

Article

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)

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Abstract: The objective was to quantify the influence of thinning, high pruning and slash management on crop tree and stand growth in young even-aged stands of planted silver birch (*Betula pendula* Roth). This study was based on two field experiments, aged six and eleven years at initiation and re-measured after six and eight years, respectively. Treatments included the unthinned control, moderate thinning mainly from below (removing 28–33% of standing volume), point thinning to favor 300 trees per ha and with no thinning elsewhere in the plot (removing 16–25%), and heavy thinning leaving 600 evenly distributed potential future crop trees per ha (removing 64–75%). Slash management (extraction or retention) was applied to heavily thinned plots. High pruning removing 30–70% of the green crown was carried out in some plots with point or heavy thinning on 300 or 600 trees per ha, respectively. Stand volume growth increased with increasing pre-treatment mean annual volume increment and decreased with increasing thinning intensity as compared to the unthinned control. LS-means estimates indicated a reduction for moderate thinning by 14%, for point thinning by 12% and for heavy thinning (combined with pruning) by 62%. However, in the youngest experiment, heavy thinning (without pruning) reduced growth by 54%. Combining these results with results from a similar experiment in Canada, the reduction in stand volume growth ($Red_{IV\%}$) depending on thinning removal ($Rem_{V\%}$), both expressed as a percentage of the unthinned control, was quantified as $Red_{IV\%} = -23.67 + 1.16 \cdot Rem_{V\%}$ (calibration range: 30–83%). For heavy thinning (large quantities of slash), slash extraction resulted in no reduction in stand volume growth as compared to slash retention. The instantaneous numeric reduction in the average stem diameter of the 300 thickest trees per ha (D_{300}) due to thinning was 3.5, 15–21% and 95–11% with moderate, point and heavy thinning, respectively. The subsequent average annual increase in D_{300} during the observation period was 8.5%, 25 and 18%, respectively. In the youngest experiment, pruning in unthinned plots led to a reduction in the annual increase of D_{300} by 14%, and heavy thinning in unpruned plots led to an increase by 30%. The growth of pre-selected potential future crop trees increased with increasing thinning intensity. In heavily thinned plots, pruning reduced growth increasingly with increasing pruning severity; LS-means estimates indicated 21% larger growth on stem diameter for unpruned trees and 3% for pruned trees. As an adverse side effect, heavily thinned plots with only 600 trees per ha were at increased risk of windthrow for some years after the thinning intervention. In the oldest experiment, 95–21% of the trees in these plots were damaged by wind.

Keywords: thinning; pruning; slash; windthrow; wind stability; potential future crop trees; tree growth; stand growth; birch; Sweden

1. Introduction

Broadleaved forest types are gradually becoming increasingly important in Sweden. This is a consequence of improving growth conditions, adaptation of the forest to climate change, and increasing awareness of the economic potential and environmental value of broadleaved forests. With an above-ground, standing wood volume of $453 \times 10^6 \text{ m}^3$, or 13% of the total wood volume in the country, birch is by far the largest broadleaved forest resource [1]. Among birch species, silver birch (*Betula pendula* Roth) accounts for $329 \times 10^6 \text{ m}^3$, or 73% of the birch volume. This species consequently represents a substantial commercial potential for timber production.

For a given site and genetic origin, the commercial potential depends largely on thinning and pruning practices in the individual stand. A number of experiments and studies quantify the influence of thinning on tree and stand growth in even-aged stands of silver birch [2–7] (see also [8] and the summary overview [9]). As for pruning, most studies focus on wood quality issues (e.g., [10,11]), some on work efficiency (e.g., [12]), and very few on growth response (e.g., [13]). The studies of growth response to thinning or pruning generally refer to dense stands with complete or almost complete canopy closure, late interventions, moderate stem number reductions and moderate pruning.

Recently, some silviculturists have advocated early heavy thinning combined with early high pruning of pre-selected, potential future crop trees as a means to faster produce high-quality timber [14]. Early heavy thinning accelerates crown expansion and, in turn, diameter growth at a time when the individual tree is most responsive to increasing space and availability of growth resources. Early high pruning eliminates the disadvantage of excessive branch growth due to thinning and it furthermore improves stem quality in terms of knottiness earlier and faster than would happen through natural pruning in the absence of thinning. In summary, this early intensive silviculture works to reduce rotation length and, thereby, production risks. Birch is well suited for early intensive silviculture because it is light demanding, diameter growth peaks early, wood quality is largely independent of growth rate, branches die early and shed slowly, and the incidence of false red heart discoloration increases with increasing age [12,15–20].

During 2010–2012, we established two combined thinning and pruning experiments in young, even-aged stands of silver birch to provide a foundation for analyzing the influence of early thinning and early high pruning on crop tree and stand growth. Moreover, in some plots, slash extraction was included as an experimental factor. This paper reports some results following six to eight years of observation. The presentation is based on four analyses:

1. The effects of thinning practice on stand volume growth.
2. The effects of slash extraction/retention on stand volume growth.
3. The effects of crop tree selection, thinning and pruning on the size of crop trees and other large trees.
4. The effects of thinning intensity and pruning severity on the growth of crop trees.

2. Materials and Methods

The study was based on two thinning experiments in even-aged stands of silver birch, established by the Swedish University of Agricultural Sciences: experiment no. 1278 located at Duveke (lat. $55^{\circ}57'$, long. $13^{\circ}02'$) near the city of Helsingborg [21], and no. 1289 located at Vallerstad (lat. $57^{\circ}09'$, long. $13^{\circ}58'$) near the city of Värnamo [22].

Both stands were planted with genetically improved stock of silver birch from the breeding program of Skogforsk (the Forest Research Institute of Sweden) at Ekebo [23]. Both stands were initially fenced. The areas were formerly stocked with stands of even-aged Norway spruce (*Picea abies* (L.) Karst.).

Experiment 1278 (elevation $\approx 70 \text{ m}$) is located on soils developed from organic post-glacial deposits and, in some parts, glacial till, in both cases overlying a bedrock of Triassic Keuper sandstone or Silurian shale. The area is flat and poorly drained.

Experiment 1289 (elevation \approx 200 m) is located on glacial till overlying a bedrock of granite. The terrain is quite heterogeneous with moist patches, rocks and outcrops of bedrock.

Experiment 1278 was planted in 2001 using one-year-old seedlings originating from the greenhouse seed orchard Ekebo 3. The experiment was installed and measured during autumn 2010–spring 2011. Some plots had ingrowth of naturally seeded birch and other tree species. All plots were re-measured during spring 2019.

Experiment 1289 was planted in 2007 using one-year-old seedlings originating from the greenhouse seed orchard Ekebo 4. The experimental plots used for this analysis were installed and measured during spring 2012. All plots had ingrowth of naturally seeded birch and other tree species. All plots were re-measured during spring 2018.

Both experiments include a wide range of thinning practices. Some trees in some plots were subjected to different degrees of early high pruning (cf. 'Pruning treatments' below and [12]). Moreover, in some plots, one plot half was subjected to slash extraction. Due to the above-mentioned differences in initial site and stand characteristics and in experimental set-up, the two experiments were analyzed separately.

2.1. Thinning Treatments

The thinning treatments include four main regimes (Figure 1). Each thinning treatment was specified in terms of residual stem density (RSD) at different stages of stand development, expected final stem density at the end of the rotation (FSD), and target stem diameter at 1.30 m above ground level (target DBH):

- UC: Unthinned control. No pre-commercial thinning, no commercial thinning, no pruning or other management interventions at any time throughout the rotation. FSD \approx 750–900 ha⁻¹. Target DBH \approx 18 cm.
- T1500: Moderate thinning mainly from below and at regular intervals according to standard guidelines (cf. [9]). We label this treatment T1500 because RSD \approx 1500 ha⁻¹ at top height 12–13 m is a key point in the guide curve. FSD \approx 275–300 ha⁻¹. Target DBH \approx 30 cm.
- PT300: Thinning for 300 evenly distributed potential future crop trees per ha ("point thinning"; cf. [24]). Heavy point thinning at regular intervals to favor only these trees. FSD \approx 275–300 ha⁻¹. Target DBH \approx 30 cm.
- T600: Very heavy thinning leaving 600 evenly distributed potential future crop trees per ha at first thinning. Subsequent selective thinning at crown contact of individual trees, resulting in a gradually decreasing stem density. FSD \approx 100 ha⁻¹. Target DBH \approx 50 cm.

Experiment 1278 includes three replicates of each thinning treatment and three additional unthinned control plots, located in three randomized blocks (mean plot size \approx 0.20 ha, range: 0.10–0.31 ha). Blocking was based on pre-treatment total above-ground wood volume. All thinning treatments were initiated at installation of the experiment (Table 1).

In terms of standing wood volume, the thinning removals in 1278 were 28–33% in T1500, 16–25% in PT300 and 72–75% in T600. The corresponding residual basal areas were 68–72%, 75–85%, and 24–28%, respectively, of the plot-specific pre-treatment basal areas. The three heavily thinned T600 plots were damaged by windthrow during a violent windstorm on 28–29 October 2013, according to the Swedish Meteorological and Hydrological Institute (SMHI) with mean wind speed on nearby locations at up to 31 m·s⁻¹. This reduced the residual stem number by 9, 12 and 21% in each T600 plot, respectively. Most damaged trees were uprooted. We further examine the windthrow in the final discussion (Section 4.5).

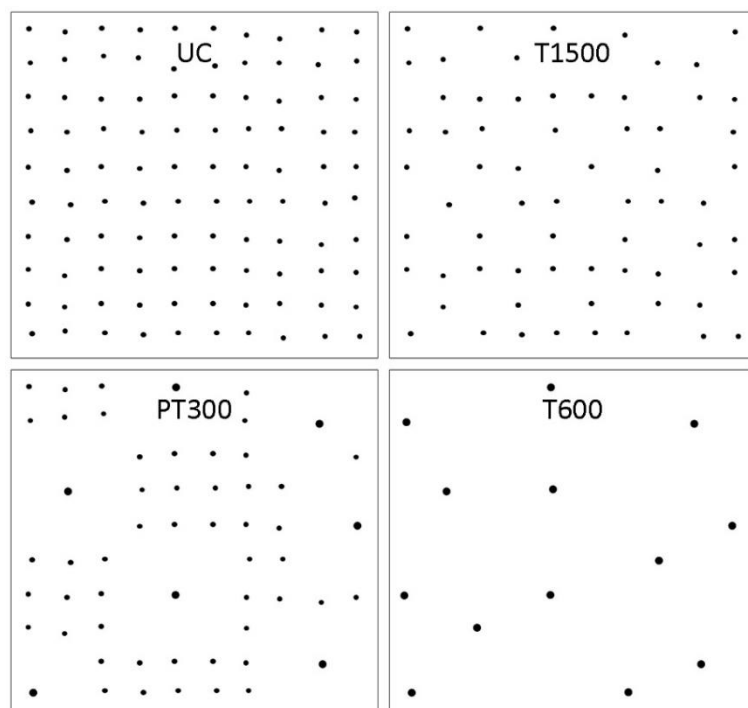


Figure 1. The four thinning treatments: UC = unthinned control, T1500 = moderate thinning mainly from below ($N = 1500 \text{ ha}^{-1}$ at $H = 12 \text{ m}$), PT300 = point thinning for 300 pre-selected potential future crop trees per ha, T600 = very heavy thinning ($N = 600 \text{ ha}^{-1}$ after first thinning intervention). Legend: small dot = a tree, large dot = a potential future crop tree.

Table 1. Number of research plots used for analyses of *stand* volume growth, *crop tree* growth and *slash* management effects. Nominal thinning treatment indicates the treatment applied during the observation period (exp. 1278: 2011–2019; exp. 1289: 2012–2018) and may deviate from the treatment scheduled for continuation (for example, some unthinned plots in exp. 1289 were pruned in 2012 and thinned in 2018, cf. Table 2 and the main text).

Treatment		Exp. 1278			Exp. 1289		
Thinning	Pruning	Stand	Crop Tree	Slash	Stand	Crop Tree	Slash
UC	No	6			9	4	
UC	Yes					4	
T1500	No	3					
PT300	No	3	3				
T600	No		3		2	2	
T600	Yes	3	3	3			

Table 2. Number of *pruned* and *unpruned* trees available for the analysis of crop tree growth and of pruning effects on individual tree growth. Nominal thinning treatment indicates the treatment applied during the observation period (PT300 or T600) or the treatment scheduled to be initiated later (PT300 unthinned and T600 unthinned).

Treatment	Exp. 1278		Exp. 1289	
	Pruned	Unpruned	Pruned	Unpruned
PT300	0	158	-	-
PT300 unthinned	-	-	138	547
T600 unthinned	-	-	257	0
T600	327	83	0	298

Experiment 1289 includes two blocks, one with five plots and one with seven (mean plot size \approx 0.21 ha, range: 0.12–0.30 ha). Blocking was based on geographic proximity. Due to insufficient natural pruning, thinning was postponed to 2018 in all but two T600 plots. One unthinned plot was excluded from the analysis due to issues with the measurement of tree height in 2012. In terms of thinning treatment, experiment 1289 contributed nine unthinned plots and two plots thinned as T600 (Table 1).

In terms of standing wood volume, the thinning removals in 1289 were 64–69% in T600. The corresponding residual basal areas were 31–35% of the pre-treatment basal areas. Here, scattered windfall in the two T600 plots amounted to 1.6% and 0.5%, respectively, based on stem number.

In both experiments, potential future crop trees in PT300 and T600 plots were selected based on superior growth potential (large stem diameter and large, essentially symmetrical crown), high stem quality (straight and upright stem, no low forking, preferably thin branches), absence of visible 'defects', and good health. In order to ensure an even spatial distribution of crop trees, each plot was subdivided into squares of approximately 10 m \times 10 m aiming for three or six crop trees in each square, depending on thinning regime, and an approximate stem map was drawn continuously during the selection process. We quantify the immediate numeric effects of the selection as part of the analysis of the size and change in size of crop trees and other large trees ('*D₃₀₀ selection and treatment effects*').

2.2. Pruning Treatments

In experiment 1278, high pruning was carried out in the three T600 plots [12]. In these plots, most trees were pruned, but some remained unpruned. In experiment 1289, no pruning was carried out in T600 plots thinned in 2012. Instead, high pruning was done on pre-selected potential future crop trees in two plots scheduled for thinning treatment PT300 and in two plots scheduled for T600 thinning at a later stage of stand development.

Pruning was carried out by removing all living and dead branches from below to a certain height above ground level (bottom-up pruning). Trees in experiment 1278 were pruned in June 2011, February 2012 and May 2012 (two trees per 10 m \times 10 m square on each occasion) using a pole-saw. Trees in experiment 1289 were pruned in July and August 2012, on some trees using pruning shears (secateurs), on others using a pole-saw.

In experiment 1278, the height of pruned trees ranged from 7.7 to 10.0 m, and on average trees were pruned to 6.11 m (range 4.20–6.82 m). In experiment 1289, the height of pruned trees ranged from 2.8 to 6.7 m, and on average trees were pruned to 2.71 m (range: 1.23–4.81 m).

2.3. Slash Management

A randomized split-plot design was applied to plots treated with T600 thinning. In one half of each plot the thinning slash was removed (slash extraction), in the other half it remained on the ground (slash retention). The installation of this treatment was motivated by the large quantities of slash following T600 thinning, its possible impact on tree growth, soil processes and biodiversity (ground flora, soil fauna, etc.) and the commercial potential of slash for firewood, woodchips, advanced biomaterials and other products.

Felling was carried out during the leaf-off season. Slash removed comprised wood residues left on the ground after felling, including stems, branches and the majority of twigs. No stumps or roots were removed. A small terrain vehicle was used for extraction.

Due to irregularities in the procedure the exact borderlines in experiment 1289 could not be retraced at re-measurement. So, only three plots in experiment 1278 (mean size of plot halves \approx 0.13 ha, range: 0.10–0.16 ha) were available for the analysis of slash management effects (Table 1). The proportion of trees damaged by wind was evenly distributed across plot halves and ranged between 7.5 and 12.0%, except in the northern half of the northernmost plot where 31.7% was damaged.

2.4. Data Collection

All trees in the experiments were numbered individually and measured for stem diameter at 1.30 m above ground level (d , cm; also referred to as diameter at breast height or dbh), and a sample of trees in each plot was measured for total tree height (h , m). The height of trees not measured for height was calculated based on the standard model $h = 1.30 + (d/(\alpha + \beta \cdot d))^3$, where α and β are plot-specific coefficients [25,26]. Total above-ground single-tree volume (v , m³) was calculated based on a regional model for birch (for $d \geq 4.5$ cm: [27], eq. 190–01; for $d < 4.5$ cm: [28]).

From these basic variables, stand values were derived for quadratic mean diameter (D_g), mean diameter of the 300 thickest trees per ha (D_{300}), stand top height (H_{100} , the average height of the 100 thickest trees per ha), stand basal area (G), stand volume (V) and other variables reflecting stand structure and growth. These were considered as potential explanatory variables in models used for the analyses (final models explained below). As an example, pre-treatment stand volume varied from 52.7 to 75.6 m³ha⁻¹ in experiment 1278 and from 3.4 to 8.5 m³ha⁻¹ in experiment 1289 (Table 3). Differences within an experiment in this order of magnitude may certainly affect tree and stand growth and are therefore included in the modelling procedure.

Table 3. Stand values for stem number (N , including ingrowth), stand basal area (G), stand volume (V), quadratic mean diameter (D_g), stand top height (H_{100} , the average height of the 100 thickest trees per ha), number of pre-selected potential future crop trees (N_{PFCT}) and arithmetic mean diameter of potential future crop trees (D_{PFCT}) at initiation of the experiment and at the end of the observation period for experiments 1278 (age: 11–19 years) and 1289 (age: 6–12 years). The table includes unadjusted mean values per treatment type (n = number of plots). Legend: PT300u and T600u refer to so far unthinned plots.

Exp	Treatment	n	Before Thinning			Remaining Stand/After Thinning						Thinning Removal					
			Age	N	G	V	N	N_{PFCT}	G	V	D_g	D_{PFCT}	H_{100}	N	G	V	D_g
			years	ha ⁻¹	m ² ha ⁻¹	m ³ ha ⁻¹	ha ⁻¹	ha ⁻¹	m ² ha ⁻¹	m ³ ha ⁻¹	cm	cm	m	ha ⁻¹	m ² ha ⁻¹	m ³ ha ⁻¹	cm
1278	UC	5	11	3938	12.96	59.8	3869		12.96	59.7	6.6		9.12	0	0.00	0.0	0.0
			19	2822	25.21	161.6	2817		25.21	161.3	10.7		14.51				
	PT300	3	11	3666	13.54	63.0	3040	299	10.84	50.0	6.8	9.0	9.49	563	2.70	12.7	7.8
			19	2335	22.70	146.3	1288	256	13.92	89.9	11.8	14.5	14.45	1041	8.78	56.3	10.4
	T1500	3	11	5466	13.78	63.8	3853		9.71	44.6	5.8		9.12	1401	4.07	18.5	6.2
			19	2615	23.48	152.6	1193		14.61	97.4	12.5		14.76	1386	8.87	55.1	9.1
T600	3	11	3998	14.11	66.3	602	602	3.71	17.8	8.8	8.7	9.45	3351	10.40	48.2	6.6	
		19	792	9.60	56.6	519	519	8.90	53.0	14.8	14.6	13.55	228	0.70	3.5	6.2	
1289	UC	5	6	2778	1.41	5.5	2723		1.4	5.5	2.8		4.36	0	0.00	0.0	0.0
			12	14270	8.10	53.4	7893		7.9	46.6	4.1		8.81				
	PT300u	2	6	2724	1.68	5.6	2682	303	1.68	5.6	2.8	3.6	5.53	0	0.00	0.0	0.0
			12	14080	10.43	59.0	6728	299	8.05	39.0	3.9	8.3	10.58	622	2.39	11.9	6.9
	T600u	2	6	2603	2.37	8.0	2599	609	2.37	8.0	3.4	3.9	5.83	0	0.00	0.0	0.0
			12	11867	10.52	56.0	6370	565	4.01	20.1	2.9	8.4	11.06	1723	6.51	33.0	6.3
	T600	2	6	2481	1.89	6.3	583	583	0.62	2.1	3.7	3.6	5.38	1877	1.27	4.2	2.9
			12	20786	5.88	31.6	12328	577	5.87	28.4	2.5	10.0	10.76	6	0.01	0.0	4.0

For pruned and some unpruned trees, a number of stem quality variables were also measured. These included height above ground level of the lowest live branch (h_{llb} , m), pruning height (h_p , m; height above ground level of the lowest remaining, live branch after pruning) and forking height (not used in this analysis).

At re-measurement, all potential future crop trees and other trees used for comparison in the analyses of individual tree growth were re-identified accurately and re-measured (Table 2). Due to ingrowth, some other trees in some plots could not be re-identified reliably by their number, but all trees were measured and identified as originally planted or as ingrowth.

2.5. Stand Volume Growth and Thinning Practice

For some plots, the analysis of thinning effects included the combined effect of thinning and pruning, which, due to the experimental design, could not be separated (cf. Tables 1 and 2). For T600 plots, whole-plot estimates of stand volume growth were used (i.e., including both

plot halves) and the effect of slash management was analyzed separately (cf. ‘Stand volume growth and slash management’).

In both experiments, ingrowth occurring after installation of the treatments was accounted for. In all plots, ingrowth during the observation period was negligible in terms of tree size and, consequently, in terms of competition with the birch originally planted on the area.

Stand volume growth depending on thinning practice was analyzed and hypotheses tested based on analyses of covariance. The variation in site productivity among experimental plots was accounted for by including the pre-treatment mean annual volume increment (MAI) of each individual plot as a covariate (cf. [29,30]). When calculating pre-treatment MAI, the denominator was adjusted by subtracting the age of the seedlings at planting.

In mathematical terms, the full model may be specified as

$$I_{Vj} = \mu + \alpha_{TC}(TC_j) + \beta \cdot MAI_{pre-trt,j} + \varepsilon_j \quad (1)$$

where I_V denotes mean annual stand volume growth (total above-ground wood volume, including ingrowth) during the observation period, TC is a class variable referring to treatment combination (Table 1), $MAI_{pre-trt}$ denotes pre-treatment mean annual volume increment at plot level, μ is the overall mean, α_{TC} and β are coefficients, $\varepsilon \sim N(0, \sigma^2)$ are model residuals, and subscript j refers to plot number.

Due to the extent of windthrow in T600 plots and the essentially solitary nature of trees, initial post-thinning volume estimates for T600 plots were adjusted to include only trees surviving to the re-measurement. Moreover, for comparability across plots, stand volume growth was scaled proportionally to stem density in order to represent 600 trees per ha, i.e., $I_{V,600} = I_{V,adjusted} \cdot 600 / N_{end}$, where N_{end} is the stem density at re-measurement.

The model was iteratively reduced based on the usual F -test in a backward elimination process until all remaining variables were significant. The test level was set at $p = 0.05$. Throughout, the tests were based on the assumption of homogeneous variance and independently, normally distributed errors. Based on the inspection of residual plots, mean and median values and distribution percentiles (not shown), these assumptions were justified.

The statistical analyses of stand volume growth and thinning practice were performed using SAS version 9.4 (SAS Institute, Cary, NC, USA).

2.6. Stand Volume Growth and Slash Management

Stand volume growth depending on slash management (retention or extraction) was analyzed based on pairwise comparison of paired plot halves (t -test) in the three heavily thinned T600 plots in experiment 1278. It was a pre-requisite for this analysis that the inherent site productivity of pairwise plot halves were roughly identical. Pre-treatment stand volume (adjusted and scaled to 600 trees per ha as previously explained) differed among plot halves by 0.6, 1.4 and 4.5%, respectively, while post-treatment average tree height differed by -0.2 , -0.3 and -2.7% , respectively. Considering the small variation of both variables, we found it justified that data could be analyzed in a pairwise comparison.

The basic variable used in the analysis was

$$\Delta_j = I_{V,jR} - I_{V,jE} \quad (2)$$

where I_V denotes mean annual stand volume growth (no ingrowth included as very little was present in these plots) during the observation period, subscript j refers to plot number, R refers to slash retention, and E refers to slash extraction. For comparability across plot halves, stand volume growth was adjusted and scaled to 600 trees per ha as previously explained.

The null hypothesis $\Delta_{mean} = 0$ (no influence of slash management on stand volume growth), where Δ_{mean} denotes the mean value of Δ , was tested based on the usual t -test

under the assumption of normally, independently distributed errors. The test level was set at $p = 0.05$.

The statistical analyses of stand volume growth and slash management were performed using SAS version 9.4 (SAS Institute, Cary, NC, USA).

2.7. D_{300} Selection and Treatment Effects

In this analysis, we aimed to quantify the combined effects of crop tree selection, thinning and pruning on the size of crop trees and other large trees. Potential future crop trees were identified in treatments PT300 and T600 already at installation of the experiment, while in treatments UC and T1500 no such trees were selected. Moreover, in T1500, the selection criteria for trees to remain or remove were different. In order to establish a baseline for comparison across all treatments, we based the analysis on D_{300} . We used the immediate change in D_{300} at initiation of the experiment to quantify the numeric, instantaneous effect of crop tree selection and of thinning, and we refer to this as the selection effect. We used the average annual increase in D_{300} during the observation period as a proxy for the growth of the expected final crop trees.

The selection effect ($\Delta_{D_{300}init}$) was quantified based on the model

$$\Delta_{D_{300}init,j} = \mu + \alpha_T(T_j) + \beta \cdot MAI_{pre-trt,j} + \varepsilon_j \quad (3)$$

where $\Delta_{D_{300}init,j} = D_{300initBT,j} - D_{300initAT,j}$, $D_{300init}$ is the mean dbh of the 300 thickest trees per ha at initiation of the experiment, subscript *BT* refers to the before thinning status, *AT* refers to the after thinning status, and other symbols, specifications and procedures are as explained for Equation (1). The rationale of testing $MAI_{pre-trt}$ as co-variate was that stand density, as considered in three-dimensional space, might influence the selection, and, since $MAI_{pre-trt}$ was used in other models, we preferred this over V_{init} . The test level was set at $p = 0.05$. $D_{300initBT}$ was tested as an additional or alternative co-variate in Model (3), but was rejected (the correlation between $MAI_{pre-trt}$ and $D_{300initBT}$ was $r = 0.730^{**}$ for exp. 1278 and $r = 0.919^{***}$ for exp. 1289).

The average annual increase in the mean dbh of the 300 thickest trees per ha ($I_{D_{300}}$) was analyzed based on the model

$$I_{D_{300},j} = \mu + \alpha_T(T_j) + \beta \cdot MAI_{pre-trt,j} + \varepsilon_j \quad (4)$$

where $I_{D_{300}} = D_{300init} - D_{300end}$, $D_{300init}$ and D_{300end} are the mean dbh of the 300 thickest trees per ha at initiation of the experiment (after thinning) and at the end of the observation period, respectively, and all other variables, specifications and procedures are as explained for Equation (1). For treatments PT300 and T600, D_{300} was calculated based only on the selected crop trees and only those that remained alive until the end of the observation period. For other treatments, D_{300} was calculated based on the 300 thickest trees per ha in the residual stand at any time.

The statistical analyses of D_{300} selection and treatment effects were performed using SAS version 9.4 (SAS Institute, Cary, NC, USA).

2.8. Crop Tree Growth

The growth of pre-selected potential future crop trees was analyzed for treatments PT300 and T600 based on dbh. In some plots, additional trees had been measured to a similar standard and were thus available for comparison (Table 2).

We tested three alternative, mixed linear models (5.1, 5.2 and 5.3), which were calibrated for different subsets of data. The models can be specified in a common equation as

$$i_{d,ij} = \mu + \beta_T(T_j) + \beta_P(P_{ij}) + \beta_S(S_{ij}) + \theta \cdot MAI_{pre-trt,j} + \sum \delta_k \cdot x_{ijk} + \alpha_j + \varepsilon_{ij} \quad (5)$$

where i_d denotes average annual growth on dbh during the observation period, T is a class variable indicating thinning treatment, P is an indicator variable of pruning or no

pruning, S is an indicator variable of the presence or absence of slash at the base of the individual tree, $MAI_{pre-trt}$ denotes pre-treatment mean annual volume increment during the observation period, x is a set of continuous variables reflecting the growth capacity of an individual tree, μ is the overall mean, $\beta_T, \beta_P, \beta_S, \theta$ and δ are coefficients, $\alpha \sim N(0, \sigma_\alpha^2)$ is the error attributed to plot, $\varepsilon \sim N(0, \sigma_\varepsilon^2)$ is the residual error, subscript i refers to tree number, j refers to plot number, and k identifies the relevant continuous variable. The specification of x -variables varied among models.

Model (5.1) was calibrated with all trees available for analysis. Model (5.1) included d_{init} (dbh at initiation of the experiment) as the only continuous predictor variable x , and the slash variable S was excluded. Model (5.2) was calibrated with pruned trees for which pruning height had been measured. Model (5.2) included $d_{init}, c_l = h - h_p$ (reflecting remaining crown length) and all class variables as candidate predictor variables. Model (5.3) was calibrated for pruned trees for which pruning height and the height of the lowest live branch had been measured. Model (5.3) included $d_{init}, c_{prop} = (h - h_p) / (h - h_{lb})$ (the proportion of crown remaining after the treatment, reflecting pruning severity) and all class variables as candidate predictor variables.

Prior to the final analyses logarithmic transformation of numeric variables was considered. Moreover, d_{init}^2 was tested as a potential predictor in the otherwise untransformed models. In all cases, the untransformed variables were found to perform better.

The goodness-of-fit of each model was evaluated graphically based on residual plots (not shown) and by the coefficient of determination (R^2). As there is no consensus for calculating R^2 in mixed models, we adopted a method [31] according to which

$$R_m^2 = \frac{\sigma_f^2}{\sigma_f^2 + \sigma_\alpha^2 + \sigma_\varepsilon^2} \quad (6)$$

and

$$R_c^2 = \frac{\sigma_f^2 + \sigma_\alpha^2}{\sigma_f^2 + \sigma_\alpha^2 + \sigma_\varepsilon^2} \quad (7)$$

where R_m^2 is the marginal coefficient of determination concerned with variance explained by fixed factors, R_c^2 is the conditional coefficient of determination concerned with variance explained by both fixed and random effects, σ_f^2 is the variance calculated from the fixed effects components of the mixed model, and other terms are as explained above.

Due to opposite effects on the individual tree growth of pruning and canopy closure in unthinned plots of experiment 1289 scheduled for PT300 or T600 treatment, and due to unbalanced data in terms of dbh and treatments, Model (5) could not be calibrated with reasonable and consistent parameter estimates. Consequently, the final analysis of crop tree growth included only experiment 1278.

The statistical analyses of crop tree growth were performed using the free software R (The R Foundation).

3. Results

3.1. Stand Volume Growth and Thinning Practice

In experiment 1278 (15 plots), stand volume growth during the observation period (age 11–19 years) varied between 4.54 and 16.03 m³ha⁻¹year⁻¹. Two plots deviated from the general pattern and, based on statistical tests, were considered outliers. One of these (T1500) suffered from extremely poor drainage at installation, and the other one (UC) had ingrowth with a large proportion of birch of genetically unimproved origin. These plots were omitted from the final analysis. The final model included no interaction term.

According to the final model, stand volume growth depended on site productivity (as reflected by pre-treatment MAI) as well as on thinning treatment (Figure 2). Growth increased with increasing pre-treatment MAI and was largest in the unthinned control, marginally smaller in the two classical thinning treatments T1500 and PT300 and substan-

tially smaller in the very heavy thinning T600 (Table 4). LS-means estimates indicated a growth reduction for the T1500 treatment by 13.7% as compared to the unthinned control, by 12.3% for PT300, and by 62.4% for T600.

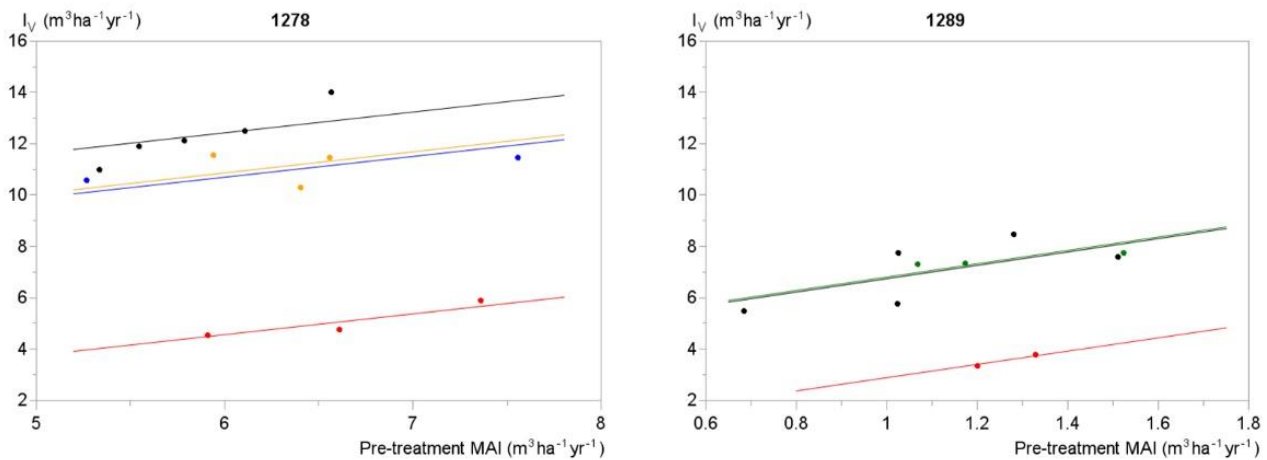


Figure 2. Mean annual stand volume growth (I_V , $\text{m}^3\text{ha}^{-1}\text{year}^{-1}$) vs. pre-treatment mean annual volume increment ($MAI_{pre-trt}$, $\text{m}^3\text{ha}^{-1}\text{year}^{-1}$) depending on treatment. Parameter estimates for the regression lines are given in Table 4. Legend for treatments: UC = black, UC-pruned = green, PT300 = yellow, T1500 = blue, T600 = red.

Table 4. Parameter and LS-means estimates for the final model of stand volume growth depending on treatment and pre-treatment MAI ($MAI_{pre-trt}$, $\text{m}^3\text{ha}^{-1}\text{year}^{-1}$). Legend: n = number of observations, R^2 = coefficient of determination.

Variable/ Treatment	Estimate	p -Value	LS-Means ($\text{m}^3\text{ha}^{-1}\text{year}^{-1}$)
Exp. 1278 ($n = 13$, $R^2 = 0.963^{***}$)			
Intercept	7.5315	0.005	
$MAI_{pre-trt}$	0.8134	0.038	
UC	0.0000	-	12.60
PT300	-1.5440	0.022	11.05
T1500	-1.7183	0.025	10.88
T1500	-7.8607	<0.0001	4.74
Exp. 1289 ($n = 11$, $R^2 = 0.872^{**}$)			
Intercept	4.1405	0.017	
$MAI_{pre-trt}$	2.6000	0.054	
UC	0.0000	-	7.21
UC Pruned	0.0582	0.925	7.27
T600	-3.8598	0.001	3.35

In experiment 1289 (11 plots), stand volume growth during the observation period (age 6–12 years) varied between 3.35 and 8.46 $\text{m}^3\text{ha}^{-1}\text{year}^{-1}$. One unthinned pruned plot was an outlier and was consequently omitted from the final analysis. The final model included no interaction term.

Pre-treatment MAI was barely significant ($p = 0.054$) in this experiment, but considering the large heterogeneity in site and pre-treatment stand conditions, we decided to keep this variable in the final model. The final model also included thinning treatment (Figure 2). Growth increased with increasing pre-treatment MAI, was largest and essentially identical in unthinned plots, whether without or with some pruned trees, and was substantially smaller in heavily thinned T600 plots (Table 4). LS-means estimates indicated a growth reduction for the T600 treatment by 53.5% as compared to the unthinned control.

3.2. Stand Volume Growth and Slash Management

Stand volume growth in the T600 treatment of experiment 1278 varied between 4.65 and 6.52 $\text{m}^3\text{ha}^{-1}\text{year}^{-1}$ (mean = 5.30 $\text{m}^3\text{ha}^{-1}\text{year}^{-1}$) in plot halves with slash extraction and between 4.44 and 5.42 $\text{m}^3\text{ha}^{-1}\text{year}^{-1}$ (mean = 4.89 $\text{m}^3\text{ha}^{-1}\text{year}^{-1}$) in plot halves with slash retention (age 11–19 years). On average, slash retention reduced growth by $-0.42 \text{ m}^3\text{ha}^{-1} \text{ year}^{-1}$ or approximately 8% as compared to slash extraction, but the difference between the two treatments was not significant ($p = 0.353$).

3.3. D_{300} Selection and Treatment Effects

Due to the selection criteria, $D_{300\text{initAT}}$ was inevitably smaller than $D_{300\text{initBT}}$ in all treatments but the unthinned control. Pre-treatment MAI was not significant in either experiment ($P_{1278} = 0.108$, $P_{1289} = 0.330$), although scatterplots (not shown) indicated a tendency for increasing selection effect ($\Delta D_{300\text{init}}$) with increasing pre-treatment MAI. The relative magnitude of the selection effect (Table 5) was consistent across the two experiments and was largest in the PT300 treatment (15–21%), smaller in the T600 (9–11%), and smallest in the T1500 (3.5%).

Table 5. Quantification of the selection effect depending on thinning practice based on change in D_{300} ($\Delta D_{300\text{init}}$). Percentage change was calculated as $100 \cdot \Delta D_{300\text{init}} / D_{300\text{initBT}}$. Legend: s = standard deviation.

Treatment	Experiment 1278			Experiment 1289		
	$\Delta D_{300\text{init}}$ cm	$\Delta D_{300\text{init}}$ %	s cm	$\Delta D_{300\text{init}}$ cm	$\Delta D_{300\text{init}}$ %	s cm
T1500	0.35	3.5	0.06			
PT300	1.53	14.6	0.19	0.95	21.0	0.10
T600	0.93	8.8	0.33	0.54	11.0	0.08

In experiment 1278, I_{D300} (the average annual increase in D_{300}) ranged from 0.59 to 0.79 $\text{cm} \cdot \text{year}^{-1}$. Two plots were outliers (one T1500 and one UC) and were omitted from the final analysis (these were consequently also omitted from the final analysis of selection effects). Pre-treatment MAI was barely significant ($p = 0.131$), but the trend was evident from the scatterplot (Figure 3). LS-means estimates for I_{D300} increased by 2% with point thinning, 8.5% with T1500 thinning, and 18% with very heavy T600 thinning, as compared to the unthinned control (Table 6).

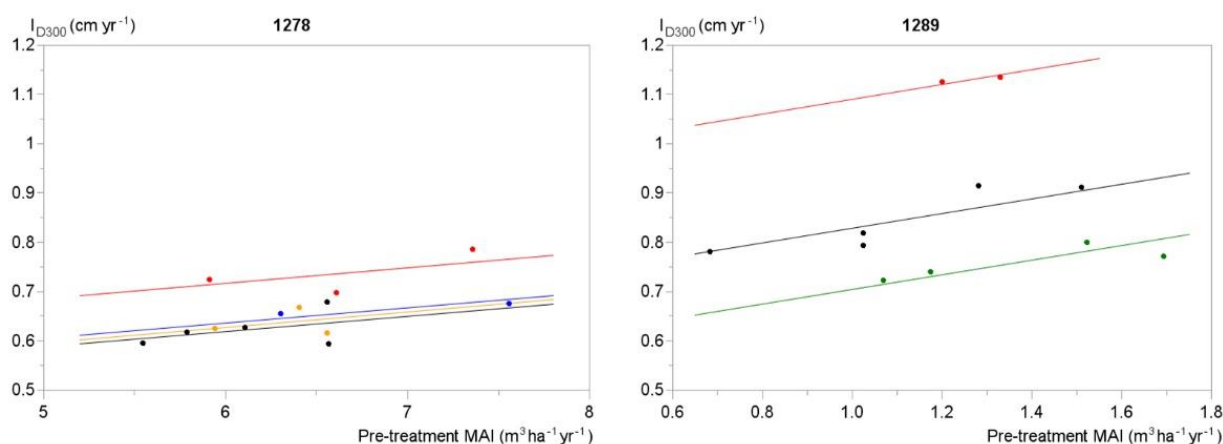


Figure 3. Mean annual change in D_{300} (I_{D300} , $\text{cm} \cdot \text{year}^{-1}$) vs. pre-treatment MAI ($MAI_{\text{pre-trt}}$, $\text{m}^3\text{ha}^{-1}\text{year}^{-1}$) depending on treatment. Parameter estimates are given in Table 6. The regression lines for 1278 were not significant ($p = 0.131$) and are shown only for orientation. Legend for treatments: UC = black, UC-pruned = green, PT300 = yellow, T1500 = blue, T600 = red.

Table 6. Parameter and LS-means estimates for the final model of mean annual change in D_{300} (I_{D300}) depending on treatment and pre-treatment MAI. Legend: n = number of observations, R^2 = coefficient of determination.

Variable/ Treatment	Estimate	p -Value	LS-Means ($\text{m}^3\text{ha}^{-1}\text{year}^{-1}$)
Exp. 1278 ($n = 13$, $R^2 = 0.712^{**}$)			
Intercept	0.6226	<0.0001	
UC	0.0000	-	0.62
PT300	0.0142	0.584	0.64
T1500	0.0427	0.170	0.67
T600	0.1138	0.001	0.74
Exp. 1289 ($n = 11$, $R^2 = 0.973^{***}$)			
Intercept	0.6785	<0.0001	
$MAI_{pre-trt}$	0.1498	0.0037	
UC	0.0000		0.86
UC Pruned	-0.1241	0.0006	0.74
T600	0.2617	<0.0001	1.12

In experiment 1289, I_{D300} ranged from 0.72 to 1.13 $\text{cm}\cdot\text{year}^{-1}$. According to the final model, I_{D300} increased with pre-treatment MAI and depended on thinning treatment (Figure 3). Comparing unthinned plots with or without the pruning of 300 trees per ha, LS-means estimates indicated a reduction in I_{D300} by 14% due to pruning (Table 6). Comparing unthinned plots and the heavily thinned T600 plots, in both cases without pruning of any trees, T600 thinning resulted in an increase in I_{D300} by 30%.

3.4. Crop Tree Growth

The average annual growth on the dbh of pre-selected potential future crop trees in plots treated with PT300 or T600 in experiment 1278 varied between 0.01 and 1.25 cm (Figure 4). No interaction terms were significant in any of the three models calibrated.

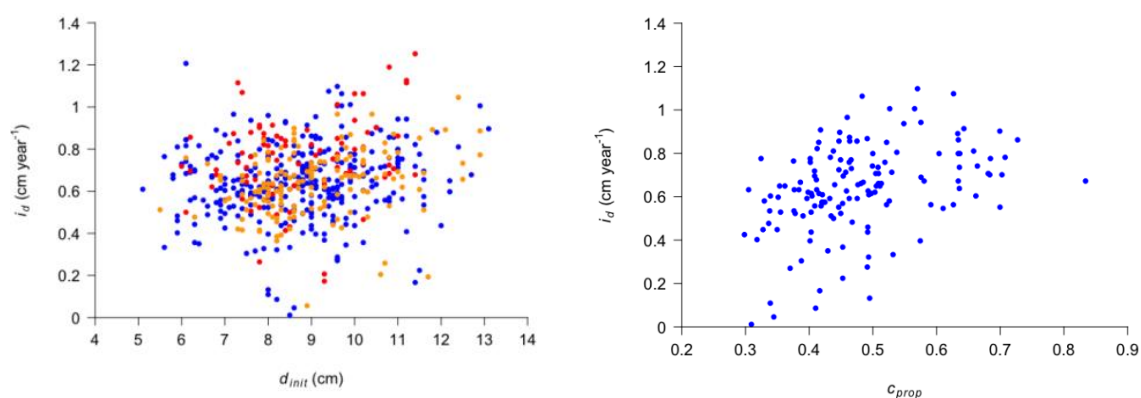


Figure 4. Experiment 1278. Left: individual tree growth (i_d) for crop trees of treatments PT300 and T600 vs. initial stem dbh (d_{init}). Right: individual tree growth (i_d) for pruned crop trees of treatment T600 vs. remaining crown proportion (C_{prop}). Legend: PT300 unpruned = yellow, T600 unpruned = red, T600 pruned = blue.

According to the final version of Model (5.1) calibrated on all available data, growth on dbh increased with increasing initial dbh (larger stem size), was positively influenced by heavy thinning on the whole plot (T600) as compared to point thinning (PT300) and was negatively influenced by high pruning (Table 7). Using $d_{init} = 8.81$ cm and unpruned trees in PT300 as the baseline, LS-means estimates indicated 21% larger growth on unpruned trees in T600 and 3% larger growth on pruned trees in T600 (Table 8). Pruning in T600 led to 14% less growth on dbh as compared to unpruned T600 trees. For (hypothetical)

pruned trees in PT300, the model indicates 17% less growth as compared to unpruned trees in PT300.

Table 7. Parameter estimates for the final model of individual crop tree growth on dbh. Legend: d_{init} = initial stem dbh, c_l = remaining crown length, c_{prop} = remaining crown proportion, n = number of observations, R_m^2 = marginal coefficient of determination concerned with variance explained by fixed factors, R_c^2 = conditional coefficient of determination concerned with variance explained by both fixed and random effects, σ_a^2 = variance attributed to plot, σ_ε^2 = residual variance.

Variable/Treatment	Estimate	p-Value
Exp. 1278 ($n = 568$, $R_m^2 = 0.083$, $R_c^2 = 0.116$)		
<i>Fixed</i>		
Intercept PT300-unpruned	0.4464	<0.001
d_{init}	0.0208	<0.001
T600	0.1299	0.020
Pruned	−0.1097	<0.001
<i>Random</i>		
σ_a^2	0.0010	
σ_ε^2	0.0276	
Exp. 1278 ($n = 327$, $R_m^2 = 0.092$, $R_c^2 = 0.106$)		
<i>Fixed</i>		
Intercept	0.3567	<0.001
c_l	0.1006	<0.001
<i>Random</i>		
σ_a^2	0.0004	
σ_ε^2	0.0266	
Exp. 1278 ($n = 143$, $R_m^2 = 0.147$, $R_c^2 = 0.156$)		
<i>Fixed</i>		
Intercept	0.2867	<0.001
c_{prop}	0.7362	<0.001
<i>Random</i>		
σ_a^2	0.0003	
σ_ε^2	0.0345	

Table 8. LS-means estimates for the final model of individual crop tree growth on dbh (cf. Table 7).

Variable/Treatment	LS-Means (cm year ^{−1})	
Exp. 1278, model 1	d_{init} (cm)	
PT300 unpruned	8.81	0.631
PT300 pruned	8.81	0.521
T600 unpruned	8.81	0.761
T600 pruned	8.81	0.651
Exp. 1278, model 2	c_l (m)	
Min.	1.70	0.528
Mean	2.86	0.645
Max.	5.16	0.876
Exp. 1278, model 3	c_{prop}	
Min.	0.29	0.506
Mean	0.48	0.640
Max.	0.83	0.901

Remaining crown length after the pruning of pre-selected potential future crop trees in T600 plots in experiment 1278 varied between 1.70 and 5.16 m. In a subset of trees, the

remaining crown proportion varied from roughly 30 to 70% (mean value = 48%) and were evenly distributed across this range.

According to the final models for pruned trees only, Model (5.2) for crown length logically indicated increasing growth with increasing crown length, and Model (5.3) for crown proportion indicated increasing growth with increasing proportion of crown remaining after the pruning (Table 7). In these two models, no influence was found of initial dbh, pre-treatment MAI or slash management (retention or extraction). Although calibrated on a smaller number of observations, the crown proportion model had higher R^2 -values than the crown length model. Considering that Model (5.3) was calibrated on a subset of the data used for Model (5.2), LS-means estimates agreed well across the range of data.

4. Discussion

4.1. Stand Volume Growth and Thinning Practice

In our study of young silver birch, stand volume growth increased with increasing pre-treatment stand volume (or pre-treatment mean annual volume increment) and decreased with increasing thinning intensity as compared to the unthinned control. For shade-tolerant tree species, stand volume growth is often quite insensitive to thinning over a broad range of thinning grades (when thinning from below), whereas thinning of light-demanding tree species often leads to a reduction in growth [32,33].

Referring to both experiments, the observed responses of stand volume growth to pre-treatment MAI emphasizes the importance of including an indicator of inherent site productivity in stand level thinning analyses. However, due to the age-related pattern of volume growth, pre-treatment MAI did not allow for an immediate comparison across the experiments. Asynchrony of age across experiments particularly hampers comparisons based on pre-treatment MAI for tree species with rapid growth in youth, such as silver birch, simply because of the relatively large impact of age in calculating MAI.

As an alternative to pre-treatment MAI, pre-treatment stand basal area, stand top height or soil variables could have been used [29,30]. In our case, no soil variables were available and site index based on stand top height could not be derived reliably due to the young age of experiment 1289. Moreover, at initiation of the experiment, height in this very young stand might still be influenced by stand establishment practices (the importance of which usually vanishes with increasing age).

The purpose of including a co-variate characterizing the plot or stand at initiation of an experiment obviously is to account for pre-treatment variation among plots and in doing so reducing the residual variation of the final model. Likewise, and considering the within-treatment variation in thinning removals and residual basal area, it could be desirable to specify the treatments numerically rather than as categorical variables, for example, by residual basal area as in classical thinning response analyses [32]. However, this approach is meaningful only if the selection principle is similar across treatments (for example, thinning from below only). Moreover, in our case the specification of treatments by a categorical variable resulted in a higher coefficient of determination.

In 1278, moderate thinning reduced growth by 14% and heavy thinning (combined with pruning) by 62%. Adjusting for the pruning on 80% of the residual trees in heavily thinned plots brings the reduction with heavy thinning down by approximately 0.7%-points (14% less growth on dbh of each pruned tree \approx potentially 2.33% larger growth on basal area of each unpruned tree (mean dbh = 8.8 cm) \approx 1.86% larger growth at stand level \approx stand volume growth would have been 38.3% instead of 37.6% of the unthinned control). No adjustment was justified for slash extraction on approximately half of each of the heavily thinned plots.

The smaller growth reduction with heavy thinning in 1289 (54%) could be due to incomplete canopy closure at initiation of the experiment, resulting in less than maximum growth in the unthinned control. Alternatively, the difference between experiments could be due to trees being more responsive at a younger age. This would be in contrast, however, to the response pattern for pedunculate oak (*Quercus robur* L.), another light-demanding

species, for which the growth reduction due to thinning (relative to the unthinned control) decreases with increasing age [34].

Interestingly, point thinning resulted in a growth reduction almost identical to that of moderate thinning throughout the whole plot (exp. 1278). With point thinning the only trees removed in thinning were immediate competitors of the potential future crop trees, and no thinning was carried out in the space between these. This means that the thinning response of pre-selected potential future crop trees did not completely compensate for the reduction in stand growth due to the thinning removal.

On a pro rata basis, the reduction/removal-ratio for moderate thinning was 0.46 and for point thinning 0.60. This supports the growth reduction as being located mainly in pre-selected potential future trees. In 1278, the reduction/removal-ratio for heavy thinning was 0.85 (adjusted to 600 trees per ha and no pruning), and in 1289 it was 0.80.

Clearly, there was a disproportionately large reduction in stand volume growth with heavy thinning. Moreover, there was less reduction with thinning scattered throughout the stand as compared to point thinning. Both of these results indicate that canopy closure, or the regain of canopy closure, is essential in order for young birch stands to fully utilize the growth potential. However, the long-term effect of one or few heavy thinning interventions (such as T600) as compared to repeated moderate thinning (such as T1500) still has to be evaluated. The quantification of these relationships throughout the rotation will depend on the long-term development of the experiments.

Only a few other studies quantify the influence of thinning practice on stand growth in even-aged silver birch. In Finland, preliminary results from a series of 14 experiments somewhat comparable to experiment 1278 indicated a similar response to thinning intensity. For example, in the experiment at Padasjoki (160 km north of Helsinki), initiated at a slightly more advanced stage of stand development, two thinning operations, first to 50%, then to 35% of the basal area of the unthinned control, reduced stem volume growth by approximately 30%, with lighter thinning regimes leading to less reduction [5].

In Canada, results from an experiment in 9–13 year-old naturally regenerated paper birch (*Betula papyrifera* Marsh.) with three from-below thinning treatments and an unthinned control, all replicated three times on each of the four different sites, indicated a response pattern for 5-year post-treatment growth similar to that of experiment 1278 [35]. The experiment included residual stem densities of 3000, 1000 and 400 trees per ha. Post-treatment plots had a sparse admixture of other tree species. Based on mean values reported in the publication, we calculated the thinning removals at 54%, 69% and 83%, respectively, and the residual basal areas at 42%, 26% and 14%, respectively. The resulting growth reductions (based on stem volume inside bark) were 34%, 59% and 74%, respectively, as compared to the unthinned control, and the corresponding reduction/removal-ratios were 0.62, 0.85 and 0.89.

Our results for silver birch are clearly consistent with those reported for paper birch. Consequently, results from the experiments in Sweden and from the experiment in Canada may be combined and summarized in a simple model for birch of growth reduction at stand level as a linear function of thinning removal, with both variables expressed as a percentage of the unthinned control (Figure 5). In the absence of better information, this model may serve to provide an indication of the expected growth reduction for from-below thinning in young birch stands and could be used for developing thinning guidelines.

4.2. Stand Volume Growth and Slash Management

The slash extraction in heavily thinned plots of experiment 1278 comprised 71–75% of the total above-ground wood volume on the area and thus represented a rather substantial removal. Slash extraction had no statistically significant impact on volume growth at stand level for the entire observation period (eight years after the first and only thinning intervention). No re-measurements were made during the observation period, so the temporal development in growth could not be specified. The possible influence of slash management also remained undetected in the growth of individual, pruned crop trees when using crown length or remaining crown proportion as main predictor.

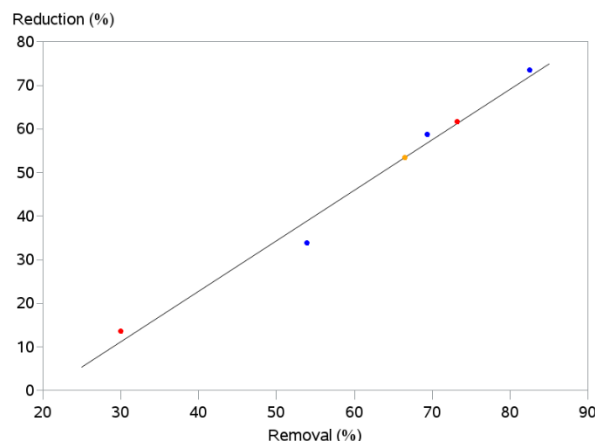


Figure 5. Results from experiments 1278 (red dots) and 1289 (yellow dot) in Sweden and an experiment (blue dots) in Canada [35] summarized in a simple model for the reduction in stand volume growth ($Red_{IV\%}$) as a linear function of thinning removal ($Rem_{V\%}$), both expressed as a percentage of the unthinned control. Excluding point thinning, for which the selection criteria differ substantially, the following model was calibrated (black line): $Red_{IV\%} = -23.67 + 1.16 \cdot Rem_{V\%}$ ($R^2 = 0.980^{***}$, $n = 6$, calibration range: 30–83%).

Whole-tree harvesting without stump and root extraction is the most common type of slash removal and has been studied extensively mainly in conifer-dominated forest types. The impact on tree growth tends to be site-specific, in the short-term negative, and in the long-term less clear (e.g., [36–38]). One study comprising two-storied stands of silver birch (overstorey) and Norway spruce (understorey, 20–30 years old) found no short-term influence of whole-tree harvesting of birch on the growth of either species in the residual stand [39]. However, in all such studies, site- or management-specific confounding factors may mask any direct effect of slash management (e.g., [40–42]).

Logically, harvesting combined with slash extraction removes nutrients that would otherwise remain on the area to become available for residual trees and other vegetation. Harvesting of stump and root systems obviously further depletes the nutrient pool [43]. Other contributing factors to site modification include soil compaction by machinery and derived effects from change in microclimate near the soil surface brought about by the presence or absence of slash. In turn, any or all of these site modifications may influence long-term site productivity.

As judged by the subsequent development of ground flora in different T600 plot halves of experiment 1278, site modification became apparent soon after the thinning intervention. Similar indications of site modification are known from a thinning experiment in young pedunculate oak in Denmark [44]. The degree of cover and the diversity of ground flora were inventoried in great detail when the experiments were initiated, but have not been re-inventoried. Any quantitative correlation with site or stand productivity remains to be investigated.

Slash (harvest residues) is an abundant by-product in managed forests, with significant potential as feedstock for renewable energy systems or advanced biomaterials. Slash management is nutrient management, but it also involves biodiversity, soil properties and other issues not included in our study. Due to the potentially conflicting interests of commercial slash extraction, forest productivity and environmental concerns, slash management may be critical for long-term forest sustainability and warrants further consideration.

From an operational perspective, slash retention may be a problem in heavily thinned stands simply because the slash may hamper access to the area (for example, for subsequent pruning). However, during thinning operations in young stands, slash can easily, and at little cost, be arranged in lines, for example, along rows or transportation tracks, and this is recommended.

4.3. D_{300} Selection and Treatment Effects

The relative magnitude of the selection effect was consistent across the two experiments as measured by the instantaneous numeric change in D_{300} due to thinning. The selection effect was largest with point thinning (PT300, 15–21%), smaller with heavy thinning (T600, 9–11%), and smallest with moderate thinning (T1500, 3.5%).

The selection was supervised by the senior author in both experiments and was implemented by two different co-authors (one for each experiment). The consistency indicates adherence to the general guidelines. For PT300 and T600, these can be summarized as positive selection for regular spatial distribution, superior growth potential, high stem quality, absence of visible ‘defects’, and good health. In contrast, selection in T1500 was negative and against undesired trees in the stand. This resulted in less change in D_{300} . Although the selection criteria for potential future crop trees were, in principle, identical for PT300 and T600, the prescribed treatment of each plot was known in advance and clearly influenced the selection.

During selection in PT300, it was considered that nearby neighbor trees on the periphery of the gap created around each selected crop tree will remain in the stand for a while and that the gap will be gradually enlarged in subsequent thinning interventions. Moreover, it was considered that pruning was not an option for improving stem quality (pruning of trees in PT300 plots of experiment 1289 was decided at a later stage and did not influence the selection of crop trees).

During selection in T600, it was considered that the (best) trees were to be pruned, so branch size mattered less. Consequently, different types of trees were selected and there was a different attitude to, for example, wolf trees (dominant trees with short stem, thick branches and widely spreading crown). Finally, the selection of 600 vs. 300 trees worked in a similar direction.

In experiment 1278, the average annual change in D_{300} , I_{D300} , increased with increasing thinning intensity. This could indicate that potential future crop trees in PT300 plots would have benefitted from thinning sooner than after eight years.

In experiment 1289, I_{D300} was substantially larger than in 1278, reflecting the rapid growth in the youth of silver birch and its vigorous, but with age declining, responsiveness to increasing space. Moreover, I_{D300} in 1289 clearly demonstrated the negative impact of pruning and the positive impact of heavy thinning on the growth of pre-selected crop trees as compared to socially dominant trees in unpruned or unthinned stands, respectively.

4.4. Crop Tree Growth

The analyses of crop tree growth in experiment 1278 revealed 21% larger growth on the dbh of unpruned trees in heavily thinned plots as compared to unpruned trees in point thinning plots, while pruned trees in heavily thinned plots had 3% larger growth than unpruned trees in point thinning plots and 14% less than unpruned trees in heavily thinned plots. In other words, most of the growth stimulation due to thinning was lost in pruning.

This result is in line with the analysis of the D_{300} treatment effect and, as for the pruning in heavily thinned plots, with results from a similar experiment in young European beech (*Fagus sylvatica* L.). The beech experiment comprised unthinned control plots, strip thinning removing 50% of the stem number, and heavy thinning (with or without pruning) leaving only 200 trees per ha [45]. Potential future crop trees had been selected in all treatments and according to criteria identical to those used in our birch experiments.

Although not explicitly part of the selection criteria, potential future crop trees were selected partly based on social dominance. Larger growth on dbh of socially dominant trees following thinning has been observed in a number of other studies, including some for silver birch in Finland [4,5], paper birch in North America [35,46] and beech in Europe [47–49].

Diameter growth generally increases with increasing growing space, but it was somewhat surprising that heavy thinning as applied in the T600 treatment resulted in increased dbh growth as the dramatic change in stand-interior forest conditions resulting from this treatment might be expected to reduce stand level as well as individual tree growth. The

increase in dbh growth was reduced when heavy thinning was combined with pruning, reflecting the immediate reduction in foliage volume. Due to the lack of re-measurements on an annual basis, the temporal pattern of individual tree growth, i.e., the immediate growth reduction due to foliage loss followed by a gradual recovery, could not be quantified.

The two models that include measurements of remaining crown size quantify the reduction in growth for the duration of the whole observation period depending on remaining crown length or on the proportion of crown remaining after pruning. Due to the overwhelmingly large number of unpruned trees and their variability in growth, neither of these models could be calibrated in a meaningful way by including unpruned trees (crown proportion = 1.0) in calibration data. Anyhow, the models were calibrated for a large range of pruning severity and clearly indicate larger growth on stem diameter with larger crown and larger growth with larger remaining crown proportion.

In experiment 1278, roughly 30–70% of the crown length was removed in the pruning. Extrapolating from this range to 100%, the model for remaining crown proportion indicates a growth reduction for dbh at approximately 50% when removing two-thirds of the crown and at approximately 25% when removing one-third. This is qualitatively and quantitatively consistent with studies of birch species in Asia [50,51] and North America [52–54]. Moreover, the sensitivity of birch to reductions in foliage at tree level is consistent with its sensitivity or limited capacity at stand level to recover from thinning.

4.5. Windthrow

As an unintended side-effect of heavy thinning, all T600 plots in experiment 1278 were damaged during a windstorm in the autumn of 2013, three growing seasons after thinning. Damage occurred mainly in streaks along the main direction of the wind and the proportion of damaged trees was evenly distributed among plot halves, except one plot half with a three times larger blowdown. Being located near the northern (upwind) edge of the forest, this plot was more exposed. No other treatments suffered notable damage.

Most of the damaged trees were uprooted, possibly influenced by the combination of organic soil, poor drainage (shallow root systems) and widespread root rot due to *Heterobasidion annosum* (Fr.) Bref. (identified in stem disc samples), *Armillaria gallica* Marxm. and Romagn. (identified on site by rhizomes) or other, unidentified fungi. However, the occurrence of root rot was investigated prior to the windstorm and was not restricted to T600 plots. Moreover, no pattern relating to site conditions or slash management was apparent in the spatial distribution of the wind damage.

A likely explanation for the observed windthrow pattern is increased canopy roughness due to canopy gaps created by thinning as this makes recently thinned stands more vulnerable (cf. [55]). Following heavy thinning, wind can penetrate deeper into the canopy with a subsequent increase in the wind load imposed on the remaining trees, while dense stands dissipate incoming wind. A tree is uprooted if the total turning moment exceeds the support provided by the root-soil plate anchorage, and if the stem does not break prior to uprooting. The canopy closure and the root expansion following thinning may gradually improve stand stability but, apparently, this process had not progressed sufficiently in the T600 plots of experiment 1278.

For birch growing in average forest conditions, mechanistic simulation studies indicate that the critical wind speed for uprooting 12 m tall trees is 1.5–2 times larger for trees without than for trees with leaves and increases by 50%, to approximately $32 \text{ m}\cdot\text{s}^{-1}$, for an increase in dbh from 10 to 15 cm [56]. Based on linear interpolation, stand top heights (dominant trees) in our T600 plots were 10.4–11.4 m at the time of the 2013-windstorm. However, the combination of age, height and stand density was probably beyond the calibration range of the model.

The more widespread damage at the long-established upwind forest edge or, more accurately, immediately behind the edge, is consistent with general experience in silviculture [57], wind simulation studies [58] and research on birch [59]. Consistent with the

simulation studies specifically for birch [56], unthinned plots and ‘normally’ thinned plots (stand top height \approx 10.1–11.7 m) in experiment 1278 remained undamaged.

Broadleaved forest usually remains unaffected by windstorms during the dormant season [60–62]. Nevertheless, our observations indicate that heavily thinned stands of birch are vulnerable to windthrow for some years following thinning intervention. We found no other reports of this in literature. However, plots of young pedunculate oak thinned to a residual stem density of 300 or 100 trees per ha, replicated in five experimental blocks on three different glacial till sites in Denmark [44,63], all suffered damage in windstorms shortly after the first thinning intervention. In the oak experiments, windthrow occurred mainly on high terrain or on moist parts of the area, and most damaged trees were blown into a leaning stem position rather than being uprooted or having the stem broken (based on unpublished data collected by the senior author). This is consistent with differences in soil type (organic soil vs. glacial till) and with the general notion of better root anchorage for oak than for birch.

Observations of windthrow are almost always situational. This also holds for our study and we consequently caution the general validity of our interpretations and of suggested hypotheses. Nevertheless, any observations from accidental case studies such as this may accumulate to form or corroborate scientific hypotheses, whether testable or untestable.

5. Conclusions

Despite the importance of silver birch in boreal and, to some extent, temperate forests in Europe and Asia, the effects of early thinning and pruning on tree and stand growth are poorly quantified in research literature, and the effect of slash management remains un-investigated or, at least, un-reported. Our study in even-aged stands of silver birch aged 6–19 years demonstrates a general reduction in stand level growth with increasing thinning intensity as compared to the strictly unthinned control. Even less severe removals such as with point thinning reduced growth at stand level. For heavy thinning with large quantities of slash, we found no significant reduction in stand level growth after slash extraction. The growth of pre-selected potential future crop trees increased with increasing thinning intensity. In heavily thinned plots, pruning reduced growth increasingly with increasing pruning severity. Throughout, the temporal trend in growth responses during the observation periods was not included in the analyses.

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