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The Effect of Supply System on the Wood Paying Capability of a Kraft Pulp Mill Using Scots Pine Harvested from First Thinnings

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The efficiencies of wood supply systems based on cut-to-length (CTL) harvesting, the harvesting of loose whole trees, and whole-tree bundling were compared using the relative wood paying capabilities (WPC) of a kraft pulp mill as decisive criteria. The WPCs from mill to stump were calculated for three first-thinning stands of Scots pine (*Pinus sylvestris* L.) with mean breast-height diameter of the removal of 6, 8, and 12 cm. Pulp price had a strong effect on the WPC, and the CTL system resulted in the highest WPC per m^3 at stump. The savings in procurement costs and gains in energy generation from additional raw material acquired with the harvesting of loose whole trees did not compensate the losses in pulp production. Considering removal per hectare, loose whole trees gave the highest WPCs at stump in the two stands with the smallest trees and the highest proportion of additional raw material. Decrease in pulp price and increase in energy price improved the competitiveness of the whole-tree systems. In the case of whole-tree bundling, savings in transportation costs did not balance the high cutting and compaction costs, and the bundling system was the least competitive alternative.

Keywords cut-to-length harvesting, integrated wood harvesting, residual value, whole-tree harvesting, whole-tree bundling
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1 Introduction

1.1 Background

Young stands are potential sources of pulpwood and energy wood. Due to high harvesting costs resulting from small stem size and low removal per hectare, early thinnings are largely neglected, especially in the Nordic and Baltic countries (Röser et al. 2003). In addition, the quality of small-diameter pulpwood is considered a limiting factor (e.g. Hakkila et al. 1995). The current need for first thinnings in Finland, for example, is 300 000 ha a^{-1} (Korhonen et al. 2007). In the 2000's, on average only 190 000 hectares have been annually thinned (Juntunen and Herrala-Ylinen 2009). Neglecting silvicultural thinnings may endanger future roundwood supply of the forest industries, especially that of saw and veneer logs. Due to ebbing raw wood imports from Russia and increasing demand for energy wood, however, the Finnish forest industries are increasingly seeking for energy wood and substitutive pulpwood, especially from thinnings.

The use of small-diameter thinning wood tends to increase wood procurement and manufacturing costs of the forest industries. In the case of Nordic softwood kraft pulp, wood is the second cost factor in importance, after capital costs, with the proportion of 30–60% of the total manufacturing costs, depending on the cost allocation in the accountings (Pentikäinen 2006, Diesen 2007, Kangas 2008). The downward trend of the real price of most bulk products will likely continue. Therefore, good cost competitiveness is a key factor for success to the pulp and paper industry (Diesen 2007).

Integration of energy wood procurement into the harvesting of pulpwood is considered a means for reducing procurement costs of small-diameter pulpwood and energy wood (e.g. Puttock 1994, Hudson 1995, Hakkila 2004, Oikari et al. 2010). In the "two-pile cutting method", industrial roundwood and energy wood are stacked into own piles, which are transported to separate destinations. In the classic whole-tree system, all biomass components above the stump cross-section are harvested (Hakkila 1989, Stokes et al. 1989), and the pulp and energy fractions are separated from each other at the end-use facility or terminal. However, high transportation costs resulting from bulky loads are a problem. They constitute 20–30% or even more of the production costs of forest chips made from small-tree material (Ryymin et al. 2008).

In the adapted whole-tree system by whole-tree bundling, multi-tree handling is applied, and the trees are compacted into cylindrical bundles of about 0.5 m^3 in solid volume and 2.7 m in length. In this way, the load sizes can be markedly increased (Laitila et al. 2009). When applied to integrated wood harvesting, the separation of the pulp and energy fractions does not take place before the wood reaches the debarking drum. Therefore, separate crushing of the energy fraction is not needed as in most integrated supply systems of pulpwood and energy wood designed for thinnings (e.g. Puttock 1994, Han et al. 2004, Baker et al. 2010, Spinelli and Magagnotti 2010). The experiment reported by Jylhä and Keskinen (2006) showed that bundles containing undelimbed Scots pine (*Pinus sylvestris* L.) tree sections can be processed as blends with conventional pulpwood harvested from first thinnings without deteriorating pulp quality. However, wood losses at various phases of the process can increase, but the effect of these losses on the economy of pulp production is poorly known.

The amount of biomass harvested per unit of area affects harvesting costs. Moreover, whole-tree material originating from young stands differs from conventional pulpwood in terms of the ratio of pulpwood (stem wood) to energy wood (stem bark, branches and foliage). There are also differences in the physical and chemical properties of pulpwood (Hakkila et al. 1995). Most studies on raw wood supply systems of chemical forest industries deal with the raw wood logistics prior to the pulp mill (e.g. Eickhoff 1989, Kärhä et al. 2009, 2010). Comprehensive studies considering also the effects of raw material yield and its composition on the economy of pulp making are lacking.

The aim of the present study was to evaluate the efficiency of three supply systems of Scots pine harvested from first thinnings using relative wood paying capabilities (WPC) of a virtual kraft pulp mill as decisive criteria. The WPCs were calculated for three experimental stands with breast height diameter of the removal as a distinctive factor, and the effects of pulp and energy prices, as well as wood transportation distances on the WPC at stump (WPC_{stump}) were examined.

2 Material and Methods

2.1 The Concepts of Wood Paying Capability

The wood paying capability (WPC) is considered a residual value that the forest product or the industrial process can "pay" after all costs (excl. wood) have been reduced from the sales prices (Pihlajamäki and Kivelä 2001, Paavilainen 2002). The capital costs of pulp production, however, are dependent on the investment cost, depreciation schedule, and interests, and they are difficult to sort out from the public financial accountings of the forest integrates. Therefore, the capital costs of pulp manufacturing were excluded, and the formula of Diesen (2007) was modified as in Eq. 1.

$$\mathrm{WPC}_{mill} = \frac{M - (V + P)}{W} \quad (1)$$

where

WPC_{mill} = wood paying capability at mill, € m^{-3}
M = sales incomes from pulp, energy, and by-products per air dry ton of pulp (ADt, dry content 90%), €
V = manufacturing costs (excl. wood cost) per ADt, €
P = fixed costs (excl. financing costs) per ADt, €
W = the total wood consumption per ADt, m^3

In our study, wood procurement was considered a part of the pulp production process. The WPC at stump per m^3 of conventional pulpwood or whole trees was derived from the WPC_{mill} as follows:

WPC_{mill} (WPC at mill)
– overheads
– truck transportation costs

WPC_{road} (WPC at roadside)
– forwarding costs

WPC_{strip} (WPC at strip road)
– cutting (+compaction) costs

WPC_{stump} (WPC at stump)

From the definitions above it can be seen that an increase in the WPC indicates an increase in the efficiency of the process, i.e. a decline in production costs and wood consumption improve the WPC. Due to omitting capital costs and some minor cost factors (e.g. storing and handling of wood at mill yard), relative WPCs were reported instead of absolute ones. WPC per ha is of great interest to forest owners and wood procurement organisations. Therefore, also areal-based WPCs were computed.

2.2 Stand Data

Wood paying capabilities were calculated for three pure Scots pine stands, located on mineral soil in Central Finland, with mean ages of the removal of 26, 33, and 37 years, respectively (Table 1). On each stand, a rectangular sample strip of 20 m × 50 m was harvested using the second prototype of the Fixteri bundle harvester (Kärhä et al. 2009 , Nuutinen et al. 2010). The stand data before and after harvesting were collected from each strip as reported in Jylhä and Laitila (2007).

Stem volumes (incl. stem bark) were computed using the taper curve model of Laasasenaho (1982). Pulpwood removal for Option 1 was calculated with a minimum top diameter of 6 cm and a bolt length of 3–5 m. The amounts of crown mass (branches and foliage) in the whole-

Table 1. Stand data prior to harvesting and removal parameters affecting harvesting costs.

	Stand 1	Stand 2	Stand 3
Initial stand			
No. of trees ha^{-1}	5300	2150	2000
Mean breast height diameter, cm	7	9	14
Mean height, dm	75	77	139
Mean crown ratio, %	53	57	42
Removal			
No. of trees ha^{-1}	4000	1100	1100
Mean breast height diameter, cm	6	8	12
No. of pulpwood dimensioned trees ha^{-1}	1050	550	1100
Mean pulpwood volume, dm^3	26	43	89
Mean whole-tree volume, dm^3	18	34	103

tree options were based on the branch proportions obtained from a hydrostatic sampling of the whole-tree bundles harvested from the experimental stands (see Kärhä et al. 2009). Five bundles per strip were analyzed individually, representing 36–45% of the number of bundles produced. Branch volumes were obtained by subtracting the volumes of the stem sections from the total bundle volumes. Recovery of the branch biomass was assumed to be equal in the whole-tree systems (Options II–III), and potential harvesting losses were expected not to affect relative proportions of the crown mass components.

2.3 Wood Procurement Costs

2.3.1 Productivity Parameters

The supply systems included in the comparison were as follows:

– Option I: cut-to-length (CTL) harvesting with single-tree handling using a medium-sized single-grip harvester, forwarding with a standard medium-sized forwarder, and road transportation with a standard timber truck and trailer
– Option II: whole-tree cutting with a medium-sized single-grip harvester equipped with multi-tree handling accessories, forwarding with a medium-sized standard forwarder, and road transportation with a biomass truck and trailer equipped with solid side panels and bottom
– Option III: multi-tree cutting and compaction of whole trees using a bundle harvester, forwarding with a medium-sized standard forwarder, and road transportation with a standard timber truck and trailer

The cutting productivities in Option I were calculated by applying the time consumption model of Kärhä et al. (2006a). The productivity of multi-tree cutting of whole trees was based on the model of Kärhä et al. (2006b). In the case of bundle harvesting, the model of Kärhä et al. (2009) was used. The forwarding productivity of conventional pulpwood was calculated using the model of Kärhä et al. (2006a). When forwarding loose and bundled whole trees, the functions of Laitila et al. (2007 and 2009) were applied. The load size of the medium-sized forwarder was set at 11.0 m³ for pulpwood, 6.5 m³ for whole trees, and 24 pieces for bundles (Kärhä 2006a, Laitila 2008, Laitila et al. 2009).

The total length of the strip road network at stand was assumed to be 600 m ha^{-1}, based on an average strip road spacing of 20 m (Niemistö 1992). Forwarding distance in all harvesting options was assumed to be 296 m, which corresponds to the mean forwarding distance of the database of Metsäteho Oy, composed of 22 873 first-thinning stands harvested in Finland in 2006–2007. The effective time (E_0) productivities of cutting and forwarding were converted into gross effective time (E_{15}) productivities with the coefficients applied in the study of Kärhä et al. (2009).

Conventional pulpwood and whole-tree bundles were transported using a timber truck with a trailer, assuming a load size of 45 m³ for pulpwood (Nurminen and Heinonen 2007). In the case of bundle trucking, a maximum payload of 86 pieces or 37 083 kg with green density of 900 kg m^{-3} was used (Peltola 2004, Lindblad et al. 2008, Kärhä et al. 2009). The truck load volume of loose whole trees was set at 25 m³ (Laitila 2008). The road transportation times were composed of driving with an empty load, driving loaded and terminal times (incl. loading, unloading, waiting, and auxiliary time).

The loading time of a truck with single sourced pulpwood was calculated using the time consumption models of Nurminen and Heinonen (2007). For whole-tree bundles, the loading time was obtained by multiplying the loading time of pulpwood with the coefficient 1.37 based on the comparative study of Laitila et al. (2009), resulting in a loading time of 67.4 minutes per load. In the case of loose whole trees, a loading time of 60.0 minutes of the biomass truck was used (Laitila 2008). The unloading times of conventional pulpwood and whole-tree bundles were set at 35.0 minutes, and unloading of loose whole trees by the crane of the truck-trailer unit was assumed to take 48.0 minutes (Laitila 2008). Unloading times of all assortments included auxiliary and waiting times at mill. The time consumption for driving empty and loaded was calculated as a function of transportation distance and the driving speeds, derived from the speed functions of the timber trucks (Nurminen and Heinonen 2007). The truck transportation distance of all timber processed at

Table 2. Hourly cost calculations for the machinery (VAT 0%).

	Harvester	Forwarder	Biomass truck	Timber truck
Purchase price, €	350000	225000	278396	223215
Salvage value, €	140000	90000	111358	89286
Life span, years	4.6	4.6	4.6	4.6
FIXED COSTS				
Depreciation, € a^{-1}	45652	29348	36313	29115
Interest, € a^{-1}	16070	10330	12782	10248
Insurance, € a^{-1}	2350	2350	8173	8173
Administration, € a^{-1}	6500	6500	7323	7323
LABOUR COSTS				
Annual gross effective working time, h	2600	2600	2600	2600
Annual working time, h	3230	3050	2808	2808
Degree of machine utilization (MU), %	80	85	93	93
Average wage of the operator, € h^{-1}	11.3	10.4	12.7	12.7
Indirect wage costs, %	63	63	68	68
Salaries, € a^{-1}	59713	51462	59959	59959
OPERATING COSTS				
Fuel cost, € a^{-1}	35094	25735	57420	54450
Oil and lubricant cost, € a^{-1}	2098	962	2354	2354
Service and maintenance cost, € a^{-1}	18581	5870	18050	18050
Work travel expenses, € a^{-1}	9500	9500	665	665
Transfer costs, € a^{-1}	6500	6500	–	–
Risk and profit margin (5%), € a^{-1}	10103	7428	10153	9517
TOTAL COSTS	212159	155984	213220	199860
Operating hour cost, € E_{15}–h^{-1}	81.6	60.0	82.0 for driving & 53.1 for terminal time	76.9 for driving & 49.1 for terminal time

the virtual pulp mill was assumed to be 106 km (Kariniemi 2009).

2.3.2 Hourly Costs of the Machinery

The hourly costs (excluding VAT) of the harvesters, forwarders and truck-trailer units shown in Table 2 were calculated per gross effective hour (E_{15}–h), i.e. operating hour including interruptions shorter than 15 minutes (Harstela 1993). The purchase prices of the machinery were acquired from the manufacturers. When calculating capital costs, an interest rate of 6% was used. The machine utilization (MU) degrees were obtained from the study of Laitila (2008). The annual cost factors and other parameters needed for hourly cost calculations were obtained from the Trade Association of Finnish Forestry and Earth Moving Contractors and the Association of Forest Industry Road Carriers. The hourly cost of truck transportation was allocated to driving and terminal times. Most parameters needed for hourly cost calculation of the bundle harvester are not known. Therefore, its hourly cost was set at 107 € E_{15}-h^{-1} as in the study of Kärhä et al. (2009).

The unit costs (€ m^{-3}) of cutting and forwarding were computed by dividing the hourly costs by the hourly productivities. The overhead costs of the procurement organisation were set at 3.15 € m^{-3} for all assortments (Kariniemi 2009).

2.4 Pulp Production

2.4.1 The Material Balance Model

The wood paying capabilities at mill by stand, and by supply chain were calculated using a material balance model constructed with Microsoft Excel spreadsheet. The model was composed of three modules; i.e. wood handling (incl. debarking and chipping), fiberline, and chemical recovery. The virtual pulp mill incorporated in the model was assumed to apply the Best Available Techniques to its processes (European Commission 2001).

The separation of pulp chips from the solid energy fraction at the debarking plant of the pulp mill was included in the wood handling module. In order to minimize wood losses in the wood handling and pulping processes, the wood harvested from the case stands was assumed to be processed simultaneously with conventional (delimbed) pulpwood harvested from first thinnings (cf. Hakkila et al. 1998). All external branches were supposed to end up in the debarking residue, and the chips were expected to be free from branch particles.

When constructing the raw material balances of wood handling, 30% of the stem volumes with diameter less than 6 cm were assumed to be conveyed directly into combustion among the debarking and washing residue in the whole-tree options (Kokko, Pekka, Andritz Oy, Chief Engineer, pers. comm. 2009). These volumes (39%, 15% and 5% of the total stem volume in Stands 1–3, respectively) were obtained applying the taper curve model of Laasasenaho (1982) to the removal data. For larger stem sections (incl. Option I), the losses shown in Table 3 were used. The sisal cord used for tying up the bundles (250 g per bundle, ca. 50 m) was ignored in the material balance calculations.

Initial stand-wise bark percentages (17.5, 17.6, and 13.7% in Stands 1–3, respectively) and wood densities (416, 404, and 401 kg m^{-3}) for whole stems were calculated using the volumetric models of Hakkila et al. (1995). Tentative differences in bark percentages and wood densities between stem sections were based on coefficients derived from the average values of pulpwood-dimensioned wood and top sections reported by Hakkila et al. (1995). The bark contents of the pulpwood logs in Option I were calculated by multiplying the stem-wise bark percentages by the coefficient of 0.987. In the whole-tree options (II–III), the stem bark percentages of the top sections less than 6 cm in diameter were set at 17.4% (Hakkila et al. 1995), and the bark percentages of the remaining stem sections were obtained by subtracting the bark volume of the top sections from the total stem bark volume. These initial bark contents were expected to have been reduced by 10% throughout the whole stem due to losses at various phases of the procurement chain (Hakkila 2004). The densities of pulpwood-dimensioned wood in Option I were obtained by multiplying the stem-wise densities by a coefficient of 1.005 derived from the study of Hakkila et al. (1995).

Table 3. Volume-based stemwood losses of the stem sections larger than 6 cm in diameter based on expert's judgement (Kokko, Pekka, Andritz Oy, Chief Engineer, pers. comm. 2009).

	Option I	Option II	Option III
	Debarking loss of stemwood, %		
Stand 1	2.5	2.7	2.6
Stand 2	2.3	2.5	2.4
Stand 3	1.9	2.3	2.2

Basic densities of the biomass components were needed for converting intake volumes into dry masses for the material balance calculation. Mean basic density for the branch fraction was computed by weighing the basic densities of branch wood, branch bark (Kärkkäinen 1976) and foliage (Gislerud 1974) by their relative proportions of the crown mass reported by Hakkila (1991). For stem bark, the basic density reported by Hakkila et al. (1995) was used.

The proportions of stem bark ending up into the pulp chip fraction were derived from the dry mass based bark contents set for the pulp chips. In the CTL option (I), the bark content of the chips was set at 0.6%. In the whole-tree options (II–III), a bark content of 1.0% was used (cf. Hakkila et al. 1998, Gullichsen and Fogelholm 2000). The procedure described above resulted in the raw material balances shown in Table 4.

The effective heating values of the solid energy fractions were obtained by weighing the effective heating values of their components (Nurmi 1993)

Table 4. Raw material balances of wood handling.

	Stand 1 Option I	Stand 1 Option II	Stand 1 Option III	Stand 2 Option I	Stand 2 Option II %	Stand 2 Option III	Stand 3 Option I	Stand 3 Option II	Stand 3 Option III
Total intake*									
– Stem	100	83.7	83.7	100	80.4	80.4	100	90.6	90.6
– Branches	0	16.3	16.3	0	19.6	19.6	0	9.4	9.4
Stem sections*									
– Wood	84.2	84.0	84.0	84.1	83.9	83.9	87.6	87.5	87.5
– Bark	15.8	16.0	16.0	15.9	16.1	16.1	12.4	12.5	12.5
Stemwood**									
– pulp fraction	97.5	86.7	86.7	97.7	93.5	93.6	98.1	96.5	96.6
– energy fraction	2.5	13.3	13.3	2.3	6.5	6.4	1.9	3.5	3.4
Stem bark**									
– pulp fraction	4.9	7.1	7.1	4.7	7.4	7.4	6.3	11.2	11.2
– energy fraction	95.1	92.9	92.9	95.3	92.6	92.6	93.7	89.8	89.8
Total output**									
– pulp fraction	87.6	66.0	66.0	87.4	67.9	68.0	90.2	81.0	81.0
– energy fraction	12.4	34.0	34.0	12.6	32.1	32.0	9.8	19.0	19.0

* volume basis, ** dry mass basis.

Table 5. The essential fiberline and chemical recovery parameters (Dahl et al. 2009).

Parameter	Value
The total yield of fiberline	43.4%
The yield of by-products from wood	3.0%
The yield of by-products from bark	4.5%
Alkali charge in cooking wood*	18.6%
Alkali charge in cooking bark contaminants	27.8%
The total dry solids of black liquor	1.73 t ADt^{-1} **
– inorganics in black liquor	0.65 t ADt^{-1}
The total energy production from black liquor***	14.5 GJ ADt^{-1}
Energy from additional fuel	0.3 GJ ADt^{-1}
Heat consumption	13.38 GJ ADt^{-1}
Electricity consumption	2.48 GJ ADt^{-1}

* The amount of effective alkali 110 kg m^{-3}, the recovery rate of cooking chemicals 95%.
** ADt = air dry ton of pulp (solid content 90%).
*** A recovery boiler efficiency of 75%; steam production 80%, electricity production 20%.

by their relative proportions in the debarking residues. The mean heating value for branches was calculated by weighing the heating values of needles, branch wood, and branch bark by their proportions in the crown mass reported by Hakkila (1991). Dry content of debarking residues was set at 45% (Impola 2000), and the effective heating values with moisture were calculated as in Nurmi (1993). Steam and electricity consumptions in wood handling were set at 0.15 GJ ADt^{-1} and 55 kWh ADt^{-1}, respectively (European Commission 2001). For the bark boiler, a total efficiency of 85% was used, and 70% of its capacity was expected to be used for steam generation and 30% for electricity generation (European Commission 2001).

The essential fiberline and chemical recovery parameters common to all supply systems and stands are shown in Table 5.

2.4.2 Cost and Revenue Variables

The virtual pulp mill was assumed to produce 600 000 ADt a^{-1} of softwood kraft pulp. In the basic calculation, a pulp price of 500 € ADt^{-1} was used. The price of by-products (tall oil and turpentine) was set at 350 € t^{-1}, and the surplus electricity and process steam were expected to be sold at the prices of 50 € MWh^{-1} and 10 € MWh^{-1}, respectively. Incentive wages of the employees were set at 12.6 million € a^{-1}. Fixed costs (excl. financing costs) were expected to be 60 million € a^{-1}. Chemical costs were set at 48.0 € ADt^{-1}, and chemical consumption in cooking and bleaching of bark contaminants was assumed to be fivefold compared to that of wood.

3 Results

3.1 Removals

The total removals in Stands 1–3 were 73, 38, and 114 m^3 ha^{-1} (Fig. 1). Whole-tree harvesting (Options II–III) increased removals by 169%, 58%, and 16% when compared to CTL harvesting. In Stand 1, however, the trees below pulpwood dimensions constituted 47% of the stemwood removal (incl. stem bark). In Stand 2, their proportion was 15%, while all trees harvested from Stand 3 fulfilled pulpwood dimensions.

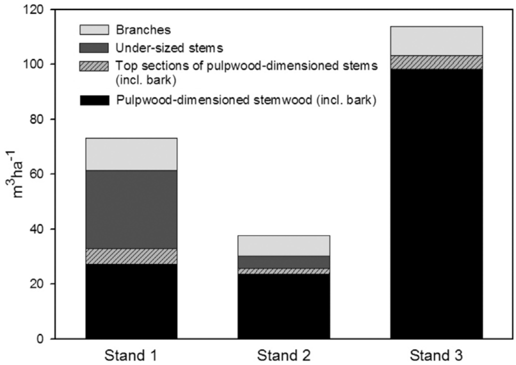

Fig. 1. Composition of the removal in the case stands.

Table 6. Cost structure of the wood harvested from the case stands by procurement option.

Cost factor	Option I	Option II Cost, € m^{-3}	Option III
STAND 1			
Cutting (+compaction)	31.69	19.74	43.87
Forwarding	7.01	6.48	3.62
Truck transportation	7.06	14.43	9.45
Overheads	3.15	3.15	3.15
Total	48.91	43.80	60.09
STAND 2			
Cutting (+compaction)	21.11	12.56	33.72
Forwarding	7.26	7.60	3.07
Truck transportation	7.06	14.43	7.46
Overheads	3.15	3.15	3.15
Total	38.58	37.74	47.40
STAND 3			
Cutting (+compaction)	9.99	5.74	24.00
Forwarding	5.52	5.84	2.45
Truck transportation	7.06	14.43	8.11
Overheads	3.15	3.15	3.15
Total	25.72	29.16	37.71

3.2 Costs and Revenues

The lowest procurement costs per m^3 with all supply systems were achieved in Stand 3 with the highest removal and largest trees (Table 6). The supply system based on CTL harvesting resulted in the lowest unit procurement cost in Stand 3, while standard whole-tree harvesting was the most cost-efficient option in the cases of Stands 1 and 2. In Stand 2 with the lowest removal, however, procurement cost with loose whole trees was only slightly (2%) below that with the CTL option.

The harvesting of loose whole trees reduced cutting costs per m^3 by 38–43% compared to the CTL system. In Stands 2 and 3, forwarding costs of conventional pulpwood were 4–5% (0.3 € m^{-3}) lower than those of loose whole trees. Due to increase in removal, forwarding cost of loose whole trees in Stand 1 was 8% (0.5 € m^{-3}) lower than that of conventional pulpwood, and standard whole-tree harvesting (Option II) was a competitive alternative to CTL harvesting in terms of unit procurement cost. Whole-tree bundling reduced forwarding costs of whole trees by 44–60% and truck transportation costs by 43–48%. These savings did not compensate for the high cutting and compaction costs in Option III.

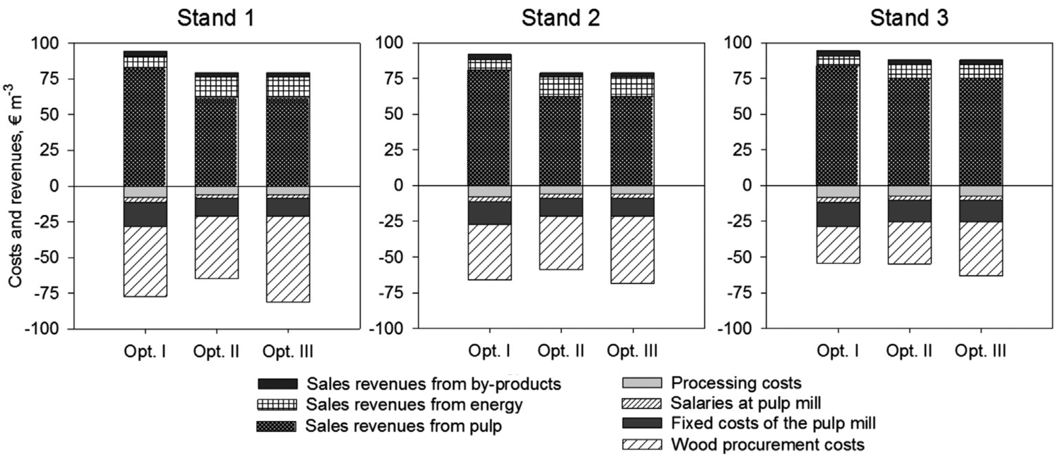

Fig. 2. Revenues and costs (excl. capital costs of the pulp mill and stumpage prices) per m^3 of wood processed at the virtual pulp mill by stand and supply system. Cost and revenue parameters as in Ch. 2.4.2.

Fig. 2 shows that the cut-to-length system gave the highest revenues of pulp production per m^3 of wood processed at the virtual pulp mill, and there were only minor differences in the revenues between the stands. In the whole-tree options, increase in surplus energy did not compensate for the losses in pulp production. Differences in the net revenues per m^3 of wood processed at the virtual pulp mill between the stands can be for the most part explained by the differences in wood procurement costs.

Table 7. Wood consumption and surplus energy per a ton of air-dry pulp (ADt) by stand and supply chain.

	Stand 1	Stand 2	Stand 3
Wood consumption, m^3 ADt^{-1}			
– stem sections (incl. bark)			
Option I	6.00	6.18	5.95
Option II	6.75	6.45	6.04
Option III	6.75	6.44	6.04
– the total wood consumption			
Option I	6.00	6.18	5.95
Option II	8.03	7.99	6.66
Option III	8.03	7.98	6.65
Surplus of electricity, GJ ADt^{-1}			
Option I	2.31	2.33	2.02
Option II	5.70	5.36	3.20
Option III	5.70	5.35	3.19
Surplus of heat, GJ ADt^{-1}			
Option I	4.67	4.72	3.99
Option II	12.58	11.80	6.76
Option III	12.58	11.75	6.73

3.3 Wood Paying Capability at Mill

3.3.1 Basic Calculation

The highest initial WPCs per m^{-3} at the mill were obtained in the cases of all stands when using conventional delimbed pulpwood as raw material (Fig. 3). This can be explained by its beneficial raw material balance with the highest proportion of pulp chips (Table 4) and the lowest wood consumption per a ton of pulp (Table 7). In the cases of the whole-tree options, increment in surplus energy was insufficient to compensate for higher wood consumption in pulping with the price relations applied in the basic calculation. The minor differences between the raw material balances of debarking loose and bundled whole trees resulted in absolute disparities of at maximum 0.03 € per m^3 at mill, and their initial WPCs were virtually equal. Also the differences in wood consumption and energy production were negligible.

If increases in the removals in the whole-tree options were considered, the whole-tree alternatives would give the highest WPCs per hectare at mill, especially in the case of Stand 1 with the highest proportion of additional raw material (Fig. 3). The WPCs per hectare for loose whole

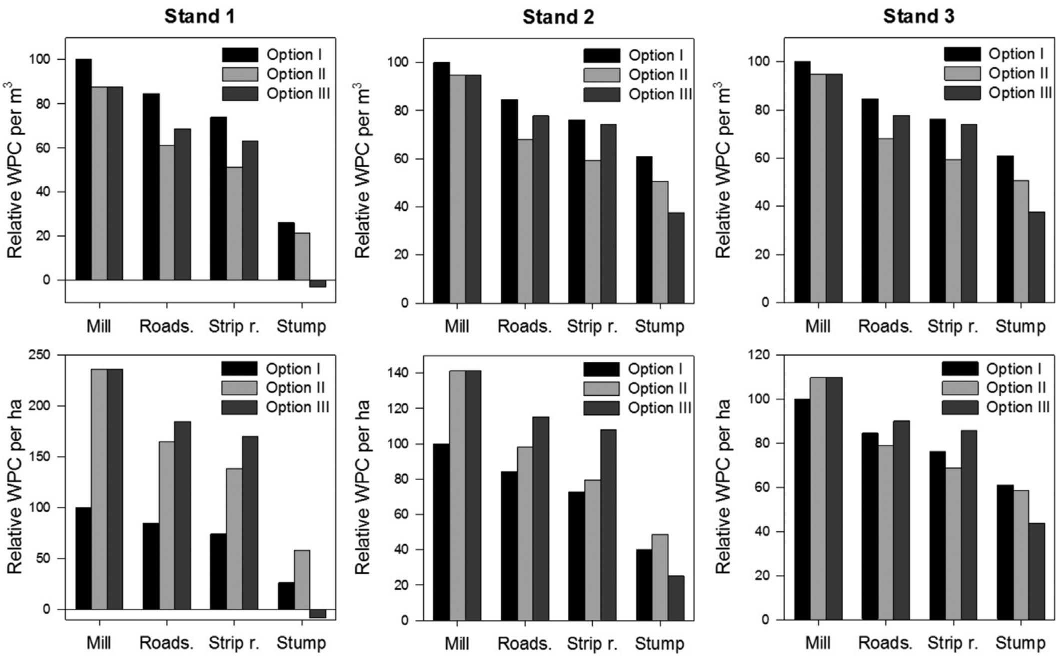

Fig. 3. Relative wood paying capabilities of raw materials per m^3 and ha at mill, roadside, strip road, and stump by stand and by supply system with the basic price parameters (pulp 500 € ADt^{-1}, electricity 50 € MWh^{-1}, process steam 10 € MWh^{-1}). WPC at mill with Option I = 100 on each stand.

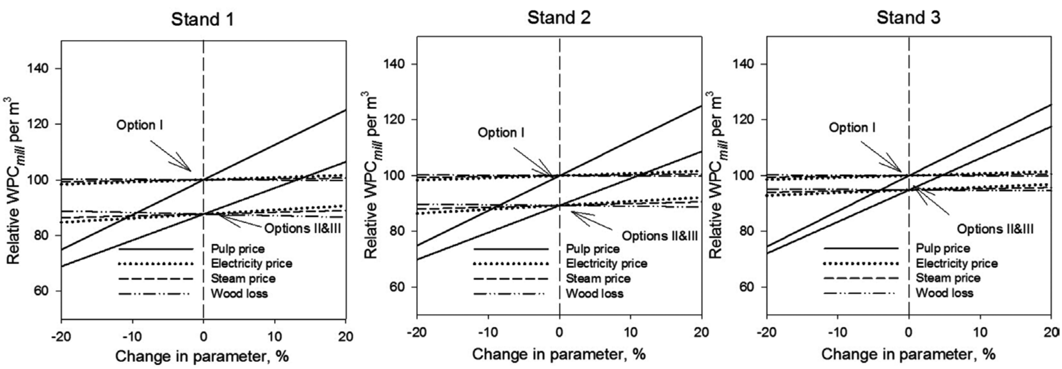

Fig. 4. The effect of end product (pulp, electricity, steam) prices and debarking loss of stemwood on relative wood paying capabilities per m^3 at mill by stand and by supply system. WPC at 0% change with Option I = 100 in each stand. Price and debarking parameters at 0% change as in the basic calculation (see Table 4 and Ch. 2.4.2).

trees remained higher than for conventional pulpwood throughout the supply chain in all stands. Savings in transportation costs with whole-tree bundling did not balance the high cutting and compaction costs, and whole-tree bundling gave the lowest WPCs in all stands.

3.3.2 Sensitivity Analysis

Fig. 4 shows that conventional pulpwood gave the highest wood paying capabilities at mill per m^3 in all case stands. The differences in assumptions on the debarking losses of stemwood larger than 6 cm (Table 3) resulted in negligible differences

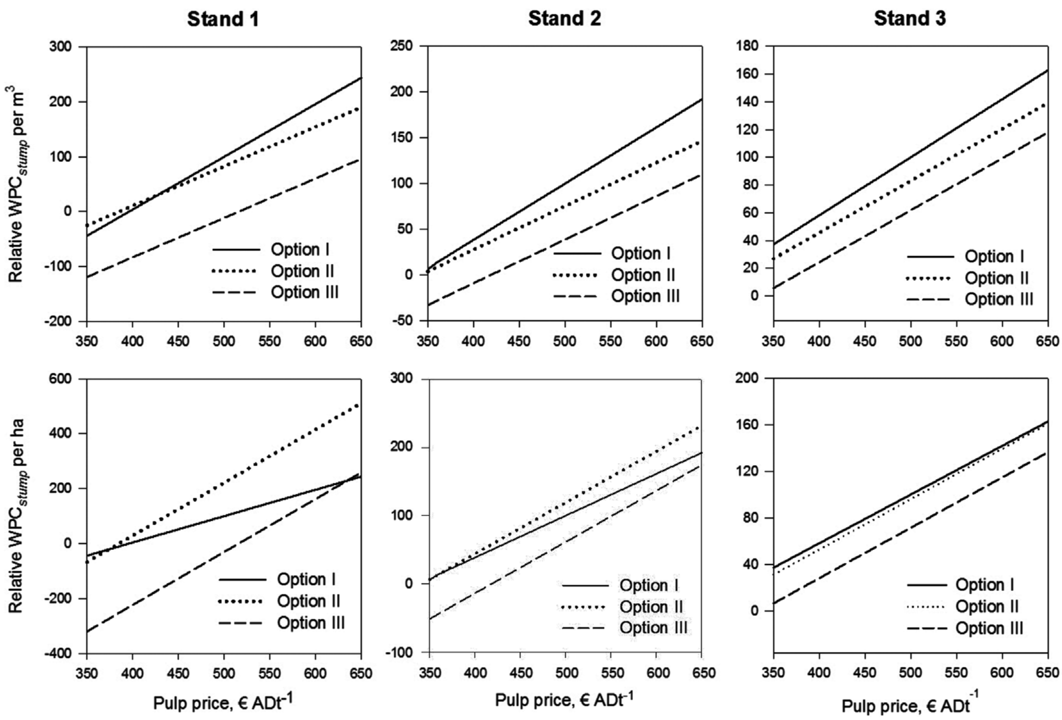

Fig. 5. The effect of pulp price on relative wood paying capabilities at stump per m^3 and ha. WPCs at 500 € ADt^{-1} with Option I = 100 on each graph.

in the raw material balances of the whole-tree options. Therefore, the WPCs at the mill could not be clearly distinguished.

Of the examined parameters, pulp price had the strongest effect on the initial WPCs at mill. Energy prices and debarking loss of stemwood had only minor effects, electricity price being a slightly more important factor than steam price and debarking loss. The stronger the effect of pulp price was, the higher was the proportion of the pulpwood fraction of the raw material, while energy prices had an adverse effect. An increment of 10 € ADt^{-1} in pulp price increased the absolute WPCs at mill by 1.6–1.7 € m^{-3} when using conventional pulpwood and by 1.2–1.5 € m^{-3} with the whole-tree assortments. An increase of 10 € MWh^{-1} in electricity price increased the absolute WPCs at mill by 0.9–1.1 € m^{-3} with conventional pulpwood and by 1.3–2.0 € m^{-3} when processing whole-tree assortments. An increment of one € MWh^{-1} in steam price increased WPC$_{mill}$s by 0.2 € m^{-3} with conventional pulpwood and by 0.3–0.4 € m^{-3} with the whole-tree materials. Ignoring the effect of wood loss on the bark content of pulp chips, an increase of one percentage point (pp) in stemwood loss decreased the absolute wood paying capabilities by ca. 0.3 € per m^3 with all assortments.

3.4 Wood Paying Capability at Stump

3.4.1 The Effect of Pulp Price

After subtracting wood procurement costs from the initial WPCs at mill, the supply system based on the CTL harvesting gave the highest residual values at stump per m^3 throughout the pulp price range of 350–650 € ADt^{-1} in Stands 2 and 3 (Fig. 5). Decline in pulp price improved the competitiveness of the whole-tree options, and the supply system based on the harvesting of loose whole trees gave the highest WPCs at stump with pulp price less than 427 € ADt^{-1} in Stand 1. Due to lower truck transportation and forwarding costs, the WPC per m^3 for whole-tree bundles

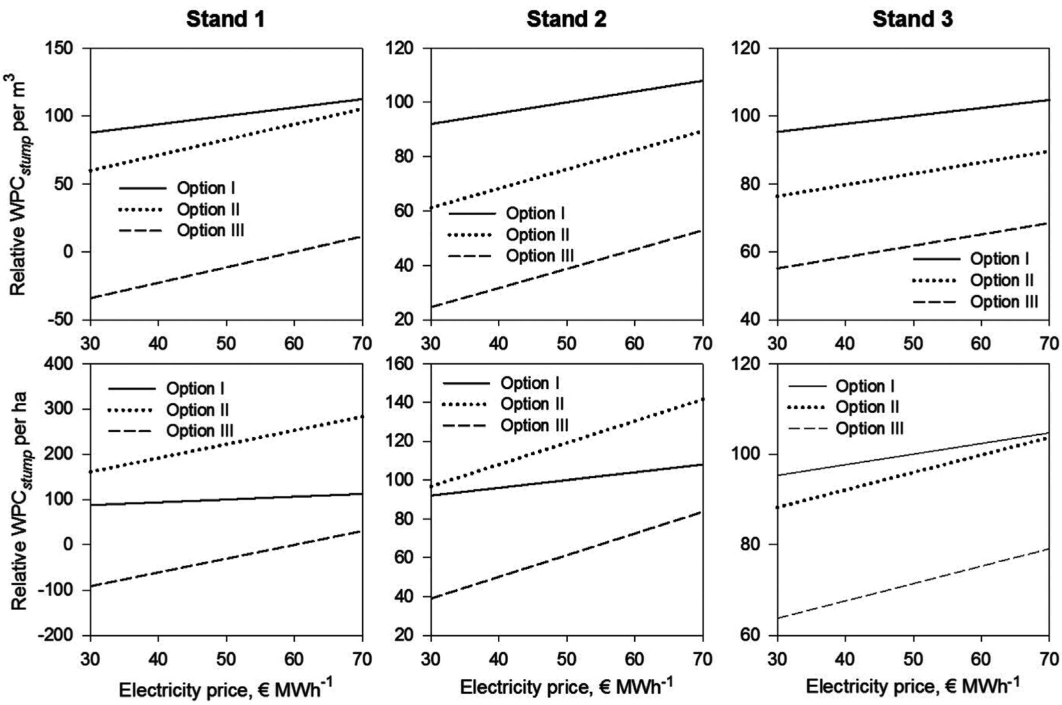

Fig. 6. The effect of electricity price on relative capabilities at stump per m^3 and ha. WPCs at 50 € MWh^{-1} with Option I = 100 on each graph.

remained higher than for loose whole trees from mill to strip road. The WPC at strip road for whole-tree bundles even slightly exceeded that for conventional pulpwood with pulp prices below 410–420 € ADt^{-1} in Stands 2 and 3. The savings in transportation costs, however, did not balance the high cutting and compaction costs in Option III, which was the least competitive alternative in terms of WPC at stump per m^3 throughout the entire pulp price range in all stands.

Considering also the increase in removal per hectare improves the competitiveness of the whole-tree alternatives. In the cases of Stands 1 and 2, standard whole-tree harvesting resulted in the highest residual values at stump per hectare with pulp prices more than 359–374 € ADt^{-1}. In Stand 1 whole-tree bundles gave higher WPC$_{stump}$ than conventional pulpwood with pulp price above 632 € ADt^{-1}. In Stand 3, conventional pulpwood gave slightly higher residual values per hectare at stump than loose whole trees throughout the pulp price range. The lines representing the WPCs with the whole-tree options were parallel due to negligible differences in their raw material balances, and pulp price had no effect on their reciprocal competitiveness. The differences in their residual values can be explained by the differences in wood procurement costs.

3.4.2 The Effect of Electricity Price

An increase in electricity price improves the WPCs for the whole-tree assortments more rapidly than for conventional pulpwood (Fig. 6). However, conventional pulpwood gave the highest residual values per m^3 from mill to stump within the electricity price range of 30–70 € MWh^{-1} in all examined stands. Savings in transportation costs raised the WPC with whole-tree bundles above that of loose whole trees from mill to strip road. Due to the high cutting and compaction costs, however, whole-tree bundles gave the lowest WPCs at stump.

When removal per hectare was considered, the harvesting of loose whole trees resulted in the

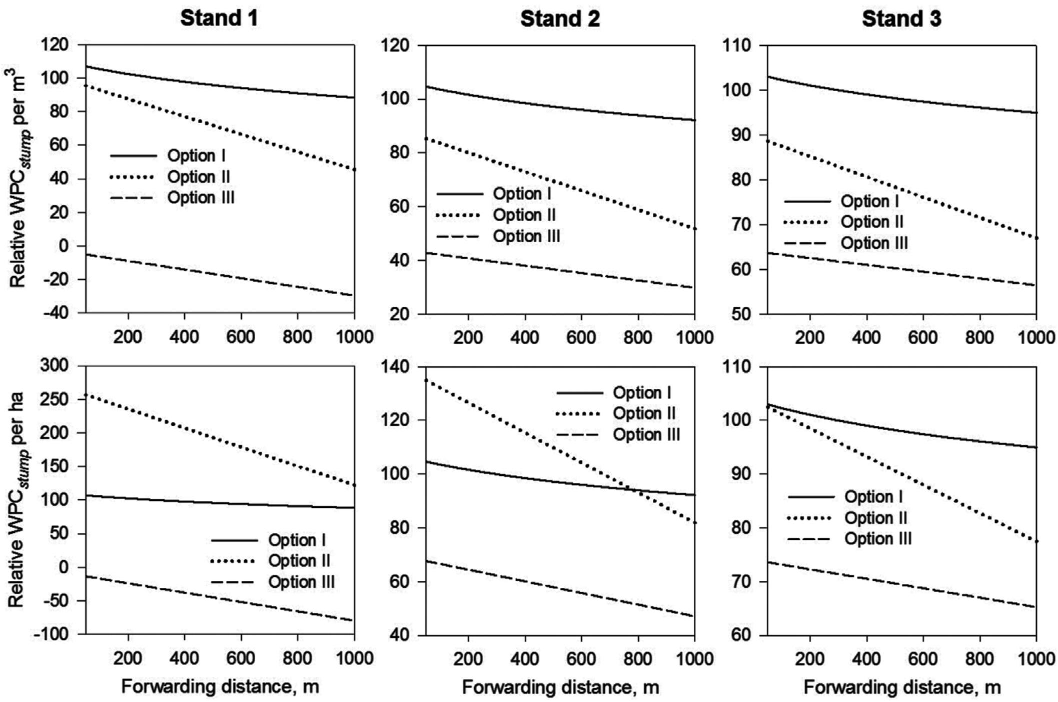

Fig. 7. The effect of forwarding distance on the WPC at stump. WPCs at 296 m with Option I = 100 on each graph.

highest WPCs at stump in Stands 1 and 2. In Stand 3, the low increase in removal with Option II did not compensate the increase in forwarding and truck transportation costs, and the supply chain based on CTL harvesting gave the highest residual value on areal basis. The savings in transportation costs with whole-tree bundles were insufficient to offset the increase in cutting costs, and the areal-based residual values with Option III were remarkably lower than with the other alternatives.

3.4.3 The Effect of Wood Transportation Distances

The WPCs for conventional pulpwood were the least sensitive to changes in forwarding distance (Fig. 7). The use of conventional pulpwood resulted in the highest residual value per m^3 at stump throughout the range of 50–1000 m in all stands. An increase in forwarding distance widened the gap between conventional pulpwood and the whole-tree assortments, and decreased the differences between the whole-tree options. The residual value of whole-tree bundles at stump, however, did not reach that of loose whole trees by the forwarding distance of 1000 m. When removal per hectare was considered, the usage of loose whole trees gave the highest WPC$_{stump}$ in Stand 1 throughout the entire range, and in Stand 2 up to 780 m. The WPC$_{stump}$ with whole-tree bundles remained the lowest within the examined forwarding distance range. In the case of Stand 3 with the lowest increase in removal by whole-tree harvesting, CTL harvesting resulted in the highest residual value also on areal basis.

As regards to truck transportation distance, conventional pulpwood had the highest residual value per m^3 at stump within the range of 5–500 km in Stands 2 and 3 (Fig. 8). The WPC$_{stump}$ per m^3 of whole-tree bundles exceeded that of loose whole trees only after 435–450 km. In Stand 1, loose whole trees gave the highest WPC$_{stump}$ with truck transportation distances less than ca. 30 km. If the increase in removal in the whole-tree options

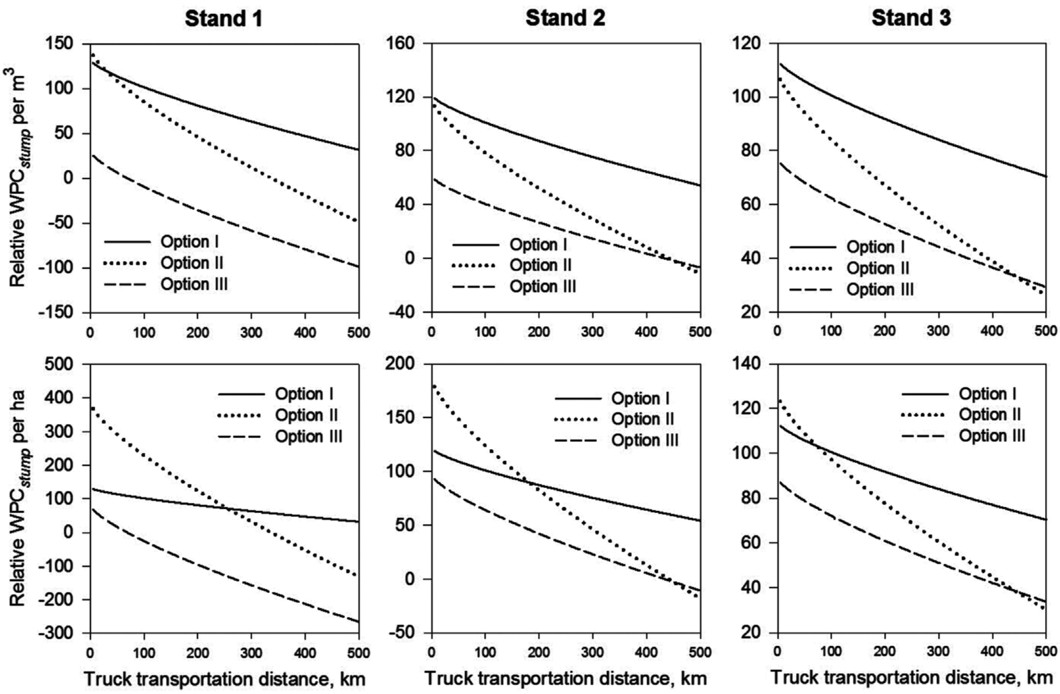

Fig. 8. The effect of truck transportation distance on the WPC at stump. WPCs at 106 km with Option I = 100 on each graph.

is taken into account, the intersectional points of Options I and II move to 70–250 km, and whole-tree bundling becomes a competitive alternative to the harvesting of loose whole trees with road transportation distances more than 440–450 km.

4 Discussion

4.1 Research Approach

Integration of energy wood procurement into that of industrial roundwood has been justified by the effect of increase in removal on the unit procurement cost (e.g. Hakkila 2005). Only in a few studies in wood procurement logistics attention is paid to the value of the wood harvested from the end user's point of view (e.g. Parikka and Vikinge 1994, Imponen et al. 1997, Korpilahti and Poikela 1998, Pihlajamäki and Kivelä 2001). Residual value at stump as a criterion for the competitiveness of the supply systems synthesises these aspects.

The WPC is the maximum tolerated price for wood, and an implication of potential for profit (Fors 2009). Due to omitting capital costs and some minor cost factors, using the absolute WPCs at mill (58–65 € m^{-3} with the basic parameters) instead of relative ones as a basis for the calculations would have resulted in far too high residual values compared to the WPC of 32 € m^{-3} reported by Suomi (2007) from kraft pulping with softwood in Finland. In the calculation of Diesen (2007), capital costs constituted 36% of the total production costs of kraft pulp mill with a capacity of 600000 ADt a^{-1} of softwood pulp. However, the deficiencies described above do not likely affect reciprocal competitiveness of the supply systems as the differences in the omitted cost factors between the supply systems per a ton of pulp are likely small in relation to the differences in wood procurement costs.

Recovery rate of crown mass in whole-tree harvesting is poorly known. According to Hakkila et al. (1995), crown mass recovery in first thinning of Scots pine corresponds with the biomass of living crown, i.e. most dead branches are likely to shed on the ground while harvesting. This is in accordance with the study of Kärhä et al. (2009) on the composition of Scots pine whole-tree bundles, and justifies the assumption of identical removals in the whole-tree systems in the present study. However, the feeding and compression processes of the bundle harvester can increase especially the losses of foliage and top sections. The effect of the degree of biomass recovery is a controversial issue. Losses can slightly increase unit procurement cost and impair the competitiveness of the bundling system. It is also possible that aiming at maximal biomass recovery can increase time consumption in bundle harvesting. On the other hand, decline in the branch fraction improves the wood paying capability of the pulp mill, and foliage shedding on the ground can be beneficial to the forest ecosystem as it reduces nutrient losses and thereby can maintain site productivity (e.g. Jacobson et al. 1996).

4.2 Process Calculations

Empirical results from debarking and chipping of small-diameter Scots pine whole trees are lacking. Therefore, the raw material balances of wood handling were constructed recoursing to expert's judgement. Solid energy fraction constituted 10–13% of the raw material in the cases of conventional pulpwood and 19–34% with the whole-tree assortments. These ratios match with the calculations of Häggblom and Peltonen (1984) on debarking and chipping of Scots pine tree-sections harvested from thinnings. They concluded that 13% of conventional Scots pine pulpwood and 29% of the tree section material end up in energy generation in the form of debarking and screening residues. The slightly lower wood loss with bundled than with loose whole trees was based on the fact that debarking of short logs is faster, resulting in lower wood losses with higher chip cleanliness than with longer logs (Rieppo and Korpilahti 2001). On the other hand, the sisal cord used for tying up the bundles can cause entanglements on the conveyors of the debarking plant, resulting in increase in operating costs.

Wood is the most important variable cost factor in pulp production with a proportion of more than 60% of the variable costs (Diesen 2007). Therefore, wood losses in debarking and chipping should be kept reasonable. In our study, the highest proportion of solid energy fraction was obtained in the case of Stand 1 with the highest amount of under-sized stems. According to Gullichsen and Fogelholm (2000), small-sized pulpwood produces always higher debarking losses than larger-sized, and debarking of small-diameter pulpwood with branches among larger-sized conventional pulpwood can cause stemwood losses up to 10%. The idea on blending the wood harvested from the experimental stands with conventional pulpwood harvested from first thinnings was based on the fact that wood losses can be reduced by homogenising size distribution of the logs (Hakkila et al. 1998, Gullichsen and Fogelholm 2000). Hakkila et al. (1995) have recommended to keep proportion of undelimbed pulpwood below 10–15% in drum debarking.

Due to lack of applicable information, most wood handling and all fiberline and chemical recovery parameters were kept constant, although there are differences in them between the assortments included in our study. For example, undelimbed material reduces debarking capacity by 20–40% (Gullichsen and Fogelholm 2000), and it increases the need for storage space and wearing of chipper blades (Häggblom and Peltonen 1984). Consequently, an adequate wood handling capacity is a prerequisite for the use of whole-tree material. Based on the study of Jylhä and Keskinen (2006), particles of external branches are likely to end up in the chipper. Twigs, foliage and bark consume more chemicals and their fibre yields are very low (Virkola 1981). However, small-diameter and short top sections with inferior quality do likely not end up in the energy fraction to great extent, and the amount of branch particles can be efficiently reduced by screening (Virkola 1981). Energy (electricity, steam, and hot water) constitutes about 3% of wood handling costs (Rieppo and Korpilahti 2001), and chemicals and energy constitute less than one tenth of the total variable costs of pulp production (Diesen 2007). The wood ending up in the energy fraction, either in solid residues or in black liquor, partly compensates for the losses caused by the use of whole trees. Consequently, constructing a more elaborated material balance only for wood supply chain analysis would not have been worthwhile.

4.3 Competitiveness of the Supply Systems

According to Paavilainen (2002), the harvesting factors (stand density, average stem size, removal per hectare) have a more significant effect on the residual value at stump than physical and chemical raw material properties. This is in accordance with our study, in which the gap between the absolute minimum and maximum WPCs of the nine combinations of stand and supply system expanded from 9 € m^{-3} to 42 € m^{-3} between mill and stump with the basic parameters.

Decrease in pulp price and increase in energy price improved the competitiveness of the whole-tree systems. However, the gains in energy generation from additional raw material acquired with whole-tree harvesting did not offset the losses in pulp production. Using the WPC per m^3 as a criterion for the competitiveness, the CTL system with single-tree harvesting was the most efficient option in all cases, except for in Stand 1 with the lowest pulp prices and the shortest truck transportation distances. Competitiveness of the CTL system could further be increased by adopting multi-tree cutting (e.g. Bergkvist 2003). If removal per hectare was taken into account, the supply chain based on the harvesting of loose whole trees resulted in the highest residual values at stump in Stands 1 and 2 in most cases. With extremely low pulp prices and negative WPCs per m^3, the CTL system results in the highest WPC also on areal basis. In Stand 3 with the lowest increment in removal, whole-tree harvesting was competitive neither on areal basis, except for with short truck transportation distances.

With the current cost and performance level of the bundle harvester, whole-tree bundling was the least competitive alternative of the examined supply systems. In the study of Kärhä et al. (2009, 2010), the "two-pile system" resulted in the lowest pulpwood procurement costs of the supply systems included in the comparison, and also the procurement costs of energy wood were competitive. Decrease in stem volume improved the competitiveness of whole-tree bundling, and first-thinning stands with breast height removal of 7–10 cm were considered its optimal field of application. As in Kärhä et al. (2009), increases in transportation distances improved the competitiveness of the bundling system. In the future, it might be possible to extend the procurement area of whole-tree material by the combination of whole-tree bundling and trail transportation sequence.

4.4 End-Use of Small-Diameter Scots Pine

There is vertical variation in the basic density and bark percentage of Scots pine (Hakkila 1967, 1996). Based on the technical wood properties, Scots pine harvested from young stands is considered as potential pulpwood up to 5 cm small-end diameter (Hakkila et al. 1995). In general, raising the minimum pulpwood diameter is considered as a means for cost reduction and quality improvement both in pulp and energy industries (Andersson et al. 2002). When raising the minimum diameter of pulpwood in first-thinning stands, however, harvesting costs tend to increase with only minor improvement in pulpwood quality (Hakkila 1996, Pihlajamäki and Kivelä 2001). In the study of Pihlajamäki and Kivelä (2001), maximum net residual value of Scots pine harvested from first thinnings was achieved with a minimum pulpwood diameter of 6 cm. The residual value of sections below 4 cm was close to zero, and in the case of pulpwood with a diameter below 6 cm, it was less than half of the residual value of larger pulpwood.

In the beginning of the 1990's, the wood paying capability of the forest industry for Scots pine pulpwood at stump was negative when breast height diameter of the trees was less than 12 cm (Harvennushakkuiden… 1992). In the present study, negative residual values at stump, even though they were given in relative form, indicate poor profitability of pulp production from small-diameter pulpwood. If all cost factors, especially capital costs, had been considered, the residual values would have fallen below zero with higher product prices and shorter transport distances than in Figs. 5–8. The lowest wood paying capabilities per m^3 were obtained in Stand 1 with the smallest tree size and the highest proportion of energy fraction. In practical forestry, these kinds of stands are usually subjected to direct combustion at heat and power plants. Due to the risk of biased results, potential subsidies allocated to silvicultural thinnings of young stands with poor profitability were ignored.

With the wood procurement factors of the present study and the cost of chipping at a heating and power plant of 2.0 € m^{-3} (Kärhä et al. 2009), the residual values of whole-tree chips (moisture content 50%) harvested from Stands 1–3 would have been –13.2, –7.2, and 1.4 € m^{-3} at stump without potential subsidies, respectively. These residual values were derived from the mean forest chip price of 17.84 € MWh^{-1} (ca. 33 € m^{-3}) in 2009 (Puupolttoaineiden… 2010) using the heating value of Nurmi (1993) and the basic density of whole trees by Hakkila et al. (1978). They indicate that direct combustion can be a more rational end-use for small-diameter wood than pulp production, especially with low pulp and high energy prices.

5 Conclusions

In most cases, conventional pulpwood gave the highest residual values per m^3 as savings in procurement costs and gains in energy generation from the additional raw material acquired with whole-tree harvesting did not compensate for the losses in pulp production with the price relation of pulp and energy applied in the present study. Considering removal per hectare improves the competitiveness of the whole-tree options drastically, especially when also lower stumpage price of whole-tree material is taken into account. However, the surplus of domestic pulpwood creates opportunities for increasing the efficiency of both pulp and energy industries by careful allocation of first-thinning stands between pulp and energy industries. With scarcity of pulpwood and high demand of energy wood, integrated harvesting by the two-pile method enables maintaining pulpwood quality cost-efficiently.

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