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Effect of boom corridor and selective thinning on the post-treatment growth of young Scots pine and birch stands

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Highlights

- During the 4–5-year post-treatment period, boom corridor thinning did not result in growth and yield losses compared to selective thinning.
- Within the boom corridor and selective thinning treatments, the increment of trees at the edge of strip roads or corridors was higher than at those trees located in the middle of strip roads and/or corridors.

Abstract

Boom corridor thinning (BCT) is a harvester's working method, primarily suitable for dense, unmanaged young stands. The method was first studied in Sweden in the early 2000s. In Finland, the idea has been further developed and studied for Finnish forests. The advantage is in the corridor, where the harvester head can move more swiftly, and there is no need to identify trees to grow as much as when using the traditional selective thinning (Sel) method. Moreover, the method can be conducted without cost-intensive pre-clearing of undergrowth, creating post-stands with higher biodiversity. This study is the sequel to a previous study in which experiments on BCT and Sel were established in 2017–2018. The experiments were remeasured 4–5 years after their establishment, and the effect of BCT treatments of Scots pine (*Pinus sylvestris* L.) and silver birch (*Betula pendula* Roth) on the post-treatment growth and growth reaction of individual trees within the treatments was compared to traditional Sel. During the post-treatment period, BCT did not result in growth or yield losses compared to Sel. Within the treatments, the increment of trees at the edge of strip roads or corridors was higher than that of trees located in the middle of strip roads and/or corridors. A longer post-treatment period needs to be studied to analyse the effect of BCT on the total yield and especially the yield of saw logs during the rest of the rotation period.

Keywords geometrical thinning; systematic thinning; thinning reaction
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1 Introduction

For a young forest, the timing and intensity of first thinning is crucial for favourable stand structure and growth, as well as for the development of high-quality saw logs (Niemistö et al. 2018). Young forests cover a significant proportion of the boreal forest area (Witzell et al. 2019). In the 2000s, the area of unmanaged young forests in Finland rose to more than one million hectares (Korhonen et al. 2017; Luonnonvarakeskus 2019). Simultaneously, the loss of forest natural diversity and climate crises call for the improvement of biodiversity sustainability and carbon sequestration of forests (Peura et al. 2018). In Finland, some forest owners have little motivation to conduct the first thinning because it has a high harvesting cost and produces little income. Several studies have stated that small stem size and low removal per hectare decrease the profitability of harvester work (Kuitto et al. 1994; Sirén 1998; Kärhä 2001; Ryynänen and Rönkkö 2001; Kärhä et al. 2004; Oikari et al. 2010; Brunberg and Iwarsson-Wide 2013). Often, in the first thinning, there is dense undergrowth, which must be pre-cleared for the harvester work to be successful and becomes an additional cost (Kärhä 2006; Nuutinen et al. 2021). In Finland, harvesters' productivity has soared over the past 25 years. This increase has been a result of more efficient harvesters and operator training. However, the improvement began to slow down after the early 2000s and now has come to a near halt (Nuutinen et al. 2020).

Traditionally, in Nordic countries, the first thinning is conducted using selective thinning (Sel) (Mielikäinen and Valkonen 1991; Mäkinen et al. 2006; Karlsson et al. 2012; Niemistö et al. 2018). In dense small-wood stands, the Sel method may not adequately consider movement nearly two metres wide at the maximum harvester head in the areas between the remaining trees because some of the harvester's slewing torque of boom is unexploited because the damage to trees must be avoided when moving the harvester head.

Developing harvester technology alone is unlikely to achieve sufficient cost savings. Development work also needs to be based on an operator-friendly thinning work method that considers both efficient harvesting and recommendations for good forest management. A potential working method could be boom corridor thinning (BCT). In Nordic countries, BCT and other geometrical thinnings (GT) have been studied in a few previous studies (see the literature review of Nuutinen et al. 2020). In GT, trees are harvested in systematic corridors, lines, rows or strips (Rummer 1993; Suadicani and Nordfjell 2003). BCT is a single-grip harvester thinning method for young stands where trees are harvested in corridors that are 1–2 metres wide aligned with the strip road and at a length corresponding to the used boom's reach (about 10 m) (Bergström 2009; Sängstuvall et al. 2011; Jundén et al. 2013; Bergström et al. 2022). The width and spacing of corridors are placed flexibly according to the trees to be grown. The advantage of BCT is in the corridor, where the harvester head can move more swiftly, and there is no need to identify trees to grow as much as when using the traditional Sel method (Bergström et al. 2007, 2022). Efficiency is also increased by the fact that the size of trees being removed from the corridors is larger, on average, than in Sel (Nuutinen et al. 2021).

Nuutinen et al. (2021) established field experiments on BCT and Sel treatments and described the post-treatment stand structures and spatial patterns of two Scots pine stands (*Pinus sylvestris* L.) and one birch-dominated (*Betula pendula* Roth with natural downy birch, *B. pubescens* Ehrh.) stand. According to Nuutinen et al. (2021), after the treatments, the number of stems per hectare in BCT was higher than in Sel. However, the number of future crop trees was at the same level.

The use of BCT raises questions about its impact on the growth, quality and damage of future crop trees, especially the yield of saw logs throughout the entire rotation period, as well as the structure and biodiversity of the stand. According to Ahnlund Ulvcrona et al. (2017), BCT maintained a higher diversity of tree sizes, including deciduous species. Nuutinen et al. (2021)

simulated the future growth and management of pine stands in their study. In simulations using Sel in all future thinnings, the total removal of thinnings and clearcutting in BCT treatments was 10–18% higher, and the saw log volumes were at the same level as in Sel.

This study is a sequel that of Nuutinen et al. (2021). We remeasured the BCT and Sel experiments 4–5 years after the establishment of the experiments in pine and birch stands. In this study, we reported and studied the effects of different thinning treatments on post-treatment mortality and growth of pine and birch. We also analysed the growth reactions of individual trees within the treatments.

2 Material and methods

2.1 Description of sites and treatments

The experiments of BCT and Sel were established in seeded (in Suonenjoki, Northern Savo) (62.63582, 27.51160) and planted pine stands (in Konnevesi, Central Finland) (62.75851, 26.28591) and a planted birch stand (in Kontiolahti, North Karelia) (62.70178, 29.91882) in November 2017, September 2018, and June 2018, respectively (see more details in Nuutinen et al. 2021). The Sel and BCT treatments applied in the experiments are described in Table 1. The remaining trees of the seeded and planted pine stands and the planted birch stand were measured in May 2018, September 2018, and September 2018, respectively. All remaining trees (dbh > 70 mm) were mapped and measured by species and diameter at breast height (dbh). Tree height was measured from the sample trees.

Table 1. Definitions of thinning treatments in the experiments. In all treatments, the width of the strip road was between 4.0–4.5 m, and the strip roads were pre-marked in the centre of the plot. In selective thinning (Sel) treatments, the areas between strip roads were thinned from below, removing the smallest, poorer and possibly damaged trees. In systematic boom corridor (BCT_p, BCT_f) treatments, 2.5 m-wide corridors, with 7 m between the machine position, were harvested. In all BCT treatments, the areas between the corridors were left untreated.

Treatment	Definition
Sel_1	Selective thinning, no pre-clearing needed.
Sel_2	Selective thinning, pre-cleared (i.e., undergrowth hindering harvester work was removed before test cutting).
BCT_p	Completely systematic perpendicular boom corridor thinning, no pre-clearing needed. Corridors 90° from each machine position were harvested. The trees to be removed from the corridors were marked.
BCT_f	Completely systematic fan-shaped boom corridor thinning, no pre-clearing needed. Corridors 30° from each machine position were harvested. The opposite corridors of the machine positions were staggered at 2 m. The trees to be removed from the corridors were marked.
BCT_{semi1}	Semi-selective boom corridor thinning, no pre-clearing needed. In the middle of the plot, the advisory corridor locations on opposite sides of the strip road were marked. The width and distance of the corridors were, on average, the same as in BCT_p and BCT_f. The operator chose the exact location of the corridors based on the standing trees. The trees to be removed from the corridors were not marked.
BCT_{semi2}	Semi-selective boom corridor thinning, pre-cleared. In the middle of the plot, the advisory corridor locations on opposite sides of the strip road were marked. The width and distance of the corridors were, on average, the same as in BCTp and BCTf. The operator chose the exact location of the corridors based on the standing trees. The trees to be removed from the corridors were not marked.
BCT_{semi3}	Semi-selective boom corridor thinning, no pre-clearing. In the middle of the plot, the advisory corridor locations on opposite sides of the strip road were marked. The width and distance of the corridors were, on average, the same as in BCTp and BCTf. The operator chose the exact location of the corridors based on the standing trees. The trees to be removed from the corridors were not marked.
BCT_{sel}	Selective boom corridor thinning, no pre-clearing needed. The width and distance of the corridors were, on average, the same as in BCT_p and BCT_f. The operator independently chose the location of the corridors based on the standing trees.

The experiments were re-measured in September–November 2022, i.e., five growing seasons after the first measurement of the seeded pine stand and four growing seasons after the first measurement of the planted pine and birch stands. All trees with dbh > 70 mm at the time of establishment were measured by dbh and sample trees by height. To analyse the edge effect of strip roads and open corridors on tree growth, the location of each tree was classified as: 0 – not at the edge of the strip road or corridor, 1 – at the edge of the strip road, 2 – at the edge of the corridor, or 3 – at the edge of both the strip road and the corridor. The tree location was visually determined to be at the edge of the strip road or corridor when the tree crown was growing free from competition in the direction of the strip road or corridor.

2.2 Methods

Species- and stand-wise height models were fitted using the heights of the sample trees and the Näslund height-diameter function (Näslund 1936). The NLR procedure in IBM SPSS Statistics 28 (IBM Corp. Released 2021) was used to fit the height models. In the seeded pine stand, the heights of birches and spruces (*Picea abies* (L.) H. Karst.) were not observed. Thus, the height model for pine was applied to predict the heights of birches, and the height model for spruce fitted by Nuutinen et al. (2021) was also applied in this study. In the planted birch stand, the common height model for pines and spruces fitted by Nuutinen et al. (2021) was also applied in this study. The dbh and height of trees and species-wise volume functions were used to calculate stem volumes (Laasasenaho 1982). Stand characteristics, such as basal area weighted mean diameter and height, stand basal area, and stem volume, were calculated for each treatment plot. The tree and stand characteristics 4–5 growing seasons after the establishment of the experiments were compared among the BCT and Sel treatments. Because few fallen or broken trees were observed in re-measurements in 2022, the initial stand variables measured in 2018 were re-calculated without these trees and used in the analyses.

The effect of thinning treatment on the stand variables was evaluated using an analysis of covariance, as follows:

$$y_{jk} = \mu + Tr_k + \beta \times X_{jk} + e_{jk}, \qquad (1)$$

where y is the stand variable (i.e., mean diameter, mean height, stand basal area or volume); μ is the overall mean; Tr is the effect of thinning treatment; β is the regression coefficient; subscripts j and k refer to plot and treatment, respectively; and e is the random error term with a mean of 0 and constant variance. The initial differences among the plots were removed using the corresponding variable measured after the establishment of the experiments as a continuous covariate (X). Model 1 was fitted separately for each experiment, and the estimated marginal means for the thinning treatments were predicted using the UNIANOVA procedure in IBM SPSS Statistics 28 (IBM SPSS Inc. 2021).

At the tree level, the statistical significance of the differences between the treatments and tree locations in relation to the strip roads and corridors was evaluated by fitting linear mixed-effect models:

$$y_{ijkl} = \mu + Tr_k + Lo_l + Tr_k \times Lo_l + \beta \times X_{ijkl} + u_j + e_{ijkl}, \qquad (2)$$

where y is the mean annual increment of the tree variable (i.e., dbh, height or stem volume) during the 4–5-year period after thinning; μ is the overall mean; Tr is the effect of thinning treatment; Lo is the effect of tree location in relation to the strip roads and corridors; β is the regression coefficient;

subscripts *i*, *j*, *k* and *l* refer to tree, plot, treatment and tree location, respectively; and *u* and *e* are the random plot effect and random error term with a mean of 0 and constant variance, respectively. The interaction of thinning treatment and tree location was included in the model. The initial tree variable corresponding to the dependent variable was used as a covariate (*X*). Model 2 was fitted separately for each experiment, and the estimated marginal means for all level combinations of the thinning treatments and tree locations were predicted using the model fitted by the MIXED procedure in IBM SPSS Statistics 28 (IBM SPSS Inc. 2021).

Using the predicted marginal means, pairwise comparisons between the thinning treatments and tree locations in relation to the strip roads and corridors were performed using the least significant difference (LSD) post hoc test because the data were homogeneous (according to Levene's test of homogeneity of variances). A significance level of 0.05 was applied to detect statistically significant differences in pairwise comparisons.

3 Results

In the seeded and planted pine stands, the number of dead (fallen or broken top) trees was 10 and 4 trees ha^{-1}, respectively. In the seeded pine stand, dead trees were found only in BCT; in the planted pine stand, dead trees were also observed in Sel. In the seeded pine stand, the mean diameter and total volume of dead trees were 9.3 cm and 0.56 m^3 ha^{-1}, respectively, and in the planted pine stand, they were 10.6 cm and 0.28 m^3 ha^{-1}, respectively. No tree mortality was observed in the planted birch stand.

The effect of thinning treatment on the stand variables in 2022 was analysed using the corresponding stand variables in 2018 as covariate variables. The thinning treatment had no significant effect ($p > 0.05$) on the increment of stand variables, except on the stand basal area increment in the planted birch stand (Table 2). In the planted birch stand, the stand basal area increased more in BCT (BCT_{semi3}) than in Sel (Sel_2).

The thinning treatment had no significant effect ($p > 0.05$) on the increment of diameter at breast height (dbh) and stem volume of individual trees (Table 3). In contrast, tree location in relation to strip roads and corridors had a logical effect on the increment of individual trees. In general, the increment of trees at the edge of strip roads or corridors was higher than in trees located in the middle of strip roads and/or corridors (i.e., had no free growing space towards strip roads or corridors). The interaction between thinning treatment and tree location was not significant.

Table 2. Tests of thinning treatment effects and estimated marginal means (adjusted by covariate effects) and standard errors (SE) in ANOVA for stand characteristics 4–5 growing seasons after selective thinning (Sel) and boom corridor thinning (BCT) treatments (Eq. 1). Thinning treatments are described in Table 1. Significant treatment effects are shown in bold.

Experiment	No. of plots	Stand basal area ($m^2\ ha^{-1}$)		Volume ($m^3\ ha^{-1}$)		Mean diameter (cm)		Mean height (m)		Mean stem volume (dm^3)	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Seeded pine											
Treatment		F = 0.59	p = 0.630	F = 0.52	p = 0.676	F = 0.21	p = 0.891	F = 1.49	p = 0.257	F = 0.58	p = 0.637
Sel_1	5	15.0a	0.14	109.5a	1.10	16.4a	0.06	14.6a	0.02	138.4a	1.13
BCT_p	5	15.0a	0.11	109.1a	0.83	16.3a	0.06	14.6a	0.02	136.4a	1.10
BCT_f	5	15.1a	0.11	110.2a	0.83	16.4a	0.06	14.6a	0.02	137.9a	1.15
BCT_{semi1}	5	15.2a	0.12	110.5a	1.00	16.4a	0.06	14.6a	0.02	137.5a	1.11
Planted pine											
Treatment		F = 0.65	p = 0.542	F = 0.66	p = 0.537	F = 0.72	p = 0.506	F = 0.81	p = 0.470	F = 0.80	p = 0.474
Sel_1	5	17.8a	0.30	126.3a	2.38	16.9a	0.22	14.4a	0.07	139.7a	2.71
BCT_{semi1}	4	17.7a	0.33	125.3a	2.63	16.8a	0.24	14.3a	0.08	136.8a	2.90
BCT_{sel}	6	18.1a	0.26	128.8a	2.10	17.2a	0.19	14.4a	0.06	141.4a	2.33
Planted birch											
Treatment		**F = 9.20**	**p = 0.021**	F = 3.80	p = 0.099	F = 0.26	p = 0.778	F = 0.62	p = 0.575	F = 0.22	p = 0.808
Sel_2	3	**10.7a**	**0.11**	82.1a	0.74	14.7a	0.12	15.8a	0.16	115.7a	1.65
BCT_{semi2}	3	**11.1ab**	**0.11**	84.7a	0.73	14.7a	0.09	15.9a	0.11	115.6a	1.14
BCT_{semi3}	3	**11.4b**	**0.11**	84.6a	0.74	14.9a	0.11	15.7a	0.15	114.5a	1.40

Data for the same experiment marked with different letters are significantly different ($p < 0.05$) based on the estimated marginal means and post hoc LSD tests after Levene's test for equal variances.

Table 3. Tests of thinning treatment and tree location effects and estimated marginal means (adjusted by covariate effects) and standard errors (SE) in mixed model ANOVA for annual increment of diameter (dbh), height and stem volume of trees during 4–5 growing seasons after selective thinning (Sel) and boom corridor thinning (BCT) treatments (Eq. 2). Thinning treatments are described in Table 1. Significant treatment and tree location effects are shown in bold.

Experiment	No. of trees	Dbh increment (mm year^{-1})		Height increment (m year^{-1})		Volume increment (dm^3 year^{-1})	
		Mean	SE	Mean	SE	Mean	SE
Seeded pine							
Treatment		F = 3.29	p = 0.035	**F = 5.60**	**p = 0.003**	F = 3.35	p = 0.032
Sel$_1$	340	3.0a	0.12	**0.30a**	**0.003**	7.1a	0.21
BCT$_p$	416	2.7a	0.13	**0.28bc**	**0.004**	6.7a	0.23
BCT$_f$	443	2.9a	0.12	**0.29ac**	**0.004**	7.0a	0.22
BCT$_{semi1}$	436	2.7a	0.13	**0.28b**	**0.004**	6.6a	0.24
Tree location		**F = 45.54**	**p < 0.001**	**F = 26.19**	**p < 0.001**	**F = 41.10**	**p < 0.001**
0	450	**2.3a**	**0.08**	**0.27a**	**0.003**	**5.9a**	**0.15**
1	173	**3.0b**	**0.13**	**0.29bc**	**0.005**	**7.1b**	**0.25**
2	729	**2.7b**	**0.07**	**0.28b**	**0.002**	**6.6b**	**0.13**
3	283	**3.4c**	**0.09**	**0.30c**	**0.003**	**7.9c**	**0.17**
Treatment × Location		F = 1.40	p = 0.201	F = 1.68	p = 0.111	F = 0.99	p = 0.435
Planted pine							
Treatment		F = 1.40	p = 0.278	F = 3.36	p = 0.061	F = 1.02	p = 0.385
Sel$_1$	405	4.2a	0.23	0.57a	0.011	11.2a	0.60
BCT$_{semi1}$	391	3.7a	0.26	0.54a	0.013	10.3a	0.68
BCT$_{sel}$	555	4.2a	0.21	0.57a	0.010	11.4a	0.55
Tree location		**F = 20.73**	**p < 0.001**	**F = 11.85**	**p < 0.001**	**F = 5.66**	**p < 0.001**
0	451	**3.7a**	**0.15**	**0.54a**	**0.008**	**10.3a**	**0.43**
1	223	**4.3b**	**0.17**	**0.56b**	**0.010**	**11.2ab**	**0.52**
2	518	**3.6a**	**0.17**	**0.55ab**	**0.008**	**10.4a**	**0.45**
3	159	**4.5b**	**0.19**	**0.59c**	**0.011**	**12.1b**	**0.57**
Treatment × Location		F = 3.76	p = 0.005	F = 0.95	p = 0.433	F = 1.02	p = 0.397
Planted birch							
Treatment		F = 1.02	p = 0.394	F = 0.76	p = 0.489	F = 0.25	p = 0.784
Sel$_2$	177	4.9a	0.23	0.56a	0.021	10.6a	0.33
BCT$_{semi2}$	238	4.8a	0.25	0.60a	0.022	10.6a	0.37
BCT$_{semi3}$	259	5.3a	0.24	0.56a	0.022	10.6a	0.35
Tree location		**F = 9.10**	**p < 0.001**	**F = 3.28**	**p = 0.020**	**F = 11.03**	**p < 0.001**
0	153	**4.4a**	**0.20**	**0.54a**	**0.019**	**9.4a**	**0.33**
1	101	**5.4bc**	**0.25**	**0.59bc**	**0.023**	**11.2bc**	**0.42**
2	308	**5.0b**	**0.17**	**0.57ab**	**0.015**	**10.4b**	**0.23**
3	112	**5.5c**	**0.21**	**0.61c**	**0.019**	**11.6c**	**0.32**
Treatment × Location		F = 1.88	p = 0.113	F = 0.57	p = 0.682	F = 0.82	p = 0.515

Data for the same experiment marked with different letters are significantly different ($p < 0.05$) based on the estimated marginal means and post hoc LSD tests after Levene's test for equal variances. Tree location: 0 – not at the edge of the strip road or corridor, 1 – at the edge of the strip road, 2 – at the edge of the corridor, and 3 – at the edge of both the strip road and corridor.

4 Discussion and conclusion

No differences in the 4–5-year stand-level growth or mortality were found among the Sel and BCT treatments. Previously, the long-term experiments indicated higher post-treatment growth after Sel compared to geometrical thinning (GT). In the study of Mäkinen et al. (2006), during a 19-year post-treatment period, the average annual volume increment of pine was 5% higher in Sel than in GT and 15% higher for spruce. In the pine experiments, the proportion of saw log volume was 43% in Sel and 38% in BCT; for spruce, the saw log proportions were 57% and 53%, respectively. In the 22–28-year-long experiment of Karlsson et al. (2012), the volume increment in Sel was 27–44% higher compared to GT, depending on the soil type. The corresponding difference in the average annual diameter growth was 14–28%.

In our study, the 4–5-year growth of individual trees reacted logically to the change in growing space; the trees located at the edge of both strip roads and corridors had a higher growth rate compared to trees facing more competition. This result is supported by earlier studies on the effect of competition on the growth of pine (Pukkala et al. 1998) and silver birch (Maleki et al. 2015). Previously, higher growth of trees was observed next to a strip road in both spruce and pine stands (Isomäki 1986; Niemistö 1989; Mäkinen et al. 2006; Wallentin and Nilsson 2011; Kuliešis et al. 2018; Stempski et al. 2021). However, a positive effect of strip roads on tree growth has been found only at a distance of 2–3 m from strip roads (Isomäki 1986; Niemistö 1989; Mäkinen et al. 2006). Thus, the edge effect mainly affects trees whose crowns and roots are in touch with strip roads or corridor openings.

Mäkinen et al. (2006) investigated the effect of tree location in relation to corridors on tree growth in GT treatments. Five years after thinning, in both pine and spruce stands, tree growth improved along the corridors but only in a zone less than 2 m away from the corridors. However, the increase in growth of the edge trees of the 4–5 m-wide corridors compensated for 40% of the growth loss caused by the area effect of the corridors.

However, in Mäkinen et al. (2006) and Karlsson et al. (2012), growth was recorded after manual first thinning, and intermediate thinning was not conducted. This does not correspond to today's actual harvester work, where thinning is done two or three times per rotation time. Additionally, the results of both studies on the treatment effects on stand development were based on small datasets.

In conclusion, during the 4–5-year post-treatment period, BCT did not result in growth and yield losses compared to Sel. The positive effect of corridor opening on tree growth corresponded to that of strip roads. A longer post-treatment period needs to be studied to analyse the effect of BCT on the total yield and especially the yield and quality of saw logs during the rest of the rotation period.

Declaration on the availability of research materials

The data are available from the corresponding author upon reasonable request.

Author's contributions

YN: Funding acquisition; Experimental arrangement; Data acquisition; Conceptualization; Data analysis; Interpretation of results; Writing – original draft; Writing – review & editing; Final approval of the manuscript to be published.
JM: Conceptualization; Data analysis; Interpretation of results; Writing – review & editing.

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