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Comparison of Boom-Corridor Thinning and Thinning From Below Harvesting Methods in Young Dense Scots Pine Stands

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At present, only a small proportion of the potential extractable bioenergy from young dense forests in Sweden is utilized. The conventional mechanized first thinning systems used in such stands suffer from low productivity, so the operation is only profitable in stands with bigger trees and high standing volumes. Conventional harvesters are used for this operation equipped with accumulating felling heads designed for handling several trees during each crane cycle. In thinning from below the felling and bunching work requires many time-consuming non-linear crane movements to avoid felling or damaging of future crop trees. However, higher productivity can be achieved when trees between strip roads are harvested in about 1 m-wide corridors with a length corresponding to the reach of the crane. We refer to this operation as boom-corridor thinning. The objective of this study was to compare felling and bunching productivity in young dense stands when employing thinning from below or boom-corridor thinning. Experiments were performed using a randomized block design involving between 4400 and 18 600 trees×ha^{-1} with a corresponding average tree size of 7.2 and 3.2 cm dbh, respectively. Based on the average tree being removed at a dbh of 5.7 cm, the productivity (ODt ×PW-hour^{-1}) was significant (almost 16%) higher for the boom-corridor thinning than for thinning from below treatment. At the same time, the time taken for the work element "Crane in-between" (the period between the loaded crane starting to move towards a tree and the felling head rapidly slowing down for positioning) was significantly reduced, by almost 17%. The positive results were achieved even though the operator was new to the method. To achieve a significantly higher efficiency during the felling and bunching operation, development of new harvesting equipment and operating techniques seems crucial.

Keywords bioenergy, comparative time studies, energy wood, geometric thinning, pre-commercial thinnings, systematic thinnings
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1 Introduction

To make bioenergy derived from young forest stands economically competitive, the costs of harvesting must be reduced and the biomass yield per ha must be high (Hakkila 2005). Keeping young stands dense until the first commercial thinning by not undertaking pre-commercial thinning (PCT) or by reducing its intensity would significantly increase the biomass yield (Claesson et al. 1999). In Sweden, there is a total of 2.77 million ha of young stands that are less than 12 m tall and contain more than 30 oven-dry tonnes (ODt) per ha of biomass, of which as much as 5 million ODt could be harvested annually for energy purposes (Nordfjell et al. 2008). At present only an insignificant proportion of this biomass is utilized, but with increasing demand for bioenergy, interest in harvesting such stands is also likely to increase. However, conventional mechanized first thinning (FT) systems suffer from low productivity in young dense stands; they are only profitable in stands with high standing volumes and harvested tree diameters greater than 8–10 cm.

FT operations for extracting fuel wood use conventional harvesters equipped with accumulating felling heads (AFH) designed for handling several trees in each crane cycle to compensate for the small size of the trees. Usually, whole trees (full tree; tree above felling cut) are felled and bunched by thinning from below along strip roads then hauled to the roadside with conventional forwarders. The productivity of the felling and bunching operation is related to factors such as the average harvested tree size, stand density and intensity of removal (Kärhä et al. 2005), frequency of multiple felling (Johansson and Gullberg 2002), frequency of accumulation (Liss 1999) and the presence of Norway spruce (*Picea abies* L. Karst) undergrowth that interferes with the work (Kärhä 2006). The productivity of the operation ranges from about 1.0 to 8.0 solid cubic metres of biomass (m^3biomass) (~ 0.5–4.0 ODt) per hour of productive work time (PW-hour; IUFRO WP 3.04.02. 1995) across a range of types of young forests, systems and machinery (Gullberg et al. 1998, Liss 1999, Kärhä et al. 2005). Trees thinned from below are felled one by one, resulting in many time consuming non linear crane movements in order to avoid future crop trees (Johansson and Gullberg 2002). To facilitate high felling and bunching productivity in stands with relatively small trees, the AFH's capacity for multiple felling is crucial. However, with the AFHs currently available, multiple felling is limited due to the spacing between trees, their use being possible only in cases where trees are closely spaced. To our knowledge, no specialized AFHs for multiple felling of small diameter trees spaced further apart than a few dm have yet been developed. We believe that a felling and bunching productivity of at least 8 m^3biomass×PW-hour^{-1} is needed to ensure profitability at an operational cost below 10 €×m^{-3} biomass (i.e., at an operational cost of 80 €×PW-hour^{-1}) (see Bergström et al. 2007).

According to simulations by Bergström et al. (2007), using a commercial AFH in geometrical (corridor) thinning systems significantly reduces the time consumption per tree, increasing the felling and bunching productivity (m^3biomass×PW-hour^{-1}) by up to 44%. Corridor thinning systems for young dense stands could be designed so that trees between strip roads are harvested in narrow corridors with a length corresponding to the crane reach (about 10 m); such corridors could be perpendicular to the strip-road and approximately 1 m wide. We name this boom-corridor thinning. In such systems the time taken to re-position the AFH in each crane cycle would be reduced since trees that are in the way are removed as the boom-corridor is harvested. Liss (1999) did not find any increased productivity in feller-buncher operations in early thinnings where trees were felled and accumulated only by linear crane movements. However, the method used in the Liss (1999) study was a combination of geometric thinning and thinning from below and trees were not harvested exclusively in boom-corridors.

The objective of this work was to assess the effects of harvesting trees between strip roads in narrow boom-corridors in young dense stands on productivity relative to a thinning from below treatment, using conventional harvesting equipment.

Table 1. Stand properties in average values of the blocks used in thinning experiments.

Stand properties	Block 1	2	3	4	5	6	7	8	Mean
Density (trees×ha^{-1})	18600	10075	8750	8250	6150	5625	4500	4400	8294
Dbh (cm)	3.2	4.4	4.0	4.6	6.1	5.0	6.0	7.2	5.1
Dbh[1] (cm)	9.0	10.3	7.5	8.3	10.0	9.0	10.6	12.5	9.7
Height (m)	3.9	4.8	4.7	5.2	6.0	5.3	6.0	6.7	5.3
Height[1] (m)	8.0	8.7	7.7	7.9	8.5	8.2	9.8	9.5	8.5
Basal area (m²×ha^{-1})	28.8	26.0	17.0	19.7	26.3	16.3	17.2	25.1	22.1
Biomass[2] (ODt×ha^{-1})	82.8	76.8	45.9	54.6	79.9	47.4	51.2	79.6	64.8

[1]Weighted by basal area. [2]Calculated according to Ulvcrona et al. (2010).

2 Materials and Methods

The study was carried out during June 2007 in the community of Nordmaling in the northern part of Sweden (N63º34’, E19º33’, 40 m.a.s.l.). The study site was part of a 15 ha forest stand with an annual growth potential of 3.1 m³×ha^{-1} (H100: T18) (Hägglund and Lundmark 1987). The forest was approximately 30-years-old and was dominated by Scots pine (*Pinus sylvestris* L). It was natural regenerated and had not been subjected to a PCT. Some parts of the site contained considerable quantities of undergrowth, mainly Norway spruce.

Sixteen plots were selected in order to maximize the variation in trees × ha^{-1} and diameter at breast height over-bark (dbh). Each plot measured 50 m × 20 m, corresponding to at least 30 minutes of PW harvesting time. In each plot a centre line (strip road centre), a start position and a stop position were marked out for the machine to follow. In all plots, the terrain difficulty (ground strength, surface structure and slope) were measured to 1.1.1 (Berg 1992): i.e., the ground had high bearing capacity and the surface was smooth with almost no slope. The tree species, dbh, height and diameter at stump height (d_{stump}; ~15 cm above ground level) were then recorded in the plots in eight systematically distributed plots (each 25 m^2). All trees taller than 1.3 m were inventoried. The plots were then blocked on the basis of similarities in average dbh and trees × ha^{-1} (Table 1).

The experiment was laid out using a randomized block design comprising eight blocks. Each block consisted of two thinning treatments: thinning from below (the control) and boom-corridor thinning. Treatments in each block were assigned by randomization. The results were assessed by analysis of variance using the model:

$$y_{ij} = \mu + t_i + b_j + e_{ij}$$

were μ is the grand mean, t_i the treatment main effect, b_j the block main effect and e_{ij} the error term. Differences were considered significant if $p \leq 0.05$.

The proportions of trees × ha^{-1} of pine, spruce and broadleaved were 70, 15 and 15%, respectively, of which the latter two were mainly undergrowth (trees < 4 cm at dbh). Fig. 1 shows the distribution of trees × ha^{-1} per block in four size classes.

The base machine used was a Valmet 911.1 (Komatsu Forest AB, Sweden) harvester, which has a mass of 16 500 kg and a width of 2.6 m. The crane used was a Cranab CRH 16 (Cranab AB, Sweden), which has a reach of 11.3 m. The AFH used was a Bracke C16.a (Bracke Forest AB, Sweden) with a mass of 500 kg (rotator not included), a width of 925 mm and a height of 1145 mm. It cuts trees with a saw chain attached to a circular disc. The diameter of the disc was 800 mm and it could cut trees up to 26 cm in diameter. The saw chain was of a larger size than ordinary harvester saw chains. The distance between saw chain rivets was 19 mm. The operator was skilled at using this machinery in thinning, and he conducted all the thinning throughout the experiment.

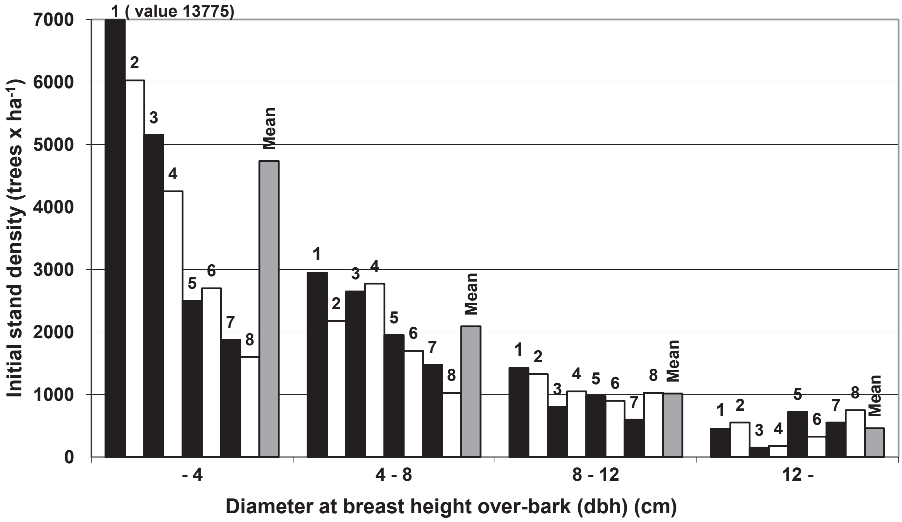

Fig. 1. Initial stand density in each diameter class and block (1–8) and the mean value of respective class.

During the harvest, trees < 4 cm dbh ("undergrowth") were if possible not cut. It was intended that the remaining stands should contain approximately 1500 trees × ha^{-1} ≥ 4 cm dbh after harvest. In the thinning from below treatment harvested trees were bunched in appropriate gaps beside the strip road with the butt ends pointing towards the strip road. In the boom-corridor treatment, trees between strip roads were harvested in narrow 1 m-wide boom-corridors being as close to perpendicular to the strip road as possible. Trees were then bunched in the boom-corridors with the butt ends pointing towards the road. The operator selected the location, length and width of boom-corridors during harvesting. The thinning methods differed only with respect to harvesting between strip roads (Fig 2.). The thinning quota was calculated as the average diameter of harvested trees through the average diameter of trees in the original stand (dbh(harvest) × dbh(original stand)$^{-1}$).

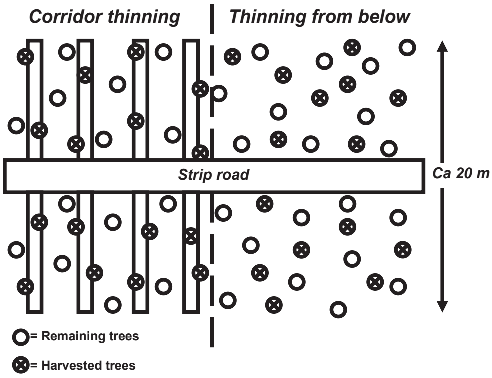

Fig. 2. Schematic representation of the boom-corridor thinning and thinning from below methods used in the experiment.

The time consumption for the felling and bunching work was recorded continuously with a field computer (Huskey Hunter) using the Siwork 3 software. The work was divided into eight work elements (Table 2).

The order in which the study units and their treatments were harvested was randomized. The time study was performed in daylight conditions over a period of four days; one block was harvested before lunch and one after lunch each day.

After harvest, the felled and bunched trees in each study unit were measured and the species and d_{stump} recorded; from this data the tree height and dbh were calculated. Subsequently, the biomass content was calculated based on the functions presented by Ulvcrona et al. (2010). Damage to the remaining trees was recorded in two rectangular areas (4.5 m × 22.0 m) right through the strip road,

Table 2. Definitions of the measured work elements for the felling and bunching work during whole tree thinning in strip road systems. If two work elements occurs simultaneously, the one with highest priority is registered (1 have higher priority than 2 etc.).

Work element	Definition	Priority
Move	The period when the machine is moving; the wheels are turning	2
Crane out	The period between the unloaded crane starting to move towards a tree and the felling head rapidly slowing down for positioning (~1 m from the tree)	1
Positioning and felling	The period between Crane out or Crane in-between element ending and the tree(s) being cut	1
Crane in-between	The period between the loaded crane starting to move towards a tree and the felling head rapidly slowing down for positioning (~1 m from the tree)	1
Crane in	The period between the loaded crane beginning to move towards the base machine for bunching trees and the harvester head pivoting for unloading	1
Bunching	The period between the end of Crane in and the harvester head being empty	1
Miscellaneous	Other work, e.g. moving dropped trees to a bunch	3
Delays	Interruptions and breaks not related to the operational work; mechanical and operator related disturbances, e.g. hydraulic problems and telephone calls	3

one located 15 m in from the start position and the other 15 m in from the stop position. Tree damage was considered to have occurred when sapwood was clearly visible, with no restrictions on size, on trees ≥4 cm in dbh (see Wallentin 2007). Damage adjacent to the strip road and within the stand was recorded separately. The width of the strip road and the distance between strip roads were measured at three specific places along the strip road centre: 10 m in from the starting position, in the middle and 10 m before the stop position. The width of the strip road was defined as the distance between two trees on either side of the strip road and measured perpendicular to the centre line. The distance between strip roads was defined as the distance between two trees, one on each side of the road, harvested furthest from the strip road centre and was measured perpendicular to the centre line.

3 Results

No significant differences were found between treatments with respect to the harvest properties (Table 3). On average, for the thinning from below and boom-corridor thinning treatments, the harvesting intensities were 29.7 and 32.9% based on number of trees × ha^{-1}, 36.0 and 36.4% based on basal area and 34.0 and 34.8% based on ODt × ha^{-1} (see Table 3). The number of harvested trees per bunch was 9.7 for the thinning from below and 10.5 for the boom-corridor treatment while the biomass content per bunch was 84 and 90 ODkg in the thinning from below and boom-corridor treatments, respectively. The thinning quota, based on the arithmetic dbh, was 1.14 for the thinning from below and 1.13 for the boom-corridor treatment. The corresponding values for the dbh weighted by basal area were 0.91 and 0.95, respectively.

In the remaining stands the average distance between strip roads was significantly different and 0.7 m (3.6%) longer in the boom-corridor than the thinning from below treatment (Table 3). In addition, the distance between strip roads seemed to decrease with increasing trees × ha^{-1} for both treatments (data not shown). As a proportion of the total harvested area, the strip road accounted for 17.8 and 16.9% of the thinning from below and boom-corridor treatments, respectively. The number of damaged trees was 0.7%-unit less for the thinning from below treatment, but the difference was not significant (Table 3). The average stump height on strip roads was 11 cm (27.4%) lower than between the strip roads.

For all tree species, the average share of tree

Table 3. Properties of the original stands, harvest and remaining stands; values are averages per treatment with minimum and maximum values in brackets.

Properties	Treatment Thinning from below (n=8)	P-value Boom-corridor (n=8)	Treatment
ORIGINAL STAND			
Density (trees × ha^{-1})	8300 (4600–18650)	8290 (4200–18550)	
Dbh (cm)	5.0 (2.7–7.1)	5.1 (3.7–7.3)	
Dbh[1] (cm)	9.6 (7.8–12.2)	9.7 (7.2–12.9)	
Height (m)	5.3 (3.5–6.5)	5.4 (4.3–6.8)	
Height[1] (m)	8.6 (7.7–10.7)	8.5 (7.5 9.6)	
Basal area (m^2 × ha^{-1})	21.4 (14.4–25.1)	22.8 (13.8–32.6)	
Biomass (ODt × ha^{-1})	62.7 (39.8–77.1)	67.0 (39.8–93.1)	
HARVEST			
No. of trees × ha^{-1}	2462 (1665–3264)	2724 (1337–5319)	0.598
Dbh (cm)	5.7 (5.0–6.8)	5.8 (4.2–7.6)	0.615
Dbh[1] (cm)	8.7 (7.5–10.5)	9.2 (7.3–11.2)	0.246
Height (m)	6.3 (5.8–6.8)	6.4 (5.0–7.5)	0.817
Height[1] (m)	8.1 (7.5–8.8)	8.3 (7.4–9.2)	0.204
Basal area (m^2 × ha^{-1})	7.7 (4.8–9.2)	8.3(5.8–10.5)	0.261
Biomass (ODt × ha^{-1})	21.31 (12.6–25.4)	23.34 (16.4–30.0)	0.150
Tree size (ODkg × $tree^{-1}$)	8.9 (6.4–13.5)	10.3 (5.2–16.8)	0.272
Bunches (no. × ha^{-1})	253 (194–312)	259 (212–342)	0.784
REMAINING STAND			
Strip road width (m)	3.5 (3.2–3.9)	3.4 (3.0–3.8)	0.735
Distance between strip roads (m)	19.7 (18.1–21.1)	20.4 (19.1–21.6)	0.024
Stump height in strip roads (cm)	28 (24–33)	26 (23–30)	0.233
Stump height between strip roads (cm)	36 (32–39)	38 (30–54)	0.544
Damaged strip road trees[2] (trees × $100m^{-1}$)	2.1 (0–4.0)	1.9 (0–9.9)	0.826
Damaged trees, total values[3] (%)	1.5 (0–2.4)	2.2 (0–6.1)	0.491

[1] Weighted by basal area. [2] Based on trees ≥ 4 cm at dbh just beside the strip road. [3] Based on all remaining trees ≥ 4 cm at dbh.
Differences were considered significant if $p \geq 0.05$.

mass (OD) of stem wood, branches and needles/leaves was 70, 16 and 14%, respectively. For the four dbh size classes (<4 cm, 4–8 cm, 8–12 cm, >12 cm) on average 20, 55, 39 and 22% of the trees were removed (Fig. 3). In the thinning from below treatment, the total biomass harvested per size class, from smallest to largest was 6, 36, 38 and 20%, respectively. The corresponding values for the boom-corridor treatment were 6, 30, 36 and 28%, respectively. On average about 54% more trees ≥12 cm at dbh were harvested in the boom-corridor than in the thinning from below treatment (Fig. 3), but no significant differences in biomass removal (ODt × ha^{-1}) were found between treatments (Table 3). Between 844 and 3374 remaining trees×ha^{-1} ≥4 cm dbh were found in both treatments, with an average density of 1921 trees × ha^{-1}. The corresponding values for trees ≥8 cm dbh were 484–1440 trees × ha^{-1}, with an average density of 978 trees × ha^{-1} (Fig. 1 and 3).

The felling and bunching operation was studied for a total of 9.66 hours, of which 8.3% was Delay time. Hereafter Delay time is excluded from the analysis. The work element Positioning and felling was the most time consuming (close to one third of PW) in both treatments. For both treatments, the combined work elements Move, Crane in and Bunching accounted for about one third of the PW consumption (Table 4). The numbers of trees harvested per crane cycle for the thinning from below and boom-corridor treatments were 3.4 and 3.7, respectively. In the boom-corridor treatment, the work element Crane in-between accounted for 16.7% less time; this difference was significant at the 99% level (Table 4). The produc-

Table 4. Time consumption and productivity per treatment; values are averages with minimum and maximum values in brackets. Note: no time was spent on the work element Miscellaneous, it is therefore not included in the table.

Work element	Treatment				p-value Treatment
	Thinning from below ($s \times tree^{-1}$) (n=8)	Proportion of total time (%)	Boom-corridor ($s \times tree^{-1}$) (n=8)	Proportion of total time (%)	
Move	0.89	11	0.93	12	0.696
Crane out	1.33	17	1.39	18	0.778
Positioning and felling	2.48	31	2.31	30	0.372
Crane in-between	1.44	18	1.20	16	0.002
Crane in	0.95	12	0.93	12	0.711
Bunching	0.84	11	0.92	12	0.478
Total time consumption	7.93	100	7.66	100	0.691
Time consumption ($PW\text{-}hour \times ha^{-1}$)	5.4 (3.4–7.4)		5.2 (3.6–7.8)		0.757
Productivity ($trees \times PW\text{-}hour^{-1}$)	459 (397–527)		496 (339–681)		0.411
Productivity[1] ($trees \times PW\text{-}hour^{-1}$)	311 (224–351)		312 (280–343)		0.959
Productivity ($ODt \times PW\text{-}hour^{-1}$)	4.0 (3.4–5.4)		4.6 (3.3–5.7)		0.024

[1]Based on harvested trees ≥ 4cm dbh.

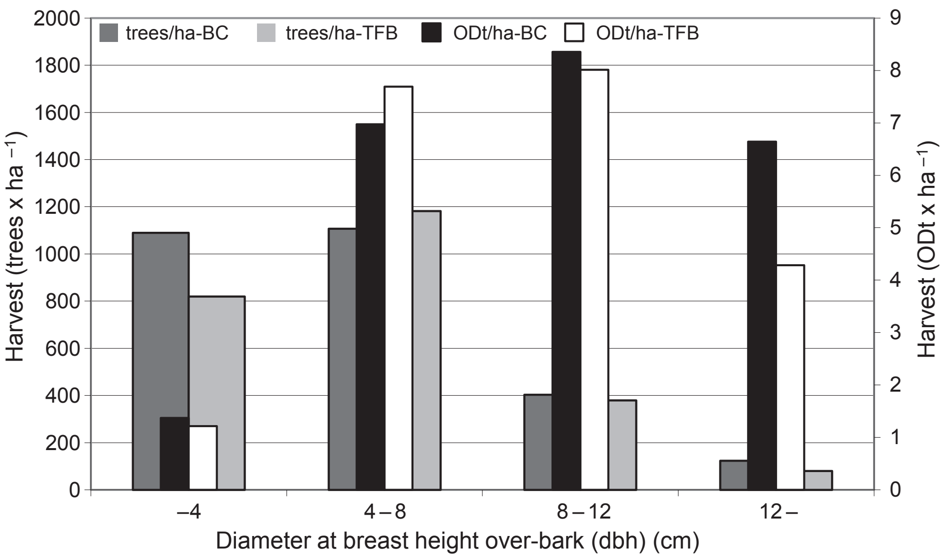

Fig. 3. The average distribution of harvested intensity ($trees \times ha^{-1}$) and corresponding harvested biomass contents in the different size classes for the thinning from below (TFB) and boom-corridor thinning (BC) treatments.

tivity in terms of harvested trees×PW-hour^{-1} was 8.1% higher for the boom-corridor treatment but the difference was not significant (Table 4). The corresponding productivity based on harvested trees ≥ 4 cm dbh was about 310 trees×PW-hour^{-1} for both treatments (Table 4). On average, the productivity (ODt×PW-hour^{-1}) was 15.8% higher for the boom-corridor treatment; this difference was significant (Table 4). Further, the difference in absolute values increased as the size of the harvested trees decreased (Fig. 4).

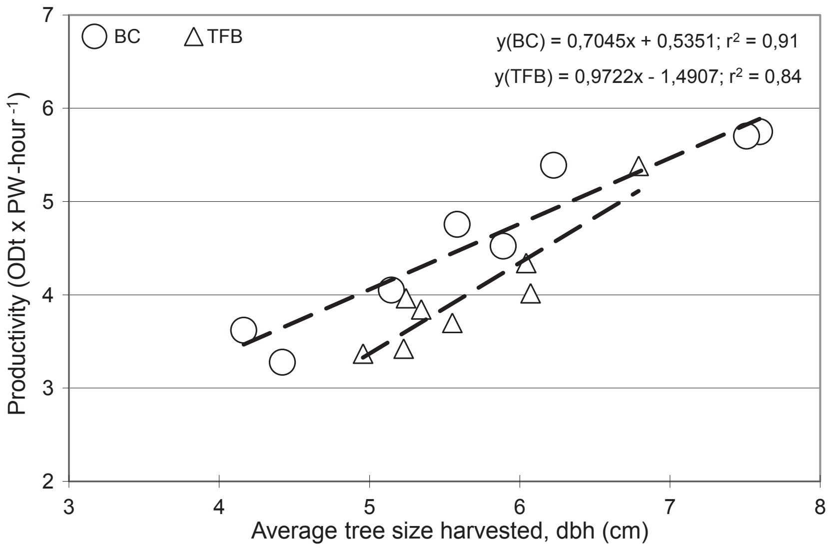

Fig. 4. The productivity of the boom-corridor (BC) and the thinning from below (TFB) treatments as a function of the average tree size harvested. Each marking represents a study unit.

4 Discussion

In comparative studies of forest operations it is important that the conditions for the treatments are similar, and one strategy to achieve such conditions is to keep irrelevant and influencing factors controlled (Bergstrand 1987). In present study a wide range of trees × ha^{-1} and tree sizes varied in 8 blocks (16 study units). The boom-corridor and thinning from below treatments were assigned to study units within blocks by randomization (Table 1). Variation in extraneous factors such as the terrain, machinery and operator was minimized between blocks which all were dominated of Scots pine in terms of standing volumes. The experimental design of present study permitted a precision estimation of the mean values of treatments which then could be compared by Analyses of variance. However, only under the studied conditions the results are valid. To generalize the effects of assessing boom-corridor thinning in operational forestry more experiments with varying e.g. stand conditions, machinery and operators must be performed.

In the boom-corridor treatment, the operator chose the location of the boom-corridors during harvest, in order to leave 1500 remaining trees × ha^{-1}. His aim for the resulting boom-corridor stands was to be as similar to the thinning from below treatment stands as possible: e.g., similar spatial distribution of the trees remaining. However, once the location of the boom-corridor had been selected, the trees were harvested exclusively by linear crane movements within the boom-corridor and the boom-corridor was harvested to the full reach of the crane. Consequently, the boom-corridor thinning method was not completely standardized; the harvested corridors were not exactly perpendicular to the strip road and their width and spacing were not constant. The width of boom-corridors or their placement in relation to the strip road was not measured, but the angle of corridors (assessed visually) did not exceed ±10° from a line perpendicular to the strip road. The number of boom-corridors (which roughly corresponded to the number of bunches) averaged 53 (26.5 per side of the strip road) per 100 m, giving a calculated boom-corridor distance of about 4 m. The spatial distribution of the remaining trees was not measured; however, a visual assessment indicated that there were only minor differences between the two treatments. Had the boom-corridor treatments been performed according to strict criteria, the visually differences could be expected to be greater. However, in future studies, it is essential to assess fully the effects of boom-corridor thinning of the future stand development.

If geometric thinning is applied, the thinning quota is 1.0: i.e., the average tree size (dbh) harvested compared to the average tree size of the initial stand. Thinning from below is the most common treatment in thinning, and this has a thinning quota of less than 1 (Lageson 1996). Thus, at any given density of removal, the harvested trees are larger in geometric thinning compared to thinning from below. In the current study, the harvested tree sizes and harvesting intensity were slightly higher in the boom-corridor treatment, but the differences were not significant (Table 3). The thinning quota based on the dbh weighted by basal area was closer to 1 for the boom-corridor treatment (0.95) than for the thinning from below treatment (0.91). Furthermore, the average tree size (dbh) harvested per treatment was only about 2% larger for the boom-corridor treatment. However, the dbh range of harvested trees was 4.2 to 7.6 cm for the boom-corridor treatment and 5.0 to 6.8 cm for the thinning from below treatment (Table 3.). For both treatments the thinning quota based on the arithmetic dbh was above 1, indicating that the relative proportion of trees removed was higher for the larger trees (Figs. 1 and 3). This is the result of trees smaller than 4 cm dbh not being harvested whenever possible.

The distance between strip roads was 0.7 m longer in the boom-corridor thinning treatment; this difference was significant (Table 4). However, the operator was instructed to use the same approach in both treatments: to harvest to the full reach of the crane. Thus, it appears that boom-corridor thinning results in efficient harvesting at the longest crane reach. About 2% of the remaining trees were damaged in both treatments; this can be considered to be a low level (Wallentin 2007). However, damage was recorded before forwarding, an operation that can result in additional damage. In mechanized PCT an average of 5.2% damaged trees has been recorded, and an average range of 0 to 4.8% in motor manual work (Ligné et al. 2005). In present study, during experiments, the operator did not take any "risks" of sawing in to e.g. stones, which resulted in relative high stumps at long crane reach (at reduced sight conditions). Consequently, the stump heights on strip roads become circa 27% lower than stump heights between strip roads. In the current study, the stands contained a considerable number of trees < 4 cm dbh after harvest; such trees should not compete in terms of growth yield with the remaining main trees. However, for the forest owner the presence of a significant amount of "undergrowth" might be disturbing. If this undergrowth has to be removed, motor manual cleaning after harvesting would be much cheaper than PCT before harvest.

Although the operator was new to the boom-corridor thinning method, the felling and bunching productivity (ODt × PW-hour^{-1}) for trees with an average dbh of 5.7 cm was almost 16% higher in the boom-corridor thinning treatment than the thinning from below treatment (Table 4). The time consumption (s × tree^{-1}) for the work element Crane in-between was almost 17% and was highly significantly lower for the boom-corridor treatment (Table 4). Furthermore, in both treatments the work element Positioning and felling alone accounted for about one third of the total time consumption; it was the single most time-consuming element. Equivalent results were found by Kärhä et al. (2005) for felling and bunching under similar stand conditions. The differences in productivity (ODt × PW-hour^{-1}) in absolute values between treatments increased when the average tree size harvested decreased (Fig. 4). Using the linear regression functions presented in Figure 4, at harvested tree sizes of 4.5 cm and 7.5 cm, the differences are 28 and 0%, respectively. Thus, the boom-corridor thinning system seems to result in higher work efficiency with smaller harvested trees; in this case in stands containing a significant number of small trees and undergrowth (Figs. 3 and 4). The difference in average productivity between the treatments was 16% in the present study but a difference of 44% in productivity was found in a simulation study by Bergström et al. (2007). However, in the simulation study, strict boom-corridor thinning was performed which might result in higher efficiency. In comparison to published field studies, the productivity (ODt × PW-hour^{-1}) of the thinning from below treatment (control) in the present study was about two-folds higher in similar stands at an average tree size removal of 6 cm dbh (Liss 1999, Kärhä et al. 2005). Whether this is a consequence of the operator being very skilful (e.g., with respect to cutting techniques, motoric skills, planning of work, experience, etc. (Ovaskainen et al. 2004), or a consequence of working with more suitable (better) technology, cannot be determined. In general, the operational work ran smoothly during the experiment; only a little time was spent on the work element Delays and no time was recorded for the work element Miscellaneous. In the current study, the operator experienced no operational problems when performing the boom-corridor treatment compared to the thinning from below treatment. To gain more information about boom-corridor thinning, it would be important to evaluate whether the time consumption ($s \times tree^{-1}$) can be significantly reduced if the boom-corridors had been marked out beforehand, resulting in strict boom-corridor thinning. It can be expected that the decision-making time for the operator would be reduced. Furthermore, in FT for round wood it is quicker to use a crane with an extra pivoting point on the outer boom which makes it possible to reach behind residual trees (Lindroos et al. 2008) and this technique can also be applicable to FT for fuel wood. Combining boom-corridor thinning methods with new and improved harvesting techniques can improve the supply of biomass from young dense stands (Bergström et al. 2007). The technique of boom-corridor thinning should be developed so that the felling unit only needs a single position for an entire corridor. Felling and accumulation of trees would then be possible in one linear crane movement per boom-corridor

5 Conclusions

The study demonstrated that almost 16% higher productivity was achieved by changing the harvesting method from a thinning from below to a boom-corridor thinning treatment. This despite that the operator was new to the method and that the technology used was not developed for boom-corridor thinning. In this study the thinning operations in young dense stands were performed using technology mainly designed for round wood extraction. This limits the potential for improving the operational efficiency with the present machinery and improvements were limited to changing the operating technique. To achieve a significantly higher efficiency during the felling and bunching operation, development of new harvesting equipment and operating techniques is crucial.

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