Effect of Forest Structure on Operational Efficiency of a Bundle-Harvester System in Early Thinnings

Dan Bergström, Fulvio Di Fulvio, Yrjö Nuutinen

Abstract

The objective of the study was to improve knowledge on effects of harvested tree size and density of undergrowth on the operational efficiency of a bundle-harvester that produces 2.6 m long bundles, with ca. 60–70 cm diameter, in early fuel wood thinnings. In total 26 time study plots were marked out in 30 to 35 year old Scots pine dominated stands with initial density of 2800–9300 trees/ha and stem size range of 15–43 dm^3. Ten of the units, randomly chosen, were precleared of undergrowth trees (≤2.5 cm at breast height diameter) prior to harvesting.

There were no significant differences between treatments (preclearing vs. no preclearing) in properties or operational efficiency of the harvested and remaining stands. The average height of cut trees and volume of cut stems were 7.4 m and 16.2 dm^3, respectively, and on average, 3554 trees/ha were removed. The bundles had a mean fresh mass of 439 kg and the mass was correlated to the proportion of birch trees cut. The productivity was, on average, 3.1 OD t/PM$_0$H (6.6 fresh t/PM$_0$H; 15.1 bundles/PM$_0$H, where PM$_0$H is productive machine hours, without delays) and was modeled with the harvested stem volume (dm^3) as a single independent variable. The study provides complementary knowledge to earlier studies of the system's performance, especially for harvesting stems <30 dm^3. Its productivity was limited by the cutting efficiency and could probably be significantly increased by using a felling and bunching head that could cut and accumulate trees during continuous boom movements. Thus, it would be informative to evaluate such a system in various early thinning stand conditions, including assessments of its manoeuvrability in more difficult terrain.

Keywords: pre-commercial thinning, productivity, Scots pine, bioenergy

1. Introduction

Small-diameter trees in young dense forests are already harvested in the Nordic countries to produce fuels for heat and power generation, and harvests are expected to increase as demand for high quality residual biomasses for biorefining rises (Bergström and Matisons 2014). In Sweden, potential annual extractions of such trees amount to ca. 6.5x10^6 m^3; five times more than current harvests (Routa et al. 2013). Corresponding quantities for Finland are 7.7x10^6 m^3, which would give 33% more than currently (Routa et al. 2013). Small heating plants often require deliveries of comminuted fuels, while large-scale heat and combined heat and power plants can normally comminute material on-site, and thus also receive unprocessed tree parts. The biomass can also be delivered unprocessed or comminuted to terminals for reloading, intermediate storage and/or comminution before further transportation (Kons et al. 2015). This is a potentially important difference, as high payloads during terrain and road transportation are crucial for producing and delivering forest fuels with high cost efficiency. Comminution at roadside landings increases payloads for bulky materials like logging residues from clear cuts and small-diameter whole trees from early thinnings, but it accelerates degradation, so comminuted material must be delivered to industrial sites quickly to avoid significant biomass losses (cf. Jirjis 1995). Another drawback is that specially designed trucks for comminuted materials must be used rather than standard timber trucks in the supply chain. Further, comminution is more costly at landings than at terminals or industrial sites as the operational efficiency is affected by the scale of machinery (cf. Kärhä 2011). Alternatively, the biomass could be compressed and bundled into ca 2.5–3.5 m long bundles with densities of 270–780 kg/m^3 in the stand, or at roadside, before further handling and transport (Nordfjell and Liss 2000, Pettersson and Nordfjell 2007, Johansson et al. 2006, Kärhä and Vartiamäki 2006, Jylhä and Laitila 2007). Such systems have been studied, and results indicate that they may have sufficient advantages throughout the supply chain, if convenient bundles for transport on conventional timber trucks can be produced (Johansson et al. 2006, Jylhä 2011, Kärhä et al. 2011, Bergström and Di Fulvio 2014a). The bundles are easy to handle when they are reloaded, dry well during storage and can be effectively comminuted using large-scale systems. However, current bundling machinery is costly and new systems with higher cost efficiency are required. Bergström and Di Fulvio (2014a) have shown that with further development bundle-harvesting systems for young dense thinnings could be up to 15% more cost efficient (when including transportation in analysis) than conventional tree-part handling systems.

In tests of a prototype whole-tree bundle-harvester for small-diameter trees in Finland, reported by Jylhä and Laitila (2007), bundling productivity was limited because simultaneous harvesting and bundling phases accounted for only 8–18% of the monitored effective working time. The cited authors concluded that the studied system was not competitive with conventional harvesting systems but had great potential for future development. Nuutinen et al. (2011) found that a second prototype of the machine had 38–77% higher productivity than the first, due to a higher cutting-accumulation capacity and better bundling hydraulics, which increased possibilities for simultaneous cutting and bundling.

A third version of the bundle-harvester system was launched in 2013, with reported increases in efficiency (time/bundle) of 111–133% compared to the previous version (»Fixteri II«), providing productivities of 9.7–13.8 m^{3}solid /PM$_0$H when thinning Scots pine dominated stands, removing stems with average volumes of 27–84 dm^3 (Nuutinen and Björheden 2015). The solid volumes of the produced bundles range from 0.3 to 0.5 m^3 (Jylhä and Laitila 2007) and their use increases forwarders and trucks payloads by ca 50%, respectively, in comparison to handling loose materials (Laitila et al. 2009). However, the system's productivity has not been extensively studied in stands with an average harvested tree volume <30 dm^3, in which there may be significant proportions of disturbing undergrowth trees that may reduce cutting productivities (cf. Kärhä 2006, 2015a, 2015b, Jonsson 2015), and hence cost efficiency.

1.1 Objectives

The objective of the study presented here was to evaluate effects of harvested tree size and density of undergrowth on the operational efficiency of the third version of the Fixteri bundle-harvester in early fuel wood thinnings.

2. Material and methods

2.1 Treatments

A stand containing patches dominated by broadleaves and conifers of various characteristics was selected. The stand area was divided into time study plots, aiming to isolate homogeneous areas in term of dendrometrical features (species composition, size of trees to be removed, density, etc.). Each time study plot was 20 m wide (the distance reachable during harvesting with a 11 m crane from a strip road) and 40–60 m long. In total 26 time study plots were marked out for cutting and bundling work, each with an average area of 1215 m^2 (*SD* 227), covering a total area of 3.2 ha.

2.2 Study site

The study site was located in Holmsund (N 63°43′, E 20°25′), near the coast of northern Sweden, in a 30–35 year old stand containing mostly Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst.) and birch (*Betula* spp.). Some grey alder (*Alnus incana* (L.) Moench.) and lodgepole pine (*Pinus contorta* Douglas) were also present in some patches. The forest had not been previously pre commercially thinned and some parts contained considerable amounts of undergrowth, mainly consisting of birches and Norway spruce (Table 1). The ground generally had good bearing capacity, the surface had no obstacles, the slope was slight and it was classified as 2.1.1 according to Berg´s (1992) terrain classification system.

2.2.1 Time study plot preparation

Prior to thinning, strip road center lines were marked out in each time study plot. Two permanent 100 m^2 transects (5 m wide and 20 m long) were laid out at 25 m spacing perpendicular to the strip road in each time study plot for inventories of dendrometric features before pre-clearing and thinning work and after thinning work (Table 1). In total 397 trees were sampled and their height and diameter at stump height (15 cm above ground level) were measured.

Table 1 Characteristics of the 26 time study plots before pre-clearing and thinning work. *DBH*=diameter at breast height, *OD*=oven-dry, *SD*=standard deviation

	Trees >2.5 cm *DBH*												Trees ≤2.5 cm *DBH*				
	DBH[1]	*DBH* basal[2]	Basal area	Stem volume[4]	Density	Height	Stem volume[4]	Biomass volume[5]	Biomass[5]	Pine	Spruce	Birch	Density[6]	Pine	Spruce	Birch	Post density[7]
Stats.	cm	cm	m^2/ha	dm^3	trees/ha	m	m^3/ha	m^3/ha	*OD* t/ha	%[3]	%[3]	%[3]	trees/ha	%[3]	%[3]	%[3]	trees/ha
Mean	7.1	8.0	26.3	26.5	5406	8.2	133.9	189.2	92.3	27.4	23.5	48.4	4523	6.1	33.9	60.0	1516
Min.	5.5	6.3	17.8	15.0	2765	7.0	91.0	124.0	54.0	1.0	0.0	5.0	134	0	0	0	0
Max.	8.5	9.9	36.4	43.0	9302	9.7	206.0	302.0	148.0	95.0	75.0	89.0	11,951	55.0	100	96.0	4289
Median.	7.0	8.0	25.6	24.5	5200	8.1	131.0	173.5	91.0	17.0	16.0	60.5	3648	2.0	25.5	69.0	1165
SD	0.9	1.0	5.3	8.1	1583	0.7	28.9	48.7	24.9	25.8	21.0	28.3	3509	12.1	28.9	29.1	1517

[1] Arithmetic mean; [2] Weighted by basal area; [3] In number of trees; [4] Stem volume on bark; [5] Whole tree volume/mass (incl. tops and branches); [6] All plots before pre-clearing; [7] All plots after pre-clearing of ten plots

Trees ≤2.5 cm in diameter at breast height (*DBH*) were only counted and registered.

After inventory, ten of the 26 time study plots were pre-cleared, by cutting undergrowth trees of ≤2.5 cm (*DBH*) with a cleaning saw and leaving them on the ground before thinning.

2.3 Machine system

The machine system studied was a harwarder equipped with a felling crane and a bundling unit capable of bucking the cut trees and bundling them into 2.6 m long cylinders with ca. 60–70 cm diameters (Fig. 1). The base machine was an 8 wheeled Logman 811FC harwarder (Logman Oy) with 125 kW engine power, 15 t mass, 2.8 m width and 65 cm ground clearance. It was equipped with an 11 m reach Logfit FT100 crane (Logfit AB) integrated on a rotating cabin with endless turning. The crane was equipped with a Nisula 280E+ (Nisula Forest Oy) accumulating felling head with a mass of 330 kg and maximum cutting diameter of 28 cm.

Fig. 1 The bundle-harvester system

The bundling unit was a Fixteri FX15a machine (mass ca. 6500 kg, width 240 cm, length 410 cm, height 280 cm; www.fixteri.fi). It has two feed rollers, a cut-to-length guillotine and a compression and bundling compartment. The bundling chamber has a fixed length of 2.6 m, three sets of chains used for compression and a vertically sliding frame. On one side of the compression chamber, two rolls of plastic net (4000 m long) are mounted. On the opposite side of the chamber, there are two mobile arms for integrating scaling and dropping-off of bundles.

2.3.1 Work sequence

Whole trees are cut, accumulated and fed to the bundling unit for processing (Fig. 2). Once the compartment contains sufficient material for producing a bundle (ca. 450–500 kg of fresh mass), the bunch of trees is lifted up to a compaction chamber, where it is compressed by revolving chains and tied up using a plastic net. At the same time, the lower compartment can be fed with other trees. Once the bundle reaches sufficient density, it is automatically unloaded from the compaction chamber to two side arms. The bundle is automatically scaled and information on time of production and mass is recorded on the base machine. The bundle is then dropped on the ground from the arms and a new bundling cycle starts. The bundling process is automated with possibilities for the operator to control the process. The felling, feeding, dropping and weighing work can be performed simultaneously with the bundling process.

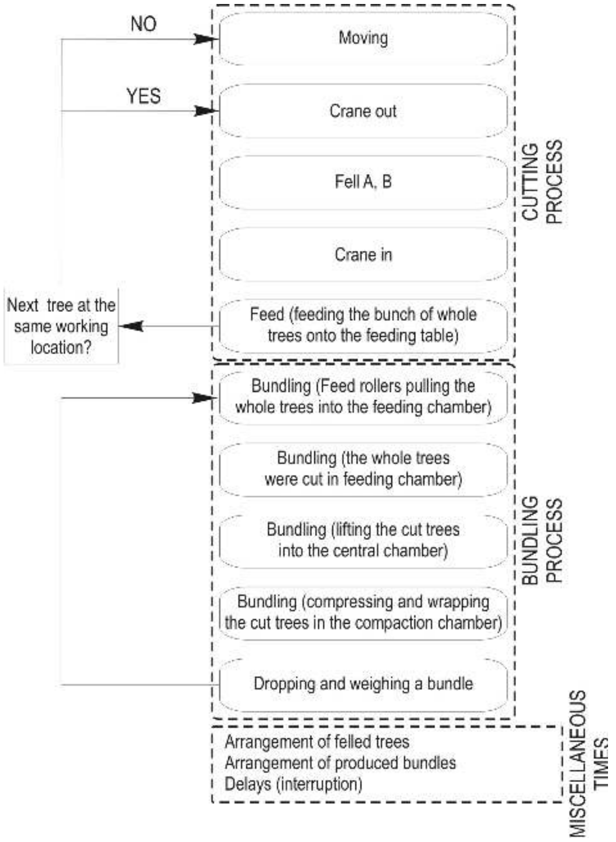

Fig. 2 Flow chart of work processes for the studied bundle-harvester (cf. Nuutinen et al. 2011, Nuutinen and Björheden 2015). Fell A, B indicate that the work can include accumulation of several trees

2.3.2 Operator

The operator had one year of experience in early thinning operations and had been working for six months with the studied machine in thinnings before our experiment. Before the time studies, the operator had a half day training session at the study site, and was subjectively judged to be »more skilled than the average operator«.

2.3.3 Thinning work method

The thinning was carried out selectively from below along strip road systems, with broadleaves prioritized for removal and targeting a residual density of at least 1200–1500 future crop trees/ha (*DBH*>6–7 cm). Trees with *DBH*≤2.5 cm were only cut and accumulated if they obstructed the crane from harvesting larger trees.

2.4 Time study

The time study was conducted between the 5th and 14th of May 2014, and the total duration of the monitored work was 29.40 $PM_{15}H$ (productive work time including delay time less than 15 min). The work time consumption was continuously recorded with an Allegro Field PC® running SDI software (Haglöf AB) recording 0.6 second (1 cmin) time-steps (Table 2) (cf. Nuutinen 2013). Delay time was separately recorded. The highest priority in the time recording was given to the crane work, i.e. if the crane work and bundling were performed at the same time, the crane was prioritized. During harvesting, the number of felled trees per crane cycle (*DBH*>2.5 cm) was also recorded (the *DBH* threshold was visually estimated).

At the same time, the machine computer created a dataset for each time study plot, including the time (hour: minute: second) when each bundle was expelled from the bundler and its fresh mass as acquired from the integrated scale.

2.5 Stand quality measures

After the time study, the *DBH* and species of all trees, and numbers of undergrowth trees, were recorded again in the inventory transects. The cut area in each time study plot was accurately measured using a Personal Digital Assistant with an external GPS antenna at 1 m precision. The height of all stumps located less than 1 m from the center line of each transect (i.e. along a line perpendicular to the strip road direction) was also measured. The strip road width was measured according to Björheden and Fröding (1986). The distance between strip roads (defined as the sum of the distances on either side of the strip road from the road center to the furthest cut tree, along a line perpendicular to the strip road) was also measured within the transects. The stem volumes of trees with *DBH*≤5 cm and >5 cm were calculated using functions presented by Andersson (1954) and Näslund (1947), respectively. The oven-dry (*OD*) biomass content of stems, branches and needles was calculated using functions presented by Marklund (1987), and for conversion to solid volumes, basic density values for crown biomass obtained by Hakkila (1978) were used. Damage was recorded when there was visible harm to sapwood of trees with *DBH*>2.5 cm, with no restriction on wound size (cf. Wallentin 2007), registering whether the damaged tree was adjacent to a strip road or located inside the stand.

2.5.1 Bundle mass

The fresh mass of each bundle was acquired directly from the machine database and converted to oven dry (*OD*) mass using the moisture content (*MC*) of material sampled from each time study plot (determined as described below). The bundles' solid volumes (m^3) were also calculated from their dry masses (in *OD* kg) using average densities of 450, 554 and

Table 2 Definitions of recorded work elements

Work element (Abbreviation)	Description	Priority*
Boom out (Crut)	Starts when an empty crane moves towards the first tree to be harvested and stops when the tree has been reached	1
Felling (Fell)	Starts when the first tree has been reached and stops when the last tree in a crane cycle has been felled (moving to successive trees is included)	1
Boom in (Crin)	Starts when the last tree in the crane cycle has been felled and stops when the felling head drops the bunch of trees on the bundler feeding plate/on the ground	1
Arrangement of felled trees on the ground (Artr)	Starts when the felling head drops the bunch of trees on the ground and ends when the cross-cut tree parts are dropped on the ground/on the bundler feeding plate	1
Arrangement of bundles on the ground (Arbu)	Starts when the crane grabs a bundle and ends when the bundle is dropped on the ground	1
Moving (Move)	Starts when the base machine wheels start turning and ends when the base machine stops	2
Bundling (Bundle)	Starts when the crane/base machine wheels are idling and the bundling unit is feeding/compressing trees and ends when the crane/machine starts to move for felling or a bundle is dropped on the scale	3
Scaling and dropping (Drop)	Starts when the crane/base machine wheels are idling and a bundle is dropped on the scale and ends when the bundle is dropped on the ground or the crane/base machine starts moving	3
Miscellaneous (Other)	Other activities e.g. trees are dropped and then picked up again	4
Delays	Time not related to effective work time, e.g. personal breaks, repairing	4

*The lower the number, the higher the priority

536 kg/m^3 calculated for pine (10 plots), spruce (3 plots) and birch (13 plots). The calculated basic density (weighted by tree species) was 505 kg/m^3.

2.5.2 Moisture content

Immediately after harvesting, a 10 cm thick slice (weighing at least 500 g) was cut from half way along a randomly selected bundle from each of the time study plots using a chainsaw. The *MC* of the sample was determined following standard method CEN/TS 14774-2 (2004), and the average *MC* for units dominated by pine, spruce and birch was found to be 53.4 (*SD* 2.5), 58.7 (*SD* 1.3) and 52.6% (*SD* 3.0), respectively.

2.5.3 Fuel consumption and energy efficiency

Throughout the entire field trial period, from May 5–16, the system consumed 1619 liters of diesel fuel during 98.5 PM$_{15}$H (including moving between harvesting units, etc.), of which data recorded during 29.40 PM$_{15}$H were used in the time study. Thus, 69.1 hours of additional time also included unproductive work such as moving between harvesting units, etc. This operational work was performed in the study site under the same conditions, on average, as the average stand conditions during the time study (cf. Table 1). During the total running time (98.5 PM$_{15}$H), 1444 bundles with a total fresh mass of 305,779 kg were produced. The energy efficiency (MJ/*OD* t) and energy return over energy invested (*EROEI*) were calculated using the total fuel consumption, total *OD* mass harvested, heating values of diesel fuel and the biomass of 35.3 MJ/l (cf. Athanassiadis 2000) and 19.2 MJ/kg *TS* (Ringman 1996), respectively, and a *MC* of 53.4% (average value obtained for samples collected from the time study plots).

2.5.4 Other measurements

The biomass losses during the bundling process were measured in a separate test, as follows. The bundling chamber was emptied and then fed with weighed, cut tree sections until it contained enough to produce a full bundle. The bundle was then weighed, and biomass losses were calculated by simply subtracting its mass from the mass of material used to create it. In total 13 bundles were produced using representative samples of trees with close to average characteristics for their respective stands (Table 1). The average mass of these 13 bundles was 493 kg (*SD* 115).

2.6 Analysis and statistics

The remaining stands properties and the time consumed (s/tree), when harvesting precleared and not precleared time study plots, were compared by analysis of variance (ANOVA). Correlation analysis was applied to evaluate correlations between independent variables using Pearson´s correlation test. Analysis of covariance (ANCOVA) was used for analyzing the combined effects of treatments and independent variables on the productivity (*OD* t or bundles/PM$_0$H). Regression analysis was used for testing possible significant predictors of the bundles mass (*OD* kg/bundle). 95% confidence intervals (*CI*) were calculated for the biomass losses (fresh kg) of the bundles. A *p*-level of ≤0.05 was used as a threshold for statistical significance.

3. Results

3.1 Harvest and thinning quality

There were no significant differences in properties between time study plots that were precleared and not precleared prior to thinning, in either harvested (e.g. tree volume, tree height and density) or remaining stands (e.g. basal area, stand density, stem volume, height, damage and strip road spacing). The average tree and average stem volumes cut were 23.3 dm^3 (*SD* 7.7, range 9–28 dm^3) and 16.2 dm^3 (*SD* 5.0, range 12–43 dm^3), respectively. The average tree height and numbers of removed stems for all time study plots were 7.4 m (*SD* 0.7) and 3554 trees/ha (*SD* 1184), respectively.

The remaining stands had, on average, 1852 trees/ha (*SD* 455, in the range of 1014–2651/ha), of which 39, 20 and 41% were pine, spruce and birch, respectively. The number of birch trees per ha was highly correlated to the numbers of both pine trees (*p*=0.04) and spruce (*p*=0.01) per ha, but there was no correlation between numbers of pine and spruce trees per ha. On average, 5.5% (*SD* 4.2) of the remaining trees were damaged and 5.7% (*SD* 7.9) of the strip-road trees. The strip-road width, the distance between strip-roads and the stump height were, on average, 4.5 m (*SD* 0.3), 19.8 m (*SD* 1.3) and 18.3 cm (*SD* 4.5), respectively.

The bundles had a mean fresh weight of 439 kg (*SD* 24.1, in the range of 391–493 kg), and mean dry mass of 203.4 *OD* kg (*SD* 17.3). A correlation test showed that the *OD* mass of the bundles was positively correlated to the proportion of birch trees (*R*=0.394; *p*=0.046) and negatively correlated to the proportion of spruce trees (*R*=–0.409; *p*=0.038) used to create them. There were negative correlations between both proportions of bundled birch and spruce trees (*R*=–0.610; *p*=0.001) and proportions of birch and pine trees (*R*=–0.548; *p*=0.004). Therefore, the following prediction model, with *OD* t/bundle as a dependent variable and proportion of birch trees in the bundle as an independent variable, was constructed:

$$\text{Bundle mass}\left(\frac{OD\text{t}}{\text{bundle}}\right) = 190.27 +$$

$$+0.249\times\left(\text{share of birch, \% No. of trees cut}\right)\left(R^2\left(\text{adj.}\right)\right) =$$

$$= 0.12,\ p = 0.046) \tag{1}$$

3.2 Time consumption

The productive machine hours without delays during the time study amounted to 26.76 PM$_0$H, and delays accounted for 9.1% of the monitored time. Pre clearance (and thus the density of undergrowth trees during thinning) had no significant effect on the harvesting and bundling work time consumption (Table 3). The felling crane was idling 7.4% of the PM$_0$ time, mainly due to problems with feeding large trees and dropping bundles. On average, 4.1 trees/crane cycle were harvested (*SD* 1.0) and there were no differences between treatments in this respect (*p*=0.926). On average, each crane cycle took 44.6 sec (*SD* 4.2), and 5.5 crane cycles (*SD* 0.7) were required to produce a bundle. Hence, on average, 4.1 min of work time was required per produced bundle (*SD* 0.7).

3.2.1 Bundler work

The number of crane cycles required per bundle was highly correlated to the average harvested tree size (*R*=–0.775; *p*<0.001). The time required to produce a bundle was far from significantly correlated to the

Table 3 Distribution of effective work time (s/tree) in work elements (mean values for precleared and not precleared time study plots). *SD*=standard deviation. *p*-values are given for the treatment effect (preclearing vs. no preclearing)

	Stats			
Work element	Mean, s/tree	SD	%	*p*-value
Move	0.8	0.2	7.4	0.661
Fell	5.8	0.5	51.6	0.229
Crut	1.5	0.4	13.2	0.902
Crin	2.1	0.6	18.6	0.792
Artr	0.1	0.1	1.1	0.901
Arbu	<0.1	0.1	0.2	0.240
Bundle	0.5	0.3	4.5	0.848
Drop	0.3	0.1	2.9	0.660
Other	0.1	0.1	0.4	0.658
Total	11.2	2.0	100	0.864

fresh weight of the produced bundles (*R*=0.215; *p*=0.291), but close to significantly correlated to the number of crane cycles required per bundle (*R*=0.367; *p*=0.065) and strongly correlated to the time consumption of the cutting work per bundle (*R*=0.787, *p*=<0.001) (Fig. 3). Thus, the time consumption per bundle was modeled as a function of the time consumption per crane cycle (Fig. 3):

$$\frac{\text{Time}}{\text{bundle}}\left(\text{min}\right) = -1.95 + 0.136\left(\frac{\text{time}}{\text{crane}}\text{cycle, s}\right),$$

$$R^2\left(\text{adj.}\right) = 0.60\%,\ p =< 0.001 \qquad (2)$$

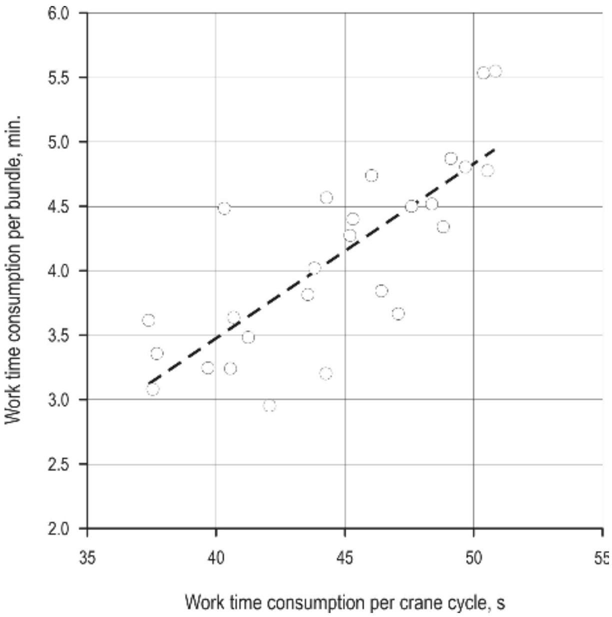

Fig. 3 Time consumption (PM_0) of the bundle-harvester to produce a bundle as a function of time consumption per crane cycle work. Calculations are based on average values for 26 time study plots

3.3 Productivity

The productivity reached, on average, 3.1 *OD* t/PM_0H (*SD* 0.6) (6.6 fresh t/PM_0H, *SD* 1.2) (Table 4 and Fig. 4). The independent variable harvested stem volume (dm^3) provided the highest predictive power, R^2(adj) value, and hence was used as a single covariate in the ANCOVA analysis. All combinations of other inde-

Table 4 ANCOVA table and linear regression model of the bundle-harvester productivity (*OD* t/PM_0H)

Source	*DF*	Seq. *SS*	Adj. *SS*	Adj. *MS*	*F*	*p*	R^2	R^2, adj.
Stem volume, dm^3	1	6.625	6.813	6.813	–	<0.001	–	–
Treatment	1	0.197	0.197	0.197	54.36	0.222	–	–
Error	23	2.882	2.883	0.125	1.58	–	–	–
Total	25	9.705	–	–	–	–	0.700	0.68
Regression terms	Coeff.	*SE* coeff.	T	–	–	–	–	–
Constant	1.3865	0.2410	5.75	–	–	<0.001	–	–
Stem volume, dm^3	0.10556	0.01432	7.37	–	–	<0.001	–	–

Table 5 ANCOVA table and linear regression model of the bundle-harvester productivity (bundles/PM_0H)

Source	*DF*	Seq. *SS*	Adj. *SS*	Adj. *MS*	*F*	*p*	R^2	R^2, adj.
Stem volume, dm^3	1	138.598	142.074	142.074	78.55	<0.001	–	–
Treatment	1	3.560	3.560	3.560	1.97	0.174	–	–
Error	23	41.602	41.602	1.804	–	–	–	–
Total	25	183.760	–	–	–	–	0.77	0.75
Regression term	Coeff.	SE Coeff	T	–	–	–	–	–
Constant	7.3805	0.9154	8.06	–	–	<0.001	–	–
Stem volume, dm^3	0.48205	0.05439	8.86	–	–	<0.001	–	–

pendent variables gave less good predictions and/or were biased by multicollinearity (Tables 4 and 5).

On average, 15.1 bundles/PM_0H were produced (*SD* 2.7, in the range of 10.8–20.3; Fig. 4). The stem volume provided slightly better productivity predictions, R^2(adj.) values of 0.75 vs. 0.68, in terms of bundles/PM_0H than in terms of *OD* mass (cf. Tables 4 and 5).

3.3.1 Energy efficiency and biomass losses

During the total field trial period (98.5 $PM_{15}H$), the system consumed 15.87 MWh of diesel fuel and produced 1392 MWh of biofuel, corresponding to an average energy efficiency of 401 MJ/OD t (PM15 time) (441 MJ/OD t in PM_0 time) and an EROEI of 80.6 (in PM_{15} time) (88.7 in PM_0 time). On average, a bundle had a fresh weight of 454 kg, corresponding to 0.96 MWh, and fuel consumption averaged 15.1 l/PM_0H (16.4 l per hour of machine work time during the whole trial period (approximates to PM_{15} time)).

The tree sections lost, on average, 37 kg (*SD* 29) mass during the bundling process, as measured in the separate test, 7.1% of their mean mass (±3.0%; in the range of 4.1–10.1%). By visual inspection, this mass consisted mainly of fine branches and needles.

4. Discussion

Unexpectedly, the density of undergrowth trees did not significantly affect the efficiency of the cutting work, as found in previous studies (e.g. Kärhä 2006, Jonsson 2015). A possible contributory factor explaining the results in the present study is related to the nature of the undergrowth, as the study was performed in the beginning of May, when broadleaves have just started to sprout and thus might have only slightly reduced visibility. Accordingly, Jonsson (2015) found that defoliated undergrowth reduces visibility much less than fully leafed trees. Furthermore, the operator used techniques with efficient crane movements, similar to those applied in boom-corridor thinning as described in Bergström et al. (2007), which could have minimized the effects of undergrowth. The undergrowth did not affect the quality of the thinning work either, which is consistent with the hypothesis that the undergrowth did not significantly impair visibility of the operator. However, few of the harvested units in our study had dense spruce undergrowth, which may be significant as spruce has greater branchiness than pine and birch (cf. Kärhä 2006), and thus may have stronger effects. In conventional pulpwood and energy wood thinning, only tree-sizes above ca 7–9 cm *DBH* are extracted as commercial assortments, meaning that undergrowth trees are defined as trees below ca. 7–9 cm *DBH*. In that sense, comparing the cutting efficiency in precleared stands not precleared stands would likely give higher effects than found in this study. Thus, it is likely that the effects of undergrowth clearance up to ca. 8 cm *DBH* would have given significant differences in work efficiency between the treatments. However, such comparison would be irrelevant since we studied whole tree biomass thinning, which here is defined as utilization of all trees, including their tops and branches, above 2.5 cm *DBH*. The productivity recorded in the present study

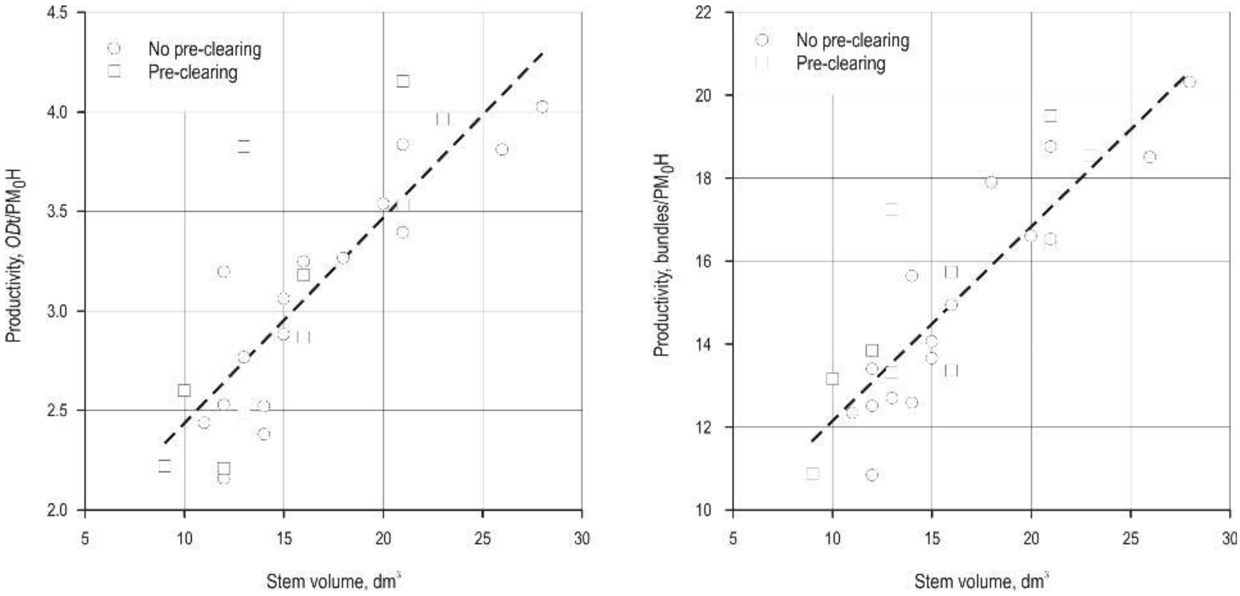

Fig. 4 Productivity (to left, *OD* t/PM_0H and to right, bundles/PM_0H) of the bundle-harvester system as a function of average size of harvested tree

was 23% and 9% lower than values recorded by Nuutinen and Björheden (2015), for harvesting trees of 27 dm^3 and 44 dm^3, respectively, when the same bundle-harvester system was used for thinning pine dominated stands during winter (Fig. 4). However, the cited authors only used fresh masses in their production estimates, without measuring the *MC*, and for conversion to solid volumes, they used a density of 855 kg/m^3solid, thus for comparison to values presented here, a *MC* of 53.4% was assumed for their biomass. Furthermore, the uncertainties (deviations of average values) of the data are not stated in the cited study, therefore, no definitive conclusions regarding similarities or differences in productivity can be drawn, but as indicated by the trends shown in Fig. 5, the results seem to be consistent.

The results presented here and by Nuutinen and Björheden (2015) show that the cutting efficiency is the limiting factor for the system. The bundle-harvester system monitored in both studies was equipped with a Nisula 280E+ accumulating felling head that cuts trees with sheares/knives. This type of head is robust and requires less hydraulic pressure than heads with saws, but the cutting efficiency is generally limited by the need to keep the head still while cutting a tree, regardless of the tree size cut. However, the Bracke C16 can sweep short distances (ca 1–2 m) during cutting (www.brackeforest.com), and thus cut trees during a continuous movement. This technique can provide improvements in productivity that are negatively related to the size of cut trees and positively related to the degree of continuous crane movement used, as shown by e.g. Bergström et al. (2007), Bergström (2009) and Sängstuvall et al. (2012). Bergström and Di Fulvio (2014a) modeled operations of an optimized bundle-harvester based on the Bracke C16 accumulating felling and bunching head, with no idle time between the crane and bundling work, and obtained simulated productivities (assuming the same conversion rate as used above) of 15 and 21 m^3/PM_0H for harvesting trees of 27 dm^3 and 44 dm^3, respectively. These values are in average 55% and 76% higher, for trees of corresponding sizes, than those recorded in the present study and by Nuutinen and Björheden (2015). The modeling indicates that there is significant potential to increase productivity if efficient felling and bunching technologies are integrated with bundling systems.

Bergström and Di Fulvio (2014a) also considered new cutting technologies especially designed for continuous cutting and accumulation in boom-corridors combined with optimized bundling systems (i.e. with no idle time between cutting and bundling). Such bundle-harvester systems could significantly reduce costs in stands where the average size of cut trees is <30 dm^3. They also show that a conventional bundle-harvester system, such as the Fixteri system equipped with (for instance) a Bracke C16 head, is less costly when cutting trees from ca. 30 to ca 70 dm^3.

It should be noted that biomass losses during the bundling process lead to proportional losses in productivity, and are probably correlated to the sizes of cut trees, and ratios of conifers to broadleaves. However, in a study of a test-bench for compression-processing of bunched small-diameter conifer trees, Bergström et al. (2010) found that processing fresh bunches resulted in mass losses of about 10% to 15% (for trees of 5–8 and 12–15 cm *DBH*, respectively), with 35–50% reductions in ash contents and 80–160% increases in bulk and net energy density. In the present study mass losses of 4–10% were recorded, consisting mainly of nutrient-rich fractions (according to visual observations), indicating that the ash content in stands, where mostly conifers are cut, could be decreased by up to ca 35%.

Whether the losses due to bundling should be minimized or set at certain levels is a question of prioritizing productivity or nutrient removal and fuel quality. This question is highly relevant when considering stands that are sensitive to nutrient removal as the studied bundle-harvester cut and bundle the whole tree above ground. For instance, in Finland the whole-tree harvesting guidelines for early thinnings report that ca. 30% of the biomass cut after whole-tree harvesting should be left at the felling site (cf. Kärhä 2015a), e.g. by preclearing trees below 7–9 cm *DBH* and by delimbing the trees cut by harvester. In studies of the Bracke MAMA prototype head designed for compression-processing, Bergström and Di Fulvio (2014b) found that biomass losses during processing reduced harvesting yields by 10–23%. Thus, bundling using the Fixteri FX15 system seems to result in relatively low biomass losses and to be less »aggressive« than the feed-roller-based compression-processing techniques studied by Bergström et al. (2010) and Bergström and Di Fulvio (2014b). However, the magnitude of losses due to compression/bundling should be controlled, regardless of the technology and system used, to optimize the balance between productivity and losses in accordance with stand conditions and economic goals. The additional tests of biomass losses during processing of bundles did not cover all possible types of tree mixtures that can occur in thinnings, but the results indicate possible losses for pine-dominated stands. Losses are likely to be similar for spruce-dominated stands and lower for birch-dominated stands, but differences in losses between seasons are also likely, because (for instance) branches are more brittle when frozen.

The study provides predictive models for early thinnings from below in dense stands, in which trees with 9–28 dm^3 stem volumes are cut, and production data in both fresh and *OD* masses per effective hour of work, derived using moisture contents of representative samples. The productivity prediction models are highly significant and provide high precision estimates. The overall productivity for the whole trial time is very similar to values obtained from the time study, corroborating the robustness of the models obtained from the time study plots. However, users should be aware of the limited numbers of operators and stand types that the models are based upon. The operational fuel consumption during the field trial period is consistent with earlier measurements under somewhat different conditions (Jylhä 2011), indicating that the system consumes ca. 16 l diesel/PM$_{15}$H. However, effects on fuel consumption of variations in sizes of cut trees (and hence productivity) were not measured due to limitations in resources.

The conditions at the study site are representative of large tracts of forest in Sweden, especially in northern parts (cf. Fernandez-Lacruz et al. 2015). To cover forests more representative of southern parts, spruce-dominated stands with high proportions of suppressed birch trees and spruce undergrowth should be included in further studies. The study was conducted in forest sites with good bearing capacity, low roughness and limited slopes. Due to the system's high mass, it could potentially be limited by difficult soil conditions, thus further studies are also needed to assess effects of soil properties on its operational efficiency. The machine's center of gravity was not measured, but it is likely to be higher than for a standard harvester, due to the addition of the bundling unit. This might also somewhat restrict the machine's operational maneuverability on slopes, and warrants investigation.

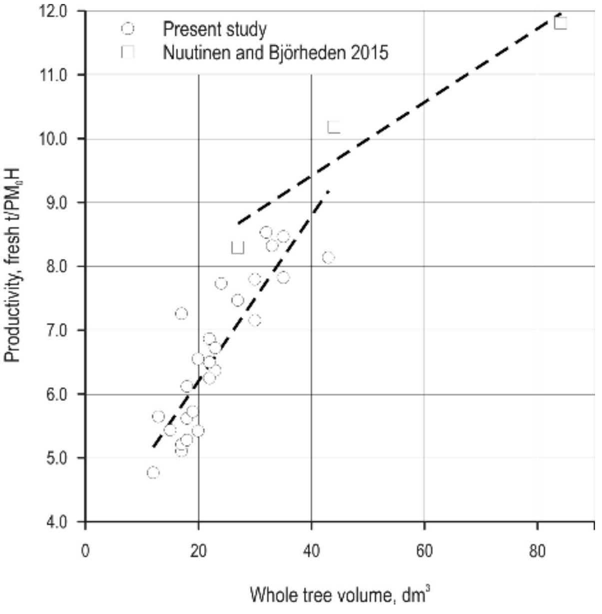

Fig. 5 Productivity as a function of harvested whole tree size (stem+branch volume) recorded in the present study and according to findings by Nuutinen and Björheden (2015)

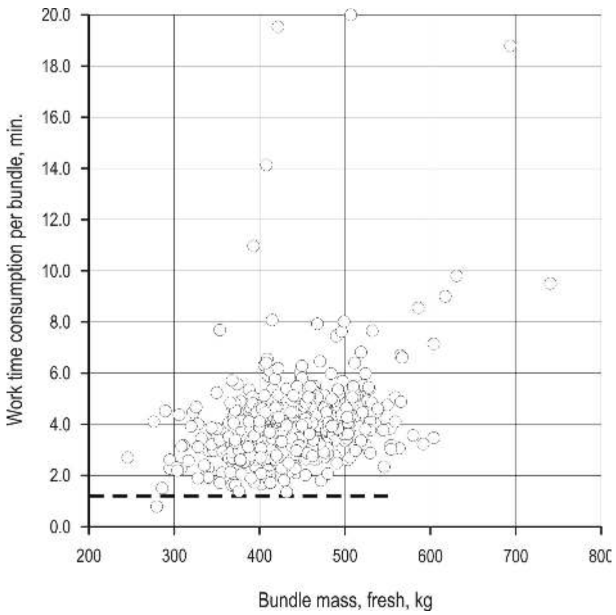

Fig. 6 Time consumption to produce a bundle as a function of the bundles mass. The dotted line indicates the maximum capacity of 1.2 min/bundle, reached for bundles with masses between 400 and 500 kg in the study. Values of time consumption lower than ca. 7 min are considered as PM$_0$ time, i.e. work with no delays

The operator's effect was kept constant during the trials, although the time study covered all weekdays and daylight hours. In order to obtain more comprehensive results, reflecting variations in operator skills, using several drivers would be advantageous, as operators strongly affect the performance of harvesters in thinning (cf. Väätäinen et al. 2005, Lindroos 2010). However, the main aims of the study were to study the effects of undergrowth density on productivity, as well as productivity levels *per se*. Thus, the study design included compromises intended to meet these twin aims, and keeping the operator constant reduces both costs and management complexities. During the whole trial period, between the time studies another operator also drove the machine. The mean productivity during this period was 14.7 bundles/PM$_{15}$H or 3.1 *OD* t/PM$_{15}$H (very similar to PM_0H values since delays were minor), in line with the time study, which indicates that differences in productivity levels between operators were minor. However, the cutting work with the head used here is relatively slow and straightforward. Thus, if a felling and bunching head affording higher cutting efficiency (and hence more complex movements) was used, there would probably be greater differences in the efficiency between operators. In such cases crane manoeuvrability can be supported to a higher extent by shared control/semi-automation (cf. Jundén et al. 2012).

The average mass of bundles produced in the time study was 439 kg, and their masses were correlated to the proportions of birch trees in the initial stands, as birch wood is generally denser than pine and spruce wood. The dotted line in Fig. 6 indicates the minimum bundling time that was approximately reached for bundles with a fresh weight between 400 to 500 kg, showing that the maximum capacity of the system was ca. 1.2 min per bundle. This would correspond to a crane cycle time of 23.2 sec, according to the function in Fig. 3, and provide productivity of 20 fresh t/PM_0H. Assuming that the factor for conversion to $PM_{15}H$ is 1.3, the productivity would be ca. 100% higher when harvesting trees with an average volume of 23 dm^3 than reported by Bergström and Di Fulvio (2014a).

During the time studies, it was noted that some extra »planning time« occurred during unloading/dropping of bundles, as the operator had to check that there was enough space in the place allocated for unloading in order to avoid damaging the remaining trees and ensure that bundles were located off-road, which is highly important for efficient forwarding work. For example, sometimes dropped bundles fell into the strip road area and had to be relocated before forwarding, since the allocated forwarder crane work area is in the opposite direction to the driving direction.

5. Conclusions

The efficiency of the studied bundle-harvester was not affected by the density of undergrowth trees, but highly correlated with the size of harvested trees. The study provides information about the system's performance that complements earlier findings, especially when handling relatively small trees, and the recorded productivity is consistent with previous reports. The system's time consumption per bundle was not affected by either tree size or the mixture of tree species harvested, but the mass of the bundles was positively correlated with the proportion of birch trees cut. The bundling unit maximum efficiency was not reached during the trial, but estimates indicate that it could be significantly (perhaps up to 100%) higher. However, to reach such efficiency, the system would have to be equipped with a felling and bunching head that can cut trees during continuous boom movements. In the near future it should be equipped with a head with higher cutting efficiency, e.g. the Bracke C16 head, and its productivity, manoeuvrability and quality of bundles should be further investigated in various forest conditions.

Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2012-2015) [grant agreement no. 311881] and the SKM project was funded, *inter alia*, by the Swedish Energy Agency.

6. References

Andersson, S.O., 1954: Funktioner och tabeller för kubering av småträd [Functions for stem volume prediction of small trees]. Meddelanden från Statens Skogsforskningsinstitut, Band 44 nr 12. (In Swedish).

Athanassiadis, D., 2000: Energy consumption and exhaust emissions in mechanized timber harvesting operations in Sweden. Sci Total Environ. 255(1–3):135–143.

Berg, S., 1992: Terrain classification system for forestry work. Kista: The Forest Operations Institute of Sweden. 28 p.

Bergström, D., 2009: Techniques and systems for boom-corridor thinning in young dense forests. Doctoral thesis. Acta Universitatis Agriculturae Sueciae, 87 p.

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

Bergström, D., Nordfjell, T., Bergsten, U., 2010: Compression processing and load compression of young Scots pine and birch trees in thinnings for bioenergy. International Journal of Forest Engineering 21(1): 31–39.

Bergström, D., Matisons, M., 2014: Forest Refine 2012–2014 – Efficient forest biomass supply chain management for biorefineries. Synthesis report. Swedish University of Agricultural Sciences, Department of Forest Biomaterials and Technology, Work report 2014:18.

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

Bergström, D., Di Fulvio, F., 2014b: Studies on the use of a novel prototype harvester head in early fuel wood thinnings. International Journal of Forest Engineering, 25(2): 156–170.

Björheden, R., Fröding, A., 1986: A new routine for checking the biological quality of thinning in practice. The Swedish University of Agricultural Sciences, Department of Operational Efficiency Research Notes 48, 14 p.

CEN/TS 14774-2, 2004: Solid biofuels – Methods for the determination of moisture content – Oven dry method – Part 2: Total moisture – Simplified method.

Fernandez-Lacruz, R., Di Fulvio, F., Athanassiadis, D., Bergström, D., Nordfjell, T., 2015: Distribution, characteristics and potential of biomass-dense thinning forests in Sweden. Silva Fennica 49 (5): article id. 1377, 17 p.

Hakkila, P., 1978: Harvesting small-sized trees for fuel. Folia Forestalia, 342, 38 p.

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.

Jirjis, R., 1995: Storage and drying of wood fuel. Biomass and Bioenergy 9 (1–5): 181–190.

Jylhä, P., Laitila, J., 2007: Energy wood and pulpwood harvesting from young stands using a prototype whole-tree bundler. Silva Fennica 41(4): 763–779.

Johansson, J., Liss, J.E., Gullberg, T., Björheden, R., 2006: Transport and handling of forest energy bundles–advantages and problems. Biomass and Bioenergy 30(4): 334–341.

Jonsson, F., 2015: Hur påverkar avlövad underväxt kvaliteten och drivningskostnaden i gallring? [Effects of defoliated undergrowth trees on harvesting cost in thinnings]. Master's thesis. Swedish University of Agricultural Sciences, Department of Forest Biomaterials and Technology, Work report 2015:08. (In Swedish).

Jylhä, P., 2011: Harvesting undelimbed Scots pine (*Pinus sylvestris* L.) from first thinnings for integrated production of kraft pulp and energy. Academic dissertation. Dissertationes Forestales 133. University of Helsinki, 73 p.

Jylhä, P., Latila, J., 2007: Energy wood and pulpwood harvesting from young stands using a prototype whole-tree bundler. Silva Fennica 41(4): 763–779.

Kons, K., Bergström, D., Eriksson, U., Athanassiadis, D., Nordfjell, T., 2014: Characteristics of Swedish forest biomass terminals for energy. International Journal of Forest Engineering 25(3): 238–246.

Kärhä, K., 2006: Effect of undergrowth on the harvesting of first-thinning wood. Forestry Studies 45: 101–117.

Kärhä, K., 2011: Industrial supply chains and production machinery of forest chips in Finland. Biomass and Bioenergy 35(8): 3404–3413.

Kärhä, K., 2015a: Alikasvoksen ennakkoraivaus ja ensiharvennuspuun korjuu [Preclearing of undergrowth and harvesting of pulpwood in first thinnings]. TTS:n tiedote: Metsätyö, –energia ja – yrittäjyys 1/2015 (781). 8 p. (In Finnish).

Kärhä, K., 2015b: Towards better pre-clearance guideline of undergrowth in first thinnings: Case study Stora Enso Wood Supply Finland. Proceedings of the 48th FORMEC Symposium 2015 – Forest Engineering: Making a positive contribution, October 4–8, Linz, Austria.

Kärhä, K., Vartiamäki, T., 2006: Productivity and costs of slash bundling in Nordic conditions. Biomass and Bioenergy 30(12): 1043–1052.

Kärhä, K., Jylhä, P., Laitila, J., 2011: Integrated procurement of pulpwood and energy wood from early thinnings using whole-tree bundling. Biomass and Bioenergy 35(8): 3389–3396.

Laitila, J., Kärhä, K., Jylhä, P., 2009: Time consumption models and parameters for off and on-road transportation of whole-tree bundles. Baltic Forestry 15(1): 105–114.

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.

Marklund, L.G., 1987: Biomassafunktioner för tall, gran och björk i Sverige [Biomass functions for pine, spruce and birch in Sweden]. Sveriges lantbruksuniversitet, Institutionen för skogstaxering, Rapport 45, 79 p. (In Swedish).

Nordfjell, T., Liss, J.E., 2000: Compressing and drying of bunched trees from a commercial thinning. Scandinavian Journal of Forest Research 15(2):284–290.

Nuutinen, Y., Björheden, R., 2015: Productivity and work processes of small-tree bundler Fixteri FX15a in energy wood harvesting from early pine dominated thinnings. International Journal of Forest Engineering, http://dx.doi.org/10.1080/14942119.2015.1109175

Näslund, M., 1947: Functions and tables for computing the cubic volume of standing trees. Pine, spruce and birch in southern Sweden and in the whole of Sweden. Reports of the Forest Research Institute of Sweden, 36, 1–41.

Nuutinen, Y., Kärhä, K., Laitila, J., Jylhä, P., Keskinen, S., 2011: Productivity of whole tree bundler in energy wood and pulpwood harvesting from early thinnings. Scandinavian Journal of Forest Research 26(4): 329–338.

Nuutinen, Y., 2013: Possibilities to use automatic and manual timing in time studies on harvester operations. Doctoral thesis. Dissertationes Forestales 156, 68 p.

Pettersson, M., Nordfjell, T., 2007: Fuel quality during seasonal storage of compacted logging residues and young trees. Biomass & Bioenergy 31(11): 782–792.

Ringman, M., 1996: Wood fuel assortments – definitions and properties. Department of Forest Products. Report No. 250. The Swedish University of Agriculture Sciences. Uppsala. ISSN 0348-4599.

Routa, J., Asikainen, A., Björheden, R., Laitila, J., Röser, D., 2013: Forest energy procurement: State of the art in Finland and Sweden. Wiley Interdisciplinary Reviews: Energy and Environment 2(6): 602–613.

Sängstuvall, L., Bergström, D., Lämås, T., Nordfjell, T., 2012: Simulation of harvester productivity in selective and boom-corridor thinning of young forests. Scandinavian Journal of Forest Research 27(1): 56–73.

Väätäinen K, Ovaskainen H, Ranta P, Ala-Fossi A. 2005: Hakkuukoneenkuljettajan hiljaisen tiedon merkitys hakkuutulokseen työpistetasolla [The significance of the harvester operator's tacit knowledge on cutting with a single grip harvester]. Metsäntutkimuslaitoksen tiedonantoja 937; 100 p. (In Finnish).

Wallentin, C., 2007: Thinning of Norway spruce. Acta Universitatis Agriculturae Sueciae, 29. Doctoral Thesis. ISBN 978-91-576-7328-2.

Received: May 29, 2015
Accepted: November 30, 2015

Authors' address:

Researcher, Assoc. prof. Dan Bergström, D. Tech.*
e-mail: dan.bergstrom@slu.se
Department of Forest Biomaterials and Technology
Swedish University of Agricultural Sciences
SE-901 83 Umeå
SWEDEN

Researcher, Fulvio Di Fulvio, PhD.
e-mail: fulvio.di.fulvio@slu.se; difulvi@iiasa.ac.at
Department of Forest Biomaterials and Technology
Swedish University of Agricultural Sciences
SE-901 83 Umeå
SWEDEN

and
International Institute for Applied Systems Analysis
Ecosystems Services for Applied Systems Analysis
A-2361, Laxemburg
AUSTRIA

Researcher, Yrjö Nuutinen, PhD.
e-mail: yrjo.nuutinen@luke.fi
Natural Resources Institute Finland
FI-801 01 Joensuu
FINLAND

* Corresponding author