

# Techniques and Systems for Boom- Corridor Thinning in Young Dense Forests

Dan Bergström

*Faculty of Forest Sciences*

*Department of Forest Resource Management*

*Umeå*

Doctoral Thesis

Swedish University of Agricultural Sciences

Umeå 2009

Acta Universitatis Agriculturae Sueciae

2009:87

ISSN 1652-6880

ISBN 978-91-576-7434-0

© 2009 Dan Bergström, Umeå

Print: Arkitektkopia, Umeå 2009

# Techniques and Systems for Boom-Corridor Thinning in Young Dense Forests

## Abstract

Young dense stands could be thinned and the cut trees could be sold for bioenergy purposes, thus generating an income at an early stage of rotations. However, to make the utilization of young stands competitive, the costs of harvesting must be reduced while the value of the remaining stands is maintained at high levels. A possibility could be to develop a strip road and boom-corridor system for thinning young stands with high biomass, as an alternative to conventional pre-commercial thinning. The objectives of the studies underlying this thesis were to evaluate the effects of using new methods and techniques intended to promote efficient felling, bunching and compression of trees in boom-corridor thinning systems. As shown by simulations, combining boom-corridor thinning methods with conventional accumulating felling heads (AFHs), improved AFHs for multiple felling (AFH-2m<sup>2</sup>) and new techniques for continuous felling boom-corridor-wise (AFH-corr) would provide higher productivity in the order AFH-corr > AFH-2m<sup>2</sup> > AFH (the AFH-corr system gave about two-fold higher productivity compared to the AFH system) (I). In field studies, boom-corridor thinning using a conventional AFH gave a significant, 16%, increase in productivity compared to a standard thinning from below treatment (II). The potential utility of a prototype felling head designed for continuous felling in boom-corridors in the field was also studied (III). The results show that felling speeds of about 1.3 m×s<sup>-1</sup> can be achieved if cranes that allow higher movement speeds are used. Further, the performance of a prototype compression processing device was investigated in field studies, and the results show that the density of fresh Scots pine bunches could be increased by up to 160%, while reducing their ash contents (and hence nutrient losses) by 50% (IV). It was also found that load compression techniques can raise payloads (IV). In conclusion, if new techniques especially designed for boom-corridor thinning are developed and used in appropriate harvesting systems the productivity, cost-efficiency and profitability of the operation can be greatly increased.

*Keywords:* geometric thinning, pre-commercial thinning, thinning systems, bioenergy, fuel wood, small diameter trees.

*Author's address:* Dan Bergström, Department of Forest Resource Management, SLU Skogsmarksgränd, SE-901 83 Umeå, Sweden.

*E-mail:* Dan.Bergstrom@srh.slu.se



# Contents

List of Publications	6
1 Introduction	7
1.1 Objectives	13
2 Materials & Methods	15
2.1 Paper I	15
2.2 Paper II	16
2.3 Paper III	17
2.4 Paper IV	21
3 Results	25
3.1 Paper I	25
3.2 Paper II	26
3.3 Paper III	27
3.4 Paper IV	28
4 Discussion	30
4.1 Starting point	30
4.2 Effects of work method on efficiency	31
4.3 Effects of techniques on efficiency	31
4.4 Some aspects of cutting techniques	32
4.5 Compression and required techniques	33
4.6 Financial aspects	35
4.6.1 Productivity, costs and their dependence on tree sizes	35
4.6.2 Harvesting energy wood or pulpwood versus PCT	38
4.7 The future stand	40
4.8 Systems for boom-corridor thinning	41
5 Conclusions	43
6 Future research	45
References	49
Acknowledgements	53

## List of Publications

This thesis is based on the work contained in the following papers, which are referred to by the corresponding Roman numerals in the text:

- I Bergström, D., Bergsten, U., Nordfjell, T. & Lundmark, T. (2007). Simulation of geometric thinning systems and their time requirements for young forests. *Silva Fennica* 41(1): 137-147.
- II Bergström, D., Bergsten, U. & Nordfjell, T. Boom-corridor thinning productivity in young dense Scots pine stands. Manuscript.
- III Bergström, D., Bergsten, U. & Nordfjell, T. Continuous felling of small diameter trees in boom-corridors. Manuscript.
- IV Bergström, D., Nordfjell, T. & Bergsten, U. Compression processing and load compression of young Scots pine and birch trees in thinnings for bioenergy. *International Journal of Forest Engineering*. Accepted.

Paper I is reproduced with the permission of the publisher.

# 1 Introduction

The value of wood is currently based essentially on the suitability of trees for manufacturing sawn wood or pulp and paper. Managing stands for these purposes has been profitable for a long time, and there has been little incentive for investigating other possible commercial uses of the wood. However, in a few decades when oil supplies decline, there will be major changes in society's energy sources, and considerable increases in the supply of biomass are likely to be required (NREL 2002). Fortunately, in many boreal countries woody biomass (including the biomass in young stands) has great potential to meet growing demands for bioenergy. To meet these demands it is important to increase biomass growth in the forest (Anon. 2003). Over an entire rotation period, biomass production in young forest stands can be increased considerably by maintaining a high stem density (Pettersson 1992), and to maximise biomass production the stand must have a high leaf area index and a good supply of plant nutrients (Linder 1987, Berg et al. 2005). However, it is generally recommended that pre-commercial thinning (PCT) operations should be performed in young stands when the main stems are about 3 m tall, and the residual stand should be widely spaced, often with 2 000 – 3 000 trees $\times$ ha<sup>-1</sup>, to promote large diameter growth and to create stable forest stands (Claesson et al. 1999, Varmola & Salminen 2004). The cost of PCT increases with increasing stem density and stand height (Ligné et al. 2005a), and the operation is normally performed motor-manually.

During the last 20 years the annual forest areas subjected to PCT has decreased (Anon. 2004) and a major reason for the decrease is the high costs of the PCT. Attempts to reduce the costs of PCT operations by mechanization have been made either by using small machines driven inside stands equipped with boom-tip devices for felling trees (Heikkilä et al. 2005, Ligné 2005b), or using machines that fell trees as they are driven, thus creating open strips (Bergkvist & Glöde 2004). However, in

Fennoscandia motor manual PCT is still cheaper, due to the high operational costs of mechanized operations (Heikkilä et al. 2005, Ligné 2005b). Of the total land area in Sweden (about 41.3 million ha), 55.4% is forested, including 12% supporting young, dense stands with trees less than 12 m tall and biomass contents exceeding 30 oven-dry tonnes per hectare ( $\text{ODt} \times \text{ha}^{-1}$ ) (Anon. 2007, Nordfjell et al. 2008). Instead of being subjected to a PCT these stands could be harvested for bioenergy purposes, which could generate an income for the forest owners at an early stage (or at least cover a major proportion of the PCT costs). However, intensive recovery of biomass can result in losses of nutrients from the forests, therefore it is important to consider carefully the suitability of potential harvesting sites and to develop appropriate systems to ensure that any management practices applied are sustainable (Jacobson et al. 1999, Hakkila 2005). For instance, it may be necessary to balance the increased risks of reductions in growth rates of thinned stands by appropriate fertilization (Jacobson et al. 1999, Eriksson 2006). The annual harvest of whole trees (full tree; i.e. all the material above the felling cut) from young stands in Sweden today is minor in comparison to the potential harvest (Nordfjell et al. 2008), but to make the utilization of bioenergy from young stands competitive, the costs of harvesting must be reduced and the biomass yield per ha must be high (Hakkila 2005).

In general, in mechanized first thinning (FT) operations of young stands, trees are felled, bunched along strip roads and hauled to the roadside using conventional harvesters and forwarders. The trees between strip roads are thinned from below. The width of the strip roads that are constructed and the distances between them depend on the size of the machines used and reach of the cranes, but generally the width and distance between strip roads are about 3 - 4 m and 20 m, respectively. In the felling and bunching operation accumulating felling heads (AFHs) designed for handling several trees in each crane cycle are used to compensate for handling small trees. For example, to harvest one ODT about 25, 50 or 100 trees with diameters at breast height over-bark (dbh) of 10, 8 and 6 cm, respectively, are required (Fig. 1).



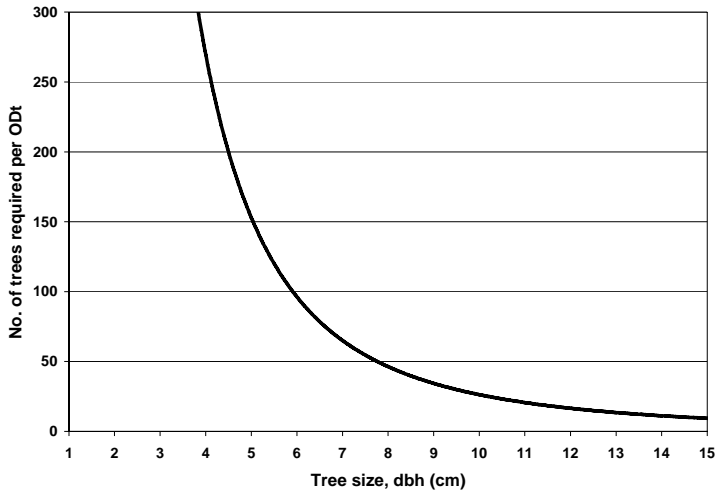


Figure 1. The number of young Scots pine (*Pinus sylvestris* L.) trees of different sizes required for one ODt (whole trees including branches and needles). Based on data from Study II.

The productivity of the felling and bunching operation in young stands has been correlated to factors such as the average size of harvested trees, stand density, density and the volume of removal, (Kärhä et al. 2005), frequency of multiple felling (Johansson & Gullberg 2002) and frequency of accumulation (Liss 1999). The productivity of these operations ranges from about 1 to 7.5 solid cubic metres of biomass ( $\text{m}^3\text{biomass}$ ) ( $\sim 0.5 - 3.7$  ODt) per hour of productive work time (PW-hour; Anon. 1995) across various types of young forests, systems and machinery (Gullberg et al. 1998, Liss 1999, Kärhä et al. 2005). In thinning from below using AFHs trees are normally selected and felled one by one, hence many time-consuming non-linear crane movements around future crop trees are required. For high felling and bunching productivity in dense stands with relatively small trees the AFH used must have a multiple felling ability (Johansson & Gullberg 2002) (see Fig. 1). However, with currently available AFHs multiple felling is limited by the spacing between trees, and it is only practical in cases where trees are closely grouped. No specialized AFHs for multiple felling of small diameter trees more widely spaced than a few dm apart have been developed and commercialized as yet.

A possibility for the future could be to develop a strip road and corridor system for thinning, bunching and bundling, instead of PCT, in young stands with high biomass. The narrow corridors between the strip-roads

could be created using conventional AFHs or more area-based AFHs specially designed for corridor thinning, mounted at the boom-tip of a machine with a long crane reach. Such thinning systems are here named boom-corridor thinning systems, focusing on the work method, i.e., the intention is not to create corridors in the remaining stand but to take out trees corridor-wise. Up to a certain tree size, harvesting techniques based on area instead of single-tree positioning would probably be more efficient. If techniques and appropriate equipment are developed to fell, cut-to-length, and bunch within almost the same time, regardless of the number of trees in the handled area, the cost reductions should be large. Various geometric boom-corridor patterns could be used, e.g., a strictly perpendicular pattern or a fan-shaped pattern (Fig. 2).

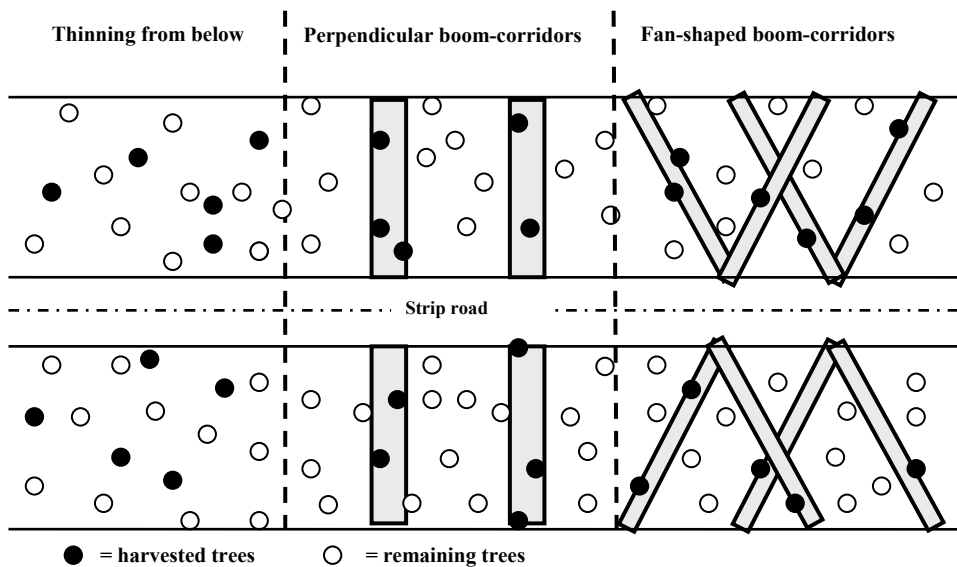


Figure 2. Sketch of possible thinning methods: thinning from below and two boom-corridor thinning patterns between strip roads.

A boom-corridor system for thinning young dense stands using conventional machinery could be designed in which (for instance) trees between strip roads are harvested in narrow boom-corridors, perhaps perpendicular to the strip-road and about 1 m wide, with a length corresponding to the crane reach ( $\sim 10$  m) (Fig. 2). In such systems the time required for re-positioning the AFH in each crane cycle should be reduced since trees hindering its movement would be removed as the boom-corridor is harvested. Liss (1999) found that use of a feller-buncher in early

thinnings, in which trees were felled and accumulated solely by linear crane movements, provided no increase in productivity compared to conventional thinning from below. However, the method examined in the cited study involved a combination of geometric thinning and thinning from below, and trees were not exclusively harvested in boom-corridors. Previous studies on geometric thinning have mainly considered strict line/row-thinning systems. In some systems the base machine is driven in the corridors that it produces (Rummer 1993), in other systems cut trees are pulled to the corridor using cables (Bennecke 1985), or rows of trees parallel to the strip-road (at a distance of, for instance, three rows from the strip-road) are harvested (Suadicani & Nordfjell 2003).

Since stacks of small trees are bulky (with solid masses accounting for ~ 25 – 35% of their total volumes), only about 30 – 60% of forwarders' load capacities are normally used when they are handled (Nordén 1991). Hence, the productivity of off-road transport is generally low, especially over long hauling distances. An obvious way to increase forwarder payloads is to enlarge the load-space by widening and/or elongating it (Brunberg 1999). This may be advantageous for purposes such as forwarding loose logging residues in clear cuttings. However, it is not suitable for thinning since strip roads are kept narrow and the remaining trees are likely to be damaged if large/wide loads are transported along them. Alternatively, as demonstrated by Nordén (1984), load densities could be increased by 35 – 60% by compressing (load compression) small diameter trees harvested in early thinnings. Similar approaches have also been tested in Finland (Kallio & Leinonen 2005).

Factors that must be considered, since they may strongly affect the sustainability of any proposed thinning regime, is that foliage is nutrient-rich (Ringman 1996) and the crown OD mass to stem mass ratio of trees decreases as they age (Hakkila 1991). In addition, properties of the raw material used as fuel wood – such as its moisture and ash contents, chemical composition, bulk density, presence of microbes and heating values – are all important factors to take into account (Nurmi & Hillebrand 2007) and it is desirable to have low contents of ash (nutrients) and inorganic materials (contamination) during its combustion (Nordin & Levén 1997). Thus, in harvesting operations it would often be desirable to compress trees and to leave as much foliage as possible evenly distributed in the stand, before transporting the rest of the harvested material to roadside, in order to reduce losses of nutrients from the stands, improve the efficiency of off-road transport and enhance the harvested materials' fuel properties. Developmental efforts to meet the latter objective should focus

on the upper parts of the trees' crowns since most nutrients are concentrated in these parts.

For the extraction of the felled and bunched trees a mobile chipper equipped with a container for the chips can be used (Brunberg et al. 1998, Asplund et al. 1999, Talbot & Suadicani 2005). However, such chipping systems cause many logistic problems, and high costs occur when a machine in this chain is standing idle. With this system only small, low-productivity chippers can be used in the field. Chips are also perishable, and storage results in substance losses and fungal decomposition (Thörnqvist & Jirjis 1990). Therefore, in Sweden and Finland chipping mainly takes place at the roadside or at industrial sites (Asplund et al. 1999). A further important factor is the pulpwood to fuel wood price ratio, which obviously affects the relative profitability of chipping (Liss 2004). Hence, for instance, mobile chipping systems have also been used sometimes when relatively large-dimension trees have been thinned and the price ratio between fuel-chips and pulpwood has exceeded a certain threshold (Suadicani & Nordfjell 2003).

However, bundling whole trees or parts of trees at high density before leaving the stand facilitates handling and offers logistical advantages compared to the use of separate systems for round wood and fuel wood, i.e., transporting round wood in conventional trucks, but loose tree parts and chips in specially designed trucks (Richardson et al. 2002, Johansson et al. 2006). Using both conventional and prototype off-road bundling machines it has been shown that bundles of small Scots pine, Norway spruce (*Picea abies* (L.) Karst.) and birch (*Betula pubescens* Ehrh.) trees (dbh ranging from 1.7 to 10.4 cm) with densities of 236 - 537 kg×m<sup>-3</sup> green weight (GW) can be obtained (Jylhä 2004, Pettersson & Nordfjell 2007). The bundling process may also significantly reduce the amount of foliage attached to the handled material, especially if the raw material has been stored before bundling since dried needles are less firmly attached to branches than fresh needles (Jirjis & Norden 2005, Röser et al. 2008). However, off-road bundling machines are expensive and generally have low productivity (Richardson et al. 2002). Systems involving the use of a single machine to both fell and bundle trees simultaneously (i.e., a bundle harvester) and a forwarder to transport bundles to roadside might be preferable to systems requiring the use of more machines, but use of a prototype bundle harvester for first thinnings proved to have low productivity in a field study published by Jylhä and Latila (2007). In order to improve the productivity of bundling several factors should be considered, including the following. Substantially higher forces are required to produce high density bundles than to produce medium density

bundles, for instance Nordfjell and Liss (2000) found that forces of 16 kN and 53 kN were needed to compress fresh, small (dbh, 7.5 cm; height, 8.0 m) Scots pine, Norway spruce and birch trees into bundles with bulk densities of  $270 - 460 \text{ kg}\times\text{m}^{-3}$  and  $520 - 780 \text{ kg}\times\text{m}^{-3}$ , respectively. On the other hand, compressed bundles almost dry as well as non-compressed bundles and require less time to chip (Nordfjell & Liss 2000). In addition, according to Danielsson et al. (1977), less force is required to compress fresh, small Scots pine and Norway spruce trees than materials that have been stored over a season, and storage of whole trees either in-stand or at roadside, especially over the summer period, significantly reduces their moisture contents (Nurmi & Hillebrand 2007). To optimize the delimiting of small trees Dahlin (1989) found that cradle-type systems for multi-stem delimiting provide the greatest flexibility, and can be used in cases where portable (off-road), lightweight and compact bunch delimiting systems are required.

In conclusion, in spite of the development efforts that have already been made there is an obvious need to develop systems that can be applied to utilize the potential biomass in dense, young stands.

## 1.1 Objectives

The overall objectives of the studies this thesis is based upon were to evaluate (theoretically and in the field) the effects of using new methods and techniques intended to promote efficient felling, bunching and compression of small diameter trees in boom-corridor thinning systems. The work provides indications for possible further developments to improve efficiency of the wood supply chain from young dense forests to commercial products. The specific objectives in the studies described in Papers I-IV (which are sometimes referred to in the text as Studies I-IV, for convenience) were as follows:

The objective in Study I was to quantify, in simulations, the potential effects on harvesting time requirements of operations using more area-based machines and techniques in boom-corridor thinning than those currently used in thinning from below.

The objective in Study II was to assess the effects of harvesting trees between strip roads in narrow boom-corridors in young dense stands on productivity relative to a thinning from below treatment, using conventional harvesting equipment.

The objective in Study III was to evaluate the possible felling speed of a prototype boom-tip mounted felling head designed for continuous felling of small diameter trees in boom-corridors.

Two series of experiments were performed in Study IV. The objective of the first series was to evaluate the utility of experimental technical devices for compressing and semi-debranching (compression-processing) bunched, young harvested Scots pine trees (with 2-5 trees per bunch), while the objectives of the second series were to explore the potential advantages, disadvantages and parameters of compressing forwarder loads of young Scots pine and birch trees.

## 2 Materials & Methods

### 2.1 Paper I

Data on two stands, a young first thinning (FT) stand and a delayed PCT stand (DPCT) described by Bredberg (1972) and Gustavsson (1974), respectively, were used in simulations to compare harvesting operations with two different boom-corridor patterns (perpendicular and fan-shaped, see Fig. 2) and three boom-corridor harvesting approaches. These approaches were designated *AFH-5tr*, *AFH-2m<sup>2</sup>* and *AFH-corr*, which respectively simulated a felling head cutting and accumulating trees one-by-one, a felling head cutting and accumulating trees within areas of two square metres (1 m wide and 2 m long) per movement and a felling head cutting and accumulating all trees boom-corridor-wise. The specifications of the *AFH-5tr* felling head were equivalent to those of small AFHs currently available from commercial suppliers. As a reference harvesting approach for the FT stand a conventional thinning from below treatment using the *AFH-5tr* head was simulated, designated *AFH-5tr selective*. Data presented in time-studies of conventional AFHs were used (Gullberg et al. 1998, Kärhä et al. 2005), together with results from a simulation of single-grip harvesters (Eliasson 1999), to set values for the *AFH-5tr* and *AFH-5tr selective* approaches. To set values for the hypothetical *AFH-2m<sup>2</sup>* and *AFH-corr* approaches, for which no empirical data are available, their properties relative to those of *AFH-5tr* were considered.

The time required for boom movement and processing consists of up to eight different elements for each of the harvesting approaches. Available stand data enabled harvests to be simulated in 27 and 30 perpendicular and fan-shaped boom-corridors, respectively, in the FT stand, and 16 and 20 perpendicular and fan-shaped corridors, respectively, in the DPCT stand. Data from initial simulations were then used to calculate and simulate

harvests giving adequate harvesting intensities of 35% of the total stand area, including the strip-road. The total number of perpendicular and fan-shaped boom-corridors was 18 in the FT stand and 12 in the DPCT stand in this case.

Simulations were manually performed. The distances required for the simulations were obtained by measuring them on a map showing the Cartesian coordinates of the trees in each stand, after drawing the strip road and boom-corridor structures on it. To simplify the manual work involved in the simulations all trees were considered to have the same size (and hence average volume) in their respective stands. Trees harvested in each simulation were then identified, and the time requirements were calculated manually. Data regarding time consumption per corridor were tested for homogeneity of variances (Levene's statistic), and an analysis of variance was performed. When significant treatment effects were found, Dunnett's T3 test was used, due to non-homogeneity of variances, to test for significant differences ( $p \leq 0.05$ ) between treatments. Time consumption data were used to calculate productivity at the stand level. For each complete simulation (including harvesting of strip-roads) the proportions of time spent on different work elements were calculated. The resulting intensity and harvested volume per machine position for harvesting with the target intensity of 35% were also calculated, as averages, at the stand level.

## 2.2 Paper II

A comparative time study of the felling and bunching work in thinning from below and boom-corridor thinning was performed, in which a 16.5 t harvester equipped with a Bracke C16.a (Bracke Forest AB, Sweden) AFH was used and manoeuvred by an experienced operator. The experiment had a randomized block design with eight blocks, each including two treatments: thinning from below (control) and boom-corridor thinning. The study was carried out during June 2007 in stands in the municipality of Nordmaling in the northern part of Sweden (N 63° 34', E 19° 33', 40 m a.s.l.), where the forest was about 30 years old and dominated by Scots pine. It had been naturally regenerated and had not been subjected to PCT. The stand density ranged from 4400 to 18600 (mean 8300) trees $\times$ ha $^{-1}$ , with respective tree sizes (dbh) on average of 7.2 and 3.2 cm (mean 5.1 cm) in the study blocks. On average the whole tree biomass was 65 ODt $\times$ ha $^{-1}$ . The terrain conditions were good, with high ground strength, smooth surface



structure and gentle slopes. Experiments were performed in daylight at a temperature of about 15 °C at times when there was little or no rain.

During harvest trees with < 4 cm dbh (“undergrowth”) were not cut, whenever possible. After harvest the target density for the remaining stands was approximately 1500 trees×ha<sup>-1</sup> with ≥ 4 cm dbh. In the control treatment cut trees were bunched wherever an opening at the strip roadside was found, with their butt ends pointing towards the strip road. In the boom-corridor thinning treatment trees were thinned in narrow (~ 1 m wide) corridors and as close to perpendicular to the strip road as possible. Trees were then bunched in the boom-corridors with their butt ends pointing towards the strip road. The location, length and width of boom-corridors were planned and decided by the operator during harvesting. The only difference between the thinning methods was in the harvesting of trees between the strip roads.

The time consumed by the felling and bunching work was recorded continuously and the work was divided into eight work elements: *Move*, *Crane out*, *Positioning and felling*, *Crane in-between*, *Crane in*, *Bunching*, *Miscellaneous* and *Delays*. After harvest, the felled and bunched trees and damage to remaining trees in each study plot were measured. The effects of the treatments were assessed by analysis of variance and differences were considered significant if  $p \leq 0.05$ .

### 2.3 Paper III

Two experiments were performed. In the first experiment the time required for perpendicular boom-corridor felling in stands with different conditions was measured. In the second experiment the maximum felling speeds when cutting trees of different sizes were compared. The experiments were carried out in the municipality of Vindeln (N 64° 10', E 19° 37', 150 m a.s.l.), in the northern part of Sweden. The study area was dominated by Scots pine stands, 18-year-old with on average 10800 trees×ha<sup>-1</sup> and an average height and dbh of 5.6 m and 5.6 cm, respectively. The ground was flat and had no visible boulders. The experiments were performed during one week in November 2007 under daylight conditions at a temperature of about -5 °C and the ground was covered with a thin layer of snow.

The machine used was a conventional medium-sized harvester (~ 12 t) and the crane used was a modified Cranab (Cranab AB, Sweden) with a total reach of 9.34 m, of which the telescope boom accounted for 3.28 m.

The felling head used was a prototype designed for continuous felling of small diameter trees (Fig. 3), with a construction based on the SuperCut 300 (Hultdin System AB, Sweden) cutting unit. For practical reasons (limitations of the hydraulic steering system) only the crane's telescopic parts were moved in the experiment.



Figure 3. The base machine and prototype felling head used in the experiments.

The theoretical felling speed of the felling head – defined as the chain's maximum ability to cut through wood, derived from the measured number of cutters on the chain (33), the gauge depth (1.8 mm) and the chain speed ( $29.5 \text{ m}\times\text{s}^{-1}$ ) – was  $0.71 \text{ m}\times\text{s}^{-1}$ .

For the boom-corridor felling experiment 15 rectangular plots were marked out perpendicular to a pre-harvested strip road. The width and length of the plots were 1.5 and 8.0 m, respectively, sized to fit the harvester's crane reach and the possible felling capacity (length of the chain saw blade, 0.95 m). The machine was positioned on the strip road with a plot located perpendicular to the machine in the line of the crane pillar. Then the felling head was moved out with the chainsaw blade pointing in a forward direction until the telescopic boom extended to its maximum reach. The felling head was then positioned about 8 m from the strip road, approximately 20 cm above ground and about 5 cm from the first tree to be cut (Fig. 4a). The felling unit was then activated by starting the felling head chain to rotate at full speed and moving the saw blade horizontally through  $90^\circ$  so it was perpendicular to the boom (Fig. 4b), after which at a given signal the boom was moved inwards at full speed. The time was measured until the boom had moved to its full extension without the telescopic feature (max. distance of 3.28 m) or stopped for other reasons (Fig. 4c). The moved distance was also measured and the

felled trees were registered. Subsequently, in the same plot and close to the first stop, a new start position was marked. Then the machine was repositioned to allow the telescopic boom to be retracted via the same movement and distance as in the first run (Fig. 4c). The procedure was repeated as described above (Fig. 4d). In total, 30 runs were performed. Differences between runs 1 and 2 in any given plot were considered significant if p-values  $\leq 0.05$  according to Student's t-test.

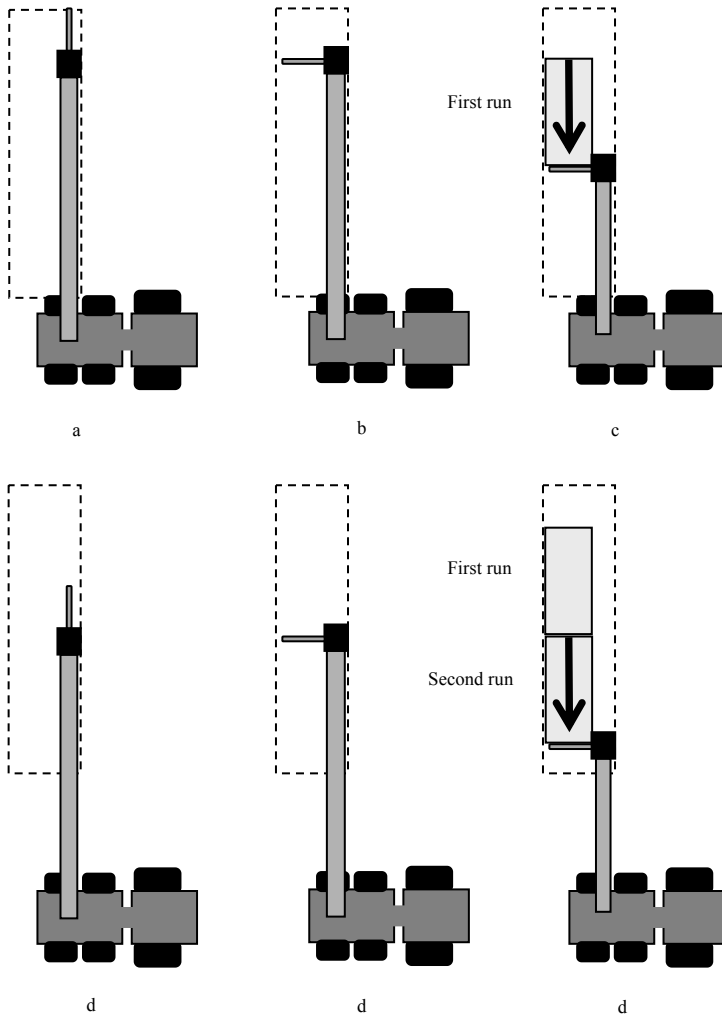


Figure 4. Sketch plan of the crane cycle: a) the crane positions the felling unit with the telescopic boom fully extended; b) the felling head is activated; and c) the crane moves inwards for felling; d) the machine is repositioned and the procedure is repeated, i.e., in each plot two runs were performed.

Subsequently, the positions of felled trees lying on the ground were measured; a felled tree with bole lying within  $20^\circ$  from the centre line with the butt end towards the strip road was defined as lying in a “positive felling direction”. Other directions were defined as a “negative felling direction”.

### Experiment 2: Maximum felling speed

The maximum speeds for felling trees of different sizes (dbh ranging from 6.7 to 16.2 cm) were assessed in 28 runs, in each of which a single tree was felled by moving the crane sideways. In each case the diameter of the tree (at the cutting height) was measured. The felling speeds were derived from the time consumed during the movement of the felling head from a given distance (3 m) from the tree to be felled until it was cut (Fig. 5).

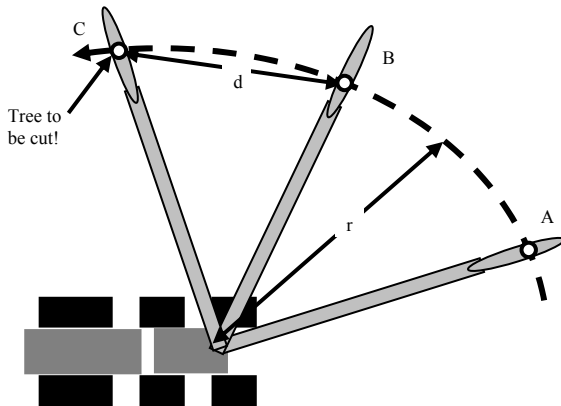


Figure 5. Sketch of the variables recorded for estimating the maximum speed for cutting trees of different diameters. The distance between the centre of the crane pillar and the specific point on the cutting unit (chainsaw blade) where the tree was cut ( $r$ ) was set to 4.7 or 5.5 m to achieve different movement speeds. The distance between points A and B was approximately 4 m and the linear distance between points B and C ( $d$ ) (to the tree) was 3.0 m, giving an arc (CB) measuring approximately 3 m.

## 2.4 Paper IV

### Experiment 1: Compression processing

An experimental boom-tip mounted unit for compressing and semi-debranching tree bunches was designed, constructed and mounted on a conventional medium-sized harvester (~ 12 t), with four aggressive feed rollers to break and flatten branches, and reduce small branches and foliage during processing (Fig. 6). The calculated force with which a bunch was gripped by the front feed rollers/grapple arms during processing was about 9.8 kN at the mid-point of the roller.

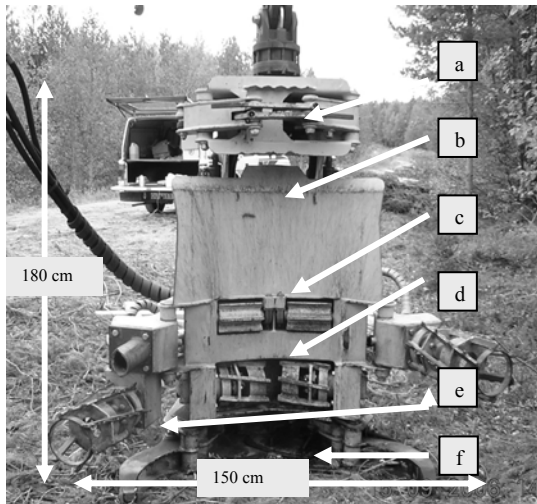


Figure 6. The experimental unit for compressing and processing tree bunches from young stands: (a) two grapple arms for accumulation on the top; (b) defoliation supporting plate; (c) two “support” rollers on the body; (d) two feed rollers attached to the body; (e) two horizontal front feed rollers attached to grapple arms; and at the bottom, (f) knives for cutting the trees/bunches. The height and width (open) of the unit are 180 cm and 150 cm, respectively.

This part of the study was conducted in a forest stand dominated by Scots pine (in terms of volume), located in Vindeln, Sweden (N 64° 10', E 19° 37', 170 m a.s.l.). The annual growth potential of the stand was  $3.7 \text{ m}^3 \times \text{ha}^{-1}$  and on average it had  $15940 \text{ trees} \times \text{ha}^{-1}$  (21% pine, 14% spruce and 65% birch), a basal area of  $39.8 \text{ m}^2 \times \text{ha}^{-1}$ , and the average dbh and height of the trees was 4.9 cm and 5.7 m, respectively. Compression processing took place under controlled conditions at the roadside, but the prototype system is intended eventually to work on-site.

The experiment had a  $2 \times 2 \times 2$  randomized factorial design, in which the factors were: two types of raw materials, fresh (*Fresh*) and stored in-stand over winter (*Stored*); of two size classes, represented by (i) trees with dbh ranging from 5 to 8 cm (*5-8cm trees*), bunched in sets of five, and (ii) trees with dbh of 12 to 15 cm (*12-15cm trees*), bunched in pairs; and two treatments, processed (*Proc.*) and control (*C*) bunches. Treatments were replicated from 5 to 14 times and in total 64 runs were made.

Trees were randomly selected for each bunch and were then manually felled and gathered, after which their dbh, height, height to the first living branch and GW were determined. Experiments on fresh bunches and stored

bunches were performed in August 2006 and June 2007, respectively. Bunches to be stored were placed on the ground in the stand at the felling site. Bunches were processed at full feeding speed, from the butt end to the top end, until the whole bunch had been passed through the experimental unit (Fig. 7).



Figure 7. The compression and semi-debranching sequence of a bunch processed from the butt end (a) to the top end (d).

After processing, the GW of each bunch was measured again and (for stored bunches) the weight of broken-off large branches with needles intact was also measured. The volume of each bunch was measured as the bundled bulk volume; a bunch was bucked at half length and then stacked on a flat surface and subsequently bundled by tying a piece of inelastic plastic string around it at three specific positions. The circumference and length of the bundle were then measured. In total, 24 bunches (three per treatment) were randomly selected and chipped (using a tractor-mounted chipping device) for later determination of their moisture content (MC%-wet-basis) and ash contents.

#### Experiment 2: Load compression

A 2.9 t Vimek 606 BioCombi (Vimek AB, Vindeln, Sweden) forwarder equipped with a device for compressing the trees on the load-bed was used

in Scots pine and birch tree load compression experiments. This part of the study was carried out at two sites in the municipality of Skellefteå in the northern part of Sweden – Vikmyran (N 64° 38', E 21° 4', 53 m a.s.l.) and Bergsbyn (N 64° 42', E 21° 7', 5 m a.s.l.) – where compression parameters of loads of Scots pine (*Pine*) and birch (*Birch*) trees, with dbh ranging from 5 to 15 cm, were evaluated in July 2006 and August 2006, respectively. The experiment included two treatments: compressed (*Compr.*) and control (*C*) loads. The treatments were paired and their order was randomized. Five loads per tree type (*Pine & Birch*) and treatment (*Comp. & C*) were made, hence in total 20 loads were examined. Trees were compressed by moving the stakes, from the outward to the inward position, thereby compressing loaded trees. The GW of each load was measured using a mobile weighing system.

In the *C* treatment the four stakes were positioned and locked at the normal vertical position throughout each loading cycle, but in the *Comp.* treatment they were oriented in the outward position when loading and moved towards the inward position between loading cycles for compression. Each load was stacked to a level of the top-ends of the stakes (in the normal position). At full load the length and GW of the load were measured.

The effects of the treatments on the measured variables were assessed by analysis of variance using a general linear model, calculated by Minitab 15 (Minitab Ltd.). Differences between treatments were considered significant if  $p \leq 0.05$ . In the analysis of the data acquired from the bunch compression investigation a full factorial model with three fixed main effects was used and differences between mean values obtained for the eight treatment combinations were analyzed using Tukey's simultaneous test of means, while in the analysis of data from the load compression investigation a one-way layout was used.



## 3 Results

### 3.1 Paper I

Significant differences in time consumption between the *AFH-corr* and the other two boom-corridor harvesting approaches were found, for both thinning patterns in both stands (ca. two-fold in the FT stand and ca. three-fold in the DPCT stand). However, there were no significant differences in time requirements between perpendicular boom-corridor and fan-shaped boom-corridor thinning patterns for any of the harvesting approaches. The productivity ( $\text{m}^3 \times \text{PW-hour}^{-1}$ ) was 1.5-2.3 times higher in the FT stand than in the DPCT stand. In general, for each harvesting approach, the difference in productivity between thinning patterns was small. However, the productivity of the harvesting approaches differed, in the order  $AFH-5tr < AFH-2m^2 < AFH-corr$ , especially for the DPCT stand, where there was a 2.4-fold difference between *AFH-5tr* and *AFH-corr*. In the FT-stand, the productivity of the thinning from below treatment (*AFH-5tr selective*) was 30% lower than that of *AFH-5tr* (Table 1).

Table 1. Effects of stand type, harvesting approach and thinning pattern on time consumption per corridor and stand level productivity.  $s^2$  = standard deviation.  $m^3$  = whole tree biomass volume above ground, including branches and needles. PW = productive work time (Anon. 1995)

Stand type*	Harvesting Approach**	Thinning Pattern***	Time consumption per corridor <sup>1)</sup> (s, $s^2$ )	Productivity ( $m^3 \times PW\text{-hour}^{-1}$ ), (rel. values in %)
FT	<i>AFH-5tr</i>	P	69.3(32.8)a	8.5 ( <i>100</i> )
		F	62.6(23.7)a	8.0 (94)
	<i>AFH-2m<sup>2</sup></i>	P	56.7(15.7)a	11.1 (131)
		F	49.2(14.1)a	11.6 (137)
	<i>AFH-corr.</i>	P	38.0(4.3) b	12.8 (151)
		F	32.1(3.7) b	14.0 (165)
<i>AFH-5tr selective</i>	Sel	-	5.9 (70)	
DPCT	<i>AFH-5tr</i>	P	127.3(76.2)a,b	3.7 ( <i>100</i> )
		F	103.0(44.9)a	3.8 (101)
	<i>AFH-2m<sup>2</sup></i>	P	64.0(9.8)b,c	7.4 (200)
		F	60.8(9.6)c	7.0 (190)
	<i>AFH-corr.</i>	P	40.3(2.7)d	8.8 (237)
		F	41.1(1.5)d	8.7 (233)

\*FT = First thinning stand (dbh = 9.3 cm, trees $\times$ ha<sup>-1</sup> = 3590), DPCT = Delayed pre-commercial thinning stand (dbh = 4.8 cm, trees $\times$ ha<sup>-1</sup> = 8600).

\*\**AFH-5tr* = Conventional accumulating felling head cutting trees one by one and accumulating up to five trees, *AFH-2m<sup>2</sup>* = accumulating felling head harvesting trees within a 1 m wide and 2 m long area in one movement, *AFH-corr* = accumulating felling head harvesting all trees corridor-wise in one movement, *AFH-5tr selective* = same as *AFH-5tr*, but thinning from below.

\*\*\*P = Perpendicular, F = Fan-shaped, Sel = (thinning from below, no corridors) (see Fig. 2). <sup>1)</sup>Within stand-type, treatments with different letters are significantly different according to Dunnett T3 tests ( $p \leq 0.05$ ).

Generally, the proportion of time spent on the various work elements did not differ greatly between perpendicular and fan-shaped boom-corridor patterns for any of the approaches.

### 3.2 Paper II

No significant between-treatment differences were found in harvest parameters, e.g., tree sizes and density of removal (i.e. proportion of the basal area of stems removed per unit area). On average, about 2600 trees $\times$ ha<sup>-1</sup> were harvested, with an average dbh and OD weight of 5.7 cm

and 9.5 kg, respectively. The average percentage of trees removed $\times\text{ha}^{-1}$  was about 36%, corresponding to about 22 ODt $\times\text{ha}^{-1}$ . The distance between strip roads was about 20 m, and on average the boom-corridor treatment resulted in a significantly longer (0.7 m, or 3.6% greater) distance between strip roads. The distance between strip roads decreased with increasing initial stand density for both treatments. On average, for both treatments, the number of remaining trees $\times\text{ha}^{-1}$  with  $\geq 4$  cm dbh ranged between 844 to 3374, with an average density of 1921 trees $\times\text{ha}^{-1}$ , and corresponding values for trees with  $\geq 8$  cm dbh ranged from 484 to 1440, with an average density of 978 trees $\times\text{ha}^{-1}$ .

The work element *Positioning and felling* was the most time-consuming element (accounting for nearly a third of the total) in both treatments. For both treatments, the work elements *Move*, *Crane in* and *Bunching* collectively accounted for about a third of the effective time consumption. The numbers of trees harvested per crane cycle in the thinning from below and boom-corridor treatments were on average about 3.5. In the boom-corridor treatment, the effective time consumption ( $\text{s}\times\text{tree}^{-1}$ ) for the work element *Crane in-between* was 16.7% lower than in the thinning from below treatment, while on average the productivity (ODt $\times\text{PW-hour}^{-1}$ ) was 15.8% higher in the boom-corridor treatment. For both variables the differences were significant at the  $\alpha\leq 0.05$  level, and for the latter case the difference increased with decreasing size of harvested trees.

### 3.3 Paper III

No significant differences in measured variables were found in this experiment between duplicates in pairs of runs (1 and 2) (see Fig. 4). On average, almost 84% of all trees felled pointed in a positive direction ( $\pm 20^\circ$  from the centre line). In most runs the crane reached its maximum telescopic range (3.28 m), and the distance moved was shorter than the maximum possible in only five of the total number of 30 runs. Neither the harvested distance nor felling speed, which averaged 3.0 m and  $0.4 \text{ m}\times\text{s}^{-1}$ , respectively, was clearly affected by the size of harvested trees. The felling time per tree relative to harvested tree density in boom-corridors followed a negative exponential curve, and the time consumed when cutting trees in a plot with 5000 trees $\times\text{ha}^{-1}$  was about twice as long the time required when cutting trees in a plot with 10000 trees $\times\text{ha}^{-1}$ . On average, the productivity of the felling work was 12.2 ( $\text{s}^2 8.0$ ) ODt $\times\text{PW-hour}^{-1}$ .

The maximum felling speeds of the felling head when cutting trees of about 15 cm and 8 cm dbh without stops were about  $1.0$  and  $1.3 \text{ m}\times\text{s}^{-1}$ ,

respectively. Hence, in plots with densities of 5000 and 10000 trees $\times$ ha<sup>-1</sup> the time consumption would be about 70% lower, and the productivity on average about 79% higher than corresponding values recorded in the boom-corridor experiment.

### 3.4 Paper IV

Processing *Fresh 5-8cm trees* and *12-15cm trees* bundles resulted in significant increases in bulk density, of up to 80 and 160%, respectively, with significant corresponding decreases in bundle diameter (up to 26 and 40%, respectively) compared to controls. The processing caused a significant reduction in mass of *12-15cm trees* bundles, but not of *5-8cm trees* bundles. For *Stored* bundles the effects of processing were not as clear as those for *Fresh* material, and the differences in diameter ( $p=0.06$ ) and bulk density ( $p=0.15$ ) of *5-8cm trees* bundles were not significant. Processing resulted in significant mineral losses from *Fresh 5-8cm trees* and *12-15cm trees* bundles, with reductions of up to 35% and 50%, respectively, in ash contents.

The proportions of fine branches and needles and large branch masses lost (GW) during processing *Stored 5-8cm trees* bundles were found to be 61% and 39%, respectively, while corresponding values for *12-15cm trees* bundles were 65% and 35%, respectively. During in-stand storage the dry matter (DM) losses of *5-8cm* and *12-15cm* bundles were small; reductions of only 3.1 and 1.0% were found, respectively, but their MC values dropped almost 20%. The subsequent processing did not affect their MC and their proportional losses of DM were similar to those of fresh material. The recorded reductions in net energy contents due to processing were highest from *Stored* bundles (~ 30%). However, their net energy density increased significantly during storage (by up to approximately 160%).

The load compression significantly increased (by more than 30%) the bulk density of *Birch* loads, and had a positive (but not statistically significant) effect on the bulk density of *Pine* loads ( $p=0.087$ ). Compressed loads of both *Pine* and *Birch* reached almost 75% of the load capacity of the forwarder (3 t), while corresponding values for control loads were only about 60% and 55%, respectively. In addition, the load density and net energy density of compressed *Pine* loads were 40% and 8% higher,

respectively, than those of compressed *Birch* loads, but the net energy content per load was about 25% higher for *Birch* loads.

## 4 Discussion

### 4.1 Starting point

There are powerful reasons for developing systems to utilize the potential biomass in dense, young stands since there is a need to increase biomass supplies and the conventional treatment for such stands, PCT, is often neglected due to high costs. The high expenses of PCT could be transformed into income, or at least a major proportion of PCT costs could be covered, by selling low value trees as fuel wood to the energy sector (which does not have any requirements in terms of minimum tree dimensions, unlike conventional forest industries). Ideally, when performing any thinning operation efforts should be made to optimise the balance between maximising the value of the remaining stand and the net income (or minimizing the costs). However, these conflicting objectives are currently far from balanced (and often neither goal is met). The work underlying this thesis was intended to identify ways to address these issues by exploring methods and techniques that could be used now, or developed quickly, to make thinning operations in young dense stands efficient and cost effective.

The annual sales of forest machines are small compared to those in other sectors (e.g., farming and construction) (Drushka & Kontinen 1997). Consequently, when developing more efficient forest harvesting systems the most convenient starting point is to identify strategies based on the use of existing prime movers. Thus, the most rational approach is to focus on the development of more appropriate attachments (e.g. booms, harvester heads and control systems) and working practices instead of on the prime mover itself.

## 4.2 Effects of work method on efficiency

In general, if the trees to be harvested are either smaller or larger than trees that the machinery and associated equipment used are designed to handle, productivity is likely to be low (Sundberg & Silversides 1988) and viable use of such machinery will be limited to certain stands. However, even if the machinery is not ideal for some conditions, a change in work methodology might increase efficiency. In the mechanized felling and bunching of young stands few attempts have been made to increase the efficiency of the operation by changing the work methods, e.g., by changing the work patterns of the crane. Liss (1999) studied the effects of restricting the crane movements between trees to linear movements, but no significant effects were found. In contrast, in Studies I and II a similar approach was examined, but all trees within a boom-corridor were harvested in linear movements. In Study II it was found that this approach significantly reduced the time consumption for the work element *Crane in-between*, in comparison to a thinning from below treatment. It was also found in Studies I and II that changing the work method, from the thinning from below to the boom-corridor treatment, significantly increased productivity even though the equipment used (AFH) was not designed for the boom-corridor method. However, the increase in productivity was substantially lower in the field study (16% on average, Paper II) than in the simulation study (44% on average, Paper I). It is likely that the stronger effects found in the simulation study were due to the clearer distinctions in the crane movements between the methods than in the field study, where the movements of the crane did not differ so much (the boom-corridor thinning was not performed strictly, since the operator decided the location and size of each boom-corridor). Further, results of any simulation are dependent on the inherent assumptions and simplifications of the model (Eliasson 1998). In the models of the harvesting approaches considered in Study I machine and crane movements were predetermined and did not change with stand properties. An additional contributory factor may have been that the operator had no previous experience of applying the boom-corridor treatment.

## 4.3 Effects of techniques on efficiency

In order to further increase efficiency the equipment and the way it is used must also be adjusted to fit the work approach. The *AFH-2m<sup>2</sup>* harvesting system simulated in Study I can be considered an improved version of currently available conventional AFHs, but with modifications for multiple tree felling. In comparison to boom-corridor thinning with the *AFH-5tr* approach (conventional) the *AFH-2m<sup>2</sup>* approach significantly increased

productivity ( $\text{m}^3 \times \text{PW-hour}^{-1}$ ) in the FT and DPCT stands, by 38% and 92%, respectively. It seems that in order to design efficient technology for harvesting young dense stands single trees should not be considered as handling units (see Fig. 1). Instead, a group of trees (e.g., all trees within  $2 \text{ m}^2$ ) should be considered a unit, and handled in a single movement. For such operation the harvester head would have to be able to handle various numbers of trees, reflecting differences in stands in terms of  $\text{trees} \times \text{ha}^{-1}$  and sizes of trees. Further, for high efficiency the capacity of the harvester head must correspond to the felling approach. For example, if a whole boom-corridor is to be harvested in a single crane cycle, then the next logical step is to consider all trees in a boom-corridor, perhaps 1 m wide and 10 m long, as “a handling unit”. However, for such an approach completely new equipment would be required. In Study I it was found that the time consumption per boom-corridor for the *AFH-corr* approach (continuously felling and accumulating trees boom-corridor-wise) was significantly lower than the time required for the *AFH-2m<sup>2</sup>* harvesting approach, and its productivity was more than two-fold higher than that of the *AFH-5tr* approach.

Further, in Study III the continuous felling approach (simulated in Study I) was evaluated in the field in experiments with a prototype felling head specially designed for the purpose. It was found that the time consumed using the tested technique per tree was greatly reduced as the density of the harvested stands increased, and that the felling speed may vary, depending on the size of the tree being cut. Further, if the achievable felling speed is only dependent on the size of the tree being cut, and not on the stand density, the variation in productivity between different types of stands will be reduced.

#### 4.4 Some aspects of cutting techniques

The experiments with the prototype equipment in Study III were limited due to technical restrictions, such as limitations in the boom reach and boom movement speed, but it was found to be possible to fell trees inwards to a distance almost corresponding to the maximum outer boom reach of ca. 3.3 m and at a maximum crane movement speed of ca.  $0.4 \text{ m} \times \text{s}^{-1}$ . Even though this was the first experiment with the prototype only minor disturbances occurred. To determine its maximum possible felling speed, which was much higher than the speed limited by the crane, an additional experiment was designed in which the crane was moved sideways, allowing it to move at much higher speed. The results showed that it was possible to fell trees of 15 cm and 8 cm dbh at speeds of 1.0 and  $1.3 \text{ m} \times \text{s}^{-1}$ , respectively, without reducing the movement speed of the crane (as visually



observed). This means that the possible felling speed could be higher than that found in the boom-corridor felling experiment. The prototype felling head used in Study III was based on the Supercut 300 (Hultdins Systems AB, Sweden) unit, equipped with a chain which (in theory) could cut trees at a maximum speed of approximately  $0.7 \text{ m} \times \text{s}^{-1}$ . However, if the chain was designed to allow even faster cutting (e.g., with increased chain speed and/or with a larger gauge depth) the potential felling speed of trees of different sizes is likely to be even higher.

If a chain is used for cutting there are high risks of lost productivity due to hitting hard objects such as stones. The majority of conventional AFHs on the market are equipped with shears or guillotines for cutting, which are less sensitive to stony conditions. However, for continuous cutting the use of shears is not appropriate. One alternative would be to use a large-diameter circular disc with “non-sensitive” cutters (Quadco Equipment Inc. website, 2009). This cutting equipment is similar to (but more robust than) the Bracke C16.a (Bracke Forest website, 2009) AFH used in Study II, which cuts trees with a chain attached to a circular disc. Using a disc, the cutting capacity is limited by the radius of the disc. Hence, if the disc is enlarged the capacity will be increased, which would be appropriate for increasing the capacity to enable multiple tree felling. However, if there is a desire to attain a certain cutting capacity while minimizing the weight of the equipment a chainsaw blade is likely to be a better option than a disc.

#### 4.5 Compression and required techniques

To optimise the subsequent handling and transport of the felled and bunched trees it is important to ensure that the material is easy to handle and facilitates carriage of high payloads. Depending on the site characteristics, it might also be important to leave some of the nutrients at the felling site in order to enhance both future wood production and the fuel properties of the harvested material (Hakkila 2005). In Study IV it was found that the studied prototype equipment for simultaneously compressing and processing facilitated the production of denser bundles with reduced nutrient contents. The nutrient content-reducing effect was greatest on bundles of fresh, relatively large trees (*Fresh 12-15cm trees*), but the bulk densities of bundles of such trees were similar to those of bundles containing smaller trees (*Fresh 5-8cm trees*) (Fig. 8).

The obtained densities were also found to be similar to the densities of bundles generated using significantly higher forces (Nordfjell & Liss 2000), showing that the technique is efficient in terms of the required force. However, if fertilization will be used to compensate for any removal of

nutrients through biomass harvesting (or if the stand has high production capacity, even if whole trees are extracted) no major reduction of foliage is needed. For such cases the compression/processing unit examined in Study IV could be modified to reduce (or increase) the effects of processing in terms of losses of fine branches and needles. The force, feeding speed and feed-roller design for compression processing could all be adjusted to modulate the compression and processing parameters as desired.

Alternatively, or in combination with the use of less aggressive feed rollers, load compression could be used. For instance, as shown in Study IV, the use of four flexible stakes attached to the load space of a forwarder to compress loads significantly increased the density of birch loads and close to significantly increased the density of Scots pine loads. Assuming a tight loading of bundles (i.e., no space in-between bundles), the bulk densities achieved with compression-processed bunches were close to the target for full payloads ( $300 \text{ kg}\times\text{m}^{-3}$ ) of the small forwarder used in Study IV, while the effects of load compression were minor compared to compression-processing (Fig. 8). However, the effects of load compression found in Study IV could easily be increased by applying higher compression forces since the forces used were relatively low (see Norden 1984). If compression processing is used prior to load compression one could expect even greater effects on load density in comparison to loads of un-compressed trees and tree parts. In contrast to the small forwarder used in Study IV, a large forwarder, e.g. the Valmet 860 (Komatsu Forest website, 2009) would require a load density of  $447 \text{ kg}\times\text{m}^{-3}$  to obtain full payloads (maximum payload, 14000 kg, with a load area and length of  $5.7 \text{ m}^2$  and  $5.5 \text{ m}$ , respectively, giving a maximum load volume of about  $31.4 \text{ m}^3$ ). However, if such a forwarder was equipped with flexible stakes for load compressing, giving a possible densification effect of 30%, a payload of about 12000 kg would be achieved, which is close to the maximum payload.

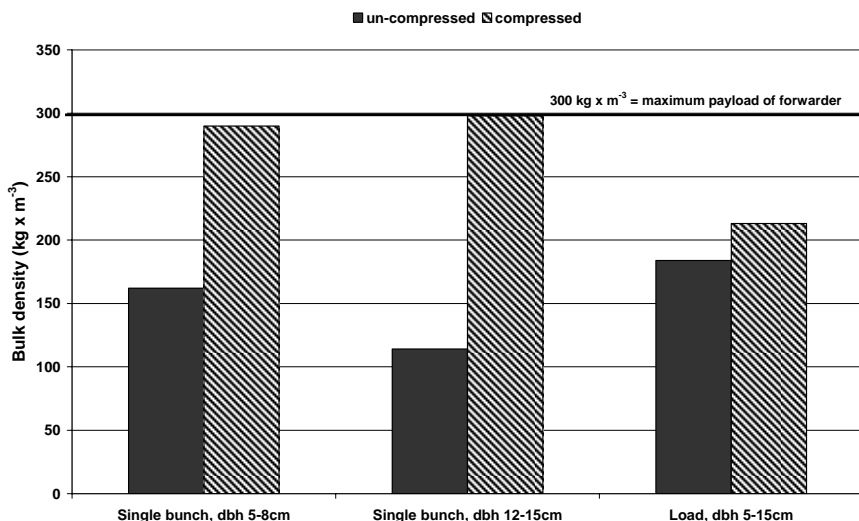


Figure 8. Bulk densities achieved by compressing single bunches of trees of two size classes and loads of fresh Scots pine in comparison to a target of  $300 \text{ kg} \times \text{m}^{-3}$  corresponding to a full payload for the forwarer used (load capacity:  $10 \text{ m}^3$  at 4.5 m load length and 3000 kg). Derived from Study IV.

## 4.6 Financial aspects

### 4.6.1 Productivity, costs and their dependence on tree sizes

The productivities ( $\text{trees} \times \text{PW} \cdot \text{hour}^{-1}$ ) in Figure 9 are based on a simplified linear interpolation between the productivities found in the two stands (DPCT and FT) for the three harvesting approaches (*AFH-5tr*, *AFH-2m<sup>2</sup>* and *AFH-corr*) considered in Study I. The figure also shows the productivity that could be obtained if the felling speed in the *AFH-corr* approach (in which the felling and bunching work element accounted for about a third of PW) could be increased from 1 to  $1.5 \text{ m} \times \text{s}^{-1}$ , which seems likely according to the findings presented in Paper III. This should result in 15% higher productivity and is named *AFH-corr-15%*. The productivity values ( $\text{ODt} \times \text{PW} \cdot \text{hour}^{-1}$ ) presented in Figure 10 are based on data displayed in Figure 9 and the biomass content per tree (ODkg) from Study II.

Using more efficient than current felling and bunching techniques in combination with boom-corridor thinning methods should allow improvements in cost-efficiency, even if the hourly costs of the new

techniques are higher (Fig. 10). For example, assuming that the maximum cost for felling and bunching to break even (BE) is 20 euro $\times$ ODt $^{-1}$  and the hourly costs are 80 euro (*AFH-5tr*), 90 euro (*AFH-2m<sup>2</sup>*) and 100 euro (*AFH-corr* and *AFH-corr+15%*), the required productivity of the *AFH-5tr*, *AFH-2m<sup>2</sup>*, *AFH-corr* and *AFH-corr+15%* approaches would be about 4, 4.5, 5 and 5 ODt $\times$ PW-hour $^{-1}$ , respectively. The corresponding harvested average tree sizes (dbh) would be approximately 8.2, 6.6, 6.2 and 5.6 cm, respectively (Fig. 10). Thus, even though the hourly costs of the area-based harvesting approaches are anticipated to be 10-20% higher, their significantly higher productivities make them more cost effective than current approaches.

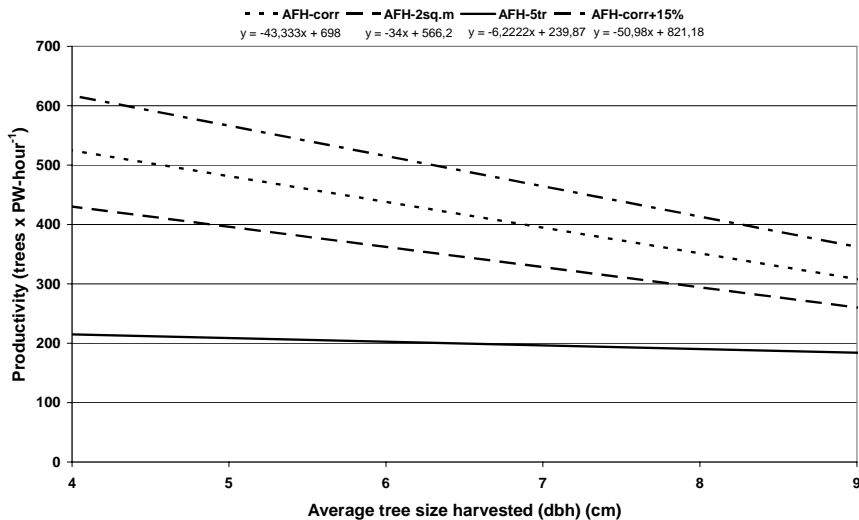


Figure 9. Productivity of the felling and bunching work as functions of harvested tree size for different harvesting approaches in boom-corridor thinning. Functions are based on stand data in Study I (DPCT, stand density of 8600 trees $\times$ ha $^{-1}$  at a harvested tree size of 4.8 dbh and FT, 3590 trees $\times$ ha $^{-1}$  at 9.3 dbh) and the time consumption values obtained in Studies I and III. *AFH-5tr* = conventional accumulating felling head cutting trees one by one and accumulating up to five trees, *AFH-2m<sup>2</sup>* = accumulating felling head harvesting trees within a 1 m wide and 2 m long area in one movement, *AFH-corr* = accumulating felling head harvesting all trees corridor-wise in one movement, *AFH-corr-15%* = same as *AFH-corr* but with 15% higher productivity: the felling and bunching work element of the *AFH-corr* approach accounted for one third of PW and the felling speed is increased from 1.0 to 1.5 m $\times$ s $^{-1}$ , giving 15% higher productivity.

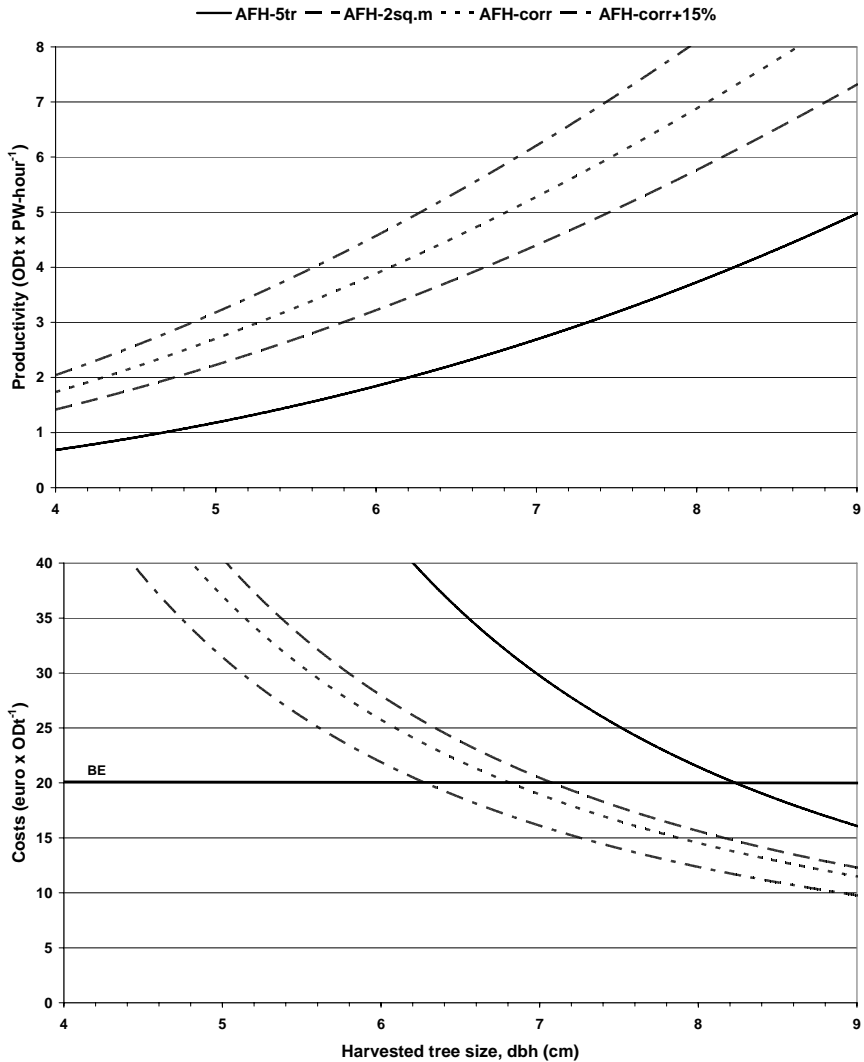


Figure 10. Productivity and costs of the felling and bunching of trees of different sizes using conventional, improved and new AFH techniques in boom-corridor thinning. Stand density of 8600 trees $\times$ ha<sup>-1</sup> at a harvested tree size of 4.8 dbh respectively 3590 trees $\times$ ha<sup>-1</sup> at 9.3 dbh. Hourly costs are assumed to be 80 euro (*AFH-5tr*), 90 euro (*AFH-2m<sup>2</sup>*) and 100 euro (*AFH-corr* and *AFH-corr+15%*). A break even (BE) example for a cost of 20 euro $\times$ ODt<sup>-1</sup> is included. One ODt corresponds to approximately 2 m<sup>3</sup> (solid) of biomass. The productivity (ODt $\times$ PW-hour<sup>-1</sup>) is based on the data displayed in Figure 9 and the biomass content per tree (OD kg) values from Study II.

#### 4.6.2 Harvesting energy wood or pulpwood versus PCT

Whether the biomass in a stand should be harvested as energy wood or pulpwood, or the stand should be subjected to a PCT, depends on the merchantable volumes, their values and the costs of the respective operations, as well as targets for future stand treatment. The merchantable volumes per ha (gross values) for a given stand vary with the standing volume of biomass, numbers of trees $\times$ ha $^{-1}$  to be removed and tree sizes. Figure 11 presents calculated values of the merchantable volumes of energy wood and pulpwood assortments in the DPCT and FT stands (from Study I), based on fuel wood and pulpwood prizes of 15 euro $\times$ MWh $^{-1}$  and 30 euro $\times$ m $^3$ s u.b. $^{-1}$ , respectively. The results clearly show that the energy wood assortment would have higher value than the pulpwood, about two to three times higher, for the given type of stand and harvest intensity.

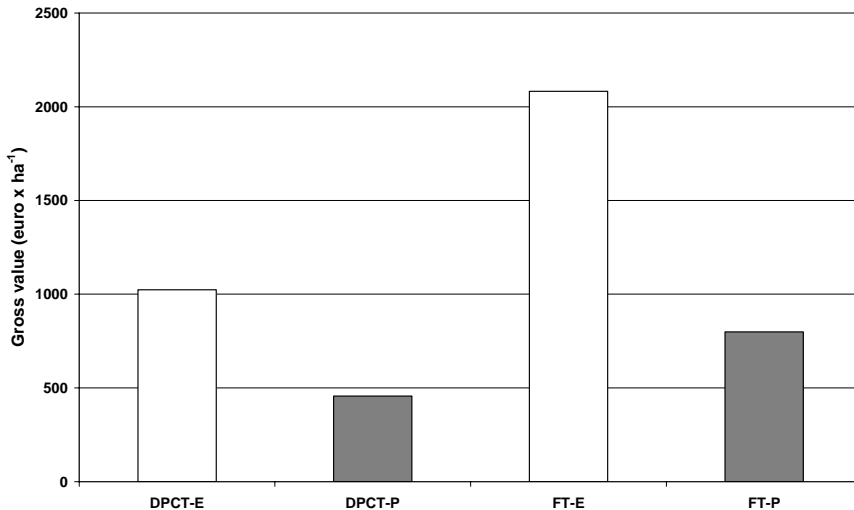


Figure 11. Gross values of merchantable energy wood (E) and pulpwood (P) volumes from a DPCT and FT stand (Study I) given: 35% removal of the total merchantable volumes; prices for energy wood and pulpwood of 15 euro $\times$ MWh $^{-1}$  and 30 euro $\times$ m $^3$ s u.b. $^{-1}$ , respectively; an energy content of 4.65 MWh $\times$ ODt $^{-1}$  (whole trees with a MC of 50%); and merchantable pulpwood log sizes corresponding to a minimum log length of 3 m and minimum top diameter of 5 cm. Harvested mass/volumes: DPCT stand, 14.7 ODt $\times$ ha $^{-1}$  or 15.2 m $^3$ s u.b. $\times$ ha $^{-1}$ ; FT stand, 29.8 ODt $\times$ ha $^{-1}$  or 26.6 m $^3$ s u.b. $\times$ ha $^{-1}$ .

Figure 12 shows the net income at strip road side (excluding extraction) in  $\text{euro}\times\text{ha}^{-1}$  of energy wood and pulpwood harvests in the DPCT and FT stands with 35% removal of merchantable volumes. For reference, an average PCT cost of  $230\text{ euro}\times\text{ha}^{-1}$  for the DPCT stand (Ligné 2004) is also displayed. Calculations are based on: the harvesting costs; an energy wood (E) harvest in perpendicular corridors with the *AFH-5tr* approach at a productivity of  $3.7\text{ m}^3\times\text{PW}\text{-hour}^{-1}$  in the DPCT and  $8.5\text{ m}^3\times\text{PW}\text{-hour}^{-1}$  in the FT stand and with the *AFH-corr* approach at a productivity of  $8.8\text{ m}^3\times\text{PW}\text{-hour}^{-1}$  (see Table 1); a pulpwood (P) harvest with a single-grip (SG) harvester at a productivity of  $1.7$  and  $4.4\text{ m}^3\times\text{PW}\text{-hour}^{-1}$  in the DPCT and FT stands, respectively (Kärhä et al. 2004); assumed hourly costs of the *AFH-5tr* and SG treatments of  $80\text{ euro}\times\text{PW}\text{-hour}^{-1}$  and  $100\text{ euro}\times\text{PW}\text{-hour}^{-1}$  for *AFH-corr*. Both the pulpwood harvest and PCT in the DPCT stand have negative results (incur costs), while the energy wood harvest with both the *AFH-5tr* and the *AFH-corr* approaches yields positive results (generates income). Thus, even if conventional AFHs are used in a DPCT a positive result is achievable. In the FT stand the energy wood harvest yields about three-fold higher net income compared to the pulpwood harvest. If extraction costs are included, the values in Figure 12 have to be reduced by approximately  $170$  to  $230\text{ euro}\times\text{ha}^{-1}$  for the *AFH-5tr* and *AFH-corr* approaches in the DPCT stand and  $300$  to  $380\text{ euro}\times\text{ha}^{-1}$  for the *AFH-5tr* approaches in the FT stand. The calculations are based on data presented by Latila et al. (2007) and an hourly cost of  $70\text{ euro}\times\text{PW}\text{-hour}^{-1}$  for the forwarder.

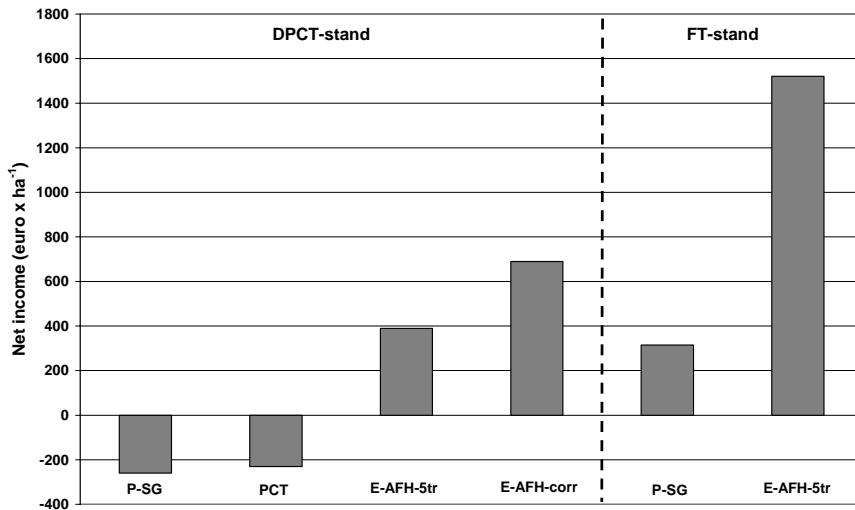


Figure 12. The net income or cost at strip road side (excluding extraction) of energy wood (E) and pulpwood (P) harvests in a DPCT and a FT stand given 35% removal of merchantable volumes. Energy wood is assumed to be harvested by an *AFH-5tr* or *AFH-corr* approach (Study I) in perpendicular boom-corridors. The pulpwood is harvested with a single-grip (SG) harvester (Kärhä et al. 2004). Hourly costs are 80 euro×PW-hour<sup>-1</sup> for the *AFH-5tr* and SG treatments and 100 euro×PW-hour<sup>-1</sup> for the *AFH-corr* treatment. The costs of the motor-manual PCT is 230 euro×ha<sup>-1</sup> (Ligné 2004).

#### 4.7 The future stand

It is obvious from a forest management perspective that the distribution of the remaining trees after a boom-corridor treatment differs from that after a thinning from below treatment. However, if a stand to be thinned contains 9000 trees×ha<sup>-1</sup> and the target is to reduce its density to 4000 trees×ha<sup>-1</sup> using a fan-shaped boom-corridor pattern there is likely to be sufficient trees that are both suitable for use as future crop trees and well distributed over the area. In the simulations in Study I boom-corridor treatments reduced the density by 35%, corresponding to 5500 and 2300 remaining future crop trees per hectare in the DPCT and FT stands, respectively. In Study II the spatial distributions of neither the remaining trees, nor the boom-corridors, was examined, but visual observations indicated that the between-treatment differences in this respect were minor. In contrast to the distribution that a strict boom-corridor thinning pattern would leave, it seems that a “selective” placement of boom-corridors promotes a wider spatial distribution of remaining trees. It is also possible that some stands



could be subjected to boom-corridor thinnings in both the first and second thinnings, perhaps by using systems such as boom-corridor patterns that overlapped in the two thinnings.

Since foliage contains high concentrations of nutrients, whole-tree harvesting can reduce tree volume growth (Jacobson et al. 2000). If the felled and bunched trees are subjected to compression processing prior to extraction (Study IV) the removal of nutrients from the stand will be significantly reduced. However, if the removal is still too high compensatory fertilization can be performed (Jacobson et al. 2000).

#### 4.8 Systems for boom-corridor thinning

Three suggestions for designing the boom-corridor thinning supply chain are presented in Figure 13 (indicated by the thick arrows), designated “today”, “tomorrow” and “next week”. Firstly, by using a conventional felling and bunching technique and a forwarder with load compression even “today” it is possible to achieve higher efficiency than by thinning from below with conventional felling and bunching techniques then extracting the wood with a standard forwarder. Secondly, if improved felling and bunching equipment, designed for multiple tree felling with a compression-processing device and a forwarder with load compression were used even higher efficiency can be expected “tomorrow”. Thirdly, if new felling and bunching equipment were developed for continuous felling and bunching, and used with a forwarder designed for compression processing and load compression, significantly higher efficiency could be expected “next week”. It is also possible that other combinations of the above felling techniques and subsequent handling techniques could be combined, for instance with the use of improved AFHs and a specially designed forwarder for compression and processing (reduction of foliage) (see dotted arrows in Figure 13).

For the subsequent road transport of whole trees or tree parts it seems that conventional trucks for round wood with new attachable load compression devices (see ExTe website, 2009) can provide logistic advantages compared to the use of two different systems for transporting wood: i.e., conventional trucks for round wood, and specially designed trucks for chips and tree parts. This could eliminate the need for comminution at roadside before transportation to termini or industrial sites where large-scale and efficient processing machines are used.

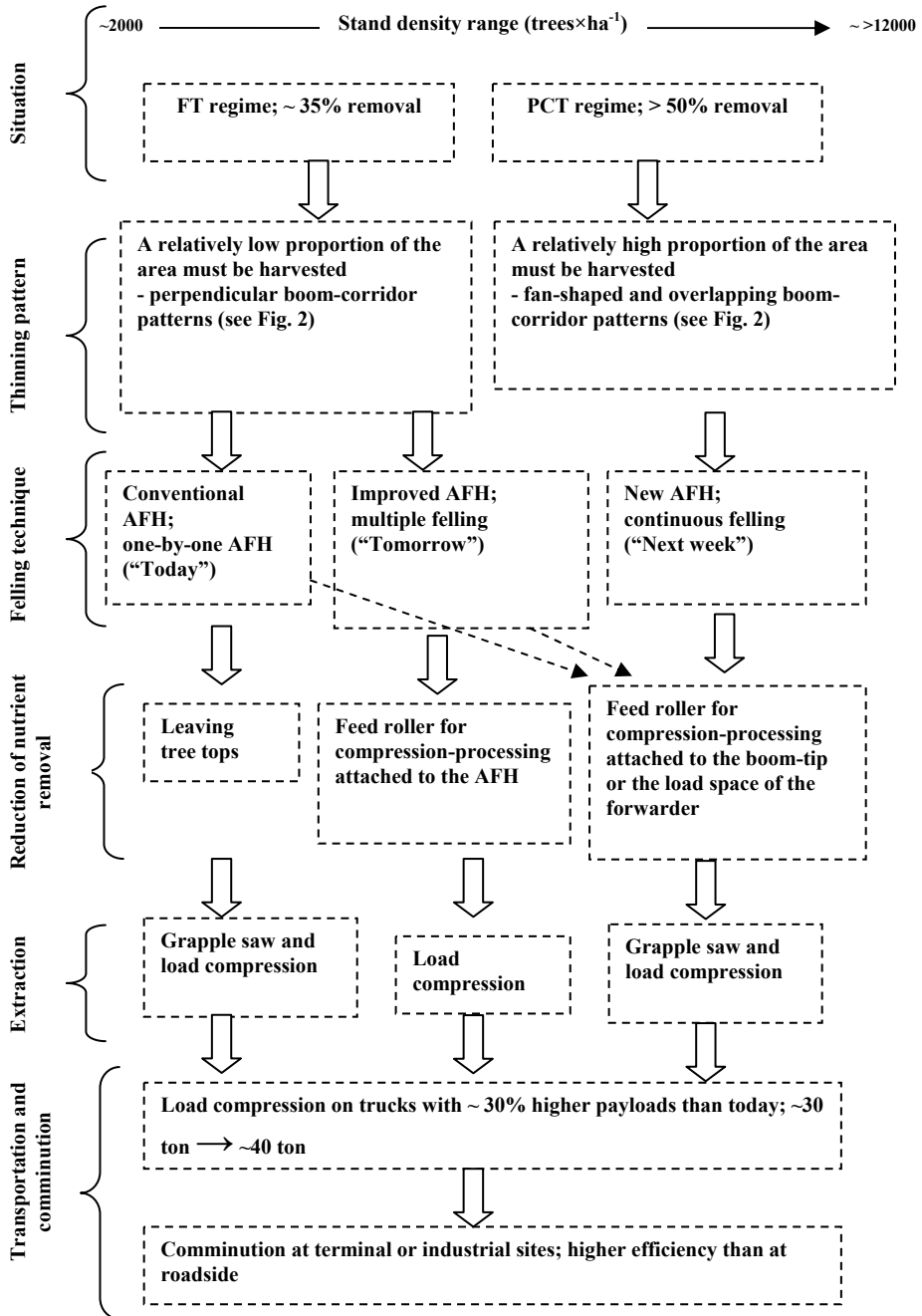


Figure 13. Boom-corridor thinning systems of “today”, “tomorrow” and “next week” and corresponding equipment for handling and moving whole trees and tree parts from the forest to industrial sites.

## 5 Conclusions

Young dense stands provide large volumes of biomass, but only minor volumes of merchantable pulpwood. In such stands it is costly to perform a PCT. It therefore seems likely that future trends will be to harvest the biomass of such stands as whole trees rather than to perform PCTs. This thesis shows that even today it is possible to perform a profitable harvest in certain young stands by conducting boom-corridor thinning.

Such harvests could generate a high net income, or at least a nil return, in very dense stands (with tress of about 6 cm dbh) if an appropriate felling and bunching technique is developed that is capable of felling and accumulating trees continuously boom-corridor-wise. Further, to maximize the financial parameters of the harvesting system, high payloads are needed, and to increase payloads early compression, during the harvest, is required followed by load compression before/at transportation. This thesis also describes techniques that reduce the foliage on harvested trees, and hence the removal of nutrients from the forest, while improving the quality of the wood as fuel (by reducing its ash contents).

If boom-corridor thinning is practiced with conventional AFHs in young dense stands the harvesting productivity increases on average by about 16%. However, if new techniques especially designed for the boom-corridor method are developed and applied, productivity and cost-efficiency could be greatly increased, up to two-fold, compared to using conventional felling and bunching techniques in boom-corridor thinning. Efforts to develop such techniques should focus on developing/improving conventional AFHs for multiple felling or on new techniques (and equipment) for harvesting a whole boom-corridor in one continuous movement. The former approach is appropriate for a FT regime and the latter for a PCT regime. Techniques specially designed for boom-corridor thinning should facilitate profitable harvests even in dense PCT stands.

Further, it seems possible to design continuous felling heads that are capable of felling trees at even higher movement speeds than those applied in the simulations and field studies this thesis is based upon. Compression processing techniques designed for processing trees bunch-wise should yield significant increases in bulk density, while reducing their ash-contents (and hence nutrient removal) to a low level. It seems likely that the studied equipment could be adjusted to fit a conventional system, e.g. by scaling it down and combining it with use of an AFH or attaching it to the frame of the load space of a forwarder. In addition, by using load compression techniques it is possible to significantly increase load bulk density to a level that would give low costs for transport in the terrain as well as on roads.

Harvesting for bioenergy not only has financial advantages in comparison to expensive PCT, but it also makes the possible volumes to harvest higher. This is of high interest for a country like Sweden, where the annual conventional harvest is not far short of the possible harvest (Anon. 2009). Since young dense stands account for about 12% of the forested area in Sweden (Anon. 2009) the main findings of the work presented in this thesis have substantial economic implications. They indicate that it may be profitable to manage young forests in such a way that they become dense and biomass rich. It may also be appropriate to perform efficient boom-corridor thinnings for bioenergy harvest in the first, and perhaps the second, management step practiced in conventional forestry. However, before applying these techniques at large-scale it is essential to assess fully the effects of boom-corridor thinning on the future stand development.

## 6 Future research

The effects of boom-corridor thinning found in Study II should be validated by repeating the experiments, under other conditions, using specially developed equipment to treat stands with different species compositions. Boom-corridor patterns other than perpendicular should also be evaluated, in trials in which harvested boom-corridors are marked out in advance for the operator to follow (since the efficiency is likely to be higher if a pre-planned thinning layout is used, because the operator would need to spend no, or at least less, time planning).

Studies to evaluate the effects of boom-corridor thinning in two stages on the remaining stands, in terms for instance of the spatial and size distribution of remaining trees, are also warranted.

There is a need to follow up the simulated findings in Study I, in which the “improved” harvesting approach *AFH-2m<sup>2</sup>* showed high efficiency. For this a prototype AFH for multiple felling should be designed and tested. A version could also be designed with an attached feed-roller-based compression-processing unit similar to the unit applied in Study IV (Fig. 14).

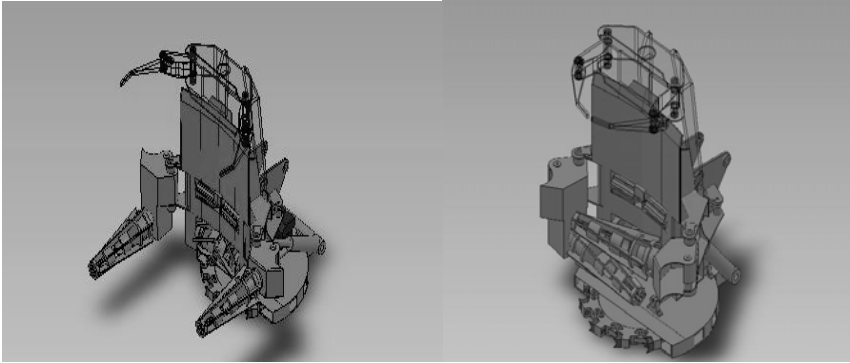


Figure 14. Sketch of an AFH with a feed-roller system for compression processing and a circular disc for cutting (Jönsson 2009).

To design and build such a harvester head should not be too difficult since even now single-grip harvester heads designed for accumulation and multiple processing are commercially available (see Waratah website, 2009). The only difference to such harvester heads would be in the ability to fell several trees in a relatively large area (e.g., 1-2 m<sup>2</sup>) and to process a large number of small trees simultaneously.

In Study III the *AFH-corr* harvesting approach (simulated in Paper I) was evaluated in the field, and although only the actual felling work was studied the overall concept looks promising to develop for use in practice. However, before the required work method is evaluated, the prototype must be further developed by e.g. increasing the possible felling distance to about 10 m; modifying the boom to allow it to move, both outward and inward, at a speed of about 1.5-2.0 m×s<sup>-1</sup> to evaluate the achievable movement speeds in stands with various densities and tree sizes; and designing, attaching and testing an accumulation device (Fig. 15).

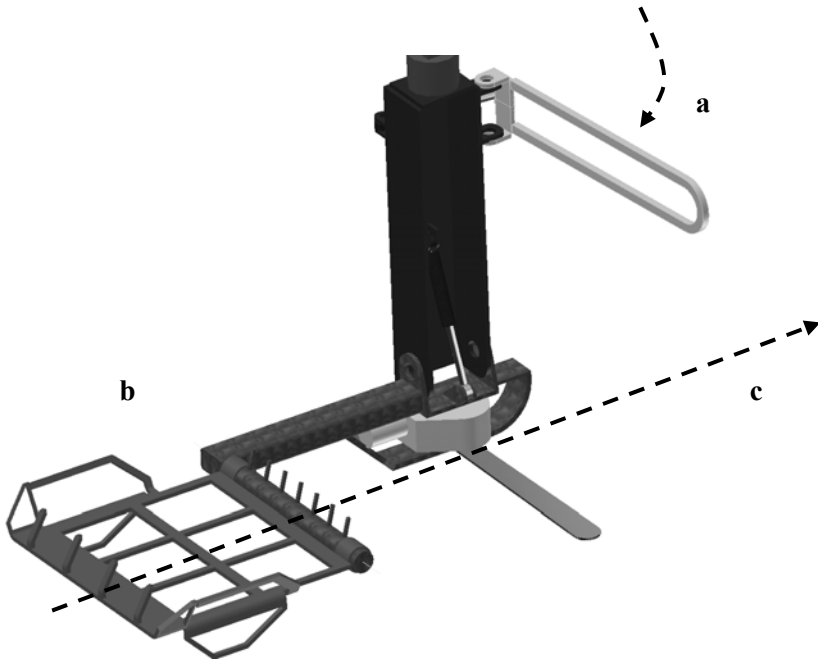


Figure 15. Hypothetical model of a felling head for continuous felling in boom-corridor thinning equipped with: a) a jointed “pusher” which swings outwards as the chain engages the tree for directing the felled trees in the desired direction; and b) a “sledge” for accumulation and pulling the felled trees to the side of the strip road. Felling direction indicated by the arrow towards “c”. Sketch by Hans Nilsson (Robotcentrum Norr AB, Umeå, Sweden).

Finally, it would be important to develop the simulation approach applied in Study I to evaluate the effects of harvesting with different types of AFHs in a wide variety of stands in combination with different boom-corridor patterns and intensities of removal. It could also be relevant to simulate the effects of using a machine equipped with two cranes for simultaneously felling and bunching in two boom-corridors (Fig. 16). The technique should be possible to use in the near future by applying some autonomous steering and shared-control functions. Significant positive effects on productivity could be expected.



Figure 16. Hypothetical harvester with two cranes for simultaneously felling and bunching in boom-corridors. Sketch by Hans Nilsson (Robotcentrum Norr AB, Umeå, Sweden).



## References

- Anon. 1995. IUFRO WP 3.04.02. Forest work study nomenclature. Test edition valid 1995-2000. Department of Operational Efficiency, Swedish University of Agriculture Sciences. Garpenberg. 16p. ISBN 91-576-5055-1.
- Anon. 2003. Avverkningen slår i taket. Skogseko Nr 2/2003 ([www.svo.se](http://www.svo.se)). (In Swedish).
- Anon. 2004. Statistical yearbook of Forestry. Official statistics of Sweden. National board of forestry, Jönköping, Sweden.
- Anon. 2007. Forestry statistics 2007 - Official Statistics of Sweden. Department of Forest Resource Management, SLU, Umeå. ISSN 0280-0543.
- Anon. 2009. Forestry statistics 2009 - Official Statistics of Sweden. Department of Forest Resource Management, SLU, Umeå. ISSN 0280-0543.
- Asplund, D., Nikku, P. & Savolainen, M. 1999. BIOENERGIA. Bioenergy research programme final report 1993-1998. Bioenergy publications no. 30. Jyväskylä Science Park Ltd. Jyväskylä. ISBN 952-5165-18-3.
- Bennecke, K. 1985. Whole-tree harvesting in young Norway spruce stands. *Allgemeine Forstzeitschrift* (19): 464.
- Berg, J., Linder, S. & Bergström, J. 2005. Potential production of Norway spruce in Sweden. *Forest Ecology and Management* 204(1): 1-10.
- Bergkvist, I. & Glöde, D. 2004. Stråkröjning – en metod med stor potential. [Corridor cleaning – a method with great potential]. Resultat nr. 3. Skogforsk. (In Swedish with English abstract).
- Bracke Forest, 2009. Technical data for Bracke C16.a. [www.brackeforest.com/](http://www.brackeforest.com/). Accessed 2009-10-28.
- Bredberg, C-J. 1972. Type stands for the first thinning. Research Notes Nr 55. Department of operational efficiency. Royal College of Forestry. Stockholm, Sweden. 42 p.
- Brunberg, T. 1999. Optimizing forwarder payloads. Skogforsk. Resultat nr. 1. ISSN 1103-4173. (Summary in English).
- Brunberg, B., Andersson, G., Nordén, B. & Thor, M. 1998. Uppdragsprojekt Skogsbränsle – slutrapport. SkogForsk Redogörelse nr. 6. Uppsala. (In Swedish).
- Claesson, S., Lundmark, T. & Sahlén, K. 1999. Treatment of young Scots pine dominated stands for simultaneous production of wood fuel and quality timber. In “Developing Systems for Integrating Bioenergy into Environmentally Sustainable Forestry” (A. T.

- Lowe & C. T. Smith, eds.), Vol. Forest Research Bulletin No. 211. 90 pp. New Zealand Forest Research Institute, Nokia, Finland.
- Dahlin, B. 1989. Cradle type multi-stem delimber. Swedish University of Agriculture Sciences. Doctoral thesis. ISBN 92-576-3849-7.
- Danielsson, B-O., Marks, J. & Säll, H-O. 1977. Compressing small trees and tree components. Royal College of Forestry. Department of Operational Efficiency. Research notes no. 119.
- Druska, K. & Konttinen, H. 1997. Tracks in the forest. Timberjack Group Oy. ISBN 952-90-8616-4.
- Eliasson, L. 1998. Analyses of single-grip harvesters productivity. Swedish University of Agriculture Sciences. Doctoral thesis. ISSN 1401-6230, ISBN 91-576-5614-2.
- Eliasson, L. 1999. Simulation of thinning with a single-grip harvester. *Forest Science* 45(1): 26-34.
- Eriksson, E. 2006. Thinning operations and their impact on biomass production in stands of Norway spruce and Scots pine. *Biomass and Bioenergy* 30: 848-854.
- ExTe, 2009. Description for the Com 90 system. [www.exte.se/eng/pages.asp?r\\_id=29614](http://www.exte.se/eng/pages.asp?r_id=29614). Accessed 2009-10-28.
- Gullberg, T. Johansson, J. & Liss, J-E. 1998. Studie av system EnHar vid uttag av skogsenergi i unga bestånd – Hamrestudien. 24 p. Arbetsdokument Nr 9. Högskolan Dalarna. Systemutveckling/Arbetsvetenskap. Garpenberg. In Swedish.
- Gustavsson, R. 1974. Type stands for cleaning. Research Notes No. 70. Department of operational efficiency. Royal College of Forestry. Garpenberg, Sweden. 58 p.
- Hakkila, P. 1991. Crown mass of trees at the harvesting phase. *Folia Forestalia* 773.
- Hakkila, P. 2005. Fuel from early thinnings. *International Journal of Forest Engineering* 16(1): 11-14.
- Heikkilä, J. Ylimartimo, M. & Mäkinen, P. 2005. Time consumption, work quality and costs of mechanized precommercial thinning. *Baltic Forestry* 11(1): 73-79.
- Jacobson, S., Kukkola, M & Mälkönen, E. 1999. Impact of slash removal and compensatory fertilization on tree stem growth in coniferous thinning stands. *Forest Ecology and Management* 129: 41-51.
- Jacobson, S., Kukkola, M., Mälkönen, E. & Tveite, B. 2000. Impact of whole-tree harvesting and compensatory fertilization on growth of coniferous stands. *Forest Ecology and Management* 129: 41-51.
- Jirjis, R. & Norden, B. 2005. Fuel quality and working environment during storage and handling of composite residue logs. Department of Bioenergy, Uppsala, Sweden. Report No. 7. ISSN 1651-0720.
- Johansson, J & Gullberg, T. 2002. Multiple tree handling in the selective felling and bunching of small trees in dense stands. *International Journal of Forest Engineering* 13(2): 25-34.
- Johansson, J., Liss, J-E., Gullberg, T & Björheden, R. 2006. Transport and handling of forest energy bundles – advantages and problems. *Biomass and Bioenergy* 30: 334 – 341.

- 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):32 – 42.
- Jylhä, P. & Latila, J. 2007. Energy wood and pulpwood harvesting from young stands using a prototype whole-tree bundler. *Silva Fennica* 41(4): 763 – 779.
- Jönsson, J. 2009. Utveckling av skördaraggregat. Tekniska Högskolan Umeå Universitet. Examensarbete: MA0909.
- Kallio, M. & Leinonen, A. 2005. Production technology of forest chips in Finland. Project Report, PRO2/P2032/05. VTT Processes.
- Komatsu Forest, 2009. Technical data for Valmet 860.4. [www.komatsuforest.se/default.aspx?mode=specs&id=10877](http://www.komatsuforest.se/default.aspx?mode=specs&id=10877). Accessed 2009-10-28.
- Kärhä, K., Rönkö, E. & Gumse, S-I. 2004. Productivity and cutting costs of thinning harvesters. *International Journal of Forest Engineering* 15(2): 43-56.
- Kärhä, K., Jouhio, A., Mutikainen, A & Mattila, S. 2005. Mechanized energy wood harvesting from early thinnings. *International Journal of Forest Engineering* 16(1): 15-26.
- Latila, J., Asikainen, A. & Nuutinen, Y. 2007. Forwarding of whole trees after manual and mechanized felling bunching in pre-commercial thinning. *International Journal of Forest Engineering* 18(2): 29-39.
- Ligné, D. 2004. New technical and alternative silvicultural approaches to pre-commercial thinning. Swedish University of Agriculture Sciences. Doctoral thesis. ISSN 1401-6230, ISBN 91-576-6715-2.
- Ligné, D., Eliasson, L. & Nordfjell, T. 2005a. Time consumption and damage to the remaining stock in mechanised and motor manual pre-commercial thinning. *Silva Fennica* 39(3): 455-464.
- Ligné, D., Nordfjell, T. & Karlsson, A. 2005b. New techniques for pre-commercial thinning – Time consumption and tree parameters. *International Journal of Forest Engineering* 16(2): 89-99.
- Linder, S. 1987. Responses to water and nutrition in coniferous ecosystems. In: Schultze, E.-D. and Zwölfer, H. (eds.), *Potentials and Limitations of Ecosystem Analysis. Ecol. Studies* 61:180-202. Springer-Verlag, New York, USA.
- Liss, J-E. 1999. Studie av system EnHar vid uttag av skogsenergi i unga bestånd – L:a Främsbacka. Arbetsdokument nr 8. Högskolan Dalarna. (In Swedish).
- Liss, J-E. 2004. Avverkningsvolym och netton i didig gallring vid alternativ skogsbränsle eller massaved. Arbetsdokument nr 4. Högskolan Dalarna. (in Swedish).
- Nordén, B. 1984. Komprimeringsutrustning till skotare. [Compression device for forwarders]. *Forskningsstiftelsen, Skogsarbeten, Resultat nr 11*. (In Swedish).
- Nordén, B. 1991. Komprimering av träddeklar och trädrester vid skotning och vidaretransport. [Compression of tree parts and logging residues in off-road and road transports]. *Forskningsstiftelsen, Skogsarbeten, Stencil*. (In Swedish).
- Nordfjell, T & Liss, J-E. 2000. Compressing and drying of bunched trees from a commercial thinning. *Scandinavian Journal of Forest Research* 15: 284-290.

- Nordfjell, T., Nilsson, P., Henningson, M. & Wästerlund, I. 2008. Unutilized biomass resources in Swedish young dense stands. Proceedings: World Bioenergy 2008, 27 -29 May, Jönköping, Sweden. pp: 323-325.
- Nordin, A. & Levén, P. 1997. Ash related operational problems in biomass fired units. Stiftelsen för värmeteknisk forskning. Stockholm. ISSN 0282-2772. (In Swedish, with summary in English).
- NREL. 2002. Transitions to a new energy future. U.S. Department of Energy's National Renewable Energy Laboratory, 2002 Research Review.
- Nurmi, J. & Hillebrand, K. 2007. The characteristics of whole-tree fuel stocks from silvicultural cleaning and thinnings. *Biomass and Bioenergy* 31: 381-392.
- Petterson, M. & Nordfjell, T. 2007. Fuel quality during seasonal storage of compacted logging residues and young trees. *Biomass and Bioenergy* 31: 782-792.
- Petterson, N. 1992. The effect on stand development of different spacing after planting and precommercial thinning in Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) stands. Doctoral thesis. Swedish University of Agricultural Sciences, Garpenberg.
- Richardson, J., Björheden, R., Hakkila, P., Lowe, A.T. & Smith, C.T. 2002. Bioenergy from sustainable forestry – Guiding principles and practice. *Forestry Sciences*. Vol. 71. ISBN 1-4020-0676-4.
- Ringman, M. 1996. Wood fuel assortments – definitions and properties. Department of Forest Products. Report No. 250. The Swedish University of Agriculture Sciences. Uppsala. ISSN 0348-4599.
- Rummer, R.B. 1993. Thinning with the Gafner Tri-Trac feller/buncher: a case study. Research Paper of the Southern Forest Experiment Station. USDA Forest Service. (SO-273): 5.
- Röser, D., Asikainen, A., Raulund-Rasmussen, K. & Stupak, I. 2008. Sustainable use of forest biomass for energy. *Managing forest ecosystems*. Vol. 12. Springer. ISBN 978-1-4020-5053-4.
- Suadicani, K. & Nordfjell, T. 2003. Operational aspects of row and selective thinning in the establishing of a shelterwood in a 50-year-old Norway spruce stand. *International Journal of Forest Engineering* 14(1): 25-37.
- Sundberg, U. & Silversides, C.R. (1988). Operational efficiency in forestry. Vol. 1: Analysis. Kluwer Academic Publishers, The Netherlands. ISBN 90-247-3683-8.
- Talbot, B. & Suadicani, K. 2005. Analysis of two simulated in-field chipping and extraction systems in spruce thinnings. *Biosystems Engineering* 91(3): 283-292.
- Thörnqvist, T. & Jirjis, R. 1990. Changes in fuel chips during storage in large piles. Swedish University of Agricultural Sciences. Department of Forest Products. Report 219. ISSN 0348-4599.
- Varmola, M. & Salminen, H. 2004. Timing and intensity of precommercial thinning in *Pinus sylvestris* stands. *Scandinavian Journal of Forest Research* 19 (2): 142-151.
- Waratah, 2009. Waratah Forestry attachments.  
[www.waratah.net/en\\_US/waratah/index.html](http://www.waratah.net/en_US/waratah/index.html). Accessed 2009-10-28.
- Quadco Equipment Inc., 2009. Technical data for saw discs and teeth.  
[www.quadco.com/english/home.html?sawteeth](http://www.quadco.com/english/home.html?sawteeth). Accessed 2009-10-28.

## Acknowledgements

This work was financed by the Petersson-Grebbe Foundation, the Kempe Foundation, the Nordic Forest Research Cooperation Committee, European Union structural funds and the research programs “Utilization of the boreal forest”, “Botnia-Atlantica (Forest Power)” and “Efficient Forest Fuel Supply Systems (ESS)”.

I would like to thank my supervisors Tomas Nordfjell and Urban Bergsten and all other colleagues concerned at the Faculty of Forest Sciences for guiding me through relevant aspects of forestry, general science and other matters.