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Harvesting undelimited Scots pine (*Pinus sylvestris* L.)
from first thinnings for integrated production of kraft
pulp and energy

Paula Jylhä

Department of Forest Sciences
Faculty of Agriculture and Forestry
University of Helsinki

Academic dissertation

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Author: Paula Jylhä

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Supervisor:

Prof. Bo Dahlin

Department of Forest Sciences, University of Helsinki, Finland

Pre-Examiners:

Prof. Antti Asikainen

Finnish Forest Research Institute, Joensuu, Finland

Prof. Rolf Björheden

The School of Engineering, Linnaeus University, Växjö, Sweden

Opponent:

Prof. Tomas Nordfjell

The Department of Forest Resource Management, Swedish University of Agricultural Sciences, Umeå, Sweden

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ABSTRACT

The present study evaluates the feasibility of undelimited Scots pine (*Pinus sylvestris* L.) for integrated production of pulp and energy in a kraft pulp mill from the technical, economic and environmental points of view, focusing on the potential of bundle harvesting.

The feasibility of tree sections for pulp production was tested by conducting an industrial wood-handling experiment, laboratory cooking and bleaching trials, using conventional small-diameter Scots pine pulpwood as a reference. These trials showed that undelimited Scots pine sections can be processed in favourable conditions as a blend with conventional small-diameter pulpwood without reducing the pulp quality. However, fibre losses at various phases of the process may increase when using undelimited material.

In the economic evaluation, both pulp production and wood procurement costs were considered, using the relative wood paying capability of a kraft pulp mill as a determinant. The calculations were made for three Scots pine first-thinning stands with the breast-height diameter of the removal (6–12 cm) as the main distinctive factor. The supply chains included in the comparison were based on cut-to-length harvesting, whole-tree harvesting and bundle harvesting (whole-tree bundling). With the current ratio of pulp and energy prices, the wood paying capability declines with an increase in the proportion of the energy fraction of the raw material. The supply system based on the cut-to-length method was the most efficient option, resulting in the highest residual value at stump in most cases. A decline in the pulp price and an increase in the energy price improved the competitiveness of the whole-tree systems. With short truck transportation distances and low pulp prices, however, the harvesting of loose whole trees can result in higher residual value at stump in small-diameter stands. While savings in transportation costs did not compensate for the high cutting and compaction costs by the second prototype of the bundle harvester, an increase in transportation distances improved its competitiveness.

Since harvesting undelimited assortments increases nutrient export from the site, which can affect soil productivity, the whole-tree alternatives included in the present study cannot be recommended on infertile peatlands and mineral soils. The harvesting of loose whole trees or bundled whole trees implies a reduction in protective logging residues and an increase in site traffic or payloads. These factors increase the risk of soil damage, especially on peat soils with poor bearing capacity. Within the wood procurement parameters which were examined, the CO₂ emissions of the supply systems varied from 13–27 kg m³. Compaction of whole trees into bundles reduced emissions from transportation by 30–39%, but these reductions were insufficient to compensate for the increased emissions from cutting and compaction.

Keywords: first thinning, integrated harvesting, Scots pine, wood paying capability, kraft pulp

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Last but not least, I want to thank my family for their patience and understanding all through these years.

LIST OF ORIGINAL ARTICLES

This thesis is based on the original papers listed below, which are referred to in the text by their Roman numerals. These papers are reprinted with the permission of the publishers.

- I** Jylhä, P. 2004. Feasibility of an adapted tree section method for integrated harvesting of pulpwood and energy wood in early thinning of Scots pine. *International Journal of Forest Engineering* 15(2): 35-42. <http://journals.hil.unb.ca/index.php/IJFE/article/view/9848/9986>
- II** Jylhä, P. & Keskinen, N. 2006. Properties of bundled tree sections of young Scots pine in debarking, chipping, and pulping. *Forest Products Journal* 56(7/8): 39-45. <http://www.forestprod.com/fpjover.html>
- III** Jylhä, P. & Laitila, J. 2007. Energy wood and pulpwood harvesting from young stands using a prototype whole-tree bundler. *Silva Fennica* 41(4): 763-779. <http://www.metla.fi/silvafennica/full/sf41/sf414763.pdf>
- IV** Jylhä, P., Dahl, O., Laitila, J. & Kärhä, K. 2010. The effect of supply system on the wood paying capability of a kraft pulp mill using Scots pine harvested from first thinnings. *Silva Fennica* 44(4): 695-714. <http://www.metla.fi/silvafennica/full/sf44/sf444695.pdf>

The author is fully responsible for article **I** and the text of this doctoral thesis. She planned and wrote the drafts of the other articles included in the thesis, and acted as the corresponding author in them. The author planned the data collection in articles **III-IV** together with the co-authors. She was fully responsible for the fieldwork in articles **II** and **IV**, and partly so in article **III**. In the case of article **II**, the results from laboratory pulps were provided by the co-author, while the author analysed the data for the most part. In **III**, the author herself was responsible for the collection and analysing of all data related to stand characteristics and bundle properties. She was responsible for article **IV**, except for the technical construction of the material balance spreadsheet, and the model selection and hourly cost calculations for wood supply chain analysis.

SYMBOLS AND ABBREVIATIONS

ADt	air-dry ton of pulp, dry content 90%
CO ₂	carbon dioxide
cr	crown ratio, i.e., the proportion of living crown to tree height
CTL	cut-to-length method
DBH	breast-height diameter
E ₀	effective time, i.e., working time excluding delays
E ₁₅	gross effective time, i.e., working time including interruptions shorter than 15 min
h	tree height
LCA	life cycle assessment
MT	<i>Myrtillus</i> site type
sd	standard deviation
SOM	soil organic matter
TS	tree-section method
VT	<i>Vaccinium vitis-idaea</i> site type
WPC	wood paying capability
WT	whole-tree method
WTB	whole-tree bundling

TERMINOLOGY

Bundle harvester	A harvester consisting of a base machine, an accumulating felling head, and a bundling device.
Bundle harvesting	Cutting and compaction of undelimited trees, either topped or whole trees, with a bundle harvester.
Cut-to-length method	Logging method which includes felling, delimiting, and bucking of stems into lengths at the harvesting site.
Tree-section method	Cutting and bucking of undelimited trees into sections to be transported to a central processing place or to industry. In the present study, top sections of the trees were assumed to be left on site (= undelimited CTL).
Whole-tree bundling	Compaction of whole trees into bundles by the bundle harvester.
Whole-tree method	Cutting of undelimited wood to be transported to a central processing place or to industry, utilization of most biomass above stump-level.
Wood paying capability	A residual value that the product or industrial process can cover after all the costs other than wood have been subtracted from the sales revenues.

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1 INTRODUCTION

1.1 Background

Finnish forests are characterized by a large proportion of young stands, about half of the forest land being covered by advanced seedling stands and young thinning stands (Peltola and Ihalainen 2010). The main aim of early thinnings is to guarantee a good supply of industrial roundwood for the future, especially saw and veneer logs. Primarily low-quality trees are removed, usually from below, in order to maintain or stimulate the growth of the remaining trees (Hyvän metsänhoidon suositukset 2006). Wood harvested from first thinnings is mostly used as a raw material for pulp and forest chips, and to some extent in sawmilling and the fibre- and particle-board industries as well. However, first thinnings have been largely neglected because of high wood procurement costs resulting from small stem size and low removal per hectare. The current need for first thinnings in Finland has been estimated to be 300,000 ha a⁻¹ (Korhonen et al. 2007). In 2000–2009, annual early thinnings averaged 185,000 hectares (Juntunen & Herrala-Ylinen 2010). In addition to harvesting factors, inferior wood quality limits the harvesting of small-diameter wood for pulp production. Small trees contain a lot of juvenile wood with short fibres and low basic density. Their bark percentage tends to be high, especially in the top sections, and excessive wood losses occur in drum debarking because of the breakage of thin logs. Owing to the low wood density of small-diameter trees, their energy content per volumetric unit is also lower than that of mature trees (Hakkila et al. 1995, Hakkila 2005).

In the 2000s, ca. 7 million m³ of pulpwood annually has been harvested from first thinnings, representing 14% of the consumption of domestic roundwood (Kärhä and Keskinen 2011). Based on the National Forest Inventory, the total pulpwood potential of delayed first thinnings is 31 million m³ (Korhonen 2008). Young peatland forests in particular show potential for increasing harvesting volumes, up to 10–15 million m³ per year (Ruotsalainen 2007). On peatlands, however, the poor bearing capacity of the soil is an additional problem associated with wood harvesting (Ala-Ilomäki 2006, Heikkilä 2007). The estimated area of delayed first thinnings located on peatlands is ca. 200,000 ha (Heikkilä 2007).

Since the 1990s, climate change has been the primary catalyst for fostering the use of wood for energy (Hakkila 2003). Based on the Kyoto Protocol, the European Commission's proposal for the renewable energy package implies a 20–30% reduction in greenhouse gas emissions by 2020 compared to the 1990 level. In 2020, renewables are supposed to cover 20% of the energy consumption of the countries in the European Union. Finland is supposed to reduce its greenhouse gas emissions by 16% from the 2005 level by 2020 (Commission of the European Communities 2008). Within that time span, the proportion of renewables is to be increased from 28.5% (Kosonen 2007) to 38% of the final energy consumption (Commission of the European Communities 2008). Finland is striving towards this target, in particular by increasing the use of various biomasses, especially forest chips, in energy generation (Ministry of Employment and the Economy 2008). The need for forest chip production is bound to the production of the forest industries, as various wood-based wastes are the major source for renewable energy. Due to the decline in the production of the forest industries in 2008–2009, the proportion of wood-based fuels in renewable energy decreased from 54% to 47%, while that of forest chips increased from 9% to 13%. Owing to the decline in pulp production, the consumption of black liquor fell by almost a quarter. However, it was still the most important source of renewable energy consumed in Finland, constituting 41% of wood-based fuels in 2009 (Ylitalo 2010a, Fig. 1).

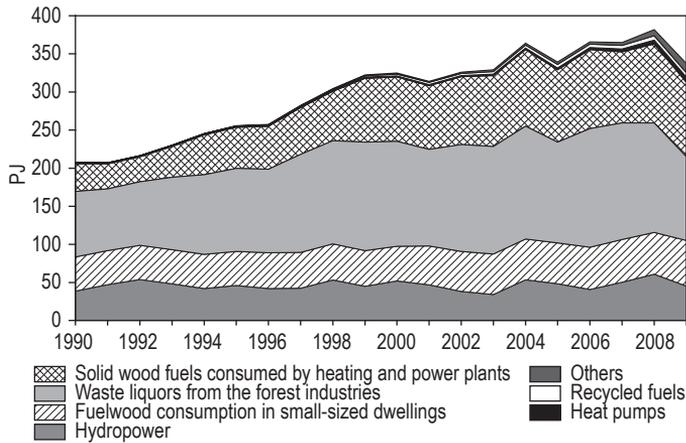


Fig. 1. Renewable energy sources 1990-2009 (Ylitalo 2010a).

Because of the capacity closures of the forest industries, the target set for forest chip production in 2020 was raised from 12 million m^3 (solid) to 13.5 million m^3 in 2010 (Ministry of Employment and the Economy 2008, 2010). This represents 84% of the technically harvestable forest chip potential of 16 million m^3a^{-1} (Laitila et al. 2008). Between 2000 and 2010, the annual consumption of forest chips of 0.9 million m^3 (1.8 TWh) increased more than sevenfold to 6.9 million m^3 (13.8 TWh) (Ylitalo 2011, Fig. 2). The target set for forest chip production is to be achieved primarily by increasing the utilization of small-diameter wood, stumps and roots (Ministry of Employment and the Economy 2010).

Whole-tree harvesting increases the efficiency of forest chip production from small-diameter material through increased recovery in the form of branches and foliage. In 2009, undelimited wood constituted 90% of the small-diameter raw material base consumed by the Finnish heating and power plants (Ylitalo 2010b). With whole-tree recovery for fuel chips, yield can be increased by 15–50 % and logging productivity by 15–40% compared to stem-only recovery, resulting in a 20–40% reduction in production costs (Hakkila 2005). In average conditions, however, production cost of whole-tree chips is ca. 50% higher than that of logging residue chips (Ryymin et al. 2008). As a result, whole-tree chips are not a

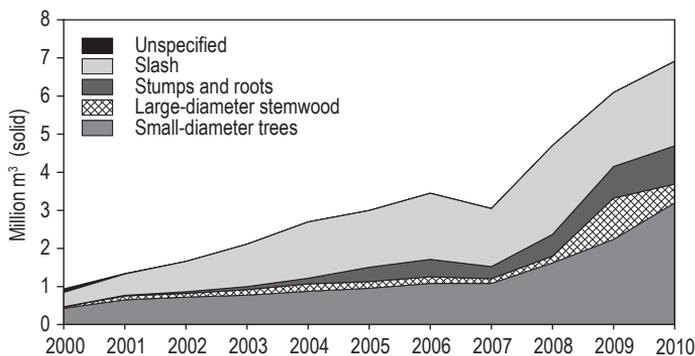


Fig. 2. Forest chip consumption in Finland by raw material source in 2000-2010 (Ylitalo 2011).

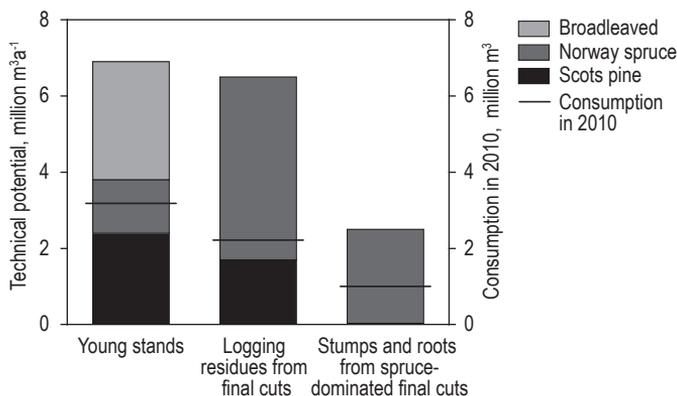


Fig. 3. Technically harvestable forest chip potential (Laitila et al. 2008) and forest chip consumption in 2010 (Ylitalo 2011) by raw material source. Forest chips combusted by small-sized dwellings were assumed to originate from young stands.

competitive fuel for large heating and power plants, and less than half the technical potential of small-diameter material was exploited in energy generation in 2010 (Laitila et al. 2008, Ylitalo 2011) (Fig. 3). High transportation costs resulting from small bulk density limits the harvesting of undelimited assortments (Andersson et al. 2002). Increasing demand for fuel chips implies the extension of wood procurement to more remote and difficult sites (such as thinning stands), which tends to further increase their production costs (Laitila 2004, Ryymin et al. 2008).

In 2010, 83% of forest chips made of small-diameter wood were comminuted at the roadside, mostly using a system consisting of a separate chipper and a chip truck (Kärhä 2011a). Work interruptions of due to an imbalance between machines are typical of this kind of “hot” supply system, resulting in an increase in production costs (Ikäheimo and Asikainen 1999, Laitila 2008). A separate chipper and chip truck can be replaced by a single chipper truck, which blows the chips directly into its own containers and hauls the load to the plant. A reduction in load capacity, however, limits its operation radius around the plant (Hakkila 2003). When applying roadside chipping in Finnish conditions with small and sparsely located forest holdings, acquiring large enough concentrations of wood for profitable production is a great challenge. Machine relocations can be reduced by transporting raw material to terminals or the end-use facility to be comminuted. Terminals offer opportunities for buffer storing and combining various transportation modes. However, the low bulk density of the initial material restricts the operation radius unless the biomass is compacted (Hakkila 2003). According to Laitila and Väättäin (2011), harvesting of delimited energy wood is a promising way to simplify operations and to reduce transportation and chipping costs. The role of chipping at terminals and end-use facilities will become more important along with increasing demand for forest chips. Terminal chipping of small-diameter wood constituted 10% and chipping at heating and power plants 7% in 2010 (Kärhä 2011a).

Wood is the most important cost factor in pulp production. In the case of Nordic softwood kraft pulp, wood constitutes 30–60% of the total manufacturing cost (Pentikäinen 2006, Diesen 2007, Kangas 2008, Korpunen et al. 2011). In 2009, first thinnings covered 13% of the volume of mechanized harvesting and 21% of the harvesting cost. The mean harvesting and transportation cost of small-diameter pulpwood (ca. 28 € m⁻³) was 12–46% higher than that originating from other thinnings and regeneration fellings (Kariniemi 2010).

The mean stumpage price of Scots pine pulpwood harvested from first thinnings in 2010 was 16–17 € m⁻³ (MTK 2011). According to Suomi (2007), the long-term wood paying capability of a Finnish kraft pulp mill with a capacity 600 000 ADt a⁻¹ from Scots pine is 32 € m⁻³. Consequently, the wood price at the mill probably exceeds the wood paying capability of the pulp and paper industry when harvested from first-thinning stands with poor conditions. A decline in tree volume implies an increase in wood procurement cost (Rummukainen et al. 2003). A reduction in the breast height diameter of recoverable trees from 8 cm to 6 cm, for example, more than doubles the cutting cost of delimbed stemwood and whole trees (Laitila et al. 2010). At the beginning of the 1990s, the wood paying capability of the forest industry for Scots pine pulpwood was negative when the breast height diameter of the removal was less than 12 cm (Harvennushakkuiden taloudellinen... 1992).

From the point of view of the economy, priority is usually given to the use of wood as industrial raw material instead of energy generation (e.g., Hakkila 2005). In 2006, the value added by the core pulp and paper industry in 27 countries of EU was more than four times the energy alternative (Jokinen 2006). Hetemäki (2008), however, has concluded that the economic impact of the use of wood for energy may exceed that of the pulp and paper industry in the future, depending on price and production technology. Increasing demand for energy wood is considered as a threat to the raw wood supply of the forest industries, since pulpwood can displace the most expensive forest chip batches in energy production (Diesen 2007, Sitra 2007, Ministry of Employment and the Economy 2008, Kärhä et al. 2009a). The resultant competition from wood can further raise the manufacturing costs of pulp and paper (Folsland Bolkesjø et al. 2006, Diesen 2007). The profitability of pulp and paper industries has already been reduced by low product prices and increased production costs (Mutanen 2010), and about one million tonnes of pulp production capacity was closed in Finland in 2008–2009 (Valtonen 2010). Figure 4 supports the theory of declining of pulp and paper product prices (see Diesen 2007, van Heiningen 2007). In contrast to pulp, the price of fuel chips has risen dramatically since the end of the 1990s. This might be due to the increase in the prices of the other energy sources (such as oil), and impaired harvesting conditions for forest chips caused by increased production volumes (Hillring 1996, Imponen et al. 1997b, Paavilainen 2002, Hakkila 2003, Folsland Bolkesjø et al. 2006, Diesen 2007). In both industries, cost competitiveness – i.e.,

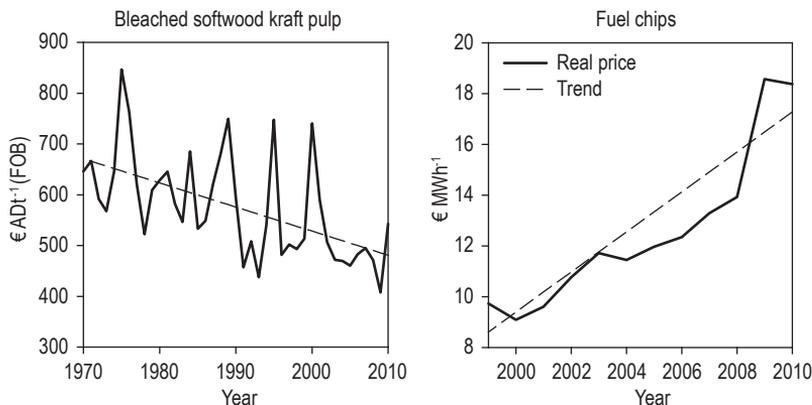


Fig. 4. Real prices of bleached sulphate pulp exported from Finland and fuel chips consumed by heat and power plants (Producer price indices 2011, Metinfo, 2011).

low manufacturing cost – is one of the key factors for success (Hakkila 2003, Diesen 2007, van Heiningen 2007).

Because of economy of scale, the size of pulp and paper mills has increased. As an offset to the increase in plant size, the availability of raw material cannot be always secured within a reasonable distance as large volumes are needed (Diesen 2007). Potential biorefineries integrated with pulp and paper mills can further increase the demand for woody biomass (Diesen 2007, van Heiningen 2007, Ranta et al. 2008). The kraft (sulphate) pulping process shows potential for increasing the utilization of small-diameter wood in pulp-making and energy generation. The kraft method, the most common way of pulping, can produce pulp with high strength properties. It can accept larger proportions of bark and resin than other common pulping processes without being seriously affected by pitch problems. Even the use of whole-tree chips and residual wood from stumps is technically feasible (Hakkila 1989). The resins and fats in pine wood can be recovered as by-products. The cost of chemicals can be greatly reduced by efficient chemical recovery, and the heat energy from the residual components of the biomass can be recovered from wood handling residues or black liquor (Hakkila 1989, European Commission 2001).

Forest fuels increase the complexity of forestry, but they can also create opportunities to increase efficiency (Björheden 2000). The cut-to-length (CTL) or shortwood method, in which trees are felled, delimbed and bucked into timber assortments in the stump area (Uusitalo 2010), is the main logging method in Nordic countries. When using pulpwood harvested in this way, bark and wood losses from wood handling form the solid energy fraction. Integrating energy wood harvesting into industrial roundwood procurement is considered a promising approach to reducing the procurement costs of small-diameter wood and increasing the production of renewable energy (Puttock 1994, Hudson 1995, Rummukainen et al. 2003, Oikari et al. 2010). Puttock (1994) and Hudson (1995) defined integrated harvesting as the harvesting of forest biomass in a single-pass operation in such a way that wood fuel can be produced along with conventional forest products. In first thinnings, integration aims at lower total supply chain costs than in separate procurement of roundwood and energy wood (Laitila et al. 2008, Kärhä et al. 2011). The cost savings are based mainly on an increase in biomass yield and the productivity of logging by whole-tree harvesting. Stands dominated by Scots pine (*Pinus sylvestris* L.) are of particular interest because of their great potential for increasing recovery in the form of crown mass (branches and foliage). The total amount of crown mass in Finnish Scots pine first-thinning stands ranges from 123 to 141 kg (dry) per removed m³ of stemwood (incl. bark) (Hakkila 1991).

Hakkila (1992) enumerates three large-scale options for integrating the harvesting of industrial roundwood and energy wood from young stands in the Finnish conditions. In the *whole-tree chipping* system (1), trees are chipped as whole, and the pulp and energy fractions are subsequently separated from each other in dedicated chipping and sorting plants. Problems associated with these plants are their high cost, insufficient capacity for large-scale operation, and poor pulp chip quality and, alternatively, high wood losses (Hakkila 1992, Hämäläinen and Korpilahti 1998). In the standard *tree-section system* (2), stem sections with branches are taken to the defiberizing plant, where they are delimbed and debarked simultaneously with conventional pulpwood in a rotating debarking drum. In this system, separate comminution of the energy fraction is eliminated, and there are no significant technical limitations, except for potential wood losses and the high procurement costs of small-diameter wood (Korpilahti 1998). The development of the tree-section method was motivated by the need for increasing the productivity of motor-manual cutting by eliminating delimiting. It has never been widely used, partly because of the increased efficiency of single-grip harvesters (Hudson 1995, Korpilahti

1998, Andersson et al. 2002). The pulp and energy fractions of whole trees could also be separated from each other at the debarking plant of the pulp mill (Kärhä et al. 2011). Parallel to the tree-section system, in the *chain-flail system* (3) trees are delimbed and debarked prior to chipping at landing (Hakkila 1992, Watson et al. 1993, Korpilahti 1998, Koskinen 1999). In Finnish conditions, with small and sparsely located logging units, large enough concentrations required for cost-efficient operation are difficult to organize (Hakkila 1992). Cutting energy wood and industrial roundwood into separate piles to be transported to separate destinations (the “*two-pile system*”) represents a looser mode of integration (Tanttu et al. 2004, Kärhä and Mutikainen 2008, Kärhä 2011b). By integrating pulpwood and energy wood harvesting by tree-section (TS) or whole-tree (WT) methods, the amount of combustible biomass for energy generation can be as much as four or five times that acquired by conventional methods in which trees are delimbed (Korpilahti 1998).

In all the integrated systems described above, trees and tree sections with branches still attached are transported from forest to intermediate storage, terminal, or end-use facility. Load space is often a limiting factor when transporting undelimbed assortments, and the carrying capacities of the vehicles cannot be fully utilized, resulting in high transportation costs (Hakkila 1989, Korpilahti 1998, Andersson et al. 2002, Ranta and Rinne 2006). Terrain and road transportation are typically responsible for ca. 35% of the production cost of forest chips from small-diameter trees (Ryymän et al. 2008). There are also some safety risks associated with branches that extend beyond the normal dimensional envelope for highway trucks (Hakkila 1989). Increasing bulk density in a cost-efficient manner is considered crucial to reducing the procurement costs of energy wood (Lilleberg 1997). Besides compaction, transportation costs could be reduced by using rigs with large volume – or by taking both these measures within the limits of permissible maximum vehicle weight and dimensions. Loads could be compacted using a permanently mounted load compaction device in the form of telescopic stakes. Loader-manipulated compaction devices have also been developed (Carlsson and Rådström 1984). So far, these compaction technologies have been excessively time-consuming or too capital-intensive to make a break-through, or have led to decreased overall system performance (Björheden 2000).

Compacting slash into cylindrical bales (composite residual logs) with a slash bundler was a breakthrough which enabled reduction of transportation costs and efficient process control in large-scale energy wood procurement from remote final felling sites (Berg 2003, Hakkila 2003, Eriksson and Gustavsson 2009). In addition to savings in transportation, this supply system, including chipping at the end-use facility or at the terminal, is not as vulnerable to interruptions as systems based on chipping on site or at the roadside (Johansson et al. 2006). Expanding bundling to thinnings is considered one of the potential steps in the development of energy wood harvesting, but confined working space in dense stands is seen as a technical barrier (Hakkila 2004). A supply chain composing of a feller-buncher, a forwarder, and a bundling machine operating at the roadside landing is not a competitive alternative, because the savings in long-distance transportation and crushing at the end-use facility do not cover the costs of compacting (Laitila et al. 2004). In the simulation study by Björheden et al. (2003), a bundler complemented by an accumulating felling head showed potential when harvesting small-diameter (DBH 3.0–10.5 cm) energy wood. Combining bundling technology with current harvester technology was seen a complex technological and economic problem to which there was no solution in view (Hakkila 2004). In 2007, however, the first prototype of a bundle harvester capable of cutting and compaction of whole-trees into cylindrical bundles with a solid content of 0.3–0.5 m³ was launched (Fig. 5). The working technique can be modified into tree-section harvesting by topping the tree bunches with the chain saw installed



Fig. 5. The second bundle harvester prototype.
Photo: Juha Laitila

at the feeding gate of the bundling unit. Bundle harvesting enables in-depth integration of pulpwood and energy wood procurement as the separation of the pulp and energy fractions does not take place before the wood reaches the debarking plant of a pulp mill. Undesirable tree species and small-diameter trees can be accumulated into separate energy wood bundles, which are transported to an end-use facility to be crushed for energy generation. Standard vehicles can be used in terrain and long-distance transportation.

Increasing the intensity of biomass removal from a stand through integrated operations may have some negative impacts that must be assessed. The most problematic aspect is the risk of excessive nutrient loss and the effect that this may have on future stand growth (Puttock 1994). The need for nutrients is at its greatest when the volume growth of trees is greatest (Saarsalmi and Tamminen 2001). In Scots pine and Norway spruce stands on typical forest sites in Southern Finland (MT and VT), the largest volumetric growth takes place in the stand age of 30–50 years (Nyyssönen 1954, Vuokila 1956, Kukkola 2003), i.e., at thinning stage. Branches and foliage have higher nutrient concentrations than stem wood (Mälkönen 1974, van Lear et al. 1984, Nisbet et al. 1997, Wang et al. 1999, Egnell et al. 2001), and whole-tree harvesting increases the export of nutrients from the forest by 50–150% compared to stem-only harvesting (Hakkila 2005). Each percentage increase in biomass recovery represented by crown mass with foliage is estimated to increase nutrient losses amounting to 2–3% for pines, 3–4% for spruces and 1.5% for leafless hardwoods (Hakkila 2002). Since removing branches and foliage also affects soil organic matter (SOM) content, long-term degradation of site productivity due to intensive biomass removal has been widely discussed (Mälkönen 1976, Smith 1995, Jurgensen et al. 1997, Nisbet et al. 1997, Fox 2000, Egnell et al. 2001, Mälkönen et al. 2001, Nurmi and Kokko 2001, Burger 2002, Helmisaari et al. 2008, Luiro et al. 2009). In Finland, about half the reserves of small-diameter energy wood are located on peatland forests or infertile mineral soils (Laitila 2004). Whole-tree harvesting from these sites is of special concern (Hillring 1995, Helmisaari et al. 2008, Hytönen and Moilanen 2008, Hytönen et al. 2010, Laitila et al. 2010, Äijälä et al. 2010). In thinning operations, a certain amount of damage to stems, roots and ground is also unavoidable. Such damage degrades the quality of the timber and affects the future productive capacity of the stand (Vasiliuskas 2001). Logging residues reduce soil compaction and rutting by providing a pressure-absorbing layer and reducing the net ground pressure of passing equipment (McDonald and Seixas 1997), while harvesting of undelimited assortments reduces the amount of protective logging residues.

The protection offered by brush mat against soil compaction and rutting has been verified in several studies (McDonald and Seixas 1997, Hutchings et al. 2002, Han et al. 2006, Eliasson and Wästerlund 2007, Han et al. 2009). The reinforcement of strip roads by slashing is of great importance, especially on sensitive areas (Eliasson and Wästerlund 2007).

1.2 Approach

Sustainable forest management is defined as the management of forests following the principles of sustainable development, which has very broad social, economic and environmental goals (Björheden 2000, Henriksson et al. 2002, Hyvän metsänhoidon suositukset 2006, Straka and Layton 2010). Decision-making on wood-harvesting actions is usually focused on operational efficiency, which is defined as efficient utilization and economical management of the resource (forest) (Silversides and Sundberg 1989). In regular harvesting, the criterion for utilization is that the revenues from wood should exceed the variable cost of harvesting it. However, the efficiency of the system can be understood in a broader sense, considering flexible adjustment, good product quality, and minimum environmental effect as well at each point of the supply system (Hudson 1995, Björheden 2000, Hakkila 2003).

The wood used as a raw material of the forest and energy industries must meet the quality requirements of the end-user. The composition of undelimited wood differs drastically from conventional pulpwood, since it contains external branches and foliage, and the proportions of bark and small-diameter topwood are greater. These factors affect the economy of pulp production through raw material consumption (wood, chemicals) and the energy balance of the pulp mill (Virkola 1981, Hakkila 1996 and 1998, Koskinen 1999). In the case of the solid energy fraction, heating value (moisture content) is the most important quality parameter (Alakangas 2000). Wood paying capability (WPC) can be used as a criterion for the economic efficiency of the wood supply systems. It is considered as the residual value that the product or industrial process can cover after all the costs other than wood have been subtracted from the sales revenues (Pihlajamäki and Kivelä 2001, Paavilainen 2002). In addition to production costs, WPC takes into account the value of raw material from the end-user's perspective. The residual value at stump can be used as an indicator of the efficiency of the entire production process. The WPC is the maximum price tolerated for wood and provides an indication of the companies (or process involved) potential for profit (Fors 2009).

In evaluating the environmental effects of thinnings, emphasis is put on the silvicultural impact of harvesting in particular (Harvennushakkuiden... 1992, Pesonen et al. 1993, Andersson et al. 2002). Estimating the economic effect of potential productivity reductions resulting from intensified harvesting is problematic. Silversides and Sundberg (1989) defined the combined silvicultural and harvesting problem as maximizing the value of:

$$\text{revenues} - \text{costs} + \text{value of the residual stand.}$$

In the case of integrated operations, Puttock (1994) suggested using a conventional present value calculation, i.e., comparing the value of additional biomass with the discounted value of any future yield losses attributed to reduced site productivity or any costs of sustaining site productivity, e.g., by fertilization.

In forest engineering, the environmental effects of harvesting are evaluated indirectly by the status of forest after harvesting. Silvicultural outcome, or the quality of work is defined as the state of the stand and forest floor after harvesting operations have been conducted, with a focus on the productive capacity of the stand (Rieppo et al. 2002). The factors affecting the silvicultural status of the stand include rut formation, tree damage, spacing between strip roads, width of forwarding tracks, stand density before and after thinning, the choice of

trees removed, and the type of machinery used (Rieppo et al. 2002). Practical inventories of silvicultural outcome after thinning record trail depth, strip road spacing and width, thinning intensity, as well as damage to remaining trees (Rieppo 2001, Äijälä 2010).

Concern over the direct and indirect environmental consequences of producing and using materials and products is increasing. Life cycle assessment (LCA) is a tool for evaluating environmental and some social impacts attributed to a product or process. In LCA, these effects are quantified from extraction to disposal and recycling (Straka and Layton 2010), attention in wood procurement being paid mainly to energy expenditure and emissions (LeVan 1995, Athanassiadis 2000, Forsberg 2000, Berg and Lindholm 2005, González-García et al. 2009, Chauvet et al. 2010). Fossil fuels are a diminishing natural resource, and transport, especially road vehicles, is the main source of the pollutants caused by incomplete combustion of petroleum fuels. Complete combustion of fuels releases water vapour and carbon dioxide (CO₂), which is a greenhouse gas accumulating in the atmosphere (Greene and Wegener 1997). Since the other emissions from wood procurement (e.g., carbon monoxide, hydrocarbons, nitrogen oxides, and particles) are also dependent on the combustion process, they are more difficult to estimate. In the study by Michelsen (2008), wood procurement including logging, transport by forwarders and trucks, was responsible for 84% of all greenhouse gas emissions of the value chains from seedling production to the delivery of logs to a downstream user.

1.3 Study objectives

The present study was intended to evaluate the feasibility of tree-section and whole-tree harvesting of Scots pine (*Pinus sylvestris* L.) from first thinnings for integrated production of pulp and energy in a kraft pulp mill from the technical, economic and environmental points of view, focusing on the potential of bundle harvesting. More specific study objectives were as follows:

- 1) To estimate the amount and composition of additional raw material recovered by harvesting of undelimited assortments (**I, III, IV**).
- 2) To evaluate the feasibility of undelimited assortments for the production of kraft pulp (**II, IV**).
- 3) To evaluate the competitiveness of integrated supply systems using the wood paying capability of a kraft pulp mill from small-diameter Scots pine and logistic viewpoints as determinants (**I, IV**).
- 4) To evaluate the environmental consequences of harvesting undelimited assortments in terms of potential nutrient losses (**I**), damage to the remaining stand (**III**), energy expenditure, and the carbon emissions of the wood procurement chains.

2 MATERIAL AND METHODS

2.1 Recovery of additional biomass

The technological, economic and environmental potentiality of integrated supply systems of pulpwood and energy wood is interlinked through the intensity of biomass recovery. Its removal and composition affect wood procurement costs and the usability of the raw material in pulp and energy production, as well as the potential environmental consequences of wood procurement.

Biomass recovery by bundling undelimited Scots pine, either as topped tree sections or as whole trees, was explored in the studies reported in **I**, **III**, and **IV**. In **I** and **IV**, the effect of cutting method on biomass recovery was also evaluated. In all, seven Scots pine –dominated first-thinning stands located on mineral soils in Central Finland were included in the study. The stands were inventoried before and after harvesting, and the sample plots covered 2–20% of their area.

In **I**, a 35-year-old pure Scots pine compartment with an area of 10.7 ha was harvested using a standard feller-buncher and forwarder. The trees were topped, and the tops left on site. Topped trees bucked into sections of 5–6 m were forwarded to a roadside landing to be bundled with a standard slash bundler. The green mass and volume of the bundle recovery was obtained from the wood receiving station of a pulp mill, where the bundles were transported to be processed in the industrial experiment reported in **II**. The composition of the bundles was based on their fractioning into stem and crown mass components, complemented with moisture sampling of these fractions. The dry masses of the fractions were converted into volumes using their basic densities as reported in **I**. Since Scots pine is considered potential pulpwood up to 5 cm diameter based on its technical properties (Hakkila et al. 1995), the target for the topping diameter of the trees was set at that measure. In calculating increase in the solid energy fraction, branches (incl. foliage) were considered as additional fuel recovered by the adapted tree-section method in **I**. The models of Laasasenaho (1982) and Poikela (1996) were applied to the stand data in evaluating the effect of topping diameter on removal in the tree-section method.

In **III** and **IV**, six cutting strips of 20 m x 50 m represented the stands. The strips were harvested using the first and second prototype of the bundle harvester, applying whole-tree bundling. In **III**, the branch proportions of the whole-tree bundles were based on bundle sampling, in which bundles were fractioned into stem and branch components. Green masses of these fractions were converted into dry masses based on their moisture content determined from moisture samples. Dry crown mass was distributed into fractions based on the studies of Kärkkäinen (1976) and Hakkila (1991), and the dry masses of these fractions were converted into volumes using the basic densities listed in **I**. In **IV**, volumetric branch proportions were obtained from a hydrostatic sampling in which the bundles were fractioned into stem sections and branches. Five bundles per stand were analysed individually, representing 36–45% of the number of bundles produced. Recovery and its composition were assumed to be identical with those of loose whole trees. Stemwood removals (incl. stem bark) in the alternative supply systems were based on the pre- and post-harvesting stand data and Laasasenaho's taper curve model (1982).

2.2 Raw material properties

The feasibility of bundled Scots pine tree sections for pulp production was tested by conducting an industrial experiment, including wood-handling trials, laboratory cooking and bleaching trials (II). The tree-section bundles processed in the wood-handling plant of a pulp mill were produced using a standard slash bundler operating at a roadside landing. The wood incorporated into the bundles was harvested from one *Vaccinium*-type (VT) first-thinning stand with a removal of 10 cm mean breast-height diameter (I). In order to facilitate forwarding, the trees (excl. top sections) were cut into two sections of 5–6 m in length, their top sections being left on site. Based on post-harvesting inventory, the mean topping diameter was 5.7 cm (sd = 0.6 cm).

In the 12-hour wood-handling experiment (III), 190 m³ of bundles were debarked as 8% and 16% blends with conventional, delimbed first-thinning pulpwood, a batch containing 100% of conventional first-thinning pulpwood being used as a reference. The bundles were blended with the main wood feedstock of conventional pulpwood by feeding them onto the receiving conveyor as piles with an average solid volume of 12 m³. In all, ca. 2500 m³ of bundles and conventional pulpwood was consumed in the experiment. The delimbed pulpwood used as the main raw material originated from nine separate VT first-thinning stands located in Central Finland as well. Crown mass (branches and foliage) constituted 1.3% and 2.4% of the wood intake (dry mass) in the blend batches.

For the laboratory cooking trials, unscreened chip samples (2 per batch) were compiled during the wood-handling experiment. Material balances for wood handling and the entire process including cooking and bleaching were calculated for each batch. The physical properties of the chips and the papermaking properties of the laboratory pulps were tested, applying the standard procedures listed in II.

In the wood-processing calculations reported in IV, the branch proportions in the whole-tree options were based on hydrostatic volume sampling (see Ch. 2.1). The basic stemwood density and bark proportion of the stem volume were based on the study by Hakkila et al. (1995). A loss of 10% caused by wood procurement operations was assumed for stem bark (Hakkila 2004).

2.3 Competitiveness of the supply systems

The cost-efficiency of the supply systems based on the harvesting of whole trees, either loose (WT) or bundled (WTB), was evaluated in terms of the wood paying capability (WPC) of a virtual kraft pulp mill with a capacity of 600,000 ADt a⁻¹ from Scots pine (IV). The supply system based on the cut-to-length (CTL) method was used as a reference. The WPCs were calculated for three empirical first-thinning stands with the breast-height diameter (DBH) of the removal (6–12 cm) as the main distinctive factor (Fig. 6).

The capital costs of the pulp mill were ignored because of the lack of applicable financial accounts of the forest integrates and the great variation in capital costs between companies and production plants. When calculating the WPCs, the formula employed by Diesen (2007) was modified as follows:

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

where WPC_{mill} = wood paying capability at mill, € m⁻³
 M = sales incomes from pulp, energy, and by-products, € ADt⁻¹

- V = manufacturing costs (excl. wood), € ADt⁻¹
 P = fixed costs (excl. financing costs), € ADt⁻¹
 W = the total wood consumption, € ADt⁻¹

The WPCs at mill were calculated using a material balance model composed of three modules –wood handling, fiber line, and chemical recovery. Since the parameters of fiber line and chemical recovery were kept constant in the comparisons, the material balance of wood handling was decisive for the WPC. The intake volumes of the raw material fractions were converted into dry masses using their basic densities, and the material balance of wood handling was constructed as reported in **IV**. In the basic WPC calculations, the following price parameters were used: pulp 500 € ADt⁻¹, electricity 50 € MWh⁻¹, thermal energy (process steam) 10 € MWh⁻¹, and by-products (tall oil and turpentine) 350 € t⁻¹.

The WPC at stump was derived from the WPC at the mill by subtracting the overheads of the wood procurement organisation (Kariniemi 2009) and the costs of truck transportation, forwarding, and cutting (and compaction) as described in **IV**. Unit costs (€ m⁻³) of the sub-operations included in the supply systems were obtained by dividing the hourly costs of the machinery (Table 2 in **IV**) by their hourly productivities as reported in **IV**. The models of Kärhä et al. (2006a,b) were used to calculate the cutting productivities in the CTL and WT alternatives. The model of Nuutinen et al. (2011) was used to calculate bundle harvesting productivity, based on a time study conducted with the second version of the bundle harvester. The forwarding productivity of conventional pulpwood was based on Kärhä's model (2006a). The models of Laitila et al. (2007, 2009) were applied to forwarding loose and bundled whole trees. The truck transportation productivities derived from the studies by Nurminen and Heinonen (2007), Laitila (2008) and Laitila et al. (2009). In the basic calculations, a forwarding distance of 296 m (Kärhä and Keskinen 2011) and a truck transportation distance of 106 km (Kariniemi 2009) were used.

The sensitivity analyses (**IV**) were focused on the effects of pulp and energy prices as well as transportation distances on the competitiveness of the supply systems. A stumpage price of 13.87 € m⁻³ was assumed for conventional pulpwood in evaluating the effect of cooking yield on the economy of pulp making (MTK 2011). For the whole-tree assortments, stand-wise stumpage prices were obtained by weighing the prices of conventional pulpwood and energy

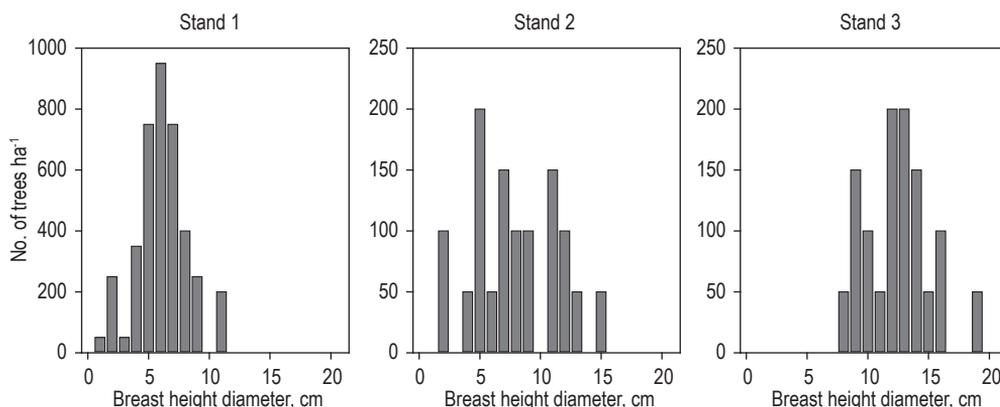


Fig. 6. Breast-height diameter distributions of the removals in the stands included in article IV. Mean DBHs of the removal in Stands 1–3 were 6, 8, and 12 cm respectively.

wood (13.87 € m⁻³ and 7.66 € m⁻³, MTK 2011) by their relative proportions of pulpwood (stemwood and stem bark) and energy wood (branches) in the biomass recoveries.

The bundle harvester concept evolved from an idea to prototypes in the course of the study. Following the guidelines of constructive research, the practical functionality of the innovation and its applicability were evaluated from case studies (Lukka 1993). Once the first prototype of the bundle harvester was constructed, the bottlenecks of the bundle harvesting process were identified for further development, based on time studies conducted in three first thinning stands (**III**). Performance levels were determined and distributions of work elements were analysed in the time studies. The results were compared with the performance of the second prototype in similar conditions, based on the model of Nuutinen et al. (2011). The potential of bundle harvesting was assessed by calculating the minimum performance level or maximum hourly cost for each stand of **III-IV** where total wood procurement costs break even with the supply system based on the harvesting of loose whole trees. Furthermore, a synthesis of the feasibility of the supply chain based on bundle harvesting for the production of pulp and energy in a kraft pulp mill was created using the properties of raw material acquired by bundle harvesting (**I-IV**) and the economic competitiveness of the supply system (**IV**). The environmental competitiveness of the system was also considered, as described in Ch. 2.4.

2.4 Environmental sustainability

Empirical biomass and nutrient balances were constructed for a Scots pine first-thinning stand harvested by applying an adapted tree-section method (TS), and the nutrient loss was compared to the CTL and WT methods (**I**). The above-ground biomass balance was constructed based on pre- and post-harvesting stand inventories, bundle recovery (see Ch. 2.1), and the slash inventories carried out in the stand and at the bundling site as reported in **I**. The biomass of the remaining stand was obtained by subtracting the removal of biomass from that of the initial stand. The nutrient balances were calculated using the concentrations presented by Mälkönen (1974). The potential consequences of intensified biomass removal and nutrient export were evaluated based on the literature. The possibility of damage to remaining trees caused by bundle harvesting was monitored on the circular sample plots in **III**.

Energy expenditure and the carbon dioxide (CO₂) emissions of the machinery involved in wood procurement were derived from the energy and carbon content of the fuel consumed (Spielmann and Scholz 2005). Energy contents of 35.1 and 35.9 MJ l⁻¹ were used for one litre of light fuel oil and diesel oil (Alakangas 2000). For both fuel assortments, a carbon dioxide emission of 2660 g l⁻¹ was assumed (LIPASTO 2011). The energy expenditures and emissions per cubic metre of wood were derived from the hourly fuel consumption of the machines or vehicles and their hourly outputs. The hourly fuel consumptions of harvesters and forwarders were divided by their hourly productivities obtained in **IV**. The fuel consumptions of harvesters (10.7 l h⁻¹) and forwarders (9.2 l h⁻¹) in first thinnings were obtained from the follow-up study of Rieppo and Örn (2003), and the fuel consumption of the bundle harvester was assumed to be 16 l h⁻¹ (Romo, Pasi, Fixteri Oy, pers. comm. 2010). Dividing the fuel consumption on the two-way trip of 212 km (**IV**) by the load volumes used in **IV**, ignoring the differences in terminal times, provided the fuel consumptions of the trucks per one m³ of wood (see Laitila et al. 2009). The fuel consumptions were calculated using the model in Väkevä et al. (2004), assuming a mass of 22917 kg for a conventional timber truck (Peltola 2004) and 29760 kg for an empty biomass truck (Laitila and Väättäinen 2011). The additional weight of the bottom and side panels of a biomass truck (29760 kg–22917 kg = 6843 kg) was considered a part of a load in the WT option. The masses of wood loads were derived from their volumes (**IV**)

and green densities (Jylhä et al. 2003, Lindblad et al. 2008). When evaluating the energy-efficiency of the supply systems, heating values of 1.78–1.81 MWh m⁻³ at a moisture content of 50% were used for wood harvested from the stands of **IV** (Hakkila et al. 1995).

3 RESULTS AND DISCUSSION

3.1 Gain in additional raw material

The solid energy fraction of conventional pulpwood is composed mainly of stem bark. In **I**, potential energy fraction increased by ca. 150% with the adapted TS method compared to CTL harvesting with an equal topping diameter. Since the tree sections incorporated in the bundles were topped on average at 5.7 cm diameter, the proportion of undersized pulpwood in the bundles (stem diameter below 6 cm) was low. WT harvesting, with complete recovery of above-stump-level biomass (excl. dead branches) and no limitations on whole-tree dimensions, would have increased the removal by 32–73% (11–20 m³ha⁻¹) compared to CTL harvesting with a minimum top diameter of 5–8 cm. The amount of solid woof fuel would have increased by 300% compared to the CTL harvesting with a 6 cm minimum pulpwood diameter, for example.

In **IV**, the removal per ha obtained by WT harvesting was compared to potential removal with CTL harvesting applying a 6 cm minimum diameter and bolt length of 3–5 m (Fig. 7). Crown mass and especially undersized stems increased removal by up to 169% in Stand 1 with the smallest trees and the highest number of removed trees (4000 per ha). Stem sections below the current minimum diameter of pulpwood of 6 cm constituted 5–39% of the total stem volume in the three experimental stands included in article **IV**. The timing and intensity of tending the stand at the seedling stage affects the number of under-sized stems in first-thinning stands (Hakkila and Kalaja 1993). The high initial density in Stand 1 (5300 trees per ha) included in article **IV** had probably increased the number of under-sized stems sections in the whole-tree bundles and reduced the proportion of crown mass. In the study by Kärhä et al. (2009), the mean proportion of stem sections below 6 cm was 7% of the total volume and 8% of the stem volume of whole-tree bundles harvested from Scots pine first-thinning stands with a 6–12 mean DBH of the removal.

Crown mass (branches and foliage) constituted 9–22% of the total bundle volumes in the cases included in the present study, i.e., crown mass increased removal by 11–28% (Table 1). Despite topping the trees in the trial reported in article **I**, the branch proportion (17%) was within the range of the branch proportion in the other studies with whole-tree bundles (**III-IV**). Branches represented the major energy fraction of the wood harvested applying the tree-section and whole-tree methods in **I**, **III**, and stands 1–2 of **IV**. The proportion of stem

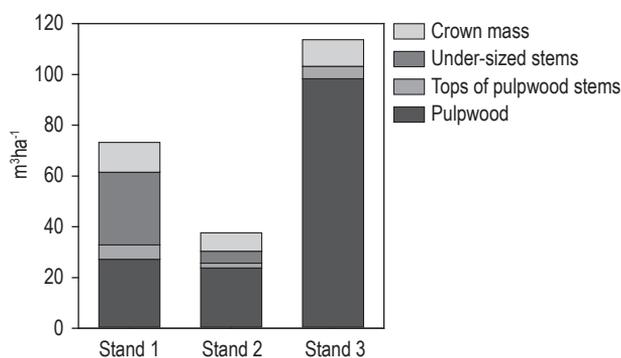


Fig. 7. Composition of removal in whole-tree bundling in the experimental stands included in article I.

bark of the wood intake in **IV** was larger than the crown mass proportion in the whole-tree options (11% vs. 9%) in the case of the stand with the largest trees. The bundle composition data from the experimental stands of article **IV** was used in a larger study reported by Kärhä et al. (2009b), composed of 10 first-thinning stands with 6–12 cm as the mean DBH of the removal. Branches (incl. foliage) constituted on average 17% of the total bundle volume as well, and the crown mass proportion was dependent on tree height and crown ratio – i.e., an increase in tree height and decrease in crown ratio decreased the crown mass proportion of the bundles (Fig. 8). The quantity and composition of crown mass are dependent on tree species, tree size, stand density, geographical location, development history, and health status of the stand (Hakkila 1991). The proportions of living and dead Scots pine crowns of tree length and branch diameter are inversely related to stand density (Oker-Blom et al. 1988, Mäkinen and Colin 1998).

Dead branches are usually expected to shed on the ground during harvesting (Hakkila and Kalaja 1993, Laitila et al. 2004, Tanttut et al. 2004, Laitila et al. 2010). In **I**, however, a marked quantity of dead branches was found in the bundles containing topped tree sections.

Table 1. Stand characteristics and properties of the pulpwood bundles in the case studies.

Article	Cutting method	Bundle harvester version	Stand no.	No of stems ha ⁻¹		Removal		
				Initial stand	Removal	Mean DBH, cm	Crown ratio, %	Crown mass, % of bundle volume
I	Tree section	–	1	1508	735	10	50	17*
III	Whole tree	1st	1	2850	2850	8	36	22
IV	Whole tree	2nd	1	5300	4000	7	53	16
IV	Whole tree	2nd	2	2150	1100	9	57	20
IV	Whole tree	2nd	3	2000	1100	14	42	10

*) Dry mass proportion; equates to volumetric proportion reported by Jylhä et al. (2003).

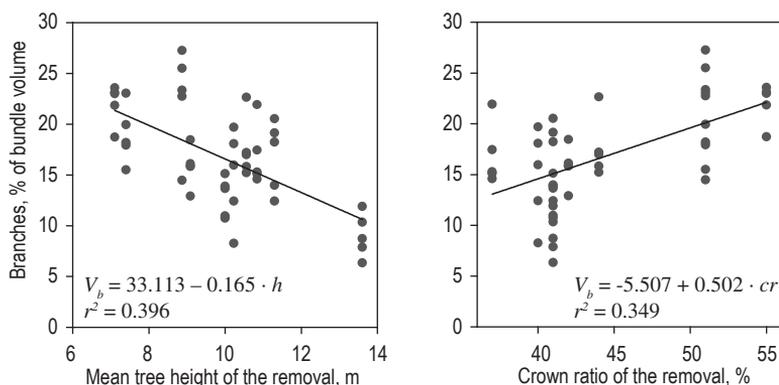


Fig. 8. Effect of mean tree height (h) and crown ratio (cr), i.e., the proportion of living crown of tree height on the volumetric proportion of branch biomass in the bundles (V_b).

Dead branches constituted 35% of recovered crown mass in tree-section bundles, and 6% of the total bundle biomass. In Hakkila (1991), dead branches constituted 17–21% of the crown mass (dry mass basis) removal in Scots pine first-thinning stands. The large proportion of dead branches in the bundles may be due to the low initial stand density (1508 trees per hectare). The branches of trees grown in sparse stands are thicker and thus more resistant to self-pruning and breaking during harvesting (Kellomäki 1983). Dead branches, concentrated in the lower parts of the crowns, were incorporated in the bundles to a great extent, while the uppermost sections composed mainly of living branches were left on site as a result of topping the trees.

In practice, the recovery of crown mass is incomplete. In the study by Hytönen et al. (2010), 10–45% of crown mass remained on site after mechanised whole-tree harvesting. In the present study, the amount of forest residue was inventoried only when harvesting topped tree sections in **I**. Forest residues composed of undersized tops and branches constituted 15% of the entire biomass removal. Thirty-seven percent of crown mass remained on site, and 9% as bundling residue at the roadside.

Lack of applicable information meant that removals in standard whole-tree harvesting and whole-tree bundling in article **IV** were assumed to be identical. However, the feeding and compaction processes are likely to increase biomass loss, especially that of foliage, and some stemwood in the form of short tops is likely to fall to the ground unintentionally while feeding them into the bundling unit. Therefore, the amount of forest residue after whole-tree bundling is probably greater than with standard whole-tree harvesting.

3.2 The quality of raw material

3.2.1 The material balance of wood handling

In the integrated supply systems included in the present study, the major separation of the pulp and energy fractions takes place in the debarking drum. In Finland, the fines separated from the pulp chips by screening are also used in energy generation in most cases (Rieppo and Korpilahti 2001). All stemwood passing the debarking drum is potential pulpwood. Based on its technical properties (bark content, wood density, fibre length, the quantity of extractives), first-thinning Scots pine larger than 5 cm in diameter is considered potential pulpwood (Hakkila et al. 1995). Typically undersized stemwood with an above-bark diameter of less than 5 cm constitutes on average 20–30% of stemwood removal in first thinnings (Hakkila 2004), and this proportion increases along with a decline in tree size. In Kärhä et al. (2009b), the mean proportion of stem sections larger than 5 cm in diameter was 85% of stemwood recovery (incl. bark) and 69% of the biomass recovery by whole-tree bundling in ten Scots pine first-thinning stands located in Central Finland.

Only minor differences in the material balances were found in the wood-handling experiment conducted on conventional small-diameter pulpwood and the blends of this material and bundled tree sections. In all batches, ca. 89% of the raw material (dry basis) was estimated to have ended up in the pulp chip fraction (**II**). Branch stubs conveyed into the chipper may have increased the chip yields in the blend batches of **II** (Fig. 9), as was the case in a Swedish experiment consisting of a series of drum debarking and chipping trials with tree sections in which 3–13% of the branch biomass ended up in the pulp line (System for trimming... 1984). The low proportion of external branches (excl. foliage) of the wood intake in the blend batches of **II** ($\leq 2.2\%$), however, means that they have only a minor effect on the chip yields. In the calculation of Korpilahti and Poikela (1998), 75–83% of the volume of

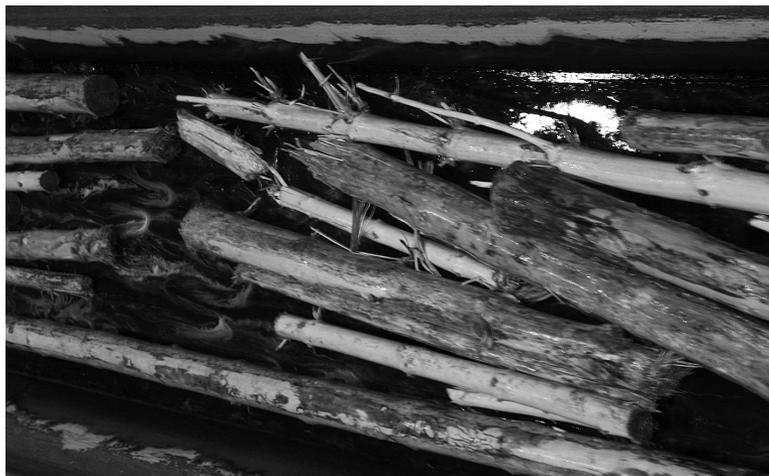


Fig. 9. Debarked wood on the washing conveyor in the wood handling experiment reported in II (16% bundle blend). Photo: Christer Backlund.

Scots pine tree sections (topped at 5 cm) was estimated to end up in the chip fraction in drum debarking.

A decrease in stem diameter increases log breakages in the debarking drum, resulting in rising wood loss (Imponen et al. 1997a, Imponen et al. 1997b, Rieppo and Korpilahti 2001). According to Rieppo and Korpilahti (2001), a debarking loss of 2–3% can be achieved in separate drum debarking of small-diameter delimbed pulpwood. Estimated stemwood losses in II were 1.9–3.1%, indicating that the level of 2–3% can also be achieved using undelimbed tree sections blended with conventional small-diameter pulpwood. The average loss in conventional pulpwood drum debarking is between 1% and 3%. In unfavourable conditions, losses up to 6% are possible, and undelimbed small-diameter wood can increase wood loss up to 10% (Koskinen 1999). Debarking loss is dependent on the type of machinery (Metlas Ky 1989, Koskinen 1999, Isokangas 2000, Isokangas and Leiviskä 2005). In the experiment reported in II, the debarking drum with relatively narrow bark slots (42 mm) was designed for undelimbed material. In addition, debarking parameters affect wood losses. For example, an increase in filling degree increases wood losses (Koskinen 1999), and a decrease in debarking time has an adverse effect (Isokangas and Leiviskä 2005).

The lowest wood loss in II was obtained in the batch with the highest proportion of undelimbed material (16%). It is possible that branches absorbed shocks to the stem sections in the debarking drum, thereby reducing wood losses to some extent. However, the debarking parameters of this batch resulted in a shorter debarking time than in the other batches because of the lower filling rate of the debarking drum and its greater debarking capacity (Isokangas and Leiviskä 2005). Furthermore, the highest mean top diameter of the main raw material, conventional pulpwood, was found in the batch with a 16% bundle proportion (Jylhä et al. 2003). Because of debarking and chipping of the bundles as blends with conventional small-diameter pulpwood, the wood losses could not be subjected to individual blend components. In IV, the behaviour of bundled whole trees in drum debarking was simulated by recourse to an expert's judgement, assuming that they are debarked as a blend of at maximum 15% with conventional small-diameter pulpwood. The assumption in constructing the material balance for debarking of the whole-tree assortments was that 30% of wood originating from stem sections below 6 cm in diameter would end up as debarking residue. The wood losses of larger stem sections were set as proportional to the mean stem volume of the trees harvested from

the case stands, which is in accordance with Imponen et al. (1997b), who stated that wood loss in drum debarking is inversely proportional to the minimum diameter of the pulpwood logs. The procedure applied in **IV** resulted in wood losses of 3.4–13.3% for whole tree stems and 1.9–2.5% for the CTL alternative, i.e., 10–34% of the wood intake (dry basis) ended up in the solid energy fraction (Table 4 in **IV**).

3.2.2 Chip properties

Cleanliness

The main aim of debarking is to remove bark to the extent necessary to ensure the quality of the final product (Koskinen 1999). When debarking undelimited assortments, delimiting also takes place in the debarking drum, and particles from external branches and branch stubs end up among the pulp chips to some extent. Knots (ingrown branchwood) and particles from external branches in pulp chips are a problem in cooking as they increase the energy and chemical consumption, and the amount of reject. Furthermore, they impair pulp quality (Hakkila 1998). Foliage and bark also consume more chemicals, and produce lower fibre yields and strength properties than stemwood (Virkola 1981).

The sulphate pulping method tolerates a poor debarking degree and a relatively high bark content in the chips (Virkola 1981, Hakkila 1989, Hillring 1995). In all the debarking and chipping batches of **II**, the bark content was very low, below 0.1%, indicating that the logs were largely debarked. Koskinen (1999) has estimated that a debarking degree of 85–92% leaves less than 1% by weight of bark on the log and satisfies the requirements of sulphate pulping. In pulping, however, no serious technical problems have appeared, even with a 25% blend of hardwood whole-tree chips (Virkola 1981). A low chip bark content can often indicate increased wood loss (Imponen et al. 1997b, Öman 2000). In **II**, however, estimated wood losses of 2–3% were typical of successful drum debarking of small-diameter pulpwood (Rieppo and Korpilahti 2001). In the blend batches, the origin of the bark contaminants could not be traced. In addition to a successful debarking process, the high chip cleanliness may be result from the originally low bark content of the delimited pulpwood used as the main raw material. From the low bark percentages of the logs (3.7–5.2% of dry mass) we may conclude that they had lost bark prior to the debarking experiment to a great extent. According to Hakkila et al. (1995), an average bark proportion of Scots pine stem larger than 6 cm in diameter is 9.8% of the dry mass, and about 10% of bark is lost at various phases of the wood procurement process (Hakkila 2004). The low bark proportions were probably caused by summer harvesting, when bark adhesion to wood is less than in the dormant season (Koskinen 1999), while the feeding rolls and debarking knives of harvester heads can cause significant unintentional debarking of wood (Liiri et al. 2004, Nuutinen et al. 2010).

Using whole trees instead of topped tree sections, branch and bark contents of the chips can be slightly higher, especially when using frozen wood (Hakkila et al. 1995) and wood harvested in the dormant season (Koskinen 1999). Since pulps made of softwood branches shrink twice as much as birch or softwood bole pulps, the pulps containing a lot of branch material cannot be used in good-quality printing papers together with normal bole wood pulp (Virkola 1981, Virkola 1986). Compression of bunches while harvesting bundled assortments causes snapping of branches, thus facilitating delimiting of the tree sections in the debarking drum. In Brunberg et al.'s study (1990), remaining branch stubs after delimiting with multi-tree handling did not have a significant adverse effect on debarking. Aggregating whole trees or tree sections into bundles reduces the risk of soil contamination. Potential residues of sisal

cord used for tying up the bundles among the chips are not harmful in pulp-making as sisal is considered a promising non-wood fibre for high quality paper-making pulp (Hurter 2001, Gutiérrez et al. 2008).

Bark as well as foliage has higher inorganic content than stemwood. A large amount of inorganics (ash) can cause serious problems in the pulp mill, especially by overloading the chemical recovery cycle. The reduced drainage properties of dirty pulps cause problems in pulp washing and at the wet end of the paper machine in the form of increased production losses (Virkola 1981). The wood-handling experiment (II) showed that undelimited tree sections can be debarked to the required cleanliness in favourable conditions. Bark content was less than 0.1% in all batches, i.e., less than one tenth of the recommended maximum in the kraft process (Koskinen 1999). Since the estimated needle proportions in the blend batches of II were less than 0.3% of the wood intakes, their probability of falling into the pulp chips after screening is negligible. When using material with a high proportion of crown mass, difficulty in removing bark and branches from the debarking drum at a high debarking capacity may occur, as was the case in one of the debarking batches included in Hakkila et al.'s study (1995). Living cells of sapwood, bark, and foliage can continue respiration for a long time, generating heat and moisture (Nurmi 2000). Chips made of poorly delimited and debarked wood are thus more susceptible to storage losses and self-ignition in large piles, because of these biotic and abiotic processes (Virkola 1981).

Size distribution

Debarked logs are comminuted into smaller pieces of relatively uniform chip size before processing them into pulp. The more uniform the chips are after chipping, the lower the raw material consumption is (European Commission 2001). In the case of chemical pulping of softwood species, an average chip length is 25 ± 3 mm and thickness 4 mm (Koskinen 1999). Oversized and undersized fractions formed in the chipping process are removed by screening in order to maintain pulp quality and yield, and to prevent complications in digester operations (Mäkelä 1977, Koskinen 1999, Korpinen 2010, Rajesh et al. 2010). Chips are upgraded by subjecting oversized chips to rechipping, slicing or crushing, so that a minimum amount of fines end up in pulp line (Koskinen 1999, Gullichsen 2000, Rajesh et al. 2010). In most Finnish pulp mills, the fine fraction is usually used as hog fuel or cooked separately (Rieppo and Korpiolahti 2001, Korpinen 2010).

Pulp chips of good quality contain more than 90% acceptable chip fractions and less than 0.5% fines prior to screening (Kangas 2008). The screening experiment reported in II shows that 75–82% of the dry mass of chips produced from conventional small-diameter pulpwood and bundled tree sections were distributed into accept fractions, and the proportions of individual accept fractions were independent of the raw material batch (Fig. 10). However, the total accept proportions were significantly higher in the blend batches than in the reference batch ($F=5.954$, $p=0.016$). Likewise, the proportion of overthick chips was 3.0–3.6 percentage points lower in the blend batches than in the reference batch containing only conventional pulpwood ($F=7.410$, $p=0.008$). Oversize (overlong) chips constituted 2.7–7% of the dry mass of the chip samples, and there were no statistically significant differences between the batches. The proportion of fines ranged from 0.6% to 0.8%. However, these differences were not statistically significant.

Chip thickness is the most critical dimension in kraft pulping, since it determines the rate and uniformity at which the alkali will penetrate chips during pulping (Virkola 1981, Virkola and Janhonen 1984, Virkola 1986, Koskinen 1999, Gullichsen 2000, Joutsimo 2004,

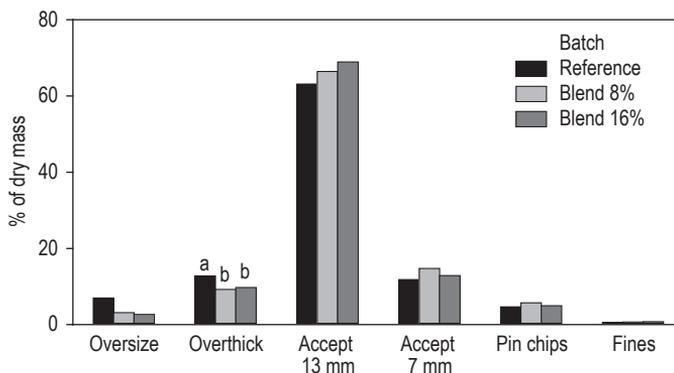


Fig. 10. Particle size distributions of the pulp chips in the wood-handling experiment. Means with the same letters did not differentiate from each other at a 5% significance level.

Rajesh et al. 2010). Uneven delignification in thick chips reduces pulping yield by increasing the amount of rejects. The thinnest chips are overcooked and lost in the recovery circulation (Koskinen 1999). A high proportion of fine particles in the chip furnish also increases alkali consumption, causes poor liquor circulation in the digesters and impairs pulp quality (Rajesh et al. 2010). Homogenous chips can be cooked to a lower kappa number than more heterogeneous chips. A decline in kappa number indicates lower residual lignin content in the pulp, enabling reduced chemical consumption in bleaching or simple bleaching procedures. This reduces environmental loading and the cost of waste water cleaning (Rieppo and Korpilahti 2001).

Wood characteristics such as density and moisture affect the chipping performance (Koskinen 1999, Rajesh et al. 2010). Branches do not chip properly at all (Koskinen 1999), and an increase in the proportion of overthick chips is often explained by branches, either internal or external, ending up in the chipper (Hakkila et al. 1995, Sikanen and Vesisenaho 1995, Imponen et al. 1997b, Hakkila 1998). The largest quantity of overthick chips in II was found in the reference batch containing only delimbed pulpwood. The differences in the proportion of overthick chips may reflect the properties of the main raw material flow originating from nine first-thinning stands rather than the amount of undelimbed material in the wood flow. For example, the wood in the reference batch may have contained more knots than the wood in the other batches. The debarking residue analyses in Jylhä et al. (2003) showed that delimbed pulpwood also conveys branches, either internal or external, to the pulp mill. The debarking residue from the reference batch contained 4.2% branch material, while the branch proportions of the blend batches were 6.3% and 7.4%. In addition, a decrease in the top diameter of pulpwood increases the proportion of overthick chips (Hakkila and Kalaja 1993, Rieppo and Korpilahti 2001). The mean top diameter of the logs of conventional pulpwood in the reference batch was slightly lower than those in the blend batches (8.6 cm vs. 8.9–9.2 cm, Jylhä et al. 2003).

Brunberg et al. (1990) concluded that incomplete delimiting of pulpwood also results in an increase in the proportion of fine chip particles. In the study by Hakkila et al. (1995), a decrease in minimum top diameter of pulpwood also increased the proportion of fines. Applying the WT method instead of the CTL or TS methods can increase the amount of top wood with unfavourable properties, especially in small-diameter stands with a high crown ratio (Kärhä et al. 2009b). Increases in branch fraction and small-diameter stemwood could cause the proportion of overthick chips and fines to increase (Hakkila et al. 1995). On the

other hand, especially narrow stem sections sticking out of the bark slots are susceptible to large wood losses in drum debarking (Hakkila et al. 1995, Korpilahti et al. 1995), which reduces the amount of material with inferior properties ending up in the chipper.

Because of the relatively high proportions of oversized chip fractions, the acceptable chip proportions in **II** were lower than in most batches in the Finnish wood-handling experiments with small-diameter Scots pine (Fig. 11). In addition to **II**, however, undelimited wood was used only in two debarking batches included in Fig. 11 (Batches nos. 6 and 13). The highest proportion of overthick chips (22%, batch no. 13) was recorded by Hakkila et al. (1995). When harvesting wood for this batch from Scots pine dominated stands (94% Scots pine, 6% Norway spruce), the CTL method was used for trees with DBH of more than 12.5 cm and the TS method for smaller trees. This procedure resulted in a raw material blend containing 7% branches, while the branch proportions in **II** were only 1.3–2.4% of the wood intake. Hakkila et al. (1995) explained the high proportion of overthick chips in batch no. 13 by the large quantity of branches and frozen wood. On the other hand, branches can be removed more easily when the wood is frozen (System for trimming... 1984). Furthermore, using Norway spruce results in a lower debarking degree than with Scots pine processed in equivalent conditions (Öman 2000). According to Sikanen and Vesisenaho (1995), branch stubs remaining on the stems after multi-tree cutting can also slightly increase the amount of overthick chips.

Beside wood properties, likely also chipping facilities affected particle size distributions in the studies included in Fig. 11. In addition to the batches included in **II**, only the batch with the highest proportion of overthick chips (Batch no. 13 in Fig. 11) was processed in a wood-handling plant lacking a short-end chipper. In the other wood-handling plants, log sections shorter than 70 cm were subjected to a separate short-end chipper. Positioning of short log pieces towards chipper blades is often incorrect, resulting in large chip particles and slats of wood (Martikainen 1984, Metlas Ky 1989, Rieppo and Korpilahti 2001). When

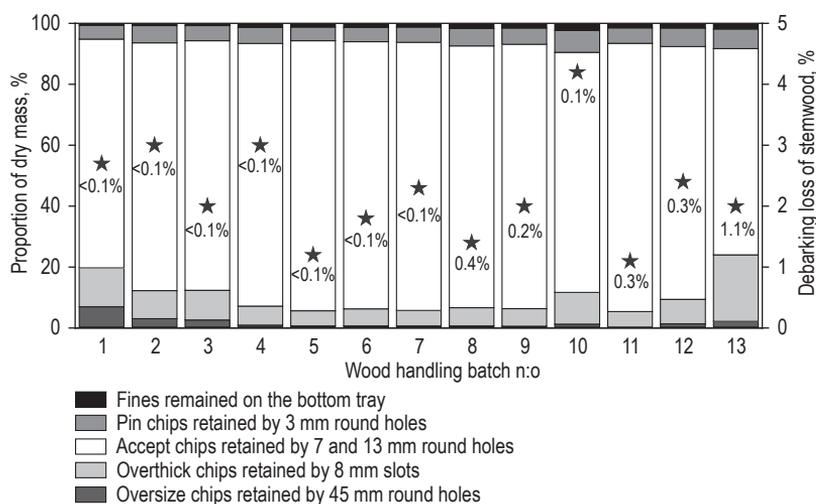


Fig. 11. Particle size distributions of the chips (left axis), stemwood losses caused by debarking (right axis, star markers on the bars), and bark contents of the chips (percentages above the star markers) in Finnish wood-handling experiments with 0–100% Scots pine harvested from first thinnings. Batches no. 1–3 were included in the present study (**II**). The studies included in the comparison and their experimental designs are summarised in Appendix 1.

harvesting the tree sections to be bundled at the roadside for the experiment reported in **II**, the tree sections had to be cut into pieces of 5–6 m in length in order to facilitate forwarding (Jylhä et al. 2003), which increased the number of short blocks of wood accumulating in the bundles. Using a bundle harvester operating on site reduces the need for bucking the stems and thus the amount of wood blocks ending up in the bundles. From the debarking point of view, ca. 3 m is considered an ideal length for pulpwood in tumble debarking. In addition to a decrease in debarking time, breaking of logs into short pieces can be reduced by applying this length, thus improving the quality of pulp chips, and reducing wood losses (Öman 2000, Rieppo and Korpilahti 2001). This principle was followed in **IV**, in which the debarking loss of pulpwood-dimensional stemwood in the bundling alternative was set slightly lower than in the case of loose whole trees. When bundling undelimited assortments, the tree sections accumulated in the bundles can be at most 2.7 m long, which is the minimum length of pulpwood logs in Finland.

3.2.3 Pulp yield and quality

Log diameter distribution, bark and branch proportion, basic density, and moisture content are among the most important factors affecting pulping yield and the processability of wood (Rissanen and Sirviö 2000). In the present study, the pulp yields were inversely proportional to the proportion of bundled tree sections in the wood flow fed in the debarkin drum (**II**). The highest screened yield (43% vs. 41–42%) was achieved in the reference batch consisting entirely of delimited pulpwood (Fig. 12), even though the proportion of acceptable chip fractions was lowest in this batch. The effect of increased proportion overthick chips in the reference batch was seen in the amount of rejects. In addition, the lowest mean wood density was found in the reference batch. Nevertheless, the lowest wood consumption (5.7 vs. 5.7–6.1 m³ADt⁻¹, under bark) was achieved in this batch.

All wood used in the experiment originated from first thinnings. Increasing the distance from the tree butt results in steeply decreasing wood density and increasing wood consumption in pulping (Virkola 1981, Päivänen 2002). Despite topping the tree sections at 5.7 cm on average, the proportion of small-diameter stem parts was probably higher than in the case of conventional pulpwood with an average top diameter of ca. 9 cm (Jylhä et al. 2003). The proportion of juvenile wood is at highest in the tops of Scots pine, resulting in a decrease in wood density and the thickness of the cell walls (Gullichsen 2000, Kärkkäinen 2007). Thin cell walls are susceptible to overcooking, and the cellulose content of top wood is lower than in the lower parts of the stem, which increases wood losses in pulping (Virkola and Janhonen 1984, Hakkila et al. 1995, Hakkila 1998, Rautiainen 2010). The branch content of the chips in the blend batches was also probably higher than that in the reference batch, especially in the batch with the highest bundle proportion (16%) and shorter debarking time due to deviating debarking parameters. Branches contain much reaction wood with higher lignin and hemicellulose content than normal wood. Branches (especially twigs)

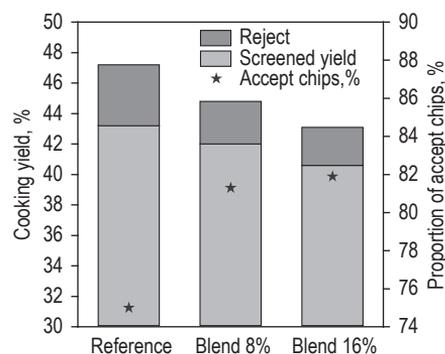


Fig. 12. Cooking yield and the proportion of accept chips in **II**.

give even lower yields than top wood (Virkola 1981, Rissanen and Sirviö 2000) (Fig. 13), and can increase the amount of rejects (Virkola 1981, Hakkila 1998). Furthermore, 40% of branches incorporated in the TS bundles were estimated to be dead (II). They may have been dry or partly decomposed, which reduces yield in pulping.

In II, the proportion of pin chips and fines was slightly higher in the blend batches than in the reference batch (5.2% vs. 5.8–6.4%). Their overcooking may have further decreased pulp yields in the blend batches (Joutsimo 2004). However, uncertainties associated with the gravimetric method applied in the cooking and bleaching experiments may partly explain the inconsistencies between the chip size distribution and the results of the cooking and bleaching experiments (Hultnäs et al. 2009). The final pulp yields in the blend batches were lower than expected based on the proportion of potential pulpwood in the blend batches, probably because of the process losses discussed above (Fig. 14).

The screened cooking yields obtained in II (43, 42, and 41%) were 0.6–5.5 percentage points lower than those in the trials in Imponen et al. (1997a) and Varhimo et al. (2003) with delimited Scots pine pulpwood harvested by various cutting methods from several first-thinning sites. However, the cooking results as such are not comparable because of differences in the cooking conditions. Furthermore, Varhimo et al. (2003) used screened chips in their kraft pulping experiment. In the cooking trial in Rajesh et al. (2010) with southern hardwood species (*Eucalyptus* sp. and *Casuarina* sp.), crushing overthick chips increased screened yields by as much as 4–5 percentage points.

The amount of wood required for manufacturing a tonne of bleached kraft pulp usually ranges from 4 m³ to 6.6 m³ (under bark) (European Commission 2001). The stemwood consumption per ADt in II was 5.6–6.1 m³. Wood consumption is highly dependent on wood properties, especially its basic density (Varhimo et al. 2003, Diesen 2007). This is affected by growth rate (see Hakkila et al. 1995, Imponen et al. 1997a, Kärkkäinen 2007), which, in turn, depends on tree genotype, soil fertility, the position of an individual tree in the stand, stand density and fertilization, for example (Hakkila et al. 1995). In IV, the stemwood densities were based on the model in Hakkila (2005), including mean DBH and the age of the trees recovered. The highest wood density was obtained in Stand 1 with the smallest trees, a result of the slow growth rate. With a total yield of 43.3–43.4%, the stemwood consumption (incl. stem bark) ranged from 6.0 m³ADt⁻¹ and 6.8 m³ADt⁻¹ and the consumption of whole trees from

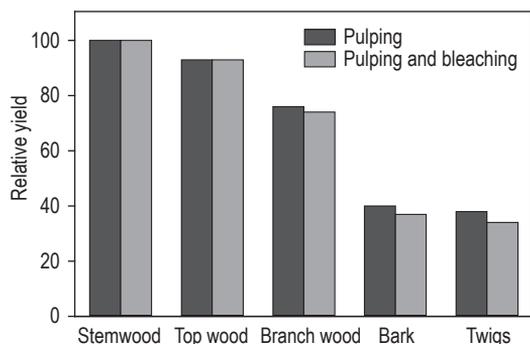


Fig. 13. Relative yields by whole-tree component in kraft pulping of Scots pine and Norway spruce to a kappa number of 35 (Virkola 1981).

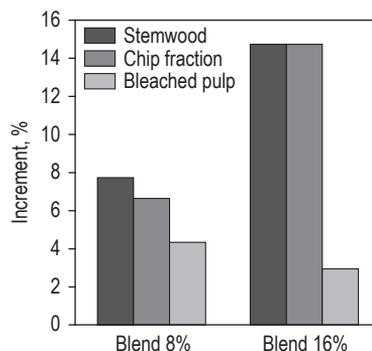


Fig. 14. The effect of bundle increment on the increases in the stemwood, chips, and pulp fractions in II.

6.7 to 8.0 m³ADt⁻¹. Considering the inferior fibre properties of the top sections would probably have decreased cooking yields in the whole-tree options. Despite disparate cooking conditions and wood properties, the wood consumption figures obtained in **II** and **IV** match the results of Imponen et al. (1997a) and Varhimo et al. (2003) with conventional Scots pine pulpwood harvested from first thinnings, in whose studies wood consumption (incl. bark) ranged from 5.8 m³ADt⁻¹ to 7.0 m³ADt⁻¹.

The short and thin-walled fibres of juvenile Scots pine impair the tearing strength of the pulps (Hakkila et al. 1995). In **II**, the pulp properties of the blend chips did not differ from those in the reference batch. In general, sheets made of first-thinning Scots pine are more dense and their Scott Bond and air resistance are higher than those of pulps made of more mature wood (Imponen et al. 1997a). Scott Bond indicates the Z-directional strength of the sheet (Levlin and Söderhjelm 1999). Small-diameter Scots pine could be suited best as the raw material for pulps with high bonding requirements, such as the top ply of multi-ply board grades or some speciality grades (Varhimo et al. 2003). Despite the beneficial properties associated with small-diameter Scots pine, these properties will not be fully utilized unless processed separately as homogenous chip batches. Paper containing a high proportion of fibres from juvenile wood also has good optical properties and an even printing surface (Moberg and Wilhelmsson 2003). Rautiainen (2010) even suggested replacing short-fibre birch pulp in the production of fine papers by pulp made of young Scots pine.

3.2.4. Technical limitations

Most plants are incapable of using excessive amounts of fuel from wood handling (Boström 1984, Korpilahti 1998, Rieppo and Korpilahti 2001). A separate power plant in close vicinity to the wood-handling plant increases the flexibility of the pulp mill's raw material choice. The recommended proportion of undelimited tree sections in drum debarking is below 10–15% (Hakkila et al. 1995, Imponen et al. 1997b), but even a proportion of 20–30% has been considered feasible (Sikanen and Vesisenaho 1995). If the hog fuel handling capacity is sufficient, debarking of whole trees, either loose or bundled, is also probably technically viable within these limits. However, the amount of branch material in the chip furnish is likely to increase when using whole trees. Debarking whole trees alone could result in drum clogs (Sikanen and Vesisenaho 1995).

When processing bundled material, the sisal cord used for tying up the bundles can become entangled with conveyors, causing delays in the process and an increase in maintenance costs. However, sisal string deteriorates and loses its strength after a relatively short period (Johansson et al. 2006), which is an advantage in wood handling. On the other hand, the poor durability of the string increases the risk of traffic hazards due to pieces of wood falling off the load from disintegrating bundles (Johansson et al. 2006). Processing of bundled material probably does not differ greatly from that of loose material with equivalent properties, because bundles with no excess tying cord loops break rapidly into tree sections when feeding them onto the receiving conveyor. In winter, it is possible that the thawing capacity of the debarking plant is insufficient for de-icing bundled material, or that the energy consumption of the de-icing system increases significantly.

The moisture requirements of pulpwood and energy wood are in conflict, although the kraft pulping process is quite tolerant with respect to chip moisture (Hakkila et al. 1995). Moisture reduces the effective heating value of the fuel fraction and the output of the boiler, especially when using wet debarking applications. In dry debarking plants, water is used for de-icing

and washing the logs (Koskinen 1999, Hakkila 2004, Holmberg 2007). Excessive moisture content can result in bridging and freezing of the fuel, and in an increase in hydrocarbon emissions due to incomplete combustion (Hakkila 2004). On the other hand, reduction in wood moisture increases the power demand in chipping, reduces chip thickness, increases the quantity of the fine chip fraction (Koskinen 1999), and retards chemical penetration into the chips, thereby reducing pulp uniformity (Jiménez et al. 1990). However, the major drawbacks of using dried-out pulpwood are associated with debarking. The bond between bark varies with the season of the year and is influenced by the moisture content and wood temperature (Koskinen 1999). The drying of sapwood impairs pulpwood quality by increasing resistance to barking (Hakkila et al. 1995, Koskinen 1999, Öman 2000, Moberg and Wilhelmsson 2003). In the debarking experiment conducted by Öman (2000), most poorly debarked logs had a sapwood moisture content below 40%. In addition, a decline in wood temperature increases the adhesive strength, which is greatest in the case of frozen wood (Hakkila et al. 1995, Koskinen 1999).

The moisture content of pine bark residue is typically 60% (Huhtinen and Hotta 1999). Dry debarking was applied in the debarking experiment reported in II, the bark press not being in use. The pre-debarking moisture content of the bundles and the conventional pulpwood used in the experiment was 53% and 48–52% respectively (Jylhä et al. 2003). The mean moisture content of the debarking residue of the blend batches was significantly lower than in the reference batch (62% vs. 64%, $F = 8.657$, $p = 0.001$) (Jylhä et al. 2003). In terms of heating value, branches can therefore have an upgrading effect on the fuel properties of debarking residue. The moisture content of the fine chip fraction conveyed to combustion was 58–59% (Jylhä et al. 2003). At an approximate moisture of 62–65%, stable combustion of hog fuel becomes difficult to maintain, and enhancing the firing with fossil fuels is required (Nickull 1984, Huhtinen and Hotta 1999, Rieppo and Korpilahti 2001, Hakkila 2004, Kangas 2008). The moisture content of debarking residues can be decreased to 50% with bark pressing applications (Koskinen 1999). In large heating and power plants, a common goal is to maintain the moisture content of forest chips below this level (Hakkila 2004). In the survey by Rieppo and Korpilahti (2001), 65% was considered the highest moisture content for economically viable combustion of debarking residues in a bark boiler. Undelimited trees harvested for energy production are usually seasoned in order to reduce moisture content and the amount of foliage. This would happen at the expense of pulpwood quality in integrated pulpwood harvesting, and the energy fraction would re-moisten in the wood-handling process. Debarking residue could be upgraded by thermal drying, but with low wood fuel prices it has not been profitable (Hakkila 2004, Holmberg 2007). Undesirable tree species and small-sized trees accumulated into separate energy wood bundles may however be seasoned prior to comminution for energy generation.

Debarking residue from undelimited assortments contains foliage rich in chlorine and alkalis (Hakkila and Parikka 2002). Extensive vaporisation of alkalis and chlorine from the fuel increases the risk of ash-related problems such as bed agglomeration, fouling, slagging and corrosion (Aho and Silvennoinen 2004). However, damage to heat transfer surfaces can be reduced by controlling the temperature in the superheater tubes of the boiler (Koskinen 2000, Nielsen et al. 2000).

3.3 Cost-efficiency

3.3.1 Wood procurement costs

The productivity and operating cost of the machinery determine the unit cost of the operation involved in the wood supply chain. In the stands in **IV**, the total wood procurement costs ranged from 26 to 60 € m⁻³ (Fig. 15). Procurement costs of conventional pulpwood harvested applying the CTL method from Stands 1 and 2 with the lowest removals and stem volumes clearly exceeded the average procurement cost of Finnish first-thinning wood (39.6–48.9 m⁻³ vs. 27.1 € m⁻³, Kariniemi 2010). In these stands, the lowest procurement costs were achieved with the supply system based on the harvesting of loose whole trees (WT), while CTL harvesting resulted in the lowest procurement cost in Stand 3 with the largest trees and the highest removal. Since no dimension requirements were set for recovered whole trees in the removal calculations in **IV**, mean stem volumes were very low in Stands 1 and 2, resulting in high cutting costs. In practical forestry, wood originating from such stands is usually subjected to energy generation instead of pulp production.

The CTL option assumed single-tree cutting. Multi-tree handling, especially in Stands 1 and 2 with the smallest trees, could decrease the cutting costs with the CTL system. Multi-tree handling increases cutting productivity by 20–30% compared to single-tree handling (Lilleberg 1997, Mäkelä et al. 2002, Bergkvist 2003, Laitila et al. 2010). An increase of 20% in cutting productivity would have reduced wood procurement costs by 5.3, 3.5, and 1.7 € m⁻³ in Stands 1–3 of **IV** respectively, making the CTL system the most cost-efficient alternative in Stands 1 and 2 as well. The degree of multi-tree handling is dependent on stem volume, a decrease in stem size increasing the number of trees accumulated per crane cycle (Kärhä et al. 2009b). Therefore, multi-tree handling can not applied to any great extent in stands with large stems, such as Stand 3 in **IV**. The bunch can be composed of 2–5 trees, and the number of trees may be even higher with small-diameter trees (Lilleberg 1997). However, the operator's skill with regard to the ability to exploit this possibility to increase productivity and, at the same time, avoid damaging the remaining trees is crucial. This is most critical in dense stands, especially if the distribution of trees is not even (Johansson and Gullberg 2002). According to Asikainen et al. (2005), the greatest potential for multi-tree handling lies in stands from which all wood is transported to only one destination, either energy or pulp industries.

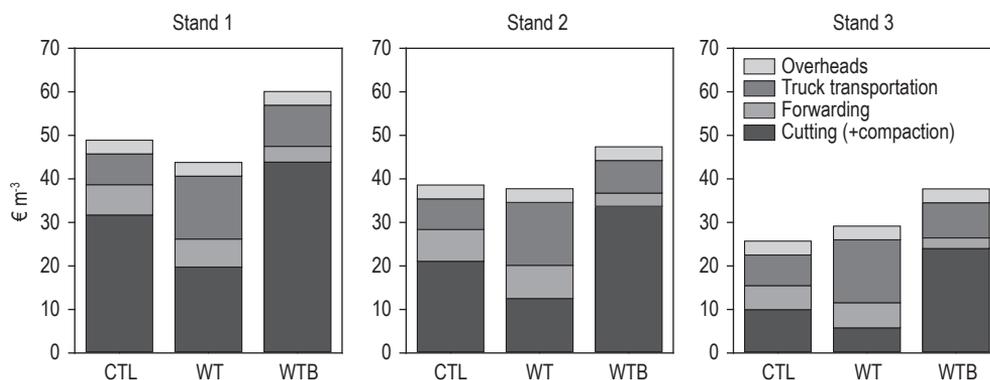


Fig. 15. Wood procurement costs by supply system in the stands of **IV**.

According to Eriksson and Björheden (1989), optimising forest fuel production essentially means minimising transportation costs. Maximisation of the delivered load up to the total weight and dimensional limits and minimisation of terminal times are the most likely ways to reduce transportation costs of uncomminuted raw materials (Ranta and Rinne 2006). This is also of great importance in the integrated systems when harvesting undelimited assortments with low bulk density (mass per unit of volume). The bulk density of loads of undelimited wood is poorly known. It is the product of moisture content, the basic density of the biomass, the presence of contaminants, and the solid content of the material (the ratio of the solid volume to the stacked volume) (Hakkila 1989). The solid content of a load depends on tree variables, such as branchiness, crookedness, diameter, length, and length distribution (Kanninen et al. 1979, Hakkila 1989, Kuitto 1989, Korpilahti 1996, Kärhä et al. 2006b, Nurminen and Heinonen 2007). Kärhä et al. (2009b) showed that stand characteristics also affect the solid volume of whole-tree bundles.

On average, only 60–70% of the load carrying capacity of forwarders can be utilized when transporting undelimited assortments (Hallonborg 1984). In the experiment by Kaipainen (1998), uncompacted Scots pine whole trees had lower solid content than topped tree sections (24–30% vs. 27–31%). Based on the studies by Kuitto (1987, 1989), the load volume of undelimited trees can be increased by 2–7% by leaving small-diameter top sections on site. The solid content of a forwarder load of undelimited Scots pine pulpwood is typically 30–35%. With the load compaction devices of forwarders, increases of 23–26% in load mass of undelimited assortments have been achieved, producing a solid content of 36–43% and a load volume of 8.6–9.5 m³ (Korpilahti 1996). When transporting topped tree sections in **I**, 56% of the carrying capacity of the forwarder with a mean load volume of 5.8 m³ was utilized. An average forwarder load in the study by Laitila et al. (2009) consisted of 22 whole-tree bundles (8–31 bundles per load). This number of Scots pine whole-tree bundles with an average solid volume of 0.5 m³ (Kärhä et al. 2009b) results in a load volume of 11 m³, indicating that the carrying capacities of forwarders applicable to thinnings (9–12 t, Uusitalo 2010) can be utilized to a high degree. With the medium-sized forwarder used in Laitila et al.'s time study (2009), a load volume of 11 m³ results in a solid content of 68%, which clearly exceeds the results achieved with specific load compaction devices.

The solid content of an uncompacted truckload composed of whole trees or tree sections ranges from 20% to 40% (Nilsson 1983, Carlsson and Rådström 1984, Kaipainen 1998, Laitila and Väätäinen 2011). In the compaction experiment with Scots pine whole trees and tree sections by Kaipainen (1998), solid contents of 38–46% and 34–49% were achieved using a dedicated test device. In the practical experiment by Tiihonen et al. (2004), a solid content of 33% for small-sized whole trees was achieved by pressing the truck load with the load space cover hatches. Oijala (1991) obtained an average solid content of 37% for truck loads composing of Scots pine tree sections by using a load compaction device pressing the pile sides. Tree sections and whole trees can be compacted into individual bundles having higher solid content than achieved by using the load compaction devices. In **I**, the mean solid content of an individual tree-section bundle was 62%. Using a solid volume of 0.5 m³ for whole-tree bundles results in an approximate solid content of 56% for an individual whole-tree bundle with average dimensions reported by Kärhä et al. (2009b). However, the frame volume of a standard timber truck can not be fully utilized when transporting bundles. In **I**, the solid content of truck loads of tree sections averaged 36%. Piling 86–90 whole-tree bundles (**IV**) with average dimensions onto a standard truck with a load space of 107 m³ (**I**) produces a solid content of 40–42% for the bundle load.

A bulk density of ca. 345 kg m⁻³ is required for full utilisation of the carrying capacity of a standard timber truck with a load space volume of 107 m³ (**I**) and a carrying capacity of ca. 37 tonnes with a crane (Peltola 2004). Biomass trucks designed for transporting logging residues and whole trees have extended load spaces with an approximate frame volume of 145–150 m³ and a carrying capacity of ca. 30 tonnes (Laitila and Väättäinen 2011). Their carrying capacity can consequently be utilized with material with a bulk density of only 200–207 kg m⁻³. In **I**, an average load bulk density of 312 kg m⁻³ was achieved with tree-section bundles at a moisture content of 53%, while a bulk density of ca. 340 kg m⁻³ would result in full utilization of the average carrying capacity of the timber trucks used in **I**. Green density of Scots pine whole trees varies from 600 kg to 1000 kg m⁻³ (Lindblad et al. 2008). Thus the theoretical bulk density of a truck load (frame volume 107 m³) consisting of 86–90 whole-tree bundles of 0.5 m³ ranges from 240 kg m⁻³ to 420 kg m⁻³. Consequently, the permissible load mass of a truck and a trailer can be even exceeded with high-volume and fresh bundles. The load volume of whole-tree bundles is of the same magnitude as conventional pulpwood, for which load volumes of 38–48 m³ have been reported (Korpilahti 2004, Nurminen and Heinonen 2007, Laitila et al. 2009). In addition to an increased load volume, bundling undelimited wood reduces the storage space requirement compared to loose whole trees and tree sections. In **I**, the solid content of a storage pile of Scots pine sections (DBH 10 cm, topping at 5.7 cm) was estimated to be 26%.

In **IV**, compacting whole trees into bundles reduced forwarding costs by 44–60% and truck transportation costs by 43–48%. These savings were insufficient to balance the high cutting cost resulting from low productivity (3.6–6.5 m³E₀-h⁻¹) and the high hourly cost assumed for the bundle harvester (107 € E₁₅-h⁻¹). Most savings in transportation costs with whole-tree bundling were due to increased load sizes. The size of a forwarder grapple load also increases with bundling, thus reducing loading and unloading times (Kärhä et al. 2009, Laitila et al. 2009b). In truck transportation, terminal operations take longer with bundles than with conventional pulpwood, because of smaller grapple loads, increased time consumption in binding the piles, and the need for cleaning slash from the working sites (Kärhä et al. 2009b). An additional translocation of the truck during loading is also required (Laitila et al. 2009). In **I**, an extension of bundle length was suggested in order to maximize load space utilization; however, placing bundles in the load space would take more time than with shorter bundles. Furthermore, even with the current bundle dimensions, the number of bundles per load has to be limited in the case of heavy bundles.

Laitila et al. (2009) have estimated that the forwarding productivity of whole-tree bundles is about double that of conventional pulpwood and loose whole trees with a forwarding distance of 300 m and a bundle volume of 0.5 m³, for example. However, the reciprocal competitiveness of the supply systems is highly dependent on harvesting factors. In the case of the stand with the smallest trees in **IV** (Stand 1), the forwarding cost of loose whole trees was less than that of conventional pulpwood. This was due to the marked increase in removal resulting from whole-tree harvesting, owing to the large number of undersized stems. According to Kärhä et al. (2009b), truck transportation costs of conventional pulpwood and whole-tree bundles are close to each other, while the cost of trucking uncompacted whole trees is about double that of the other assortments. As shown in Fig. 15, this was also the case in the present study. Insufficient information on the effects of stand characteristics on load volumes meant that fixed load volumes were assumed in the cases of forwarding and trucking of conventional pulpwood and loose whole trees in **IV**. Load haulage volumes of conventional pulpwood harvested from thinnings are smaller than with wood originating from subsequent harvesting (Erlandsson et al. 2008). Within first-thinning stands, however, the cost of truck

transportation is not sensitive to changes in tree volume (Salo and Uusitalo 2001). Applying the load size model of Kärhä et al. (2006b) for whole trees, valid only in Stands 1 and 2, would have reduced the gap between forwarding costs of whole trees in these stands from 1.1 € m⁻³ to 0.80 € m⁻³.

Korpilahti and Poikela (1998) found that the cutting costs of loose Scots pine tree sections topped at 5 cm were 28–34% lower than those of conventional single-tree cut pulpwood with an equal topping diameter. Forwarding costs were 21–25% higher, and the reduction in the total wood procurement cost was 10–16% compared to CTL harvesting. Also transportation costs of energy wood can be reduced by delimiting trees. According to Laitila et al. 2010, forwarder payloads of delimited stemwood are ca. 50% greater than in the case of whole trees (6.0 m³ vs. 9.0 m³). In Laitila and Väättäin (2011), an average timber truck payload of 41 m³ was achieved with delimited energy wood. In the case of whole tree transportation with a biomass truck, a mean load volume of 30 m³ was recorded, which is 20% greater than was assumed in **IV** and other recent studies (Laitila 2008, Kärhä et al. 2011). However, Laitila and Väättäin (2011) did not identify the effect of tree volume, bucking length, and storage time on load volume.

In **IV**, the productivities of the bundle harvester were calculated using the time consumption model reported by Nuutinen et al. (2011), based on time studies with the second prototype. Its productivity was considerably higher than that of the first prototype. In comparable harvesting conditions to the time study reported in **III**, the productivity of the second prototype would have been 34–72% higher than that of the first one (Fig. 16). In **III**, insufficient hydraulic capacity, the absence of a grapple feeding system, and the structure of the feeding table were identified as the main causal agents for poor interaction between machine components resulting in low performance. The low hydraulic capacity did not enable simultaneous cutting and bundling functions and multi-tree handling to any great extent. Cutting simultaneously with bundling covered 8–18% of the effective working time, and only 8–36% of trees were multi-tree handled. The lack of grapple feeding necessitated intermediate stacking of trees and tree bunches on the ground before feeding them into the bundling unit. This took 25–27% of the effective working time. Significant improvement in the performance of the bundle harvester was achieved by constructing an entirely new harvester head equipped with pulse feeding. A grapple feeding system decreased crane movements substantially as direct feeding of bunches into the bundling unit became possible. The bundling unit of the second prototype was mounted on a more powerful base machine with more hydraulic capacity, enabling more overlapping work phases and multi-tree handling. The need for supporting bunches protruding from the feeding gate of the bundling unit by crane was reduced by restructuring the feeding table. With the second prototype, the average proportion of multi-tree handled trees had increased up to 80%. The average number of trees per grapple load was 2.9, while it was only 1.1–1.6 in the study conducted with the first prototype (**III**). In the time study with the second prototype, the proportion of simultaneous harvesting and bundling functions of the effective working time had increased up to 34% (Kärhä et al. 2009b). The bundle harvester could also be used when harvesting tree sections. The tops of the tree bunches would be cut as usual by the chain saw installed at the in-feed gate of the bundling unit. Thereafter, the tops could be ejected on the ground by reversing the feeding rolls or by turning the feeding table. This would increase time consumption only slightly, which would probably be compensated by reduced feeding time. The decline in recovery can increase forwarding costs, depending on topping diameter, stem size distribution of the trees, and the amount of crown mass in the top sections. In **I**, in which the mean topping diameter of tree sections was 5.7 cm, forest residue composed of small-diameter tops, branches and foliage constituted 15% of the removal.

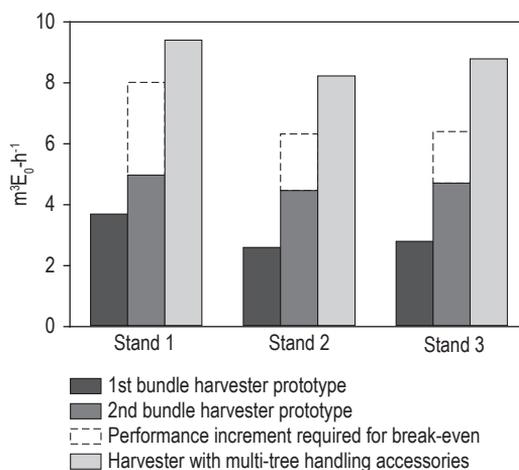


Fig. 16. Productivity of the bundle harvester prototypes, the productivity of a conventional medium-sized harvester equipped with multi-tree handling accessories, and the increment in performance level required for bundle harvesting for break-even with the supply system based on the harvesting of loose whole trees in harvesting conditions comparable to Stands 1–3 in III.

Figure 16 illustrates the need to further improve the efficiency of the bundle harvester in conditions comparable to the stands of III. An increment of 36–61% in bundle harvesting productivity of the second prototype would result in supply chain costs equal to the supply system based on the harvesting of loose whole trees. In practice, even greater improvement in performance is required for the breakthrough of the bundling concept. The pre-feasibility study by Kärhä et al. (2011) showed the greatest potential for whole-tree bundling in small-diameter stands (DBH = 7–10 cm), which is in accordance with the results of IV. In the stands of IV, reductions of 29–37% in bundle harvesting costs would result in a wood procurement cost equal to the supply system based on the harvesting of loose whole trees, i.e., cost savings in transportation would allow a 40–169% increase in cutting costs compared to the harvesting of loose whole trees. The required cost reductions would be achieved in Stands 1–3 of IV by increasing bundle-harvesting productivities by 59% (2.1 m³E₀-h), 40% (1.9 m³E₀-h), and 55% (3.6 m³E₀-h) respectively. Alternatively, the hourly cost of the bundle harvester in the stands of III-IV should be reduced from 107 € to 66–79 €. Automation of crane movements, increasing multi-tree cutting through harvester head modifications, and the placement of the feeding gate of the bundling unit parallel to a strip road have been suggested as potential ways to improve the performance of the bundle harvester further (Kärhä et al. 2009b, Nuutinen et al. 2011). On the other hand, incorporating more automation into the construction involves the risk of a substantial increase in the machine costs (Kärhä et al. 2009b).

Based on the study by Kärhä (2011b), the two-pile cutting method seems a promising way to integrate procurement of pulpwood and energy wood from first thinnings, especially from stands with 7–11 cm as the DBH of the removal. The two-pile method applies multi-tree processing, and the pulpwood and energy wood fractions are sorted into separate piles for transportation to separate destinations. The energy wood section of the bunch remains undelimited, and the delimiting of the lower pulpwood section is incomplete because of multi-tree processing. Allocating the cutting cost evenly to these fractions, the cutting costs of the energy fraction were 6–7% higher than with whole-tree harvesting applying multi-tree

processing when the whole-tree volume was 50–100 dm³. The cutting costs of the pulpwood fraction in the two-pile method were significantly lower than separate cutting of pulpwood with single-tree processing, which was assumed in Option I in **IV**. When considering forwarding as well, the harvesting costs allocated to the pulpwood fraction in the two-pile method were 43–64% lower than those in separate pulpwood harvesting, when the DBH of the removal was 7–11 cm. The harvesting costs of the energy fraction were 5–7% above those of separate harvesting of energy wood with the whole-tree method. However, since wood-harvesting costs are highly dependent on removal, Kärhä (2011b) has concluded that a minimum removal of 40–50 m³ is required for cost-efficient harvesting with the two-pile method, and its competitiveness is dependent on cost allocation between the pulp and energy fractions, as well as the stumpage prices of these fractions. In the study by Tantt et al. (2004), recovery of energy wood in conjunction with pulpwood harvesting was unprofitable in most young thinning stands entitled to subsidies for silvicultural thinnings and energy wood production, because of the high harvesting cost of the energy fraction. The transportation distances from the stand to the end-use facilities should also be considered in evaluating the potential for the two-pile method (Kärhä 2011b). The payloads with the top sections of the pulpwood stems are probably smaller than with whole trees, resulting from low volume of the stem sections and greater amount of crown mass attached to them. On the other hand, the distances to heating and power plants consuming wood fuels are likely to be shorter than the distances to pulp mills. It is also possible to delimb the bunches composing of the top sections when applying the two-pile method, which increases the size of payloads and reduces chipping costs (Laitila and Väättäin 2011).

The integrated harvesting of pulp and energy wood using the whole-tree systems, as included in the present study, simplifies wood procurement operations compared to alternatives where fractions are transported to separate destinations. This also has the potential to reduce overhead costs. A study by Korpilahti (2005) dealing with the harvesting of industrial roundwood showed potential for direct cost savings attributed to decreased need for sorting assortments. He estimated that if pulpwood was divided into two fractions, cutting costs increased by 10%, forwarding costs by 20–30%, and the costs of long-distance transportation by 5%. When cutting, time spent bucking and piling increases, together with a decrease in the size of the forwarder grapple loads. An increase in the number assortments not only increases driving during loading, but also reduces load sizes. Bundling creates more opportunities also to get real-time information about the daily production and inventories required for an effective process control than harvesting loose whole trees or tree sections, especially when using bundling units equipped with a scale.

3.3.2 Overall efficiency

Most studies dealing with the efficiency of wood supply systems concentrate on wood procurement costs. Only a few studies examine the value of raw material from the end-user's perspective (e.g., Pihlajamäki and Kivelä 2001). In addition to wood procurement costs, wood processing costs and wood consumption were also considered in **IV**, using relative wood paying capability (WPC) as a determinant of the efficiency of the entire process from stump to the end product.

The paying capability of the forest industries for energy wood is lower than for pulpwood (Hillring 1995, Hillring 1996, Björheden 2000, Paavilainen 2002). The competitiveness of applicable integrated harvesting techniques is dependent on the value of crown mass as a fuel, which is affected by the price of competing fuels (Imponen et al. 1997b, Paavilainen

2002). Organic by-products play a limited economic role in most kraft pulp mills (European Commission 2001). Based on the activity-based cost model developed by Korpunen et al. (2011), the profit of a kraft pulp mill using conventional small-diameter Scots pine pulpwood from crude tall oil and turpentine is ca. 1% of the profit from pulp, while the profit from heat and electricity is ca. 8% of that from pulp. Hillring (1995, 1996) analysed the competitiveness of tree-section systems applied in Sweden in the 1980s, finding that the profitability of the tree-section systems was greatest when there was a large difference between the prices of industrial roundwood and energy wood or when the price of energy wood was very high. When the price levels approached each other, harvesting of whole trees for energy became a rational alternative. In addition to the low price of the competing fuels, other external factors like demand for small-diameter pulpwood, the supply of forest fuels and changes in taxes affected the competitiveness of the integrated supply systems. In addition, other political issues such as the price of an emissions allowance and subsidies allocated to silvicultural thinnings and forest chip production are important factors influencing the competitiveness of energy production from woody biomass (Paavilainen 2002).

Placing the focus of the present study on the efficiency of the supply systems mean that the external factors above were ignored. Pulp price is by far the most important factor affecting pulp-making profitability (see Diesen 2007, Korpunen et al. 2011). As shown in Fig. 4 in **IV**, energy prices have only a small effect on the wood paying capability of the pulp mill compared to the effect of the pulp price, regardless of the assortment. Electricity price had a greater effect on the WPC than the heat price. With the price relations of pulp and energy applied in the basic calculation of **IV**, the supply system based on CTL harvesting was the most efficient option as a result of its beneficial material balance with the highest proportion pulp chips and the lowest wood consumption. The gains from the energy fractions were insufficient to compensate for the losses in pulp production. The sensitivity analysis in **IV** shows that a decline in pulp price and increase in energy price improves the competitiveness of the whole-tree systems, especially in the cases of Stands 1 and 2 with the smallest trees and the highest proportion of energy fraction. In Stand 3 with the largest trees and the lowest proportion of energy fraction, the changes in the prices of the main products had only a minor effect on the competitiveness of the supply systems. Within the range of pulp price examined (350–650 € Adt⁻¹), the CTL system was the most efficient option in Stands 2 and 3 in terms of relative wood paying capability. In the cases of small-diameter stands located close to the pulp mill, however, using loose (uncompacted) whole trees could be a more profitable alternative for the pulp mill, especially when considering the hypothetically lower stumpage price of undelimited material (Imponen et al. 1997b, Korpilahti and Poikela 1998). In Stand 1 with the smallest trees, the supply system based on the harvesting of loose whole trees resulted in the highest WPC when the pulp price was less than 427 € Adt⁻¹. As shown in Fig. 4, the pulp price has remained above this level in recent decades. Despite ignoring the capital costs of the pulp mill in the present study, very low or even negative residual values were obtained at stump with the lowest pulp prices, indicating that the option with the highest WPC is not necessarily a rational solution from the economic point of view. Eickhoff (1989) and Parikka and Vikinge (1994) concluded that simplifying operations by harvesting only energy assortments might be an economically viable alternative in small-diameter stands with a large proportion of unmerchantable or low-value stems.

An increase in electricity price improved the WPC from the whole-tree assortments more rapidly than from conventional pulpwood (see Fig. 6 in **IV**) because of the higher proportion of the solid energy fraction. Owing to negligible differences in the material balances, the lines representing the effects of product prices on the wood paying capability of the whole-tree

assortments were parallel. In **IV**, an increase in forwarding and truck transportation distances improved the competitiveness of the supply system based on whole-tree bundling. The high cutting and compaction costs, however, meant that the bundling system became competitive only when the truck transportation distance exceeded 400 km. The mean truck transportation distance of industrial roundwood in Finland was 109 km in 2009, and the total transportation distance was 171 km (Kariniemi 2010).

In **IV**, no requirements were set for the dimensions of a recoverable whole tree. In Laitila (2004), for example, trees smaller than 9.5 cm at breast height were deemed to be non-industrial wood. In the CTL method, ca. 7 cm was the minimum DBH required for a pulpwood log conforming to the dimensions applied in **IV**. If only trees with minimum breast height diameter of 7 cm had been recovered, the mean whole tree volumes would have increased from 18 and 34 dm³ to 36 and 52 dm³ in Stands 1 and 2 respectively. In turn, recovery per ha would have decreased by 46% and 11%. The dimension requirements did not affect removal parameters and production costs in any of the cut-to-length options or in the whole-tree options in Stand 3 with no under-sized trees. Table 2 shows the effects of setting a minimum diameter for recoverable trees on the wood paying capability per m³ of wood from mill to stump with the basic price parameters applied in **IV**. The increments in the residual values at mill were due to the more favourable material balances with higher pulp fraction proportions and a lower proportion of the less valuable energy fraction. Whole-tree consumption per ton of pulp would have decreased by 6% if trees with a minimum DBH of 7 cm only had been harvested from Stand 1 with an abundance of small-diameter trees. The reduction in wood consumption with wood originating from Stand 2 was only 1–2%, owing to the slight change in the material balances. Considering the potential reductions in the branch proportions of the whole-tree assortments (Kärhä et al. 2009b) and the decrease in debarking loss (Imponen et al. 1997a, Imponen et al. 1997b, Rieppo and Korpilahti 2001) would have further improved the WPC from the whole-tree assortments.

The most drastic effect of increasing stem size was seen in Stand 1, where the cutting cost of loose whole-trees was reduced by 39% and the cost of bundle harvesting by 25%. The forwarding cost of loose whole trees increased slightly in Stand 1 because of the decrease in recovery. When trucking whole-tree bundles, however, the increases in bundle sizes and load volumes compensated for the losses in forwarding. The increments in the revenues from pulp

Table 2. The effect of setting minimum breast height diameter of 7 cm for recoverable trees in Stands 1–3 included in **IV** on the wood paying capability per m³ of wood.

	Change in wood paying capability, € m ⁻³								
	Stand 1			Stand 2			Stand 3		
	CTL	LWT	WTB	CTL	LWT	WTB	CTL	LWT	WTB
Pulp manufacturing	0	+1.6	+1.6	0	+0.3	+0.3	0	0	0
Wood procurement									
- Overheads	0	0.0	0.0	0	0.0	0.0	0	0	0
- Truck transport	0	0.0	+2.1	0	0.0	+0.6	0	0	0
- Forwarding	0	-1.0	-0.6	0	-0.2	+0.2	0	0	0
- Cutting (+compaction)	0	+7.6	+10.8	0	+3.3	+3.9	0	0	0
Total at stump	0	+8.1	+13.8	0.0	+3.4	+5.0	0.0	0.0	0.0

production and cost savings in wood procurement by limiting stem size indicate an increase of 8–14 € m⁻³ in WPC at stump in the whole-tree options in the case of Stand 1. The size restriction also affects the competitiveness of the supply systems in terms of relative WPC at stump by raising the supply system based on the harvesting of loose whole trees as the most cost-efficient option in Stand 1 (Fig. 17). In these calculations, however, the trees with DBH below 7 cm were assumed to be left intact on site. There was no undergrowth in the stands researched, and in the time consumption models used in II, only spruce undergrowth was considered as increasing time consumption in cutting and forwarding. It is possible that the cost savings ascribed to increase in tree size were overestimated because of the increased number of remaining trees, especially in Stand 1. The greatest decline in productivity is likely to occur in whole-tree bundling where, in addition to the other working phases, remaining trees also hamper feeding whole-tree bunches into the bundling unit.

In IV, single-tree cutting was applied in the CTL option. As shown by Lilleberg (1997), Mäkelä et al. (2002) and Bergkvist (2003), the harvesting costs with the CTL system could be reduced by multi-tree cutting. However, multi-tree processing can increase the recovery of small-diameter top wood, which increases the total pulp production costs (Imponen et al. 1997b). Based on studies with conventional pulpwood, the minimum top diameter of pulpwood affects wood consumption, pulp quality, the quantity of by-products, pulp production costs, and the energy balance of the pulp mill. Imponen et al. (1997b) obtained the lowest total pulp production costs with Scots pine harvested from first thinnings when the minimum top diameter of pulpwood logs was 8 cm. With that diameter and equal stumpage prices, however, pulpwood harvested from final fellings resulted in 25% lower production costs. In the studies by Imponen et al. (1997b) and Korpilahti and Poikela (1998), multi-tree cutting of small-diameter Scots pine reduced pulp production costs by 7–8% compared to single-tree harvesting with the same top minimum diameter (5–7 cm), depending on the compensation from the solid energy fraction. Even lower pulp production costs were achieved with the tree-section method. In Imponen et al.'s study (1997b), this reduced pulp production costs by 10% over the CTL system with single-tree cutting. The pulpwood sections attained by the two-pile method can be left undelimited or delimited as bunches. In terms of branch proportion and top diameter, their quality is at least equivalent to conventional tree sections. Imponen et al. (1997b) concluded that recovery of top sections with whole-tree harvesting

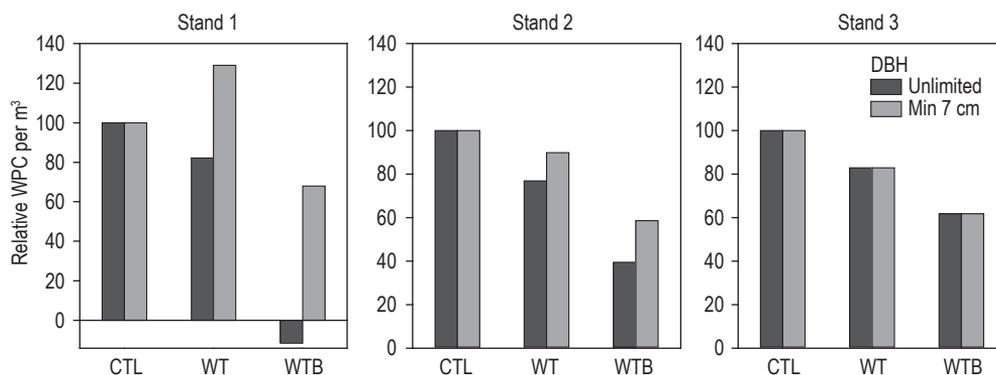


Fig. 17. The effect of setting minimum DBH of 7 cm for recoverable trees on relative WPCs at stump in the stands in IV. WPC with the CTL system and unlimited stem size = 100 in all stands.

is counterproductive from a pulp-making point of view, as an increase in bark content in the top sections and a decrease in wood density increase pulp production costs. Furthermore, a minimum diameter below 5 cm impairs the fibre properties of pulpwood.

Modern kraft pulp mills produce excess heat and electricity from debarking residues and black liquor (European Commission 2001, Wessman 2007). Processing tree sections and whole trees utilizes virtually all material lost in energy generation, which creates opportunities for increasing direct energy production from the solid energy fraction consisting mainly of branches and stem bark. The processing of wood harvested from the stands of **IV** generated 18–26 GJ ADt⁻¹ of thermal energy (heat) and 5–8 GJADt⁻¹ of electrical energy. The proportion of energy generated in the bark boiler increased with the proportion of the solid energy fraction (debarking residue) of the raw material (Fig. 18). When processing conventional pulpwood, most electrical and thermal energy was generated from black liquor. In the cases of Stands 1 and 2, with the highest proportion of energy fraction, most electrical energy originated from debarking residues.

An increase in small-diameter stemwood increases stemwood debarking losses (Imponen et al. 1997a, Imponen et al. 1997b, Rieppo and Korpilahti 2001), and probably the amount of fine chips ending up in energy generation as well (Brunberg et al. 1990, Hakkila et al. 1995). In **IV**, the debarking process was assumed to be ideal with complete delimiting of the whole tree assortments. With the price ratio of energy and pulp applied in **IV**, an increase in wood loss decreased WPC, as revenues from the solid energy fraction did not compensate for the losses in pulp production.

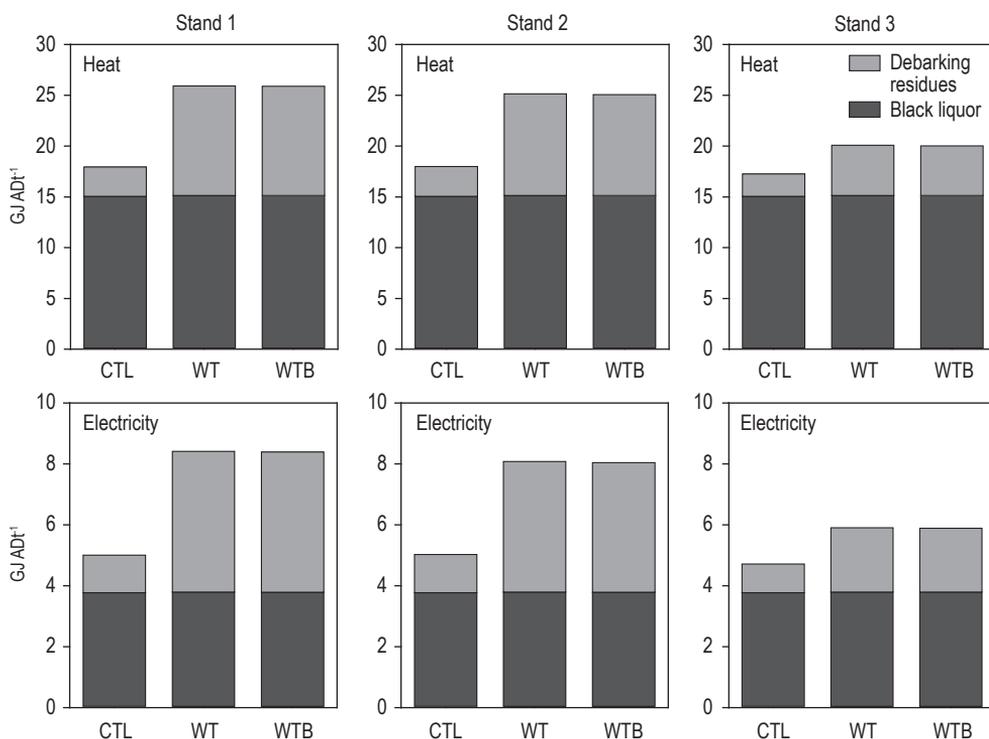


Fig. 18. Generation of thermal and electrical energy (heat and electricity) at the pulp mill from the by-products of processing wood harvested from the stands of **IV**.

Undelimited small-diameter wood gives lower pulping yields than conventional small-diameter pulpwood (Virkola 1981, Hakkila et al. 1995). Material losses from cooking end up in black liquor, which, after evaporation, is combusted in a recovery boiler (European Commission 2001). With the basic price parameters used in IV, a decrease of one percentage point in cooking yield would have increased revenues from energy by 4–5 € ADt⁻¹. On the other hand, a decline in yield would have increased the wood cost by 9–13 € ADt⁻¹ (Fig. 19). In addition, the chemical cost would have increased slightly. In the calculation above, constant stumpage prices for pulpwood and the energy wood fraction of the whole-tree assortments were used in all stands. In practice, there would probably have been differences in the stumpage prices between the stands because of the variation in harvesting conditions (Heikkilä et al. 2007).

Vikingo (1995) showed that moisture content of the energy wood is an important factor in evaluating the competitiveness of energy wood procurement systems. As an offset to the savings in the comminution costs in the integrated alternatives included in the present study, the moisture content of the energy fraction also increases when using dry debarking applications. In the debarking experiment of II, the moisture content of the unpressed debarking residue was as high as 62–64% (Jylhä et al. 2003). A moisture content of 50% can be achieved using a bark press (Koskinen 1999). In IV, a moisture content of 55% was used for the debarking residue. If the moisture content was reduced to 50%, for example, the wood paying capabilities at the mill would increase by 0.4 € m⁻³ in Stands 1–2 and by 0.2 € m⁻³ in Stand 3. If these increments were allocated to the solid energy fractions, the reduction in moisture content would increase the paying capability from the debarking residue by 1.1 € m⁻³ (Stands 1–2) and 0.9 € m⁻³ (Stand 3). With the mean price of forest chips consumed by large heat and power plants in Finland in 2010 (17.78 € MWh⁻¹), the same decline in the moisture content of Scots pine whole tree chips would increase their value by ca. 1.0 € m⁻³ as well (Nurmi 1992, Hakkila et al. 1995, Puupolttoainneiden... 2011). With transpiration drying, the moisture content of whole Scots pine trees can be reduced even to 30% within a few months, but it usually remains at 35–45%. However, some material, especially foliage and twigs, is lost during seasoning (Hakkila 1989). The drying properties of whole trees compacted into bundles are poorly known. In the experiment conducted by Nordfjell and Liss (2000), seasoning a bundle composed of small-diameter whole trees was almost as fast as the drying of uncompressed whole trees. In the experiment by Erkkilä et al. (2011) with two pairs of piles consisting mainly of small-diameter Scots pine, the drying

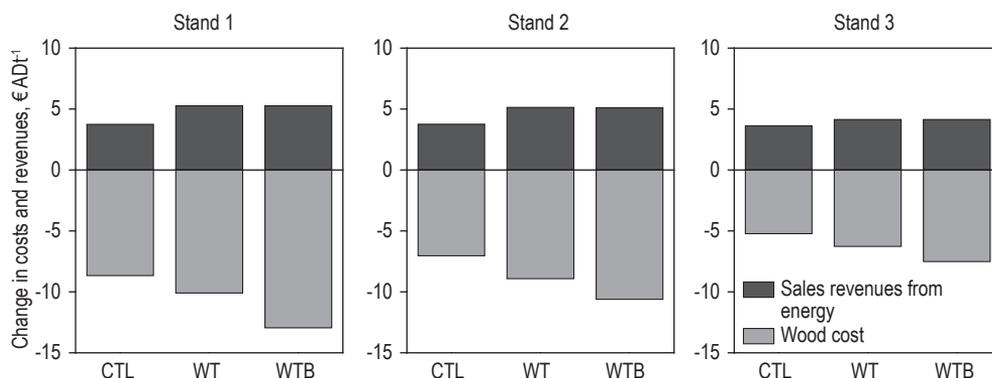


Fig. 19. The effect of a decline of one percentage point in cooking yield on revenues from energy generation and wood cost by supply system in the stands of IV.

of the pile of whole-tree bundles produced by a bundle harvester did not differ from the pile of loose whole trees when the storage was located at a roadside landing. At the terminal, the pile of whole-tree bundles dried faster than the pile of loose whole trees. On the other hand, precipitation wet the bundle pile more rapidly than the pile of whole trees.

The elimination of separate comminution of the energy fraction is one of the justifications for integrated supply systems utilizing drum debarking (Hakkila 1992, Korpilahti 1998, Jylhä et al. 2007). However, the capacity and productivity of wood handling depend on raw material properties (Imponen et al. 1997b), whose inter-relationships are poorly known. Therefore, the effect of assortment on wood-handling costs were ignored in the simulations in **IV**, a fixed wood-handling cost per one ton of bleached pulp being used. Rieppo and Korpilahti (2001) have estimated that delimbed pulpwood harvested from first thinnings reduces the capacity of the debarking drum by a fifth and undelimbed tree sections by a third, compared to conventional pulpwood of larger diameter. In the 1990s, the cost of drum debarking of conventional pulpwood was estimated to be ca. 1.5 € m⁻³ and that of tree sections ca. 2.4 € m⁻³ in the case of small-diameter Scots pine. In the study by Korpunen et al. (2011), the cost of receiving and debarking of conventional pulpwood was 3.6 € Adt⁻¹, i.e., 4.2% of the total pulp production cost (excl. wood price). Kärhä et al. (2009b) assumed twice the debarking cost for whole-tree bundles compared with debarking of conventional small-diameter pulpwood (0.4 vs. 0.8 € m⁻³), and the comminution costs of whole-tree bundles and loose whole trees at the heating and power plant were assumed to be 1.6 € m⁻³ and 2.0 € m⁻³ respectively. The debarking cost of loose whole trees is probably similar to that of bundled whole trees. The order of the figures above indicates that comminution is much less important than harvesting factors, and is not decisive in evaluating the competitiveness of the supply systems.

According to Pihlajamäki and Kivelä (2001), a wood pricing system that takes the value of first-thinning wood from the end-user's point into account is required for optimum allocation between the forest and energy industries. The methodology applied in article **IV**, which was neutral with respect to stumpage prices, showed that conventional pulpwood is a more valuable raw material to a kraft pulp mill than undelimbed wood. The paying capability of the pulp mill for wood delivered at the mill decreased as the energy fraction of the raw material increased. With the basic parameters, the pulp mill would have an 8.2, 6.9, and 3.4 € higher capability to pay for a solid cubic metre of conventional pulpwood than for a cubic metre of whole trees, either loose or bundled, procured for the mill from Stands 1–3 respectively. At stump, the paying capability from loose whole trees harvested from these stands would be 3.0, 6.1, and 6.9 € m⁻³ lower than from conventional pulpwood and, compared to bundled whole trees, conventional pulpwood would have 19.3, 15.7, and 15.4 € m⁻³ higher residual values respectively. In the cases of Stands 2 and 3, the difference in residual values at stump corresponds to the difference in the stumpage prices of small-diameter pulpwood and energy wood in Finland. In 2010, the mean stumpage price of energy wood was 6.3 € m⁻³ lower than Scots pine pulpwood harvested from first thinnings (13.85 vs. 7.51 € m⁻³, MTK 2011). In **IV**, the residual value of undelimbed Scots pine at stump was higher than that of conventional pulpwood only with the combination of an extremely low pulp price and small tree size. Under these circumstances, pulp production is probably unprofitable.

Direct energy generation is an alternative use for industrial processing of small-diameter wood. Based on the studies of Heikkilä et al. (2007, 2009) and Ahtikoski et al. (2008), however, large-scale consumers of energy wood in Finland are not able to pay any stumpage price for small-diameter energy wood without subsidies. With the basic harvesting factors applied in **IV**, a positive residual value at stump would have been achieved only in Stand 3, where mean pulpwood volume and recovery clearly exceeded the mean values recorded from commercial

first thinnings conducted in Scots pine –dominated stands in Finland in the 2000s (77 dm^3 and $45 \text{ m}^3\text{ha}^{-1}$, Kärhä and Keskinen 2011).

The tree-section system and the whole-tree systems included in **IV** represent highly integrated supply chains. Separate facilities for processing undelimited material are not required, if the capacity of wood handling is sufficient. In the whole-tree systems, however, machinery deviating from the standard fleet is required. Especially an investment on the bundle harvester increases commitment and the economic risk. As long as the prices of alternative fuels are low, the projected financial performance of forest fuel recovery can be too poor to justify such risks (Björheden 2000). According to Kärhä and Mutikainen (2008), the volume of integrated harvesting is determined by the situation in the wood markets, i.e., high demand for and price of pulpwood and energy wood improve the competitiveness of the integrated supply systems. The demand for small-diameter pulpwood is currently lower than the supply potential (Anttila 2009), which limits the potential to separate small-diameter pulpwood into separate batches for processing (Pihlajamäki and Kivelä 2001).

Korpilahti (1998) has stated that whole-tree and tree section methods can play only a minor role in replacing fossil fuels. However, potential biorefineries (stand-alone or integrated with pulp and paper mills) can increase the consumption of woody biomass. This implies an increase in transportation distances. Timber trucks can operate profitably only with relatively short transportation distances (Ranta et al. 2008); the system analysis of Erkkilä et al. (2011) suggests that train transportation of whole-tree bundles was more profitable than direct truck transportation to the end-use facility when the train transportation distance exceeded 65 km and the driving distance to the train loading station was less than 30 km. According to Ranta et al. (2008), terminals preventing “overheating” of the supply systems are an essential part of the logistics for any material when the supply volumes are high. Long-distance transportation modes including waterways and railways and their integration into the supply terminals may be potential logistic solutions for supply of biomass to the biorefineries. In Nordic conditions, with poor trafficability of unfrozen peat soils and traffic limitations on the forest road network in autumn and spring, terminals are a prerequisite for continuous raw material flow to the end-users. When handling large volumes of bulky biomass, storage space can be a limiting factor. Whole-tree bundles create an opportunity for flexible storage with reasonable space requirement at any location along the route from stump to end-use facility. However, the end-users’ paying capability and requirements regarding supply security, volume, and quality determine the logistical framework and potential to use alternative supply systems (Ranta et al. 2008). The WPC of pulp and paper production is still higher than that of liquid fuels. Previous studies have indicated a WPC of $15\text{--}25 \text{ € m}^{-3}$ for biofuels (Strengell 2008) and 32 € m^{-3} for pulpwood (Suomi 2007). Based on the report by Sitra (2007), however, the second-generation biofuels may have greater WPC in the future than the pulp and paper industries, especially if the production of biofuels is subsidised through tax relief.

3.4 Environmental effects of wood procurement

3.4.1 Site productivity

Nutrient loss

The nutrient export from the stand can be controlled by leaving the top sections of felled trees on site. In the adapted tree-section method applied in **I**, the trees were topped, and the tops left on site. The thinning implemented was quite intensive, with 40% of the above-ground

biomass (dry basis) being removed. Forest residues constituted 15% of the total removal. Furthermore, ca. 3% of the biomass removal remained at the roadside landing as bundling residues. Topping the trees at ca. 6 cm meant that 48% of living branch biomass removal and 63% of needle removal remained on site (Fig. 20). The harvesting method applied in **I** is comparable to the study by Hakkila and Kalaja (1993), in which 19% of above-ground biomass of removed Scots pines with 10–12 cm DBH was left on site after motor-manual felling piling and topping the trees at 5–7 cm.

In **I**, ca. 3 dry tonnes of branches and foliage was exported from the stand through the harvesting of topped tree sections. If all crown mass had been removed by whole-tree harvesting, the export would have been ca. 4.7 tons. The harvesting of topped tree sections increased the estimated losses of nutrients (N, P, K, Ca) by 48–88% compared to the CTL method (Fig. 21). Nutrient exports in WT harvesting with complete removal of crown mass would have caused 104–210% greater nutrient losses than the CTL method. The relatively greatest increase in nutrient loss was obtained for nitrogen and phosphorus because of their high concentrations in the crown mass (Mälkönen 1974). Except for calcium, the estimated nutrient removals per hectare in the whole-tree option were within the ranges reported by Luuro et al. (2009). The higher estimate for calcium export in **I** (28.5 kg ha⁻¹ vs. 12.2–26.8 kg ha⁻¹) was probably due to the relatively high removal of stemwood in **I**. According to Mälkönen (1974), a majority (61%) of the calcium in the above-ground biomass of Scots pine is bound into stemwood and bark. However, deficiency of Ca has not been shown to limit tree growth in Finnish conditions (Helmisaari et al. 2008). Ca deficiency in natural stands is limited, and additions of Ca associated with liming have often elicited a negative response (Grigal 2000,

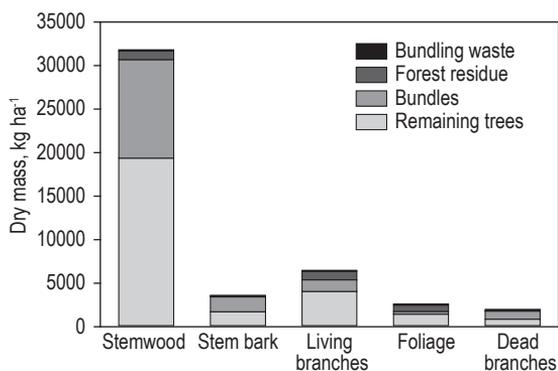


Fig. 20. Division of above-ground biomass components into recovered (bundles) and residual fractions in the experimental stand of article I (VT site, index $H_{100}=24$ m, see Vuokila and Väliäho 1980).

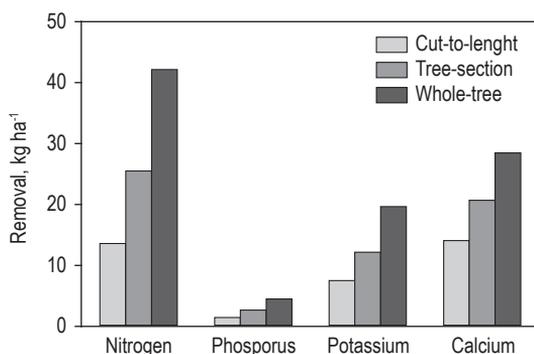


Fig. 21. Effect of harvesting method on nutrient removal on the experimental stand of article I.

Saarsalmi and Tamminen 2001). Nevertheless, there is concern about depletion of Ca over time because removals apparently exceed the natural replacement rate (Grigal 2000).

Considerable interest has developed in leaving adequate amounts of woody residues on site after harvesting. The optimal amount of this biomass depends on habitat type (Jurgensen et al. 1997). Based on the Finnish recommendations, 30% of crown mass should be left on site after whole-tree harvesting (Koistinen and Äijälä 2006, Äijälä et al. 2010). Based on the study by Hakkila (1991), the total amount of crown mass in Finnish Scots pine first-thinning stands ranges from 123 to 141 kg (dry) per removed m³ of stemwood (incl. bark). In the inventory of Hytönen et al. (2010), the dry mass of Scots pine logging residues after wintertime whole-tree harvesting by single-grip harvester was 47-76 kg per one m³ of stemwood (incl. bark) removal (3–7 ton ha⁻¹). Even after manual post-harvesting collection of the logging residues, 0.5–2.5 ton ha⁻¹ of slash was found on the experimental plots (6-27 kg per m³ of stemwood removed). Consequently, no additional measures in favorable conditions are needed in conventional whole-tree harvesting to keep the crown mass recovery rate below the recommended level of 70% (Koistinen and Äijälä 2006, Äijälä et al. 2010). However, slash is not evenly distributed across the stand after mechanised harvesting, which may affect the availability of nutrients released from slash to the remaining trees. Especially with bundle harvesting, slash is concentrated on strip roads or in their close proximity. Due to the compaction process, foliage in particular is likely to be shed on the ground.

Growth of remaining stand

In Scandinavian studies, no significant growth reductions due to whole-tree harvesting from Scots pine first-thinning stands have been observed within the follow-up periods of at most 20 years. In Egnell and Leijon (1997), a non-significant decrease in growth due to whole-tree harvesting of Scots pine was observed 10 years after harvesting. Jacobson et al. (2000) found volume growth reduction of 5% in Scots pine during the first 10-year post-thinning period when compared to CTL harvesting, which they suggested resulted from the reduced supply of nitrogen. Fox (2000) has concluded that intensive whole-tree harvesting has only a slight impact on soil nutrient and organic matter content and subsequent biomass production, even on naturally infertile sandy soils. Luiro et al. (2009) hypothesized in their study covering 12 long-term thinning experiments (3–20 years) in Finnish Scots pine and Norway spruce stands on mineral soils that removal of nitrogen and base cations (Ca, Mg, K) in logging residues would lead to lower concentrations in the needles because of decreased nutrient availability. Their findings did not support this assumption, and there were no significant differences in the volume growth of the trees either. In the simulation by Heikkilä et al. (2007) based on nitrogen removal from the sites, leaving 40% of logging residues on Finnish first-thinning sites increased stem volume by 2.6% over a 10-year post-harvesting period compared to complete whole-tree harvesting. In the newly established thinning experiment located on drained peatland, the degree of biomass removal had only a minor effect on the foliar nutrient concentrations of remaining trees during the first five post-harvesting years (Hytönen et al. 2010). Based on the nutrient balance of peatland forests, energy wood harvesting is not recommended, especially on sites with a thick peat layer, because of the risk of phosphorus, potassium and boron deficiencies (Helmisaari et al. 2008).

In evaluating the results from the yield studies on whole-tree harvesting, one should note that the experimental designs differ from practical harvesting operations. Complete removal of crown mass on the sample plots representing whole-tree harvesting and even distribution of residual crown mass in control plots representing conventional stem-only logging have

particularly been criticized (Hakkila 2002). In mechanized cut-to-length harvesting, the majority of logging residue is usually concentrated in piles on strip roads or in their immediate proximity. The nutrients released from logging residues are thus not available to the remaining stand evenly. In whole-tree harvesting, recovery of crown mass is not complete. These factors level out the hypothetical differences in the productive capacity of the soil between the harvesting methods.

As shown by Kärhä et al. (2011) and Laitila et al. (2010), for instance, whole-tree harvesting is a prerequisite for competitive production of forest chips for large-scale consumers. Potential growth losses due to intensified biomass removal can affect the economic result of wood production, but knowledge of the effects of harvesting undelimited assortments is still insufficient (Heikkilä et al. 2007). In the simulation by Heikkilä et al. (2007) covering one rotation, harvesting of industrial roundwood was a more profitable alternative for the forest owner than energy wood harvesting in first thinnings, when recovery of pulpwood was more than $20 \text{ m}^3 \text{ ha}^{-1}$. Energy wood harvesting was competitive with industrial roundwood harvesting when the removal of wood meeting industrial dimensions was a maximum of $20 \text{ m}^3 \text{ ha}^{-1}$ and the number of remaining trees was 1000–1200 per ha. Of the eight alternatives simulated, omitting thinnings produced by far the poorest economic outcome from the forest-owner's point of view. A Canadian study showed that the silviculture cost savings and the value of energy biomass more than offset the loss in long-term value, owing to slower stand growth following intensive harvesting of black spruce (*Picea mariana*) and balsam fir (*Abies balsamea*) by the whole-tree method at final felling and thinning (Zundel and Lebel 1991).

The guideline for the intensity of crown mass removal can probably also be followed in bundle harvesting. The working pattern of the bundle harvester described in article III, however, means that the majority of logging residues will accumulate on and beside the strip roads, and the nutrients released from them are not evenly available to the remaining trees. Recovery of crown mass between strip roads is nearly complete. The bundles in the studies reported in articles III-IV were composed mainly of whole trees, and the amount of logging residue was not controlled in these experiments. Compared to conventional harvesting of whole trees, the compaction process will probably increase the amount of foliage and twigs shedding on the strip roads, and some top sections may also fall. Consequently, the risk of growth losses due to recovery of crown mass with bundle harvesting will probably not exceed that caused by conventional whole-tree harvesting. Nutrient losses can be further reduced by ejecting the top sections rich in crown mass on the site. According to Hakkila (2004), leaving top sections of ca. 3 m in length in young Scots pine stands after harvesting is a compromise between potential growth losses and fuelwood yield. While this reduces the needle recovery by 52%, the fuel recovery is reduced by only 8%. On the other hand, removal of crown mass can also have positive effects by reducing the leaching of the nutrients released from logging residues into the water system (Nisbet et al. 1997). Nutrient losses could also be reduced by littering foliage and small twigs from whole trees with transpiration drying, in which trees are left on the ground with their crowns intact (Hakkila 2002). When seasoning bundled material on site, littering could happen only to a limited extent. In the case of integrated harvesting of pulpwood and energy wood, drying would deteriorate pulpwood quality (Hakkila 1998, Koskinen 1999, Öman 2000).

Silvicultural outcome

Rieppo (2001) has estimated that strip roads and their rutting constitute 70% of the financial losses caused by harvesting within stand rotation in Finnish conditions. However, forest harvesting by itself rarely has a direct impact on soil quality or long-term site productivity (Fox 2000). In thinnings, this may be because the root system of the remaining stand is mostly located outside the strip roads, in uncompacted soil (Eliasson and Wästerlund 2007), and the positive effects of thinnings (increase in mineral nutrient and light availability) can compensate for the potential negative effects of soil disturbance (Jansson and Wästerlund 1999). In addition to soil compaction, strip roads can cause growth losses from a decreased productive area and deviation from the optimal selection of the trees to be removed (Isomäki and Väisänen 1980, Niemistö 1989, Kokko 1995). However, increased growth of the trees located on the edge of strip roads partly compensates for the growth reduction (Mäkinen et al. 2006).

Soil damage is particularly affected by soil moisture content, the number of machine passes, and the amount of slash (Han et al. 2006). The export of crown mass and small-diameter stemwood increases when harvesting undelimited assortments. In the experimental stand of I, for example, tree-section harvesting and the harvesting of whole trees with complete recovery of living crown mass increased biomass removals by 3.0 and 4.7 dry tons per ha compared to CTL harvesting. Bundle harvesting can slightly increase biomass losses when compared to conventional harvesting of whole trees. However, logging residues shedding on the strip roads are mainly composed of foliage and twigs. According to Han et al. (2006), small amount of slash does not provide enough cushioning to absorb the ground pressure and vibration when the soil is wet. Furthermore, small-sized slash particles tend to be crushed into smaller pieces that can no longer distribute and absorb the machine's ground pressure and vibration in order to lessen its impact. Ejecting top sections of whole-trees on the ground makes them likely to fall largely outside the strip roads, with no cushioning effect.

Soil compaction and rutting can degrade soil quality by increasing soil bulk density and soil strength, and by reducing soil porosity (Fox 2000). These factors affect soil water relations, nutrient availability and root penetration. Since soil compaction can also increase surface runoff because of the reduced infiltration rate and removal of vegetation (Greacen and Sands 1980, Nugent et al. 2003), rutting can cause serious erosion, leading to increased siltation and turbidity in local watercourses (Nisbet et al. 1997, Grigal 2000, Egnell et al. 2001, Burger 2002, Helmisaari et al. 2008). Soil compaction and rutting occur especially when the soil is wet (McDonald and Seixas 1997, Hutchings et al. 2002, Han et al. 2006, Eliasson and Wästerlund 2007, Han et al. 2009), fine-grained, and has high organic matter content and low bulk density (Aries et al. 2005). From the machine manoeuvrability point of view, repetitive passes improve trafficability on friction soils, while the strength of cohesion soils is reduced as a function of repetitive passes because of the deterioration of cohesive bonds (Saarilahti 2002, Uusitalo 2010). Therefore, soil compaction and rutting can deteriorate site manoeuvrability and increase the risk of machine sinkage (Nugent et al. 2003), in particular on peat soils.

In the Northern hemisphere, rutting is seen as a more serious problem than soil compaction, especially when using wheeled forwarders (Saarilahti 2002). The cutting effect of the wheels reduces soil bearing capacity by breaking the reinforcing root network of the soil (Wästerlund 1989, Ess et al. 1998, Bygdén and Wästerlund 2007). In thinnings, damage to the roots of remaining trees is the major disadvantage associated with machine traffic (Nugent et al. 2003, Eliasson and Wästerlund 2007). The shearing forces of wheels or tracks cause root breakage

and peeling, thus exposing the remaining trees to fungal attack (Saarilahti 2002). Soil disturbance also increases the risk of windthrow (Nugent et al. 2003). In order to reduce the risk of soil disturbance without slash reinforcement, technical solutions such as larger tyres, lower tyre pressure, and bogie tracks can be used (Nugent et al. 2003, Eliasson 2005, Raper and Kirby 2006, Eliasson and Wästerlund 2007). Reducing ground pressure by lowering tyre pressure, however, can reduce the risk of soil compaction only on strip road sections with a maximum two passes (Eliasson 2005).

Damage to trees caused by forest machinery may increase financial losses due to discoloration and wood decay resulting from fungal attack (Vasiliauskas 2001). Typically, 3% of remaining trees are damaged in first thinning for pulpwood (Sirén 2002). The proportion of damaged trees should not exceed 4% of the remaining trees in good-quality stands (Poikela 2008). From Äijälä (2010) it can be concluded that whole-tree cutting as applied in energy wood harvesting increases the risk of damage to the remaining trees. In the Finnish inventory carried out in 2009, the proportion of damaged trees after energy wood thinning was double that of conventional thinnings (6.3% vs. 3.1%). This can be explained by more difficult harvesting conditions in energy-wood thinning, resulting from higher stand density, undergrowth, and the high proportion of sprout-originated trees (Äijälä 2010). Multi-tree handling also tends to increase the risk of damage to the remaining stand, especially in selective thinnings (Johansson and Gullberg 2002). No damage to remaining trees caused by whole-tree bundling was observed in the post-harvesting inventory of the present study (III), even after forwarding the bundles to the roadside. This was also the case in the study by Lazdiņš (2008), covering four first-thinning stands harvested by the first prototype of the bundle harvester. The absence of damage can partly be explained by the fact that both inventories were carried out in stands harvested in winter. Frozen soil reduces soil rutting (Shoop 1995), and the dormancy of the trees reduces their susceptibility to mechanical damage (Liiri et al. 2004, Nuutinen et al. 2010). In bundle harvesting, however, bunches of whole trees accumulated in the harvester head are transferred in the upright position. It is possible that existing damage to the upper parts of the remaining trees was not recorded in these inventories. Although directing the bunches into the feeding system of the bundling unit can further increase the risk of damage to remaining trees, it is probable that bundle forwarding causes less damage to remaining trees than forwarding of loose whole trees and conventional pulpwood. The bundles are concentrated along one side of the strip road, and an increase in grapple load volume reduces crane movements when loading the forwarder. A decline in grapple load length further decreases the risk of damage to the remaining stand.

In general, damage to remaining trees is most often caused by transportation of wood (Rieppo 2001, Vasiliauskas 2001). Raper and Kirby (2006) found reducing vehicle mass was a primary method of reducing deep subsoil compaction, but payload reduction implies a decrease in productivity and an increase in harvesting costs (Saarilahti 2002). An increase in removal and decrease in bulk density of the loads leads to the harvesting of undelimited assortments increasing site traffic compared to conventional cut-to-length harvesting. By compacting whole trees into bundles, roughly double payloads can be achieved, depending on bundle volume. The payload with large and fresh whole-tree bundles can exceed even that of conventional pulpwood (Kärhä et al. 2009b, Laitila et al. 2009). Bundle harvesting implies a reduction in the number of passes and an increase in load mass over forwarding of loose whole trees or undelimited tree sections. In turn, the increment in vehicle weight increases ground pressure and thus the risk of soil damage (Nugent et al. 2003, Raper and Kirby 2006). Most soil compaction is usually assumed to occur after the first few passes (Silversides and

Sundberg 1989, Grigal 2000, Eliasson 2005, Han et al. 2006, Raper and Kirby 2006, Han et al. 2009), and major compaction is caused by the harvester (Nugent et al. 2003, Eliasson and Wästerlund 2007). The risk of soil damage caused by a bundle harvester is probably higher than with a conventional harvester because of its high service weight. The mass of the second bundle harvester prototype was as much as ca. 30 tons (Kärhä et al. 2009b), while the weight of standard harvesters ranges from 8 to 24 tons (Uusitalo 2010). On the other hand, decreased site traffic could partly compensate for the soil damage caused by the increased ground pressure. On soils with poor bearing capacity (such as peatlands), the risk of damage to soil and remaining trees can be reduced by operating when the soil is frozen (Silversides and Sundberg 1989, Sirén 1998, Egnell et al. 2001). The bundles produced by the bundle harvester used in the present study are large objects with an approximate length of 2.7 m and a diameter of 0.6–0.7 m (Kärhä et al. 2009b). Terrain transportation of bundles produced when the soil is unfrozen could be postponed until soil freezing, because the bundles remain visible when the ground is covered by snow.

It is recommended to keep strip road spacing above 20 m and its width below 4.5 m (Äijälä 2010). Positioning the bundling unit mounted on the rear-end of the bundle harvester can increase the need to clear wider strip roads. However, this was not apparent in the post-harvesting inventory reported by Lazdiņš (2008), in which strip road width averaged 4 m. Since the boom stretch of the bundle harvester does not differ from that of conventional machinery, differences in strip road spacing between whole-tree bundling and harvesting of loose whole trees are not likely. In the inventory published by Lazdiņš (2008), a strip road spacing of 20–25 m was recorded. However, applying multi-tree cutting at the extreme extension of the boom, especially with large trees, may increase the risk of reduced road spacing. Thinning intensity is also an indicator of the production potential of the stand, but it is not directly affected by the harvesting method.

3.4.2 Energy expenditure and CO₂ emissions

The direct CO₂ emissions of cutting (and compaction), forwarding, and truck transportation of one m³ of wood harvested from the stands of **IV** varied from 12.7 kg m⁻³ to 27.2 kg m⁻³ (Fig. 22). This corresponds to 3.4–7.3 kg carbon per cubic metre of wood harvested and transported to the pulp mill (see Jungmeier et al. 2003). Compaction of whole trees into bundles reduced CO₂ emissions from transportation by 30–39%. This reduction was insufficient to compensate for the increased emissions from cutting and compaction resulting from the low productivity and high fuel consumption of the bundle harvester. The total energy consumption per m³ of biomass harvested from the stands was 47–101 kWh m⁻³. In a moisture content of 50%, for example, 3–6% of the heating value of the biomass would be consumed in wood procurement.

The CO₂ emissions and energy expenditure were dependent on stand properties through the productivity of the supply system sub-operations. The lowest energy consumption and CO₂ emission per m³ of wood was obtained in Stand 3, regardless of the supply system. Low load volumes made truck transportation the main energy consumer and the source of emissions per m³ in the procurement of loose whole trees. The carrying capacity of the trucks was fully utilized only with conventional pulpwood and whole-tree bundles harvested from Stand 3 containing the largest trees. Current legislation limits the expanding load spaces of the trucks. Consequently, energy expenditure and emissions from wood procurement could be controlled by increasing the efficiency of off-road operations by careful selection of stand and harvesting method. Energy expenditure and emissions from truck transportation could

be reduced by avoiding driving unloaded (Forsberg 2000). In appropriate circumstances, the environmental load caused by long-distance transportation could also be reduced by applying transport modes with lower energy consumption per cargo unit, such as rail and ship transport (Karjalainen and Asikainen 1996, Berg and Karjalainen 2003, Spielmann and Scholz 2005).

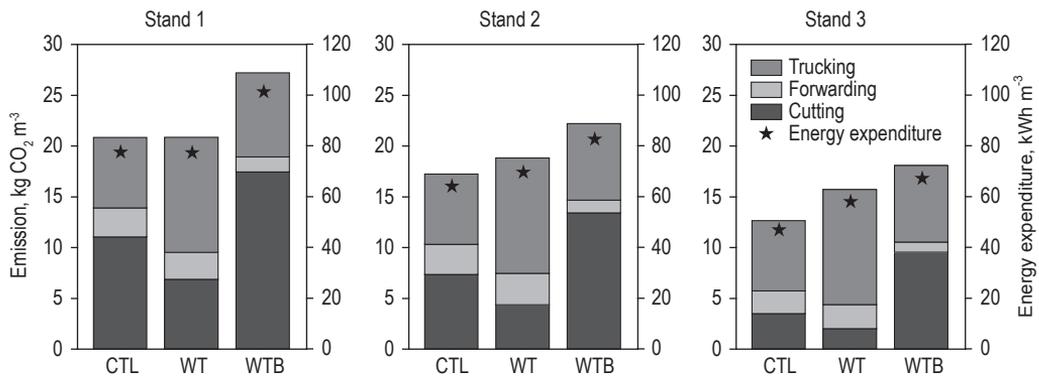


Fig. 22. CO₂ emissions and energy expenditure resulting from cutting, forwarding and truck transportation of wood harvested from the stands in IV.

4 CONCLUSIONS

The present study, composed of several case studies evaluates the feasibility of harvesting undelimited assortments of Scots pine for integrated pulp and energy production in a kraft pulp mill. It was shown that any increase in recovery by harvesting of undelimited assortments is heavily dependent on stand properties (diameter distribution, crown length), cutting methods and the dimension requirements set for recoverable trees. There are no significant technical barriers to using undelimited Scots pine tree sections, either loose or bundled, in kraft pulp mills. It is possible to debark undelimited tree sections to the required cleanliness as a blend with conventional first-thinning pulpwood in favourable conditions. Whole-tree material can also probably be used within the limits set by the debarking and hog fuel combustion capacities of the mill. It is possible that the debarking degree of whole trees remains lower than in the case of topped tree sections. In addition, the quantity of branches and small-diameter stem sections ending up in the chipper is likely to increase, which can increase the amount of oversized and fine chip fractions. The chips can be upgraded by re-chipping or crushing of oversized fractions and separation of the fines. Adding 8–16% bundled tree sections in the flow composed of conventional small-diameter pulpwood did not impair pulp quality.

Using undelimited material increases wood losses in wood handling. Branch particles and juvenile wood from the top sections ending up in pulp chips reduce yield in cooking. These losses are utilized in energy generation, either in the form of solid residues from debarking and chipping or as black liquor. An increase in energy price and decline in pulp price improves the competitiveness of undelimited assortments as the raw material of a pulp mill. With the current relation between pulp and energy prices, however, the gains from energy generation do not offset the losses in pulp production. High moisture content reduces the heating value of debarking residue, impairing thereby the paying capability from the solid energy fraction. Aiming at a material balance with a high pulp yield is of great importance since the wood paying capability of the pulp mill decreases with the increase in energy fractions of the raw material. Harvesting small-sized whole trees below pulpwood dimensions is not economically viable as a result of the unfavourable material balance of wood processing and high harvesting costs. Direct combustion of wood harvested from first-thinning stands with the smallest trees is thus probably a more rational end-use than pulp production. However, the stumpage price of undelimited wood per volumetric unit is expected to be lower than that of conventional pulpwood, and its use may already be more profitable than the conventional pulpwood, especially when procured from small-diameter stands located in close proximity to pulp mills.

Especially in small-diameter stands, harvesting costs can be significantly reduced by applying whole-tree harvesting. Harvesting undelimited assortments increases nutrient export from the site, and whole-tree harvesting also increases the risk of damage to the remaining trees. The effects of whole-tree harvesting on site productivity are relatively well known. From the nutrient export point of view, this method is not recommended on most peatlands and infertile mineral soils, although recovery of crown mass is incomplete. Applying whole-tree harvesting increases site traffic due to increased recovery, which increases soil compaction and rutting. On peatlands and mineral soils with poor bearing capability, whole-tree bundling increases the risk of soil damage, because of the great weight of the bundle harvester and the increased forwarder payloads. Environmental effects of energy wood harvesting on sensitive soils can be minimised by delimiting the stems or leaving the top sections on the site.

Even if compacting undelimited trees into bundles offers many logistic advantages, it is an additional link which results in increased production costs, energy expenditure and emissions

from wood procurement. The behaviour of bundled material in wood handling probably does not differ greatly from that of loose material. Increase in transportation distances improves the competitiveness of the bundling system. In the Nordic conditions, the bundling system can also be justified when large buffer storages of biomass are needed to supply potential biorefineries. In the present circumstances, significant reduction in the hourly cost and/or increase in productivity are required for the breakthrough to the bundling system. In the stands of the present study, increments of ca. 40–60% in the performance level of the second bundle harvester prototype would result in a break-even with the supply chain based on the harvesting of loose whole trees.

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APPENDIX 1

Batch no.	Study	Raw material						Wood handling facilities					
		First-thinning pine			Other pulpwood (delimbed)			Bark slot dimensions	Drum dimensions (diameter/length)	Short-end chipper			
		Delimbed		Undelimbed	Proportion	Cutting method ²	Mean log dimensions (top diameter/length)				Proportion	Cutting method	Mean log dimensions (top diameter/length)
		Proportion	Cutting method ¹	Mean log dimensions (top diameter/length)	Proportion	Cutting method ²	Mean log dimensions (top diameter/length)	Proportion	Cutting method	Mean log dimensions (top diameter/length)	Bark slot dimensions	Drum dimensions (diameter/length)	Short-end chipper
1	II	100%	CTL	8.6 cm/4.0 m ³	0%	-	-	0%	-	-	42 mm x 600 mm	6.0 m/35 m	no
2	II	92%	CTL	8.9 cm/4.1 m ³	8%	TS+bundling	5.7 cm/≤ 3 m	0%	-	-	42 mm x 600 mm	6.0 m/35 m	no
3	II	84%	CTL	9.2 cm/4.0 m ³	16%	TS+bundling	5.7 cm/≤ 3 m	0%	-	-	42 mm x 600 mm	6.0 m/35 m	no
4	Sikanen and Vesisenaho (1995)	100%	CTL+MTH	9.0 cm/4.2 m ⁴	0%	-	-	0%	-	-	width 40-50 mm	5.5 m/38 m	yes
5	Sikanen and Vesisenaho (1995)	10%	CTL+STH	9.0 cm/4.2 m ⁴	0%	-	-	90%	CTL	10.8 cm/3.9 m	width 40-50 mm	5.5 m/38 m	yes
6	Sikanen and Vesisenaho (1995)	0%	-	9.0 cm/4.2 m ⁴	10%	TS	9.0 cm/4.2 m ⁴	90%	CTL	10.8 cm/3.9 m	width 40-50 mm	5.5 m/38 m	yes
7	Sikanen and Vesisenaho (1995)	100%	CTL+STH	9.0 cm/4.2 m ⁴	0%	-	-	0%	-	-	width 40-50 mm	5.5 m/38 m	yes
8	Hakkila et al. (1995)	100%	CTL+STH	9.0 cm/4.0 m	0%	-	-	0%	-	-	width 40-50 mm	5.5 m/38 m	yes
9	Hakkila et al. (1995)	100%	CTL+STH	9.0 cm/4.0 m	0%	-	-	0%	-	-	width 40-50 mm	5.5 m/38 m	yes
10	Hakkila et al. (1995)	100%	CTL+MTH	7.2 cm/4.0 m	0%	-	-	0%	-	-	width 40-50 mm	5.5 m/38 m	yes
11	Hakkila et al. (1995)	100%	CTL+STH	11.8 cm/4.0 m	0%	-	-	0%	-	-	width 40-50 mm	5.5 m/38 m	yes
12	Hakkila et al. (1995)	100%	CTL+STH	6.3 cm/4.0 m	0%	-	-	0%	-	-	width 40-50 mm	5.5 m/38 m	yes
13	Hakkila et al. (1995)	-	CTL ⁵	10.0 cm/4.4 m ⁶	-	TS ⁵	-	0%	-	-	width 45 mm	5.5 m/26 m	no

¹⁾ CTL = cut-to-length method, MTH = multi-tree handling, STH = single-tree handling. ²⁾ TS = tree-section method. ³⁾ Reported by Jylhä & Keskinen (2003). ⁴⁾ Reported by Hakkila et al. (1995). ⁵⁾ CTL for trees larger than 12.5 cm in DBH, TS for smaller trees. The proportions of undelimbed and delimbed wood were not defined. The total branch proportion in the batch was 7%. This raw material batch unintentionally contained 6% Norway spruce.

⁶⁾ Common average dimensions for the whole batch.

CORRECTIONS TO ORIGINAL PAPERS

- IV: Table 4 on page 701 The proportion of stem bark in Stand 3, Options II and III: 11.2% → 10.2%.
- IV: Figure 3 on page 704 Partial graph on WPC per m³ in Stand 2 was a replica of WPC per m³ in Stand 3. Correct figure below.

