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Harvesting Alternatives, Accumulation and Procurement Cost of Small-Diameter Thinning Wood for Fuel in Central Finland

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This study compared harvesting alternatives, accumulation and procurement costs of small-diameter thinning wood chips for fuel, when trees were harvested either as delimbed stemwood or whole trees. The calculation was made for a hypothetical plant located in Central Finland and the radius of the procurement area was 100 km via the existing road network. Cutting was done with conventional harvester head equipped with multi-tree-handling (MTH) accessories, with the logged trees being chipped at the roadside storage. The cost of delimbed stemwood chips at heating plant was 24% higher compared to the cost of whole tree chips. The availability analysis attested that delimbing lowered the regional cutting removal by 42% compared to the whole tree harvesting, when the minimum accumulation for the fuel fraction at the stand was set at 25 m³/ha. Delimbing diminishes the recovery rate at the site, resulting in a diminishing number of potential recovery sites meeting the threshold volume. However, the study showed that the forest energy potential is increased and procurement costs are reduced, if delimbed stemwood is harvested from stands where the whole tree harvesting is not acceptable due to nutrient loss or for other ecological reasons. Intelligent selection of cutting methods for different stands enables minimization of transport distance and control of procurement cost.

Keywords biomass resources, multi-tree-handling, delimbed stemwood, whole trees, Finland, early thinnings, forest chips
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1 Introduction

The use of commercial fuel chips produced from small-sized trees of young stands was 699 000 m³ (solid) in 2007 in Finland (Ylitalo 2008). Of that volume, chips made from whole trees constituted 86%, while the remainder was produced from delimbed stemwood (Ylitalo 2008). It has been estimated that the annual cutting potential of small-sized thinning wood for fuel, when using whole tree harvesting, is about 6.9 million m³ (Laitila et al. 2008). The cutting removal of small trees from early thinnings is usually composed of broadleaved species or Scots pine (Laitila et al. 2008), with almost half of the potential (3.4 million m³) being located on peatland forests or on unfertile mineral soil stands (Laitila 2004). The cutting of small-sized energy wood is mechanized in Finland (Kärhä 2006, Laitila 2008).

The crown mass is the most nutrient rich part of the tree (e.g. Mälkönen et al. 2001). Therefore the intensified loss of nutrients from the forest soil, due to biomass recovery, must be clearly taken into account in stand selection and in the development of harvesting methods (Hakkila 2005) in order to avoid substantial increment losses. According to the Finnish recommendations, whole tree harvesting should be avoided in spruce dominant stands, unfertile mineral soil stands and almost all types of peatland forests (Koistinen and Äijälä 2005). The nutrient losses can be reduced mechanically if whole trees are topped and the 1–2 meter length tops are left at the site, or trees are delimbed (Koistinen and Äijälä 2005).

According to Hakkila (2005) delimbing of small trees decreases the fuel potential and as a result the cost of chips is increased. Furthermore, the effective heating value of oven dry matter (q_V(net)) of whole trees is higher than the delimbed stemwood, because of the higher heating value of the crown biomass compared to pure stemwood (Nurmi 1993, Nurmi 1997). Under Finnish conditions, whole tree recovery increases the fuel yield by 15–50% and productivity of cutting by 15–40%, compared to only stemwood recovery (Hakkila 2005). However, whole tree harvesting increases the loss of nutrients by as much as 50–150%.

Harvesting trees with branches also reduces the quality of the chips, but this is a critical issue only for small heating plants, which require stick-free chips to operate properly. Delimbed material produces uniform fuel stock devoid of needles and branches which may be a benefit at some power plants with a restricted capability to handle high levels of chlorine and alkali metals contained in the branch material (Nurmi and Hillebrand 2007). Sufficient quantities of alkali metals and chlorine causes agglomeration of bed sand as well as corrosion in fluidized and circulating fluidized bed boilers and heat exchangers (Nurmi and Hillebrand 2007). The problem is greatest with the logging residue chips not with whole tree chips.

Mechanized whole tree harvesting has been covered in several studies in Nordic countries (Hakkila et al. 1978, Lilleberg 1995, Gullberg et al. 1998, Liss 1999, Erikson and Norden 1999, Eriksson and Rytter 2000, Hämäläinen et al. 2001, Johannsson and Gullberg 2002, Björheden et al. 2003, Kärhä et al. 2005, Laitila and Asikainen 2006, Kärhä 2006, Jylhä and Laitila 2007, Spinelli et al. 2007, Laitila 2008). The mechanized topping of trees, harvesting trees as delimbed for fuel or the defoliation of tree bunches has not been studied to such a level (Mattila 1998, Ihonen 1998a, b, Laitila et al. 2004, Tanttu and Mutikainen 2004, Heikkilä et al. 2005, Bergström et al. 2007, Lehtimäki and Nurmi 2007).

Multi-tree handling technique was developed in the late 1980s for increasing the productivity of single grip harvesters in the cutting of pulp wood (e.g. Lilleberg 1997, Gingras 2004). The multi-tree processing technique aims to achieve higher efficiency through processing more than one stem per processing cycle (e.g. Lilleberg 1997, Gingras 2004, Bergkvist 2003). The processed bundle can consist of 2–5 trees, and with small trees the number can be even higher. In comparative time studies the productivity of pulp wood cutting has been 18% (Bergkvist 2003) or even 20–30% higher (Lilleberg 1997, Gingras 2004) in multi-tree cutting than in single-tree cutting. When using the multi-tree processing technique, timber measurement requirements are not dealt with as well as in single-tree processing where the harvester measuring method can be used (Lilleberg 1994). Whereas the quality of delimbing has been good; it is possible for it to be regulated depend-

Fig. 1. Mechanized cutting of delimbed stemwood for fuel using the multi-tree handling technique with a Timberjack 745 harvester head (Photo: J. Heikkilä).

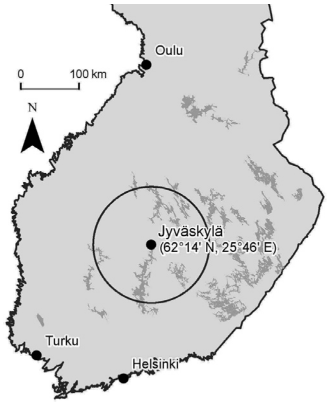

Fig. 2. Location of Jyväskylä in Finland.

ing on the end use of the wood (Lilleberg 1997). For multi-tree handling, the normal harvester head is equipped, for example, with accumulator arms and special feed rollers for the effective feeding of tree bundles. The harvester head discussed in this paper should not be confused with simple accumulating felling heads that are only designed to fell and bunch trees.

Conventional single-grip harvester heads equipped with multi-tree handling equipment, such as John Deere 745, Keto Forst Energy, Moipu 300ES and 400ES, Logset 4M Hamster and Valmet 945 "shear-head", are also suitable for cutting whole trees and delimbed stemwood (Kärhä 2004, Heikkilä 2005, Heikkilä et al. 2005, Kärhä 2006, Lehtimäki and Nurmi 2007). The working technique of whole tree cutting and delimbed stemwood cutting is basically the same apart from the delimbing of the tops of tree bunches (Heikkilä et al. 2005).

In energy wood cutting, with single grip harvesters, the trees are cut and accumulated to the chamber of the multi-tree handling harvester head. Subsequently the tree bunch is moved to an upright position alongside the strip road for the processing of the trees to forwarding length and piling. In whole tree harvesting the tree bunch is fed through the feed rollers and delimbing knives of the harvester head up to the cross-cutting point of forwarding length (5–7 meters). After cross-cutting the un-delimbed top bunch is moved by the harvester crane movement onto the base bunch alongside the strip road. In the delimbed stemwood harvesting, both the base and top bunch of the trees is fed through the feed rollers and delimbing knives of the harvester head and piled at the side of the strip road (Fig. 1). The top bunch is topped at the top diameter of 3–5 cm and the target length of the bolts is usually about 5 meters. After multi-tree delimbing only short bits of branches are left in the tree bunches (Heikkilä et al. 2005).

Holistic studies about the effects of energy wood harvesting alternatives to the accumulation of fuel chips and procurement costs do not exist. One of the aims of this study was also to modify the methodology, used in the supply cost estimation of logging residue chips (Asikainen et al. 2001, Ranta 2002), to the thinning conditions.

The aim of this study was to estimate and compare the harvesting costs of whole tree and delimbed stemwood chips production. Furthermore, the accumulation and procurement costs of small diameter tree chips was estimated within a 100 kilometer radius from a hypothetical combined heat and power plant located in Jyväskylä in Central Finland (Fig. 2), when using different stand selection criteria and cutting methods. The analyses were performed as simulated treatments in young stands based on existing productivity and cost functions and yield calculations to the sample plots of the 9th National Forest Inventory of Finland. It was assumed that all the small diameter wood chips from the potential procurement area were freely available without the prior sorting of different companies or ownership structure.

2 Material and Methods

2.1 Procurement of Chips

In this study the small trees were harvested from early thinnings. Small-sized whole trees are mainly harvested from young stands approaching the stage of first commercial thinning. Due to the failure to conduct pre-commercial thinning, these stands are dense and in need of thinning, but the removal structure of the stands does not enable profitable first commercial thinning if only industrial wood is harvested.

The production stages of the procurement system are demonstrated in Fig. 3. It was assumed that conventional harvester-forwarder chain was used in logging operations. A normal harvester head, suitable for timber cutting, was equipped with accumulating accessories capable for multi-tree processing and trees were recovered for energy purposes. Logged trees were chipped at the roadside landing directly into the load space of the truck-trailer unit. After the chipping the fuel chips were transported to the plant. At the plant the chips were unloaded after weighing to the hopper of the delivery bay.

2.2 Productivity Parameters of the Procurement System

The productivity of cutting whole trees and delimbed stemwood using the multi-tree processing technique was based on the study of Heikkilä et al. (2005) and the productivity model is published in the Excel-based “Cost calculator for delimbed energy wood” cost calculation program (Laitila 2006). According to the study of Heikkilä et al. (2005) the handling time of whole trees is equal to the handling time of delimbed stemwood when using multi-tree processing. However, the cutting productivity of delimbed stemwood is

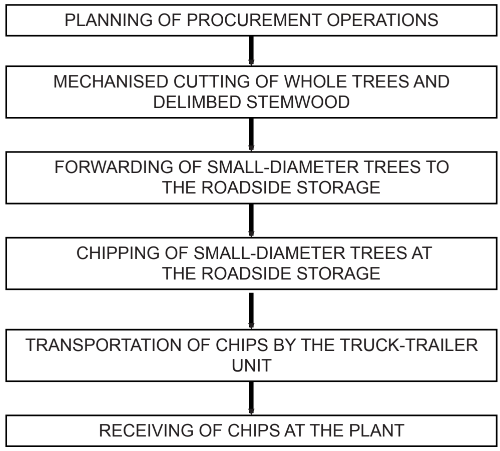

Fig. 3. The production stages of the mechanized procurement system.

10–40% lower than in whole tree cutting, mainly due to the decreased volume (Heikkilä et al. 2006). With small trees the relative productivity difference is the largest since the proportion of crown biomass of the total tree volume is bigger than with larger trees. The harvester’s effective time (E_0) productivity was converted to the gross effective time productivity (E_{15}), which included delays shorter than 15 min, by the coefficient 1.3 (Laitila 2008).

The productivity of forwarding whole trees was calculated according the models of Laitila et al. (2007). The forwarding productivity of delimbed stemwood was calculated by the time consumption models for forwarding long pulpwood (3–5 meters) in thinning conditions (Kuitto et al. 1994). The load size of the medium sized forwarder was estimated to be 6.0 m³ for whole trees and 9.0 m³ for delimbed stemwood (solid). The forwarder’s effective time (E_0) productivity was converted to the gross effective time productivity (E_{15}) by the coefficient 1.2 (Laitila 2008).

The chipping was done at the roadside storage by truck-mounted drum chipper. The chipper’s productivity was estimated to be 34 m³ (85 loose-m³) per operating hour (E_{15}) for both whole trees and delimbed stemwood. The chips were transported by truck-trailer unit with a load volume of 44 m³ (solid). The transportation time consisted of: driving with empty load, driving

Table 1. Cost details of the logging machines, chipper and truck-trailer unit.

	Harvester	Forwarder	Chipper	Truck-trailer unit
Purchase price, € (VAT 0%)	350 000	225 000	400 000	232 000
Salvage value, € (VAT 0%)	140 000	90 000	160 000	92 800
Lifespan, years	4.6	4.6	4.6	4.6
FIXED COSTS:				
Depreciation, € a^{-1}	45 652	29 348	52 174	30 261
Interest, € a^{-1}	16 070	10 330	18 365	10 652
Insurance, € a^{-1}	2350	2350	8173	8173
Administration, € a^{-1}	6 500	6 500	8 000	6 463
LABOUR COSTS:				
Annual gross effective working time, h	2600	2600	2600	2600
Annual working time, h	3230	3050	4010	2886
Degree of machine utilization (MU),%	80	85	65	90
Average wage of the worker, € h^{-1}	11.3	10.4	11.9	11.7
Indirect wage costs, %	63	63	68	68
Wage costs total, € a^{-1}	59 713	51 462	80 246	56 776
OPERATING COSTS (VAT 0%):				
Fuel price, € l^{-1}	0.9	0.9	0.97	1.1
Fuel cost, € a^{-1}	35 094	25 735	163 910	51 480
Oil and lubricant cost, € a^{-1}	2098	962	1599	1700
Service and maintenance cost, € a^{-1}	18 581	5870	33 832	18 658
Work trip compensation, € km^{-1}	0.44	0.44	0.44	0.44
Work travel expenses, € a^{-1}	9500	9500	9900	639
Translocation cost with truck, € km^{-1}	1.35	1.35	–	–
Transfer costs, € a^{-1}	6500	6500	–	–
Risk and profit margin (5%), € a^{-1}	10 103	7428	18810	9 240
TOTAL COSTS (VAT 0%):	212 159	155 984	395 009	194 040
Operating hour cost, € E_{15}^{-1}	81.6	60.0	151.9	74.6 for driving & 47.0 for terminal time

with load and terminal time. The terminal time included loading, unloading, waiting and auxiliary time. Time consumption of driving, with and without load, was calculated as a function of transportation distance according to the speed functions for chip trucks (Ranta 2002). The loading time of the truck-trailer unit was 1.29 hours, which is equal to the chipping time. The unloading time of chips at the end-use facility was estimated to be 0.8 hours, which also included the auxiliary and waiting time. Terminal times are identical to the study of Laitila (2008). The trucks were assumed to drive to the destination fully loaded and return to the starting point empty, with the same transporting distance was used for driving both with and without load.

2.3 Cost Calculation

The operating costs (excluding VAT) of the logging machines, chipper and truck-trailer unit were calculated per gross effective hour (E_{15}) using the common machine cost calculation method (e.g. Harstela 1993) and costs were presented in Euros (€). The costs included both time-dependent costs (e.g. capital depreciation, interest expenses, labor costs, insurance fees and administration expenses) and variable operating expenses (e.g. fuel, repairs, service and machine transfers). In addition to the annual total cost, 5% was added to take into account the risk of entrepreneurship. The values used are presented in Table 1.

The lifespan of the logging machines, chipper and truck-trailer unit were standardized as 12 000 operating hours (4.6 years). The salvage value of

40% and an interest-rate of 6% were applied in the calculation. The average purchase prices were acquired from the manufacturers. The machine utilization (MU) degrees were identical to the study of Laitila (2008). The MU represents both the technical reliability of the machine and the operational efficiency of the organization (e.g. Harstela 1993).

The calculation values for labour costs, fuel, insurance fees, repairs and service expenses were obtained from Koneyrittäjien Liitto ry (The Trade Association of Finnish Forestry and Earth Moving Contractors) and Metsäalan Kuljetusyrittäjät ry (The Association of Forest Industry Road Carriers). In Finland the logging machines and chippers can use the partially tax free diesel oil while the lorries use taxable diesel oil.

For the truck transportation the hourly cost was divided between driving and terminal times. In the calculation the annual driving kilometers of the truck-trailer unit were 90 000 km. When calculating the terminal time cost of the truck-trailer unit, the fuel, oil and service costs were excluded from the total costs.

The unit costs (€ m^{-3}) of the working phases were calculated by dividing the hourly cost by productivity. The overhead costs of the procurement operations were estimated to be 3.1 € m^{-3}, which corresponds to the average organization costs of industrial roundwood in Finland (Kariniemi 2007). The organization cost was set as the same for both whole trees and delimbed stemwood. A stumpage price for the harvested raw material was not included in this study.

2.4 Forest Data

The estimated accumulation of forest chips from young forests around the city of Jyväskylä was based on sample plot data from the 9th Finnish National Forest Inventory (NFI 9) from the forestry centres of Etelä-Pohjanmaa, Etelä-Savo, Häme-Uusimaa, Keski-Suomi, Pirkanmaa and Pohjois-Savo (Tomppo et al. 1998a, Tomppo et al. 1999, Korhonen et al. 2000a, b, Tomppo et al. 2001). Satellite images and other auxiliary data were used to down-scale the data from forestry-centre level to municipality level (Tomppo et al. 1998b). Calculations of forest chips resources were made for the sapling stands (dominant height >1.3 m, diameter at breast height (dbh) <8–10 cm) and young thinning stands (dominant height usually >7 m, dbh 8–16 cm) needing improvement thinning within the first five-year period. The maximum transportation distance was 100 kilometers along the existing road network (Ranta 2002).

The area that a NFI sample plot represents in a certain municipality and stand development class was calculated as follows (Laitila et al. 2004, Ranta et al. 2007):

$$N_{khl,y} = \frac{\frac{a_{khl}}{A_{khl}} \times A_{khl,y}}{n_{khl}}$$

where a_{khl} was the area estimate for improvement fellings according to the NFI in the development class khl in the forestry centre, A_{khl} was the estimate of total area for development class khl according to the NFI in the forestry centre, $A_{khl,y}$ was the area estimate for development class khl in municipality y according to multi-source NFI data, and n_{khl} was the number of sample plots needing improvement fellings in the forestry centre. The volume of harvested biomass in the calculated area unit, $N_{khl,y}$, was obtained by multiplying the area with the biomass yield per hectare in the sample plot. Harvesting volume for the five-year period was converted to annual harvesting volume simply by dividing it by five.

2.5 Computation of the Cutting Removal

The removal of stem wood was calculated for each sample plot by simulating the tending of a young stand or thinning according to silvicultural guidelines (Luonnonläheinen metsänhoito – Metsänhoitosuositukset, 1994). In the simulation, trees tallied to the plot were first sorted by diameter. Starting from the smallest tree, trees were harvested until the basal area of the remaining trees reached the recommended basal area after thinning. The volume of the removed stems was then totalled. Trees with a dbh of more than 9.5 cm were classified as industrial roundwood, while those with dbh of less than 9.5 cm and more than 4 cm were classified as energy wood. Trees less than

4 cm dbh were not included in the total energy wood accumulation. The roundwood assortment had to fulfil the common quality requirements for the pulpwood (birch, pine or spruce, minimum top diameter 6 cm and the length of the bolt >2 m). In the total accumulation, trees were not classified as industrial roundwood or pure energy wood because all trees were harvested either by the whole tree or delimbed stemwood method for energy, if the below-mentioned stand selection criteria were fulfilled. In the calculation, the recovery percentage of biomass in the harvesting operations was assumed to be 100%.

When using the whole tree method, the crown mass was added to the total stem wood accumulation using crown mass factors (Hakkila 1991). The dry mass was then further converted to volume using dry mass density factors (Hakkila 1978). The crown mass included living branches and needles. Dead branches were excluded, as they were assumed to be lost during the harvesting.

In the delimbed stemwood harvesting, the allowed lengths of the bundle delimbed and bucked stems were both 3 meters and 5 meters while the minimum top diameter was 4 cm. For the trees of which the usable stem part was longer than 3 meters but shorter than 5 meters the cross cutting was done at the 4 cm top diameter point. The length of the base bolt was thus exceptionally allowed to vary between 3–5 meters.

The bucking and bolt volume of the delimbed stemwood was calculated as a function of tree species as well the average height and dbh of trees at the NFI sample plot. The bucking simulation and volume calculation for the NFI sample plots were done by the Excel based RUTILA-program (Pasanen 2004, Heikkilä et al. 2005). With RUTILA, the calculation was based on the taper curve models by Laasasenaho (1982).

2.6 Transporting Distances and Stand Selection Criteria

The calculation of transporting distances, via the existing road network to Jyväskylä, were based on GIS-analysis and databases of forestry companies from the year 2000 (Asikainen et al. 2001, Ranta 2002). The transporting distance from municipality x to Jyväskylä was the average transporting distance from the felling stands of the municipality x. The average transporting distances varied between 12 and 100 kilometers. For the procurement cost calculation the average forwarding distance in each municipality was also calculated. The calculations were also based on databases of felling stands of forestry companies from the year 2000 (Asikainen et al. 2001, Ranta 2002). The forwarding distances varied between 181 and 301 meters, with the average being 232 meters.

The NFI sample plot data contained information on, for example, soil type (mineral or peat soil), habitat type, dominant species and average diameter and height of the trees. Furthermore, the cutting removals of industrial roundwood, whole trees and delimbed stemwood per hectare were calculated in a way as presented earlier in this article. For the final summing of yield potential, different stand / sample plot selection criteria were applied. These criteria were:

1) The maximum allowable removal of industrial roundwood was 25 m³ (solid) per hectare and minimum accumulation of the energy fraction (whole trees or delimbed stemwood) was 25 m³ (solid) per hectare.
2) Trees were harvested, delimbed, from peat soil stands, spruce dominant stands and mineral soil stands of which habitat was *Vaccinum*-type or poorer.
3) Whole tree harvesting was applied in mineral soil stands habitat of *Myrtillus*-type or more fertile, excluding spruce dominant stands.

3 Results

3.1 Logging Costs and Cost Structure of Fuel Chips

In the sensitivity analysis of logging cost as a function of diameter, the logging costs of delimbed pine stemwood were 14–76 € m^{-3} (Fig. 4). Cutting costs were 9.8–69.3 € m^{-3} and forwarding costs 4–6.3 € m^{-3} (Fig. 4). The logging costs of the pine whole trees were 12.4–53.1 € m^{-3}. Of that the cutting costs were 7.8–45.3 € m^{-3} and forwarding costs 4.6–7.9 € m^{-3} (Fig. 4). In the

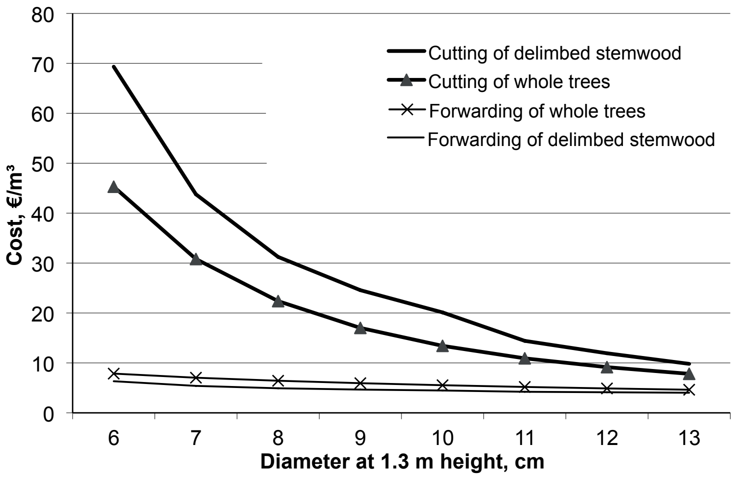

Fig. 4. The cutting and forwarding costs of delimbed pine stemwood and pine whole trees.

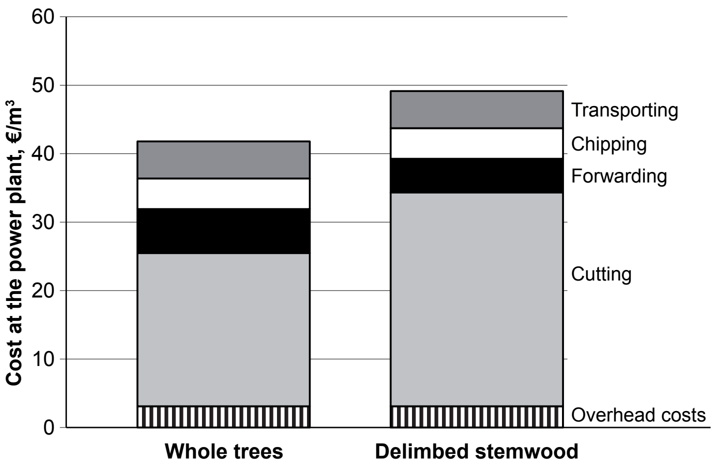

Fig. 5. The procurement cost structure of fuel chips made of whole trees or delimbed stemwood.

example sensitivity analysis presented in Fig. 4, the cutting removal was 1500 stems per hectare, forwarding distance was 230 meters, dbh 6–13 cm and height of the pines 5.5–11.8 meters.

The procurement costs of fuel chips made from delimbed stemwood and whole trees were 49.1 and 41.8 € m^{-3}, respectively (Fig. 5). The cutting costs of whole trees were 22.4 € m^{-3} and delimbed stemwood 31.2 € m^{-3}, when dbh was 8 cm. The forwarding costs of whole trees were 6.4 € m^{-3}. The forwarding costs of delimbed stemwood were 1.5 € m^{-3} lower due to higher bulk density and therefore bigger load volumes. The overhead (3.1 € m^{-3}), chipping (4.5 € m^{-3}) and transporting (5.4 € m^{-3}) costs were the same for both raw materials in the comparison (Fig. 5).

The procurement cost structure comparison of whole tree and delimbed stemwood chips was made for an example stand where the cutting removal was set at 28.7 m^3 ha^{-1} for delimbed stemwood and 41.3 m^3 ha^{-1} for whole trees (Fig. 5). The number of removed trees was 1500 stems per hectare. The volumes of the removed pines were 19.1 liters for delimbed stemwood and 27.5

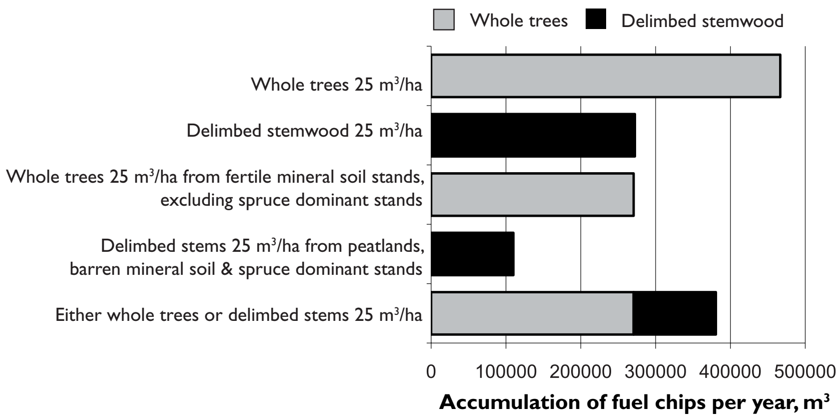

Fig. 6. The accumulation of energy wood around the city of Jyväskylä when using different stand selection criteria and alternative cutting methods. Maximum transportation distance was 100 km.

liters for whole trees, respectively. The average diameter of the thinned pines at the 1.3 meter height was 8 cm and the height from the butt to the top was 7.4 meters. The forwarding distance was 230 meters and the transporting distance from the roadside landing to the plant was 50 kilometers.

3.2 Accumulation of Whole Trees and Delimbed Stemwood around Jyväskylä

The availability analysis attested that delimbing lowered the cutting removal by 42% compared to the whole tree harvesting, when the minimum accumulation for the fuel fraction at sample plot was set at 25 m³ ha^{-1}. Delimbing decreases the recovery rate at the site and as a result the number of potential recovery sites becomes too small in volume. Around the city of Jyväskylä, the accumulation of whole trees was 467 000 m³ (solid) per year and delimbing decreased the accumulation of the recovered fuel fraction to 272 000 m³ per year (Fig. 6). When the whole tree harvesting method was limited to fertile mineral soil stands, excluding spruce dominant stands, the accumulation of recovered fuel fraction was 271 000 m³ per year. When harvesting fuel wood as delimbed from peatlands, unfertile mineral soil stands (poorer than *Myrtillus*-type) and spruce dominant stands, the annual accumulation was 110 000 m³ per year. Thus the maximum accumulation of fuel fraction from young thinning stands was 381 000 m³ per year (271 000 m³ whole trees + 110 000 m³ delimbed stemwood) in Jyväskylä, when logging was carried out according to the current harvesting recommendations (Koistinen and Äijälä 2005).

3.3 Procurement Cost of Whole Trees and Delimbed Stemwood for Energy around Jyväskylä

The procurement costs of fuel chips from young stands, when applying the above mentioned restrictions for logging sites, were calculated for a hypothetical plant located in Jyväskylä. The logging costs at the sample plot stands of NFI were calculated using the productivity models and cost parameters described in Chapters 2.2 and 2.3. The transporting costs were calculated as a function of transport distances from municipalities of the procurement area to Jyväskylä. The stand-wise procurement cost of chips at the Jyväskylä plant was calculated by totalling the logging, chipping, transporting and overhead costs. Fig. 7 illustrates marginal costs as a function of harvested volume.

The accumulation and procurement cost data of fuel chips were summarized and data was sorted according to the procurement costs. The

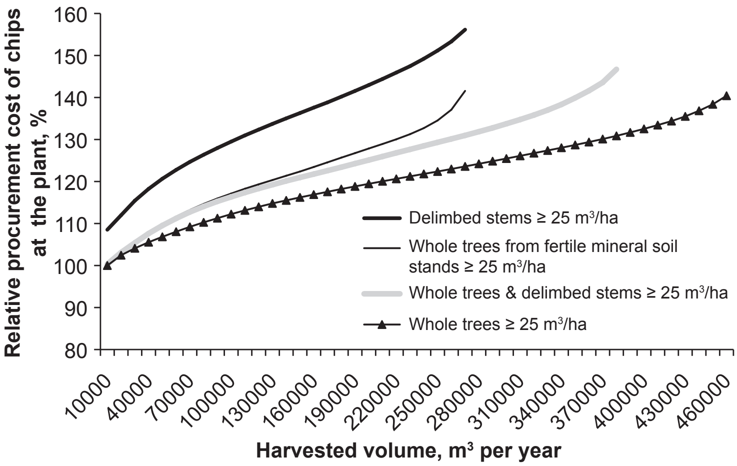

Fig. 7. The relative procurement cost of chips around Jyväskylä when using alternative cutting methods and stand selection criteria.

cumulative accumulation of fuel chips at marginal procurement cost was calculated for four harvesting alternatives and cost at plant was expressed as relative value. The marginal procurement cost was 100% when the annual procurement volume was 10 000 m³ and trees were harvested using the whole tree method in all sample plot stands of the NFI (Fig. 7).

The procurement costs of whole tree chips were the lowest and the delimbed stemwood chips the highest if not using the stand selection criteria of soil type or habitat (Fig. 7). When the annual procurement volume of chips were 100 000 m³ the marginal cost of delimbed stemwood chips were 15% higher compared to procurement cost of whole tree chips. If the whole tree harvesting operations were limited only to the fertile mineral soil stands, the procurement costs were the second highest and the costs increased steeply, especially in the bigger procurement volumes. When combining the procurement of both whole tree and delimbed stemwood chips the procurement costs were the second lowest due to the increased harvesting potential. The cost difference, compared to the whole tree harvesting was 4%, when the annual procurement volume of chips was 100 000 m³ (Fig. 7).

4 Discussion and Conclusions

Reliable knowledge of energy wood resources and procurement costs is needed when planning new plant investment (Möller and Nielsen 2007) or making decisions on both a strategic and operational level. In this study, by using the sample plot data of NFI9, it was possible to make detailed regional plant-specific chip procurement costs and availability analysis when using alternative cutting methods and stand selection criteria. The calculation method enabled the use of time consumption functions for different production stages linked with worksite factors for different supply chains. One of the themes of this study was to modify the methodology, used in the supply cost estimation of logging residue chips, to the thinning conditions (Asikainen et al. 2001, Ranta 2002).

Mattila and Keskimölö (1994) developed a forest fuel resource estimation method based on the harvesting and management suggestions made for the sample plots used in the NFI. Malinen et al. (2001) introduced an estimation method based on alternative cutting scenarios; describing the intensity of forest utilization for a certain period. Energy-wood cutting alternatives and industrial roundwood harvesting alternatives were simulated based on data provided by NFIs.

Cost models for energywood harvesting were also added to the so called Energy-MELA system (Malinen et al. 2001). The transportation and forwarding distances were based on defaults in the Energy-MELA system. In the present study the forwarding and transporting distances were based on authentic stand data of forestry integrates (Asikainen et al. 2001, Ranta 2002) and GIS analysis via the existing road network from surrounding municipalities to Jyväskylä. In the study of Malinen et al. (2001) the integrated harvesting of energy wood and industrial roundwood from pine-dominated first thinning was based on flail delimbing which is no longer used as a procurement method in Finland (e.g. Jylhä and Laitila 2007).

Objectively sampled and measured NFI plots guarantee unbiased estimates of forest resources within large areas and conventional forestry attributes can be scaled down to a municipality level in multi-source NFI. However, in this study scaling down poses a problem: It was assumed that the development-class level proportion of energy-wood stands would be constant within a forestry centre, which is not always the case. The same problem was faced when the accumulations with different stand selection criteria were estimated. The habitat types within a municipality were assumed to be distributed similarly as within the forestry centre.

It is easy to see that estimating the accumulation of small-diameter thinning wood is neither trivial nor unambiguous. Firstly, the potential depends heavily on selection criteria set for sample plots. If, for example, the minimum accumulation of energy wood is raised to 40 m^3 ha^{-1}, the potential drops 20% on a national level (Anttila et al. 2008). Secondly, the potential depends on limits for industrial roundwood. Here all trees smaller or equal to 9.5 cm at breast height were deemed as non-industrial wood. On the one hand, usually one pulpwood bolt can be obtained even from trees with a dbh as low as 8 cm. On the other hand, harvesting of these small bolts is extremely costly, their quality is low and losses in drum debarking high. Therefore, the division to industrial and non-industrial roundwood used here is justified.

Furthermore, the accumulation includes all the tendings and thinnings, which can be done within the next five-year period according to silvicultural guidelines (Luonnonläheinen metsänhoito – Metsänhoitosuositukset, 1994). The accumulation is, thus, technical potential that would be available, if all legal tendings and thinnings would be carried out and all the wood would come to the markets. Additionally, no predictions regarding the future were made.

The logging cost of delimbed stemwood was 26% higher compared to the logging cost of whole trees (Fig 4 and 5). The cost difference decreased when the stem volume increased (Fig 4), which denotes that the delimbed stemwood harvesting for fuel is feasible with rather big trees (dbh = 7–13 cm). With broadleaved trees the delimbing increases the logging costs less compared to pine or spruce, because usually the proportion of crown biomass of the total tree volume is smaller (Heikkilä et al. 2005).

The cutting to the exact length, and especially to the exact top diameter, is in practise impossible when multi-tree handling is being carried out. The point at which the minimum utilization diameter arises may not occur at the same position on each stem and therefore the rougher cutting by eye is allowed. In this study the bucking was based on average height and diameter of removed trees. When cutting whole trees with the conventional harvester head, the butt is delimbed when feeding the tree bunch through the feed rollers and delimbing knives of the harvester head up to the cross-cutting point. The butt of pine and birch is usually free of branches and therefore the bias in the results of the present study due to the butt delimbing is therefore rather irrelevant.

The productivity models for forwarding were selected so that the relative productivity difference between whole trees and delimbed stemwood was equal to the results of Heikkilä et al. (2005). The study material of Heikkilä et al. (2005) was only 12 loads and therefore productivity models for forwarding were not made. In the studied stands the forwarding productivity of delimbed stemwood was 10–20% higher than the forwarding productivity of whole trees (Heikkilä et al. 2005). The main reasons were the improved efficiency in the loading and unloading work and especially the increase in average load size.

When the proportion of harvested thinning wood is very small, compared to the technical potential, only the best stands are harvested. This means that the procurement company can select harvesting sites located near the power plant, aiming at high yields of material per hectare, large tree sizes and short forwarding distances. As increasingly larger amounts of wood fuel are recovered, harvesting must be extended to more remote and less favourable areas, which increases the procurement costs (Asikainen and Kuitto 2000, Asikainen et al. 2001, Ranta 2002, Ranta 2005). The regional variations in availability and the level of supply cost vary significantly in different geographical conditions (Asikainen and Kuitto 2000, Asikainen et al. 2001, Ranta 2002, Ranta 2005).

The low energy-intensity and transport economy is the problem related to forest fuels. The economy of a large-scale supply will, contrary to almost all other fuels, increase the supply costs after a certain supply level is achieved (Ranta 2005). The decentralized location and small unit size of pure forest fuel user is a consequence of this cost effect. Practically, only small-scale heating plants can concentrate on using only forest fuels (Ranta 2005). The broad raw material base of biofuels for the heating or power plant will help to reduce the transporting distance and ensure a reliable and cost competitive renewable fuel supply.

The harvesting costs of small diameter thinning wood are significantly higher compared, for example, to logging residues (Hakkila 2004). Therefore energy wood thinning in young stands has been subsidized by the government since the late 1990s and this so called Kemera fund enables the harvesting activities in young stands in Finland (Tanttu and Sirén 2004, Heikkilä et al. 2007, Ahtikoski et al. 2008). State subsidies for logging are 7 € m^{-3} and for chipping 4.25 € m^{-3} (Kemera opas 2004). The subsidized procurement costs of whole tree chips and delimbed stemwood chips were in this study 30.5 € m^{-3} and 37.9 € m^{-3}, respectively, which is higher than the average price of all types of forest chips, which was 23.5 € m^{-3} at the plant in 2006 (Ylitalo 2007).

In the present study the whole potential was treated as an integral entity despite organizational territories of procurement organizations. In practice potential calculations are made separately as forest-company specific or among alliances. This will significantly decrease the potential at the plant level and increase procurement costs, because of the need for a larger procurement area to satisfy the demand (Ranta 2005).

Furthermore, the estimated potential did not take into account the consumption of forest chips by existing plants. In Central Finland there are four large CHP-plants (capacity of each plant 130–262 MW), one located in Jyväskylä and three located in the paper industry integrates of Jämsänkoski, Jämsä and Äänekoski (Kallio and Leinonen 2006). In addition there are four municipal heating plants and 20 smaller heating plants in the region. The capacities of heating plants are ranged between 10–25 MW and 1–10 MW respectively (Kallio and Leinonen 2006). The annual consumption of solid wood fuels was 3082 GWh in Central Finland, in 2006 forest chips constituted 1036 GWh of that amount (Ylitalo 2007). In the statistics, collected by the Finnish Forest Research Institute (Ylitalo 2007), the share of logging residues was 54% of the total forest chip volume. Stumps constituted 35%, whole trees 9%, delimbed stemwood 2% and mainly rotten large-sized roundwood 1% of the used forest chips volume. In the plant specific studies in order to determine the available potential, the present use must be subtracted from the total potential.

According to current forestry recommendations (Koistinen and Äijälä 2005) whole tree harvesting should be avoided in ecologically sensitive sites. However, harvesting of delimbed stemwood is possible also in these sensitive sites since the nutrient rich branches are left at the site. As a result the regional forest energy potential actually increases and procurement costs decrease when applying both delimbed stemwood and whole tree harvesting and when this is compared to the situation where trees are harvested only as whole trees and harvesting is limited only to fertile mineral soils. Intelligent selection of harvesting methods for different stands enables minimizing the transport distance and controlling the procurement costs.

From the contractor's point of view, the single-grip harvester head, capable of single- and multi-tree handling seems appealing due to its versatility. It can be used for both energy wood and industrial roundwood harvesting with small modifications. Logging sites often are comprised of several compartments and this kind of multi-functioning machine might reduce the need for machine transfers and increase operational efficiency. According to the study of Kärhä (2006) the cutting productivity with felling bunching heads were higher than with roller-fed harvester heads when the marked tree size was below 8 liters. With bigger tree sizes, the cutting productivity of the heads capable of feeding trees, surpassed that of the pure felling bunching heads. The disadvantage of the conventional harvester head in energy wood thinning is the purchase price, which is higher compared to the felling bunching head with more simplified structure and fewer components. Currently there are almost 200 harvesters cutting small-sized thinning wood for fuel and 44% of which are equipped with felling bunching heads with the remainder being single grip harvesters equipped with multi tree handling accessories (Kärhä 2007).

The annual use of forest chips for fuel is to be increased to 16 TWh (8 million m³) by 2015 (Metsäsektorin tulevaisuuskatsaus 2006) while the current use is about 3.1 million m³ (Ylitalo 2008). Public opinion favors the energy wood, because it is both domestic and renewable energy source. The harvesting of energy wood may be also seen in light of its silvicultural benefits in young and dense stands (Malinen et al. 2001). Private forest owners have been generally positive towards the increased use of forest fuels, although some concern for the effects on future yields have also been expressed (e.g. Rämö and Toivonen 2001, Bohlin and Roos 2002). According to Hakkila (2006) preconditions for the increase in the use of forest chips are the reduction of production costs, improved fuel quality and reliable delivery systems. Furthermore, the fuel must be produced using environmentally sound methods. When remembering that and the results of present study, the cutting methods capable of both whole tree harvesting and delimbed stemwood harvesting sounds very promising.

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