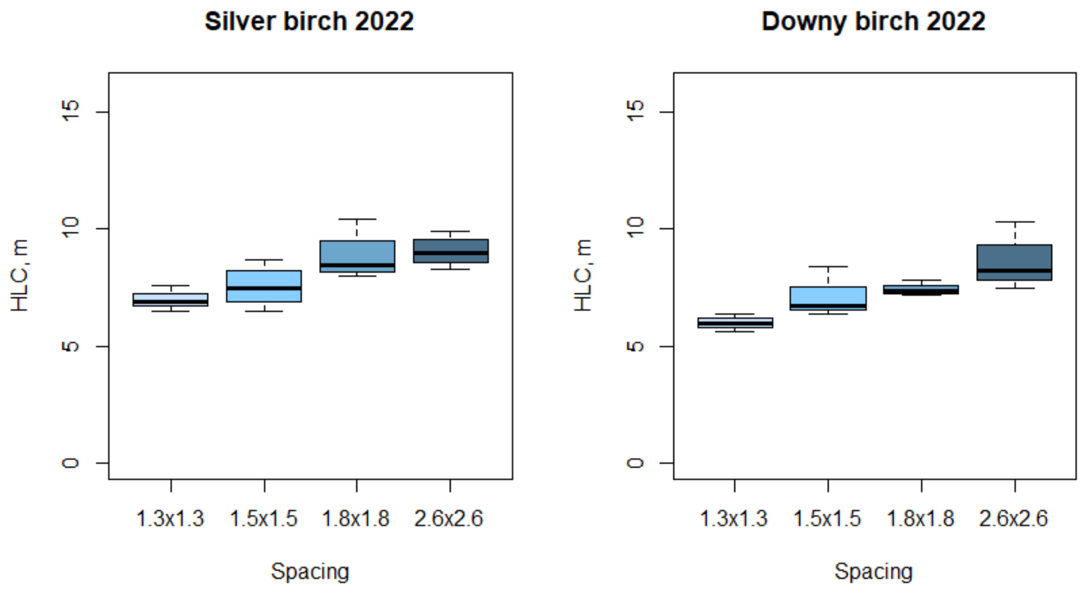


Figure 9. Initial spacing influence on the living crown for Silver birch and Downy birch in the year 2022.

3.2 Economic analysis of full rotation stands projections

For Silver birch treatment 1.8x1.8 m showed superior results by having highest maximum MAI – 7.2 m^3 ha^{-1} yr^{-1}. Similarly for Silver birch, treatment 1.8x1.8 m showed superior results by having highest maximum MAI for Downy birch, however, it was 6.6 m^3 ha^{-1} yr^{-1}, 0.6 lower than for Silver birch (Table 3) (Fig. 10).

LEV followed the same trend as MAI. Not unexpectedly, LEV was higher when the main assortment/goal of the stand was set to timber (compared to pulpwood). With timber as the main goal, LEV was the highest for both species in 1.8x1.8 m treatment - 34077 SEK for Silver birch and 26576 SEK for Downy birch. The price difference between species for timber is 7501 SEK which is a considerably large amount. The same applies for the highest LEV for pulpwood with 1.8x1.8 m treatment having the best output - 11946 SEK for Silver birch and 7902 SEK for Downy birch. The price difference for pulpwood is smaller than for timber but it is still noticeable – 4044 SEK.

The treatment 1.8x1.8 m showed the best overall results even in shortest rotation lengths for both species and both assortments being 48 years for Silver birch and 49 years for Downy birch. But the longest rotation lengths were in the largest spacing treatment of 2.6x2.6 m – 51 years for Silver birch, 55 (pulp) and 53 (timber) years for Downy birch.

The highest site index for Silver birch was shown in the treatment of 1.8x1.8 m (SI = 26.5) and the smallest in treatment 2.6x2.6 m (SI = 24). For Downy birch the highest site index also was shown in 1.8x1.8 m treatment (SI = 25.1) and the smallest site index was also shown in the treatment off 2.6x2.6 m (SI = 24).

Table 3. Simulation results.

Sim. nr.	**Treat.**	**Species**	**SI**	**Opt. Rot. P.**	**Opt. Rot. T.**	**LEV P Max**	**LEV T Max**	**MAI**
1	1.3x1.3	SB	25.4	51	51	7654.8	23817.3	6.9
2	1.3x1.3	DB	24.4	50	50	6241.4	22639.6	6.5
3	1.5x1.5	SB	25.9	51	51	8624.3	26503	6.9
4	1.5x1.5	DB	24.3	52	50	5070	22367	6.1
5	1.8x1.8	SB	26.5	48	48	11946.5	34077.6	7.2
6	1.8x1.8	DB	25.1	49	49	7902.3	26576.6	6.6
7	2.6x2.6	SB	25.3	51	51	6597.4	25600.2	6.2
8	2.6x2.6	DB	24	55	53	803.8	15872.1	5.2

Note: Treat. – treatment, SB – Silver birch, DB – Downy birch, SI – site index, Opt. Rot. (years) – optimal rotation, P – pulpwood, T – timber, LEV (SEK) - Land expectation value, MAI – mean annual increment.

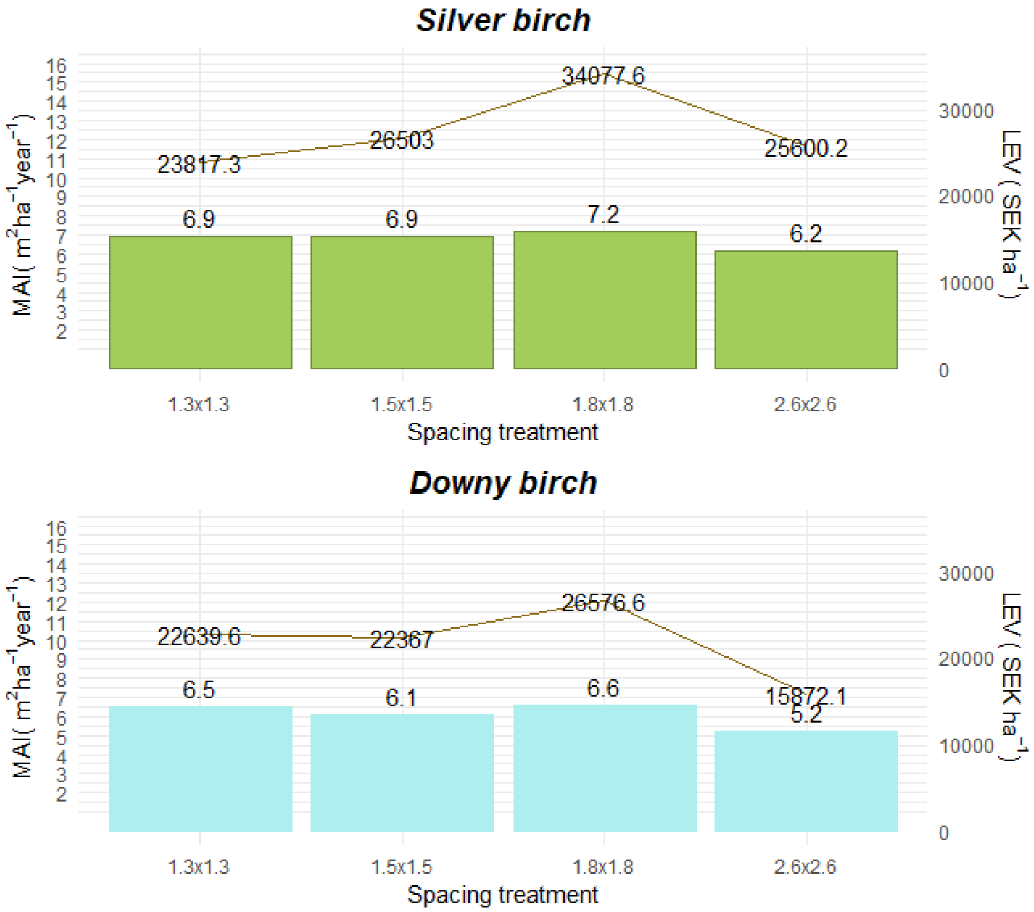


Figure 10. Simulation results – MAI, LEV, treatment, species.

Discussion

4.1 Growth dynamics

The statistical analyses showed that initial spacing had a significant impact on diameter growth and HLC for both species. HLC is an important factor that has a direct effect to the growth of the tree. By having a larger living crown (rule of thumb for birch = 50% of the height of the tree) at mature age will have positive impact to the tree's growth further on (Mäkinen, 2002). This must be considered if the goal is to produce large diameter trees in the shortest amount of time. Statistical analysis showed that Silver birch HLC is more affected by initial spacing than Downy birch, but even then this factor of having large crowns is important for both species. Then spacing of 1.8x1.8 m or larger will give the trees a good opportunity for big crowns. But at the same time too sparse stands might have birches with great crowns for growing but it will not outweigh the results that having a greater number of trees have. The same results were seen in Estonian research where the density of the birch stand strongly influenced the living crown (Jõgiste et al., 2003).

The most affected growth parameter was tree diameter or QMD (according to the variable tested in this thesis). The positive effect of sparser spacing treatments on diameter growth clearly endorses bigger diameter trees that could potentially be used for timber. The diameter growth increased with larger initial spacings, however, there was a stop in the trend after the spacing of 1.8x1.8m, with the next spacing of 2.6x2.6 m showed very much similar results. This may indicate that a spacing of 1.8x1.8 m (3086 trees ha^{-1}) is a good choice when the management goal is to promote large diameter trees but at the same time 2.6x2.6 m spacing shows similar growth results and less trees are needed to plant it, thus saving some money. As Hynynen et al. (2010) reported, pure Silver birch plantations in Nordic countries ranges from 1600-2500 trees ha-1 (2.5x2.5 m – 2x2 m) owing to having an optimal diameter growth, less managing and good economy.

Furthermore, as Niemistö (1995) has reported, densities lower than 1100 trees ha^{-1} do not increase the diameter growth anymore. The best diameter growth is reported to start at 1100 trees ha^{-1} and then the diameter growth decreases by one-third when reaching 2500 trees ha^{-1}. However, the yield is higher when stand has more than 2500 trees ha^{-1}. This shows that very sparse stands have good diameters, but it might not out-way the difference in the number of trees ha^{-1}, thus more trees with smaller diameter will be more valuable than few large diameter trees. As Daugaviete et al. (2011) have reported that densities >5000 trees ha^{-1} have small diameters that are only useful for energy production, but the accumulated volume is much greater than sparser densities.

It is worth considering the planting stock origin. In this study, the Silver birch was improved planting stock from a nursery in Finland and Downy birch was germinated from local seed sources. Improved planting material has shown to have better growth and vitality than naturally found birches (Liziniewicz et al., 2022). By having an improved plant growth the rotation length and quality of the stand are affected giving better end-rotation results, in other words, it maximizes the economic output (Liziniewicz et al., 2022). With this in mind, having a good planting material allows having less dense stands (1500-2000 trees ha^{-1}) to save money, thus also having less tending operations needed. In practical forestry in Sweden, birch is commonly planted at a density of 1800 trees ha^{-1} - to 2000 trees ha^{-1} (spacing of 2x2.5 m and sparser). Similarly, in Latvia birch is also planted at a density of 2000 trees ha^{-1}, however, the tendency in short-rotation plantations is to plant birch in a sparser spatial arrangement (e.g., 1500-1600 trees ha^{-1}). This lowers the management intensity when compared to spacings of 2x2 m (2500 trees ha^{-1}) or lower. Niemste et al. (2008) has reported that the best optimal density is 1600 trees ha^{-1} to grow quality birch. As Hynynen et al. (2010) reported pure Silver birch plantations in Nordic countries ranges from 1600-2500 trees ha^{-1}.

The height was barely affected by initial spacing. The statistical tests showed that clearly. The same results were also achieved by Daugaviete et al. (2011) and Hynhynen et al. (2010). This parameter should not be considered first in management when the talk is about the initial spacing.

Lastly yet importantly, it must be noted, that the different spacing treatments had undergone different management prior to the first inventory in 2005 – a factor that was not considered when analysing growth of the different treatments in this study – yet one of major importance and a potential to alter the results of this study. That said, it may not be entirely fair to draw final conclusions just from this study.

4.2 Economic analysis

The simulations of full rotation showed the already expected result – Silver birch outperforms Downy birch when it comes to growth and economy. For Silver birch, simulations revealed that the best growth (MAI) and thus also the best economy was achieved from the 1.8x1.8 m spacing treatment. The optimal rotation age for the 1.8x1.8 m was determined to be 48 years both for timber and pulpwood production with the LEV at the optimal rotation of 48 and 48 years for pulpwood and timber respectively. Similarly, for Downy birch, the best results were also achieved from the 1.8x1.8 m spacing. However, the growth (MAI) wasn't as high compared to Silver birch, therefore the optimal rotation age was determined to be 1 year later. These results show that when comparing the initial spacing of 1.8x1.8 m to others it is superior when applying the same management (after 2005) and looking at full projection rotations. Spacing of 1.8x1.8 seems like a good hybrid choice giving good economic output for both pulpwood and timber.

There is a large difference in the number of stems between spacings 1.8x1.8 m (3086 trees ha^{-1}) and 2.6x2.6 m (1497 trees ha^{-1}). In 2008, Niemste reported that spacing of 2.5x2.5 m (1600 trees ha^{-1}) is the most optimal because denser stands with smaller spacings than 2x2.5 m (>2000 trees ha^{-1}) would require additional PCT which is an unwanted extra cost (Niemste et al., 2008). Also having larger amounts of saplings that need to be planted will bring extra costs due to the high price of the planting material. With that, in mind, initial spacing of 1.8x1.8 m might not be the best economical decision. It can be argued that initial spacing of 2x2.5 m (2000 trees ha^{-1}) is more viable owing to large number of trees that have the same good diameter growth compared to spacing 1.8x1.8 m while not needing an extra PCT. Planting 1600 - 2000 birch trees ha^{-1} is practised in Latvian and Finnish forestry for it being the golden mean to have a sufficient number of large diameter trees while also having the least extra expenses that higher densities bring. Of course, these stands are planted with improved planting material which cost a lot, but that allows sparser stands due to better growth. Table 4 sums up the discussion part. Each treatment has its own pros and cons so depending on the management goals, appropriate spacing can be chosen.

Table 4. Sum up of treatments

	1.3 x 1.3 and 1.5 x 1.5	**1.8 x 1.8**	**2.6 x 2.6**
Stem number	Large	Average	Small
Diameter growth	Small	Large	Large
Total production	Largest	Large	Large
High quality timber	No	Maybe	Yes
Establishment	Natural	Natural/Planted	Planted

4.3 Limitations of the study

A major limitation in this study was the fact that there were major differences between management of the different spacing treatments. All except 2.6x2.6 m spacing treatments had undergone a thinning prior to 2005. While the management can be expected to differ due to different initial phase of the treatments, it is uncommon not to carry out any management operation given the age and growth parameters of those found in 2.6x2.6 m. Furthermore, it was not possible to recover any of the data on thinned plots/trees, making it hard to compare the growth dynamics between different treatments and making it impossible to compare the net total production. As a result, the fact that 1.8x1.8 treatments were thinned and 2.6x2.6 treatments were not, could have been a contributing factor for the calculations showing similar if not better diameter growth for 1.8x1.8 treatment.

Secondly, larger experimental plots could give more data on tree growth. However, the bigger limitation of this study in the respect of a size could be that this experiment was established only on one site. From an experiment point of view, a randomized block design implemented on sites of varying site indices would have been statistically more pleasing. At the same time, establishing such experiments requires a lot of resources and all the logistical requirements to be met. Lastly, one of the plots was entirely cut in 2021 so in the last data collection this plot was missing.

Thirdly, an improvement of the current version of the spacing experiment in birch could be diversifying the experimental design. Different spacing treatments would only enrich the data, but it would also lead to bigger expenses to establish the experiment. This is a trade-off that a lot of new studies must balance due to funding being a limited resource.

Finally, the full rotation results are based on simulations, and it is a limitation for several reasons. First, it is a simulation, based on several assumptions (fixed prices, fixed interest rate, certain % of timber/pulpwood obtained from stands etc.). It has also led to an accumulation of errors, but we will never know how much it deviates from the "real scenarios".

4.4 Suggestions for future research and management of birch

As for the future research, addition of other parameters to the long-term measurements, e.g., the HLC parameter could be measured together with other parameters from a point of a young stand up until the time when the trees have reached maturity. That would give a better perspective on how the initial spacing and thinnings influence crown height development for Silver birch and Downy birch. In addition, other, eco-physiology related parameters could be interesting to follow/look at over a long-term period.

Another suggestion could be to add the mixture element to the, e.g., a potential study could be to test two of the best performing initial spacings but making it as mixture of Silver birch and Norway spruce for instance, while also having different species distribution ratios: 100/0; 35/65; 50/50; 65/35; 0/100 % of proportion of birch in a stand (plot) respectively.

When it comes to the management of birch for timber and pulpwood production improved planting material is a good investment. Less trees for planting, less tending operations, and better growth. However, it can be argued that when investing in a genetically improved planting material, pulpwood should not the considered as the primary goal of a stand, but it should be managed towards high quality timber production. Best initial spacing for this could be somewhere between 2.5x2.5 m (1600 trees ha^{-1}) to 2x2.5 m (2000 trees ha^{-1}). Furthermore, if timber production is of importance, Silver birch should be the species chosen. Similarly, as in other studies (e.g. Hytönen et al., 2014), in this study, Silver birch showed superior production compared to Downy birch, although it was not statistically tested. In addition, an interesting finding from this study was that of the Gini index analysis revealing a more irregular diameters for Downy birch compared to Silver birch. So, if the goal is to have more similar diameters at the end of the rotation, then Silver birch should be the choice. However, further research is needed to confirm this.

Alternatively, denser spacings could be better for total net volume production, i.e., from 2x2.5 m (2000 trees ha^{-1}) to 1.8x1.8 m (3086 trees ha^{-1}). Ultimately, if the main goal of a stand is high quality timber production, a final number of future crop trees will not change much, regardless of the initial density. Therefore, one must contemplate about the additional benefit this brings, if any besides increased production (Karlsson et al., 1997). As an alternative, natural regeneration of birch could be used for this purpose, as a successful natural regeneration of birch delivers denser stands (>5000 trees ha^{-1}) (Lehtosalo et al., 2010), however, naturally regenerated birch is known to be inferior to planted birch stands (using improved material) both production and quality-wise (Lidman et al., 2023). At the same time, natural regeneration could be the best choice because of lower establishment costs (Liepiņš et al., 2013).

Conclusion

In this thesis four different initial spacing treatments were applied to two most common birch species in Sweden and the results showed that spacing of 1.8x1.8 m could be considered the best overall treatment owing to good growth and the best economy out of all compared treatments. This study shows that spacing affects diameter development and HLC for both species, however, other tested variables showed varied results. Effect of spacing on HLC proved to be significant only for Silver birch, whereas stand structure (Gini index) was significantly affected only for Downy birch. Full rotation projections confirmed the superior performance of the 1.8x1.8 m spacing treatment for both when the main goal was set to pulpwood and timber production. Optimal rotation age for Silver birch of the 1.8x1.8 treatment was 48 years with the LEV of 34078 SEK. Spacing treatment of 2.6x2.6 m showed similar growth dynamics; however, the simulation revealed a more substantial difference between the two treatments. This could partially be explained by suboptimal management prior to start of the simulation year. Further research is needed to determine the long-term effects of different spacing treatments on growth and production of birch.

References

Beck, P., Caudullo, G., Rigo, D. De, & Tinner, W. (2016). Betula pendula, Betula pubescens. *European Atlas of Forest Tree Species*, 70–73.

Bērziņa, D., Miezīte, O., Rūba, J., Sisenis, L., & Liepa, I. (2018). *Increment Differences of Silver Birch Betula Pendula Roth and Downy Birch B. Pubescens Ehrh. Growing in Drained Soils in South Latvia*. https://doi.org/10.15544/rd.2017.113

Brandel, G. (1990). Nya volymfunktioner för tall, gran och björk. In *Skogsfakta* (Vol. 11).

Cameron, A. D. (1996). Managing birch woodlands for the production of quality timber. *Forestry*, *69*(4), 356–371. https://doi.org/10.1093/forestry/69.4.357

Daugaviete, Mudrite, Lazdins, A., Lazdina, D., Makovskis, K., & Daugavietis, U. (2017). Growth and Yield of 15-Year Plantations of Pine, Spruce and Birch in Agricultural Land. *Rural Sustainability Research*, *37*(332), 38–50. https://doi.org/10.1515/plua-2017-0005

Daugaviete, Mudrīte, Liepiņš, K., & Liepiņš, J. (2011). Kārpainā bērza (Betula pendula Roth.) dažādas biezības plantāciju augšanas gaita. *Mežzinātne*, *24*(57), 3–16.

Dubois, H., Verkasalo, E., & Claessens, H. (2020). Potential of birch (betula pendula roth and b. pubescens ehrh.) for forestry and forest-based industry sector within the changing climatic and socio-economic context ofwestern Europe. *Forests*, *11*(3), 1–26. https://doi.org/10.3390/f11030336

Goude, M. (2021). *Hybrid growth models for Norway spruce and Scots pine Hybrid growth models for Norway spruce and Scots pine*.

Hynynen, J., Niemistö, P., Viherä-Aarnio, A., Brunner, A., Hein, S., & Velling, P. (2010). Silviculture of birch (Betula pendula Roth and Betula pubescens Ehrh.) in Northern Europe. *Forestry*, *83*(1), 103–119. https://doi.org/10.1093/forestry/cpp035

Hytönen, J., Saramäki, J., & Niemistö, P. (2014). Growth, stem quality and nutritional status of Betula pendula and Betula pubescens in pure stands and mixtures. *Scandinavian Journal of Forest Research*, *29*(1), 1–11. https://doi.org/10.1080/02827581.2013.838300

Jõgiste, K., Vares, A., & Sendrós, M. (2003). Restoration of former agricultural fields in Estonia: Comparative growth of planted and naturally regenerated birch. *Forestry*, *76*(2), 209–219. https://doi.org/10.1093/forestry/76.2.209

Karlsson, A., Albrektson, A., & Sonesson, J. (1997). Site index and productivity of artificially regenerated betula pendula and betula pubescens stands on former farmland in southern and central Sweden. *Scandinavian Journal of Forest Research*, *12*(3), 256–263. https://doi.org/10.1080/02827589709355408

Lehtosalo, M., Mäkelä, A., & Valkonen, S. (2010). Regeneration and tree growth dynamics of Picea abies, Betula pendula and Betula pubescens in regeneration areas treated with spot mounding in southern Finland. *Scandinavian Journal of Forest Research*, *25*(3), 213–223. https://doi.org/10.1080/02827581.2010.489514

Lidman, F. D., Karlsson, M., Lundmark, T., Sängstuvall, L., & Holmström, E. (2023). Birch establishes anywhere! So, what is there to know about natural regeneration and direct seeding of birch? *New Forests*, *0123456789*. https://doi.org/10.1007/s11056-023-09971-z

Liepiņš, K., Daugaviete, M., & Zālītis, P. (2013). *Bērza audzēšana lauksaimniecības zemēs*.

Liziniewicz, M., Barbeito, I., Zvirgzdins, A., Stener, L. G., Niemistö, P., Fahlvik, N.,

Johansson, U., Karlsson, B., & Nilsson, U. (2022). Production of genetically improved silver birch plantations in southern and central Sweden. *Silva Fennica*, *56*(1), 1–20. https://doi.org/10.14214/sf.10512
Mäkinen, H. (2002). Effect of stand density on the branch development of silver birch (Betula pendula Roth) in central Finland. *Trees - Structure and Function*, *16*(4–5), 346–353. https://doi.org/10.1007/s00468-002-0162-x
Niemistö, P. (1995). Influence of initial spacing and row-to-row distance on the growth and yield of silver birch (betula pendula). *Scandinavian Journal of Forest Research*, *10*(1–4), 245–255. https://doi.org/10.1080/02827589509382890
Niemste, P., Vihere-Ārnio, A., Vellinga, P., Herejervi, H., & Verkasalo, E. (2008). *Bērzu audzēšana un izmantošana*.
Sjödin, S. (2016). *The Forest Fire in Västmanland, South Central Sweden, and its Effects on Soils and Forest Recovery (Master's thesis)*. *371*, 52. http://uu.diva-portal.org/smash/record.jsf?pid=diva2%3A972192&dswid=9756
Tuvikene, M. (2021). *Growth and management of Silver birch and Hybrid aspen in southern Sweden*. 1–47.
R core Team (2023). R: A language environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/ [Accessed 13.03.2023]
SMHI. 2021. Årsmedeltemperatur [Online]. Available: https://www.smhi.se/data/meteorologi/kartor/avvikelse/arsmedeltemperatur-avvikelse [Accessed 13.03.2023].
SMHI. 2021. Årsnederbörd [Online]. Available: https://www.smhi.se/data/meteorologi/kartor/avvikelse/manadsnederbord-procent-avnormal-avvikelse/ [Accessed 13.03.2023].

Master’s thesis in Forest science
Swedish University of Agricultural Sciences
Southern Swedish Forest Research Centre

Popular scientific abstract Alnarp, 2023

How much birch to plant?

Edvards Romans

In these changing climate times, growing broadleaves can help tackle this problem for foresters. Also, better management practices will save a lot of resources. Birch is an amazing fast-growing species that is underutilised in Sweden and more attention should be brought to it.

Just planting random amounts of birch won’t help you to gain the most money out of that forest. It is very important to plant a certain amount per hectare or in other words the initial spacing of said plants is crucial when establishing your forest. Different spacing between the seedlings will affect the growth of the trees. Diameter is a crucial growth parameter often describing the value of the tree and it is exactly tree diameter that can be affected the most. To know more clearly what spacing would suit you the best, the first thing to do is understanding what final product you are aiming for.

If you are growing birches for top quality timber and pulpwood, spacing of 1.8x1.8 m is a good hybrid solution ensuring great growth for both assortments. If you would choose a spacing of 2x2.5 m, then you might want to buy improved planting material for better results. This spacing could be considered as the golden mean to achieve quality timber with least expenses.

If you would like to grow the birches for biomass which is also known as energy production, then spacings 1.3x.1.3 m or smaller is the choice for you. But in this scenario buying that many plants will be costly, and no one wants that. Instead, naturally regenerated birch will solve this problem because birch is known for spreading far and easy where other trees have not started to grow yet. With this in mind a lot of money can be saved, and a lot of birches can be grown in one place.

To conclude, the best spacing for quality timber is somewhere between 1.8x1.8 m and 2.6x2.6 m. Further research is needed to study spacings in between these two.

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