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Stand structure after thinning in 1–2 m wide corridors in young dense stands

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Highlights

- Boom corridor thinning (BCT) results in more stand structure heterogeneity than conventional thinning or pre-commercial thinning (PCT), maintaining both smaller-diameter trees and deciduous species.
- Neither dominant height nor number of possible future crop trees is jeopardized, and boom corridor thinning results in higher values of stem volume and biomass.
- The technique is flexible as various corridor types give similar stand structure results.

Abstract

Boom corridor thinning (BCT) has been proposed as a cost-effective technique for biomass thinning (BT) in young dense stands. The objective of this study was to determine how various BCT operations affect stand structure following biomass thinning and to compare the results with conventional selective thinning methods. Two series of field experiments were established; BCT 1-series: Three sites in south of Sweden (9 and 11 m in mean and dominating tree height) with five treatments, including a control, conventional selective thinning and three BCT treatments (1 m and 2 m wide corridors and selective BCT). The second BCT series: Three regions in Sweden (in the north, centre and in the south), with two stand sites in each region with different tree heights (4/9 m and 5/10 m in mean/dominating tree height). Treatments were control, pre-commercial thinning (PCT), conventional selective thinning and BCT (high and low thinning). Following the first biomass thinning, BCT regimes and selective thinning methods resulted in similar stand structures based on the number of possible future crop trees (>80 mm in diameter at breast height). However, BCT maintained a higher diversity of tree sizes as well as more stems per hectare, including deciduous species, than the selective thinning approaches. The stands after BCT should have more vertical complexity, especially when compared to pre-commercial thinning. The structural heterogeneity resulting from BCT may also increase stand biodiversity and ecosystem service values.

Keywords conventional thinning; future crop trees; heterogeneity; production
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1 Introduction

Young dense stands are a significant resource of biomass for the bioenergy market (Grebner et al. 2009; Karlsson et al. 2015; Fernandez-Lacruz et al. 2015). For example, Sweden, a country with boreal forests, has 23.2 million hectares of productive forest land, of which 7.2 million hectares are < 30 years old (32.4%) (Swedish statistical yearbook 2014). Depending on the constraints applied, there are between 2.1–9.8 million ha of unthinned, biomass-dense forest in Sweden, representing 9–44% of the country's productive forest land area. The minimum yearly harvesting potential of these biomass-dense forests is 3.0 million dry-weight (DW) metric tonnes (t) when calculated from delimbed stemwood (including tops), and 4.3 million DW t if the trees are harvested whole with limbs (Fernandez-Lacruz et al. 2015).

Biomass/bioenergy thinning (BT) represents one alternative for young dense stands, but it is important to consider how this silvicultural practice may affect individual trees and stand development. For example, research shows that late thinning of young dense stands increases the risk of snow damage, such as stem breakage (Valinger et al. 1994; Päätalo et al. 1999). Furthermore, stands of smaller diameter trees (diameter at breast height, DBH < 80 mm), which result from the thinning of young dense stands, are more susceptible to damage (Päätalo et al. 1999; Abetz and Klädtke 2002). On the other hand, there is evidence that BT can precede a later harvest of crop trees without risking crop tree value (Ulvcrona 2011).

Boom-corridor thinning (BCT) is a harvesting operation method that increases efficiency and cost-effectiveness by thinning strips of a defined size with boom-tip harvesting technology. Different boom corridor patterns and how they are applied give different degree of selective tree selection. For example, using a fan-shaped pattern, "laid out" by the decision of the operator, will give higher degree of tree selection than of using a perpendicular pattern laid out strictly systematically (Fig. 1). The combination of BCT and new felling technologies during BT operations (Bergström et al. 2007; Bergström 2009; Sängstuvall et al. 2011; Bergström and Di Fulvio

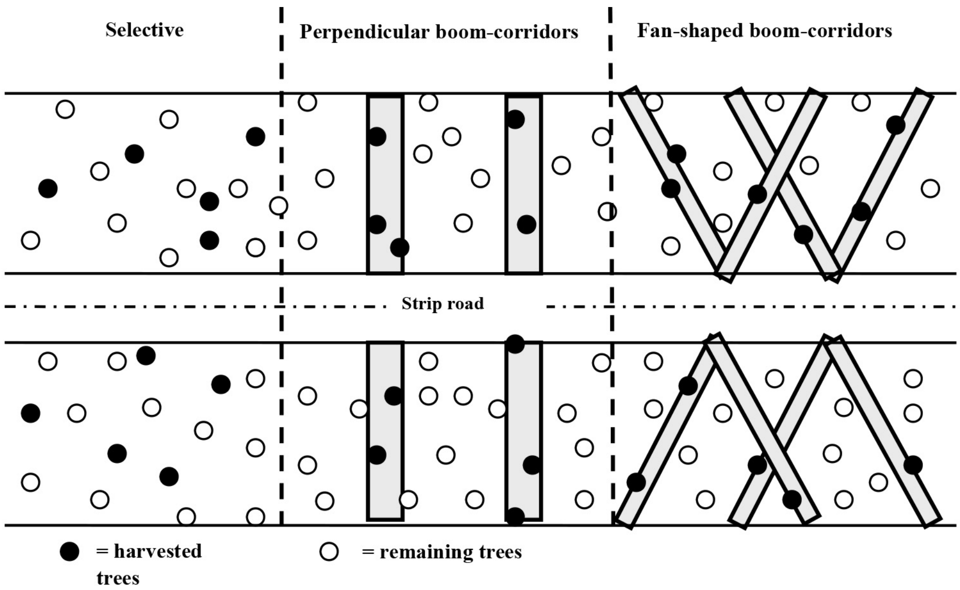

Fig 1. Sketch of possible selective thinning and two boom-corridor thinning patterns between strip roads, as described in Bergström (2009).

2014a) can significantly increase the harvesting efficiency of young dense stands. Bergström and Di Fulvio (2014a) provided quantitative evidence, showing that supply costs can decrease by 12–27% when conventional selective thinning and standard handling procedures are replaced with a BCT system that includes innovative biomass compaction and transportation methods. Furthermore, Bergström and Di Fulvio (2014a) reported that BCT systems are most efficient at harvesting trees under 30 dm^3, a size class that according to Fernandez-Lacruz et al. (2015) represents a significant portion of the potential annual harvest in young stands in Sweden.

Boom corridor thinning techniques facilitate cost-effective management of young stands and also allow aspects other than wood production to be taken into account. For example, there has been a growing concern about how forest management plans can include ecosystem services and environmental goals without jeopardizing the production of valuable biomaterials (Bengtsson et al. 2000; Führer 2000; Sullivan et al. 2011). It has been suggested that stand heterogeneity and vertical complexity promotes various ecosystem services (Puettman et al. 2009; Messier et al. 2014). Moreover, Saastamoinen et al. (2014) have begun to classify the various ecosystem services so they can be recognized by forest management plans. However, the stand structure resulting from a management regime cannot only cater to ecosystem services, but must present a cost-effective solution as well. In this way BCT is an attractive option from a forest management perspective, as it is both cost-effective and should create a more complex vertical stand structure than conventional thinning. This is because BCT methods, when strictly used, only cut trees from pre-defined areas, leaving certain areas, or strips, untouched and with their natural stand structure. On the other hand, commercial selective cutting, which includes the preclearance of any undergrowth with a stem size smaller than the commercial size, thins, in general, an entire stand to a homogeneous area containing only larger diameter trees for future harvest. In this way, the first thinning phase largely determines the stand structure for a majority of the stand rotation period. There are many thinning operations to choose from, and each can result in a different stand structure.

The objective of this paper was to measure how conventional thinning (pre-commercial and commercial) and BCT affect the stand structures of young, dense, conifer stands with various heights and compare treatments. This study was done immediately after thinning and included both low- and high-thinning BCT regimes, which target the smaller and larger trees, respectively, yet result in a similar number of trees per ha.

2 Material and methods

2.1 Description of sites

Two series of field experiments were established. The first, BCT 1, with three sites in south of Sweden (6 and 11 m in mean and dominating tree height) were all planted with Norway spruce (*Picea abies* (L.) H. Karst.) (Table 1). Other species found were *Betula* spp., *Salix* ssp., *Populus tremula* L. and *Sorbus aucuparia* L. and Norway spruce from natural regeneration.

The second, BCT 2, with three regions in Sweden (in the north, centre and in the south) (Table 2). Each region consisted of two sites with different tree heights (4/9 m and 5/10 m in mean/dominating tree height). Planted Norway spruce and Scots pine (*Pinus sylvestris* L.) dominated all sites, and *Betula* spp., *Salix* ssp., *P. tremula* and *S. aucuparia* from natural regeneration were also found. *Betula* spp. was the most common deciduous species in all sites.

Table 1. BCT 1-series. The average values of various stand structure parameters from three sites in Southern Sweden with mean and dominating heights of ca 6 and 11 m, respectively. Values are shown before and after five thinning alternatives, including a control with no thinning. The other four treatments are conventional thinning, boom corridor thinning with corridor width of 1 m and length of 10 m ($BCT_{1\ m}$), boom corridor thinning with corridor width of 2 m and length of 10 m ($BCT_{2\ m}$), and selective boom corridor thinning with corridor width of 1 m and a length of 10 m (BCT_{sel}). Values with significant differences at the 0.05 probability level based on Tukey's multiple comparison test are marked with different letters. Dg is the basal area weighted diameter at breast height (1.3 m). Diam. N_{sel} demonstrates the average DBH for each plot calculated from the same number of stems as were left in the conventional thinning plot. The removal of deciduous trees was calculated based on the amount of deciduous trees in the plot before treatment.

Parameter	Control			Conventional			$BCT_{1\ m}$			$BCT_{2\ m}$			BCT_{sel}		
	Before	After		Before	After		Before	After		Before	After		Before	After	
	All trees	All trees	DBH> 80 mm	All trees	All trees	DBH> 80 mm	All trees	All trees	DBH> 80 mm	All trees	All trees	DBH> 80 mm	All trees	All trees	DBH> 80 mm
Stem Number (ha^{-1})	9635^{a}	9635^{a}	1524^{a}	7241^{a}	1168^{c}	622^{b}	7060^{a}	3949^{bc}	812^{ab}	9891^{a}	5833^{ab}	829^{ab}	8674^{a}	4568^{bc}	1034^{ab}
Dominant height (m)	11.2^{a}	11.2^{a}	11.2^{a}	10.6^{a}	10.6^{a}	10.6^{a}	10.6^{a}	10.6^{a}	10.6^{a}	10.7^{a}	10.7^{a}	10.7^{a}	11.3^{a}	11.3^{a}	11.3^{a}
Mean height (m)	6.0^{a}	6.0^{b}	9.7^{a}	6.3^{a}	10.2^{a}	10.0^{a}	6.2^{a}	8.6^{a}	9.6^{a}	5.4^{a}	8.3^{a}	9.3^{a}	6.3^{a}	9.1^{a}	10.1^{a}
Dg (cm)	5.7^{a}	5.7^{b}	10.3^{a}	5.6^{a}	9.5^{a}	10.7^{a}	5.3^{a}	6.1^{b}	10.3^{a}	4.7^{a}	5.2^{b}	10.0^{a}	5.1^{a}	6.4^{b}	10.5^{a}
Diam. N_{sel}		10.9^{a}			8.8^{a}			9.5^{a}			9.4^{a}			10.4^{a}	
Stem volume ($m^3\ ha^{-1}$)	116.7^{a}	116.7^{a}	73.8^{a}	107.4^{a}	39.5^{b}	32.8^{a}	87.1^{a}	55.1^{b}	35.6^{a}	88.5^{a}	60.4^{b}	36.2^{a}	109.6^{a}	76.4^{ab}	53.8^{a}
Percent of before		100^{a}			39^{c}			63^{b}			67^{b}			67^{b}	
Biomass Dry weight ($t\ ha^{-1}$)	72.6^{a}	72.6^{a}	44.3^{a}	68.3^{a}	23.7^{b}	18.9^{b}	62.2^{a}	35.1^{b}	22.3^{ab}	61.4^{a}	37.5^{b}	21.6^{ab}	72.3^{a}	46.4^{ab}	31.5^{ab}
Percent of before		100^{a}			37^{c}			56^{bc}			61^{b}			63^{b}	
Removal of total (%):															
Biomass		0^{c}			63^{a}			44^{b}			39^{b}			37^{b}	
Stems		0^{c}			82^{a}			44^{b}			41^{b}			47^{b}	
Biomass deciduous Dry weight ($t\ ha^{-1}$)	21.4^{a}	21.4^{a}		18.6^{a}	1.5^{b}		18.0^{a}	10.4^{b}		17.3^{a}	11.0^{ab}		15.8^{a}	9.4^{b}	
Removal of decid. (%):															
Biomass		0^{c}			91^{a}			42^{b}			36^{bc}			34^{bc}	
Stems		0^{c}			96^{a}			45^{b}			42^{b}			53^{b}	

Table 2. BCT 2-series. The average values of various stand structure parameters from two sets of stands from sites in Northern, Central and Southern Sweden, with mean and dominating heights of 4 and 9 m or 5 and 10 m. The values are shown before and after different thinning operations. Stands with a dominating height of 9 m were subject to either selective boom corridor thinning with a corridor width of 1 m and a length of 10 m (BCT) or pre-commercial thinning (PCT). In contrast, stands with a dominating height of 10 m were subject to conventional selective thinning, boom-corridor thinning that targeted smaller-diameter trees (BCT_{low}), or boom-corridor thinning that targeted larger-diameter trees (BCT_{high}). Values with significant differences at the 0.05 probability level based on Tukey's multiple comparison test are marked with different letters row-wise. Dg is basal area weighted diameter at breast height (1.3 m). N_{sel} demonstrates the average DBH for each plot calculated from the same number of stems as were left in the conventional thinning plot. The removal of deciduous trees was calculated based on the amount of deciduous trees in the plot before treatment.

Parameter	Mean height/ Dominant height 4/9 m						Mean height/ Dominant height 5/10 m								
	PCT			BCT			BCT_{low}			BCT_{high}			Conventional		
	Before	After		Before	After		Before	After		Before	After		Before	After	
	All trees	All trees	DBH> 80 mm	All trees	All trees	DBH> 80 mm	All trees	All trees	DBH> 80 mm	All trees	All trees	DBH> 80 mm	All trees	All trees	DBH> 80 mm
Stem Number (ha^{-1})	7930[a]	2256[a]	611[a]	8456[a]	4259[a]	596[a]	9619[a]	4289[a]	852[a]	8959[a]	4611[a]	752[a]	7944[a]	1937[a]	767[a]
Deciduous															
(N ha^{-1})	2196[a]	274[b]		2170	1267[a]		3222[a]	1623[a]		3315[a]	1767[a]		2626[a]	604[a]	
(% of total)	29[a]	10[b]		27[a]	31[a]		33[a]	38[a]		33[a]	34[a]		28[a]	19[a]	
Dominant height (m)	9.1[a]	7.8[a]	7.8[a]	7.9[a]	7.9[a]	7.9[a]	10.6[a]	10.4[a]	10.4[a]	10.3[a]	9.9[a]	9.9[a]	10.2[a]	10.0[a]	10.0[a]
Mean height (m)	4.0[a]	7.2[a]	7.4[a]	3.8[a]	5.2[b]	7.5[a]	4.8[a]	5.8[a]	8.4[a]	4.7[a]	6.3[a]	8.3[a]	4.7[a]	5.9[a]	8.3[a]
Dg (cm)	7.7[a]	8.8[a]	10.7[a]	8.0[a]	8.7[a]	10.8[a]	9.1[a]	9.9[a]	11.6[a]	9.2[a]	9.4[a]	11.3[a]	9.1[a]	10.5[a]	11.2[a]
Diam. N_{sel} (cm)		9.2[a]			8.5[a]			10.0[a]			9.8[a]			10.0[a]	
Stem volume (m^3 ha^{-1})	48.1[a]	33.7[a]	22.4[a]	54.6[a]	33.5[a]	21.7[a]	94.6[a]	49.1[a]	38.2[a]	94.5[a]	47.0[a]	34.4[a]	86.0[a]	38.3[a]	33.5[a]
Percent of before		70[a]			62[a]			53[a]			49[a]			43[a]	
Biomass Dry weight (t ha^{-1})	29.7[a]	20.3[a]	13.3[a]	33.3[a]	17.7[a]	12.9[a]	58.0[a]	29.1[a]	22.4[a]	54.8[a]	27.6[a]	20.0[a]	50.7[a]	22.4[a]	19.6[a]
Percent of before		68 [a]			55[a]			52[a]			50[a]			43[a]	
Removal tot. (%):															
Biomass		32[a]			45[a]			48[a]			50[a]			57[a]	
Stems		70[a]			46[b]			56[a]			52[b]			78[b]	
Biomass Dry weight deciduous (t ha^{-1})	2.4[a]	1.0[a]		1.2[a]	0.7[a]		3.4[a]	0.8[a]		1.9[a]	0.9[a]		1.3[a]	0.3[a]	
Removal decid. (%):															
Biomass		69[a]			55[a]			72[a]			61[a]			81[a]	
Stems		87[a]			40[a]			50[a]			48[a]			88[a]	

2.2 Study design

The treatments in BCT 1 with stand height 6/11 m (mean/dominating height) were:

C: Control with no treatment.

Conv: Conventional selective thinning, including strip roads. The Norway spruce was favored; the target number for remaining trees was about 1000 stems ha^{-1} with an estimated removal of about 50% of the basal area.

$BCT_{1\,m}$: Strict boom corridor (width 1 m, length 10 m) thinning. One corridor in each direction, 90° from each machine position, with 2.67 m between machine positions.

$BCT_{2\,m}$: Strict boom corridor (width 2 m, length 10 m) thinning. One corridor in each direction (in total 2 corridors), 90° from each machine position, with 5.3 m between machine positions.

BCT_{sel}: Selective boom corridor (width 1 m, length 10 m) thinning. Two corridors (about 90° and 60°) at each side of the road (in total 4 corridors per machine position) with 5.3 m between machine positions. The corridors were not pre-determined and could during execution of treatment be selected to favor future Norway spruce crop trees. Fig. 1 shows the principal design for boom corridor thinning.

In the BCT 1-series each treatment plot had dimensions of 30 × 40 m, with a 5 m buffer zone on each side. Each site was referred to as a block.

In the BCT 2-series, the treatments for stands with mean/dominant tree heights of 4/9 m were;

BCT: Selective boom corridor (width 1 m, length 10 m) thinning. Two corridors (about 90° and 60°) at each side of the road (in total 4 corridors per machine position), with 5.3 m between machine positions. The corridors were not pre-determined and could be selected during execution of treatment to favor future crop trees. The target number for remaining (possible crop) trees was about 2000 stems ha^{-1}, which resulted in higher total number of stems ha^{-1}.

PCT: Conventional motor manual pre-commercial thinning (PCT). The target number of remaining trees was about 2000 stems ha^{-1} and cut stems were left in the plot.

The treatments for stands with mean/dominant tree heights of 5/10 m were;

BCT_{low}: Low-thinning regime with selective boom corridors (width 1 m length 10 m), i.e. thinning from below (the smallest trees were harvested), to harvest the smaller trees and maintain to ca 2000 stems ha^{-1} possible crop trees ha^{-1} (higher total number of stems). Two corridors (about 90° and 60°) at each side of the road (in total 4 corridors per machine position), with 5.3 m between machine positions. The corridors were not pre-determined and could be selected during execution of treatment to favor future crop trees.

BCT_{high}: High-thinning regime with selective boom corridors (width 1 m length 10 m), i.e. thinning from above, to harvest the larger trees and maintain 2000 stems ha^{-1}. Two corridors (about 90° and 60°) at each side of the road (in total 4 corridors per machine position), with 5.3 m between machine positions. The corridors were not pre-determined and could be selected to favor future crop trees. This treatment had the same target basal area as Conv.

Conv: Conventional selective thinning to 2000 stems ha^{-1} with an additional manual PCT of the smallest trees, leaving cut stems in the plot.

In the BCT 2-series each treatment plot had dimensions of 30 × 30 m, with a 5 m buffer zone on all sides. Each stand site was referred to as a block.

For each stand site, in both series, the plots were marked with poles in each corner. Machine positions (5.3 m distance and 2.67 m) and strip roads were also marked. Furthermore, for strict boom corridor treatments the pre-determined corridors were marked. The treatments were randomly distributed between the plots.

All treatments, except Controls and PCT, contain cut strip roads.

2.3 Execution of treatments

In both treatment series 6-wheeled thinning harvesters with a mass of ca 12 t were used for the thinning. The PCT was performed with professional use manual motor brush-saws. The BCT 1-series employed a Valmet 911 harvester (http://www.komatsuforest.se) equipped with the Bracke 16 head (Bracke Forest AB, Sweden) (http://www.brackeforest.com) and operated by an experienced driver. The PCT was performed by local contractors normally hired by the land-owner, and forest management company, Sveaskog. The BCT 2-series employed a Valmet 911 harvester equipped with the Bracke MAMA Prototype head (see Bergström and Di Fulvio 2014b), which was operated by a less experienced driver. However, the driver's work was supervised during thinning. All of the thinning and PCT operations were carried out carefully to ensure consistency and minimize the damage to the future crop trees. The BCT 1-series treatments were performed from August 2013 to May 2015 and the BCT 2-series treatments were performed from October 2013 to January 2014.

2.4 Stand structure measurements and statistical tests

The DBH (1.3 m height) was measured for all trees within the study plots before treatments began. To ensure that all trees were measured only once during each inventory, corridors about 5 m wide were created with tape measures through each plot. Once a tree was measured, the stem was marked. The same procedure was also used after the treatments were performed. Additionally, in the BCT 1-series all trees with a DBH > 45 mm were numbered and the DBH measurement position was marked before the second inventory. Randomly-selected trees were used to measure tree height so that all tree sizes would be included in the measurements. Additionally, the 9 largest trees from 900 m^2 plots (BCT 2) and the 12 largest trees from 1200 m^2 plots (BCT 1) were measured. The selection process of numbered trees for height measurements in BCT 1-series plots followed routines developed by the Swedish University of Agricultural Sciences for long term forest field experiments (Karlsson et al. 2012).

The stem volumes of trees with DBH < 45 mm were estimated using volume functions according to Andersson (1954), and those of trees with DBH ≥ 45 mm were estimated with volume functions according to Brandel (1990). Equations from Repola and Ulvcrona (2014) were used to estimate the DW of biomass.

Trees with DBH > 80 mm were analyzed for comparisons of the largest trees in each treatment and as a measure to forecast the possible amount of future crop trees in the plot.

Analysis of variance, using the GLM procedure in Minitab 16 (Minitab2010), was then applied to evaluate (fixed) effects of the treatments (α), with sites as blocks (random effects, b) using the following model (Eq. 1):

$$Y_{ij} = \mu + \alpha_i + b_j + \varepsilon_{ij} \qquad (1)$$

where Y_{ij} is the dependent variable, μ is the grand mean, α is the fixed effect of treatment, b the random effect of site and ε the residuals.

Prior to analyses, Levene's test was used to ensure that data showed a homogeneity of variance (Tamhane and Dunlop 2000), and that no transformations were required (cf. Sabin and Stafford 1990). Tukey simultaneous tests for multiple comparisons of means were used to assess any significance of differences in mean values of measurements between treatments. For all statistical tests, detected differences were deemed significant if $p \leq 0.05$.

2.5 Simpson index

Simpson index (D) was used to estimate the biodiversity among tree species (Simpson 1949), Eq. 2.

$$\mathrm{D} = \frac{\sum n(n-1)}{N(N-1)} \tag{2}$$

where n = the total number of organisms of a particular species, and N = the total number of organisms of all species.

Simpson index of diversity (1–D) represents the probability that two samples randomly selected from a sample will belong to different species (Simpson 1949). The value ranges between 0 and 1, e.g. 0 give no diversity (only one species).

3 Results

3.1 Stand structure parameters of BCT 1-series treatments

There were no significant differences between any plots in the stand parameters before the treatments began (Table 1). The stem number of the control plots (9635 ha^{-1}), which did not receive silvicultural treatment, was about eight-fold compared to conventional thinning (lowest stem number was 1168 ha^{-1}), and about three- and two-fold compared to $\mathrm{BCT}_{1\,\mathrm{m}}$ (3949 stems ha^{-1}) and $\mathrm{BCT}_{\mathrm{sel}}$ (4568 stems ha^{-1}), respectively. There were significantly more stems remaining per hectare following $\mathrm{BCT}_{2\,\mathrm{m}}$ treatment as compared to the conventional thinning treatment (Table 1). There were no significant differences between treatments regarding either dominant height or mean height after treatment. Furthermore, conventional thinning showed a significantly higher basal area weighted diameter, 9.5 cm, (calculated from DBH) than the other treatments. When the average DBH was calculated for each plot from the same number of stems as were left in the conventional thinning plot, and based on the larger stems, there were no significant differences between treatments (Table 1). The two highest values for stem volume and total biomass (DW) were found in the control treatment (116.7 m^3 ha^{-1}, 72.6 t ha^{-1}), and in the $\mathrm{BCT}_{\mathrm{sel}}$ treatment (76.4 m^3 ha^{-1}, 46.4 t ha^{-1}). The conventional thinning treatment had the lowest values for stem volume and biomass (39.6 m^3 ha^{-1}, 23.7 t ha^{-1}), both of which were significantly lower than the respective control values. The removal, in percent of total biomass and number of stems, resulting from conventional thinning (biomass 61%; stems 82%) was significantly higher than that of BCT-treatments. Additionally, conventional thinning harvested significantly more deciduous species than any of the BCT-treatments, in terms of both biomass and stem number (Table 1, Figs. 2a–b).

The only significant difference in the total number of stems with a DBH > 80 mm was between the control (1524 stems ha^{-1}) and conventional thinning (622 stems ha^{-1}) plots (Table 1). Also for basal area the highest value was found in the control (13.4 m^2 ha^{-1}). Significant higher only compared to the conventional thinning (5.8 m^2 ha^{-1}). The same pattern was also found for total biomass, 44.3 and 18.9 respectively. No significant difference was found for the basal area weighted diameter at breast height (1.3 m) (Dg), mean height or stem volume (Table 1).

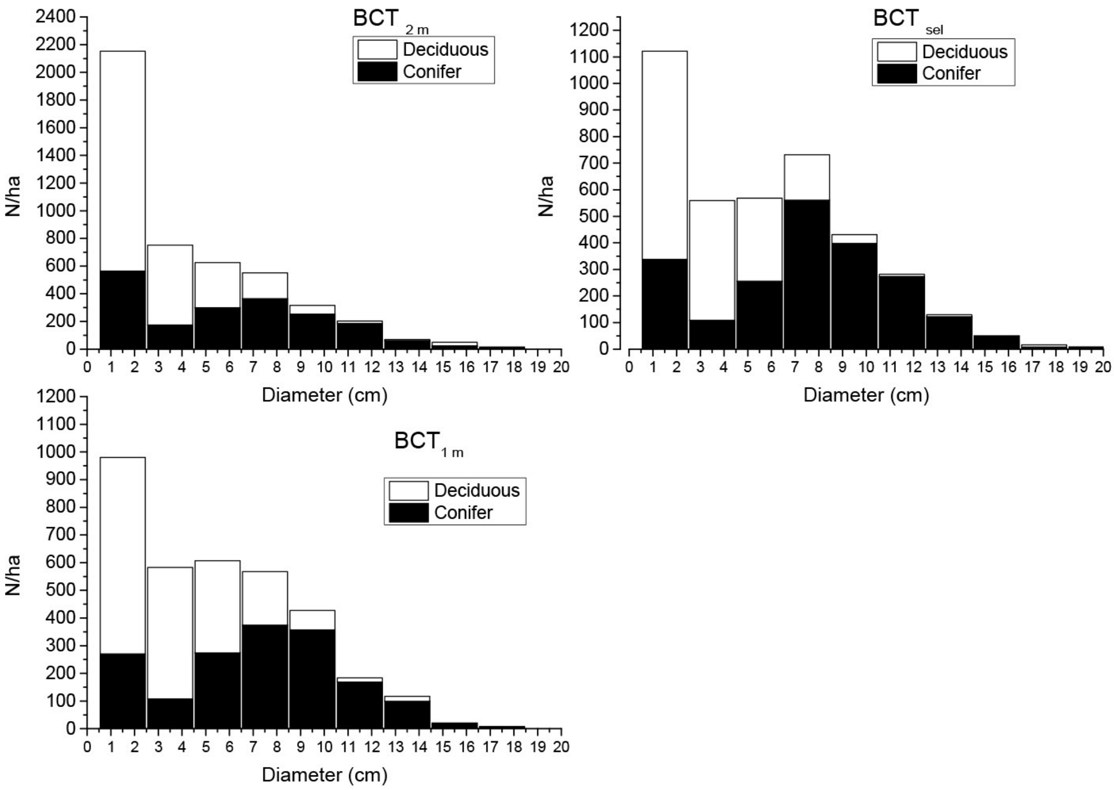

Fig. 2a. Number of stems ha^{-1} for conifer and deciduous species for diameter classes 0–20 cm, mean values for all sites. BCT 1-serie, mean and dominant tree height 6 and 11 m; treatment $BCT_{2\ m}$, $BCT_{1\ m}$ and BCT_{sel}.

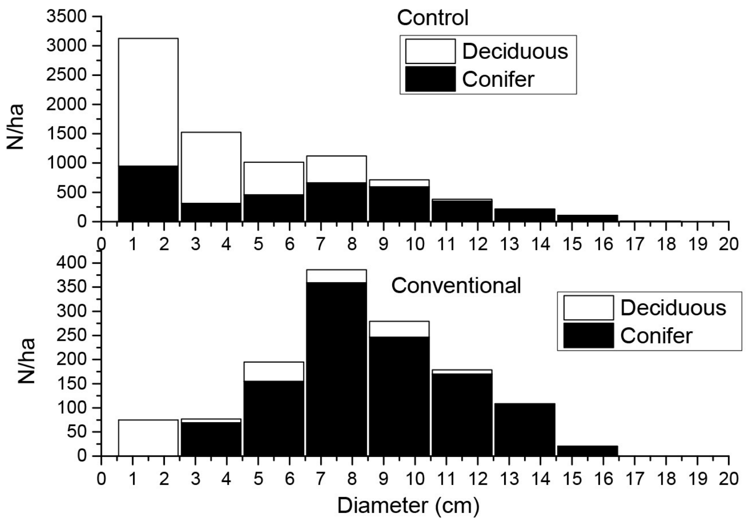

Fig. 2b. Number of stems ha^{-1} for conifer and deciduous species for diameter classes 0–20 cm, mean values for all sites. BCT 1-serie, mean and dominant tree height 6 and 11 m; control and conventional treatments.

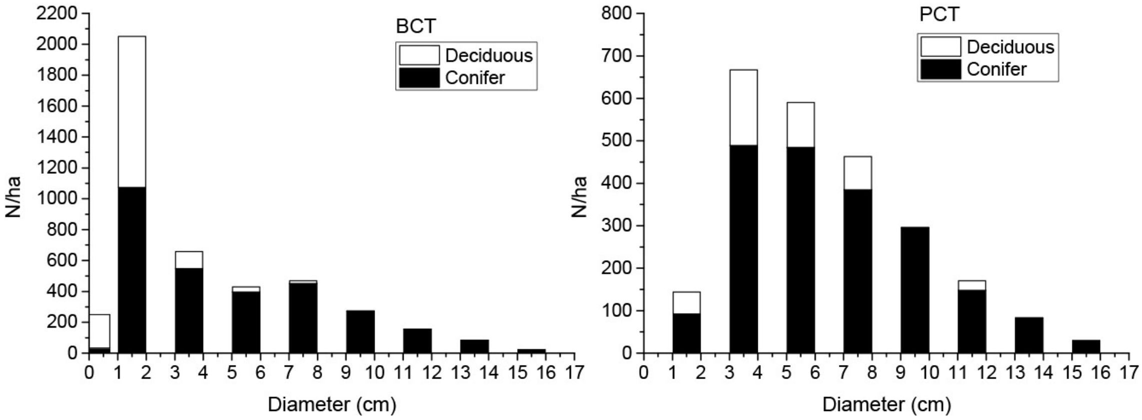

Fig. 2c. Number of stems ha^{-1} for conifer and deciduous species for diameter classes 0–17 cm, mean values for all sites. BCT 2-series, mean and dominant tree height 4 and 9 m, treatment BCT and PCT.

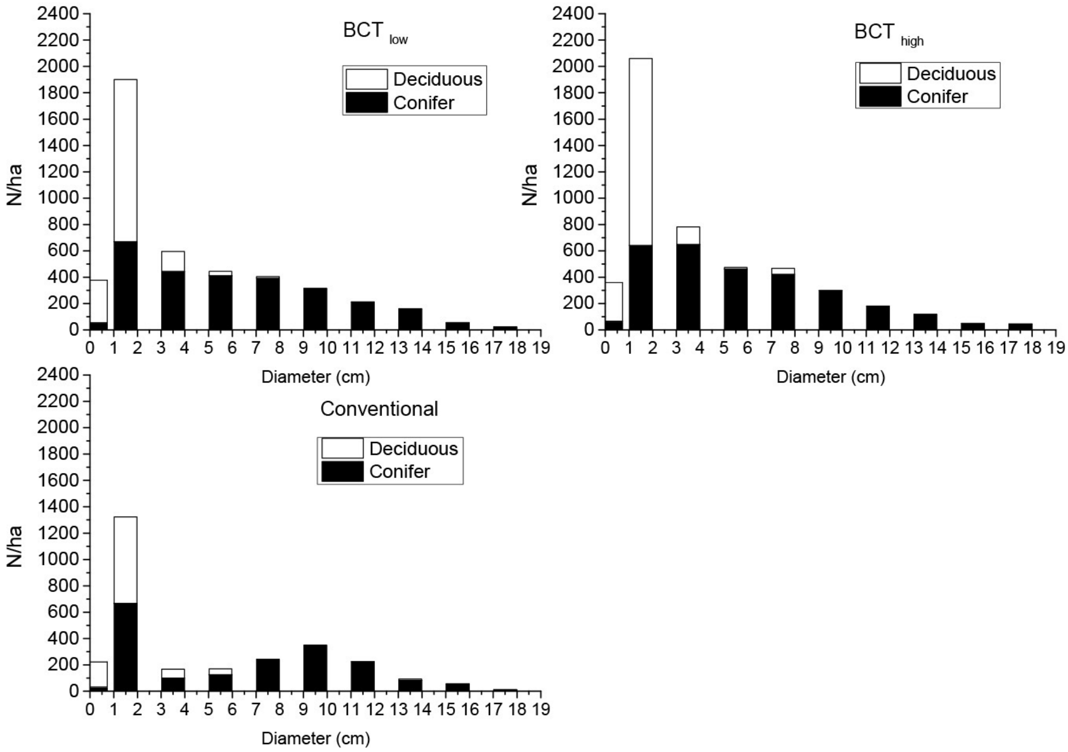

Fig. 2d. Number of stems ha^{-1} for conifer and deciduous species for diameter classes 0–19 cm, mean values for all sites. BCT 2-series, mean and dominant tree height 5 and 10 m treatments BCT_{low}, BCT_{high} and conventional.

3.2 Stand structure parameters of BCT 2-series treatments

The measurements from stands with the same dominant height were compared before and after the silvicultural treatments. Thus, in the three stands with a dominant height of 9 m the PCT and BCT treatments were compared, whereas in the three stands with a dominant height of 10 m the $BCT_{low,}$ BCT_{high} and Conv treatments were compared. As in the BCT 1-series, there were no significant differences between plots in any of the measured parameters before the treatments began (Table 2). However, following the treatments in stands with a dominant height of 9 m there were a significantly higher number of deciduous stems in BCT treatment plots (1267 stems ha^{-1}, 31%) compared to PCT treatment plots (274 stems ha^{-1}, 10%). Furthermore, the PCT plots were characterized by a significantly larger mean height (7.2 m) than BCT plots (5.2 m). The PCT treatment also resulted in a higher removal, both overall and of deciduous trees, than the BCT treatment (Table 2, Figs. 2c–d).

Following the thinning operations in stands with a dominant height of 10 m, conventional thinning resulted in the lowest stem number, but this value was not significantly less than either of the two BCT-treatments. Furthermore, there were no significant differences between treatments in dominant height, mean height, basal area based on DBH, or amount of large trees left following treatment. The BCT_{low} treatment resulted in the highest values for stem volume and total DW of biomass, but these values were not significantly higher than those of conventional thinning, which had the lowest values (Table 2). The conventional thinning also harvested more deciduous trees than the BCT-treatments, but the difference was not significant (Table 2).

For the largest trees (i.e. DBH > 80 mm), no significant differences between treatments were found in stem number, basal area, stem volume, total biomass, mean height or the Dg for both tree heights, 4/9 as well as for 5/10 (Table 2).

Treatments where boom-corridor thinning have been applied clearly show higher degree of tree size and species heterogeneity compared to selective treatments (Figs. 2c–d).

Simpson index for biodiversity resulted in higher values for BCT-treatments compared to selective thinning and PCT-treatments, with the same patterns for both series. For BCT 1, $BCT_{1\ m}$ (0.47), BCT_{sel} (0.46), $BCT_{2\ m}$ (0.46) and the control (0.45) there were significant higher values compared to the conventional thinning treatment (0.21). For BCT 2, neither were significant differences found between treatments in the stands with lower tree height (mean/dominant: 4/9 m); PCT (0.12) and BCT (0.42), nor in the stands with higher trees (5/10 m); BCT_{low} (0.26), BCT_{high} (0.17) and Conventional (0.12).

4 Discussion

The results show that overall, the BCT-treatments resulted in a more heterogeneous stand structure than other thinning operations, such as conventional thinning or PCT, shown by more trees per ha, somewhat smaller if mean tree height is considered, as well as more deciduous trees per plot. This heterogenic stand structure could create habitats for certain organism groups and thus positively affect ecosystem values (McElhinny et al. 2005). For each treatment the number of stems with a DBH > 80 mm was also counted to determine the amount of possible future crop trees, as previous studies have shown that trees in young stands with a DBH ≤ 80 mm have an increased risk of damage, such as broken stems or windthrow, especially after the thinning of dense stands (Päätalo et al. 1999; Abetz and Klädtke 2002). Results indicates that BCT could be a cost-effective thinning technique in young dense stands without risking that the number of larger trees in the stand decrease.

Furthermore, all BCT treatments provided similar results, as neither the geometric strictness of boom corridor layout nor the choice of high- or low-thinning approaches showed significant differences in stand structure parameters. Thus, BCT operations could provide a highly efficient and cost-effective technique for first thinning that can handle a variety of tree sizes (Bergström 2009) and simultaneously potentially increase local biodiversity through stand heterogeneity. Conventional thinning methods, on the other hand, attain higher cost efficiency when they are used in stands that have been pre-cleared or earlier subject to PCT. It remains to be seen whether the combination of conventional thinning and BCT techniques can increase biodiversity and ecosystem values.

Early thinning of dense stands through BCT results in harvested biomass that contains a higher share of branches and needles compared to pre-cleared stands. When this biomass is used as solid biofuel there is a small difference in quality between thinning methods, and thus, the values per DW t between thinning approaches should be similar. However, if the biomass is used for the extraction of chemicals, then the biomass resulting from BCT has a higher proportion of extraction-rich fractions, such as bark and needles (Backlund et al. 2014). These extraction-rich fractions mean that more valuable nutrients are removed from the stand. Technologies that compress and semi-defoliate biomass at the stand before extraction allow forest managers to control which fractions are extracted from a stand (Bergström et al. 2010).

All of the thinning treatments in both series were performed by a mechanized thinning harvester. Each series had one machine operator, who performed all the treatments included in that series. All of the cutting and bunching work was performed in a controlled manner to ensure that trees remaining after thinning not were damaged. In BCT 1-series plots the cutting of strip-road trees was strictly controlled, whereas in BCT 2-series plots the operator choose which trees to cut himself, resulting in a marginally higher strip-road area cut and thinning intensity than had been planned. Still there was no treatment where the area differed from the target width.

The next inventory will be performed in five years from set-up, and we expect that all the treatments will have similar production of future crop trees because the number of trees with a DBH > 80 mm was about the same for all treatments. Additionally, we expect that very few of the larger trees will be damaged due to snow and wind. Moreover, we expect that the smaller trees will show increased mortality due to high competition between trees in dense stands.

5 Conclusions

After the first biomass thinning, BCT and selective thinning approaches result in similar stand structures based on the amount and average sizes of remaining possible future crop trees. However, BCT also maintains diverse tree sizes, deciduous species, and leaves more trees per ha. Hence, BCT should be a cost-effective option for thinning that can increase vertical complexity in stands, and as a result possibly increase biodiversity and ecosystem service values.

In our study we only consider tree species for biodiversity analysis and in the studied forest the number of species are low and predominated (in terms of volume) by conifers (pine and spruce). The index shows that the diversity of tree species for all trial series is somewhat higher for boom-corridor treatments than selective ones. However, the differences are significant only for BCT 1. Thus, schematic thinning renders keeping the tree diversity at the same level as for the untreated stands.

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