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Thinning silver birch stands in Finland: impacts on growth, yield and carbon dynamics

Pentti Niemistö^{a,*} , Saija Huuskonen^b 

^a Natural Resources Institute Finland (Luke), Kampusranta 9, 60320 Seinäjoki, Finland

^b Natural Resources Institute Finland (Luke), Latokartanonkaari 9, 00790 Helsinki, Finland

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ABSTRACT

There has been a notable increase in interest in deciduous trees, particularly the silver birch (*Betula pendula* Roth.), in Finland and other Nordic countries. However, there is a need for updated knowledge and tools on the growth and management of silver birch. The objective of this study was to evaluate the growth and yield of silver birch stands subjected to varying intensity of thinning. The extensive set of long-term experiments with a monitoring period of 30 years on average, provides updated information on the growth and yield of mature silver birch in Finland. The experimental design comprised seven thinning treatments from below: two heavy thinnings, one heavy thinning, light and heavy thinning, two moderate thinnings, moderate and light thinning, one or two light thinnings, and an unthinned control, applied in the first commercial thinning (FCT) following a second thinning mostly after ten years. In certain instances, second one was a cautious thinning from above. Additionally, a heavy thinning was done in some plots after 20–25 years of FCT. The findings indicated that more intensive thinning procedures resulted in a reduction in the overall yield of silver birch stands. Nevertheless, intensive thinnings exhibited a higher diameter development. The commercial wood production maintained an average level following moderate thinnings or after one heavy thinning. However, it was reduced following two heavy thinnings and increased following less intensive treatments. In particular, the removal of a significant proportion of the trees through heavy thinning led to an increase in the yield of sawlogs. Former agricultural sites exhibited higher growth rates and yields in comparison to forest sites with similar site indices. However, as the site index increased, the discrepancy in growth and yield between the site classes diminished. Conversely, former agricultural sites exhibited a markedly higher mortality rate in mature stands. Therefore, it would be prudent to consider shorter rotations in former agricultural sites in comparison to forest sites. Further research is required to investigate the impact of juvenile stand management on both yield and profitability, with a particular focus on wood quality.

1. Introduction

The prevailing silviculture system in Finland's production forests has favored coniferous species, particularly Norway spruce (*Picea abies* Karst.) and Scots pine (*Pinus sylvestris* L.). From the perspective of the forest industry, coniferous tree species are more productive and valuable than broadleaved tree species. Furthermore, the elevated risk of browsing by cervids has diminished the appeal of establishing broadleaved dominated or mixed stands. This situation has prevailed for decades. Consequently, the majority of commercial forests are either pure coniferous stands, or strongly dominated by spruce or pine. However, scientific evidence indicates that species diversity can provide increased

biodiversity, strengthened vitality, and improved resilience, making them more adaptive to environmental changes (Felton et al., 2016; Huuskonen et al., 2021). Commercial wood production can also benefit from increased species diversity, supporting raw material stability and a widening product portfolio in a changing operational environment. Additionally, if forests could provide more ecosystem services due to increased species diversity, it could improve the public acceptability of commercial forest use. As a result, there is a growing interest in deciduous trees, particularly the silver birch (*Betula pendula* Roth.), in Finland and other Nordic countries. However, updated knowledge and available tools for the growth and management of silver birch forest stands remain very limited.

* Corresponding author.

E-mail addresses: ext.pentti.niemisto@luke.fi (P. Niemistö), ext.saija.huuskonen@luke.fi (S. Huuskonen).

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The silver birch is distributed throughout Eurasia and has the widest range of all European broadleaved tree species. Additionally, it displays a high degree of phenotypic plasticity (Dubois et al., 2020). In recent decades, the focus on silver birch (*Betula pendula*) for commercial purposes has been limited to the Baltic countries and Finland (Dubois et al., 2020; Hynynen et al., 2010). However, recent studies have identified a growing interest also in temperate Western Europe (Dubois et al., 2021; Zeoli et al., 2025) due to the attractive option of supporting and addressing current and future challenges related to climate change, adaptation and biodiversity issues.

In Finland, the total volume of birch resources is estimated approximately 418 million cubic meters, representing 17 % of the country's total forest volume (Kulju et al., 2023). Approximately half of this volume is found in naturally regenerated mixed forests. The proportion of silver birch in the total volume of birches is approximately 29 % (Korhonen et al., 2021) due to the significant amount of downy birch found on peatlands as well as on mineral soils in northern and western Finland. The area comprising birch-dominated or pure birch stands is approximately 1.7 million hectares, representing 9.2 % of the total forest area. Of this, 6 %-units are dominated by downy birch and 3.2 %-units by silver birch (Korhonen et al., 2021). While planted silver birch stands cover over 160,000 hectares in Finland, this only represents 10 % of the entire birch-dominated area. However, the importance of planted birch in wood production is higher than its proportion of total area or volume due to its high productivity on fertile site types and the high value of birch logs.

The majority of birch plantations in Finland are located in the southern and central regions of the country on former agricultural land. The practice of planting birch trees on a larger scale began in the late 1960s, with annual rates of 5,000 to 8,000 hectares from 1971 to 1976 (Niemistö and Korhonen, 2008). However, there was a decrease in the annual planted area for a period of ten years due to damage caused by factors such as unfavorable site conditions or animals, including voles, moose, and hares. In the mid-1980s, the afforestation of agricultural land increased once more, with the planting of silver birch rapidly expanding to 15,000 hectares per year. In previous years, the annual rate of silver birch planting has been reduced to 3,400 hectares per year (Kulju et al., 2023), primarily due to increased browsing by cervids.

The planting of silver birch benefits from tree breeding, aimed at improving volume growth and quality traits (Niemistö et al., 2008). Genetic gains from Finnish silver birch seed orchards, active since the 1970s, have led to significant improvements in stem volume (1.0 % to 31.1 %) and quality, such as a reduction in ramicorn branches and forks by 16.2 % and 6.8 %, respectively (Haapanen, 2024). The use of improved silver birch material has been shown to enhance stand productivity, shorten rotation periods, and increase profitability (Liziniwicz et al., 2022).

Silver birch is a pioneer species that thrives in full sunlight and shows the best juvenile growth potential among Finland's native trees when planted on fertile mineral soils. However, its growth slows as the trees mature, diminishing their competitive edge over Norway spruce. The growth patterns of silver birch and Norway spruce on nutrient-rich soils differ in rotation period and light requirements. Downy birch, another major species in Finland, generally has lower growth potential than silver birch, except on peatlands or wet mineral soils (Hytönen et al., 2014; Karlsson et al., 1997; Koivisto, 1959).

In Finland, birch plantations are typically pure stands with a recommended density of 1,600 seedlings per hectare on fertile mineral soils. Research on birch forestation, spacing, and growth is limited (Niemistö, 1995; Raulo, 1981, 1978, 1977; Raulo and Koski, 1977). Growth and yield tables specific to silver birch plantations in southern Finland were published by Oikarinen (1983), although the study had limitations due to a small sample size and short measurement period. These findings laid the foundation for current silver birch guidelines in Finland. Recently, models for stand-level growth and self-thinning have been developed (Lee et al., 2024, 2025), but further research is needed

to better understand the growth, yield, and carbon mitigation potential of silver birch plantations under various management practices.

Similar growth and yield results and models have been reported from other Nordic countries where birch is a vital forest resource, including Norway (Braastad, 1977, 1967), Sweden (Eriksson et al., 1997; Fries, 1964) and the Baltic countries (Maleki et al., 2015; Uri et al., 2012). However, these findings primarily concern natural stands of pure and mixed silver birch and downy birch, as well as the results of Gustavsen and Mielikäinen (1984); Koivisto (1959).

The objective of this study is to evaluate the growth and yield of silver birch stands until maturity with a particular focus on the impact of varying management intensity. The extensive set of long-term experiments, with a monitoring period of mostly 30 years, provides updated information on the growth and yield of birch in Finland. Consequently, the objective of this study is to present novel findings pertaining to the development, growth, yield, and carbon mitigation of differently managed planted silver birch stands. The findings can contribute to the refinement of forest management strategies for silver birch plantations.

2. Material and methods

2.1. Experimental stands

The study material consisted of long-term silver birch thinning experiments conducted in southern and central Finland (Fig. 1, Table 1). The experiments were established by the Finnish Forest Research Institute (Metla) between 1985 and 1992 and are currently maintained by the Natural Resources Institute Finland (Luke). A total of 17 thinning experiments were conducted, comprising 174 experimental plots (see Table 1, Fig. 1). The experimental sites were selected from young,

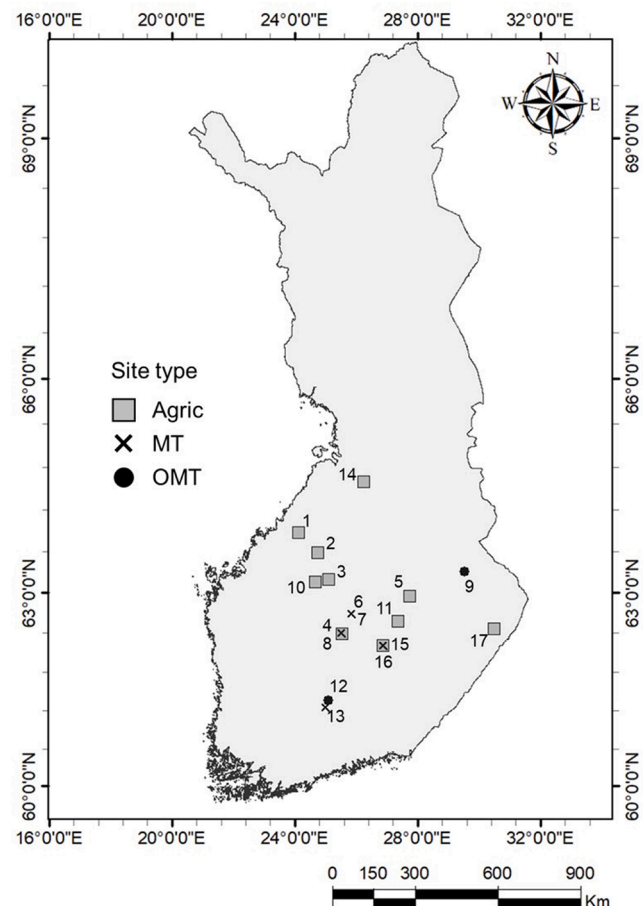


Fig. 1. Location of the experiments by site type.

Table 1
Thinning experiments.

Experiment	East coord. km	North coord. km	Elevation above sea m	Temp. sum >5C d.d.	Site type	Site index* H ₅₀ , m	Onset year	Age at onset a	Study period a	Initial plot N	Missed plot N
832	358.68	7086.53	85	1106	agr.	23.8	1989	22	30	6	
833	386.97	7052.87	145	1115	agr.	26.8	1989	21	30	8	
834	404.42	7009.03	135	1205	agr.	28.2	1989	19	30	12	
835	422.79	6919.80	195	1187	MT	27.6	1989	23	30	14	3
836	537.49	6980.87	90	1302	agr.	31.7	1989	20	25	6	
837	440.10	6952.37	130	1228	MT	27.7	1989	22	30	15	
838	439.90	6951.95	130	1195	MT	25.9	1989	23	30	10	
839	423.31	6919.35	205	1187	agr.	30.6	1989	16	30	12	2
840	625.90	7023.18	130	1159	OMT	27.8	1989	20	30	8	
841	381.71	7006.69	205	1132	agr.	26.0	1990	22	29	8	
842	517.70	6938.47	105	1262	agr.	27.4	1990	20	29	12	
845	398.47	6804.48	150	1276	OMT	25.3	1990	22	29	10	
846	391.62	6793.97	110	1248	MT	23.6	1990	23	29	13	1
857	463.35	7164.92	80	1070	agr.	19.9	1992	22	24	10	
859	492.78	6897.78	140	1219	agr.	28.8	1985	17	30	10	
860	492.54	6897.59	150	1219	MT	27.6	1985	17	30	15	
867	679.35	6931.46	190	1192	agr.	25.2	1985	17	26	5	

*according to Lee et al. (2024).

unthinned, planted silver birch stands located in the southern half of Finland, on mineral soil with as uniform growing stock and site conditions as possible. Ten experiments were conducted on former agricultural fields, and seven on forest lands. Of these, five were Myrtillus forest site types (MT) or fresh heath, while two stands were growing on higher fertility Oxalis-Myrtillus forest site types (OMT) or grove-like heath (Cajander, 1949; Tonteri et al., 1990). In each stand, rectangular plots were established in each stand, with an average plot size of 959 m² (range 490–1710 m²).

2.2. Measurements

The experiments were conducted at five-year intervals, with the observation period ranging from 29–30-years in most cases, with the exception of three cases where the observation period was 24 to 26 years (Table 1). The plot measurements were conducted at the beginning of the monitoring period, prior to the first commercial thinning, when the trees were between 16 and 23 years of age. Remeasurements were conducted at five-year intervals on six occasions, with the exception of three experiments which were only measured on five occasions. Furthermore, the duration of the last period was four years in five experiments and six years in one experiment (Table 1).

All trees on the plots were mapped with their x and y coordinates and measured for diameter at breast height from two perpendicular directions. For each tree on the plot, the species, retention class (living and to be retained, living and marked for removal in harvesting, dead, or disappeared), and any damage were recorded. The selection of sample trees was based on the individual tree basal area distribution, with the objective of including approximately 40 sample trees on each plot prior to the implementation of thinning treatments. The probability of a tree being selected was proportional to its basal area at breast height; however, the sample trees were randomly located on the sample plots. The same sample trees were subjected to all subsequent measurements, and no additional sample trees were incorporated into the study following the thinning treatments.

The height of the sample trees of silver birch was measured, as well as the height of the crown base, defined as the height of the lowest living branch. The initial measurement of the diameter at a height of 6 metres from two perpendicular directions (d6.0) was conducted using ladders, and subsequently with an electronic caliper. It was not deemed appropriate to include trees displaying visible signs of disease or damage as sample trees.

2.3. Calculations

The stand parameters were calculated using KPL software (Heinonen, 1994), based on the tree data. In order to estimate the height (h) and height to crown base (hcb) for all trees, the plot-wise curves of (Näslund, 1936) were employed. The stem volume (v, dm³) for the sample trees was determined using the volume functions of (Laasasenaho, 1982) taking into account the diameter at breast height (d1.3), diameter at 6 m (d6), and height (h). A d-h curve was fitted to the sample tree data on a plotwise basis in order to calculate the volume for all trees, in accordance with the procedure outlined by (Heinonen, 1994). The stand-level variables basal area (G) and stem volume (V) were subsequently aggregated from the tree data. The dominant height (H_{dom}) and dominant diameter (D_{dom}) were calculated as the mean values of the 100 thickest trees per hectare. The growth parameters for the consecutive five-year periods were calculated as the difference between subsequent measurements.

The merchantable stem volume was calculated using the assortment rules widely applied in Finland. For the estimation of pulpwood, a minimum length of 3.0 m and a minimum top diameter of 6.0 cm was used. For sawlogs, the minimum length of 3.1 m was applied, along with a minimum top diameter over bark was of 18 cm. The assortment volumes were calculated according to tree dimensions and no sawlog reductions were assumed (i.e., expecting a lower quality than optimal due to form, branches, decay, and other issues).

The temperature sum was employed to delineate the geographic distribution of stands in Finland. For each stand, the long-term average of the annual effective temperature sum (in degree-days, d.d., threshold value +5 °C) was calculated for the period 1981–2010. The threshold value refers to the thermal growing season (daily mean temperature is permanently above +5 °C). The calculation of the temperature sum was based on latitude, longitude, and elevation of each stand, with the data estimated using climate data with a 10 × 10 km grid resolution (Venäläinen et al., 2005). The annual temperature sum varied from 1,070 to 1,302 degree-days.

The accumulated carbon on trees through growth and the lost carbon lost due to removals and decomposition was calculated by biomass components. The determination of dry weight in living biomass, encompassing both above-ground and below-ground components (such as stem, branches, needles and leaves, stumps, and roots larger than 2 mm), was based on models developed by (Repola, 2008) for silver birch and downy birch. Furthermore, the models accounted for biomass loss resulting from the decomposition of dead biomass (mortality) and logging residues post-thinning. The decomposition of above-ground

biomass, including stems and branches of dead trees, was estimated using the models of (Mäkinen et al., 2006). It is noteworthy that the decomposition rate of dead stumps and roots of silver birch exceeds that of the stems (e.g. Shorohova et al., 2008). Therefore, for the former, the method outlined in (Hynynen et al., 2015) was employed with the stem wood decomposition model for below-ground biomass compartments being adjusted accordingly. The predicted percentage of remaining biomass in the stump and roots 40 years after the tree's death was found to align with the findings presented in the referenced articles. Subsequently, the carbon content was deemed to be 0.5 of the dry weight of the biomass and expressed as CO₂ equivalent (Mg CO₂Eq ha⁻¹).

2.4. Treatments

The Experimental design comprised seven thinning programmes consisting of the first commercial thinning and a potential second thinning. These were as follows: (1) Two heavy thinnings, (2) One heavy thinning, (3) Light and heavy thinning, (4) Two moderate thinnings, (5) Moderate and light thinning, (6) One or two light thinnings and (7) Unthinned control.

The thinning intensity of the first commercial thinning (FCT) was based on the basal area, with an unthinned control (level= 100 %) representing the baseline (Fig. 2). The remaining levels were as follows: light thinning (level= 80 %), moderate thinning (level= 65 %), and heavy thinning (level= 50 %). In certain instances, portions of the unthinned and light-thinned plots were subjected to heavy thinning following a five-year period of FCT (level= 40 %). In other instances, the second thinning was conducted 10 years after the initial FCT, with varying intensities: heavy (level= 35 %), moderate (level= 50 %), or light (level= 60 %).

The thinnings were conducted as thinning from below, with the

exception of ten plots in five experiments where the second thinning, conducted ten years after the initial one, was a cautious thinning from above. In this method, trees of all sizes were removed, including the largest dominant trees. The thinning programmes were implemented for the initial 20 years of the experiments. In 33 plots (19 %), no thinning was conducted, allowing the trees to grow without thinning. The plots that had been treated with different thinning programmes (and thus were not unthinned or subjected to two heavy thinnings) were subjected to a further heavy thinning 20 years (19 plots) or 25 years (18 plots) after the initial thinning (Fig. 2). This will henceforth be referred to as 'Late heavy thinning 20 y' and 'Late heavy thinning 25 y', respectively.

The results were examined across the entire dataset over a 20-year period (17 experiments, 174 plots). The data set was analysed separately over a 30-year research period for measurements from six 5-year intervals (14 experiments and 145 experimental plots), including treatments designated as "late heavy thinnings."

At the time of establishment, the mean age of the stands was 20 years, with a range of 17 to 23 years (Table 1). The mean site index (SI) (Lee et al., 2024) for a stand aged 50 years was 26.8 m (range: 19.9–31.7 m). In the establishment phase, the mean stem number was 1745, with a range of 966–2747 trees per hectare. The four experimental stands had undergone prior light thinning, resulting in a lower initial stand density than the other stands. In the experiments in which no treatment was applied, the stem number was, on average, 1928 trees per hectare, the basal area was 16.0 m² per hectare, and the stem volume was 95.1 m³ per hectare prior to the implementation of treatments. In the establishment phase of all experiments, the dominant height ranged from 12.0 to 16.9 m, the dominant diameter from 12.8 to 17.4 cm, and the height to crown base from 2.9 to 7.0 m (Table 2).

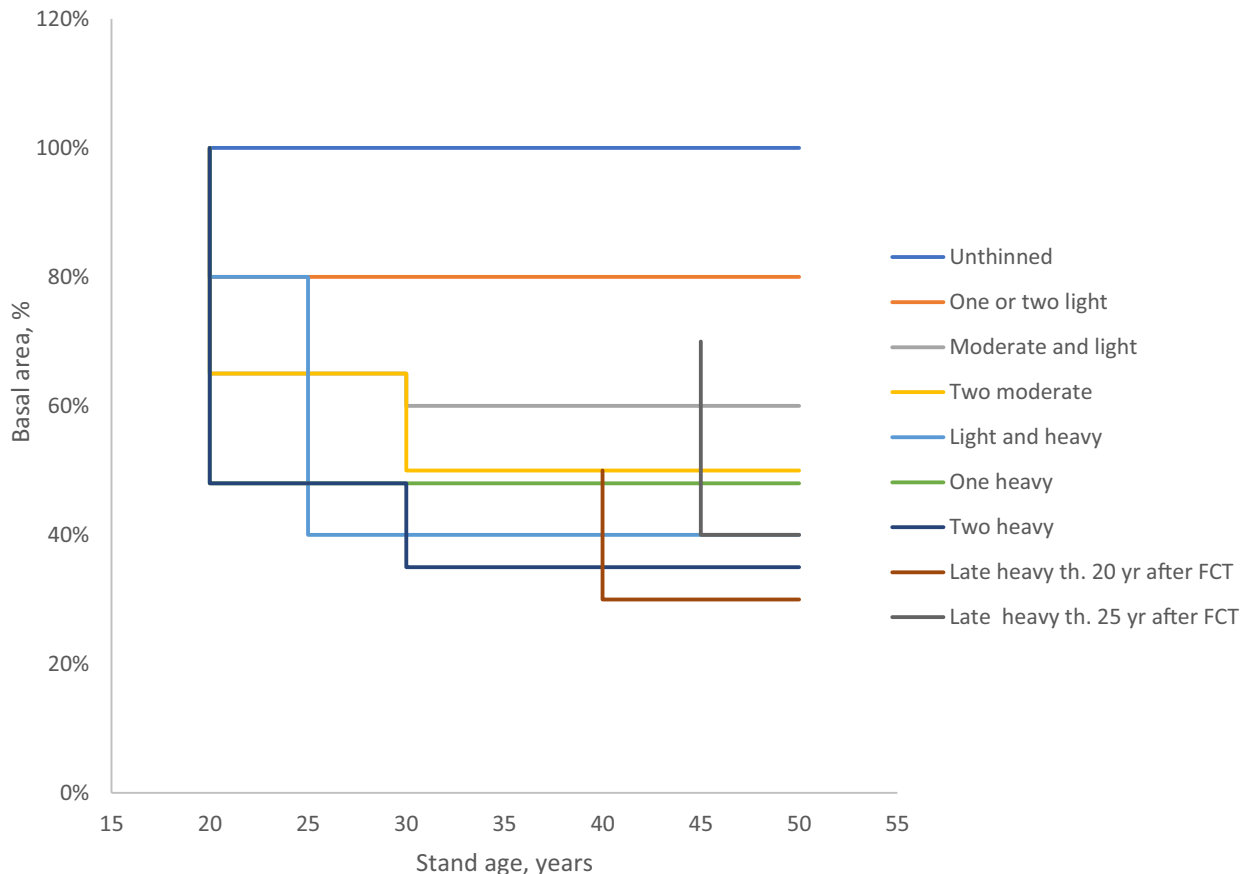


Fig. 2. Schematic view of treatments and their timing in experiments. Treatments intensity is based on proportion of unthinned treatment.

Table 2

The characteristics of the experiments prior to their first thinning at the start of the study period. Experiments 859 and 860 (partially), along with 835 and 841, underwent a light thinning five years before experiment establishment.

Experiment	Stem number		Basal area		Stem volume		Mean* diameter	Dominant diameter	Mean* height	Dominant height	Crown base
	mean N ha ⁻¹	sd N ha ⁻¹	mean m ² ha ⁻¹	sd m ² ha ⁻¹	mean m ³ ha ⁻¹	sd m ³ ha ⁻¹	cm	cm	m	m	m
832	1362	160	13.3	1.5	68.7	11.4	12.1	15.1	11.1	12.1	3.7
833	1907	430	19.6	1.2	118.5	10.1	12.4	16.1	13.1	14.3	6.0
834	1459	145	15.0	1.7	88.7	16.0	12.1	15.1	12.4	13.5	4.1
835	966	73	14.3	1.7	102.8	18.8	14.4	17.4	15.2	16.2	5.8
836	1693	273	19.8	1.7	142.9	18.1	13.0	16.6	15.7	16.9	7.0
837	1745	176	17.9	1.8	115.9	16.3	12.2	15.9	13.8	15.3	5.4
838	1971	376	15.1	0.8	91.8	7.8	11.1	14.9	13.0	14.7	4.6
839	2028	442	13.3	1.5	69.0	9.2	10.4	14.3	10.9	12.2	3.0
840	2163	186	19.2	1.0	122.2	7.6	11.5	15.4	13.5	14.9	6.2
841	1042	77	12.0	0.6	72.0	3.8	12.6	15.2	12.8	13.7	5.2
842	2152	247	17.5	1.9	101.7	15.4	11.2	15.2	11.8	13.3	5.3
845	1760	169	13.6	1.5	75.8	11.5	10.8	14.5	11.7	13.3	4.1
846	2148	274	14.1	1.5	83.6	14.0	10.2	13.9	12.3	14.0	4.8
857	2110	341	15.8	1.3	74.7	12.0	11.4	15.5	10.6	12.0	2.9
859	1544	538	15.0	3.4	88.6	21.3	11.7	14.1	12.9	13.9	4.1
860	1582	530	12.2	2.0	67.8	13.3	10.9	14.0	11.9	13.0	3.2
867	2747	354	15.1	0.7	86.9	5.8	9.4	12.8	10.9	12.4	4.0
Total**	1745	515	15.3	2.8	91.6	23.8	11.7	15.1	12.6	13.9	4.6

*basal area weighted, **mean and sd values from plot level

2.5. Statistical methods

The effects of the thinning programme on stand-level characteristics, growth, and yield in both former agricultural and forest sites (soil class) were analysed using linear mixed models (IBM Corp., 2021). The thinning treatments included both thinning from above and late heavy thinning. In the models, the experimental stand was treated as the random variable, while the site index (dominant height at age 50) (H_{50}) was employed as a covariate in the fixed part. In order to obtain the site index, the dominant height at age 50 was calculated as the mean of measurements taken at each plot using the SI model proposed by (Lee et al., 2024).

$$Y_{ijk} = \beta_0 + \beta_1 \text{Thinning program}_{ijk} + \beta_2 \text{Soil class}_i + \beta_3 \text{Late heavy}_{ik} + \beta_4 \text{Thinning type} + \beta_5 X_{ijk} + \mu_i + \mu_{ij} + \varepsilon_{ijk} \tag{1}$$

where Y_{ijk} is one of the variables of interest on plot k in measurement time j in stand i . β_n are fixed coefficients, X the covariate value (H_{50}), μ random effects for each plot and measurement time (replicate) and ε is the random error.

3. Results

3.1. Stand development

The thinning program had a significant impact on the development

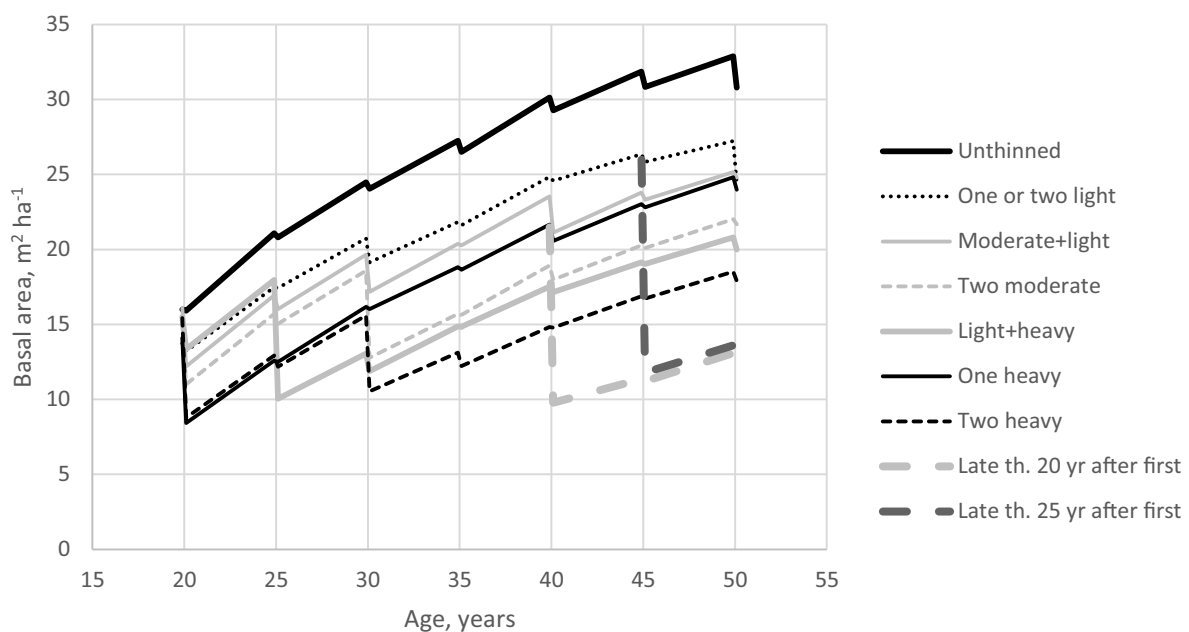


Fig. 3. Development of stand basal area in different silver birch thinning programs during 30 years after the first thinning at age of 20 years (total stock at the end and living stock at the beginning of each 5-year period).

of basal area, diameter, and crown ratio in the planted silver birch stands. However, it did not have a notable effect on the growth of the dominant height.

The development of average basal area in the birch stands was consistent with the pattern illustrated in Fig. 3. It is evident that the highest basal area was observed in unthinned plots, reaching an average of 30 m² ha⁻¹ at approximately 40 years of age. Subsequently, the maximum basal area demonstrated only a slight increase, the mean basal area of living trees, at an age of 45 years, being 29.2 m² ha⁻¹ on agricultural sites and 32.2 m² ha⁻¹ on forest sites. The variation in the basal area of the unthinned plots increased markedly towards the end of the study period. At 40–45 years of age, the standard deviation, which had previously been approximately 3 m² ha⁻¹, rose to 3.8, and at 50 years of age it reached 4.5 m² ha⁻¹.

Without a late heavy thinning, the average basal area reached 20–25 m² ha⁻¹ at the end of the study period in the different thinning programs, except for the two heavy thinnings, which averaged 18 m² ha⁻¹. The mean basal area for the late-thinned plots at the end of the study period was 13 m² ha⁻¹.

The data demonstrate a clear and consistent effect of thinning

programs on the dominant diameter of tree stands. The results indicate that intensive thinning resulted in higher dominant diameter development (Fig. 4). At the end of the study period, the mean dominant diameter of the unthinned birch stand was 25.0 cm (s = 2.5), while in lightly thinned stands, it was 26.0 cm (s = 1.4). The largest dominant diameter was achieved in two heavy thinnings, with a value of 28.3 cm (s = 2.3), followed by one heavy thinning with a value of 28.0 cm (s = 2.0). The diameter differences between treatments were greater in terms of the basal area weighted mean diameter compared to the dominant diameter (Fig. 4).

The mean dominant height of the stand at the end of the study period was 27.2 m, with no significant differences observed among the thinning programs (p = 0.313). However, the one heavy thinning treatment exhibited a notable acceleration in dominant height growth during the latter half of the study period, displaying a faster rate of increase compared to the other treatments.

The thinning programs also had a significant impact on the canopy of the birch trees. According to Fig. 5, the live crown ratio of the trees in the unthinned birch stand was 61.4 % (s = 7.3) at the beginning of the study period and decreased to 37.8 % (s = 3.6) after 30 years. During the study

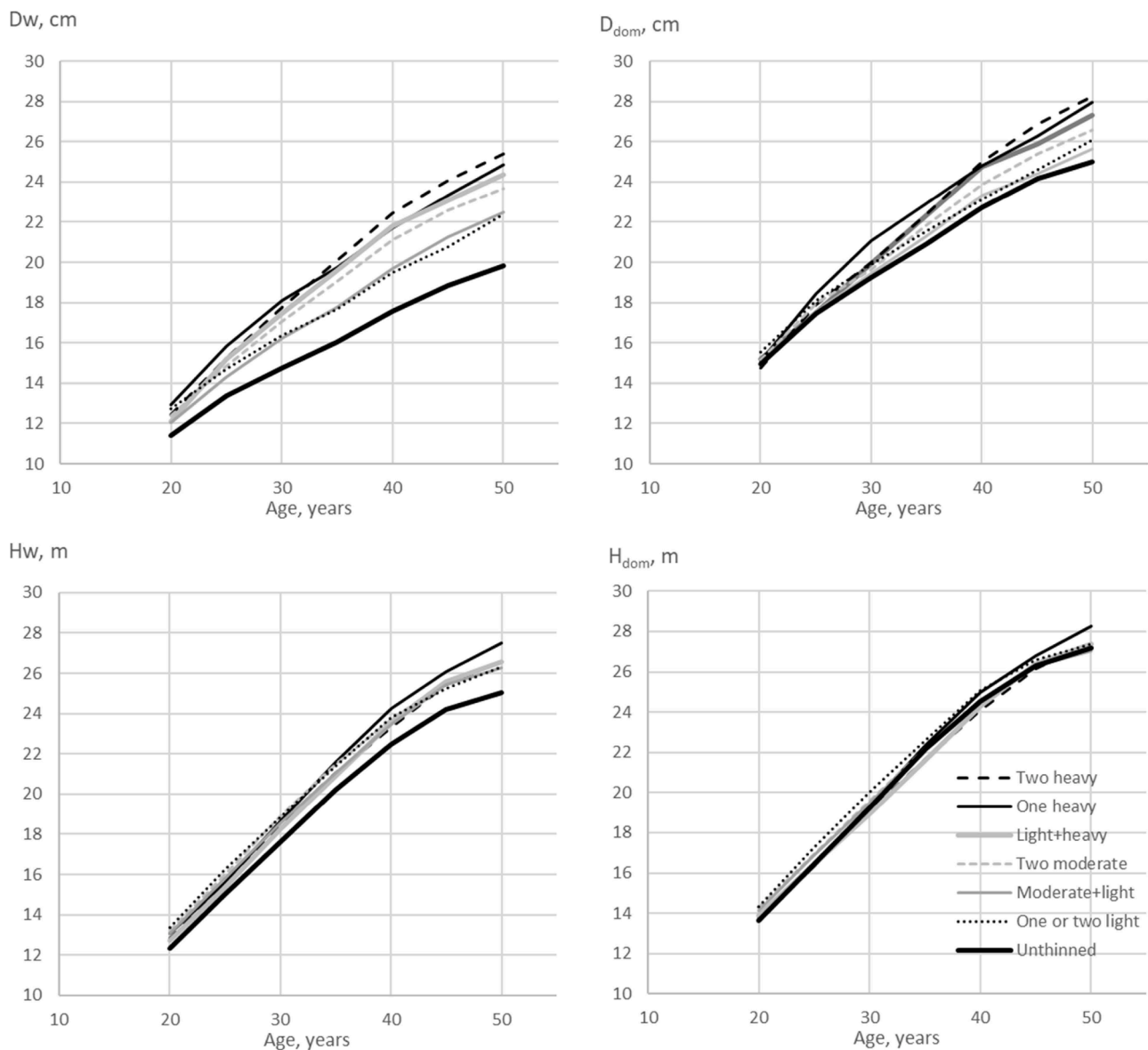


Fig. 4. Development of basal area weighted mean diameter (Dw) and dominant diameter (D_{dom}), as well as basal area weighted mean height (Hw) and dominant height (H_{dom}), in different thinning programs for 30 years after the first commercial thinning.

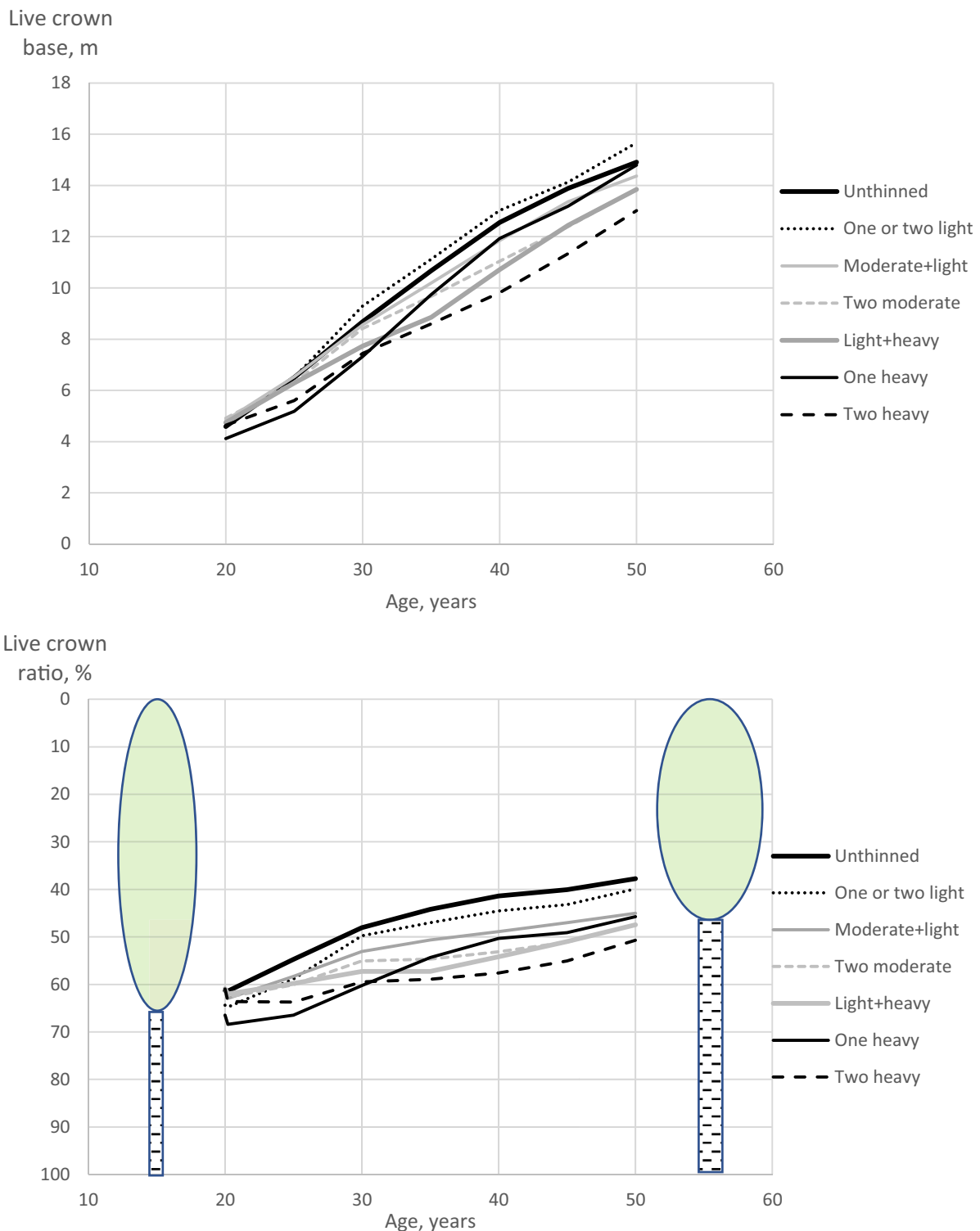


Fig. 5. The average development of the live crown base and the crown ratio (the live crown height divided by the tree’s height) in planted birch stands under different thinning programs for 30 years after the first commercial thinning.

period, the live crown length in the unthinned birch stand increased by only 2 m, from an average of 7–9 m. In lightly thinned birch stands, the live crown ratio was approximately three percentage units higher than in the unthinned stands, with the lower limit of the live crown rising to an average height of 15–16 m in these dense stands.

In the thinning program involving two heavy thinnings, the crown base height at the end of the study period was on average 13 m, with the length of the live crown exceeding 13 m. This resulted in an average

crown ratio of 50.5 % ($s = 6.3$). With regards to the one heavy thinning treatment, the live crown was in the first part of the study period longer than in the other treatments. However, following the midpoint of the study period, the live crown exhibited a similar growth pattern to that observed in the moderately thinned stands. Except for the program involving two heavy thinnings, at the end of the study period, all other heavily or moderately thinned birch stands reached an average crown ratio of 45–47 % (Fig. 5) and a crown length of 12.0–12.5 m. In thinning

programs one heavy and moderate thinning live crown did not differed statistically significantly from each other's ($p < 0.05$).

3.2. Growth and mortality of stands in 5-year periods

The total annual growth of the stand's basal area, including the growth due to natural mortality, was highest during the first measurement period regardless of the treatment applied (Fig. 6). The growth exhibited a declining trend throughout the entire study period, with the exception of an increase that followed the second thinning. Following the second thinning, a substantial increase during the second five-year period was observed, which corresponds to 16–20 years after the first commercial thinning, but five years earlier in the "light + heavy" treatment, where the second thinning occurred only 5 years after the first commercial thinning. It is also possible that the weather conditions during this period were more favourable, as the total growth of the unthinned stand also increased during that time. Indeed, the basal area growth of the unthinned stands was the highest throughout the entire study period, except for the final two measurement periods, during which the "moderate and light" thinning program exhibited a similar growth rate.

Intensive thinning reduced the growth of the basal area, although not consistently, as the growth of once heavily thinned stands only declined slower than the others. On the other hand, the growth of once or twice lightly thinned stands was lower than the others, but the sample size was small (possibility of chance).

The annual volume growth of the stand, including the natural mortality, remained relatively stable for approximately 20 years, following the first commercial thinning, up until the stand age 40, after which a decline was observed (Fig. 6). The decline in growth was particularly pronounced in the last measurement period (1.4–2.8 $m^3 ha^{-1} a^{-1}$), except for initially heavily thinned stands at the beginning of the study (one or two heavy thinning). Additionally, a decline in volume growth was observed during the five-year period following the second thinning, followed by a notable increase in growth, except for the program comprising two heavy thinning, where volume growth exhibited a consistent decline throughout the study period. The volume growth of lightly thinned stands exhibited a value approaching the mean of all treatments, while their basal area growth was markedly lower, suggesting a tendency towards a slender stem form.

The mortality rate was analysed in the data set, comprising 111 sample plots. The analyses included the plots with the study period of at least 29 years and excluded the plots exhibiting late heavy thinning. The mortality of birch trees increased significantly during the last two

measurement periods, around after 40 years of age (Fig. 7), with an earlier increase observed in unthinned and lightly thinned stands. The mortality rate was found to be approximately three times higher in former agricultural sites than in forest sites. By the end of the study period, approximately 50 years of age, the cumulative mortality in unthinned plots averaged $79 m^3 ha^{-1}$ in former agricultural sites and $24 m^3 ha^{-1}$ in forest sites, through there was considerable variation ($s_{agr} = 33$ and $s_{for} = 20$). In heavily or moderately thinned birch stands, the corresponding average mortality was $18.6 m^3 ha^{-1}$ on former agricultural sites and $6.8 m^3 ha^{-1}$ on forest sites. The standard deviation of mortality across the entire dataset was significantly higher in plots with one heavy thinning ($s = 29$) compared to other thinned stands ($s = 7-16$), indicating a higher vulnerability to risks.

3.3. Stand growth for a 20-year period after first commercial thinning

3.3.1. Basal area and volume growth

This study examined the growth of stand basal area and volume over a 20-year period, with a focus on stands aged between 20 to 40 years old and following the first commercial thinning in the entire dataset (Fig. 8, Table 3, 168 sample plots). The thinning program had as significant effect on basal area growth (Model 1, Table 3). A nearly significant difference was between forest and former agricultural sites ($p = 0.078$). No significant interactions were observed between the predictors. The annual growth of the basal area (including growth due to natural mortality) over the 20-year period was dependent on the thinning program, with an average of $0.64-0.76 m^2 ha^{-1} a^{-1}$ observed for forest sites with an average site index of 27.2 m (Table 3 and Fig. 8A). The lowest basal area growth was subjected to two heavy thinning, while the highest growth was recorded in moderately or lightly thinned and unthinned stands. In former agricultural sites, the mean basal area growth was $0.09 m^2 ha^{-1} a^{-1}$ higher than in forest sites, regardless of site index and thinning program.

The thinning program and site index had a significant effect on stem volume growth over a 20-year period. However, the difference between forest and former agricultural sites was not significant ($p = 0.105$) (Model 3, Table 3). The annual stem volume growth ranged from 8 to $11 m^3 ha^{-1} a^{-1}$, depending on the thinning program, with an average site index of 27.2 m (Table 3 and Fig. 8B). An increase of one meter in site index resulted in an average growth increase of $0.4 m^3 ha^{-1} a^{-1}$. The lowest volume growth was observed in the two heavy thinning treatments at $8 m^3 ha^{-1} a^{-1}$, while the highest growth was observed in the lightly thinned and unthinned stands, at $10-11 m^3 ha^{-1} a^{-1}$.

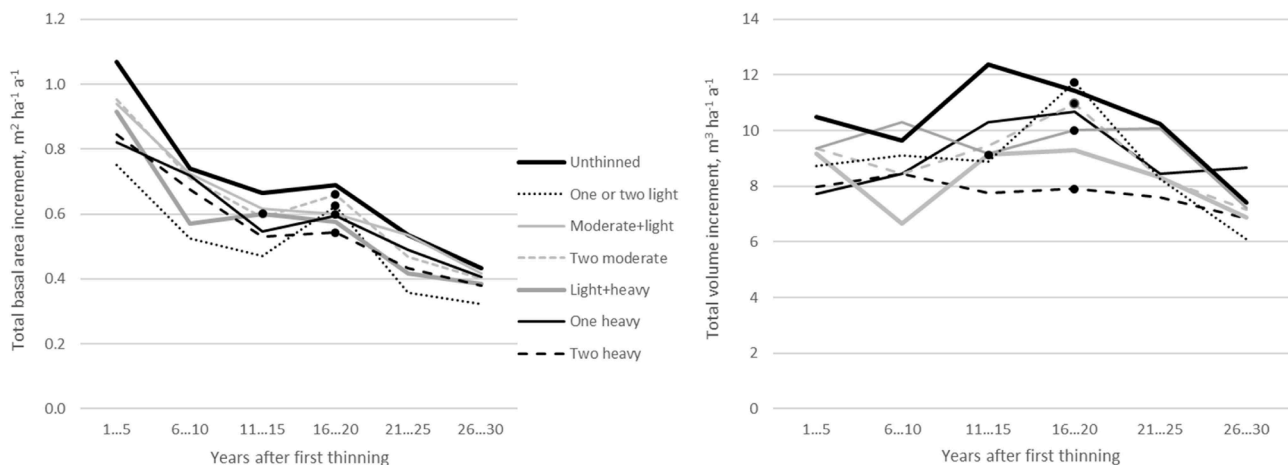


Fig. 6. Annual average growth of basal area and stem volume in planted birch stands under different thinning programs during six 5-year periods for 30 years after the first commercial thinning of the stand. Averages were calculated from 111 sample plots without any subsequent late heavy thinning. The symbol "●" indicates the growth increase in the second 5-year period following the second thinning.

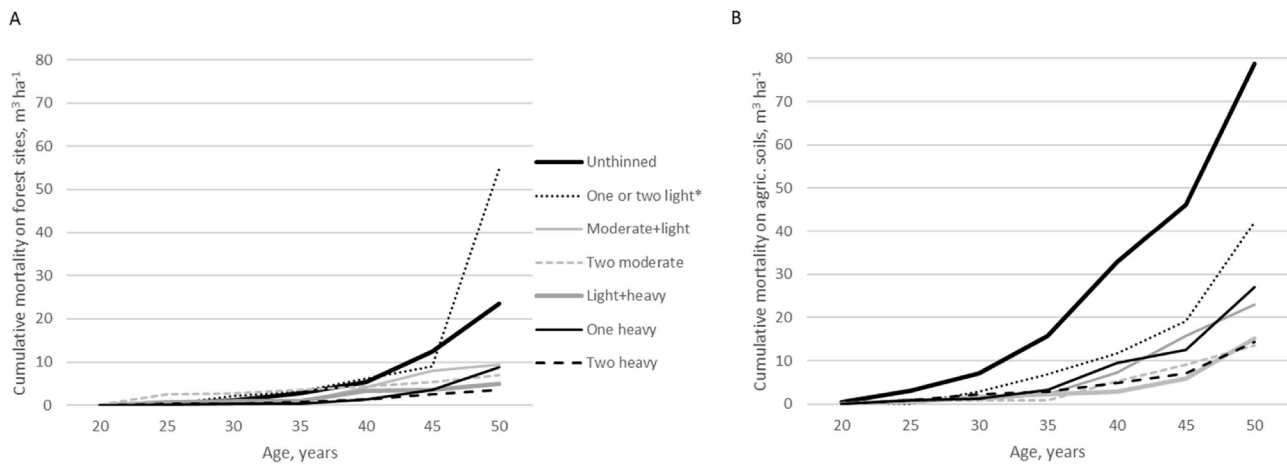


Fig. 7. Cumulative mortality in planted birch stands on forest sites (A) and former agricultural soils (B) under different thinning programs measured throughout the entire 30-year study period. Averages were calculated from 111 sample plots without any subsequent late heavy thinnings. *) Only 3 observations at last period on forest sites.

3.3.2. Dominant diameter and mean diameter

The impact of thinning treatments on dominant diameter (D_{dom}) and basal area weighted mean diameter (D_w) over a 20-year period following the first commercial thinning (when the stand age was approximately 20 to 40 years) was modelled using a dataset that had been measured for a minimum of 20 years (160 sample plots) (Table 4, Models 5 and 6). The development of dominant diameter was significantly affected by site index, dominant diameter at the time of the first commercial thinning, soil class, and thinning method at the second thinning. An increase of one meter in site index was found to result in a 0.28 cm increase in dominant diameter at the time of the initial thinning, with this effect increasing to 0.46 cm over the subsequent 20-year period for both dominant diameter and mean diameter. The dominant diameter was observed to be 1.2 cm larger ($p = 0.011$) and the mean diameter was 0.84 cm larger ($p = 0.013$) on former agricultural sites in comparison to forest sites. A thinning from above carried out 10 years after the first thinning resulted in a reduction of the dominant diameter by 1.42 cm ($p = 0.000$) and the basal area-weighted mean diameter by 1.48 cm ($p = 0.000$).

Twenty years after the first commercial thinning, the highest basal area weighted mean diameter and dominant diameter were 22.8 cm and 25.3 cm (Fig. 9A, B). These results correspond to an average site index of 27.2, a two heavy thinning program, and represents the average for former agricultural and forest sites. When the birch stand was thinned more lightly, the corresponding mean diameter and dominant diameter were observed to be smaller. In unthinned stands, these diameters were observed to be 17.3 cm and 22.7 cm, respectively.

3.4. Mature birch stand growth during a 21–30 -year period after first commercial thinning

3.4.1. Basal area and volume increment

The growth of the stand in the 21–30 -year period, which corresponds to a stand age approximately 40 to 50 years, in mature birch stands was also examined. The analysis was conducted on a subset of the data set comprising a minimum measurement period of 29 years (see Figs. 10–12, 147 plots).

The thinning program, soil class, late heavy thinning of mature forests, and height-based site index (conversion of $1/H_{50}$) were identified as significant factors influencing basal area and stem volume growth, including natural mortality (Models 2 and 4, Table 3, 142 sample plots). The impact of the thinning method on the outcome variables was not statistically significant. The annual growth of the basal area was observed to be $0.085 \text{ m}^2 \text{ ha}^{-1}$ higher on former agricultural sites in

comparison to forest sites, with a corresponding difference in annual volume growth of $1.55 \text{ m}^3 \text{ ha}^{-1}$. The late heavy thinnings were conducted at approximately 40 or 45 years of age, 20 or 25 years after the first thinning. The results indicated that these treatments reduced the annual basal area growth by an average of $0.07 \text{ m}^2 \text{ ha}^{-1}$ and the volume growth by $2.1 \text{ m}^3 \text{ ha}^{-1}$.

A one-meter increase in height-based site index (H_{50}) was found to result in an annual volume growth increase of $0.18 \text{ m}^3 \text{ ha}^{-1}$ on the most fertile forest sites (OMT) and $0.25 \text{ m}^3 \text{ ha}^{-1}$ on the fertile sites (MT). The corresponding effect on annual basal area growth was not statistically significant. In the absence of thinning of mature stands, the annual average growth of basal area was observed to be $0.39\text{--}0.48 \text{ m}^2 \text{ ha}^{-1}$ (Fig. 10A). The highest basal area growth was observed in the treatments designated as “moderate and light” and “unthinned”, while the lowest was observed in the treatment designated as “two heavy” (Fig. 10A). The overall volume growth exhibited a comparable trend, with values ranging from 7.1 to $9.1 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$ across different treatments (Fig. 10B).

3.4.2. Mean diameter and dominant diameter

The factors that explain the annual growth of basal area weighted mean diameter and dominant diameter during the 21–30-year observation period were the thinning program, late heavy thinning of mature stands, and the initial basal area weighted mean diameter or dominant diameter at the beginning of the observation period (models 7 and 8, Table 4, 142 sample plots). The difference between soil classes (forest/former agricultural sites) was found to be nearly significant ($p = 0.071$). The effect of site index was not found to be significant. The annual growth of dominant diameter on former agricultural sites was 0.056 cm greater than on forest land, while the difference in mean annual diameter growth was 0.038 cm. Following the implementation of a late heavy thinning regime on mature birch stands, the annual growth of dominant diameter and mean diameter was observed to be 0.11–0.12 cm higher during the subsequent 10-year period in comparison to stands that had not undergone late thinning. In late heavy thinned stands, the increase in annual diameter growth was less than half that observed during the five-year period at approximately 45 years of age.

The modelled estimates for dominant and mean diameters were calculated as follows: firstly, the diameter estimates for the below-thinned stands were calculated as a function of site index for the entire dataset using models 5 and 6 at 20 years after the first thinning (at approximately 40 years old). Subsequently, the 10-year growth was incorporated using models 7 and 8, based on a subset of data that had been measured for an additional ten years. The calculations for the end

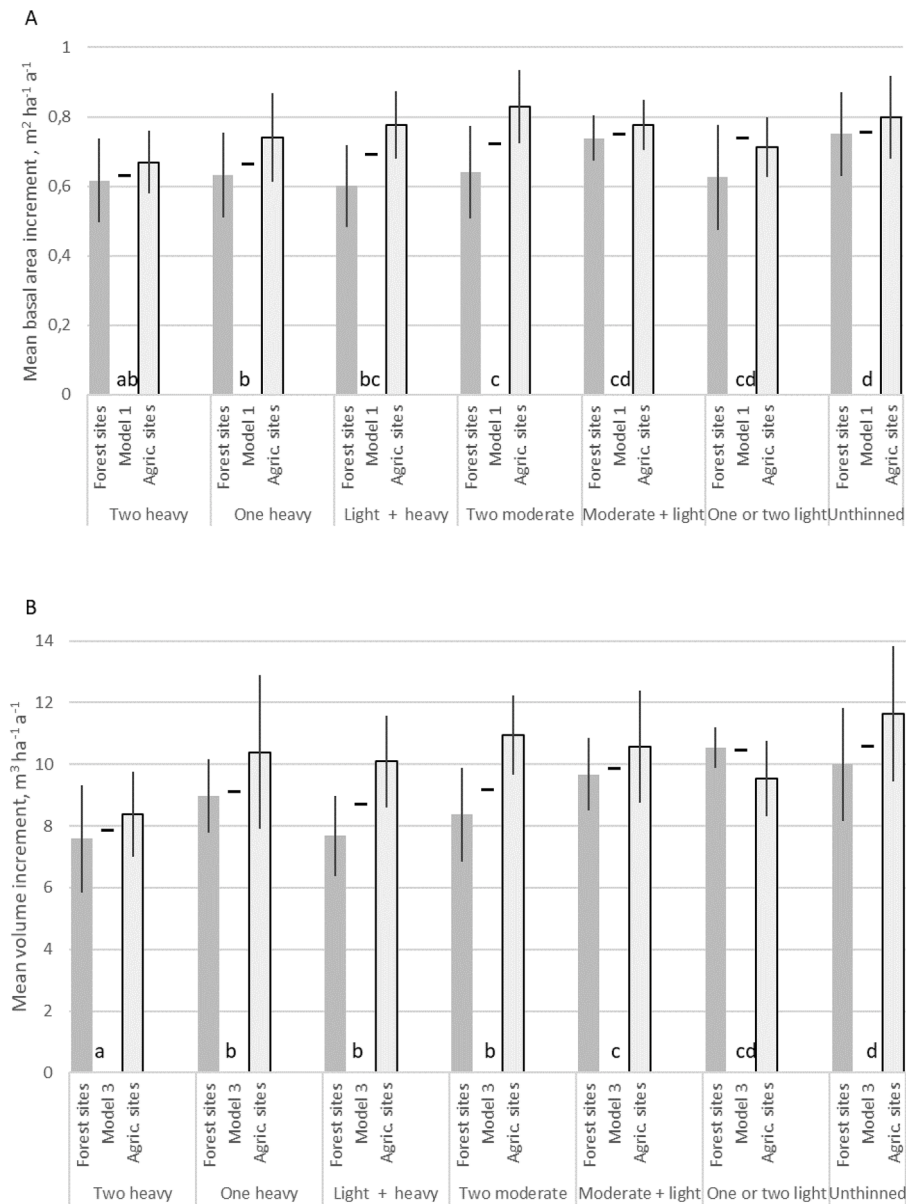


Fig. 8. Annual total growth of basal area (A) and stem volume (B) in birch stands (including natural mortality) for a 20-year period following the first commercial thinning under different thinning programs in the entire study dataset. The bars represent the average growth separately for former agricultural and forest sites, and the vertical lines represent the standard deviation of growth. The symbol "-" indicates growth estimates calculated by models 1 and 3 as the average for forest and former agricultural sites when the site index was the dataset's average of 27.2 m. According to the model, there was a statistically significant difference ($p > 0.05$) between the treatments labeled with different letters (a–d).

of the study period were conducted separately for each thinning program on former agricultural and forest sites, with a discrepancy of 1.22 cm in dominant diameter and 0.84 cm in mean diameter at age 40, exhibiting higher values for former agricultural sites. According to the models, the mean diameter of the unthinned birch stand with an average site index of 27.2 m was 19.0 cm at the end of the study period. Additionally, the mean dominant diameter was 25.4 cm, representing the average of former agricultural and forest sites (Fig. 11). In the two heavy thinning program, the corresponding diameters were 25.9 cm and 28.9 cm. This indicates that, over a 30-year period following the first thinning, the mean diameter (BA-weighted) and dominant diameter differed by 6.9 cm and 3.5 cm, respectively, between unthinned and heavily thinned stands. In the absence of late heavy thinnings in mature stands, diameter estimates increased with increasing thinning intensity, ranging from the minimum to the maximum, except for the "One heavy" thinning

treatment, where the mean diameter was particularly lower than other heavy and moderate thinning treatments (Fig. 11).

The late heavy thinning, implemented 10 years prior to the end of the study period, resulted in an increase of 1.1 cm in the dominant diameter, whereas the late heavy thinning conducted 5 years before the end of study period resulted in a mere 0.2 cm increase. The impact on the basal area weighted mean diameter is more pronounced because the mean diameter exhibited an increase during the tree selection process for late heavy thinning, with an average increase of 0.7 cm, and further due to the thinning reaction. The overall effect of late heavy thinning carried out at the age of 40 years on mean diameter was found to be 2.0 cm and 1.3 cm in stands that were heavily thinned five years later.

Table 3

Details for the mixed linear models of annual basal area (I_G) and stem volume (I_V) growth of the silver birch stands with different thinning programs at the age periods of 21–40 (n = 160) years and 41–50 years (n = 142).

		Basal area, m ² ha ⁻¹ a ⁻¹				Stem volume, m ³ ha ⁻¹ a ⁻¹			
		Model 1		Model 2		Model 3		Model 4	
		I_{G21-40}		I_{G41-50}		I_{V21-40}		I_{V41-50}	
		R ² = 0.28		R ² = 0.31		R ² = 0.56		R ² = 0.40	
		F	Sig.	F	Sig.	F	Sig.	F	Sig.
Fixed parameters									
b_0	Intercept	64.3	0.000	20.7	0.000	170	0.000	30.5	0.000
b_1	Thinning programs	15.9	0.000	5.8	0.000	29.5	0.000	4.7	0.000
b_2	Agricult/Forest	3.6	0.078	5.7	0.033	3.0	0.105	4.8	0.049
b_3	Late heavy thinning			14.0	0.000			30.4	0.000
b_4	1/H ₅₀	2.4	0.126	0.5	0.501	47.9	0.000	6.1	0.000
	b_4 coefficient	-4.42		-1.84		-281.6		-145.2	
Random parameters									
	Estim.	Std.e.		Estim.	Std. e.	Estim.	Std. e.	Estim.	Std. e.
δ^2_{stand}	Stand	0.0081	0.0032	0.00041	0.0017	0.981	0.419	1.585	0.184
δ^2_e	Residual	0.0036	0.0004	0.0030	0.0004	0.781	0.094	1.451	0.712

Table 4

Details for the mixed linear models of basal area weighted mean diameter (D_w) and dominant diameter (D_{dom}) of the silver birch stands with different thinning programs at the age of 40 years (n = 160) and diameters growth (I_{Dw} and I_{Ddom}) at the age period of 41–50 years (n = 142).

		Diameter, cm				Diameter growth, cm a ⁻¹			
		Model 5		Model 6		Model 7		Model 8	
		D_{w40}		D_{dom40}		$I_{Dw41-50}$		$I_{Ddom41-50}$	
		R ² = 0.81		R ² = 0.72		R ² = 0.65		R ² = 0.43	
		F	Sig.	F	Sig.	F	Sig.	F	Sig.
Fixed parameters									
b_0	Intercept	0.2	0.682	2.4	0.125	4.6	0.035	8.7	0.004
b_1	Thinning programs	90.5	0.000	30.8	0.000	11.1	0.000	9.7	0.000
b_2	Agricult/Forest	8.6	0.013	8.5	0.011	3.9	0.071	5.0	0.043
b_3	Late heavy thinning					84.7	0.000	36.4	0.000
b_4	Thinning method	15.6	0.000	18.4	0.000				
b_5	H ₅₀	23.5	0.000	10.3	0.002				
b_5	D_{dom20}	68.7	0.000	118.9	0.000	* D_{w40}	0.000	* D_{dom40}	0.006
	Covariate coefficient	H ₅₀	0.277	H ₅₀	0.199				
		D_{dom20}	0.765	D_{dom20}	1.035	D_{w40}	.0100	D_{dom40}	.0071
Random parameters									
	Estim.	Std.e.		Estim.	Std.e.	Estim.	Std.e.	Estim.	Std.e.
δ^2_{stand}	Stand	0.185	0.126	0.568	0.256	0.0012	0.0005	0.0020	0.0009
δ^2_e	Residual	1.047	0.126	0.791	0.095	0.0010	0.0001	0.0016	0.0002

* D_{w40} calculated by model 5 including the effect of thinning from below (=+0.7 cm) and D_{dom40} calculated by model 6, for treatments and for forest sites and agric. sites separately

3.5. Wood production and mortality by the age of 50

Heavy thinnings resulted in a decreased total yield of stem wood when compared to the yield of lightly thinned and unthinned stands. However, it was observed that heavy thinnings led to an increased sawlog yield (Fig. 12). The highest rates of natural mortality and the production of small-diameter wood were observed in unthinned and very lightly thinned stands. However, heavy thinnings appeared to result in a higher mortality rate than moderate thinnings. In particular, late heavy thinnings were found to have a significant negative impact on total yield, particularly in stands that had previously undergone moderate or light thinning. The mean total yield of unthinned stands was 398 m³ ha⁻¹, whereas two heavy thinnings produced an average of 323 m³ ha⁻¹. In general, the total yield of late heavy thinnings was found to be 27 m³ ha⁻¹ lower than that of the no late thinned stand.

The thinning program, soil class, and the interaction between site type and site index were found to have a significant effect on total stem wood yield (including natural mortality) (Table 5, Fig. 13A). Late heavy thinning did not result in a statistically significant reduction in yield ($p = 0.20$), nor did the choice of thinning method. An increase of one meter in site index was found to result in a 33 m³ ha⁻¹ increase in total yield on forest sites in the fertile sites (MT), while in the most fertile sites (OMT), the yield increase was only 11 m³ ha⁻¹. The effect was found to be 8 m³

ha⁻¹ lower on former agricultural sites than on forest sites. The highest total yield was observed in unthinned stands, with an average of 405 m³ ha⁻¹ when the site index was the average of the dataset (27.2 m). However, the yield of lightly thinned stands did not significantly differ from that (Fig. 13A). The lowest total yield was observed in the "Two heavy" treatment, with a yield of 340 m³ ha⁻¹ until the age of 50 years.

The thinning program, soil class and site index were found to have a significant impact on natural mortality (see Table 5 and Fig. 13B). In stands that had been thinned, an increase of one meter in site index was found to result in an average increase in natural mortality on forest sites of 0.4 m³ ha⁻¹ on the fertile sites (MT) and 1.1 m³ ha⁻¹ on the most fertile sites (OMT). Similarly, on former agricultural sites, an increase of one meter in site index was found to increase natural mortality on the fertile sites by an average of 0.9 m³ ha⁻¹ and on the most fertile sites by 2.8 m³ ha⁻¹. Nevertheless, the influence of site index on unthinned stands was approximately four times more pronounced in comparison to thinned stands. The natural mortality of unthinned stands (42 m³ ha⁻¹) with an average site index was found to significantly exceed that of all thinning treatments (Fig. 13B). Conversely, the lowest recorded natural mortality, 5.1 m³ ha⁻¹, was observed in the "Two Heavy" treatment, which exhibited a significantly lower mortality rate than that observed in lightly thinned stands.

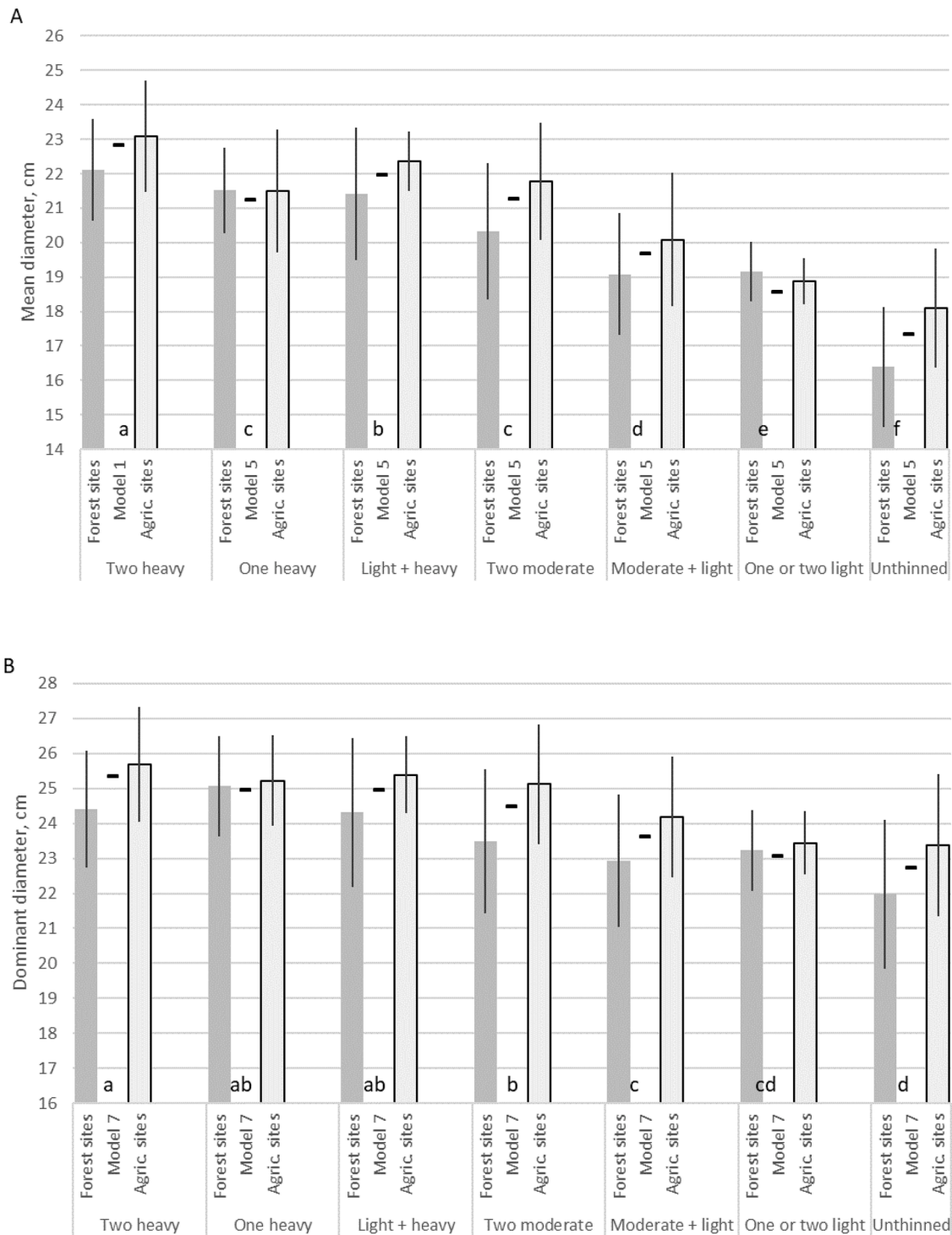


Fig. 9. Basal area weighted mean diameter (A) and dominant diameter (B) of the birch stand, 20 years after the first thinning, in different thinning programs across the entire study dataset (excluding above thinned plots). The columns represent the average diameters separately for former agricultural and forest sites, and the vertical lines represent their standard deviation. The notation "-" indicates growth estimates calculated with models 5 and 6, representing the average for forest and former agricultural sites when the site index was 27.2 m, based on the dataset's average. According to the model, the difference between treatments labeled with different letters (a–f) was statistically significant ($p > 0.05$).

3.6. Carbon balance

The thinning program, site index and late heavy thinning had a considerable impact on the carbon balance (ie. carbon accumulated through growth after thinning compensated the carbon lost due to removals) of tree biomass. No significant differences were observed between the site classes ($p = 0.15$). The two instances of heavy thinning

resulted in the lowest average amount of woody carbon over the observation period of first 20 years. The highest carbon storage was consistently observed in unthinned plots (Fig. 14A). Birch stands continued to function as carbon sink at young age, already after five years of all thinning treatments, including two heavy thinnings (Fig 14B).

The highest carbon storage at 50 years of age was observed in

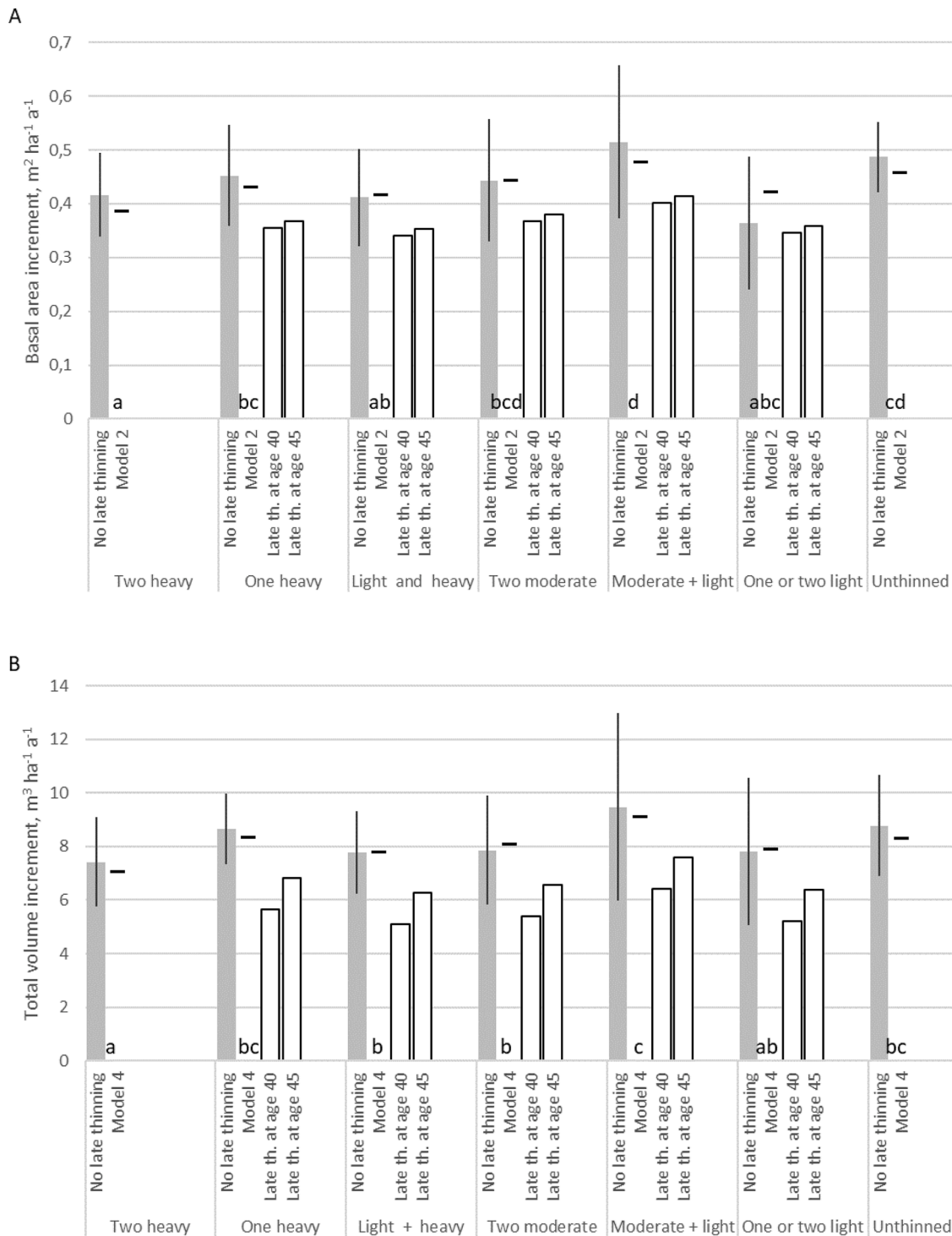


Fig. 10. Annual growth of basal area (A) and stem volume (B) of the birch stand, including natural mortality, during the 21–30 observation years period after the first thinning, in different thinning programs within a subset of data measured for at least 30 years. Dark columns represent average growth without late heavy thinnings, and vertical lines represent the standard deviation of growth. The notation “-” indicates growth estimates calculated with model 6, representing the average for forest and former agricultural sites without late thinning, when the site index was 27.2 m based on the dataset’s average. The difference between treatments labeled with different letters (a–d) was statistically significant ($p > 0.05$). Light columns represent the effects of late heavy thinnings calculated with models 2 and 4.

unthinned stands, with an average of 497 Mg CO₂ eq ha⁻¹ based on model 11 (Table 5) and an average site index of data (SI 27.2 m). The lowest carbon storage was observed in thinning program two heavy thinnings, with an average of 322 Mg CO₂ eq ha⁻¹. As obvious, late heavy thinning resulted in a lower carbon storage at end of the study period (Fig. 15). The presence of a carbon source period was only observed in

previously moderate and light thinned stands during the first five years following late heavy thinning. This occurred 20 years after the first commercial thinning and at a stand age of approximately 45 years.

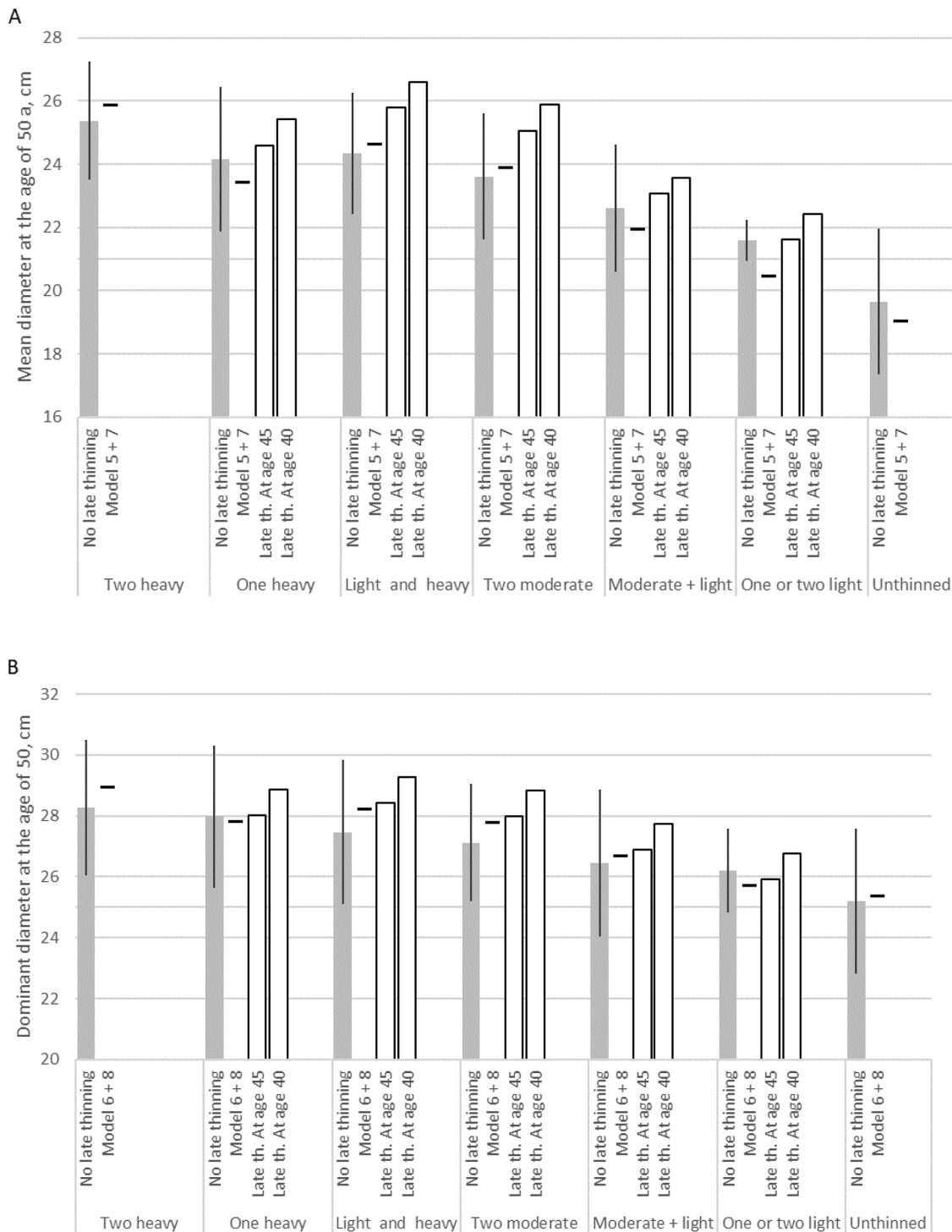


Fig. 11. Basal area weighted mean diameter (A) and dominant diameter (B) of the birch stand, 30 years after the first thinning (at stand age 50), in different thinning programs without distinguishing between former agricultural and forest sites. Dark columns represent diameters measured in a subset of data collected for at least 30 years without late heavy thinnings, and vertical lines represent their standard deviation. The notation "-" indicates estimates calculated with models 5+7 and 6+8, representing the average for forest and former agricultural sites without late heavy thinning, when the site index was 27.2 m based on the dataset's average. Light columns represent the effects of late heavy thinnings.

4. Discussion

The long-term effects of thinnings with varying intensity and timing on the development of planted silver birch stands were evaluated using an extensive data set and regular observations conducted at five-year intervals. This study presents the empirical results of silver birch stand growth and yield following the initial commercial thinning, up until the

stand reaches an age of approximately 50 years. Earlier long-term growth and yield studies of planted silver birch covered a much shorter study period, for example, five years (Niemistö, 1997). It is notable that there is a scarcity of studies examining the development of planted silver birch in Nordic countries, particularly those that employ experimental variations in thinning intensity.

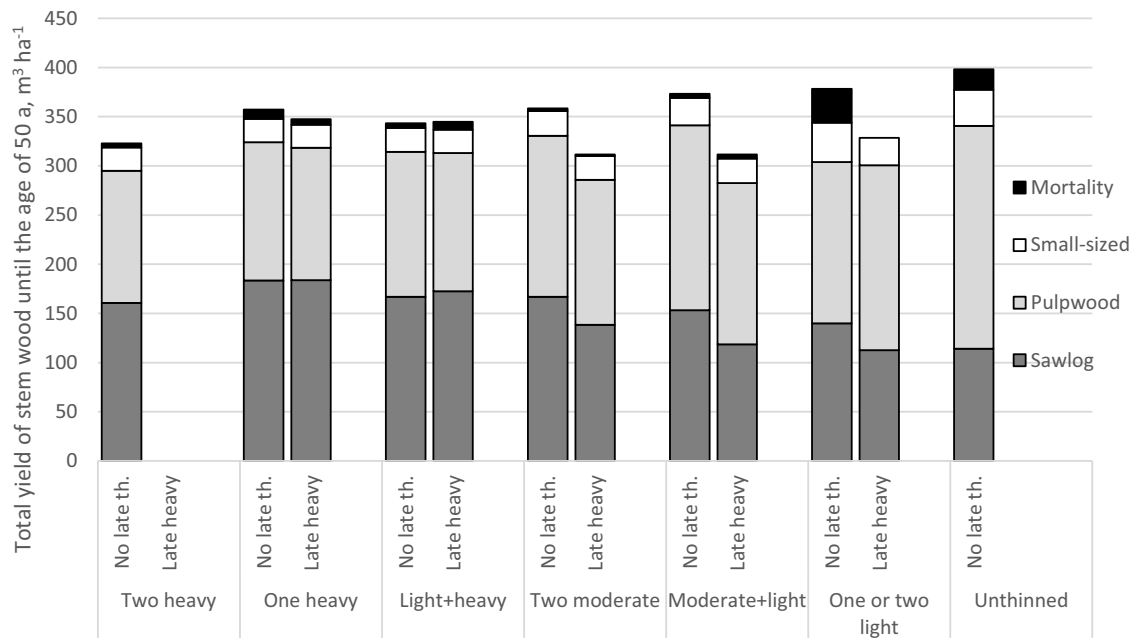


Fig. 12. Total stem wood yield and mortality by the age of 50 years by thinning programs and separately for mortality and timber assortments. Mean values calculated for the plots with study period at least 29 years.

Table 5

Details for the mixed linear models of the total volume (V_{tot}), mortality (V_{mor}) and total carbon storage (trees, excluding soil) of the silver birch stands with different thinning programs until the age of 50 years ($n = 142$).

		Total volume		Mortality		Carbon	
		$m^3 ha^{-1}$		$m^3 ha^{-1}$		$Mg CO_2 eq ha^{-1}$	
		Model 9		Model 10		Model 11	
		V_{tot50}		$\ln(V_{mor50}+1)$		$CO_2 eq_{tot50}$	
		$R^2 = 0.60$		$R^2 = 0.48$		$R^2 = 0.74$	
Fixed parameters		F	Sig.	F	Sig.	F	Sig.
b_0	Intercept	5.9	0.016	0.8	0.372	12.5	0.001
b_1	Thinning programs	19.0	0.000	12.3	0.000	47.4	0.000
b_2	Agricult/Forest	5.3	0.023	30.5	0.000	2.4	0.150
b_3	Late heavy th.	1.6	0.197			130.8	0.000
b_4	H_{50}	3.3	0.074	9.4	0.005	9.3	0.003
b_5	$\ln(H_{50})$	5.7	0.018			12.1	0.001
	$b_2 \times b_4$	4.5	0.036				
	Covariate coefficient	agric. H_{50}	-52.2	H_{50}	0.126	H_{50}	-123.4
		for. H_{50}	-44.2			$\ln(H_{50})$	3760.5
		$\ln(H_{50})$	1724				
Random parameters		Estim.	Std.e.	Estim.	Std. e.	Estim.	Std. e.
δ^2_{stand}	Stand	933.7	412.5	0.003	0.046	1599.6	202.0
δ^2_e	Residual	579.6	74.1	0.932	0.118	1412.4	651.9

4.1. Stand development

The results demonstrated that the highest mean diameter of 26 cm and dominant diameter of 29 cm by the age of 50 were attained exclusively through a thinning program that comprised two intensive thinnings. In contrast, other stands that had undergone a similar degree of thinning, either heavy or moderate, exhibited mean diameters that were approximately 2 cm smaller and dominant diameters that were 1 cm smaller. In unthinned stands, the mean dominant diameter was approximately 3.5 cm smaller, thereby underscoring the critical role of intensive thinning in optimising diameter growth. In similar growing conditions the effect of thinning on dominant diameter has been shown to be lower for Scots pine (Mäkinen and Isomäki, 2004a) and higher for Norway spruce (Mäkinen and Isomäki, 2004b).

The thinning guidelines for silver birch in Finland is based on maximizing total production of sawlogs and pulp wood. In the present

study, this is interpreted as a maximum dominant diameter of 29 cm at 50 years of age (100 largest trees per hectare). In the context of Western Europe, the management regime emphasising the cultivation of high-quality target silver birch trees underscores the potential for the production of large, valuable logs (Dubois et al., 2020). The optimal diameter growth of the best silver birch individuals has been achieved in the target tree system (Dubois et al., 2021) by providing more growing space earlier compared to the first thinning stage of this study. Intensive and early thinnings, i.e., those implemented within the first ten years, make it possible to harvest logs with a diameter of 50–60 cm within 40–50 years. Their study, which focused primarily on Belgium, demonstrated a pronounced increase in diameter growth at ages ranging from 6 to 25 years following intensive thinning. Later thinning response for silver birch was significantly lower, as also found by Vanhellemont et al. (2016). With later thinnings, even intensive thinnings, trees never regain their high diameter growth to produce large logs before the trees

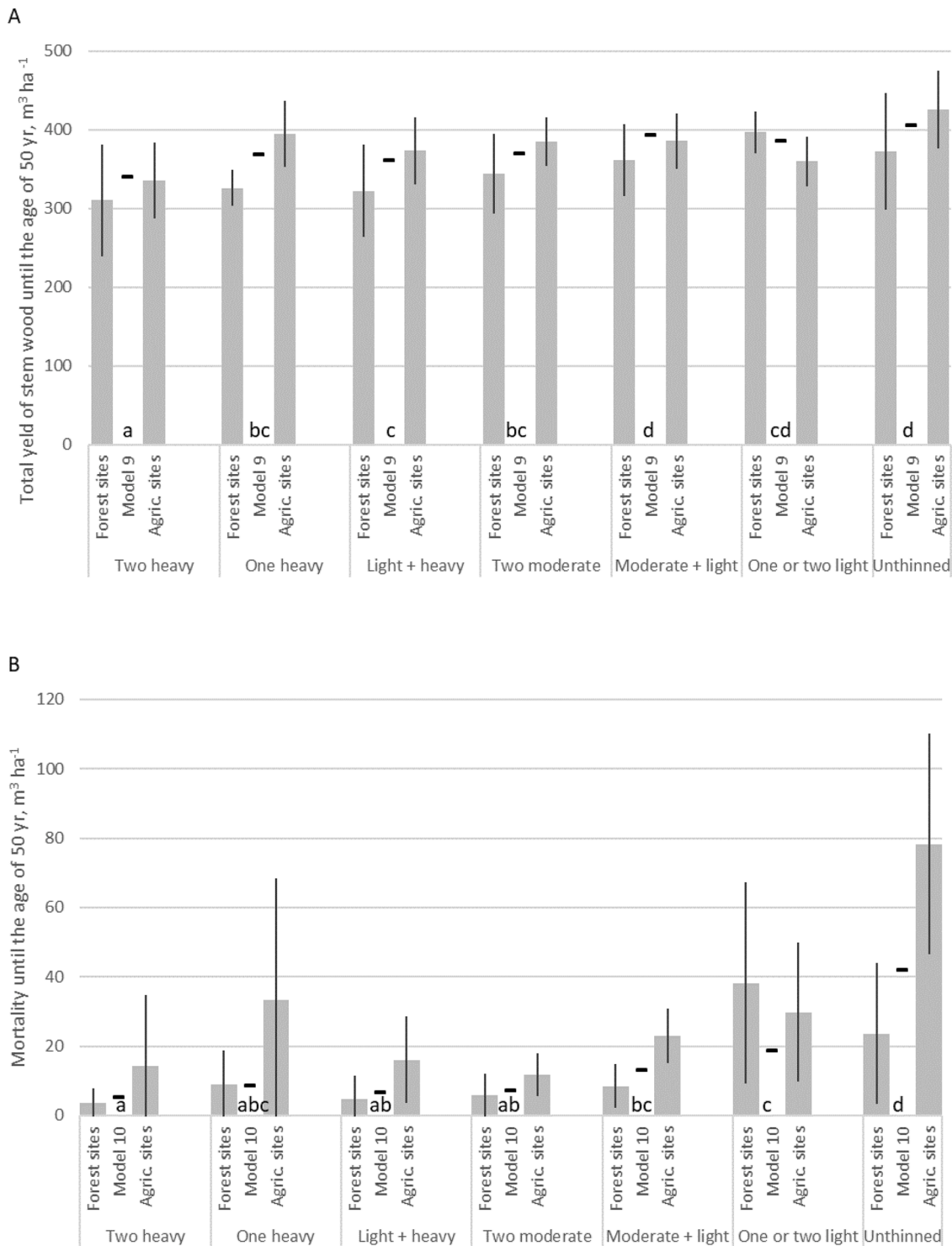


Fig. 13. Total yield (A) and natural mortality (B) of birch stands by the age of 50. Dark bars represent the average for forest and former agricultural sites in a subset measured for at least 30 years without late heavy thinning, and vertical lines represent the standard deviation. The notation "-" denotes estimates calculated with models 9 and 10 as the average for forest and former agricultural sites without late heavy thinning, when the site index was the average of dataset, 27.2 m. The differences between treatments labeled with different letters a–d were statistically significant ($p > 0.05$).

start to age, as was also found in our study.

Silver birch, a tree species with high light requirements, displays a pronounced sensitivity to changes in stand density. The development of the crown and the growth of the stem diameter of the silver birch are both impeded when the trees are grown at high densities. At the onset of this study, the live crown ratio of silver birch was found to be between 60–65 %. In the stands that were neither thinned nor lightly thinned,

however, this ratio decreased to less than 40 % at the age of 50 years. Consequently, the objective of silver birch stand management should be the maintenance of the crown to ensure vigorous growth. A living crown ratio of at least 50 % of the tree height is recommended for maintaining productivity (Raulo, 1981). Our findings indicate that two heavy thinnings are sufficient to sustain this crown ratio until age 50. In moderately or heavily thinned stands, crown ratios varied between 45–47 % at

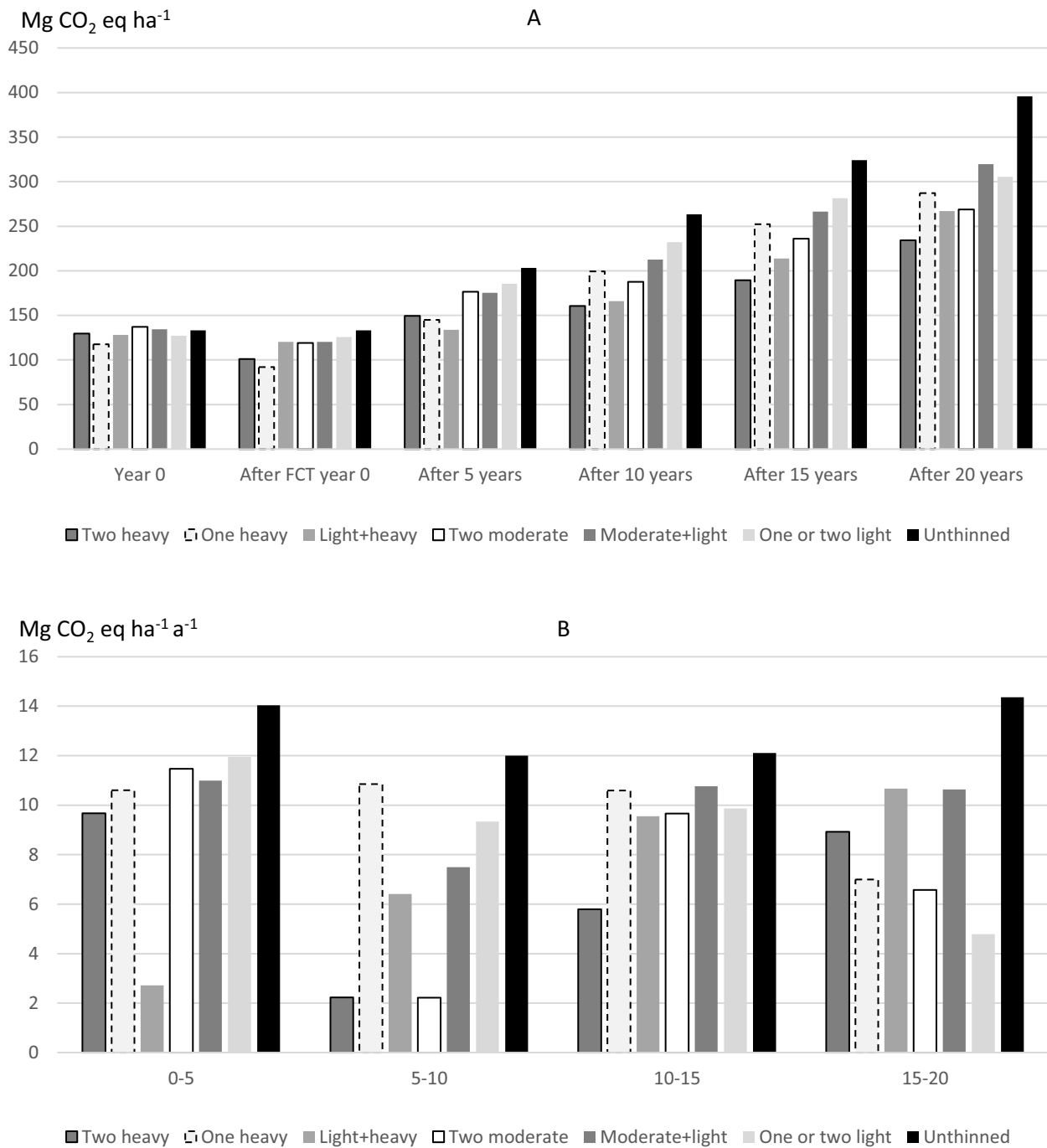


Fig. 14. Total woody (tree biomass) carbon storage (A) and annual change of woody carbon (B) of birch stands by the first 20 years, (refers to age of 40) by thinning treatments and by measurements.

50 years. In contrast, lightly thinned stands maintained a 50 % crown ratio only until age 30. These findings highlight the importance of timely, intensive thinnings for crown maintenance. Notably, our crown measurements, based on the lowest living branch height, suggest that the actual green crown height is 1–2 m higher due to sharp branch angles (Mäkinen et al., 2003).

The results obtained from this study were comparable to those observed in Scots pine stands of a similar site and development phase (Mäkinen et al., 2005; Mäkinen and Isomäki, 2004a; Valinger et al., 2019), but in older unthinned pine stands or on unfertile sites, the crown ratio was 10 % units lower. In very dense downy birch stands on peatland, the crown ratio decreased to 40 % without thinnings, but remained

at 50–60 % when lightly or moderately thinned, and increased by 10 % units after heavy thinning (Niemistö, 2013). This indicates that downy birch is more shade tolerant than silver birch (Hynynen et al., 2010), although the validity of this comparison is potentially compromised by the substantial difference in tree height. Our findings indicated that without thinning, the average length of the living crown was 9 m for silver birch. Earlier studies had demonstrated that the length of the living crown for downy birch and Scots pine was 7.0–7.5 m (Mäkinen and Isomäki, 2004a; Niemistö, 2013) However, the green crown of silver birch was shorter than the above because of the sharpness of the branch angle.

The highest basal area of living silver birches was observed in

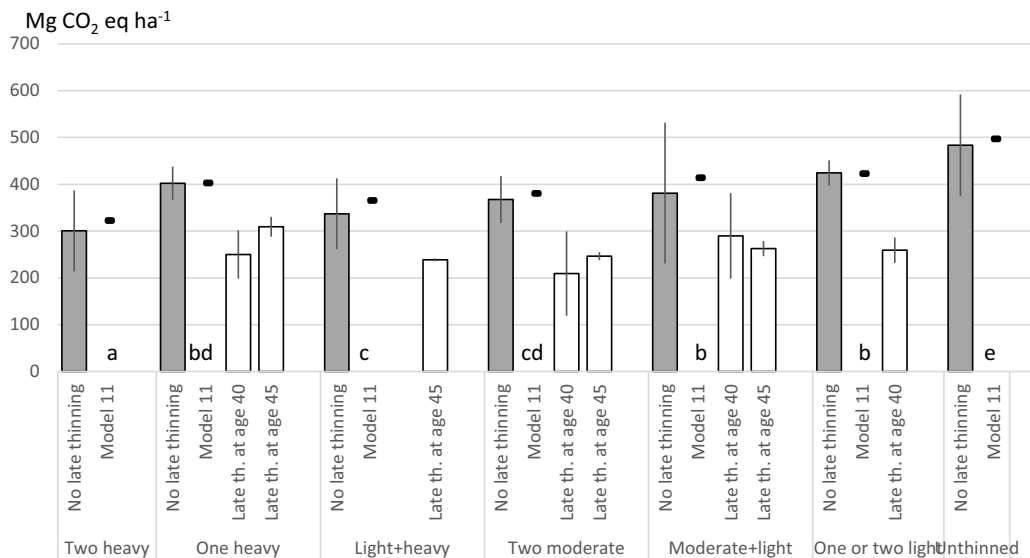


Fig. 15. Total woody (tree biomass) carbon storage of birch stands by the end of study period (30 years, refers to age of 50) by thinning treatments. Dark columns represent carbon storages measured in a subset of data collected for at least 30 years without late heavy thinnings and white bars with late heavy thinnings. Vertical lines represent the standard deviation. The notation "-" denotes estimates calculated with model 11 as the average for forest and former agricultural sites without late heavy thinning, when the site index was the average of dataset, 27.2 m. The differences between treatments labeled with different letters a–d were statistically significant ($p > 0.05$).

unthinned plots, reaching an average of $31 \text{ m}^2 \text{ ha}^{-1}$ at approximately 45 years of age. The basal area development in the present study was found to be in accordance with the models of [Liziniwicz et al. \(2022\)](#) until the age of 40 years. However, the models subsequently exceeded the findings of the present study due to a higher site index and a geographical location in southern and central Sweden, as well as an inadequate recognition of mortality in their models.

Conversely, on similar sites, the respective basal area has been $36 \text{ m}^2 \text{ ha}^{-1}$ for Scots pine and $49 \text{ m}^2 \text{ ha}^{-1}$ for Norway spruce, indicating persistent increase ([Nilsson et al., 2010](#); [Valinger et al., 2019](#)). The mean living stem volume for silver birch was found to be $347 \text{ m}^3 \text{ ha}^{-1}$ on agricultural sites and $350 \text{ m}^3 \text{ ha}^{-1}$ on forest sites, with the maximum volume recorded at $395 \text{ m}^3 \text{ ha}^{-1}$ and $460 \text{ m}^3 \text{ ha}^{-1}$, respectively. These findings reflect the observation that birch exhibits accelerated early growth but higher late-stage mortality on agricultural land compared to forest soils.

Thinning has been shown to have a significant impact on the average cumulative mortality rate of forests and agricultural soils to the age of 50 years. The study revealed that without thinnings an average cumulative mortality of $24 \text{ m}^3 \text{ ha}^{-1}$ and $79 \text{ m}^3 \text{ ha}^{-1}$ for forests and agricultural soils, respectively. It was also observed that moderately thinned silver birch stands exhibited a substantially lower mortality rate of only 20%. In Sweden the mortality rate in unthinned Scots pine stands was $60 \text{ m}^3 \text{ ha}^{-1}$ on average over a 35-year period, and this was reduced to one-third of that level following moderate thinnings. However, in fertile Norway spruce stands, the mortality rate was even higher over a 30-year period than on agricultural soils in this study ([Nilsson et al., 2010](#)). Conversely, in Finland, the mortality of Scots pine and Norway spruce has been similar to that of silver birch on comparable forest sites and development phases ([Mäkinen and Isomäki, 2004c, 2004d](#)). In downy birch stands on peatlands ([Niemistö, 2013](#)) the mortality rate has been comparable to the mean of silver birch on agricultural and forest soils, although it should be noted that the majority of affected trees are of small diameter, rather than those of commercial value. Furthermore, in coniferous stands the mortality has been more evenly distributed during the entire study period when compared to birch stands, where it has been observed to accelerate towards the end of the observed period.

4.2. Growth rhythm

Silver birch, as a pioneer species, demonstrates rapid early growth, reaching maximum height growth at 10–20 years of stand age and maximum volume growth around 5 years later ([Oikarinen, 1983](#); [Raulo and Koski, 1977](#)). The results of this study are only partly in accordance with those of earlier studies ([Dubois et al., 2020](#); [Fries, 1964](#); [Koivisto, 1959](#); [Oikarinen, 1983](#)), which confirm that the maximum standing volume of living trees is attained at approximately 50 years, after which increased mortality stabilizes volume. The height increment remained consistent between the ages of 20 and 40 years, subsequently decreasing. The volume increment also maintained its level until the age of 40 years, varying according to thinnings. However, the highest basal area increment was observed at the ages of 20–25 years regardless of thinnings.

It is important to note, that no measurements were taken before the age of 20 years, which suggest that the growth rate may have been higher before this age, especially for height growth. In Estonia, the growth of young silver birch stands on former agricultural land planted at the end of the 1990s was significantly higher than in our study material before the onset of the experiments. According to the study plots of [Lutter et al. \(2015\)](#), the basal area of $15 \text{ m}^2 \text{ ha}^{-1}$ was attained at the age of 15 years; however, in our study, this was achieved at the age of 19 years. Furthermore, [Lutter et al. \(2023\)](#) found that the mean annual volume increment in Estonia until the age of 20 years was $10 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$, but our observations revealed only half of that in our data.

The aim of silver birch management chain, which favours breeding, planting as a regeneration method and thinnings, has been to promote the rapid diameter growth of trees thus enabling a shorter rotation period ([Niemistö et al., 2008](#)). The typical thinning programs that have been recommended for implementation entail two intensive thinnings, with a removal of 30 to 40% ([Hynynen et al., 2010](#); [Oikarinen, 1983](#); [Rytter, 2013](#)). We evaluated the long-term effects of thinning intensity and timing of silver birch growth, yield and carbon balance.

A reduction in volume growth was observed in the initial period following the intervention, with a notable increase in subsequent growth rates over the subsequent five years. Otherwise, growth remained relatively stable from the age of 20 to 40. Volume growth declined after the

age of 40 and particularly noticeably after the age of 45, except for intensive thinning programs indicating more consistent growth. At ages 46–50 the mortality rate was found to be generally below $2 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$, except for unthinned former agricultural sites, where it reached $6 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$.

Over the 20 years following the first commercial thinning unthinned stands exhibited the highest mean growth rate at $11 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$ in our study, while the two-intensive thinning program demonstrated the lowest at $8 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$. A comparable pattern in the relationship between thinning intensity and silver birch stand growth has been observed by (Juodvalkis et al., 2005; Skovsgaard et al., 2021). On forest sites in our study the current annual volume increment has an average of $9.2 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$ and on agricultural sites $10.5 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$ when excluding extreme treatment with two heavy thinnings. Later in the 41–50 age range it was $1.6 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$ lower. The volume growth values observed in our study are attributable to the exclusion of the most productive southern part of Finland from the data set. The growth of silver birch on more fertile sites and southern locations is higher. According to the models developed by Liziniewicz et al. (2022), the annual volume increment for sites classified as SI 32 m in 31 years was $12.8 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$. However, with the improved genetic material, it can reach up to $14 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$.

4.3. Wood production

The findings indicated that the implementation of intensive thinning practices typically resulted in a decline in total yield. However, in the context of commercial wood production, both heavy and moderate thinning programs result in comparable outcomes, with the exception of the program with two heavy thinnings, which results in a reduction in yield. Notably, heavy thinnings have been shown to increase sawlog yield.

Our results showed that in unmanaged stands, the total yield attained by the stand age of 50 years was $398 \text{ m}^3 \text{ ha}^{-1}$ whereas two intensive thinning program produced the total yield of $323 \text{ m}^3 \text{ ha}^{-1}$ (MAI $6.6\text{--}8.0 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$, respectively). According to the Finnish yield tables, the total volume yield in managed silver birch plantations by the age of 60 years varies between 360 and $560 \text{ m}^3 \text{ ha}^{-1}$ (MAI 6 and $9.3 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$, respectively) (Oikarinen, 1983).

This study found that the mean annual volume increment ranged from 7.5 to $8. \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$, with the 50-year rotation excluding extreme treatment involving two heavy thinnings. For planted silver birch in southern Sweden, the mean volume increment was approximately $10 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$ on a corresponding rotation and site index $H50= 27 \text{ m}$ (Liziniewicz et al., 2022). Additionally, an average of $6.0\text{--}12.8 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$ was observed on average-fertile forest sites (Ekö et al., 2008), and on fertile sites, ca. $10 \text{ m}^3 \text{ ha}^{-1} \text{ a}^{-1}$ was recorded for rotations between 30 and 60 years (Dahlberg et al., 2006).

4.4. Carbon balance

Prior research conducted in Nordic countries has underscored the implications of thinning on carbon balance. Although intensive thinnings result in a temporary reduction in stand-level carbon stock, they facilitate individual tree growth, thereby enhancing the potential for carbon sequestration in harvested wood products (Lundmark et al., 2018; Lutter et al., 2021). This corroborates our findings, which demonstrate that in silver birch stands thinning from below not only optimises growth but also sustains the carbon balance by maintaining high productivity levels in the remaining trees.

The biomass of living trees represents a significant carbon stock, exhibiting dynamics that are analogous to those observed in standing volume. Nevertheless, the decomposition of the cuttings will also exert an influence on the levels of carbon stock in the trees. The impact of thinning intensity on carbon balance has been comparatively less extensively investigated than the effects of volume growth reactions on different tree species. The results demonstrated that the silver birch

stand continued to function as a carbon sink even after five years of all thinning treatments, including two heavy thinnings at a young age. Subsequently, late heavy thinnings, particularly in moderately or lightly thinned stands, resulted in a transient carbon source effect during the initial five-year period following thinning at stand age 45. A comparable pattern was observed at the ecosystem level by Aun et al. (2021), who noted that the impact of thinning on net ecosystem production (NEP) was more pronounced in the middle-aged stand than in the young stand, with a decline of 1.6 and $1.2 \text{ t C ha yr}^{-1}$ (equivalent to 23–30 % reductions).

It has been previously observed that the carbon balance of Scots pine decreases from unthinned to low and heavy thinnings at all stages (del Río et al., 2017). Earlier observations have indicated that moderate thinning reached neutrality after five years in all types of Scots pine, whereas it took more than 15 years in the case of intensive thinning (Bianchi et al., 2024). Additionally, (Aun et al., 2021) observed that while thinning resulted in a reduction in net ecosystem productivity (NEP) in the studied silver birch stands, the ecosystems remained carbon sinks.

4.5. The effects of site

The findings of our study demonstrate a notable distinction between agricultural and forest sites. Former agricultural sites demonstrated superior growth rates and yields in comparison to forest sites with analogous site indices. However, as the site index increased, the aforementioned differences diminished. The elevated mortality rates observed in agricultural sites within mature stands are likely attributable to early-stage damage, including infestation by voles, hares, and cicadas, as well as potential nutrient unbalances (Niemistö et al., 1997). Additionally, differences in stem form and crown structure were observed, with forest soils promoting the formation of more stratified crown layers than the more homogeneous conditions observed on agricultural sites. The site index had a significant impact on volume growth and yield, but a less pronounced effect on basal area growth. This effect was particularly evident at lower productivity levels, particularly on forest sites.

4.6. The effects of thinning method and late heavy thinning

Our results showed that the thinning method was not a significant factor explaining basal area or volume growth, total yield, mortality, or carbon storage. However, the thinning from above, although an infrequent strategy in this study, resulted in a notable reduction in both the dominant and basal area-weighted mean diameters, with a decrease of approximately 1.42 cm and 1.48 cm, respectively. These findings indicate that thinning from below should be the preferred method for managing silver birch stands to minimize extended rotations and associated mortality. It is notable that there is a paucity of research examining the efficacy of different thinning techniques for silver birch. In regard to significant coniferous species in Nordic countries, such as Scots pine (*Pinus sylvestris* L.), it has been observed that there is a slight increase in volume growth, with estimates ranging from a 3 % increase (Vuokila, 1977) to a 7.5 % increase (Mielikäinen and Valkonen, 1991; Niemistö et al., 2018) or even a negligible increase (Bianchi et al., 2024; Eriksson and Karlsson, 1997; Nilsson et al., 2010). However, (Pettersson, 2008) observed a 10 % reduction in volume increment for Scots pine following thinning from above in comparison to thinning from below. With regard to Norway spruce (*Picea abies* (L.) Karst), thinning from above has been observed to result in a reduction in volume increment (Eriksson and Karlsson, 1997; Mielikäinen and Valkonen, 1991; Nilsson et al., 2010), while in other instances, the volume increment has been found to be comparable to that observed following thinning from below (Vuokila, 1977).

The present study demonstrated that particularly late heavy thinnings resulted in a reduction of total yield, particularly in previously

moderately or lightly thinned stands. It is only noteworthy that at a young age silver birch stands were effective in maintaining their carbon balance; however, only late heavy thinning resulted in a slight carbon source during the first five years after thinning, at a stand age of around 45 years.

4.7. Implications for future research and management

The results of our study, based on stands established in the 1970s and first thinned commercially in the early 1990s, provide valuable insights for the management of mature silver birch stands. Nevertheless, further research is required to comprehend the growth and development of stands established with modern breeding material, which exhibits elevated growth rates (Haapanen, 2024; Liziniewicz et al., 2022). Furthermore, the seedling production has been developed for silver birch, with the small-sized container seedlings (Pikkarainen et al., 2021) replacing the large-sized bare-root seedlings that were previously utilized, and also in the study sites. It would be beneficial for future studies to explore the potential benefits of early thinnings during the sapling stage or energy wood recovery during the initial commercial thinning. Furthermore, research should address the impact of site-specific factors and stand density on crown structure, stem form, and mortality over time. Also, further research is required to investigate the relationship between yield and profitability, with a particular focus on the quality of saw logs. It is of great importance to determine whether there are discernible differences in quality between the various thinning programs.

5. Conclusions

The results demonstrated that the implementation of intensive thinning practices typically resulted in a reduction in overall yield. However, in the context of commercial wood production, both heavy and moderate thinning programs yield comparable outcomes, except for the program involving two heavy thinnings, which results in a decreased yield. In particular, the yield of saw logs is increased by heavy thinnings. In comparison, former agricultural sites demonstrated superior growth rates and yields when contrasted with forest sites exhibiting analogous site indices. However, as the site index increases, the discrepancy in growth and yield between these site classes diminishes. In contrast, former agricultural sites exhibited a markedly elevated mortality rate in mature stands. It is therefore essential to consider shorter rotation periods in these areas in comparison to forest sites.

The addition of birch has been demonstrated to enhance adaptation, mitigate risk, and increase biodiversity, thereby mitigating the effects of climate change. Nevertheless, in relation to the long-term carbon sequestration potential of the forest, soil, and wood products, birch is likely to be less competitive when compared to coniferous trees. Furthermore, an unthinned silver birch forest is considered a less preferable alternative in comparison to one that has undergone thinning, in terms of aforementioned factors. The advantage of intensive thinning is the long-term durability of the wood products and the conditions it creates for spruce regeneration in the understory. Overall, it is therefore vital to increase the variety of tree species, both through increasing pure birch stands and mixed forests, in order to adapt to a changing climate and increase forest resilience. Furthermore, this approach facilitates the reconciliation of different forest uses.

In conclusion, this study highlights the significance of implementing intensive, well-timed thinnings to optimise growth, yield, carbon balance, and crown development in silver birch stands. It is recommended that thinning from below should remain the preferred method, with adjustments for site-specific conditions to achieve an optimal balance between productivity and mortality. These findings are of critical importance for the refinement of silvicultural practices and the attaining of sustainable forest management goals in Nordic boreal regions.

Data availability

The data are stored at Natural Resources Institute Finland (LUKE) and are not publicly available due to their ownership. The data in this study are available on reasonable request by contacting the authors.

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CRedit authorship contribution statement

Pentti Niemistö: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Saija Huuskonen:** Writing – review & editing, Visualization, Validation, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Saija Huuskonen reports administrative support, equipment, drugs, or supplies, and travel were provided by Natural Resources Institute Finland. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

- Aun, K., Kukumägi, M., Varik, M., Becker, H., Aosaar, J., Uri, M., Buht, M., Uri, V., 2021. Short-term effect of thinning on the carbon budget of young and middle-aged silver birch (*Betula pendula* Roth) stands. *For. Ecol. Manag.* 480, 118660. <https://doi.org/10.1016/j.foreco.2020.118660>.
- Bianchi, S., Huuskonen, S., Hynynen, J., Niemistö, P., 2024. Comparing wood production and carbon sequestration after extreme thinnings in boreal Scots pine stands. *For. Ecol. Manag.* 553, 121641. <https://doi.org/10.1016/j.foreco.2023.121641>.
- Braastad, H., 1977. Tilvekstmodellprogram for bjørk. Norsk Institutt for skogforskning Rapport.
- Braastad, H., 1967. Produksjonstabeller for bjørk: Yield tables for birch. Alf Langsæter.
- Cajander, A., 1949. Forest types and their significance. *Acta For. Fenn* 56. <https://doi.org/10.14214/aff.7396>.
- Dahlberg, A., Egnell, G., Bergh, J., Rytter, L., Westling, O., 2006. Miljöeffekter av skogsbränsleuttag och askåterföring i Sverige – En syntes av Energimyndighetens forskningsprogram 1997 till 2004. [Environmental effects of forest fuel extraction and ash recycling in Sweden – a synthesis of the Swedish Energy Agency’s research program 1997 to 2004]. ER /Energimyndigheten. *Energimyndigheten*, pp. 1403–1892.
- Río, del, M., Bravo-Oviedo, A., Pretzsch, H., Lóf, M., Ruiz-Peinado, R., 2017. A review of thinning effects on Scots pine stands: From growth and yield to new challenges under global change. *For. Syst.* 26, eR03S. <https://doi.org/10.5424/fs/2017262-11325>.
- 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 of Western Europe. *Forests* 11, 336. <https://doi.org/10.3390/f11030336>.

- Dubois, H., Claessens, H., Ligot, G., 2021. Towards silviculture guidelines to produce large-sized silver Birch (*Betula pendula* Roth) logs in Western Europe. *Forests* 12, 599. <https://doi.org/10.3390/f12050599>.
- Ekö, P.-M., Johansson, U., Petersson, N., Bergqvist, J., Elfving, B., Frisk, J., 2008. Current growth differences of Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*) and birch (*Betula pendula* and *Betula pubescens*) in different regions in Sweden. *Scand. J. For. Res.* 23, 307–318. <https://doi.org/10.1080/02827580802249126>.
- Eriksson, H., Johansson, U., Kiviste, A., 1997. A site-index model for pure and mixed stands of *Betula pendula* and *Betula pubescens* in Sweden. *Scand. J. For. Res.* 12, 149–156. <https://doi.org/10.1080/02827589709355396>.
- Eriksson, H., Karlsson, K., 1997. Olika gallrings- och gödslingsregimers effekter på beståndsutvecklingen baserat på långliggande experiment i tall- och granbestånd i Sverige [Effects of different thinning and fertilization regimes on the development of Scots pine (*Pinus sylvestris* (L.) and Norway spruce (*Picea abies* (L.) Karst.) stands in long-term silvicultural trials in Sweden]. Swedish University of Agricultural Sciences Department of Forest Yield Research.
- Felton, A., Nilsson, U., Sonesson, J., Felton, A.M., Roberge, J.-M., Ranius, T., Ahlström, M., Bergh, J., Björkman, C., Boberg, J., Drössler, L., Fahlvik, N., Gong, P., Holmström, E., Keskkitalo, E.C.H., Klapwijk, M.J., Laudon, H., Lundmark, T., Niklasson, M., Nordin, A., Pettersson, M., Stenlid, J., Sténs, A., Wallertz, K., 2016. Replacing monocultures with mixed-species stands: Ecosystem service implications of two production forest alternatives in Sweden. *Ambio* 45, 124–139. <https://doi.org/10.1007/s13280-015-0749-2>.
- Fries, J., 1964. Vårtbjörkens produktion i Svealand och södra Norrland /av Jöran Fries = Yield of *Betula verrucosa* Ehrh. in middle Sweden and southern north Sweden. *Studia forestalia Suecica*, Skogshögskolan, Stockholm.
- Gustavsen, H.G., Mielikäinen, K., 1984. Luontaisesti syntyneiden koivikoiden kasvupaikkaluokittelu valtapituuden avulla. *Folia For.* 597, 20.
- Haapanen, M., 2024. Realised genetic gains from past Finnish silver birch seed orchards. *Silva Fenn.* 58.
- Heinonen, J., 1994. KPL - koealojen puu- ja puustotunnusten laskentaohjelman käyttöohje. [A computer programme package (KPL) for computing stand and single tree characteristics from sample plot measurements. User manual] (No. 504), Metsäntutkimuslaitoksen tiedonantoja. Metsäntutkimuslaitos.
- Huuskonen, S., Domisch, T., Finér, L., Hantula, J., Hynynen, J., Matala, J., Miina, J., Neuvonen, S., Nevalainen, S., Niemistö, P., Nikula, A., Piri, T., Siitonen, J., Smolander, A., Tonteri, T., Uotila, K., Viiri, H., 2021. What is the potential for replacing monocultures with mixed-species stands to enhance ecosystem services in boreal forests in Fennoscandia? *For. Ecol. Manag.* 479, 118558. <https://doi.org/10.1016/j.foreco.2020.118558>.
- 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. *For. Int. J. For. Res.* 83, 103–119. <https://doi.org/10.1093/forestry/cpp035>.
- Hynynen, J., Salminen, H., Ahtikoski, A., Huuskonen, S., Ojansuu, R., Siipilehto, J., Lehtonen, M., Eerikäinen, K., 2015. Long-term impacts of forest management on biomass supply and forest resource development: a scenario analysis for Finland. *Eur. J. For. Res.* 134, 415–431. <https://doi.org/10.1007/s10342-014-0860-0>.
- Hytönen, J., Saramäki, J., Niemistö, P., 2014. Growth, stem quality and nutritional status of *Betula pendula* and *Betula pubescens* in pure stands and mixtures. *Scand. J. For. Res.* 29, 1–11. <https://doi.org/10.1080/02827581.2013.838300>.
- IBM Corp., 2021. Released 2021. IBM SPSS Statistics for Windows, Version 28.0.
- Juodvalkis, A., Kairiukstis, L., Vasiliauskas, R., 2005. Effects of thinning on growth of six tree species in north-temperate forests of Lithuania. *Eur. J. For. Res.* 124, 187–192. <https://doi.org/10.1007/s10342-005-0070-x>.
- 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. *Scand. J. For. Res.* 12, 256–263. <https://doi.org/10.1080/02827589709355408>.
- Koivisto, P., 1959. Kasvu- ja tuototulukoita. Growth and yield tables. *Commun. Inst. For. Fenn. Commun. Inst. For. Fenn.* 59, 1–49.
- Korhonen, K.T., Ahola, A., Heikkinen, J., Henttonen, H.M., Hotanen, J.-P., Ihalainen, A., Melin, M., Pitkänen, J., Rätty, M., Sirviö, M., Strandström, M., 2021. Forests of Finland 2014–2018 and their development 1921–2018. *Silva Fenn. Silva Fenn.* 55, 49. <https://doi.org/10.14214/sf.10662>.
- Kulju, I., Niemistö, T., Peltola, A., Rätty, M., Sauvuja-Seppälä, T., Torvelainen, J., Uotila, E., Vaahra, E., 2023. Metsätilastollinen vuosikirja 2022. Luonnonvarakeskus.
- Laasasena, J., 1982. Taper curve and volume functions for pine, spruce and birch. Männyn kuusen ja koivun runko-käyrä ja tilavuusyhtälöt 108, 74.
- Lee, D., Siipilehto, J., Hynynen, J., 2025. Comparison and analysis of self-thinning models based on diameter-based maximum size-density relationships. *For. Ecol. Manag.* 575, 122374. <https://doi.org/10.1016/j.foreco.2024.122374>.
- Lee, D., Siipilehto, J., Miina, J., Niemistö, P., Haapanen, M., Hynynen, J., Huuskonen, S., 2024. Site index and stand characteristic models for silver birch plantations in southern and central Finland. *For. Ecol. Manag.* 563, 121998. <https://doi.org/10.1016/j.foreco.2024.121998>.
- Liziniwicz, 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 Fenn.* 56.
- Lundmark, T., Poudel, B.C., Stål, G., Nordin, A., Sonesson, J., 2018. Carbon balance in production forestry in relation to rotation length. *Can. J. For. Res.* 48, 672–678. <https://doi.org/10.1139/cjfr-2017-0410>.
- Lutter, R., Stål, G., Arnesson Ceder, L., Lim, H., Padari, A., Tullus, H., Nordin, A., Lundmark, T., 2021. Climate benefit of different tree species on former agricultural land in Northern Europe. *Forests* 12, 1810. <https://doi.org/10.3390/f12121810>.
- Lutter, R., Tullus, Vares, A., Sopp, R., Tullus, T., Kaivapalu, M., Ots, K., Kharel, B., Lundmark, T., Tulus, T., 2023. Twenty years of afforestation of former agricultural lands with silver birch plantations affects vertical distribution of SOC and macronutrients in the topsoil layer. *Plant Soil* 482, 385–400. <https://doi.org/10.1007/s11104-022-05695-9385...400>.
- Lutter, R., Tullus, A., Kanal, A., Tullus, T., Vares, A., Tullus, H., 2015. Growth development and plant-soil relations in mid-term silver birch (*Betula pendula* Roth) plantations on previous agricultural lands in hemiboreal Estonia. *Eur. J. For.* 134, 653–667.
- Mäkinen, H., Hynynen, J., Isomäki, A., 2005. Intensive management of Scots pine stands in southern Finland: first empirical results and simulated further development. *For. Ecol. Manag.* 215, 37–50. <https://doi.org/10.1016/j.foreco.2005.03.069>.
- Mäkinen, H., Hynynen, J., Siitonen, J., Sievänen, R., 2006. Predicting the decomposition of scots pine, Norway Spruce, and Birch stems in Finland. *Ecol. Appl.* 16, 1865–1879.
- Mäkinen, H., Isomäki, A., 2004a. Thinning intensity and long-term changes in increment and stem form of Scots pine trees. *For. Ecol. Manag.* 203, 21–34. <https://doi.org/10.1016/j.foreco.2004.07.028>.
- Mäkinen, H., Isomäki, A., 2004b. Thinning intensity and long-term changes in increment and stem form of Norway spruce trees. *For. Ecol. Manag.* 201, 295–309. <https://doi.org/10.1016/j.foreco.2004.07.017>.
- Mäkinen, H., Isomäki, A., 2004c. Thinning intensity and growth of Norway spruce stands in Finland. *For. Int. J. For. Res.* 77, 349–364. <https://doi.org/10.1093/forestry/77.4.349>.
- Mäkinen, H., Isomäki, A., 2004d. Thinning intensity and growth of Scots pine stands in Finland. *For. Ecol. Manag.* 201, 311–325. <https://doi.org/10.1016/j.foreco.2004.07.016>.
- Mäkinen, H., Ojansuu, R., Niemistö, P., 2003. Predicting external branch characteristics of planted silver birch (*Betula pendula* Roth.) on the basis of routine stand and tree measurements. *For. Sci.* 49, 301–317. <https://doi.org/10.1093/forestscience/49.2.301>.
- Maleki, K., Kiviste, A., Korjus, H., 2015. Analysis of individual tree competition on diameter growth of silver Birch in Estonia. *For. Syst.* 24, e023. <https://doi.org/10.5424/fs/2015242-05742>.
- Mielikäinen, K., Valkonen, S., 1991. Harvennustavan vaikutus varttuneen metsikön tuotokseen ja tuottoihin Etelä-Suomessa. *Folia For.* 776, 22. <http://um.fi/URN:ISBN:951:40-1167-8>.
- Näslund, M., 1936. Skogsförsöksanstaltens gallringsförsök i tallskog. [Thinning trials of forest research institute in Scots pine stands]. *Medd. från Statens skogsförsöksanst.* 29, 169.
- Niemistö P., 1997. Ensiharvennuksen ajankohdan ja voimakkuuden vaikutus istutetun rauduskoivikon kasvuun ja tuotokseen. Metsätieteen aikakauskirja – Folia Forestalia 4/1997. 439–454. <https://doi.org/10.14214/ma.6232>.
- Niemistö, P., 2013. Effect of growing density on biomass and stem volume growth of downy birch stands on peatland in Western and Northern Finland. *Silva Fenn.* 47.
- Niemistö, P., 1995. Influence of initial spacing and row-to-row distance on the growth and yield of silver birch (*Betula pendula*). *Scand. J. For. Res.* 10, 245–255. <https://doi.org/10.1080/02827589509382890>.
- Niemistö, P., Hukki, P., Verkasalo, E., Niemistö, P., Hukki, P., et al., 1997. Kasvupaikan ja puuston tiheyden vaikutus rauduskoivun ulkoiseen laatuun 30-vuotiaissa istutuskoivikoissa 349–374. Metsätieteen aikakausk. – Folia For. 3/1997, 349–374. <https://doi.org/10.14214/ma.6476>.
- Niemistö, P., Kilpeläinen, H., Poutiainen, E., 2018. Effect of first thinning type and age on growth, stem quality and financial performance of a Scots pine stand in Finland. *Silva Fenn.* 52. <https://doi.org/10.14214/sf.7816>.
- Niemistö, P., Korhonen, K.T., 2008. Koivuvarat ja kasvu. In: Niemistö, P., Viherä-Aarnio, A., Velling, P., Heräjärvi, H., Verkasalo, E. (Eds.), *Koivun kasvatusta ja käyttö. Metsäkustannus, Metla, Helsinki*, pp. 175–181.
- Niemistö, P., Viherä-Aarnio, A., Velling, P., Heräjärvi, H., Verkasalo, E. (Eds.), 2008. Koivun kasvatusta ja käyttö. Metsäkustannus : Metla, Helsinki.
- Nilsson, U., Agestam, E., Ekö, P.-M., Elfving, B., Fahlvik, N., Johansson, U., Karlsson, K., Lundmark, T., Wallentin, C., 2010. Thinning of Scots pine and Norway spruce monocultures in Sweden (Report No. 219). Umeå.
- Oikarinen, M., 1983. Etelä-Suomen viljeltyjen rauduskoivikoiden kasvatustallit. *Commun. Inst. For. Fenn.* 113, 75 s. <http://urn.fi/URN:ISBN:951-40-0619-4>.
- Pettersson, F., 2008. Effekt av gallringsform i tallförsöket Kolfallet – Ett underlag för utformningen av olika gallringsstrategier. [The Influence Of Thinning Form in the Kolfallet Pine Trials – An Aid to the Formulation of Different Thinning Strategies]. (Redogörelse No. 4. Skogforsk).
- Pikkarainen, L., Luoranen, J., Peltola, H., 2021. Early field performance of small-sized silver Birch and scots pine container seedlings at different planting depths. *Forests* 12, 519. <https://doi.org/10.3390/f12050519>.
- Raulo, J., 1981. Koivukirja, Gummerus. Jyväskylä 130.
- Raulo, J., 1978. Forestation chain for birch (*Betula pendula* Roth) in Finland. *Silva Fenn. Silva Fenn.* 12, 17–24.
- Raulo, J., 1977. Development of dominant trees in *Betula pendula* Roth and *Betula pubescens* Ehrh. plantations. *Commun. Inst. Fenn.* 90 (4), 15.
- Raulo, J., Koski, V., 1977. Growth of *Betula pendula* Roth progenies in southern central Finland. *Commun. Inst. For. Fenn.*, Metsäntutkimuslaitos.
- Repola, J., 2008. Biomass equations for birch in Finland. *Silva Fenn.* 42.
- Rytter, L., 2013. Growth dynamics of hardwood stands during the precommercial thinning phase – recovery of retained stems after competition release. *For. Ecol. Manag.* 302, 264–272. <https://doi.org/10.1016/j.foreco.2013.03.034>.
- Shorohova, E., Kapitsa, E., Vanha-Majamaa, I., 2008. Decomposition of stumps 10 years after partial and complete harvesting in a southern boreal forest in Finland. *Can. J. For. Res.* 38, 2414–2421. <https://doi.org/10.1139/X08-083>.

- Skovsgaard, J.P., Johansson, U., Holmström, E., Tune, R.M., Ols, C., Attocchi, G., 2021. Effects of thinning practice, high pruning and slash management on crop tree and stand growth in young even-aged stands of planted Silver Birch (*Betula pendula* Roth). *Forests* 12, 225. <https://doi.org/10.3390/f12020225>.
- Tonteri, T., Hotanen, J.-P., Kuusipalo, J., 1990. The Finnish forest site type approach: ordination and classification studies of mesic forest sites in southern Finland. *Vegetatio* 87, 85–98. <https://doi.org/10.1007/BF00045658>.
- Uri, V., Varik, M., Aosaar, J., Kanal, A., Kukumägi, M., Lõhmus, K., 2012. Biomass production and carbon sequestration in a fertile silver birch (*Betula pendula* Roth) forest chronosequence. *For. Ecol. Manag.* 267, 117–126. <https://doi.org/10.1016/j.foreco.2011.11.033>.
- Vanhellemont, M., Van Acker, J., Verheyen, K., 2016. Exploring life growth patterns in birch (*Betula pendula*). *Scand. J. For. Res.* 31 (6), 561–567. <https://doi.org/10.1080/02827581.2016.1141978>.
- Valinger, E., Sjögren, H., Nord, G., Cedergren, J., 2019. Effects on stem growth of Scots pine 33 years after thinning and/or fertilization in northern Sweden. *Scand. J. For. Res.* 34, 33–38. <https://doi.org/10.1080/02827581.2018.1545920>.
- Venäläinen, A., Tuomenvirta, H., Pirinen, P., Drebs, A., 2005. A basic Finnish climate data set 1961-200 - description and illustrations. <https://doi.org/10.13140/RG.2.2.24473.62567>.
- Vuokila, Y., 1977. Harsintaharvennus puuntuotantoon vaikuttavana tekijänä. [Principles of selective thinning from above in commercial thinnings]. *Acta For. Fenn.* 30.
- Zeoli, L., De Mil, T., Forler, A., Pau, M., Latte, N., Claessens, H., Ligtot, G., 2025. Modeling productivity of silver birch (*Betula pendula* Roth.) combining phytocentric and geocentric approaches in Northwestern Europe. *For. Ecol. Manag.* 578. <https://doi.org/10.1016/j.foreco.2024.122473>.