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Energy Wood and Pulpwood Harvesting from Young Stands Using a Prototype Whole-tree Bundler

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The productivity of cutting and bundling whole trees using the first prototype of a bundle-harvester comprised of a harwarder as the base machine, an accumulating felling head, and a compacting device was studied in three young stands in order to facilitate the further development of the concept. In addition, the removal and its composition were studied as a means of laying the foundations for developing methods for work rating and measurement on delivery. Bundling enables in-depth integration of pulpwood and energy wood procurement. Both energy wood (crown biomass) and pulpwood can be incorporated into the same bundles, and the subsequent separation of these fractions takes place at the debarking phase at the pulpmill. Bundle-harvesting productivities were relatively low (2.8–3.7 m^3/E_0-h) when compared to current harvesting technology. Improving working techniques, machine structure, and components showed great potential for increasing the efficiency of the concept. The bundles were dimensionally uniform. Their solid volume varied between 0.350 m^3 and 0.513 m^3, depending on the bundle assortment and stand properties. Integrating energy wood harvesting with pulpwood harvesting increased removal even by 59 per cent.

Keywords bundling, integrated harvesting, energy wood, pulpwood, productivity, Fixteri
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1 Introduction

1.1 Background

In Finland, more than half of the forestland is covered by advanced seedling stands and young thinning stands (Finnish… 2006). Thinning these stands is required in order to guarantee a good future supply of industrial roundwood. Due to inferior wood quality and high harvesting costs resulting from small stem sizes and low harvestable volumes per hectare thinnings have been neglected in recent years. The stand age distribution in Finnish forestry is such that harvesting of young stands is expected to increase in the near future (Rummukainen et al. 2003). Furthermore, restrictions on raw wood imports from Russia are likely to increase the demand for domestic pulpwood harvested from thinning stands (Hänninen and Kallio 2007). The increase in harvest volumes from young stands can result in a substantial increase in procurement costs if the development of harvesting methods is not approached with an open mind. The price level raw wood is a crucial issue for the forest industries.

Alongside increasing thinnings, the use of energy wood is likely to further increase. Since 2000, the annual consumption of forest chips at heating and power plants has increased almost 4-fold to 3.4 million solid m^3 (Ylitalo 2007). One of the goals of Finland's energy and climate strategies is to promote the use of forest chips and bring the consumption figure up to 5 million m^3 per year (0.9 mtoe) by 2010. The Finnish Forest Council aims to further raise the target up to 8 million m^3 by 2015 (Metsäsektorin tulevaisuuskatsaus 2006). Integrating energy wood harvesting with pulpwood harvesting is considered to be a promising solution in reducing the procurement costs of small-diameter wood (Rummukainen et al. 2003). In the future, woody biomass can be an important base material for many biorefinery products as well, e.g. transport fuels. Some forest companies have already announced their intentions to invest in new-generation biofuel production (UPM Kymmene Corporation 2006, Stora Enso Oyj 2007). Probably the most cost-efficient way to organize the raw material procurement for these products as well is to integrate it with the industrial raw wood procurement chain.

Short-haul and long-distance transportation costs amount to 30–60% of the costs of raw wood procurement at the mill or the power plant gate, depending on the distance and the harvesting method (Hakkila 2003, Kariniemi 2006a). In the case of energy wood, increasing bulk density in a cost-efficient way is regarded to be the most important means of reducing procurement costs (Rummukainen et al. 2003). At the turn of the millennium, compacting slash into cylindrical "logs" by means of a slash bundler was a breakthrough, which enabled large-scale energy wood procurement from remote final-felling sites with efficient process control. Hakkila (2004) enumerates expanding this method's field of application from logging residues to small-diameter tree material as being one of the potential steps of development in energy wood harvesting. According to Laitila et al. (2004), however, a harvesting chain including a feller-buncher, a forwarder, and a bundling machine operating at the roadside landing is not a competitive alternative when harvesting in young stands as the savings in long-distance transportation and crushing at the end-use facility are not sufficient to cover the compacting costs. Bundling might be profitable only if the bundling unit is integrated with the feller-buncher.

Glöde (2000) introduced a theoretical concept for integrated harvesting of merchantable wood and wood fuel from final fellings based on the notion of a single-grip harvester equipped with a unit for compacting the logging residues. The harvester would process the trees over a platform onto which the tops and branches would fall to be automatically compacted into bales. He demonstrated that wood fuel costs could be reduced by approximately 40% when compared to loose-chip systems and 20% when compared to the slash-baling system. Berglund et al. (1991) studied a prototype (the Long Bundler) capable of bundling small-diameter trees at the stump. Complemented with accumulating felling it was included in a simulation study conducted by Björheden et al. (2003). The system showed great potential in regard to cost reduction when harvesting small-diameter trees (DBH 3.0–10.5 cm) for fuel; the cost reduction was especially marked when dealing with the largest diameter classes. The costs of bundle forwarding were low as a result of the short times needed for loading and unloading.

Further savings were expected in long-distance transportation.

Jylhä (2004) described in her pilot study a conceptual system for in-depth integration of pulpwood and energy wood procurement from thinning stands. In this system the trees are harvested using a bundle-harvester comprised of a base machine, an accumulating felling head, and a compacting device. Both the energy wood fraction (crown biomass) and the pulpwood fraction are incorporated into the same bundles. These fractions are not separated until in the debarking plant of the pulpmill. Increased recovery in the form of tops and branches compensates for the high harvesting costs of pulpwood. Cost reduction in transportation due to load compaction, however, is estimated to be the foremost advantage of the bundling method when compared to conventional whole-tree and tree-section methods. Studies by Nordfjell and Liss (2000) and Jylhä (2004) have demonstrated that the load-bearing capacity of standard trucks can be utilized to a high degree when transporting bundled green tree-sections containing pulpwood and energy wood. For short-distance hauling using conventional forwarders, expansion of the load space was required in order to improve the degree of utilization of the forwarder's load-bearing capacity.

The feasibility of bundles containing pulpwood and energy wood for pulpmill processes has been studied by Jylhä and Keskinen (2006). In the debarking experiment, 8% and 16% (of the volume) of the bundles harvested from a young Scots pine (*Pinus sylvestris*) stand were added to a wood flow consisting of conventional pine pulpwood. The debarking experiment was successfully completed and there were no significant differences in the physical properties of the chip batches. The pulp properties of the blend batches did not differ from the reference batch containing 100% of conventional pulpwood. Process losses were; however, higher than in the reference batch. Virtually all these losses can be made use of in energy generation or as the base for biorefinery products.

1.2 The Purpose of the Study

Only recently, combining bundling machinery with conventional harvester technology was still considered to be a complex economic and technological problem for which there appeared to be no solution in sight (Hakkila 2004). Following the publication of the results of the studies described above, however, the first prototype of a bundle-harvester was constructed. It was studied in energy wood harvesting and in integrated energy-and-pulpwood harvesting in three mixed young stands. The research effort of this pilot study focused primarily on identifying bottlenecks in the bundle-harvesting process (i.e. cutting and compaction) in order to facilitate the further development of the concept. In addition, recovery estimates based on the stand data were compared with actual bundle removals and their composition in order to lay the foundations for developing methods for work rating and measurement on delivery.

2 Material and Methods

2.1 Bundle-harvester and Its Working Pattern

The studied bundle-harvester prototype (the Fixteri) is comprised of a four-cylinder Valmet 801 Combi harwarder (95 kW at 2200 rpm) as the base machine (cabin capable of 540° rotation), an accumulating felling head with guillotine blades (Naarva-Grip 1500-40E, max. cutting diameter 30 cm), and a rotating, semi-automatically operating bundling unit mounted on the rear-end of the harwarder (Fig. 1). The felling head is mounted on a parallel-action crane providing a reach of 11 meters. The capacity of the hydraulic system is 280 l/min.

The working pattern in bundle-harvesting resembles that of a two-grip harvester equipped with an accumulating felling head (Fig. 2). After felling and accumulation, the bunch of trees is laid down on the ground to enable the gripping point to be shifted from the butt-end of the bunch upwards. The bunch is lifted butt-end first onto the feeding table of the bundling unit (located at a height of 1.8 m above the ground) and to be pulled from there into the accumulation and compaction chamber. Next, the bunch is cut into length of about 2.6 m by a chainsaw installed at the chamber gate. Usually the shortest top sections fall onto the ground along the strip road

Fig. 1. The bundle-harvester prototype.

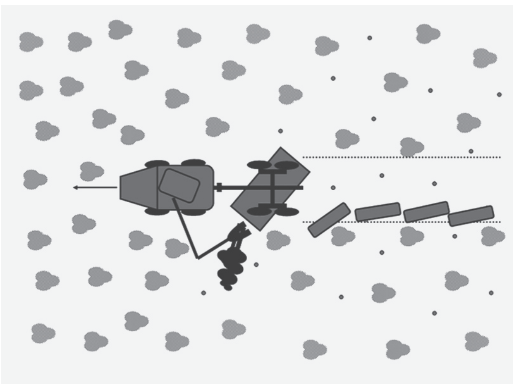

Fig. 2. Working pattern of the prototype bundle harvester.

after being cut. The feeding action has to be assisted by pushing the bunches inwards using the crane. After the feeding action is completed, the felling head is transferred to the next tree. The accumulation and compaction chamber contains a sensor, which detects the amount of woody material in the chamber. When the chamber is full, the accumulated bundle is lifted into the tying-up chamber above. After being wrapped with six loops of sisal string around each of the four binding points, the bundle is dropped onto the strip road. Meanwhile, a new bunch of wood is being accumulated in the lower chamber, and the harvesting process is designed to take place simultaneously with the bundling process. When making more than one bundle assortment, the trees are occasionally sorted and bunched along the strip road to await subsequent feeding into the bundling unit.

2.2 Time Studies

The data were collected in Kangasniemi, Central Finland, in February 2006. The productivity of the prototype bundle-harvester was studied in three stands. The time studies were carried out on plots measuring 50 m × 20 m. The tree data were collected from four circular 50 m^2-sample plots set within the time study plots as shown in Fig. 3.

The tree data were used for predicting the potential removal in bundle-harvesting. Trees with a minimum breast height diameter (DBH) of 40 mm were numbered and marked on the circular sample plots before harvesting. Besides DBH, height (H) was measured from all these

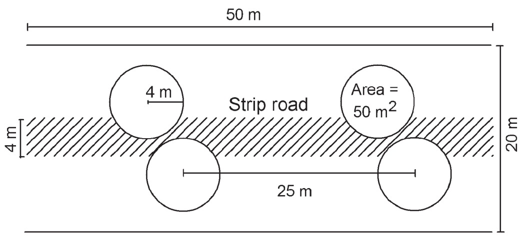

Fig. 3. Location of the sample plots for stand measurements in the time study areas.

trees. Furthermore, the number of undergrowth with diameter at stump height exceeding 1 cm was recorded on each plot. After harvesting, the remaining trees were recorded in order to compute the removal, and potential damage to remaining trees was monitored on the circular sample plots. The stem volumes of the trees were computed using Laasasenaho's (1982) models. The dry weights of the tree crowns (branches and conifer foliage) were calculated using the models of Marklund (1988) including DBH and H. The basic stand data for the initial stands and removed trees are shown in Table 1.

The time study was carried out manually using the continuous timing method and field computers. The operation was followed by two observers. One of the two concentrated on the entire process, especially on the simultaneousness of various functions of the bundle-harvester. The effective working time (E_0 the working time excluding delays) of the bundle-harvester was then divided into following work phases:

– Moving
– Clearing undergrowth (in Stand 1 only)
– Harvesting
– Harvesting simultaneously with bundling
– Moving simultaneously with bundling
– Feeding the bundler and cross-cutting the bunches

Table 1. Basic stand data.

	Stand 1		Stand 2		Stand 3	
	Initial stand	Removal	Initial stand	Removal	Initial stand	Removal
No. of stems ha^{-1}	*3950*	*2850*	*2750*	*1400*	*2650*	*1800*
– Pine	2400	1550	0	0	1200	650
– Spruce	300	300	1650	800	750	600
– Birch	1250	1000	1100	600	700	550
Mean DBH, mm	*92*	*78*	*98*	*85*	*100*	*83*
– Pine	114	98	-	-	120	95
– Spruce	54	54	92	74	94	85
– Birch	59	54	107	99	71	66
Stem volume, m^3/ha	196	96	149	56	141	55
– Pine	174	82	149	0	89	26
– Spruce	3	2	69	17	33	17
– Birch	19	12	80	39	20	12
Mean stem volume, dm^3	*50*	*34*	*54*	*40*	*53*	*31*
– Pine	72	53	-	-	74	40
– Spruce	11	11	42	21	44	28
– Birch	15	12	73	65	28	21
Mean height, dm	*92*	*94*	*95*	*83*	*101*	*91*
– Pine	109	101	-	-	107	95
– Spruce	54	54	86	71	84	77
– Birch	99	94	108	99	109	103
Amount of undergrowth ha^{-1}	*7150*		*11 350*		*4200*	
Total above-ground dry biomass, kg ha^{-1}	102 501 (91 358 [a)])	50 408 (43 713 [a)])	97 453	38 146	79 815	32 900

[a)] Deciduous trees excluded

– Compacting and tying up the bundles
– Dropping the bundles out of the tying-up chamber

The other observer monitored the harvesting process in detail, focusing especially on the crane functions. When cutting and accumulating the trees, the number of trees in each grapple load was recorded. The effective working time, E_0, was divided as follows:
– Moving
– Crane out (moving and positioning the felling head)
– Cutting and accumulating the pulpwood trees (in Stand 1 and 3)
– Laying the bunches on the ground
– Sorting
– Loading the bundling unit
– Feeding the bunches into the compacting unit
– Cutting the bunches
– Compacting and tying up the bundles
– Dropping the bundles out of the tying-up chamber
– Clearing undergrowth
– Cutting and accumulating energy wood trees (in Stand 2 and 3)

During the time studies, there was 40 cm of snow on the ground and the temperature varied between 0 °C and –5 °C. The trials were carried out in daylight. The operator had two years' experience as a harvester operator and he had operated the bundle-harvester for three months prior to the trial.

2.3 Bundle Properties

Two types of bundles were produced in the trial (Fig. 4). The pulpwood bundles (PW bundles) contained potential pulpwood (Scots pine and Norway spruce [*Picea abies*] stemwood with bark) and energy wood (crown biomass, i.e. branches and foliage). Birches (*Betula* sp.) and small-diameter conifers were either accumulated in the energy wood bundles (EW bundles, in Stands 2 and 3) or felled and left lying loose on the ground (Stand 1). In Stand 1, with the highest removal, only PW bundles were produced while in Stand 2, merely EW bundles were made. In Stand 3 both PW and EW bundles were produced. In the removal estimates based on the stand data, conifers with DBH less than 7 cm were considered energy wood in Stand 3.

Fig. 4. An energy wood bundle containing birch and small-diameter conifer material (left) and a softwood bundle containing both pulpwood and energy wood (right).

Table 2. Moisture contents of the main fractions of the bundles.

Fraction	Moisture content (w.b.)		
	No. of samples	Mean, %	SD, %-units
PW bundles (Stand 1)			
– Pulpwood fraction (stemwood and stem bark)	37	59.4	2.2
– Energy fraction (branches)	25	48.7	2.6
EW bundles (Stand 2)	15	53.1	3.5

The bundles were hauled to the roadside landing where they were separately scaled using a dynamometer. Furthermore, the lengths of the bundles produced in Stands 1 and 2 were measured. The outputs used in the time studies were deduced from the green masses of the bundles produced and their moisture contents (MC) on wet basis (w.b.), supplemented with several assumptions regarding bundle composition based on stand data and the literature.

The proportion of potential pulpwood in the PW bundles was determined from five bundles produced in Stand 1. These bundles were opened, and branches were separated from stem sections. Then the stemwood was weighed. The green mass of the branches was computed by subtracting the green mass of the stemwood from the total green mass. The proportion of stemwood in the PW bundles was assumed to be the same as in Stand 3.

The top diameters of the stem sections were measured by accessing the five opened PW bundles. Thereafter, the branch fractions of these bundles were chipped and homogenized, and five one-litre moisture samples were taken from each bundle. In order to determine the MC of the stemwood, 10-cm discs were cut halfway along the stemwood sections representing the diameter class distribution of each bundle. Each disc (6–8 discs per bundle) was split into four quadrants, and one of them was used for moisture sampling. One-litre moisture samples were compiled by chipping and homogenizing these quadrants. The MC of the EW bundles was determined from five bundles produced in Stand 2 by cutting three 20-cm sections from each of them. After chipping and homogenizing, one-litre samples were taken from them. The MCs of all the samples were determined by drying in a kiln at 105 °C for 48 hours. The moisture contents obtained for the PW and EW bundles are shown in Table 2. The MCs obtained from Stands 1 and 2 were used when computing MCs for the PW and EW bundles produced in Stand 3.

The solid volumes for each bundle component (stemwood with bark, living branches, pine and spruce needles) were computed by dividing their dry masses by their basic densities presented by Hakkila (1978), Kärkkäinen (1976), and Gislerud (1974). Before these conversions, branches were divided into branch wood and branch bark using the bark percentages reported by Kärkkäinen (1976). The green masses of the main bundle fractions were converted into dry masses using their moisture contents as determined from the samples. The green mass ratios of pine to spruce stemwood in the PW bundles were assumed to correspond to their dry mass ratios in the removals based on the tree data. The compositions of the energy wood fractions (crown biomass in the PW bundles and whole trees in the EW bundles) were assumed to be analogous to those of the removal estimates based on tree data. Dead branches were excluded from the biomass calculations. The basic densities for the whole trees in the EW bundles are based on the tree data. They were obtained by dividing the total dry masses of various biomass components by their total volumes.

3 Results

3.1 Output of Bundle-harvesting

The total number of bundles produced in the time study was 45 (12–19 bundles per time study plot of 1000 m^2) (Table 3). The mean green mass for all the PW bundles was 453 kg. The EW bundles containing mainly small-sized stems weighed on average 325 kg. The bundles were uniform in length, 256 cm on average. The mean top diameter of all stem sections was 55 mm (3–166 mm, SD = 37 mm). Stemwood with bark constituted 82% of the total green mass of the PW

Table 3. Bundle properties.

	Green mass		Length	
	PW bundles	EW bundles	PW bundles	EW bundles
Stand 1				
– mean	467 kg	-	256 cm	-
– min.	260 kg	-	248 cm	-
– max.	616 kg	-	264 cm	-
– SD	84 kg	-	4 cm	-
– n	19	-	19	-
Stand 2				
– mean	-	341 kg	-	257 cm
– min.	-	268 kg	-	249 cm
– max.	-	480 kg	-	264 cm
– SD	-	69 kg	-	4 cm
– n	-	12	-	12
Stand 3				
– mean	425 kg	276 kg	-	-
– min.	341 kg	233 kg	-	-
– max.	483 kg	303 kg	-	-
– SD	45 kg	32 kg	-	-
– n	10	4	-	-

n = number of samples, SD = standard deviation

Table 4. Removals (dry basis) per hectare based on the tree data (predicted) and on the results of the bundle analyses (actual).

		Potential pulpwood	Energy wood	Total
			kg/ha	
Stand 1	Predicted	33 099	9157	42 256
	Actual	29 495	8292	37 786
	Difference, %	11	9	11
Stand 2	Predicted	-	37 559	37 559
	Actual	-	19 196	19 196
	Difference, %	-	49	49
Stand 3	Predicted	14 613	17 488	32 101
	Actual	14 105	9143	23 248
	Difference, %	3	48	28

Table 5. Volumetric composition of the bundles.

	Stand 1	Stand 2	Stand 3
		m^3	
PW bundles	0.513	-	0.464
– pulpwood	0.398	-	0.365
– energy wood	0.114	-	0.099
EW bundles	-	0.350	0.286

bundles (79–86%, SD = 2.9 %-units). The green mass of the stemwood correlated with statistical significance with the total green mass of the bundles (Pearson's correlation coefficient $R = 0.972$, $p < 0.01$, $n = 5$). In the post-harvesting inventory, no damage to the remaining stand due to harvesting was observed on the 50-m^2 sample plots.

The dry masses of the harvested bundles and the predicted removals based on the tree data are shown in Table 4. Dead branches were not included in the predicted removals as they are likely to be shed at various stages of the process. Their calculatory dry weight amounted to 1500 kg/ha, 600 kg/ha, and 800 kg/ha in Stands 1–3, respectively. Pine and spruce needles constituted 6–11% of the predicted removals. In Stands 1 and 3 with integrated harvesting of pulpwood and energy wood, the actual removals were 89% and 72% of the removals based on the tree data. In Stand 2, with its uneven spatial and stem size distributions, the actual removal was only half of the predicted removal.

One PW bundle contained 0.4 m^3 of potential pulpwood and 0.1 m^3 of energy wood (Table 5). Energy wood constituted 22–39% of the total volume harvested in Stands 1 and 3 (Fig. 5). In all, energy wood (energy fraction of PW bundles + EW bundles) increased recovery by 59% in Stand 3, of which 54% was accumulated in the PW bundles. Increment in Stand 1 was 29%.

3.2 Distribution of Time Consumption

In the time study, different work phases did not overlap to any great extent. Due to insufficient hydraulic capacity, felling and bunching had to alternate with the bundling process. Simultaneous harvesting and bundling phases constituted only 8–18% of the total effective working time (Fig. 6). Handling cumbersome tall trees, especially in Stand 1, required the operator's full attention as the grapple lacked in feeding system. Due to the rotating bundling unit and cabin it was possible to feed the bundler from both sides of the strip road.

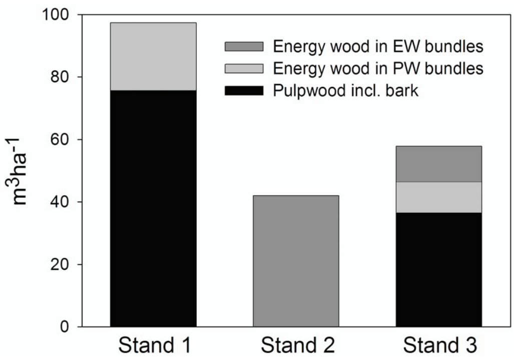

Fig. 5. Composition of the volumetric bundle-harvesting outputs per hectare. The bundle types produced were as follows: In Stand 1 PW bundles; in Stand 2 EW bundles; and in Stand 3 both PW and EW bundles.

Before turning the bundling device, however, the feeding function had to be completed, and the grapple was needed for supporting bunches hanging over the edge of the feeding table. In Stands 2 and 3, where the stand density was lower, the proportion of simultaneous bundling and harvesting was higher compared to Stand 1. Overlapping moving and bundling took 0–1% of the effective working time. In thinning stands, stem sections protruding from the feeding table usually prevented moving. Virtually simultaneous moving and bundling were possible only when tying the compacted bundles.

The highest proportion of phases related to harvesting (48%) was recorded in Stand 2, where working conditions were most difficult because of the uneven stand structure and poor visibility. In Stands 1 and 3, harvesting phases covered 39% (excl. clearing) and 38% of E_0, respectively. Clearing undergrowth and small deciduous trees took 17% of the total E_0 in Stand 1. There were only minor differences in the proportions of moving (6–10%) and feeding (10–12%) times among the stands. In Stand 1, the proportion of bundling was 29% (clearing excluded) or 24% (clearing included) of E_0. In Stands 2 and 3, bundling took 18% and 24% of E_0, respectively.

When looking at the operation in detail from the harvesting point of view, E_0 was broken down into elements as shown in Fig. 7. Excluding the time used for clearing undergrowth in Stand 1, various crane functions covered on average 52–62%, phases related to bundling 31–39%, and moving 7–8% of E_0. Intermediate stacking of felled trees, sorting, and loading took 25–27% of E_0.

On average, 1.09, 1.56 and 1.16 trees were accumulated per crane cycle in Stands 1, 2, and 3, respectively. The highest proportion of multi-tree-handled trees (36%) was recorded in Stand 2, where all trees were harvested for energy wood. In Stand 1, where the stems were the largest, only 8% of trees were accumulated during cut-

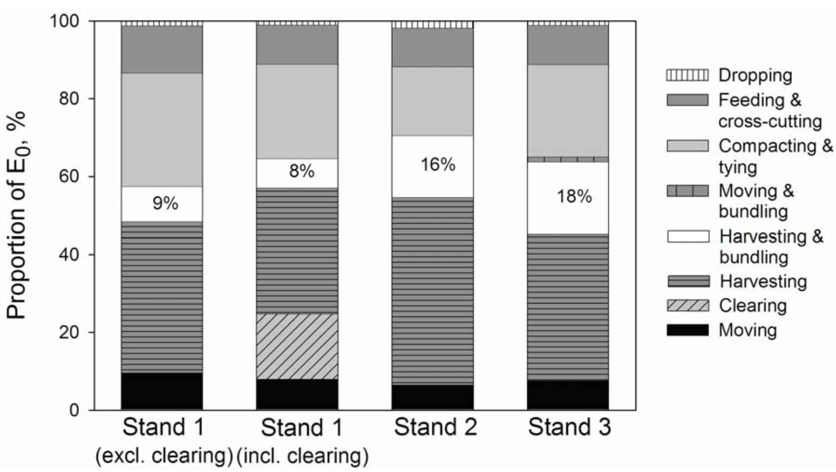

Fig. 6. Breakdown of effective working time into the main elements.

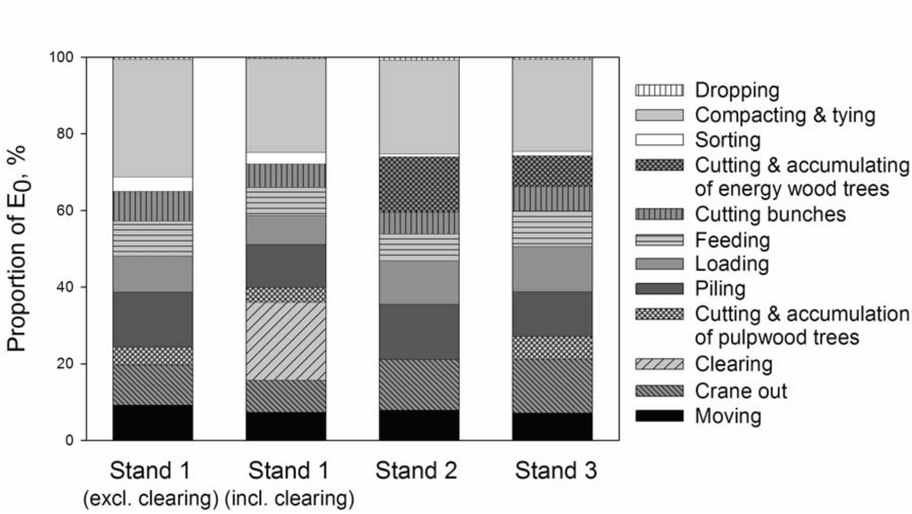

Fig. 7. Breakdown of effective working into the main elements from the harvesting point of view.

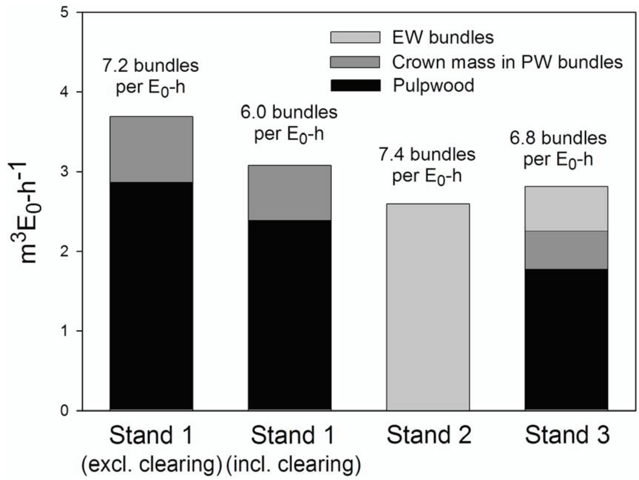

Fig. 8. Productivity of bundle-harvesting.

ting before feeding or intermediate stacking. In stand 3, the proportion of multi-tree-handled trees was 14%.

3.3 Productivity of Bundle-harvesting

The highest number of bundles per effective hour (7.4) was recorded in Stand 2, in which only EW bundles were produced (Fig. 8). Due to the low volume of the bundles resulting from the high proportion of small-diameter or crooked trees, however, the lowest productivity in terms of volume (2.6 m^3/E_0-h) was also recorded in Stand 2. Volumetric productivity was highest in Stand 1. When omitting the time used for clearing the undergrowth and some small-diameter deciduous trees, it was 3.7 m^3/E_0-h. Clearing the undergrowth and some deciduous trees decreased productivity by 17% down to 3.1 m^3/E_0-h. When making both PW and EW bundles (Stand 3), the overall productivity was 2.8 m^3/E_0-h (6.8 bundles per E_0-h.

4 Discussion

4.1 Reliability of the Output Estimates

Outputs in forest engineering work studies are usually expressed in terms of volume instead of the more accurate mass-based terms. Solid volume is applied in inspections and measurement on delivery as well. This study revealed great variation in bundle weight and volume due to variation in stand properties. There were also substantial differences between the removals based on stand data and weighed removals. These findings indicate that neither the number of bundles produced nor stand data alone can be used as the basis for work measurement and delivery, especially in integrated harvesting of pulpwood and energy wood (cf. Kärhä and Vartiamäki 2006).

In Stand 2, characterized by its abundance of undergrowth spruces and large birches, the poor representativeness of the stand data is the most probable reason for the great difference between the predicted and actual removals. In addition, biomass losses at various phases of the harvesting process increased the disparity of these two estimates. Especially branches and foliage are likely to be lost. Besides occurring in felling, raw material losses also occur at the bundling stage. Because of limited resources, it was not possible to survey the residual biomass left on the site after bundle harvesting. Dead branches were excluded from the recovery calculations in accordance with the common practice (e.g. Hakkila et al. 1995). It is probable that the bundles also contained dead branches as they did in a study by Jylhä (2004). On the other hand, the recovery of stemwood is not 100% as some tops fall onto the ground at the feeding stage.

Bundle composition was not analysed in detail. Moreover, there were many sources of errors when converting dry mass into volume. Despite the problems described above, the breakdown of the bundles into various biomass components was assumed to be equivalent to that of the removals based on the stand data and the models of Laasasenaho (1982) and Marklund (1988). Stand characteristics, however, have an effect on the biomass allocation of a tree (Kärkkäinen 2005), and there is also variation in the conversion parameters. For example, stand age, yield class, and geographical location all affect the basic density of stemwood (Rissanen and Sirviö 2000). In integrated operations, distinguishing between the energy wood and pulpwood fractions is of great importance. The stemwood content used in the present study was based on a limited sample only. The stemwood proportion obtained as a result of bundle analysis, however, was in accordance with that derived from the stand data. Even with the uncertainties described above, the output estimates were considered reliable enough for piloting purposes.

Uniformity in bundle size provides opportunities for developing a simple method of determining bundle composition; this method is based on the green mass of the bundles complemented possibly with stand data. A scaling system can be easily incorporated into the bundling unit, and an automated image analysis system could further increase measurement accuracy. This kind of real-time data on daily production and inventories provides good conditions for effective process control.

4.2 Efficiency of Bundle-harvesting

The trial was carried out using the first prototype of the bundle-harvester. The bundling device operated without any unnecessary delays due to breakdowns, and the silvicultural result was such that no damage was done to the remaining stand. Bundle-harvesting productivity figures, based on limited data with 45 bundles produced, were relatively low (2.6–3.7 m^3/E_0-h) when compared to the current harvesting technology. In the study by Kärhä (2006a), for example, the productivity of whole-tree cutting with average stem volume being approx. 30–40 dm^3 was 8–10 m^3/E_0-h.

Especially the work of the operator of the bundle-harvester is challenging. He or she has to be capable of performing several overlapping work stages simultaneously while controlling other functions and selecting trees to be harvested, and to do all this without damaging the remaining stand. The time studies were carried out using one operator with only a short experience on the bundle-harvester. In the study of Kärhä and Vartiamäki (2006), the operator of the slash bundler had the greatest effect on the productivity of bundling. In thinnings, productivity levels between harvester operators have also been reported to vary significantly, even 40–43% in similar conditions (Kärhä 2001, Kariniemi 2006b). The differences are assumed to originate from the operators cutting techniques, motoric skills, planning of work, working experience, felling order of removable trees, and decision process at the working location, for example (Ovaskainen et al. 2004).

The main objective of this study was to identify the bottlenecks of the process in order to facilitate the further development of the concept. Despite the restrictions described above, the results showed that improvements in working techniques, machine structure, and components have a substantial potential to increase the efficiency of the present machine concept.

In the experiment, only 8–36% of the bundled trees were multi-tree harvested. Productivity could be significantly increased by applying multi-tree harvesting to its full extent. In the study by Kärhä (2006a), the proportion of multi-tree-handled whole-trees was as high as 85%. In integrated harvesting of delimbed pulpwood and energy wood using standard single-gip harvesters, multi-tree handling can increase productivity by as much as 35–40% as compared to single-tree handling (Mäkelä et al. 2002, Larsson (Ed.) 2004). Omission of the multi-tree harvesting option was mainly due to the insufficient hydraulic capacity of the base machine, especially when the crane was extended to its extreme. Moreover, stand characteristics can impose constraints on multi-tree harvesting. In Stand 1, characterized by large and tall trees and high stand density, only 8% of the trees were multi-tree-handled.

In order to illustrate the effect of clearing the undergrowth and deciduous trees on the productivity of bundle-harvesting, two E_0 distributions were constructed for Stand 1. Clearing the undergrowth (initial density 7150 per hectare) decreased productivity by 17%. Felled undergrowth trees were mainly spruces, 1–2 m in height. In the study by Kärhä (2006b), undergrowth spruces with a density of 2000 per hectare (mean height 2 m) were found to decrease the productivity of a conventional harvester by 12–14% ($d_{1.3} < 7.0$ cm, $d_0 > 1.1$ cm) and with a density of 10 000 per ha the reduction was 30–40%. Deciduous undergrowth had no effect on productivity. These findings indicate that unnecessary clearing should be avoided where possible (cf. Kärhä 2006a, 2006b). There could, however, be more need for clearing the undergrowth in bundle-harvesting as it hampers bunch manoeuvring in the upright position, intermediate stacking, and feeding the bunches into the bundling unit.

Separate stacking and loading accounted for as much as 19–26% of the effective working time; this was mainly because the properties of the standard felling head used in the trial were inadequate for bundle-harvesting. The guillotine felling head had no feeding system. Hence, the accumulated bunches had to be laid on the ground before taking a new hold for loading. A feeding system (e.g. feeding rolls) on the grapple would have enabled direct bunch feeding after felling and accumulation. Moreover, then feeding tall bunches into the compaction chamber could be assisted by the grapple feeding system. In the study by Kärhä (2006a), harvester heads equipped with feeding rolls were more efficient than guillotine feller-bunchers without a feeding system when cutting whole-trees with average stem volume more than 8 dm^3. In the case of variety in bundle assortments to be produced, however, intermediate stacking and other arrangements cannot always be completely eliminated because of sorting requirements. Efficiency of the feeding system could be further increased by installing a feeding roll above the frontmost part of the feeding table hopper.

The bundle-harvester resembles a system of machines, where any imbalance between the elements in the supply chain results in the other parts of the system being idle. As a result, the total productivity of the machine decreases and costs increase (cf. Asikainen 2004). Insufficient hydraulic capacity was the foremost reason for the inadequate interaction between the machine components. This was evident especially in the absence of simultaneous functions. The bundling process was highly automated, enabling a continuous harvesting process. Ignoring the ineffectiveness of the feeding procedure, only directing the bundling unit for dropping the bundles (1–2% of E_0) required operator's intensive attention. In particular, cutting the bunches to length required a lot of power, and virtually all other functions had to be interrupted while cutting. Cutting simultaneously with bundling functions covered only 8–18% of the effective working time, and harvesting exclusively took 32–48% of E_0. The bundling unit in itself does not limit production. A performance of 13 bundles per effective hour was recorded in a separate bundling trial with the prototype bundle harvester (Laitila and Jylhä 2006). After several adjustments to the hydraulic system, the main reason for the problems was tracked back to the low performance of the 4-cylinder harwarder used as the base machine.

The improvements suggested above would not, however, eliminate the elementary defect of the concept. Incompatibility of the compacting device and the harwarder used as a base machine impeded adoption of an effective working technique with moving forwards. The machine had to reverse and transfer the trees felled from the strip road in front of the machine at upright position to the bundling unit located on the rear frame. Every single tree-bunch had to be brought from the sides, even from behind the line between operator's shoulders. When feeding the bunches, he had to look at side, and therefore the feeding table was never completely in his visual field. Tree sections protruding from the bundling unit enabled neither moving to the next conversion site nor turning the bundling unit to the other side while the feeding was still going on. Otherwise the operator could have started accumulating trees from the other side of the strip road while still feeding and turning the bundling device. Because of the location of the bundling unit, the proportion of simultaneous moving and bundling was only 0–1%. The productivity of bundle-harvesting might be increased by overlapping moving and bundling to a greater extent by modifying the base machine so that the bundling unit is relocated to be in front of the cabin.

Unless a specific base machine for the bundling unit is designed, apparently some of the present-day harvesters with crane on their front frame or integrated with the cabin could be a more feasible choice after front frame extension than the harwarder used with the first prototype. Then the bundle-harvester could operate moving forwards, and the working technique would be quicker with less crane movements. Using the present bundler construction, however, its height would limit visibility from the cabin. A bundling unit with two parallel chambers would improve visibility behind the bundler. Furthermore, the bundles would be dropped on the ground from lower level, and thus the durability requirements set to the bundles could be lowered. Consequently, consumption of tying string would reduce, as well as the risk of delays at processing plants due to string entanglements with conveyor components etc.

4.3 System Performance

Energy wood and pulpwood harvesting can be integrated in many ways. Compared to the production chains based on completely or partially delimbed conventional assortments, the increase in the form of crown biomass and top sections of stemwood is significant. In Stand 1, for example, the crown biomass alone increased the removal by 29% compared to harvesting of delimbed trees. When producing both PW and EW bundles, the increase in the harvested volume was markedly higher (59% in Stand 3). On relating this to the annual cuts from first thinnings at the national level, the whole-tree bundling method provides great potential for increasing recovery. All stemwood included in the bundles will not, however, end up in the pulp fraction. Especially small-diameter tops are likely to be crushed in the debarking drum and end up in the energy fraction.

Recovery could be increased by converting undelimbed assortments using conventional whole-tree and tree-section methods as well. Increasing the load size from the early stages of the transportation chain on, however, is of great importance. Load size had a powerful impact on productivity when forwarding uncompacted whole trees in the study by Kärhä (2006a). In his time study, the average whole-tree load volume of medium-sized standard forwarders was 6.1 m^3.

Using the green density of Scots pine whole-tree material (770– 880 kg/m^3) as presented by Lindblad (2005), results in payloads of about 5 tons. This is only about half of the carrying capacity of medium-sized forwarders (10–11 tons) as reported by Korpilahti (1996). In the study by Kärhä (2006a), increasing the load size from 6 m^3 to 9 m^3 increased productivity by 15% when the hauling distance was 300 m. In the experiment conducted by Laitila and Jylhä (2006), an average of 23 whole-tree bundles per load were transported by a standard medium-sized forwarder. Using the bundle green mass and volume data of this study (267–467 kg and 0.350–0.513 m^3) results in a load size of 6100–10 700 kg and 8–12 m^3 even without load space modification.

The long-distance transportation of loose whole-tree material requires trailers modified for carrying loose energy wood. The potential payload of these trailers is 30 tons (Ranta and Rinne 2006), which can be fully utilized even when dealing with uncompacted whole-tree material. When transporting bundled whole-tree material, standard trucks with a higher load capacity of about 40 tons (Korpilahti 1996) can be used. Their load spaces can accommodate approximately 100 bundles per load (Matti Markkila, Forest Energy Advisor, UPM-Kymmene Corporation, personal communication 9 March 2007). In the case of bundles of green material, the load capacity of standard trucks can be completely utilized. When transporting material dried beyond a critical level, volume will become a limiting factor. The efficiency of bundle forwarding and truck transportation will be further increased by faster loading and unloading times. Due to compaction, the storage space requirement is also reduced.

There is often great imbalance between the productivities of harvesters and forwarders in first thinnings, especially in energy wood harvesting (Laitila et. al 2004), and this results in increased harvesting costs due to waiting. In wintertime, harvested trees should be transported to the roadside soon after cutting because of the risk of snowfall. On peat soils with poor carrying capacity, only wintertime harvesting is possible. Because of climate change, harvesting operations on peatlands are becoming increasingly difficult. Especially forwarding over unfrozen soils can cause soil damage and damage to the remaining stand. Bundles represent a flexible system with a high disturbance tolerance. Where necessary, bundles can be stored and dried at various points along the way. With the bundling system, the carrying capacity of the soil can be improved by delaying bundle forwarding until the compacted strip roads are well frozen. Large-sized bundles remain visible even after heavy snowfalls, and they can be forwarded efficiently later on without resulting in unnecessary waiting times.

Integration of pulpwood and energy wood flows by applying the bundling method enables simplified and more cost-efficient management of operations. The bundling method can easily be incorporated into various production chains. Compared with the conventional production of forest chips, the bundle-harvester operates independently of the other machines involved in the system, and this makes the process less vulnerable. The bundles can be crushed cost-efficiently at a terminal or end-use facility instead of at the stump or at the roadside landing (Nordfjell and Liss 2000, Johansson et al. 2006). In the integrated harvesting of pulpwood and energy wood using the bundling method as introduced in this study, the need for separate crushing is completely eliminated as the fractions are separated in the normal wood handling process at the pulpmill.

In the light of the increased demand for domestic thinning wood and other woody biomasses, integrated harvesting of energy wood and pulpwood using the bundling method shows potential for stepping up both pulpwood and energy wood harvesting cost-efficiently, especially from great transportation distances. In addition, raw material procurement for potential biorefinery products holds promising prospects for the bundling method. Improving the efficiency of bundle-harvesting by reconstruction of the bundle harvester concept is of high priority. Based on the calculations of Kärhä et al. (2007), the operational advantages offset the costs of compaction only if the productivity of the bundle-harvester exceeds 4.6 m^3 per effective hour (bundle volume 0.5 m^3, 9.2 bundles/E_0-h), when the breast-height diameter of the trees to be harvested is 7 cm (stem volume approx. 20 dm^3). With DBH of 11 cm (60 dm^3), the productivity must be more than 7.6 m^3/E_0-h, and with 13 cm (95 dm^3) more than 8.7 m^3/E_0-h. In these calculations, a forest haul-age distance of 250 m and a road transportation distance of 100 km were used.

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