The Cutting Productivity of the Excavator-based Harvester in Integrated Harvesting of Pulpwood and Energy Wood

JUHA LAITILA* AND KARI VÄÄTÄINEN
Finnish Forest Research Institute, Joensuu Unit, P.O. Box 68 (Yliopistokatu 6), FI-80101 Joensuu, Finland
** Phone +358 50 391 3255, e-mail juha.laitila@metla.fi*

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Abstract

The purpose of the study was to determine the productivity of multi-stem cutting of pulpwood and delimbed energy wood, along with the time consumption of cutting work phases performed with a tracked, forestry-equipped excavator as the base machine and a Naarva EF 28 as the harvester head. On the basis of the time-study data collected, per-stem time-consumption and productivity models were prepared for the multi-stem cutting of delimbed wood. In the multi-stem cutting time-consumption model, productivity was explained in terms of stem volume and harvesting intensity (number of stems removed per hectare). Productivity was expressed in solid cubic metres per effective hour (m^3/E_0h). In the time studies, the multi-stem cutting productivity per effective hour was 12.8 m^3/E_0h and 233 stems/E_0h, on average. Cutting productivity per effective hour (m^3/E_0h) increased as the stem volume of trees grew. On the time-study sample plots, the lowest and highest values recorded for multi-stem cutting productivity per effective hour were 8.7 m^3/E_0h and 19.9 m^3/E_0h, respectively. The corresponding stem-number figures for the extremes of cutting productivity were 347 and 183 stems/E_0h. On average, the harvester head processed 1.9 stems per grapple cycle, while grapple loads processed via the multi-stem method (at least two stems in the grapple at a time) accounted for 57% of all time-study data. In total, 2,267 stems were cut in the time studies consisting of 71 m^3 of pine pulpwood and 53 m^3 of multi-stem delimbed energy wood.

Calculations using the time-consumption model have shown that when the harvesting intensity was tripled from 800 to 2,400 trees/ha, the productivity of multi-stem cutting per effective hour increased by about one solid cubic metre, whereas increasing the stem volume from 23 dm^3 to 89 dm^3 doubled the cutting productivity per effective hour. If the results of this study are generalised or compared with those of other studies, the amount of material and the effects of the harvesting site and operators must be taken into account. The results indicate that the productivity of the excavator-based harvester and the Naarva EF 28 harvester head was very high: at the same level as, or even better than, that of wheeled harvesters equipped with a conventional multi- stem harvesting equipment. The machine concept studied is a highly viable option for integrated harvesting of pulpwood and energy wood. Operation of the machine unit was problem-free throughout the time studies, with no interruptions caused by breakdowns. Moreover, the harvesting quality met the recommended standards.

Key words: Integrated harvesting, accumulating harvester head, excavator-based harvester, first thinning, pulpwood, multi-stem handling, delimbed energy wood

Introduction

Harvesting of industrial and energy wood on first-thinning sites

In Finland, the area in need of first thinning each year totals over 300,000 hectares (Korhonen et al. 2007). However, the current felled volume is considerably lower than that required for good forest management. In the 2000s, the area of first thinnings has been slightly below 190,000 ha/year (Juntunen and Herrala-Ylinen 2010). In the long term, neglect of thinnings will backfire, increasing the natural drain and slowing both diameter growth at stand level and the forest-owner's flow of income (Hakkila et al. 1995). Neglect of first thinnings is due to high logging costs caused by the small size of the trees to be cut, low removal per hectare, and poor harvesting conditions (Kärhä et al. 2006ab, Oikari et al. 2010, Kärhä and Keskinen 2011). The value of raw material can also be low in relation to logging costs (Sirén and Tanttu 2001, Jylhä et al. 2010, Jylhä 2011). However, interest in benefiting from the first thinnings has increased on account of the improved harvest potential, greater use of forest chips, and integrated harvesting of industrial and energy wood. Of the total volume of mechanised cuttings in 2011, first thinnings accounted for 10.7%, other thinnings 30.8%, and regeneration cuttings 58.5% (Strandström 2012). Most (approx. 60%) of the first-thinning stands harvested in 2000–2007 were dominated by pine (Kärhä and Keskinen 2011). The share of mixed stands was 20% (Kärhä and Keskinen 2011).

Integrated harvesting of industrial wood and energy wood is a method wherein harvesting of industrial and energy wood are integrated at some stage in the supply chain. The purpose of integrated harvesting is to achieve the lower total procurement costs than by separate harvesting of industrial wood and energy wood (Kärhä et al. 2009, Laitila et al. 2010, Jylhä et al. 2010, Jylhä 2011, Kärhä et al. 2011a, Kärhä 2011). The most commonly used cutting method in integrated harvesting in first thinnings is the ”two-pile method”, in which industrial wood is stacked separately from stacks consisting of tops and other, delimbed or non-delimbed, thinning wood that does not fulfil the requirements applied for industrial wood (Kärhä et al. 2009, Laitila et al. 2010, Kärhä et al. 2011a, Kärhä 2011, Lehtimäki and Nurmi 2011). Trees are cut to the proper length – either by eye or by means of a measurement system – and the amount of wood is measured by weight with timber crane scales, usually during forwarding (Lilleberg 2012).

The volume harvested in integrated harvesting is linked to demand for industrial and energy wood, as well as to the price paid for wood raw material (Pasanen et al. 2012). Removal of industrial and energy wood can be influenced at stand level, on the basis of the needs of the roundwood markets, by adjustment of the pulpwood length and top diameter (Pasanen et al. 2012). With an increased top diameter, the proportion of industrial wood is lower, but pulpwood quality can be improved at the same time (Lilleberg 2012). The costs of integrated harvesting are higher than those of separate harvesting of energy wood, because instead of one assortment there are at least two assortments, which must be kept separate. If removal of industrial or energy wood is likely to be poor at stand level, integrated harvesting represents an unreasonable option and harvesting as a single assortment is recommended (Kärhä 2011, Di Fulvio et al. 2011, Iwarsson Wide 2011, Rieppo et al. 2011).

For integrated harvesting to be efficient, the harvester head must be capable of both multi-stem cutting and delimbing. Multi-stem cutting of thin stems makes harvesting more efficient, and the general quality requirements set for industrial wood require delimbing of the pulpwood fraction. Multi-purpose harvester heads for thinning stands are at their best on mixed sites with pulpwood and energy-wood compartments and combinations thereof. Versatility of the harvester head can increase the utilisation rate of the base machine and even out the seasonal fluctuation in harvesting. Roller- and track-driven harvester heads can be used for producing delimbed energy wood and harvesting non-delimbed whole trees. If energy wood is harvested as delimbed energy wood, the amount of biomass falling on the forest soil is increased (Pasanen et al. 2012). One issue that can be considered strength of integrated harvesting is found in the fact that it can extend the raw-material base of forest chips to include conventional thinnings that produce industrial wood. Therefore, the availability of forest chips can be improved.

Versatility of the base machine for evening out seasonal fluctuations

On average, 1,900 harvesters and 1,970 forwarders are involved in harvesting roundwood in Finland (Anon. 2011). Machinery on such a scale is fully utilised for only around six months of the year, from September to March (Anon. 2011). The seasonal nature of wood procurement leads to under-utilisation of forest machines and employee layoffs. Idle time lowers the utilisation rate of forest machines and whittles away at the profitability of the machine-contracting business (Kärhä and Peltola 2004). Versatility of machinery and transportation equipment represents one way of achieving year-round employment and ensuring the availability and stability of a professional workforce.

Harvesting of energy wood is the major way to even out seasonal fluctuation and find an appropriate additional work for forest machines outside the harvesting season without major modifications or investments in additional equipment (Kärhä and Peltola 2004). Another way of evening out the seasonal fluctuation in harvesting would involve utilising machinery that is deployed seasonally in earthwork, forest improvement, or peat production as base machines for harvesters in logging operations during the autumn and winter. At the same time, the number of conventional harvesters would be reduced. The advantages of work machines and tractors produced in the high volumes include a purchase price that is lower than that of forest machines and, outside the harvesting season, the option of removing the forestry equipment and using the base machine in the work for which it was originally designed. A new forestry-equipped excavator or tractor can also present a viable alternative to a second-hand harvester. The investment in additional equipment and work output would improve the utilisation rate of the base machine while reducing the amount of capital tied up in the base machine per hour of its operation. However, a contractor should always bear in mind also the amount of work and money required to render the investment in additional equipment for the base machine profitable, with sufficient return on capital (Jaakkola 2011).

In Finland, the use of excavators in logging is relatively rare whereas their use is comparatively popular in North and South America, New Zealand, the United Kingdom, and Ireland (Väätäinen et al. 2004). From the delivery figures for excavator-based harvesters listed by excavator retailers and harvester-head manufacturers, one can estimate that 60–70 tracked excavators are now being used for logging in Finland (Kärhä and Palander 2012). The results shown for profitability of the use of excavator-based harvesters are mainly positive, which would also speak in favour of more extensive use of these harvesters for logging in Finland (Niemi et al. 2002, Wang and Haarlaa 2002, Väätäinen et al. 2004). It has been shown that the costs per operation hour and logging costs of excavator-based harvesters are competitive with those of wheeled harvesters, although the productivity has been slightly lower than that of purpose-built harvesters (Niemi et al. 2002, Wang and Haarlaa 2002, Väätäinen et al. 2004).

Studies carried out by Metsäteho and the University of Joensuu / University of Eastern Finland (Bergroth et al. 2006, Bergroth et al. 2007, Palander et al. 2012, Kärhä and Palander 2012) have examined the reasons for the low use of excavator-based harvesters in Finnish logging. According to those interviewed on the cutting sites, the key reason for the currently low level of excavator utilisation lies in poor off-road capabilities. Excavators' performance on boulder fields and slopes was deemed especially poor. In contrast, excavators' off-road capabilities were rated top-notch in thinnings performed on peatlands and other flat land. The second most important reason given was that conventional wheeled harvesters are better suited to logging. It was also pointed out that the ergonomics of excavator-based harvesters do not match those of conventional harvesters. Other noteworthy reasons cited include negative attitudes to excavator-based harvesters among forest-owners and wood-procurement organisations, the tradition in the Nordic countries of using wheeled harvesters, lower productivity of excavator-based harvesters, lack of excavator-based harvester models, and high prices of cutting equipment.

Aims and objectives of the study

The purpose of the study reported here was to determine the productivity of multi-stem cutting of pulpwood and energy wood along with the time consumption of cutting work phases performed with a tracked, forestry-equipped excavator as the base machine and a Naarva EF 28 as a harvester head. With the aid of the time-study data collected, per-stem time-consumption and productivity models were prepared for multi-stem cutting of delimbed wood. Under the cutting-time-consumption model, the productivity was explained in terms of stem volume and harvesting intensity (i.e. the number of stems removed per hectare). Productivity was expressed in solid cubic metres per effective hour (m^3/E_0h). In addition, the results were compared to findings from previous studies examining the harvesting of industrial and energy wood via multi-stem and single-stem methods (Ryynänen and Rönkkö 2001, Kärhä 2006a, Kärhä et al. 2006b).

Material and methods

The machinery studied

The Naarva EF 28 is an accumulating harvester head equipped with driven rollers, delimbing knives, and guillotine cutting. Developed for multi-stem cutting of pulpwood and delimbed energy wood from first or early thinnings, the Naarva EF 28 harvester head can be attached to a standard harvester, a 14–20-tonne excavator, or a harwarder. The harvester head weighs 700 kg, and its maximum cutting diameter is 28 cm. The cutting force of the guillotine cutting is 240 kN, and the cutting time is 0.7 seconds. For the base machine, the required hydraulic oil flow and pressure are 170 l/min and 240 bar, respectively. Length measurement for the timber is integrated into the feeding. The feeding force of the harvester head is 13 kN, feed speed 4 m/s, and feed diameter of the harvested stems in the range 2–39 cm. The height of the harvester head in cutting position is 116 cm, and the maximum grapple opening is 83 cm. The Naarva EF 28 harvester head is manufactured by Outokummun Metalli Oy / Pentin Paja Oy.

In the time study, the Naarva 28 EF was attached to a 2011-model New Holland Kobelco E 135 B SR LC D excavator equipped with Kesla Xtender 15H extension boom (Figure 1). The harvester head was mounted on the extension boom, providing a total reach of 9.6 metres. The weight of the base machine, equipped with a front plate, was 14,700 kg, and the power output of the four-cylinder Mitsubishi DO4 FR diesel

Figure 1. New Holland Kobelco E 135 B SR LC D excavator equipped with Kesla Xtender 15H extension boom and Naarva EF 28 accumulating harvester head

engine was 74 kW. The maximum delivery of the hydraulic system was 2 x 130 l/min. The main carriage of the excavator had no tail-swing extension (Figure 1). The excavator's width, with 700-millimetre-wide heavy-duty tracks, was 2 490 mm, and the ground clearance was 445 mm. The tank for the stump-treatment liquid (urea) was mounted on the top of the cabin, as the Figure 1 shows.

The time study

The time studies of integrated harvesting of pulpwood and delimbed energy wood took place on 11–12 June 2012 in Punkaharju, eastern Finland, and were carried out under natural lighting during the daytime. The time-study plots were 25 m long and about 20 m wide (the width of the excavator-harvester's work path as estimated beforehand), and the 30–40-year-old first-thinning stand was pure Scots pine (*Pinus sylvestris*). The area of the time-study plots (m^2) was calculated on the basis of an average strip-road spacing of 18.6 m (see Figure 9). The boundaries of the visibly numbered time-study plots were marked with ribbons and poles on the stand. The total number of time-study plots was 37 (Table 1). All of the stand's undergrowth had been cleared. During harvesting, the terrain conditions on the time-study stand were estimated in line with the Finnish classification system (Anon. 1990). The factors assessed were load-bearing capacity, roughness of terrain surface, and steepness of terrain. On the basis of the measurements, the study stand was classified as of terrain class 1 (easy conditions). Strip roads were not marked beforehand but they were planned by the harvester-operator during the cutting work. The operator also chose the trees to be removed, in accordance with silvicultural recommendations (Anon. 1994). The total number of stems harvested during the time study was 2,267.

The harvester-operator was a forest-machine entrepreneur who had 21 years of work experience in driving wheeled harvesters and several weeks of work experience in driving the excavator-harvester. Cutting was carried out by application of the multi-stem cutting of pulpwood and delimbed energy wood, and the timber fractions were stacked into two separate piles along the strip road (cf. Kärhä 2011). In the experiment, the pulpwood was harvested with a minimum top diameter of 6 cm and a bolt length of 5 m. Stems that were less than 10 cm thick at 1.3 m height were considered to be energy wood and were multi-stem-processed with the delimbing knives slightly opened (cf. Iwarsson Wide 2009, Rieppo and Mutikainen 2011). The target length of the delimbed energy wood was 5 m, and the minimum top diameter was 3–6 cm. Stems that were 10–15 cm thick at 1.3 m height were cut as one five-metre pulpwood bolt and two five-metre bolts were cut from stems that were more than 15 cm thick at a height of 1.3 m. The operator has visually estimated the diameter of the stems at that height. The tops of pulpwood stems were multi-stem-processed and cut to length for energy wood, with stacking into the same pile along the strip road. The piling and bucking of the timber fractions were similar to those in studies by Rieppo and Mutikainen (2011) and Laitila and Väätäinen (2013).

The time study was performed manually with a Rufco-900 field computer (Nuutinen et al. 2008). The working time was recorded through application of a continuous timing method wherein a clock ran continuously and the times for different elements were separated from each other under distinct numeric codes (e.g. Harstela 1991). When the entire work process was recorded, the cutting functions had the highest priority then the moving and the arrangement elements. Auxiliary time use (e.g. planning of work and preparations) was included in the work phases in which it was observed. Effective working time was divided into the following work phases:

- Moving – begins when the excavator-harvester starts to move forward and ends when it stops moving to perform another activity. Moving can be divided into driving forward from one work location to another, moving at the work location, and speeding up the boom movements by moving the base machine forward at the work location as necessary.
- Positioning to cut – begins when the boom starts to swing toward the first tree and ends when the harvester head is resting on the tree before the felling cut begins.
- Accumulating the felling – begins when the felling cut starts and ends when the accumulated tree bunch starts moving to the processing point (the number of stems in each grapple bunch is recorded).
- Transferring the bunch of trees to the processing point – the accumulated bunch of trees is moved next to the strip road for delimbing and cross-cutting. This work phase ends when the multi-stem feeding and delimbing of the stem(s) starts.
- Delimbing and cross-cutting – begins when the feeding rolls start to roll the stem(s) and ends when the last cross-cutting is done and the remaining tree top(s) is/are dropped from the harvester head.
- Arranging stems into piles – arrangement of stems into piles, with similar timber assortments kept together in the pile (separately outside the processing phase).
- Moving tops and branches to the strip road – moving of tops and branches to the strip road and away from piles.

• Driving in reverse – begins when the excavator-harvester starts to move backwards and ends when it stops moving to perform another activity. Moving can be divided into driving backwards at the work location and speeding up the boom movements by moving the base machine backwards at the work location as necessary.

• Delays – time that is not related to effective work (repairs and maintenance, phone calls, etc.).

Measurement of the timber volumes harvested

The time study's plot-wise mass and volume of harvested stemwood (for both pulpwood and energy wood) were measured during forwarding with the crane scale. Forwarding was completed immediately after cutting trials, on 13–14.6.2012, with a John Deere 1110E forwarder equipped with a Tamtron TBL-10 crane scale. The crane model of forwarder was CF 510. Pulpwood and energy wood were forwarded as separate assortments. The harvested timber was weighed first at the time-study plot during loading and a second time at the roadside landing during unloading. The purpose of the weighing at the roadside landing was to improve on the accuracy of the first plot-wise value. The values for green tonnes of pulpwood and energy wood were converted into solid cubic metres (m^3) yielding green density values of 861 kg/m^3 and 930 kg/m^3 (Anon. 2010, Lindblad et al. 2010). The total volume of the harvested stemwood was 124 m^3, of which 71 m^3 was considered to be pulpwood and 53 m^3 energy wood.

The moisture content of the forwarded stemwood was verified and determined in accordance with European Standard CEN/TS 14774-2 for 8–12 wood disks per load (cf. Spinelli and Magagnotti 2010). At the roadside landing, the centimetre-thick disks were cut from randomly selected stems at variable distance from the butt, such that the butt, the mid-stem, and the top wood were equally represented. The total number of forwarder loads analysed was 12, for examination of, in all, 13.9 kilos of fresh wood samples from pulpwood and delimbed energy wood. According to laboratory analyses, the moisture variation in the fresh stemwood samples was 58–64% and the mean moisture of the fresh stemwood was 61%.

Measurement of the stand data and harvesting quality

Tree data were collected after timber-harvesting from two 50 m^2 circular sample plots situated on the time-study plots (Figure 2). From the sample plots, number of remaining trees, mean height (m), mean diameter at 1.3 m height (mm), and basal area (m^2) were recorded. The initial number of trees on a time-study plot was obtained by summing the number of harvested and remaining trees. The average volume (dm^3) of stems harvested on a time-study plot was calculated by dividing the cutting removal (m^3) by the number of stems harvested. On the time-study plots, the average volume of the harvested stems varied in the range 26–83 dm^3 (the mean 57 dm^3) and the harvesting intensity was 538–2,558 harvested stems per hectare (Table 1).

In addition to basic tree data, both the width and the spacing of strip roads were measured at 40-metre intervals along the strip road. The width of strip roads was measured using the "SLU method", in which the distances to the nearest trees were measured at the right angles from the middle of the strip road, along a distance of 10 m on each side (Björheden and Fröding 1986). The measurement point on the trees was the cutting level, and the width of the strip road was the sum of the two distances (Björheden and Fröding 1986). These measurements were accurate to within 1 cm. The distance between two parallel strip roads was measured at the right angles from the middle of the left-hand strip road to the middle of the right strip road. The accuracy of these measurements was 10 cm.

Data analysis

The plot-wise time-study data recorded and the stemwood volumes measured were combined as a data matrix. The time consumption of the main work elements in the multi-stem cutting was formulated through

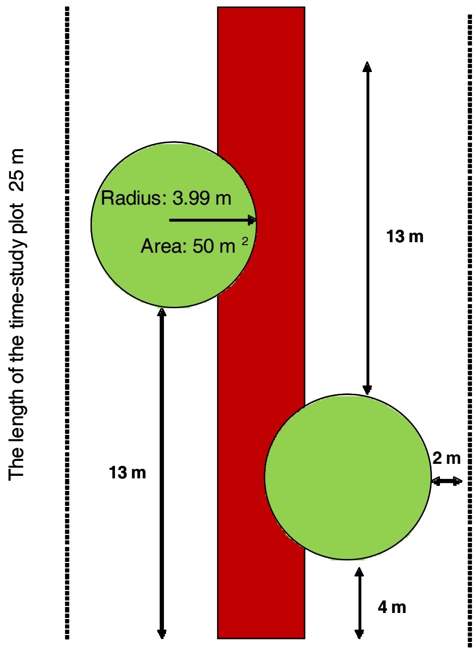

Figure 2. Location of the sample plots for stand measurements in the time-study areas

Table 1. Basic stand data for the time study plots 1–37

Plot No.	Initial stand, trees per ha	Removal, stems per ha	Average volume of stems harvested, dm^3	Mean diameter of remaining trees, mm	Mean height of remaining trees, m
1	2557	1362	68.4	152	11.7
2	2421	1088	71.3	130	11.1
3	2343	1382	52.9	130	10.6
4	2544	1104	58.6	142	11.1
5	2277	1223	74.9	147	11.0
6	2787	1361	60.4	141	11.3
7	2230	936	56.4	115	9.9
8	2414	1096	67.2	125	11.4
9	2631	1382	60.6	131	10.4
10	2396	1250	59.8	126	11.0
11	2271	1203	62.7	150	11.4
12	2502	1261	74.1	150	11.8
13	2992	1356	57.0	99	10.0
14	3417	1595	53.1	123	10.4
15	4707	2354	30.7	106	9.6
16	4184	2558	31.0	153	10.3
17	3266	1673	45.8	122	10.6
18	2429	1131	67.1	166	12.0
19	2310	1115	66.2	115	10.6
20	2155	1231	61.9	128	10.9
21	2285	1229	67.8	140	11.3
22	3903	1712	42.1	169	12.2
23	1848	863	83.0	150	12.6
24	3416	1360	64.3	175	12.9
25	2859	1285	60.6	142	11.9
26	1917	865	58.0	145	11.4
27	2079	979	56.4	142	12.2
28	2333	1217	54.4	173	12.3
29	3416	1992	26.3	131	9.6
30	3616	1503	28.7	122	9.4
31	2392	538	29.6	102	9.4
32	2602	1375	43.5	128	10.3
33	2217	1109	45.4	167	11.6
34	2304	1091	73.2	139	11.2
35	2734	1470	47.0	145	11.4
36	2605	1290	63.9	122	10.9
37	2076	885	79.0	131	10.9

the application of regression analysis, in which the harvesting conditions (the volume of harvested stems and the number of stems harvested per hectare) were independent variables. Several transformations and curve types were tested, so that we could achieve the symmetrical residuals for the regression models and ensure the statistical significance of the coefficients. The regression analysis was carried out with an SPSS statistics application. The unit for calculation of effective time (E_0h) consumption was seconds per stem, and the multi-stem cutting productivity was expressed in solid cubic metres per effective hour (m^3/E_0h). In the regression modelling, the work phases of multi-stem cutting were combined into three main work elements as the moving, the accumulating fellings, and the processing. The time used in moving was also included in reverse. The work phases of positioning to cut, accumulating felling, and transferring the bunch of trees to the processing point were included in the accumulation. Multi-stem delimbing and cross-cutting, arrangement of stems into piles, and moving of tops and branches to the strip road were included in the main work element of processing.

Results

Distribution of work elements and the cutting productivity recorded in the time study

In the time study, delimbing and cross-cutting represented 30% of the total effective working time in multi-stem cutting, and the share of felling or accumulating fellings was 24%. The proportion of the positioning-to-cut stage was 16%. Moving and driving in reverse between work locations represented 14% and 5% of the effective working time, respectively. Transferring the bunch of trees to the processing point took 11% of the effective working time and arranging stems into piles 0.3%. Moving tops and branches to the strip road represented 0.1% of the effective working time.

In the time studies, the average multi-stem cutting productivity recorded per effective hour was 12.8 m^3/E_0h and 233 stems/E_0h. On average, the harvester head processed 1.9 stems per grapple cycle, while grapple loads processed by means of the multi-stem method (i.e., at least two stems in the grapple at a time) accounted for 57% of all time-study data. Cutting productivity per effective hour (m^3/E_0h) increased as the stem volume of the trees rose (Figure 3). On the time-study sample plots, the lowest and highest values recorded for multi-stem cutting productivity per effective hour were 8.7 m^3/E_0h and 19.9 m^3/E_0h, respectively (Figure 3). The average stem volume on the sample plots of the cutting site varied from 26 to 83 dm^3 (Figure 3). Because the stem volume had afected the

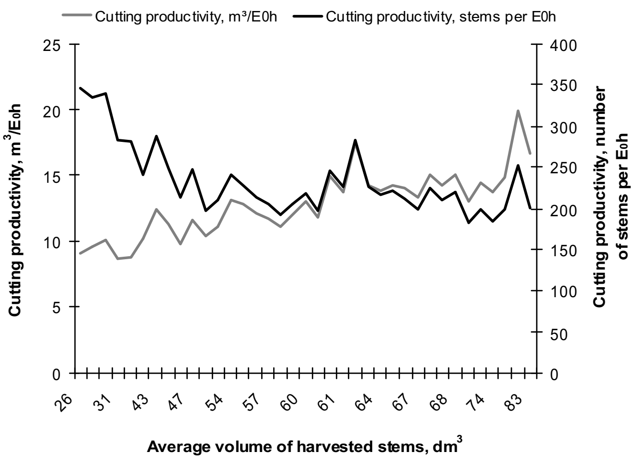

Figure 3. Cutting productivity recorded for the time plots, by average volume of stems harvested (dm^3), where cutting productivity is expressed either as a number of stems or as solid volume (m^3) per E_0h.

number of trees that fit into the harvester head, the number of trees cut per effective hour decreased as the trees' stem volume grew. As for stems, the highest and lowest values recorded for cutting productivity per effective hour were 347 and 183 stems/E_0h, respectively (Figure 3).

The time consumption models for the main work elements

Moving time (T_{Moving}) was dependent on the number of stems harvested (Figure 4). The moving time per stem harvested decreased as the number of stems harvested per hectare increased; in such cases, it was possible to cut more trees from a single work location. The time consumption of moving was formulated as

$$T_{Moving} = 9.163 - 0.859 \ln(x_1)$$

where: T_{Moving} = time for moving between work locations, expressed in seconds per stem; x_1 = number of stems harvested, stems per hectare; $r^2 = 0.120$.

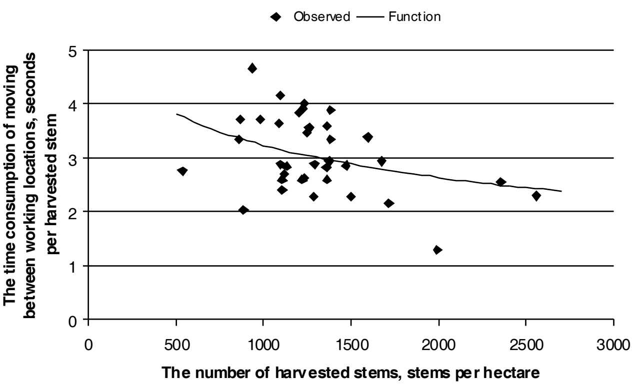

Figure 4. The time consumption of moving between work locations as a function of stems harvested per hectare

The most important productivity factors in the multi-stem cutting were the average stem volume and the number of stems in the harvester head per grapple cycle. The latter value ($N_{Number\ of\ stems\ in\ the\ grapple}$) was predicted on the basis of the average volume of the harvested stems (Figure 5):

$$N_{Number\ of\ stems\ in\ the\ grapple} = 0.761 + 58.194*1/x_2$$

where: $N_{Number\ of\ stems\ in\ the\ grapple}$ = the average number of stems in the harvester head per grapple cycle; x_2 = the average volume of the harvested stems, dm^3; $r^2 = 0.809$

The time consumed in accumulating fellings per harvested stem ($T_{Accumulating\ felling}$) was dependent on the number of stems in the harvester head in a grapple cycle (Figure 6):

$$T_{Accumulating\ felling} = 4.542 + 6.176*1/x_3$$

where: $T_{Accumulating\ felling}$ = the time for positioning to cut, accumulating the felling, and transferring the bunch of trees to the processing point, expressed in seconds per stem; x_3 = the average number of stems in the harvester head per grapple cycle; $r^2 = 0.369$.

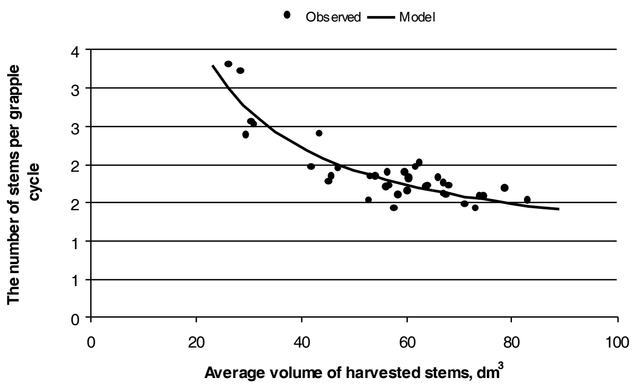

Figure 5. The number of stems harvested per grapple cycle as a function of average stem volume, dm^3

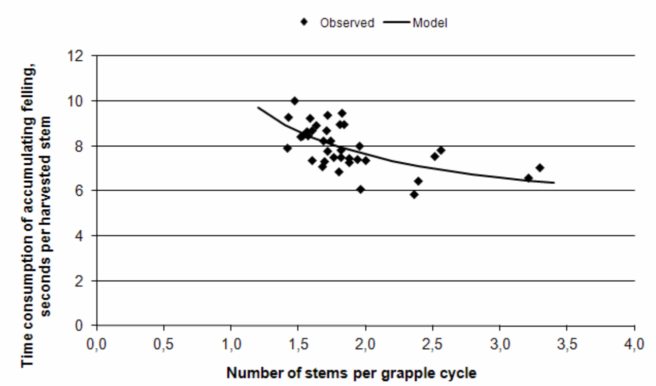

Figure 6. The time consumption of accumulating fellings (more precisely, positioning to cut + accumulating the felling + transferring the bunch of trees to the processing point) per stem harvested, as a function of stems per grapple cycle

Processing time per harvested stem ($T_{Processing}$) was modelled from the average volume of harvested stems (Figure 7):

$$T_{Processing} = -10.592 + 3.857 \ln(x_2)$$

where: $T_{Processing}$ = time consumption of multi-stem processing, expressed in seconds per stem; x_2 = the average volume of the harvested stems, dm^3; $r^2 = 0.775$.

The total time consumption (E_0h) of multi-stem cutting per harvested stem (T_{Total}) was obtained by adding up the time-consumption values for the three main work elements as follows:

$$T_{Total} = T_{Moving} + T_{Accumulating\ felling} + T_{Processing}$$

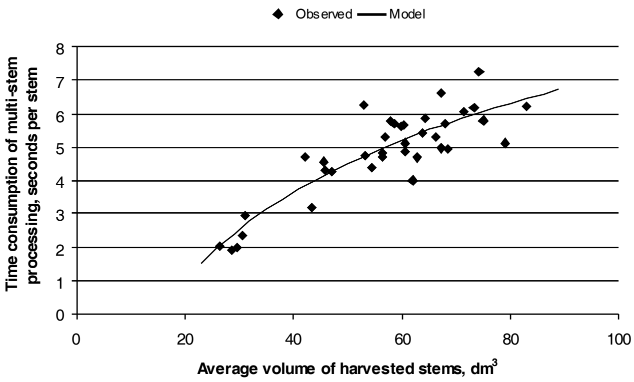

Figure 7. The time consumption of multi-stem processing as a function of average stem volume

The productivity of the multi-stem cutting

Figure 8 describes the effective-working-time productivity (E_0h) of the multi-stem cutting when the harvesting intensity was 800, 1600, or 2400 stems per hectare and the average volume of harvested stems was within the range 23-89 dm^3. Calculations using the time-consumption model (T_{Total}) showed that when the harvesting intensity was tripled from 800 trees/ha to 2400 trees/ha, multi-stem cutting productivity per effective hour increased by about a solid cubic metre (1 m^3/E_0h), whereas increasing the stem volume from 23 to 89 dm^3 have doubled the cutting productivity per effective hour (Figure 8).

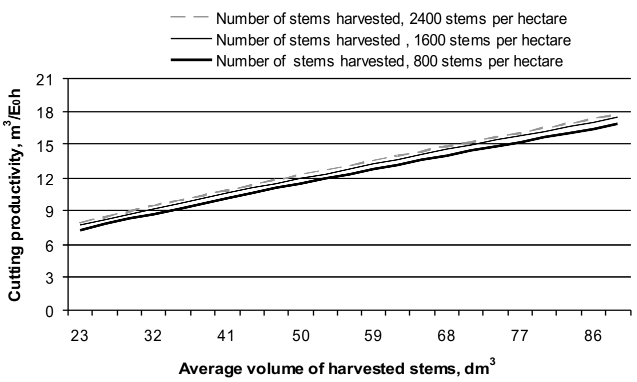

Figure 8. Cutting productivity (m^3/E_0h) as a function of average stem volume and number of stems harvested per hectare

The average spacing and width of strip roads

The strip-road spacing observed on the time-study stand varied within the range 15.8 to 23.3 m, and the average spacing was 18.6 m (Figure 9). The distances observed between the strip roads were somewhat shorter than the recommended minimum spacing of 20 m (Anon. 2003). The average width of the strip roads was 417 cm, and their length varied between 370 and 470 cm (Figure 10). For the most part, the width of the strip roads was within recommendations, i.e. the narrower than the recommended maximum width of 400 cm (Anon. 2003).

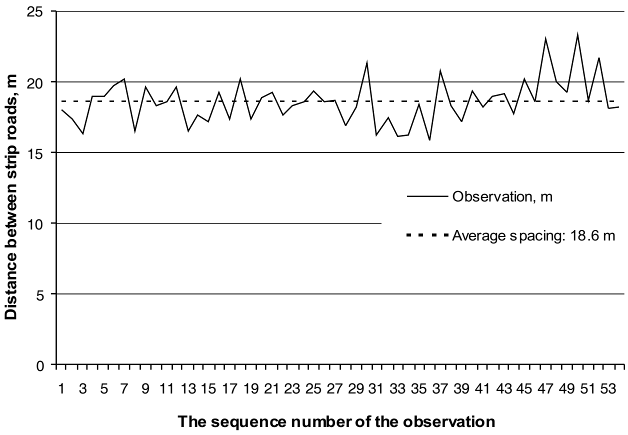

Figure 9. The observed and average strip-road spacing on the time-study stand

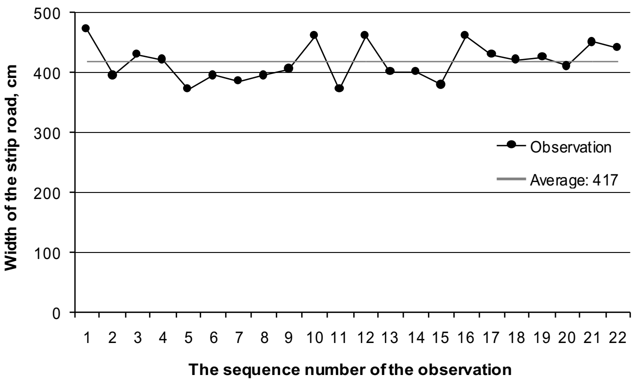

Figure 10. The observed and average width of the strip road on the time-study stand

Discussion and conclusions

The purpose of the study was to examine the efficiency and functionality of an excavator-based harvester with multi-stem processing capability. The results show that the productivity of the Naarva EF 28 harvester head and excavator-based harvester was very high, indicating that proper consideration should be given to a machine + harvester-head combination of this type when one is seeking well-functioning, efficient, and economically safe machine solutions for the harvesting of both industrial and energy wood from young-thinning stands.

Figure 11 compares the productivity results of this study with the results of previous studies of multi-stem cutting of whole trees (Kärhä et al. 2006b) and single-stem cutting of industrial wood (Ryynänen and Rönkkö 2001, Kärhä et al. 2006a) with wheeled harvesters and conventional feeding harvester heads. The comparison indicates that the cutting productivity of the excavator-based harvester equipped with a Naarva EF 28 harvester head was clearly higher than that of the single-stem method and almost the same as seen in multi-stem cutting of whole trees (Figure 11). In comparison of the results, it should be remembered that the work method selected for the present study was the so-called two-pile method. It has been observed that this reduces cutting productivity by around 10% relative to whole-tree cutting (in which there is only one assortment to be collected) (Kärhä and Mutikainen 2008). Moreover, both the industrial and energy wood were harvested delimbed, which means that, in comparison to the whole-tree cutting alternative, cutting productivity was in principle lower by the amount of the delimbing loss (Heikkilä et al. 2006, Laitila 2012).

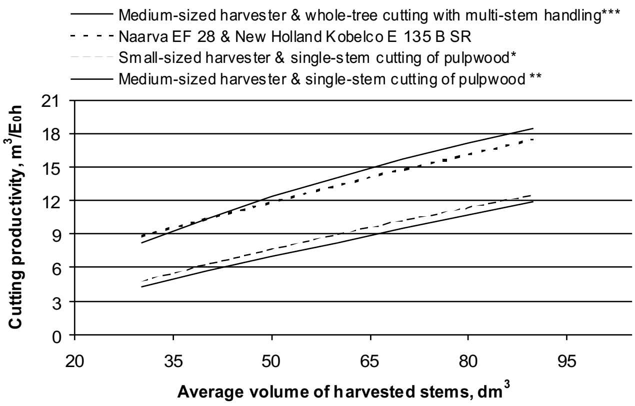

Figure 11. The cutting productivity of an excavator-based harvester equipped with Naarva EF 28 accumulating harvester head compared to single-stem cutting with a small (*) and medium-sized (**) wheeled harvester (Ryynänen and Rönkkö 2001, Kärhä 2006a) or multi-stem cutting of whole trees with a medium-sized wheeled harvester (***) (Kärhä et al. 2006b)

The productivity result was slightly higher than that in the study of the Naarva EF 28 harvester head and wheeled ProSilva 910 harvester carried out by TTS (Rieppo and Mutikainen 2011). In the TTS study, cutting productivity per effective hour for the integrated harvesting of industrial and energy wood was 11.9 m^3/E_0h when the average volume of the trees to be removed was 79 dm^3. When all trees were harvested as delimbed energy wood, productivity per effective hour was 15.2 m^3/E_0h with a stem volume of 82 dm^3 (Rieppo and Mutikainen 2011).

The productivity values obtained by TTS were at the same level as those in the recent research by Metsäteho on the most common professional harvester heads designed for harvesting industrial and energy wood (Kärhä et al. 2010, Kärhä et al. 2011b, Kärhä et al. 2011c). However, the results of the present study and those mentioned above should not be used for comparisons between machines or harvester heads, since the machine-operator has a great impact on productivity, especially during thinning work (Sirén 1998, Ryynänen and Rönkkö 2001, Kariniemi 2006, Väätäinen et al. 2005). Instead, the results should be interpreted as indicating that – on suitable sites and with a skilled operator – an excavator-based harvester in combination with a Naarva EF 28 harvester head can deliver the same level of productivity as conventional harvesters and harvester heads.

A key factor behind the high productivity results was the flawless operation of the Naarva EF 28, especially in bunch delimbing and cutting, due to the absence of interruptions caused by chain failure. The guillotine cutting system also worked well for felling cuts. The good productivity is explained also by the operator's excellent skills and reasonable and efficient use of the multi-stem processing capability of the harvester head. In addition, the operator was able to utilise the excavator's rotating main carriage in the cutting work and speed up the boom movements, by moving the base machine forward and backward at the work location as necessary. When reviewing the results, one should remember too that the cutting site was a well-managed single-species stand that was optimal for the properties of the harvester head and base machine, as well as for the work method chosen.

Account must also be taken of the fact that the results are based on only one, relatively small-scale test. Therefore, they must not be used as a baseline for productivity in determination of unit costs for the integrated harvesting of industrial and energy wood. Previous studies have shown that productivity curves based on follow-up studies are significantly lower than operating-hour productivity curves calculated on the basis of time studies (Mäki 1999, Ryynänen and Rönkkö 2001, Sirén and Aaltio 2003). The reasons for this include the fact that time studies based on brief work on sample plots do not fully correspond to real-world work. Accordingly, a long-term follow-up study would give a more reliable picture of productivity in practice (Ryynänen and Rönkkö 2001, Sirén and Aaltio 2003), as well as of the functional and technical utilisation rate of the base machine and harvester head in variable stand conditions, at different times of year.

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ПРОИЗВОДИТЕЛЬНОСТЬ ХАРВЕСТЕРА НА БАЗЕ ЭКСКАВАТОРА ПРИ ИНТЕГРИРОВАННОЙ ЗАГОТОВКИ БАЛАНСОВОЙ И ТОПЛИВНОЙ ДРЕВЕСИНЫ

Ю. Лайтила и К. Вятяйнен

Резюме

Целью данного исследования являлось определение производительности заготовки методом групповой обработки топливной и деловой древесины, а также хронометраж этих оперций в условиях, когда базовой машиной являлся гусеничный экскаватор, а валку выполняла харвестерная головка Naarva EF 28. На основе собранного материала были разработаны модели затрат времени и производительности относительно каждого обрабатываемого ствола при заготовке методом групповой обработки. В модели затрат времени определили производительность рубок путём применения показателей объёма деловой части ствола и количества заготовленных деревьев на гектаре. Производительность труда была выражена в плотных кубических метрах за один трудочас (m^3/E_0h).

Средний показатель производительности за один трудочас составил 12,8 m^3/E_0h, за это время было вырублено 233 дерева. По мере увеличения крупномерности древостоя показатель производительности рубки (m^3/E_0h) увеличивался. Нижнее значение производительности на пробной площади, пройденной методом групповой обработки, составило 8,7 m^3/E_0h и верхнее – 19,9 m^3/E_0h. В зависимости от пробной площади показатели варьировали: по объёму ствола в пределах 26-83 dm^3 (средний показатель 57 dm^3) и по числу вырубленных деревьев на гектаре - в пределах 538-2558 шт. (средний показатель 1309 шт.). На количество деревьев в пачке, захваченной оборудованием, влиял размер ствола, поэтому показатель числа вырубленных деревьев за один трудочас уменьшался по мере увеличения крупномерности древостоя. Верхнее значение производительности рубки, выраженное количеством стволов, составило 347 шт./E_0h, нижнее – 183 шт./E_0h. В среднем харвестерной головкой за один захват-цикл было обработано 1,9 стволов и доля опытной партии от обработанного материала методом групповой обработки (минимум два ствола в пачке) составила 57%. За время хронометражных исследований было заготовлено всего лесоматериалов 2267 шт., из них 71 m^3 соснового баланса и 53 m^3 топливного тонкомера.

Исследования с применением модели затрат времени показали, что при увеличении в три раза количества вырубленных деревьев на гектаре с 800 до 2400 шт. производительность рубки методом групповой обработки за один трудочас увеличилась примерно на один плотный кубометр и при увеличении объёма ствола с 23 $дм^3$ до 89 - производительность рубки за один трудочас удвоилась. При обобщении результатов и сопоставлении с результатами других исследований необходимо принимать во внимание объём материала, а также вляющие на результаты такие факторы, как объект заготовки и оператор машины. На основании результатов исследования можно сделать вывод об очень высоком уровне производительности экскаваторного харвестера и валочной головки Naarva EF 28. Эффективность работы данного комплекса сравнима или даже лучше, чем у колёсной лесной машины с харвестерной головкой для групповой обработки. Исследованная концепция является достойным вариантом интегрированной заготовки деловой и топливной древесины. Во время хронометражных исследований комплекс работал бесперебойно, качество заготовительных работ соответствовало рекомендуемым нормам.

Ключевые слова: интегрированная заготовка, харвестерная головка с погрузочным захватом, экскаватор-харвестер, прореживание, балансовая древесина, очищенная от сучьев топливная древесина