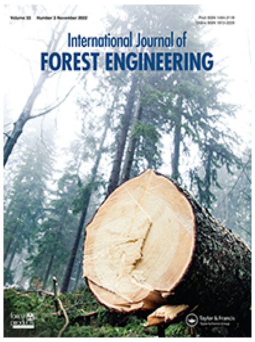

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Effects of boom-corridor thinning on harvester productivity and residual stand structure

Dan Bergström[a], Raul Fernandez-Lacruz[b], Teresa de la Fuente[c], Christian Höök[a], Nike Krajnc[d], Jukka Malinen[e,f], Yrjö Nuutinen[g], Matevž Triplat[d,h], and Tomas Nordfjell[a]

[a]Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences, Umeå, Sweden; [b]The Forestry Research Institute of Sweden (Skogforsk), Sävar, Sweden; [c]Department of Forest and Environmental Engineering and Management, Polytechnic University of Madrid, Madrid, Spain; [d]Slovenian Forestry Institute, Ljubljana, Slovenia; [e]School of Forest Sciences, University of Eastern Finland, Faculty of Science and Forestry, Joensuu, Finland; [f]University of Eastern Finland Faculty of Science and Forestry: Ita-Suomen Yliopisto Luonnontieteiden Ja Metsatieteiden Tiedekunta, Vantaa, Finland; [g]Natural Resources Institute Finland (Luke), Joensuu, Finland; [h]Biotechnical Faculty, Department of Forestry and Renewable Forest Resources, University of Ljubljana, Ljubljana, Slovenia

ABSTRACT

Biomass derived from small-diameter, dense, thinning stands is largely underutilized within the European Union, mainly because of in-effective harvesting methods and cutting technology, leading to high supply costs. Therefore, the efficacy of boom-corridor thinning (BCT) and selective thinning (ST) on harvester felling and bunching productivity was compared for the first thinning of whole tree biomass in small-diameter, dense stands. BCT working method is when trees are cut with linear movements of the harvester's boom reach, along narrow corridors, instead of cutting each tree selectively (ST). Trials were performed in six forest stands, one in Sweden, two in Finland, and three in Slovenia, using the same harvester and operator. A time-and-motion study was carried out in 64 pre-marked study units (32 replications per method), across a variety of stand conditions. The biomass removal for both treatments averaged 40.2 dry t ha -1 and BCT productivity averaged 5.4 dry t PMh -1. For BCT, harvester work time consumption (sec tree -1) and productivity (dry t PMh -1) were on average 27% lower and 16% higher, respectively, compared with ST. The effectiveness of the accumulating felling head technology used could potentially be increased by implementing a feed-roller system when handling excessive tree lengths. Developing dedicated harvesting technology for BCT could further boost productivity, facilitating cost-effective and sustainable utilization of low-value small-diameter tree biomass and replacing fossil resources.

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Bioenergy; accumulating felling head; multi-tree handling; silviculture; bioeconomy; forestry

Introduction

Tree biomass is viewed as an important alternative resource in the transition from a fossil-based economy to a bioeconomy within the European Union (EU) (Blair et al. 2021). During 1990–2020, the forest area and growing stock in Europe increased by 9% and 50%, respectively (Europe 2020), largely as a result of net planting and large areas of farmland being transformed into forest land (Fuchs 2013). In 2010, even-aged forests up to 40 years old covered ~36 M ha across Europe (Vilén et al. 2012), which will generate an increased need for thinning work.

Selective thinning from below (ST) is the most common thinning method used in Europe. With ST, usually the sub-dominant, suppressed and potentially damaged trees (i.e. low-quality trees with poor growth potential) are removed. Thinning is also carried out to reduce wildfire hazards, increase a stand's resistance to pests and drought, and for nature conservation (Hood et al. 2016; Sohn et al. 2016; Grönlund 2020; Han and Han 2020). In Sweden and Finland, conventional supply systems for pulpwood remove trees with a diameter at breast height (DBH, i.e. 1.3 m above ground level) above ~8–10 cm (Di Fulvio et al. 2011; Petty and Kärhä 2014). Trees with a DBH below 8–10 cm are typically regarded as un-merchantable (low value) and are pre-cleared prior to commercial thinning (Kärhä and Bergström 2020) or left standing. However, if whole (un-delimbed) trees are harvested, biomass removal can be increased at least two-fold (Bergström and Di Fulvio 2014a), and the biomass can be used for bioenergy (Camia et al. 2020) and bio-refining (Bergström and Matisons 2014) purposes.

Accumulating felling heads (AFHs) and harvesting heads are widely used in Europe and North America to cut small-diameter trees (Johansson and Gullberg 2002; Gingras 2004; Iwarsson Wide 2010; Hiesl and Benjamin 2013; Poikonen et al. 2020). An income can be generated from early rotations (Karlsson et al. 2015), but cutting technology and harvesting method affect the cost-efficiency (Bergström 2019). Identifying best practice could increase the willingness of, for example, non-industrial private forest owners to perform first thinnings in dense small-diameter stands (Kronholm et al. 2020), especially when pre-commercial thinning (PCT) has been neglected (Guček et al. 2020).

CONTACT Dan Bergström dan.bergstrom@slu.se Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences, Umeå, Sweden

Boom-corridor thinning (BCT) is a novel working method in which trees are cut with linear movements of the harvester's boom reach, along narrow (1–2 m wide) corridors, instead of cutting each tree selectively (cf. Bergström et al. 2007; Bergström, 2009). BCT results in effective crane movements, and previous field trials in small-diameter, dense, thinning stands have shown that it can increase harvester productivity by 16%, compared with ST (Bergström et al. 2010a). Simulations of hypothetical harvester technology combined with BCT suggest productivity can be boosted by 40–200%, with the greatest effect being seen with continuous cutting and accumulation (Bergström et al. 2007; Bergström and Di Fulvio 2014a; Sängstuvall 2018).

BCT produces more heterogeneous stand structures than ST, because sections between the boom-corridors are left untreated, which in turn supports other ecosystem services and biodiversity (Ulvcrona et al. 2017; Witzell et al. 2019). However, field trials of BCT have so far been limited, and studies of varying stand conditions are needed to verify the expected increase in harvester productivity and remaining stand quality.

The effects of BCT and stand conditions on harvester productivity and thinning quality in dense small-diameter stands were therefore investigated, and compared with ST. We hypothesized that BCT would result in ~15% higher productivity without any difference in the quality of the remaining stands.

Materials and methods

Study design

Field trials were carried out between autumn 2019 and spring 2020, in Sweden, Finland, and Slovenia. The same harvester, AFH, and operator were used throughout. The harvester was transported by truck between the different sites, and at each site, the study was performed as outlined below:

1. (1) Dense, non-commercially thinned, small-diameter forest stands (hereafter blocks) were selected, and time-study units were marked out and inventoried.
2. (2) Time-and-motion studies of the thinning harvester during ST and BCT (hereafter treatments) were carried out (Figure 1).
3. (3) Cut biomass was either scaled or calculated using biomass functions.
4. (4) Remaining stand properties and thinning quality were inventoried.

Study sites and trial execution

In total, 64 study units were marked out in six blocks, and the center line of the intended strip roads was marked out for the harvester to follow (Table 1). The number of replications per treatment was balanced in each block. Study units were ~50 m long and 20 m wide (corresponding to the harvester's crane reach, of ~10 m, on each side of the strip road) (Figure 1)

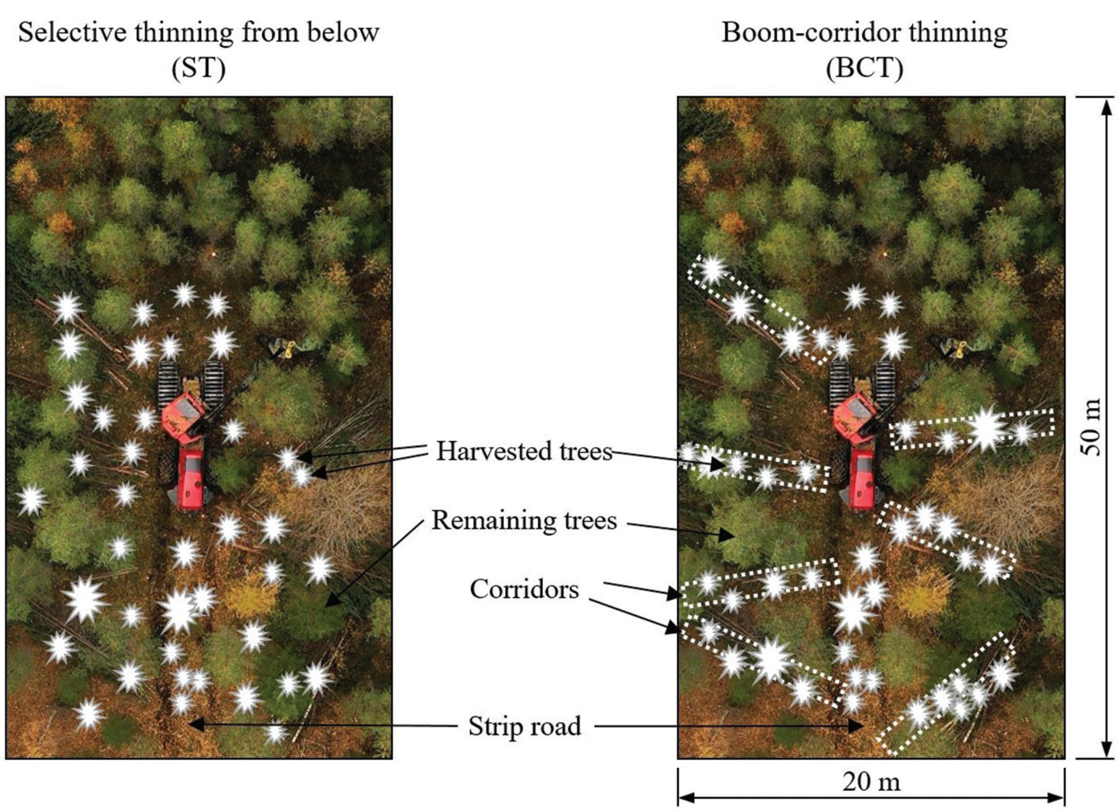

Figure 1. The rectangular time-study units and ST and BCT working methods.

Table 1. Properties of the blocks.

Block	1	2	3	4	5	6
Location	Bräcke, central Sweden	Kontiolahti, eastern Finland	Kontiolahti, eastern Finland	Mozelj, southern Slovenia	Onek, southern Slovenia	Onek, southern Slovenia
Coordinates (WSG 84)	62.809357, 15.463678	62.972617, 29.710429	62.969773, 29.712283	45.600164, 14.955126	45.629515, 14.927181	45.632019, 14.933251
Stand age (years)	26	27	26	30	20	40
Regeneration method and other remarks	Planted with pine; PCT[a]	Planted with pine; damaged by moose browsing	Naturally regenerated (overgrown farmland)	Naturally regenerated (overgrown farmland)	Naturally regenerated	Planted with spruce; PCT
Date of treatment	Oct 2019	Oct 2019	Oct 2019	Jan 2020	Feb 2020	Feb 2020
Mean terrain conditions (G.Y.L.)[a]	2.2.1.	1.1.2.	2.1.2.	2.2.1.	2.2.2.	2.2.1.

[a]Values for bearing capacity (G), ground roughness (Y), and slope (L) according to the Swedish terrain classification scheme (Berg 1992).
[b]PCT, pre-commercial thinning.

(Bergström et al. 2010a). The total time-studied area amounted to 6.2 ha (approx. 2 ha in block 1, 1.2 ha in blocks 2–3 and 3 ha in blocks 4–6). Time-study units averaged 970 m^2 (standard deviation (SD) 76 m^2). The study units' ground-bearing capacity (G), roughness (Y) and slope (L) (Table 1) were measured according to Berg (1992), and on average (pooling all units) were 2 (trafficable (almost) all year round), 2 (surface stones and boulders of variable height ~10–100 cm) and 1 (slopes between 0 and 10%) (Table 1). Blocks 4–6 were shaped by a Karst topography with sinkholes and various obstacles, resulting in a convex, stony and sloped terrain. In some of the study units, the slope was in the range of 20–33% (Table 1). No pre-clearing of the undergrowth was performed.

Pre- and post-thinning measurements

An inventory was taken in each of the study units pre- and post-thinning of various dendrometric variables (Table 2, Table 4). Two 5-m wide and 20-m long permanent transects (each 100 m^2) were laid down systematically (center distance 25 m), perpendicular to the pre-marked strip-road center-line, i.e. the transect sample area corresponded to ca. 20% of study area. In each transect, the species and DBH of all trees that had a DBH ≥1 cm were measured. In total, 4509 trees in block 1, 2199 trees in blocks 2–3 and 6661 trees in blocks 4–6 were measured. Additionally, the DBH and height of a sample of at least 30 dominant (by volume) tree species in each block were measured, to create height-diameter models (Näslund 1936) per species and block. A total of 124 trees in block 1, 160 in blocks 2–3 and 247 in blocks 4–6 were sampled. Block 1 was pine-dominated, blocks 2 and 3 were birch-dominated and blocks 4, 5, and 6 consisted of broadleaved-, beech- and spruce-dominated stands, respectively. Undergrowth trees (DBH <4 cm) were represented predominantly by Norway spruce, birch, and gray alder in blocks 1, 2 and 3, and a mix of broadleaves (mostly hazel and beech) in blocks 4, 5 and 6. For calculation of stem- and branch volumes for the different blocks we used a wide set of functions considering local conditions and tree morphology (see footnotes in Table 2).

Before extraction of the cut biomass, damage was registered for standing trees with a DBH >7 cm, adjacent to the strip road and 1 m into the stands from the strip-road borders. The length and width of the strip road was measured according to Björheden and Fröding (1986). The stump height of cut trees (with a stump diameter >1 cm) was measured along the inventory transects.

Post-thinning orthophotos were generated from aerial photos captured by an unmanned aerial vehicle (UAV) (DJI Mavic 2 Pro (SZ DJI Technology Co., China)), and processed in Agisoft Metashape Pro (Agisoft 2020). The orthophotos were analyzed visually, to provide a count of the number of piles of tree bunches along the strip roads and determine any differences in biomass concentration (no. of piles and dry metric tonnes (t) per 100 m strip road).

Measurement of harvested biomass

The felled trees were extracted with forwarders and scaled on a study-unit basis. In block 1, a Komatsu 855.1 forwarder (Komatsu Forest AB, Sweden) was used and the biomass was subsequently, within 2 days, transported by a loose residue truck to a terminal and scaled on a weighbridge. In blocks 2–3, a Komatsu 845 forwarder with an integrated crane scale was used. In block 4, a Gremo 950 R forwarder (Gremo AB, Sweden) and the portable axle load scale system Dini Argeo WWSC15T-2 (Dini Argeo S.r.l., Italy) were used. Fieldwork constraints because of the COVID-19 outbreak precluded blocks 5 and 6 from being scaled, and instead the amount of harvested biomass was estimated by using the pre-thinning and post-thinning inventory data and tree biomass functions presented by Gschwantner et al. (2019).

Table 2. Mean values (and SD) of the stand properties before thinning per treatment and block. Significant differences between treatments per block is indicated on three levels: * = p <0.05; ** = p <0.01; *** = p <0.001.

Block	Treatment	No. study units	Species[a]	DBH[b] (cm)		Height (m)		Whole-tree volume[c] (dm^c)	Stand density (trees ha^{-a})		Total biomass volume[d]	Basal area
			(%)	Arithmetic	BAW[e]	Arithmetic	BAW[e]	Arithmetic	DBH[b] ≥1 cm	DBH[b] ≥4 cm	(m^c ha^{-a})	(m^b ha^{-a})
1	ST	10	b:o:p:s 19:20:49:12	4.3 (0.7)	11.4 (0.9)	5.8 (0.6)	10.3 (0.5)	22 (7)	10,590 (4 013)	3 360 (858)	212 (47)	27 (6)
	BCT	10	b:o:p:s 21:19:40:20	4.2 (0.6)	11.5 (1.2)	5.7 (0.5)	10.3 (0.6)	21 (7)	11,890 (3 914)	3 715 (1 213)	228 (57)	29 (7)
2	ST	3	b:o:p:s 43:4:1:52	4.3 (0.9)	8.1 (2.1)	5.4 (1.3)	8.8 (2.6)	15 (6)	6 817 (2 230)	3 383 (751)	94 (21)	13 (3)
	BCT	3	b:o:p:s 60:10:0:30	4.8 (0.7)	8.8 (2.4)	6.1 (0.5)	9.6 (0.8)	19 (8)	8 717 (3 506)	4 783 (1 156)	152 (55)	22 (6)
3	ST	3	b:o:s 84:3:13	4.6 (0.2)	8.5 (0.4)	6.5 (0.5)	10.7 (0.2)	17 (1)	10,417 (1 361)	5 567 (751)	173 (13)	25 (2)
	BCT	3	b:o:s 80:2:18	4.4 (0.2)	8.1 (0.6)	6.4 (0.2)	10.3 (0.4)	15 (2)	10,700 (1 083)	5 750 (229)	162 (12)	23 (1)
4	ST	9	a:b:c:f:h:o:t 8:20:34:4:6:3:25	5.6** (0.5)	11.4 (0.9)	8.0* (0.5)	11.7 (0.5)	24* (4)	10,350 (2 165)	5 544 (971)	241 (45)	38 (7)
	BCT	9	a:b:c:f:h:o:t 5:19:48:2:10:3:13	4.9** (0.4)	10.9 (1.5)	7.5* (0.3)	11.2 (0.7)	19* (4)	11,817 (2 283)	5 906 (1 345)	221 (49)	35 (7)
5	ST	5	c:f:h:t 1:98:1:0	3.3 (0.2)	9.7 (2.6)	5.8 (0.2)	9.9 (0.9)	10 (3)	11,920 (2 772)	2 910 (765)	109 (14)	17 (2)
	BCT	5	c:f:h:t 2:97:0:1	4.0 (1.0)	7.9 (1.2)	6.6 (1.0)	9.7 (0.7)	11 (4)	11,210 (2 841)	3 950 (941)	111 (21)	20 (5)
6	ST	2	c:f:s 6:2:92	9.4 (0.3)	14.3 (0.4)	10.2 (0.1)	13.7 (0.1)	64 (6)	3 925 (106)	2 900 (71)	252 (16)	37 (0)
	BCT	2	c:f:s 13:11:76	8.1 (2.2)	15.3 (2.3)	9.1 (1.4)	14.1 (1.2)	63 (35)	5 025 (3 359)	2 775 (1 167)	258 (37)	35 (10)

[a]The proportion (%) of trees with a DBH ≥4 cm: a = sycamore (*Acer pseudoplatanus*); b = birch (*Betula* spp.); c = hazel (*Corylus avellana*); f = beech (*Fagus sylvatica*); h = hornbeam (*Ostrya carpinifolia*), o = other broadleaves (in blocks 1–3: gray alder, *Alnus incana*, rowan, *Sorbus aucuparia* and willow, *Salix* spp.; in blocks 4–6: ash, *Fraxinus excelsior*, and elm, *Ulmus glabra*); p = pine (*Pinus sylvestris*); s = spruce (*Picea abies*); t = linden (*Tilia cordata*).
[b]DBH = diameter at breast height, i.e. 1.3 m above ground level.
[c]All measured trees (DBH ≥1 cm). Stem volume on bark and above the stump (including the top), dead and living branches (including needles). In block 1, the stem volume of trees with DBH ≤5 cm was calculated according to Andersson (1954), while Näslund (1947) was used for trees with DBH >5 cm. In blocks 2–3, stem volume was calculated according to Laasasenaho (1982). In blocks 1–3, branch volume was calculated according to Marklund (1988) with basic density values from Nylinder and Kockum (2016) for conversion to solid volumes. In blocks 4–6, stem and branch volume calculations followed Gschwantner et al. (2019).
[d]Total above-ground biomass (whole-tree) volume.
[e]BAW = basal area weighted.

To estimate the dry weight of the cut biomass, 5–10 discs with a thickness of ~2 cm were sampled per block, from the butt, middle, and top of randomly chosen tree bunches containing the dominant tree species in the block, using a handsaw in blocks 1–3 and a chainsaw in block 4. The moisture content (wet-basis) of the samples was determined following CEN (2009) (24 h), and averaged 51% (SD 6), 49% (SD 0), and 34% (SD 3) in blocks 1, 2–3, and 4, respectively. In blocks 1–4, the samples were taken during extraction work.

Harvester, AFH, and machine operator

The base machine was a 2008 six-wheeled Valmet 901.4 harvester (Komatsu Forest AB, Sweden), with an engine power of 150 kW, a width of 2.8 m and a weight of ~15 t. It was fitted with chains and tracks, adding ~2 t to the weight, and equipped with a parallel crane, with a reach of ~10 m (Cranab AB, Sweden) that rotated with the cabin and featured an upgraded Bracke C16.c (Bracke Forest AB, Sweden) AFH (Figure 2). The AFH had four-jawed gathering arms, four-jawed accumulating arms, and a self-tensioning ¾″ cutting chain mounted on a circular disc, with a maximum cutting capacity of 26 cm in diameter. Unique for this study, the AFH was upgraded with a "horn-shaped" support plate (an additional weight of ~32 kg), placed between the AFH and the rotator at a distance of ~36 cm from the uppermost accumulating arm. The function of this prototype support plate was to stabilize the handling of accumulated tall trees during the movement of the loaded head. Including the support, the total weight of the AFH was ~657 kg.

Figure 2. The upgraded Bracke C16.c felling and bunching head with the "horn-shaped" prototype support plate.

The machine operator had more than five years' professional experience of ST, using a similar base machine equipped with an earlier version of the C16 head (without the prototype plate support) and operating within Swedish small-diameter, dense, thinning stands. After two hours of intensive instruction, the operator could perform BCT, and prior to the trials in block 1 practiced for a day under supervision in a nearby stand. Prior to the trials in blocks 2–3 the operator practiced for a few hours, and before working in blocks 4–6 practiced for ~1.5 working days.

Thinning treatments

The initial treatment was randomly assigned for each block, and subsequent treatments executed alternately. During BCT, the operator decided where to lay out the boom-corridors based on the stand structure, i.e. the boom-corridor width, length, and angle from each machine position varied. In all blocks, both thinning treatments were performed as quality thinning from below, to promote future production of high-quality timber. Because of the varied conditions, the operator was told the target density of the remaining trees and species according to national forest management guidelines or long-term forest management plans. In block 1, the target was 1200–1500 trees ha^{-1}, favoring pine (Bergström et al. 2010a). In blocks 2 and 3, the target was 800 trees ha^{-1} (Äijälä et al. 2014), targeting a balanced mix of birch and spruce in block 2, and favoring spruce in block 3. In block 4, the target was 1200–1500 trees ha^{-1}, maintaining the diversity of tree species without favoring any specific species. In block 5, the target was 1200–1500 trees ha^{-1}, favoring beech. In block 6, the target was 1200–1500 trees ha^{-1}, favoring spruce.

Both treatments yielded un-delimbed trees, either harvested at full length or bucked in sections (i.e., tree parts). The target length of the sections was ~6 m (the standard the operator was used to), which is a suitable length for effective forwarding work. During thinning work, the operator bucked trees taller than 6 m in two different ways. (1) One, or several, tree tops were cut off from standing trees, and bunched on the ground or accumulated during a subsequent cutting of the remaining butt parts. The top-cut on the standing tree was done at a height of ~4–5 m. (2) Alternatively, the full tree bunches were bucked on the ground. Tree bunches were piled on both sides along the strip road, with their butt-ends pointing toward the strip road.

Time-and-motion study

Time-and-motion studies of the harvester work were conducted during the leaf-drop/leaf-off period and daylight conditions. During the trials, the ground was snowless in

Figure 3. Viewing angle of the two mounted action cameras inside the harvester's cabin.

blocks 1, 4 and 5, and covered with a ~5-cm snow layer in blocks 2 and 3. Timing began when the harvester reached the starting point of the pre-marked strip road and ended when it reached the end-point.

Two action cameras (Sony X1000VR, Sony FDR-X3000R) were mounted inside the cabin with different viewing angles, and the thinning work in all study units was filmed (Figure 3). In blocks 1, 4, 5 and 6, the machine work time was also recorded by a frequency–time study (Magagnotti et al. 2012), using an Allegro Field PC® equipped with SDI software (developed by Skogforsk) and a Trimble Nomad 900 equipped with UMT Plus software (developed by Laubrass Inc.). Productive machine work time (PM) was defined as machine work time excluding delays. The active work element (Table 3) was recorded every 7 seconds by an observer sitting inside the cabin in a space behind the operator. The recorded videos from blocks 2 and 3 were used to conduct a continuous-time study (Magagnotti et al. 2012), using the open-source software Subtitle Edit (Olsson 2020) and Microsoft® Excel® for data processing. In all blocks, the videos were used to observe the number of crane cycles and piles of bunches produced, and the frequency of "top bucking." The harvester computer provided the number of accumulations by the AFH per study unit.

Statistical analyses

Statistical analyses were performed using R 4.0 (R Core Team 2020) and Minitab®18. Results were significant at a p-value <0.05. Initially, a matrix of scatterplots was created and a correlation analysis performed to identify relationships amongst the measured variables. A one-way analysis of variance (ANOVA) was used to test any differences in block properties and work elements between treatments. The covariates affecting time consumption of "top bucking" (Table 3) and the number of felled trees per crane cycle were investigated by standard stepwise regression, and modeled with linear and non-linear functions, respectively.

A linear mixed-effect (LME) regression model was used to model the harvester's productivity (dry t PMh^{-1}). The covariates included in the LME models were investigated by

Table 3. Work element definitions in the harvester work cycle.

Work element	Definition of work element	Priority[a]
Boom out	Boom out for felling or top bucking. Started when the empty boom moved out and ended when the boom slowed down for positioning the AFH on a tree.	1
Felling in the strip road	Felling of a tree in the strip road. Started when the boom slowed down for positioning the AFH on a tree and ended when the last tree in the crane cycle was cut and separated from the stump.	1
Felling in the stand	Felling of a tree in the stand (between strip roads). Started when the boom slowed down for positioning the AFH on a tree and ended when the last tree in the crane cycle was cut and separated from the stump.	1
Top bucking	Bucking of the standing tree at a height of ~4–5 m, in the stand or strip road. Started when the boom slowed down for positioning the AFH on a tree and ended when the last top bucking was done.	1
Boom in and bunching	Started when the AFH cut and separated the last tree in the crane cycle from the stump, and the boom was pulled against the machine, and ended when the AFH released the bunch.	1
Bucking of bunch	Started when the bunch was released on the ground and ended when the bucked part was put on the first part of the bunch.	1
Moving	Started when the harvester wheels turned and ended when the harvester wheels stopped.	2
Miscellaneous	Other activities such as trees being dropped and then picked up again, cutting roots of uprooted trees, etc.	1
Delays	Time not related to effective work, such as mechanical breakdowns, personal breaks, etc.	3

[a]If work elements were performed simultaneously, the element with the highest priority (lowest number) was recorded.

standard stepwise regression, to find the subset of significant covariates (i.e., continuous variables such as DBH, etc.). The LME models contained treatment as a fixed-effect factor (i = 1–2), block as a random-effect factor j (j = 1–6), and covariates. The LME models were fitted with restricted maximum likelihood, and plots of residuals were inspected for normality and homogeneity. The LME regression models of harvester productivity were formulated as described in Equation. 1:

$$y_{ijk} = \mu + \alpha_i + b_j + \beta_1 x_{ijk} + \in_{ijk} \quad (1)$$

where y_{ijk} is the response variable (dry t PMh^{-1}) of study unit k (k = 1, . . .,64); μ is the overall mean; α_i is the fixed effect of treatment i; b_j is the random effect of block j; β_1 is the slope for the covariate x_{ijk}; x_{ijk} is a covariate for treatment i, block j and study unit k; and $\in_{ijk}$ is the residual error of y_{ijk}.

The removal of biomass (dry t ha^{-1}) was modeled similarly, as described in Equation. 2:

$$y_{ijk} = \mu + \alpha_i + b_j + \beta_1 x_{ijk} + \beta_2 z_{ijk} + _{ijk} \quad (2)$$

where y_{ijk} is the response variable (dry t ha^{-1}) of study unit k (k = 1, . . .,64); μ is the overall mean; α_i is the fixed effect of treatment i; b_j is the random effect of block j; β_1 is the slope for the covariate x_{ijk}; x_{ijk} is a covariate for treatment i, block j and study unit k; β_2 is the slope for the covariate z_{ijk}; z_{ijk} is a covariate for treatment i, block j and study unit k; and $\in_{ijk}$ is the residual error of y_{ijk}.

Results

Thinning quality and production properties

On average, both thinning treatments increased the mean values of DBH, tree height, and tree volume for all blocks and decreased the stand density and basal area of the remaining stands (Tables 2 and 4). The thinning ratio, i.e. the quota of DBH of the harvested and remaining trees (Lageson 1997), ranged between 0.6 and 0.8 and averaged 0.7, while removal of the basal area ranged between 32 and 70% and averaged 56%. There were no significant differences between treatments for these properties.

The remaining stand density was on average 23% higher with BCT, but only significant in block 5. On average biomass removal was 9.7% lower for the BCT treatment, but the difference was only significant in block 3 (Tables 4 and 5). On average, there were no significant differences between treatments in the intensity of tree removal (Figures 4 and 5). For all blocks, the strip-road width averaged 4.8 m and the strip-road share of the total harvested area averaged 23.5% (Table 6). The stump height was on average 8% higher for BCT, but not significant.

For all blocks, the proportion of damaged trees along the strip roads averaged 37%, and was significantly lower for BCT. In blocks 1–3 most of the damage was "squeezed bark" on stems at heights above 1 m, while in blocks 4–6

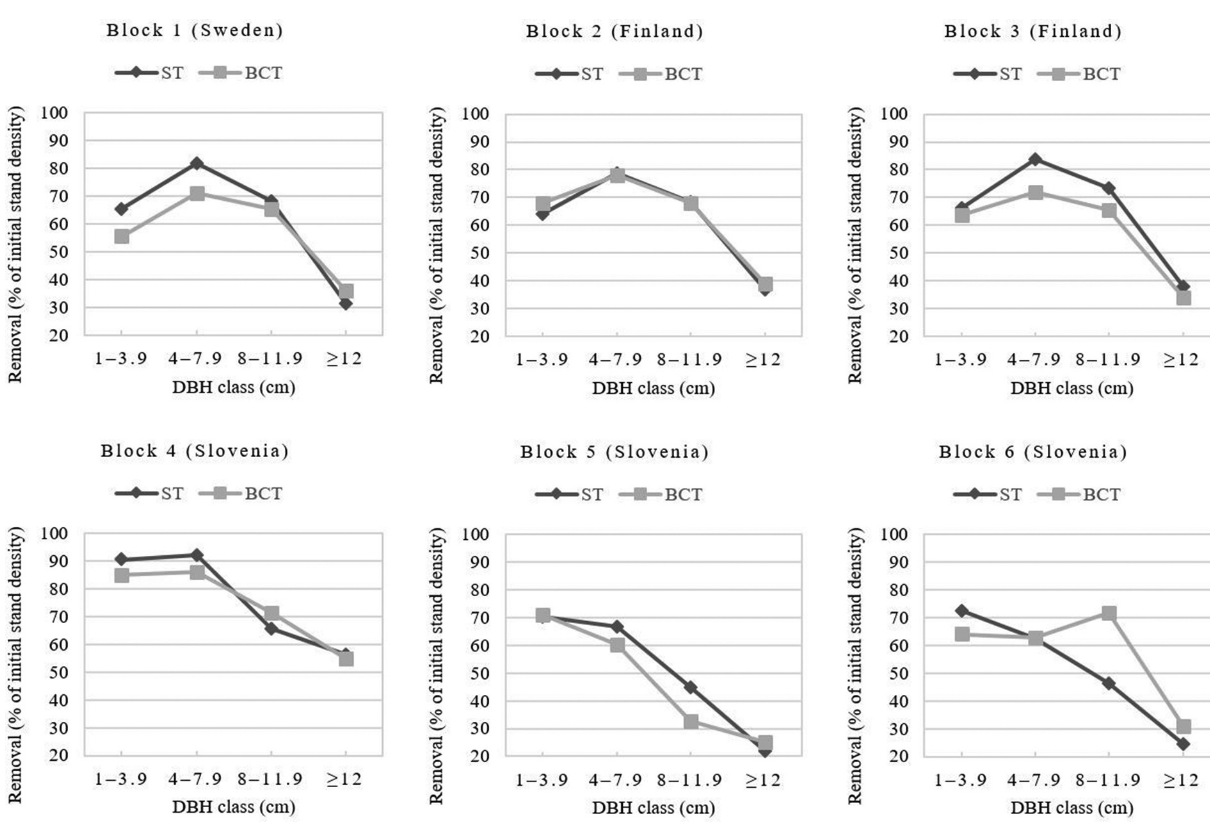

Figure 4. Average proportion (%) of initial stand density (trees ha^{-1}) removed, per block and treatment.

Table 4. Mean values (and SD) of thinning quality, stand properties, and harvested biomass per block and treatment. Significant differences between treatments per block is indicated on three levels: * = p <0.05; ** = p <0.01; *** = p <0.001.

Block	Treatment	n	Properties of harvested trees							Properties of remaining stands						
			Bio mass[a]	Removal density (trees ha^{-a})	DBH[b] (cm)		Whole-tree volume[d] (dm^c)	Pro-portion of basal area removed	Thinn-ing ratio[e]	Species[f]	DBH[b] (cm)		Height (m)	Whole-tree volume[c] (dm^c)	Stand density (trees ha^{-a})	Basal area
			(dry t ha^{-a})	DBH[b] ≥4 cm	Arith metic	BAW[c]	Arith-metic	(%)		(%)	Arith-metic	BAW[c]	BAW[c]	Arith-metic	DBH[b] ≥4 cm	(m^b ha^{-a})
1	ST	10	48.4 (13.8)	2 240 (848)	3.9 (0.6)	9.4 (0.8)	15 (4)	49 (14)	0.71	b:o:p:s 13:17:61:9	5.1 (1.0)	13.3 (1.0)	11.2 (0.4)	34 (10)	1 120 (354)	14 (4)
	BCT	10	40.7 (14.2)	2 400 (1057)	4.1 (0.7)	10.0 (1.4)	16 (5)	48 (12)	0.75	b:o:p:s 16:14:50:20	4.4 (0.7)	13.3 (1.2)	11.0 (0.5)	27 (8)	1 315 (266)	15 (4)
2	ST	3	30.7 (16.3)	2 550 (278)	4.4 (0.7)	7.2 (2.2)	14 (6)	69 (14)	0.82	b:o:p:s 26:0:2:72	4.3 (1.4)	8.7 (1.8)	9.0 (2.2)	17 (10)	833 (475)	4 (1)
	BCT	3	33.5 (15.8)	3 600 (1457)	4.7 (0.7)	7.4 (1.1)	15 (5)	64 (15)	0.72	b:o:p:s 42:4:0:54	5.2 (0.8)	10.7 (3.4)	9.9 (0.9)	27 (13)	1 183 (333)	8 (4)
3	ST	3	43.6*** (1.1)	4 317 (355)	4.7 (0.4)	7.7 (0.9)	16 (3)	69 (9)	0.75	b:o:s 69:0:31	5.0 (1.7)	10.3 (1.1)	11.7 (1.2)	26 (15)	1 250 (695)	8 (2)
	BCT	3	34.7*** (0.2)	3 917 (333)	4.4 (0.2)	7.2 (0.4)	14 (2)	61 (4)	0.81	b:o:s 70:4:26	4.6 (0.4)	8.9 (0.8)	10.8 (0.8)	19 (4)	1 833 (236)	9 (1)
4	ST	9	67.3 (19.9)	4 444 (695)	5.1*(0.5)	10.0 (1.0)	19* (4)	70 (6)	0.75*	a:b:c:f:h:o:t 8:14:15:4:9:1:49	8.6**(1.5)	13.3 (1.0)	12.8 (0.5)	52 (15)	1 100 (371)	12 (3)
	BCT	9	60.4 (13.6)	4 628 (988)	4.6*(0.3)	9.3 (1.0)	15* (3)	67 (11)	0.66*	a:b:c:f:h:o:t 10:21:32:3:11:2:21	6.6**(0.9)	14.4 (3.2)	12.8 (1.0)	43 (15)	1 278 (789)	12 (5)
5	ST	5	29.2 (6.3)	1 690 (399)	3.0 (0.2)	6.7 (1.6)	7 (2)	47 (6)	0.57	c:f:h 0:100:0	4.1 (0.4)	12.1 (3.3)	10.9 (0.7)	16 (4)	1 220* (476)	9 (1)
	BCT	5	30.3 (10.1)	2 100 (659)	3.6 (1.0)	6.5 (1.4)	8 (4)	46 (9)	0.73	c:f:h 2:98:0	5.1 (1.3)	9.0 (1.4)	10.4 (0.7)	16 (6)	1 850* (322)	11 (3)
6	ST	2	30.5 (6.8)	1 100 (141)	7.2 (0.3)	12.6 (0.0)	40 (2)	32 (7)	0.85	c:f:s 0:3:97	11.3 (0.3)	14.8 (0.9)	14.1 (0.4)	85 (6)	1 800 (212)	25 (3)
	BCT	2	33.3 (17.1)	1 475 (742)	6.9 (2.0)	12.9 (1.4)	30 (11)	36 (10)	0.75	c:f:s 0:13:87	10.2 (2.3)	17.3 (2.8)	15.4 (1.4)	103 (52)	1 300 (424)	22 (3)

[a]In blocks 1–4, scaled; in blocks 5–6, biomass functions (Gschwantner et al. (2019).
[b]DBH = diameter at breast height, i.e. 1.3 m above ground level.
[c]BAW = basal area weighted.
[d]Including all trees with DBH ≥1 cm and all tree parts above ground. In block 1 (Sweden), the stem volume of trees with DBH ≤5 cm was calculated according to Andersson (1954), while Näslund (1947) was used for trees with DBH >5 cm. In blocks 2–3, stem volume was calculated according to Laasasenaho (1982). In blocks 1–3, branch volume was calculated according to Marklund (1988), with basic density values from Nylinder and Kockum (2016) for conversion to solid volumes. In blocks 4–6, stem and branch volume calculations followed Gschwantner et al. (2019).
[e] Mean DBH_{BAW} of felled trees divided by the mean DBH_{BAW} of remaining trees.
[f]Proportion (%) of trees with a DBH ≥4 cm: a = sycamore (*Acer pseudoplatanus*); b = birch (*Betula* spp.); c = hazel (*Corylus avellana*); f = beech (*Fagus sylvatica*); h = hornbeam (*Ostrya carpinifolia*); o = other broadleaves (in Sweden and Finland: gray alder, *Alnus incana*, rowan, *Sorbus aucuparia* and willow, *Salix* spp.; in Slovenia: ash, *Fraxinus excelsior*, and elm, *Ulmus glabra*); p = pine (*Pinus sylvestris*); s = spruce (*Picea abies*); t = linden (*Tilia cordata*).

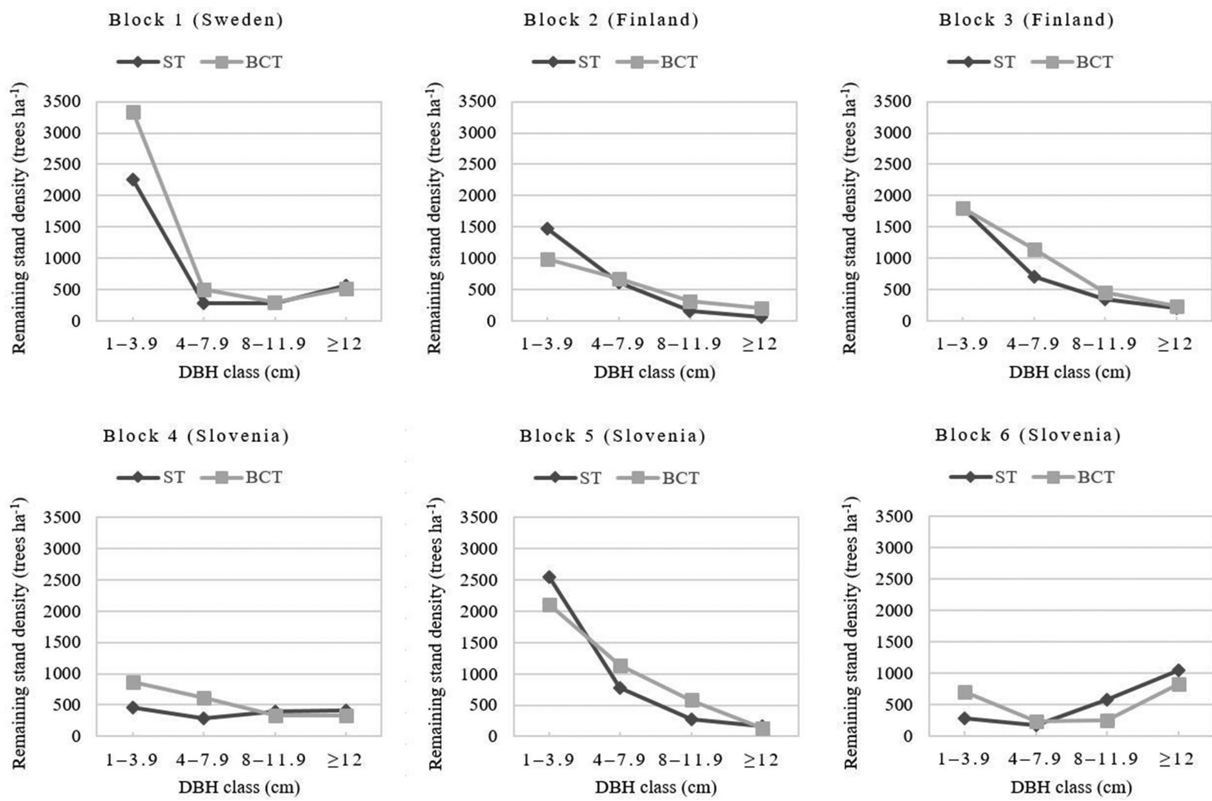

Figure 5. Remaining stand density (trees ha^{-1}), per block and treatment.

Table 5. Mean values (and SD) of harvested and piled biomass per block and treatment and pooled for all blocks. Significant differences between treatments per block is indicated on three levels: * = p <0.05; ** = p <0.01; *** = p <0.001.

Block	Treatment	n	Dry mass $pile^{-1}$ (kg)	Biomass concentration per 100 m of strip road	
				Number of piles	Mass (dry t)
1	ST	10	205 (58)	47 (5)	9.7 (2.8)
	BCT	10	158 (51)	52 (8)	8.1 (2.8)
2	ST	3	147 (98)	44 (5)	6.1 (3.3)
	BCT	3	126 (45)	52 (6)	6.7 (3.2)
3	ST	3	170*** (8)	51*** (1)	8.7*** (0.2)
	BCT	3	107*** (2)	65*** (1)	6.9*** (0.0)
4	ST	9	349 (67)	38 (5)	13.5 (4.0)
	BCT	9	325 (58)	37 (6)	12.1 (2.7)
5	ST	5	109 (18)	54 (7)	5.8 (1.3)
	BCT	5	115 (32)	52 (4)	6.1 (2.0)
6	ST	2	152 (63)	42 (9)	6.1 (1.4)
	BCT	2	147 (50)	44 (9)	6.7 (3.4)
1–6 (pooled)	ST	32	219 (104)	45 (7)	9.5 (4.0)
	BCT	32	190 (98)	49 (10)	8.6 (3.4)

Table 6. Mean values (and SD) of thinning quality per block and treatment and pooled for all blocks. Significant differences between treatments per block is indicated on three levels: * = p <0.05; ** = p <0.01; *** = p <0.001.

Block	Treatment	n	Strip road width (m)	Stump height (cm)	Damaged trees along the strip road (trees per 100 m)
1	ST	10	4.9 (0.6)	36 (4)	5.1 (2.2)
	BCT	10	4.6 (0.3)	39 (4)	4.4 (4.0)
2	ST	3	4.6 (0.2)	22 (2)	2.0 (3.5)
	BCT	3	4.5 (0.4)	22 (3)	2.7 (2.3)
3	ST	3	4.6 (0.5)	22 (4)	6.7 (6.4)
	BCT	3	4.7 (0.5)	22 (2)	2.0 (3.5)
4	ST	9	4.8 (0.9)	25 (6)	13.2** (4.8)[a]
	BCT	9	4.8 (0.3)	30 (6)	5.9** (4.4)[a]
5	ST	5	5.5 (0.4)	28 (3)	6.8* (1.1)[a]
	BCT	5	5.2 (0.7)	27 (3)	10.0* (0.0)[a]
6	ST	2	4.0 (0.4)	18 (5)	no value[a]
	BCT	2	3.7 (0.0)	23 (2)	no value[a]
1–6 (pooled)	ST	32	4.9 (0.7)	28 (7)	7.8* (5.5)
	BCT	32	4.7 (0.5)	30 (8)	4.9* (5.2)

[a]Sampling was incomplete due to operational constraints: two missing study units in block 4; six study units in block 5; four study units in block 6.

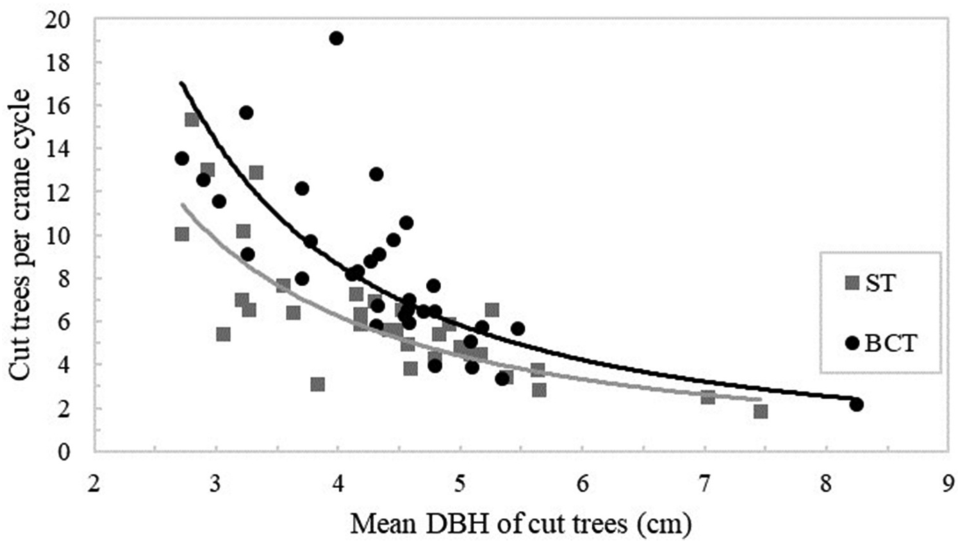

Figure 6. The number of cut trees (DBH ≥1 cm) per crane cycle as a function of arithmetic mean DBH (cm) of cut trees. ST = selective thinning (n = 32), BCT = boom-corridor thinning (n = 32). y (ST) = 53.801 × $DBH^{-1.553}$ R2(adj) = 0.676; p <0.0001; y (BCT) = 98.778 × $DBH^{-1.758}$ R2(adj) = 0.637; p <0.0001.

Table 7. Mean work time consumption (sec $tree^{-1}$, with DBH ≥4 cm) and proportion (%) of PM time devoted to each work element. Significant differences between treatments are indicated on three levels: * = p <0.05; ** = p <0.01; *** = p <0.001.

Work element	Treatment				
	ST (n = 32) (sec $tree^{-1}$)	(%)	BCT (n = 32) (sec $tree^{-1}$)	(%)	Diff. (%)
Boom out	2.71**	18.8	1.85**	17.8	−32
Felling in the strip road	2.03	14.1	1.78	17.0	−12
Felling in the stand	4.23**	29.4	2.98**	28.6	−30
Top bucking	1.04*	7.3	0.69*	6.6	−34
Boom in and bunching	2.94**	20.5	2.07**	19.9	−30
Bucking of bunch	0.43	3.0	0.34	3.2	−21
Moving	0.72	5.0	0.55	5.3	−29
Miscellaneous	0.28	1.9	0.17	1.6	−39
Total	14.38**	100	10.42**	100	−28

Table 8. Harvester productivity (dry t PMh^{-1}) and time consumption (PMh ha^{-1}), per treatment and block. Significant differences between treatments per block are indicated on three levels: * = p <0.05; ** = p <0.01; *** = p <0.001.

Block	Treatment	n	Productivity (dry t PMh^{-1})				Time consumption (PMh ha^{-1})			
			mean	SD	min	max	mean	SD	min	max
1	ST	10	5.4	0.9	4.4	6.7	9.0*	1.8	6.8	11.8
	BCT	10	6.2	1.9	3.2	8.9	6.8*	1.8	4.3	10.1
2	ST	3	4.7	1.4	3.0	5.5	6.5	2.3	4.4	9.0
	BCT	3	5.5	0.3	5.2	5.7	6.0	2.6	4.1	9.0
3	ST	3	3.6	0.3	3.3	3.9	12.2*	0.8	11.4	13.0
	BCT	3	3.5	0.1	3.4	3.6	9.9*	0.4	9.6	10.4
4	ST	9	5.2	1.4	3.9	7.9	13.0***	1.5	10.6	15.0
	BCT	9	6.1	1.4	3.6	7.8	10.0***	1.3	7.5	11.6
5	ST	5	3.3	0.6	2.4	3.8	8.9	0.9	7.8	10.1
	BCT	5	3.8	1.2	2.4	5.5	8.2	2.3	5.5	11.5
6	ST	2	4.5	1.4	3.5	5.5	6.9	0.7	6.4	7.3
	BCT	2	5.6	1.0	4.9	6.3	5.8	2.0	4.4	7.2
1–6 (pooled)	ST	32	4.7	1.3	2.4	7.9	10.0**	2.7	4.4	15.0
	BCT	32	5.4	1.7	2.4	8.9	8.1**	2.3	4.1	11.6

it mainly consisted of "scratched bark" at corresponding heights, but there were no significant differences between treatments.

Harvester work

In total, the harvester was studied for 56.43 h, of which 0.36 h (0.6%) was delay time. The delay time consisted mainly of service work, e.g. replacement of damaged cutting chain and hydraulic hoses in the AFH. PM time (excluding delay time) totaled 56.07 h, of which 26%, 18%, and 56% was spent in block 1, blocks 2–3 and blocks 4–6, respectively. Of the total PM time, 45% was devoted to BCT.

The total time consumption per tree was on average 28% less, and significant, for BCT (Table 7). BCT took on average 12–34% less consumption time for all work elements, which was significant for four out of eight work elements. The number of cut trees (DBH ≥1 cm) per crane cycle was on average 33% higher for BCT, and correlated with the arithmetic mean DBH (Figure 6). The frequency of "top bucking" was significantly correlated with the average height of cut trees, but did not differ between treatments (Figure 7). On average, BCT yielded 16% higher, and close to significant ($p = 0.054$), harvester productivity (Table 8).

Harvester work productivity- and biomass removal models

The LME regression analyses yielded four models of harvester work productivity (Table 9) and three models of biomass removal (Table 10). Models were ranked from highest to lowest on the basis of the adjusted coefficient of determination (R^2(adj)). A global intercept (β_0) was calculated, as the sum of the overall mean (μ), the fixed effect of treatment (α_i) and the random effect of a block (b_j), and reported for each combination of treatment and block.

Discussion

This study is the first of its kind. Empirical data on the effects of BCT on harvester time consumption, productivity, and thinning quality was collected across a variety of stand

Table 9. Univariate linear regression models of harvester productivity (dry t PMh^{-1}), $y = \beta_0 + \beta_1 x$, where β_0 is a global intercept and β_1 is the slope for the covariate x. BAW = basal area weighted.

Model	R^2(adj)	Term	*p*-value	Coefficient			
				β_0			β_1
				Block	Treatment		
					ST	BCT	
1	0.676	Treatment	<0.0001				
		Block	0.090	1	2.5	3.5	
				2	2.5	3.5	
				3	0.9	1.9	
				4	1.3	2.3	
				5	1.3	2.3	
				6	2.4	3.4	
				1–6	1.8	2.8	
		Covariate: x = biomass removal (dry t ha^{-1})	<0.0001				0.0608
2	0.457	Treatment	0.007				
		Block	0.117	1	2.1	2.9	
				2	2.1	2.9	
				3	1.0	1.9	
				4	2.1	2.9	
				5	0.8	1.7	
				6	0.9	1.7	
				1–6	1.5	2.3	
		Covariate: x = pre-thinning mean DBH_{BAW} (cm)	0.006				0.2782
3	0.454	Treatment	0.012				
		Block	0.130	1	2.1	2.8	
				2	2.0	2.8	
				3	0.9	1.7	
				4	2.0	2.7	
				5	1.1	1.8	
				6	0.9	1.6	
				1–6	1.5	2.3	
		Covariate: x = removed mean DBH_{BAW} (cm)	0.006				0.3336
4	0.452	Treatment	0.010				
		Block	0.098	1	1.2	1.9	
				2	0.8	1.6	
				3	−0.9	−0.1	
				4	0.6	1.4	
				5	−0.7	0.1	
				6	−0.7	0.1	
				1–6	0.1	0.8	
		Covariate: x = pre-thinning mean $height_{BAW}$ (m)	0.030				0.4028

Table 10. Multiple linear regression models of biomass removal (dry t ha^{-1}), $y = \beta_0 + \beta_1 x + \beta_2 z$, where β_0 is a global intercept, β_1 is the slope for the covariate *x*, and β_2 is the slope for the covariate *z*. BAW = basal area-weighted.

Model	R^2(adj)	Term	*p*-value	Coefficient				
				β_0			β_1	β_2
				Block	Treatment			
					ST	BCT		
1	0.583	Treatment	0.070					
		Block	0.099	1	−47.0	−52.8		
				2	−45.4	−51.2		
				3	−51.9	−57.7		
				4	−35.7	−41.5		
				5	−58.2	−64.0		
				6	−66.1	−71.8		
				1–6	−56.5	−50.7		
		Covariate: *x* = pre-thinning mean height$_{BAW}$ (m)	0.004				6.8985	
		Covariate: *z* = pre-thinning mean stand density (trees DBH ≥1 cm ha^{-1})	0.002					0.0021
2	0.575	Treatment	0.038					
		Block	0.139	1	−11.5	−18.2		
				2	−16.5	−23.3		
				3	−18.0	−24.8		
				4	−5.5	−12.3		
				5	−16.3	−23.1		
				6	−24.3	−31.1		
				1–6	−15.3	−22.1		
		Covariate: *x* = pre-thinning mean DBH$_{BAW}$ (cm)	0.006				3.2414	
		Covariate: *z* = pre-thinning mean stand density (trees DBH ≥4 cm/ha)	0.001					0.0062
3	0.564	Treatment	0.060					
		Block	0.160	1	−2.2	−8.2		
				2	−9.0	−15.1		
				3	−9.4	−15.4		
				4	1.5	−4.6		
				5	−3.7	−9.7		
				6	−11.9	−18.0		
				1–6	−5.8	−11.8		
		Covariate: *x* = removed mean DBH$_{BAW}$(cm)	0.010				3.4191	
		Covariate: *z* = removed mean stand density (trees DBH ≥4 cm/ha)	0.001					0.0069

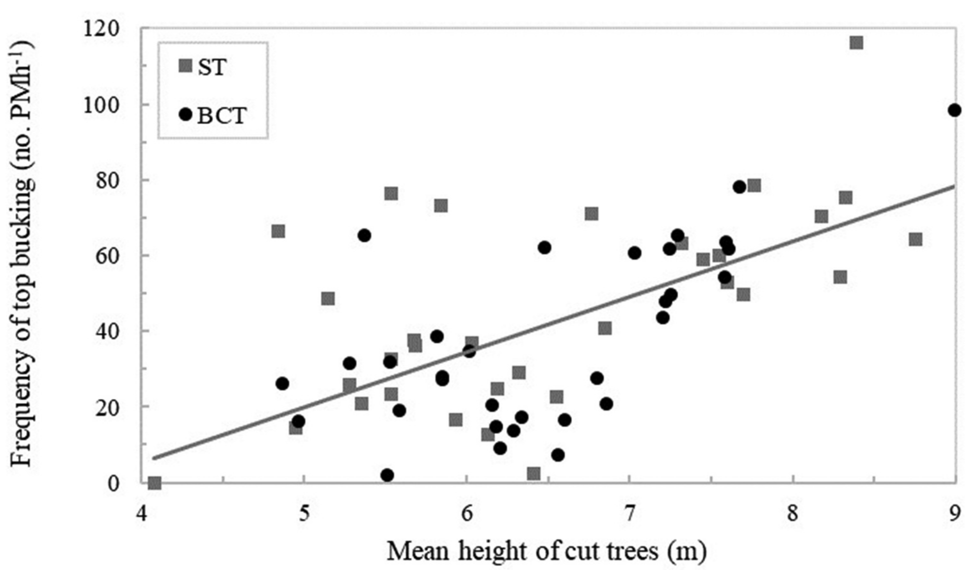

Figure 7. Frequency of "top bucking" (no. PMh^{-1}) as a function of the arithmetic mean height (m) of cut trees. ST = selective thinning (n = 32), BCT = boom-corridor thinning (n = 32). y = – 53.056 + 14.594 × height R2 (adj) = 0.384; p <0.0001.

conditions within the EU, while influencing factors such as base machine, AFH, and operator were kept constant. A core group of researchers and field staff responsible for data collection was present at all study sites, to ensure that the trials and data collection were executed in the same manner. Per-stand block groupings of time-study units with homogeneous conditions were used to ensure the same range of conditions per treatment; the initial treatment was randomly assigned to each block, and subsequent treatments executed alternately.

The fixed effect of treatment (*i*) was found to be significant in all productivity models (Table 9), while the random effect of block (*j*) was not found to be significant in the productivity nor the biomass removal models (Tables 9 and 10). Alternatively, total randomization could have been applied to the analysis of field work data. However, this would have increased the risk of generating variable conditions between the treatments, which would have affected the precision of the productivity and biomass models; therefore, blocked treatments and LME regression analyses were used.

The design could have been improved by extending the "size" of each observation, e.g., increasing the length of the time-study unit by 50%, i.e., from 50 m to 75 m. This would have lowered the risk of work efficiency biases arising from the operator switching between methods, which can cause run-in time effects at the beginning of a work period. However, the operator was very experienced with ST work and the technology used. Moreover, he was highly motivated to perform the trials, and was able to learn and perform BCT quickly. For these reasons, we decided to prioritize the number of observations instead of observation size. We collected harvester work data for a total of 56.07 PMh, i.e. ~52 min per observation. This correlates well with the time recommended for short breaks during intensive work.

As the treatments were alternated during the trials, run-in time could again have biased the results. However, as these effects were expected to be similar for both working methods/treatments, even though there was a possible relative difference, the absolute values were probably similarly biased for both treatments. The study design used makes it possible to generalize the results to a greater extent than previous studies, dependent on the work methods and stand conditions. Because the same operator performed the work in all the study units, any relative difference in productivity between the methods was probably real. However, because the operator effect can be significant (cf. Lindroos 2010), and increases with work complexity, additional trials including, e.g., operator effects, are required to improve, e.g., harvester time consumption models to generate more precise and accurate estimates of the absolute values for practical use. For example, in harvester work studies, there can be up to a 40% difference in productivity between experienced and inexperienced operators. These differences become even more pronounced as working conditions become more difficult (Ovaskainen et al. 2004).

BCT resulted in significantly lower harvester work time consumption for four (Boom out, Felling in the stand; Top bucking, Boom in and bunching) of the eight work elements, and overall work time consumption was 28% lower (Table 7). Bergström et al. (2010a) found the corresponding difference to be ~4% and not significant. One reason for this discrepancy may be because the operator in Bergström et al. (2010a) had much less experience with AFH technology and BTC, and the study was limited in size (only 16 observations). In our trials, the operator had much more training prior to the time studies.

Our study confirms previous findings on the effects of BCT on harvester work time consumption, productivity, and thinning quality. On average, productivity increased by 16%, in line with the findings of Bergström et al. (2010a). Our results were close to significant ($p = 0.054$), which meant that only on 5.4 occasions, out of 100 observations, was BCT not more productive than ST. This is an important result, considering the number of potential variables in forestry work. The biomass removal was 9.7% lower for BCT and, even though it was not significant (Tables 4 and 5), this suggests that differences in productivity may be higher if the same biomass is removed per tree and ha. However, it is also likely that, taking the operator effect into account, variance in productivity will increase, with a concomitant decrease in the likelihood of observing a significant difference. This effect could be lowered by technological developments in operator assistance, e.g. through semi-automation (cf. Jundén et al. 2013). If using the productivity model (1) (Table 9) and calculating with the mean biomass removal, 45 dry t ha^{-1}, the productivity of ST and BCT each 4.5 and 5.5 dry t PMh^{-1}, respectively, giving a relative difference of 22%. If assuming an average biomass removal of 30 (−33% to the mean) and 60 (+33% to the mean) dry t ha^{-1}, the relative difference reach 28% and 18%, respectively. As the absolute difference between treatments is constant for models 1–4 (Table 9), the relative difference increases linearly with changes in values of independent variables. A constant absolute difference cannot however always be assumed. For example, Bergström et al. (2010a) choose to model separate productivity functions for the ST and BCT treatments as, by visual inspection, the absolute difference between treatments productivity was not constant and converged, and assumption of a constant absolute difference would create invalid functions.

The only exception to the higher, albeit not significant, productivity of BCT was found in block 3 (Finland), where productivity for BCT was ~2% lower than ST. This block contained many long trees requiring top bucking (i.e. cross-cutting of the standing tree) to produce the right length of tree sections for effective forwarding work. Top bucking increased time consumption considerably, as the Bracke C16 AFH does not have feed-rollers that enable effective bunch bucking. Besides easing the forwarder's work, top bucking was also performed to pull some of the tree bunches down to the ground and reduce the risk of damaging standing trees when handling the longer trees, as they could hit or get caught in the crowns of any nearby future crop trees. The number of top buckings increased markedly with tree heights above 7 m (Figure 7). Excessive tree height could be regarded as a bottleneck in the work of the AFH (regardless of treatment), as also observed by Jylhä and Bergström (2016). According to the operator, the prototype horn-shaped support plate used in this study (Figure 2) increased the stability of the accumulated trees while moving the boom, but this was not studied specifically. Additional innovations, such as providing the Bracke C16 AFH with a feed-roller system designed for whole tree/tree part compression processing, or using a grapple-saw when forwarding (Bergström and Di Fulvio 2014b), could overcome this limitation. In this case, the function of feed rollers would be to compress the unbranched tree by breaking but not removing, twigs and fine branches, and getting the tree into the right position for cross-cutting. To increase the harvesting efficiency even more, the forwarder could be equipped with load-compression (Bergström et al. 2010b), or the biomass could be bundled prior to forwarding (Bergström et al. 2016; Nuutinen & Björheden 2016), to enhance transport efficiency. Feed-rollers in commercial AFHs are found in the shear-based ABAB Bioharvester 255 (Allan Bruks AB, Sweden).

Simulation studies (Sängstuvall et al. 2012) have shown that, by increasing the width of the boom-corridor, the cutting work productivity of BCT can be increased significantly. Bergström (2009) and Witzell et al. (2019) highlight the importance of implementing flexible BTC methods based on stand structure, management goals, and harvesting technology. In our trials, the frequency of boom-corridors and their size were not measured, but it was subjectively observed that, e.g., the width and length of boom-corridors varied throughout the trials. By using a harvester operator decision-support system for laying out the boom-corridors, e.g., which trees should be removed, efficiency could be optimized from both operative and stand management perspectives (Holzleitner et al. 2019). In the future, research on boom-corridor frequency, width, and length should be compared between operator-led decision-making and pre-marked boom-corridors regarding which trees to cut. Such a design would facilitate analysis of the effects of operator decision support on thinning quality and work efficiency.

Our modeled productivity was found to be in line with previous research on harvester work in small-diameter, dense, thinnings for bioenergy biomass using the Bracke C16 saw-disc-based AFH (Iwarsson Wide and Belbo 2009; Bergström et al. 2010a; Bergström and Di Fulvio 2014b) and slightly higher than that of shear-based AFHs (Bergström et al. 2016); (Ovaskainen et al. 2008; Iwarsson Wide and Belbo 2009; Di Fulvio and Bergström 2013) (Figure 8). Shear-based AFHs are tougher and less sensitive to stones, requiring less investment costs than saw-disc or sword-based heads (Iwarsson Wide 2009). However, saw-disc-based AFHs have a higher cutting efficiency because of the ability, at least to some extent, to cut trees with a continuous movement. In theory, AFHs that can cut and accumulate all the trees in a boom-corridor with a continuous movement could result in productivity levels twofold higher than selective cutting where the felling head stands still during cutting work (Bergström et al. 2007; Bergström et al. 2012; Sängstuvall et al. 2012).

Only in block four were there significant differences in dendrometric variables for the time-study units before thinning treatment (Table 2): ST had a 26% higher whole tree biomass volume, which affected harvester productivity considerably. However, the influence on mean productivity was minimal, because of the large number of observations. Additionally, any differences between treatments could not be discerned either by visual inspection from the ground, or from the air after inspection of aerial photos. The density of trees remaining in the blocks, for both treatments, was in line with or above the recommended target densities for conventional first thinnings in Sweden (1200–1500 trees ha^{-1}), Finland (800 trees ha^{-1}) and Slovenia (1200–1500 trees ha^{-1}). This indicated that the quantity of crop trees remaining in the stands was sufficient for future stand development, whatever treatment was considered. Ulvcrona et al. (2017) found that neither dominant height nor number of possible future crop trees was jeopardized by BCT; however, the effects of thinnings on future stand development are difficult to evaluate directly because of the long rotation of stands. Thinnings in stands in early growth stages play an essential role in the development of mature forest stands (Lombardi et al. 2018), and more research is needed to fully understand the effects of BCT on the remaining stands for different forests within the EU and for different management goals. The number of remaining trees with a DBH ≥8 cm (Figure 5) was similar for both treatments in most of the blocks; the number of trees with a DBH ≥12 cm in block 3 was 200 trees ha^{-1}, in line with Nuutinen et al. (2021) and Ulvcrona et al. (2017). On average, the density of the remaining stands was 23%

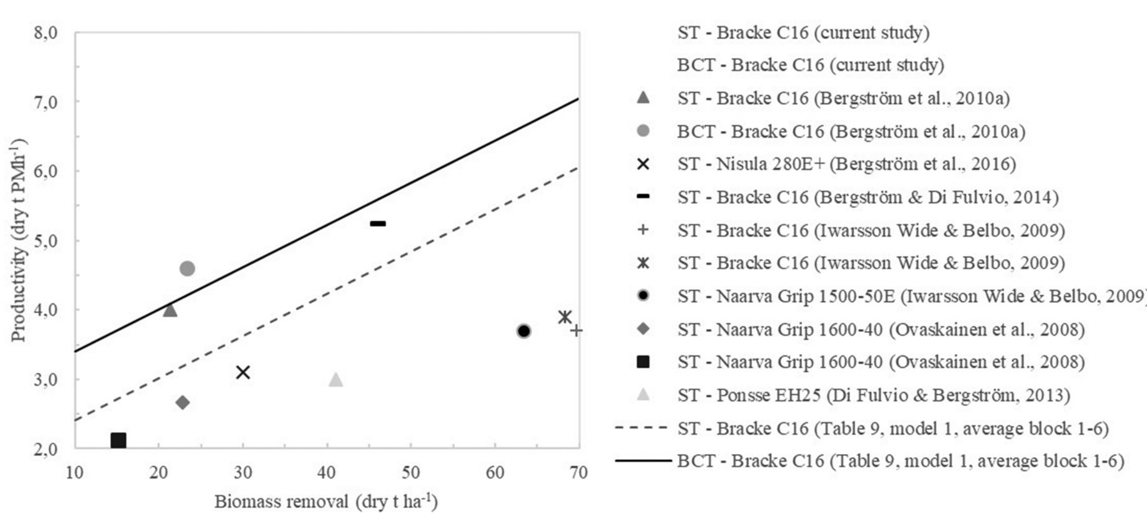

Figure 8. Productivity of harvesters equipped with AFHs during thinning work of dense small-diameter stands (y-axis) for bioenergy biomass removal (x-axis). ST = selective thinning, BCT = boom-corridor thinning.

larger, but not significant, for BCT than ST. This is in line with Nuutinen et al. (2021), who found a 16–46% higher remaining stand density for BCT than ST. The thinning ratios in the present study are also in line with Nuutinen et al. (2021).

On average, the removal of biomass was 11% larger for ST than BCT (47.5 vs. 42.9 dry t ha^{-1}), which also explains the higher biomass concentration along the strip roads for ST (Table 5). The average biomass removal for both treatments (45 dry t ha^{-1}) was two-fold larger than the average removal in conventional thinnings in Sweden, at ~20 dry t ha^{-1} (Eliasson et al. 2019), because whole trees were extracted rather than just pulpwood. Trees of all DBH classes were felled similarly for both treatments. However, as trees <8 cm (Figure 4) were cut to a greater extent than with more conventional methods, e.g., pulpwood thinnings, the ratio was relatively low, 0.7, but not unexpected. The largest relative removal of trees <8 cm occurred in block 4 (~90%), which contained dense undergrowth. Trees with a DBH <8 cm are regarded as un-merchantable in Sweden, Finland, and Slovenia, and left on the ground by PCT or pre-cleared before conventional first thinnings (Forsberg and Lodén 2020), but they represent, at a stand level, a large potential biomass resource. We used four different biomass estimation systems (tree scaling systems and biomass functions), each with different degrees of precision and accuracy. Uncertainties in the estimation of biomass production, and thus productivity, is not a problem when comparing treatments per block, but is when comparing blocks.

Removal of ~30–40% of the basal area is typically recommended for conventional first thinnings of pine-, spruce- and birch-dominated stands in Sweden and Finland (Bergkvist and Staland 2003; Di Fulvio et al. 2011). Removal of between 16 and 27% has been reported for beech stands in Slovenia (Boncina et al. 2007). In our study, except for block 6 (Slovenia), the basal area removal in most blocks ranged between 46 and 70%, which was higher than the relevant guidelines. This can be explained by the different DBH classes considered in the guideline calculations, but also by the initially larger growing stock because of the lack of PCT in most of the blocks (except blocks 1 and 6). In other words, if the initial tree density is higher than in regular stands, a higher thinning intensity can be applied without risking the number of future crop trees, which is logical. The absolute values for the remaining basal area in block 1 (Sweden) were in line with those after conventional first thinnings of similar stands (Bylund 2007). The measured values for the remaining basal areas in blocks 2 and 3 (Finland) can be regarded as heavier thinnings compared with the results of Repola et al. (2006). In Slovenia (blocks 4 and 5), the measured values were also below Slovenian recommendations; basal areas after first thinnings of at least 20 m^2 ha^{-1} have been reported by Lendvai et al. (2020) and Boncina et al. (2007). The Slovenian guidelines were developed for motor-manual operations and do not consider removal along strip roads during fully mechanized harvests. The common practice is to only remove those trees competing directly with dominant trees (i.e., not necessarily felling trees from the lower canopy), which could explain the relatively large removals in blocks 4 and 5.

The proportion of damaged trees along the strip roads was on average 37%, and significantly lower for BCT (Table 6), which is in contrast with previous findings (cf. Bergström et al. 2010a). An explanation for this is that BCT requires less maneuvering work with the crane, lowering the probability of "hitting" future crop trees. Damage was mostly caused by the AFH when maneuvering to put down tree bunches in un-thinned areas, and scratches from the wheel chains along the strip road. Damage was markedly higher in blocks 4 and 5 (Slovenia), probably because of the terrain's roughness, slope and dense undergrowth. Terrain difficulties meant the harvester had to bend gently along the strip roads, which could explain the relatively wide strip roads in blocks 4 and 5.

Stump height was similar amongst the treatments, with no significant differences. The probable reason for the higher stumps in blocks 1 (Sweden), 4 and 5 (Slovenia) was the initially dense undergrowth, which reduced the operator's line of sight and made it difficult to position the head as close to the ground as possible for cutting work. Levin (2021) found stump height to increase with the density of undergrowth. The general abundance of rocks in most study units also forced the operator to leave high stumps to avoid damaging the cutting chain in the AFH. In any case, if the chain was damaged or worn out, it was rapidly replaced (~10 minutes). If stumps can be cut lower during thinning work, the amount of harvested stemwood increases, and consequently harvester productivity.

Conclusions

This study confirms and expands our understanding that BCT is superior to ST in terms of harvester work efficiency and productivity in small-diameter, dense, thinning stands. Even though BTC is performed with less selectivity, only minor differences in the quality of the remaining stand structure and measured dendrometric variables were found between treatments (cf. Ulvcrona et al. 2017; Nuutinen et al. 2021). Overall, BCT appears to have great potential for generating higher levels of biodiversity more cost-effectively than ST, because a greater stand area is left untreated (cf. Witzell et al. 2019).

AFH, or similar technologies, and novel working methods such as BCT represent an opportunity to increase the efficiency of forest management and mechanization of small-diameter, dense, thinning stands, for which practices such as PCT have often been neglected because of high costs. An important area for future research is to investigate whether and when it is effective to replace traditional PCT systematically with whole-tree harvesting from a forest management perspective. Moreover, the use of the felling technology evaluated here, and the potential availability of small-diameter trees, has applications beyond dense forest thinnings, such as the maintenance of marginal lands, e.g., power-line corridors and roadside verges (Fernandez Lacruz 2019; Laitila and Väätäinen

2020; Fernandez-Lacruz et al. 2021). Enhanced research and development of harvesting technologies, working methods and forest management systems for the handling of small trees is of great importance for the economic and sustainable utilization of forest biomass as a substitute for fossil-based products in the EU.

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No potential conflict of interest was reported by the author(s).

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ORCID

Dan Bergström http://orcid.org/0000-0002-5729-683X
Yrjö Nuutinen http://orcid.org/0000-0003-3360-4444

Data Availability Statement

The datasets containing fieldwork data and those generated during analysis are available from the corresponding author on request.

References

Agisoft. 2020. Agisoft metashape pro (version 1.6.5). [accessed 20200405]. http://www.agisoft.com/downloads/installer.

Äijälä O, Koistinen A, Sved J, Vanhatalo K, Väisänen P. 2014. Metsänhoidon suositukset [Forest management recommendations]. Forestry Development Centre Tapio, Finland.

Andersson S-O. 1954. Funktioner och tabeller för kubering av småträd [Functions and tables for cubing of small trees]. Meddelanden från statens skogsforskningsinstitut, Band 44, nr. 12. Sweden.

Berg S. 1992. Terrain classification system for forestry work. Kista (Sweden): The Forest Operations Institute of Sweden.

Bergkvist I, Staland F. 2003. Gallra med kvalitet – förberedelser, utförande, uppföljning & återkoppling. Stiftelsen Skogsbrukets Forskningsinstitut. Uppsala (Sweden) ISBN 91 7614 104 7.

Bergström D. 2019. Cost analysis of innovative biomass harvesting systems for young dense thinnings. Croat J for Eng. 40(2):221–230.

Bergström D, Bergsten U, Nordfjell T. 2010a. Comparison of boom-corridor thinning and thinning from below harvesting methods in young dense scots pine stands. Silva Fenn. 44(4):669–679.

Bergström D, Nordfjell T, Bergsten U. 2010b. Compression processing and load compression of young scots pine and birch trees in thinnings for bioenergy. Intl J For Eng. 21(1):31–39.

Bergström D, Bergsten U, Nordfjell T, Lundmark T. 2007. Simulation of geometric thinning systems and their time requirements for young forests. Silva Fenn. 41(1):137–147.

Bergström D, Di Fulvio F. 2014a. Comparison of the cost and energy efficiencies of present and future biomass supply systems for young dense forests. Scand J For Res. 29(8):793–812.

Bergström D, Di Fulvio F. 2014b. Evaluation of a novel prototype harvester head in early fuel-wood thinnings. Int J For Eng. 25(2):156–170.

Bergström D, Di Fulvio F, Nuutinen Y. 2016. Effect of forest structure on operational efficiency of a bundle-harvester system in early thinnings. Croat J for Eng. 37(1):37–49.

Bergström D, Matisons M 2014. Forest Refine, 2012-2014: efficient forest biomass supply chain management for biorefineries - synthesis report. Umeå (Sweden): Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences.

Björheden R, Fröding A. 1986. A new routine for checking the biological quality of thinning in practice. Garpenberg (Sweden): Swedish University of Agricultural Sciences, Department of Operational Efficiency; p. 91–576-2586-7.

Blair MJ, Gagnon B, Klain A, Kulišic B. 2021. Contribution of biomass supply chains for bioenergy to sustainable development goals. Land. 10 (181). doi:10.3390/land10020181.

Boncina A, Kadunc A, Robic D. 2007. Effects of selective thinning on growth and development of beech (Fagus sylvatica L.) forest stands in south-eastern Slovenia. Ann For Sci. 64(1):47–57.

Bylund A. 2007. En analys av SCA Skog AB's metod för egenuppföljning av gallringar. Umeå (Sweden): Department of Forest Ecology and Management, Swedish University of Agricultural Sciences.

CEN. 2009. CEN/TC 335 – solid biofuels. EN 14774-2:2009. In: Solid biofuels –determination of moisture content – oven dry method – part 2: total moisture – simplified method. Brussels (Belgium): European Committee for Standardization (CEN).

Di Fulvio F, Bergström D. 2013. Analyses of a single-machine system for harvesting pulpwood and/or energy-wood in early thinnings. Intl J For Eng. 24(1):2–15.

Di Fulvio F, Kroon A, Bergström D, Nordfjell T. 2011. Comparison of energy-wood and pulpwood thinning systems in young birch stands. Scand J For Res. 26(4):339–349.

Eliasson L, Manner J, Thor M. 2019. Costs for thinning and final felling operations in Sweden, 2000–2017. Scand J For Res. 34(7):627–634.

Fernandez-Lacruz R, Edlund M, Bergström D, Lindroos O. 2021. Productivity and profitability of harvesting overgrown roadside verges – a Swedish case study. Intl J For Eng. 32(1):19–28.

Fernandez Lacruz R. 2019. Improving supply chains for logging residues and small-diameter trees in Sweden. Umeå (Sweden): Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences.

Europe F. 2020. State of Europe's forests 2020. Bratislava: Liaison Unit Bratislava.

Forsberg M, Lodén H. 2020. Förröjning i Sverige - en granskning av skogsföretagens strategier för underväxtröjning inför förstagallring [Silvicultural measures in Sweden, a review of strategies among forest companies regarding understory cleaning prior to first thinning]. Umeå (Sweden): Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences.

Fuchs R 2013 Changing face: Europe's land cover in 1900 and 2010. [accessed 20190301]. http://www.geo-informatie.nl/fuchs003/ .

Gingras J-F. 2004. Early studies of multi-tree handling in Eastern Canada. Intl J For Eng. 15(2):18–22.

Grönlund Ö. 2020. Forest operations in multifunctional forestry. Umeå: Swedish University of Agricultural Sciencies, Department of Forest Biomaterials and Technology.

Gschwantner T, Alberdi I, Balázs A, Bauwens S, Bender S, Borota D, Bosela M, Bouriaud O, Cañellas I, Donis J, et al. 2019. Harmonisation of stem volume estimates in European national forest inventories. Ann For Sci. 76(1):24.

Guček M, Pisek R, Breznikar A, Minić M, Kolsek M, Pristovnik D, Marenče M, Stergar M, Mori J, Kandare K 2020. Poročilo zavoda za gozdove slovenije o gozdovih za leto 2019 [Report of the Slovenian forest service about forests for the year 2019]. Ljublana (Slovenia): Slovenian Forest Service.

Han S-K, Han H-S. 2020. Productivity and cost of whole-tree and tree-length harvesting in fuel reduction thinning treatments using cable yarding systems. For Sci Tech. 16(1):41–48.

Hiesl P, Benjamin JG. 2013. A multi-stem feller-buncher cycle-time model for partial harvest of small-diameter wood stands. Intl J For Eng. 24 (2):101–108.

Hood SM, Baker S, Sala A. 2016. Fortifying the forest: thinning and burning increase resistance to a bark beetle outbreak and promote forest resilience. Ecoll Appl. 26(7):1984–2000.

Iwarsson Wide M. 2009. Klenträdsaggregat för skogsbränsle – en marknadsöversikt [Felling heads for small-diameter trees – a market survey]. Uppsala (Sweden): Skogforsk.

Iwarsson Wide M. 2010. Technology and methods for logging in young stands. Uppsala (Sweden): Skogforsk.

Iwarsson Wide M, Belbo H. 2009. Jämförande studie av olika tekniker för skogsbränsleuttag [Comparative study of different technologies for forest fuel extraction]. Uppsala (Sweden): Skogforsk.

Johansson J, Gullberg T. 2002. Multiple tree handling in the selective felling and bunching of small trees in dense stands. Intl J For Eng. 13 (2):25–34.

Jylhä P, Bergström D. 2016. Productivity of harvesting dense birch stands for bioenergy biomass bioenerg. Biomass and Bioenergy. 88. 142–151.

Kronholm T, Bengtsson D, Bergström D. 2020. Family forest owners' perception of management and thinning operations in young dense forests: a survey from Sweden. Forests. 11(11):1151.

Laasasenaho J. 1982. Taper curve and volume functions for pine, spruce and birch. Seloste: Männyn, kuusen ja koivun runkokäyrä- ja tilavuusyhtälöt. Commun.lnst.For.Fenn. 108:1—74. .

Lageson H. 1997. Effects of thinning type on the harvester productivity and on the residual stand. Jl For Eng. 8(2):7–14.

Laitila J, Väätäinen K. 2020. Productivity of harvesting and clearing of brushwood alongside forest roads. Silva Fenn. 54(5):21. doi:10.14214/sf.10379.

Lendvai S, Diaci J, Rozenbergar D. 2020. Response of black alder (Alnus glutinosa (l.) gaertn.) to selective thinning of various intensities: a half-century study in northeastern Slovenia. Sumar List. 144(7–8):367–378.

Levin I. 2021. Underväxtens påverkan på stubbhöjd och skador i förstagallring [The effect of undergrowth on stump height and damages in first thinning]. Umeå (Sweden): Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences.

Lombardi F, Lella S, Altieri V, Benedetto S, Giancola C, Lasserre B, Kutnar L, Tognetti R, Marchetti M. 2018. Early responses of biodiversity indicators to various thinning treatments in mountain beech forests. Biogeosc For. 11(5):609–618.

Magagnotti N, Spinelli R, Acuna M, Bigot M, Guerra S, Hartsough B, Kanzian C, Kärhä K, Lindroos O, Roux S, et al 2012. Good practice guidelines for biomass production studies. Sesto Fiorentino (Italy): CNR IVALSA.

Marklund LG. 1988. Biomassafunktioner för tall, gran och björk i Sverige. Umeå (Sweden): Department of Forest Survey, Swedish University of Agricultural Sciences.

Näslund M. 1936. Skogsförsöksanstaltens gallringsförsök i tallskog primärbearbetning. Stockholm (Sweden): Statens skogsförsöksanstalt.

Näslund M. 1947. Funktioner och tabeller för kubering av stående träd. Tall, gran och björk i södra Sverige samt i hela landet [Functions and tables for calculating the volume of standing trees. Pine, spruce and birch in southern Sweden and in the whole country]. Meddelanden från statens skogsforskningsinstitut, Band 36, nr. 3. Sweden.

Nuutinen Y, Miina J, Saksa T, Bergström D, Routa J. 2021. Comparing the characteristics of boom-corridor and selectively thinned stands of Scots pine and birch. Silva Fenn. 55(3):22. doi:10.14214/sf.10462.

Nylinder M, Kockum F 2016 WeCalc – räkna på skogsbränsle [WeCalc - forest fuel calculator]. https://www.skogforsk.se/produkter-och-evenemang/verktyg/wecalc/.

Olsson NL 2020. Subtitle Edit. [accessed 20200405]. http://www.nikse.dk/subtitleedit/.

Ovaskainen H, Palander T, Jauhiainen M, Lehtimaki J, Tikkanen L, Nurmi J. 2008. Productivity of energywood harvesting chain in different stand conditions of early thinnings. Baltic For. 14(2):149–154.

Petty A, Kärhä K. 2014. Productivity and cost evaluations of energy-wood and pulpwood harvesting systems in first thinnings. Intl J For Eng. 25 (1):37–50.

Poikonen P, Iwarsson Wide M, Laitila J, Gudynaitė- Franckevičienė V, Jakobson I, Luik A, Pošlin L, Gong P, Lazdiņš A, Bermanis R, et al. 2020. Cost-effective and sustainable harvest methods. Finland: Natural Resources Institute Finland (Luke).

R Core Team. 2020 R: a language and environment for statistical computing. http://www.R-project.org/.

Repola J, Hökkä H, Penttilä T. 2006. Thinning intensity and growth of mixed spruce-birch stands on drained peatlands in Finland. Silva Fenn. 40(1):83–99.

Sängstuvall L. 2018. Improved harvesting technology for thinning of small diameter stands: impact on forest management and national supply of forest biomass. Umeå (Sweden): Department of Forest Resource Management, Swedish University of Agricultural Sciences.

Sängstuvall L, Bergström D, Lämås T, Nordfjell T. 2012. Simulation of harvester productivity in selective and boom-corridor thinning of young forests. Scand J For Res. 27(1):56–73.

Sohn JA, Saha S, Bauhus J. 2016. Potential of forest thinning to mitigate drought stress: a meta-analysis. For Ecol Manage. 380:261–273.

Ulvcrona KA, Bergström D, Bergsten U. 2017. Stand structure after thinning in 1–2 m wide corridors in young dense stands. Silva Fenn. 51(3):15.

Vilén T, Gunia K, Verkerk PJ, Seidl R, Schelhaas MJ, Lindner M, Bellassen V. 2012. Reconstructed forest age structure in Europe 1950–2010. For Ecol and Manag. 286:203–218.

Witzell J, Bergström D, Bergsten U. 2019. Variable corridor thinning - a cost-effective key to provision of multiple ecosystem services from young boreal conifer forests? Scand J For Res. 34(6):497–507.

Kärhä K. and Bergström D. 2020. Assessing the Guidelines for Pre-Harvest Clearing Operations of Understory in First Thinnings: Preliminary Results from Stora Enso in Finland. Eur J Forest Eng 2020, 6(1): 14–22.

Karlsson L., Nyström K., Bergström D. & Bergsten U. 2015 Development of Scots pine stands after first biomass thinning with implications on management profitability over rotation, Scandinavian Journal of Forest Research, 30:5, 416–428, DOI: 10.1080/02827581.2015.1023351

Bergström, D. 2009. Techniques and systems for boom-corridor thinning in young dense forests. Doctoral thesis, Acta Universitatis Agriculturae Sueciae 2009: 87. ISSN 1652-6880. ISBN 978-91-576-7343-0.

Lindroos O. 2010. Scrutinizing the Theory of Comparative Time Studies with Operator as a Block Effect, International Journal of Forest Engineering, 21:1, 20–30, DOI: 10.1080/14942119.2010.10702587

Jundén L., Bergström D., Servin M. & Bergsten U. 2013. Simulation of boom-corridor thinning using a double-crane system and different levels of automation. International Journal of Forest Engineering, 24(1): 16–23.

Nuutinen Y. & Björheden R. 2016. Productivity and work processes of small-tree bundler Fixteri FX15a in energy wood harvesting from early pine dominated thinnings, International Journal of Forest Engineering, 27:1, 29–42, DOI: 10.1080/14942119.2015.1109175

Holzleitner F., Langmaier M., Hochbichler E., Obermayer B., Stampfer K., Kanzian C. 2019.

Effect of prior tree marking, thinning method and topping diameter on harvester performance in

Bergström D., Bergsten U., Hörnlund T. & Nordfjell T. 2012. Continuous felling of small diameter trees in boom-corridors with a prototype felling head. Scandinavian Journal of Forest Research, 27(5): 474–480.

Camia, A., Giuntoli, J., Jonsson, K., Robert, N., Cazzaniga, N., Jasinevičius, G., Avitabile, V., Grassi, G., Barredo Cano, J.I. and Mubareka, S., The use of woody biomass for energy production in the EU, EUR 30548 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-27866-5, doi:10.2760/428400, ISBN 978-92-76-27866-5.

Ovaskainen H., Uusitalo J. & Väätäinen K. 2004. Characteristics and Significance of a Harvester Operators' Working Technique in Thinnings, International Journal of Forest Engineering, 15:2, 67–77, DOI: 10.1080/14942119.2004.10702498