Citation for the published paper:
Fulvio Di Fulvio, Anders Kroon, Dan Bergström & Tomas Nordfjell. (2011) Comparison of energy-wood and pulpwood thinning systems in young birch stands. *Scandinavian Journal of Forest Research*. Volume: 26, Number: 4, pp 339-349.
http://dx.doi.org/10.1080/02827581.2011.568951.

COMPARISON OF ENERGY-WOOD AND PULPWOOD THINNING SYSTEMS IN YOUNG BIRCH STANDS

Fulvio Di Fulvio[a,*], Anders Kroon[b], Dan Bergström[a], Tomas Nordfjell[a]

[a]Department of Forest Resource Management, Swedish University of Agricultural Sciences, Skogsmarksgränd, SE-901 83 Umeå, Sweden

[b] Södra, Skogsudden, 351 89 Växjö Sweden

[*]Corresponding author: Phone +46 90 786 82 25, Fax +46 90 77 81 16,

E-mail: Fulvio.Di.Fulvio@slu.se

Abstract

In early thinning, a profitable alternative to pulpwood could be to harvest whole trees as energy-wood. In theoretical analyses we compared the extractible volumes of energy-wood and pulpwood, and their respective gross values in differently aged stands of early birch thinnings at varying intensities of removal. In a parallel field experiment we compared the productivity at harvest of either pulpwood or energy-wood, and the profitability when the costs of harvesting and forwarding were included. The theoretical analyses showed that the proportion of the total tree biomass removed as pulpwood, increased with increasing thinning intensity and stem size. The biomass volume was 1.5 - 1.7 times larger than the pulpwood volume for a 13.9 DBH stand, and 2.0 - 3.5 times larger for a 10.4 DBH stand. In the field experiment, the harvested volume per ha of energy-wood was almost twice as high as the harvest of pulpwood. The harvesting productivity (trees PW-hour^{-1}) was 205 in the energy-wood and 120 in the pulpwood treatment. The pulpwood treatment generated a net loss, while the energy-wood treatment generated a net income, the average difference being €595 ha^{-1}. We conclude that, in birch dominated early thinning stands, at current market prices, harvesting energy-wood is more profitable than harvesting pulpwood.

Keywords: Efficiency, time consumption, fuel wood, economy, field study, bioenergy.

INTRODUCTION

In Sweden, young forests, which we define here as forests dominated by trees at least 1.3 m tall and with a diameter at breast height (DBH) below 10 cm over-bark (o-b), account for 17.3 % (3.9 million ha) of the total productive area of forested land (Swedish University of Agricultural Sciences 2009). Of the total standing volume in Swedish forests, the volume of trees with DBH up to 14 cm accounts for 21.9 % (ca. 748 million m^3 solid o-b) (Swedish University of Agricultural Sciences 2009). Of this volume, Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst.) and birch (*Betula spp.*) account for about 26 %, 36 % and 25 %, respectively (Swedish University of Agricultural Sciences 2009). In Fennoscandia, the typical treatment of young stands includes a pre-commercial thinning when the average DBH is below ca. 10 cm and commercial pulpwood thinning at larger DBH. The stands are generally thinned from below, and the proportion of hardwood trees removed is often high, even in softwood stands. Especially in Finland, the typical management of birch stands includes two commercial thinnings during the rotation with removal rates ranging from 30 % to 40 %, in order to ensure a high yield of good quality timber at final felling and the adequate removal of merchantable wood (Hynynen et al. 2010). Because the first thinning treatment aims to leave a future crop at a density of about 1500 trees ha^{-1}, harvesting intensity depends on the initial stand density.

Single-grip harvester heads are commonly used in early thinnings for pulpwood, and the harvester's productivity is affected by the average size of removed stems, the stand density, and the intensity of removal (Eliasson 1999). In the cut-to-length system of harvesting pulpwood, merchantable logs must typically exceed about 3 m in length and have a cut-top diameter of at least 6 cm (o-b). As a consequence 20 % - 30 % of the cut trees are too small for pulpwood and are therefore discarded at the felling site (Hakkila 2005). Furthermore, the tops of harvested trees constitute a considerable part of harvested volume, much of which is left on the harvesting site. A more profitable alternative to harvesting pulpwood may be to harvest all the biomass above the felling cut as fuel for energy generation (Sirén et al. 2006). In the energy-wood system there are no size restrictions, and therefore the whole volume of all harvested trees is available for commercial extraction. Compared to pulpwood, harvesting for energy can remove 15 % - 50 % more biomass and multi-tree handling harvester heads can increase productivity by as much as 35 % – 40 % compared to single-tree handling (Björheden et al. 2003, Jylhä & Laitila 2007). This means that the harvesting costs from stump to roadside can be reduced by 20 % - 40 % (Hakkila 2003). In energy-wood harvesting, accumulating felling heads (AFH) are commonly used, which are mounted either on single-grip harvesters or on specially designed feller-bunchers (Johansson & Gullberg 2002, Kärhä et al. 2005, Bergström et al. 2007). Nevertheless in the energy-wood harvesting system (including forwarding and comminution), the felling and bunching operation remains the largest cost component (Kärhä et al. 2005, Laitila 2008).

A first thinning can be harvested for pulpwood or energy-wood. Which of these alternative products is most profitable depends on the relationship between merchantable volumes, biomass prices and the costs of the respective harvesting systems and supply chains.

The objectives of the present study were to compare: 1) the extractible raw material volumes of energy-wood and pulpwood and their respective gross (stumpage) values in different type of stands at varying intensities of removal; 2) the productivities of harvesting pulpwood and energy-wood (whole trees) in early thinnings of birch, using the same base machine and operator; 3) the profitability (net income) when including operational costs for harvesting and forwarding from stump to roadside.

MATERIALS AND METHODS

The present study consists of three different parts: a theoretical analysis of merchantable volume availability of energy-wood and pulpwood in first thinning type stands; a field study aimed to compare the productivity of a harvester in pulpwood and energy-wood harvesting; and an analysis of the economic profitability of the two alternative systems when also the forwarding operation to road side is included.

Theoretical study: Merchantable volume availability

The availability of merchantable volumes of pulpwood and energy-wood in different types of first thinning stands was estimated using actual data derived from real forest stands (Bredberg 1972). In the analysis, we used data from three birch-dominated stands aged 24, 30 and 35 years and situated in Central Sweden (latitude from 59°50 'N to 62°10 'N, altitude from 50 to 450 m a.s.l.). The stands contained a mixture of birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.) and other broadleaves; the composition of the broadleaves was not further specified in Bredberg (1972). In each of the stands, the volumes that would need to be removed in order to reduce the basal areas at three levels of intensity per treatment, i.e. 20 %, 30 % and 40 % were calculated. Only trees with a DBH $\geq$ 5 cm were used in the calculations, and the suggested thinning 'priority' (from below) was used based on DBH class and future stand position as given by Bredberg (1972). The proportions of pulpwood and energy-wood stem-volumes in the respective diameter classes were calculated on the basis of diameter at stump height, DBH, bark thickness, and height and length of roundwood stems. The minimum pulpwood stem diameter under-bark (u-b) was set to 5 cm and the length of merchantable logs was set to range between 3.0 m and 5.5 m. The pulpwood stem-volume u-b was calculated using the formula for the volume of a cone with the mid-length diameter of a piece of pulpwood as a parameter. The oven-dry (OD) biomass of stems, branches and needles was calculated using Marklund's (1987) functions, and converted into solid volume (m^3) by using stem basic densities and values for crown biomass given by Hakkila (1978).

Field study

The study area was located in the community of Ängelholm (56°15'N, 12°51'E) in southern Sweden. Birch (*Betula pendula* Roth) comprised 93.3 % of trees, with the remaining 6.7 % Norway spruce. It had been subjected to pre-commercial thinning before the time of the study.

Twelve experimental plots were marked out, each corresponding to at least 30 minutes of Productive harvesting Work Time (PW) (IUFRO 1995). In each of the plots, a centre line (strip road centre) with a start and stop sign were marked out. All plots were characterized by systematically measuring the DBH o-b, diameter at stump height, and height of sample trees in nine, 28.3 m² circular areas regularly placed along the centre line. The characteristics of the terrain in terms of ground strength, surface structure and slope, was measured in all plots as 1.1.1 according to Berg (1992): i.e. the ground had high bearing capacity and the surface was smooth with almost no slope. The stem-volumes of trees were calculated using Andersson's (1954) (DBH $\leq$ 5 cm) and Näslund's (1947) (DBH > 5 cm) functions. The 12 plots were then paired to form six blocks with similar tree densities and average DBH (Table 1).

The experiment was set out as a randomized block design with two treatments randomly assigned (to the plots) in each block. The effects were assessed by analysis of variance using the two-way ANOVA model:

$y_{ij} = \mu + t_i + b_j + e_{ij}$, were μ is the overall mean, t_i the treatment main effect, b_j the block main effect, and e_{ij} the random error term. The differences were considered significant if $p \leq 0.05$.

The base machine used in the experiments was an eight-wheeled GREMO 950 HPVR (Gremo AB, Sweden) harvester with a mass of 14 tonnes (t), a width of 2.6 m and a LOGLIFT 181 V crane with a maximum boom reach of 10 m (Loglift Jonsered AB, Sweden). In the pulpwood treatment, a LOGMAX 4000B (Log Max AB, Sweden) harvester head (mass 625 kg) was used, and in the energy-wood treatment a SILVATEC (Silvatec Skovmaskiner A/S, Denmark) accumulating felling head (mass 480 kg) was used. Although the LOGMAX 4000B harvester head was equipped with grapples for multi-tree handling, this feature was not used during the experiments. One machine operator, who had had six years of experience in thinning operations operating similar base machines, carried out both harvesting treatments. He had also had experience with the SILVATEC felling head and with ordinary single-grip harvester heads. Although he had had no experience with the specific LOGMAX harvester head, he did have experience with a similar harvester head.

The harvesting operation was performed as thinning from below, the operator deciding which trees to harvest and aiming to leave about 1400 future crop trees ha^{-1}. In the pulpwood treatment, trees located adjacent to the strip roads were pulled over to be processed on the opposite side of the strip road leaving branches and tops of processed trees on the strip road area. The length of the pulpwood logs should range between 3.0 m and 5.0 m with a top diameter of at least 5 cm u-b. Any felled trees that were too small for pulpwood were left lying in the stand. In the energy-wood treatment, whole trees were felled and bunched along the strip road with their butt-ends pointing towards the strip roads.

The Work Time (WT), including delays (IUFRO 1995), was divided into seven separate work elements (Table 2). In order to record work elements of rather short duration time, the time consumption was measured by a frequency time study method. The current work element was registered every seven seconds, and if two elements overlapped, only the element with highest priority (lowest number) was registered (Table 2). In addition to measuring the frequency of operations, the total time was also recorded with a stopwatch. The same researcher recorded all time data. During energy-wood harvesting, the number of accumulated trees in each crane cycle was also registered.

The experiments were performed during September 2008 in daylight conditions. The time study had an overall duration of 7.3 WT-hours. All plots were harvested from the east to the west and there were no disturbances due to weather. Only minor delays occurred during the whole experiment: e.g. some breakages of saw chains and hydraulic hoses. Because the accumulating function of the SILVATEC felling head did not work properly when harvesting the energy-wood treatment in block 4, the corresponding time consumption data were excluded from the productivity model calculations.

After harvesting in the energy-wood treatments, the diameter at stump height of each harvested tree was measured. Subsequently, all trees harvested per plot were hauled to the roadside and chipped into containers. The material was then transported to a power plant where the bulk volume, mass, moisture content and energy content of the chipped material were measured. The volume of harvested pulpwood o-b was calculated by measuring the length of each log and its mid-length diameter; the volume was then reduced by 18 % to account for the bark content (Praktisk skogshandbok 1994). In each plot, two rectangular transects (5 m × 20 m) were laid out perpendicular to the strip road centre, in which damage to the remaining trees was measured and grouped in dimensional classes according to the size and location of the damage. Any damage to trees within the stand and at the edge of the strip road was recorded separately.

Economic analyses

Stumpage prices were based on the Swedish market prices in 2009 when the roadside price of birch pulpwood o-b was 278 SEK m^{-3} (340 SEK m^{-3} u-b) and the roadside price of energy-wood (as tree parts) was 200 SEK m^{-3} (solid volume of stem, branches and needles). Prices and costs were converted into Euros (€), assuming an exchange rate of €1 = 10 SEK. The productivity of pulpwood forwarding was based on Kuitto et al.'s (1994) model for hardwood, which gives an average value of 16.3 m^3 o-b PW-hour^{-1}. The PW of whole trees (energy-wood) forwarding was based on Laitila et al.'s (2007) model for birch tree parts, which gives an average value of 13.8 m^3 biomass PW-hour^{-1}. The productivity calculations were made for a forwarding distance of 200 m and a haulage load of 8 m^3 solid for pulpwood and 6 m^3 solid for energy-wood. The PW was converted to WT using the coefficient 1.3 for the harvester and 1.2 for the forwarder (c.f. Laitila 2008). The operating costs of the harvester were set to €80 WT-hour $^{-1}$ and to €70 MW-hour $^{-1}$ for the forwarder (machine relocation costs not included). The net values of removals in all harvesting conditions were calculated.

RESULTS

Theoretical study: Volume availability

The proportion of the total tree biomass volume per ha removed as pulpwood increased with increasing thinning intensity and stem-size removal. The harvested biomass volume was 1.5 - 1.7 times higher than the pulpwood volume in the 'old' stand. In the 'middle-aged' stand 2.0 – 3.5 times more biomass than pulpwood was harvested. In the 'young' stand energy-wood biomass was almost the only material that could be harvested (Table 3). The gross income for pulpwood varied between 0 and 1551 € ha^{-1}. The corresponding values for energy-wood varied between 324 and 1715 € ha^{-1}. At 30 % intensity of removal of basal area, the gross income for pulpwood compared to energy-wood was 12 % lower in the 'old' stand, 43 % lower in the 'middle-aged' stand and 74 % lower in the 'young' stand.

Field study

No significant differences between harvesting treatments were found on the harvested properties basal area, trees ha^{-1}, strip road width and tree sizes (Table 4). The harvested volume per ha was significantly higher in the energy-wood treatment, being almost twice as high as in the pulpwood treatment due to the added volume from tops, branches, and trees that were too small for pulpwood. The biomass to pulpwood volume ratio of removal was 1.9. There was a tendency of there being more damage on remaining trees after the pulpwood treatment than after the energy-wood treatment ($p = 0.064$).

In total, 22.8 m^3 o-b of pulpwood and 40.1 solid m^3 (20 OD t) of energy-wood were harvested. The length of the harvested pulpwood logs ranged between 310 cm and 455 cm and averaged 390 cm. In the energy-wood treatment, on average 58 % of felled trees were handled in multiples, each bunch containing, on average, 1.9 trees. The PW consumption per tree was 41 % less in the energy-wood than the pulpwood treatment, the difference being highly significant ($p < 0.001$) (Table 5).This difference was mainly due to the fact that the PW consumption per harvested tree of the *Felling and accumulating* work element was 57 % less in the energy-wood treatment compared to the corresponding *Felling and Processing* work elements in pulpwood treatment. The highest share of consumed PW was found for the work elements *Boom out* and *Boom in*, which together accounted for 65 % in the energy-wood treatment and 54 % in the pulpwood treatment. The share of the work element *Felling and accumulating* accounted for 24 % of PW in the energy-wood treatment and 9 % in the pulpwood treatment. The work element *Processing* consumed about 23 % of the total PW in the pulpwood treatment. The work element *Moving* accounted for about 11 % of PW in both treatments; the similarity of this value was mainly related to both treatments working to the same strip road pattern. The share of *Delay* time of total MW was less than 3 % in both treatments.

The average number of trees harvested per PW-hour in energy-wood and pulpwood treatments was 205 and 120, respectively, and this difference was significant ($p < 0.001$). On average, the productivity was 11.2 m^3 biomass PW-hour^{-1} in the energy-wood treatment, and 3.7 m^3 pulpwood PW-hour^{-1} in the pulpwood treatment. For both treatments, the productivity increased with increasing harvested stem-volume (Fig. 1).

Economic analyses

In the energy-wood treatment the gross income was 40 % higher than that of the pulpwood treatment, the difference being €440 ha^{-1} (Table 6). The harvesting cost per hectare, including forwarding, was 12 % lower in the energy-wood system than the pulpwood system. The cost of the harvester was 60 % of total harvesting costs in the energy-wood treatment, and 85 % in the pulpwood system. On average, the net income was negative in the pulpwood treatment, but positive in the energy-wood treatment (Table 6). In both treatments, income increased with increased harvested stem-size (Fig. 2). On average, the difference in net income per ha was €595 (Table 6).

DISCUSSION

Theoretical study: Volume availability

It was found that, in first thinnings of birch-dominated stands, it is possible to extract 1.5 - 3.5 times more volume as energy-wood (solid volume) than when extracting only pulpwood. The share of harvested pulpwood volumes compared to the volumes of whole trees, increased with increasing size of harvested trees and increased thinning intensity, which is in accordance with findings of Heikkilä et al. (2007). The quantity of energy-wood volume removal per ha increases if trees below 5 cm DBH (u-b) are included in the analyses. This fraction constituted 1 % of the total in our field study (pre-cleared stand), although it can form as much as 6 % of the removal volume in dense, un-cleared stands (Bergström et al. 2010). In the present study, the stands were thinned strictly from below, i.e. remaining trees were evenly distributed with no consideration given to the opening of strip roads. If the thinning of strip roads were to be included, then the average size of harvested trees and thinning intensity would be increased.

In the volume availability calculations no consideration to ecological restrictions was taken, but whole-tree harvesting can lead to growth decreases in the short term. Mård (1998) found in early thinning stands of birch that the decrease of growth was not significant in the first 5 years after whole tree removal. Nevertheless the observation period may have been too short to give reliable results. Conversely, Jacobson et al. (2000) found a 5 - 6 % decrease of increment in the first 10 years after intensive harvesting (whole-tree removal) compared to a conventional thinning (removal of only stem-wood) in first thinning stands of Norway spruce and Scots pine . Nutrient losses can be reduced by about 40 % - 50 % by either cutting off the tree-tops and leaving them at the felling site, or by using compressing processing technology to scrape off a significant proportion of attached needles and fine branches (Jylhä 2004, Bergström et al. 2010). However another alternative, to compensate the growth reduction, is the fertilization of the stand some years after the thinning treatment (Jacobson et al. 2000).

It is important to underline the fact that the use of first thinning trees for pulpwood or energy-wood will depend on the relative prices of the two alternative products**,** as well as the relative volumes of the two products that can be harvested in a specific stand. In fact, if the yield of pulpwood exceeds 20 m^3 ha^{-1}, profitable alternatives to extracting only pulpwood are either the combined harvest of wood for industrial and energy purposes, or delayed industrial wood harvesting (Heikkila et al. 2007). If whole trees are harvested, pulpwood can still be separated at the processing terminal or industrial site, and the residues used for generating energy (Jylhä 2004). Such an integrated harvest of energy-wood and pulpwood can increase the removal rate by up to 50 % (Jylhä & Laitila 2007).

Under these circumstances, the minimum diameter for pulpwood fundamentally affects the distribution of harvested and recovered wood between industrial and energy end-uses (Sirén et al. 2006). The minimum top diameter of roundwood is especially relevant if a large proportion of the wood is not suitable for industrial use (Suadicani 2003; Suadicani & Talbot 2010).

However, the integrated production of pulpwood and energy-wood can be more expensive than harvesting only pulpwood, because several machines must necessarily operate on the same area. To reduce the number of machines, bundle harvesters can be used (Jylhä 2004) although these tend to have lower productivity.

At current market prices, the removal of whole trees for energy gives a higher gross income than if only pulpwood is extracted. In the present study, the energy-wood to pulpwood price ratio was 0.7. The equivalence of the gross income corresponds to a biomass to pulpwood product ratio (solid volumes) of 1.4, i.e. below 1.4 the pulpwood income is higher. This situation is only possible at a harvesting intensity of at least 40 % of basal area in the 'old' stand. If we take the 'middle-aged' stand and a thinning intensity of 40 % of the basal area, the energy to pulpwood (product) volume ratio is 2.0, giving a gross income for pulpwood 32 % lower than for energy-wood. If we assume a price increase of 30 % for energy-wood, i.e. from €20 m^{-3} to €26 m^{-3}, giving a price ratio of 0.9, the difference in gross income will be 47 %. The gross income will be equal if the price for energy-wood decreases by 30 % from €20 m^{-3} to €14 m^{-3}, giving a price ratio of 0.5 (Fig. 3).

In a situation in which the pulpwood price is low and the energy-wood price is high, the first thinning will lead to a pure energy-wood harvesting; while if the pulpwood price is high and the energy-wood price low, the treatment will lead to a pure pulpwood harvesting; while if both prices are high it will be possible to have a combined harvesting of the two products; conversely, if both prices are low, it will be possible to have a delayed industrial wood harvesting.

Field study

Between stem-volumes of 31 dm^3 and 44 dm^3 per harvested tree, productivity increased with increasing stem-volume and was, on average, significantly higher for the energy-wood than the pulpwood treatment. The average productivity of the energy-wood treatment found in present study is similar to that observed by Kärhä et al. (2006), the difference being less than 2%. Furthermore, in the energy-wood treatment, stem-size removal was over 35 dm^3, the average bunch size was less than two stems when using the accumulating felling head, a result also found by Kärhä et al. (2006). However, the average productivity in the pulpwood treatment was 32 % lower than that found by Kärhä et al. (2004). This difference could be due to differences of machinery, skill of the operator, and/or using less efficient working methods. The presence of undergrowth (mainly spruce) can have a negative effect on harvester productivity in thinning operations (Kärhä 2006). In the present study, a pre-commercial thinning had already been carried out in advance, so that any effects from undergrowth were minimized. The level of damage to the remaining trees was close to 5 % in both treatments, which is considered to be an acceptable level in Sweden.

Economic analyses

The energy-wood harvesting system resulted in a positive income while the pulpwood harvesting system resulted in a negative income. The field study was limited in size and therefore yielded insufficient data for operative coefficients (e.g. delay time) to be calculated. Instead, in the analysis, data obtained from other studies were used (Laitila 2008). Consequently, in the economic calculations the same values (operative coefficients) were used for both harvesting methodologies. The models that we used in forwarding productivity calculations were selected according to Heikkilä et al. (2006), who observed the productivity of forwarding whole trees to be 10 % - 20 % lower than forwarding delimbed wood, due to the reduction in load size and the lower efficiency when loading and unloading whole trees. The results of our comparison of systems would therefore differ if the forwarding distance were to be increased, since forwarding energy-wood is likely to be more sensitive to distance than forwarding pulpwood. The results of the comparison will also differ when using different models in forwarding calculations. The Nurminen et al. (2006) model for pulpwood forwarding gives a 15 % lower productivity than Kuitto et al.'s (1994) model; a difference that could be due to the fact that the former study was based on only a limited amount of observations, while Kuitto et al.'s (1994) study included different thinning conditions, machines, and operators. Accordingly if using the model provided by Nurminen et al. (2006) for pulpwood forwarding, the productivity would be the same as for energy-wood forwarding; an assumption that would be unrealistically favourable for an energy-wood system.

The economic analysis was based on the roadside price of the product. However the results of the comparison would differ if prices at the end-use facilities were assumed instead, since energy-wood is more sensitive than pulpwood to road transportation distances (Spinelli & Magagnotti 2010). Moreover, no machine's relocation costs were included in the roadside net income calculations. If we assume a cost of €200 per machine, and an average stand surface of 3 ha, the incidence of relocations will be 9 % - 10 % of total costs (€133 ha^{-1}). Thus, net income for pulpwood was - €376 ha^{-1}, and for energy-wood was €219 ha^{-1}, a difference of €595.

In the present study, either the pulpwood harvesting productivity needs to increase by 104 % in order to reach the same profitability of the energy-wood system, or the pulpwood price needs to increase by 54 %, which corresponds to an energy-wood to pulpwood price ratio of 0.5. If we assume a price increase of 30 % for pulpwood, giving a price ratio of 0.6, the difference between the two systems will be €267 ha^{-1} in favour of the energy-wood system. If the energy-wood price increases by 30 %, giving a price ratio of 0.9, the average difference between the systems will be €1055 ha^{-1} in favour of the energy-wood system. If the pulpwood harvesting productivity is instead based on Kärhä et al.'s (2004) data, the pulpwood net income becomes positive (€6 ha^{-1}) and the difference between this system and the energy-wood system in the present study would be €213 ha^{-1}, and still in favour of the energy-wood system.

Conclusions

In Sweden, the standing volume of birch dominated forests represents about 25 % of the total volume of young forests containing trees up to 14 cm DBH (Swedish University of Agricultural Sciences 2009). Our results are therefore relevant to a large number of young forests. Furthermore, the relationships between volumes and prices are almost the same in softwood stands. This indicates that this study, in general, is relevant for most young forests in Sweden with DBH of 9-14 cm. The pulpwood to energy-wood volume ratio increases with increased thinning intensity and a larger stem-size removal in the first thinning from below of birch-dominated stands. The present study shows a three times higher productivity for energy-wood harvesting (m^3 biomass PW-$hour^{-1}$) than for pulpwood harvesting (m^3 o-b PW-$hour^{-1}$). In such stands, and with current market prices, the gross value per ha of the energy-wood is superior to pulpwood. Harvesting costs per cubic metre are lower for the energy-wood harvesting system than for the pulpwood system. If the stem-size of removed material is less than 40 dm^3, the net income of the pulpwood harvest is negative due to costs, while a removal of whole trees for energy can still be profitable.

ACKNOWLEDGEMENTS

This study was financed by the research programme 'Botnia-Atlantica (Forest Power)'. We thank Sees-Editing Ltd. for the professional revision of the English language.

REFERENCES

Andersson, S-O. (1954). *Funktioner och tabeller för kubering av småträd [Functions and tables for cubing of small trees]*. Meddelanden från Statens Skogsforskningsinstitut, Band 44 nr 12, 1-29. (In Swedish).

Berg, S. (1992). *Terrain classification system for forestry work.* pp.1-28 Kista: The Forest Operations Institute of Sweden.

Bergström, D., Bergsten, U., Nordfjell, T. & Lundmark, T. (2007). Simulation of geometric thinning systems and their time requirements for young forests. *Silva Fennica, 4(1)*, 137-147.

Bergström, D., Nordfjell, T. & Bergsten, U. (2010). Compression Processing and Load Compression of Young Scots Pine and Birch Trees in Thinnings for Bioenergy. *International Journal of Forest Engineering, 21(1)*, 31-39.

Björheden, R., Gullberg, T. & Johansson, J. (2003). Systems analyses for harvesting small trees for forest fuel in urban forestry. *Biomass and Bioenergy, 24*, 389-400.

Bredberg, C.-J. (1972). *Type stands for the first thinning,* Research Notes, Vol. 55, 42 p Stockholm, Sweden: Department of operational efficiency. Royal College of Forestry.

Eliasson, L. (1999). Simulation of thinning with a single grip harvester. *Forest Science, 45(1),* 26-34.

Hakkila, P. (1978). Harvesting small-sized trees for fuel. *Folia Forestalia,* 342, 1-38. (In Finnish with English abstract).

Hakkila, P. (2003). *Developing technology for large-scale production of forest chips.* pp. 36-42. (Wood Energy Technology Programme 1999–2003, Tekes-Technology programme report). Helsinki: TEKES.

Hakkila, P. (2005). Fuel from early thinnings. *International Journal of Forest Engineering, 16(1)*, 11-14.

Heikkilä, J., Laitila, J., Tanttu, V., Lindblad, J., Sirén, M. & Asikainen, A. (2006). Harvesting alternatives and cost factors of delimbed energy wood*. Forestry Studies, (Metsanduslikud Uurimused), 45*, 49-56.

Heikkilä, J., Sirén, M. & Aijälä, O. (2007). Management alternatives of energy wood thinning stands. *Biomass and Bioenergy, 31*, 255-266.

Hynynen, J., Niemistö, P., Viherä-Aarnio, A., Brunner, A., Hein, S. & Velling, P. (2010). Silviculture of birch (Betula pendula Roth and Betula pubescens Ehrh.) in northern Europe. *Forestry, 83(1),* 103-119.

IUFRO (1995). *WP 3.04.02. Forest work study nomenclature. Test edition valid 1995-2000,* 16 pp. Garpenberg, Sweden: Department of Operational Efficiency, Swedish University of Agriculture Sciences.

Jacobson, S., Kukkola, M., Mälkönen, E. & Tveite, B. (2000). Impact of whole-tree harvesting and compensatory fertilization on growth of coniferous thinning stands. *Forest Ecology and Management, 129*, 41-51.

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.

Jylhä P. (2004). Feasibility of an Adapted Tree Section Method for Integrated Harvesting of Pulpwood and Energy Wood in Early Thinning of Scots Pine. *International Journal of Forest Engineering, 15(2)*, 35-42.

Jylhä, P. & Laitila, J. (2007). Energy wood and pulpwood harvesting from young stands using a prototype whole-tree bundler. *Silva Fennica, 41(4)*, 763-779.

Kärhä, K., Rönkkö, E.& Gumse, S.-I. (2004). Productivity and Cutting Costs of Thinning Harvesters. *International Journal of Forest Engineering, 15(2)*, 43-56.

Kärhä, K., Jouhiaho, A., Mutikainen, A.& Mattila, S. (2005). Mechanized energy wood harvesting from early thinnings. *International Journal of Forest Engineering, 16(1)*, 15-26.

Kärhä, K. (2006). Effect of undergrowth on the harvesting of first-thinning wood. *Forestry Studies, (Metsanduslikud Uurimused), 45,* 101-117.

Kärhä, K., Keskinen, S., Liikkanen, R. & Lindroos, J. (2006). *Kokopuun korjuu nuorista metsistä* [Harvesting small-sized whole trees from young stands]. *Metsätehon raportti, 193,* 34-41. (In Finnish).

Kuitto, P.J., Keskinen, S., Lindroos, J., Oijala, T., Rajamäki, J., Räsänen, T., et al. (1994). *Puutavaran koneellinen hakkuu ja metsäkuljetus* [Mechanized cutting and forest haulage]. Metsäteho. *Metsätehon tiedotus, 410,* 32-35. (In Finnish).

Laitila, J., Asikainen, A. & Nuutinen, Y. (2007). Forwarding of whole trees after manual and mechanized felling bunching in pre-commercial thinnings. *International Journal of Forest Engineering, 18(2),* 29-39.

Laitila, J. (2008). Harvesting technology and the cost of fuel chips from early thinnings. *Silva Fennica, 42(2)*, 267-283.

Mård, H. (1998). Short-term growth effects of whole-tree harvest in early thinnings of birch (*Betula* spp) and *Picea abies*. *Scandinavian Journal of Forest Research, 13,* 317-323.

Marklund, L.G. (1987). *Biomass functions for pine, spruce and birch in Sweden.* Rapport, 45, 79 pp. Umeå: Sveriges lantbruksuniversitet, Institutionen för skogstaxering, (In Swedish with English summary).

Nurminen, T., Korpunen, H. & Uusitalo, J. (2006). Time consumption analysis of cut-to-lenght harvesting system. *Silva Fennica, 40(2)*, 335-363.

Näslund, M. (1947). Functions and tables for computing the cubic volume of standing trees. Pine, spruce and birch in southern Sweden and in the whole of Sweden. *Reports of the Forest Research Institute of Sweden*, 36, 1-41. (In Swedish with English summary).

Praktisk skogshandbok (510 pp.) [Forestry Guide]. (1994). Djursholm. Sveriges skogsvårdsförbund. (In Swedish).

Sirén, M., Heikkila, J. & Sauvula, T. (2006). Combined production of industrial and energy wood in Scots pine stands. *Forestry Studies, (Metsanduslikud Uurimused), 45,* 150-163.

Spinelli, R. & Magagnotti, N. (2010). Comparison of two harvesting systems for the production of forest biomass from the thinning of Picea Abies plantations. *Scandinavian Journal of Forest Research, 25,* 69-77.

Suadicani, K. (2003). Production of fuel chips in a 50-year old Norway spruce stand. *Biomass and Bioenergy, 25,* 35-43.

Suadicani, K. & Talbot, B. (2010). Extracting and chipping hardwood crowns for energy. *Scandinavian Journal of Forest Research, 25,* 455-461.

Swedish University of Agricultural Sciences (2009). *Forestry statistics 2009. Official statistics of Sweden.* Umeå: Institutionen för skoglig resurshållning.

TABLES

Table 1. Average values of the properties of the experimental blocks.

	Block						
Properties	**1**	**2**	**3**	**4**	**5**	**6**	**Average**
DBH[a](cm)	10.9	9.1	9.7	9.4	8.4	8.8	9.4
Height (m)	11.6	10.9	11.0	10.8	10.5	10.8	10.9
Density (trees ha^{-1})	2493	3023	2631	3278	3082	2768	2879
Basal area (m^2 ha^{-1})	26.1	22.1	24.1	26.1	19.0	19.0	22.8
Stem-volume[b](dm^3)	63	42	47	46	35	40	46
Total stem-volume[b] (m^3 ha^{-1})	157	128	125	152	107	109	130
Total biomass volume (m^3 ha^{-1})	210	168	170	212	141	143	174
Total oven-dry (OD) biomass (t ha^{-1})	112	89	88	108	74	76	91

[a]Arithmetic mean diameter at breast height over-bark. [b]Stem-volume over- bark.

Table 2. Description of each work element and their respective priorities in the time study experiment of the pulpwood and energy-wood treatments.

	Treatment		
Work element	**Pulpwood**	**Energy-wood**	**Priority**[a]
Boom out	Starts when an empty crane moves towards a tree to be harvested and stops when the tree has been reached.	Starts when an empty crane moves towards a tree to be harvested and stops when the tree has been reached.	1
Felling	Starts when the tree has been reached and stops when the tree has been felled.	Starts when the first tree has been reached and stops when the last tree has been felled (moving to successive trees included).	1
Boom in	Starts when the tree has been felled and stops when the harvesting head starts processing.	Starts when the last tree in the crane cycle has been felled and stops when trees have been dropped on the ground (including fixing the bunch).	2
Processing	Starts when the harvester head starts to process a tree and stops when the last piece has been dropped.	-	1
Moving	Starts when the base machine wheels are turning and ends when the base machine stops.	Starts when the base machine wheels are turning and ends when the base machine stops.	3
Miscellaneous	Other activities e.g. trees are dropped and then picked up again.	Other activities e.g. trees are dropped and then picked up again.	4
Delays	Time not related to effective work time e.g. personal breaks, repairing.	Time not related to effective work time e.g. personal breaks, repairing.	5

[a]If more than one work element was performed at the time of an observation, the element with the highest priority (lowest number) was recorded.

Table 3. Characteristics of birch dominated type stands for thinning (Bredberg 1972) and the properties of removal at different thinning intensities.

Properties	**Stand Type**								
Initial stand	**Old**			**Middle-aged**			**Young**		
Age (years)	35			30			24		
Stand density (trees ha^{-1})	1740			2650			3590		
DBH[a] (cm)	13.9			10.4			9.3		
Height (m)	11.6			9.4			8.7		
Basal area (m^2 ha^{-1})	29.9			25.1			21.8		
Stem-volume[2] (dm^3)	99			45			33		
Total stem-volume (m^3 ha^{-1})	172			120			117		
Average tree biomass volume (dm^3)	134			63			45		
Total biomass volume (m^3 ha^{-1})	234			166			161		
Removal	***Thinning intensity (% of basal area)***								
	20	30	40	20	30	40	20	30	40
Density (trees ha^{-1})	680	880	1110	1170	1460	1630	990	1460	1880
DBH[a] (cm)	9.7	10.7	11.4	7.4	8.0	8.6	6.3	6.9	7.4
Stem-volume[b] (dm^3)	40	52	61	19	23	29	13	15	18
Pulpwood volume (m^3 o-b ha^{-1})	21	37	56	8	18	30	0	6	15
Biomass volume (m^3 ha^{-1})	36	58	86	28	43	60	16	30	45
Biomass/Pulpwood volume	1.7	1.6	1.5	3.5	2.4	2.0	[c]	5.0	3.0
Pulpwood gross income (€ ha^{-1})	587	1025	1551	233	496	825	0	155	406
Biomass gross income (€ ha^{-1})	716	1170	1715	560	865	1210	324	601	907

Notes: [a]Arithmetic mean diameter at breast height over-bark. [b]Stem-volume over-bark. [c]Value divided by zero

Table 4. Properties of the initial stand, the removal, and the remaining stand.

Properties	**Treatment**		
Initial stand	**Pulpwood**	**Energy wood***	**p-value**
DBH[a] (cm)	9.5 (0.8)	9.3 (0.8)	
Height (m)	11.0 (0.4)	10.9 (0.3)	
Stand density (trees ha^{-1})	2879 (363)	2879 (213)	
Basal area (m^2 ha^{-1})	23.0 (3.5)	22.5 (3.1)	
Stem-volume[b] (dm^3)	47 (10)	44 (8)	
Total stem-volume (m^3 ha^{-1})	134 (23)	125 (18)	
Total biomass volume (m^3 ha^{-1})	180 (35)	168 (26)	
Total biomass (OD t ha^{-1})	94 (17)	88 (14)	
Removal			
Basal area (%)	39 (6)	44 (6)	0.168
Density (trees ha^{-1})	1297 (153)	1386 (62)	0.281
Average stem-volume (dm^3)	37 (4)	40 (5)	0.385
Volume[c] (m^3 ha^{-1})	39 (5)	77 (9)	**<0.001**
Biomass[d] (OD t ha^{-1})	21 (3)	38 (5)	**<0.001**
Remaining stand after harvest			
Strip road width (m)	4.0 (0.2)	4.1 (0.2)	0.544
Strip road tree damage (%)	2.2 (1.8)	2.0 (1.7)	0.878
Stand tree damage (%)	7.2 (5.3)	2.8 (2.3)	0.144
Total tree damage (%)	9.5 (5.0)	4.8 (2.1)	0.064

Notes: Standard deviations are given in brackets. Energy wood = whole tree above felling cut. Differences are considered significant if $p \leq 0.05$.[a]Arithmetic mean diameter at breast height over-bark. [b] Stem-volume incl. bark. [c] In energy-wood the biomass solid volume; in pulpwood the pulpwood volume o-b. [d] In energy-wood the OD biomass is based on the whole tree; in pulpwood the OD biomass is based on stem-volume o-b.

Table 5. Productive work time (PW) consumption per harvesting work element[a] and treatment (excluding delay time). Standard deviations are given in brackets.

	Time consumption per tree (s)		Total time consumption (%)	
Work element	**Pulpwood**	**Energy-wood**	**Pulpwood**	**Energy-wood**
Boom out	8.4 (1.1)	6.6 (1.2)	27.8	37.0
Boom in	8.0 (1.2)	5.0 (1.2)	26.3	28.1
Felling and accumulating[b]	2.7 (0.4)	4.2 (0.7)	8.8	23.6
Processing	7.1 (0.8)	- -	23.3	-
Moving	3.4 (0.5)	1.9 (0.3)	11.3	10.9
Miscellaneous	0.8 (0.3)	0.1 (0.1)	2.5	0.5
Total time (PW)	30.3 (2.8)	17.9 (3.1)	100	100

[a]Work elements descriptions, see Table 2. [b]Accumulating was only performed in energy-wood harvesting

Table 6: Gross income, harvesting and forwarding costs, and net income (€ ha^{-1}).

	Treatment	
	Pulpwood	**Energy-wood**
Gross income	1093 (139)	1533 (181)
Harvesting cost	1133 (155)	713 (96)
Forwarding cost	203 (26)	468 (55)
Net income	-243 (207)	352 (90)

Note: Standard deviations are given in brackets.

FIGURE LEGENDS

Figure 1. Productivity as a function of harvested stem-volume for the energy-wood (m^3 biomass) and pulpwood (m^3 o-b) treatments.

Figure 2. The net income as a function of the harvested stem-volume for the energy-wood and pulpwood treatments.

Figure 3: Gross income for different energy-wood prices as a function of the biomass to pulpwood volume ratio. The curves are based on the three types of stand, each with three thinning intensities (nine cases per curve). Energy-wood + 30 % means a 30 % higher energy-wood price. Energy-wood -30 % means a 30 % lower energy-wood price.

FIGURES

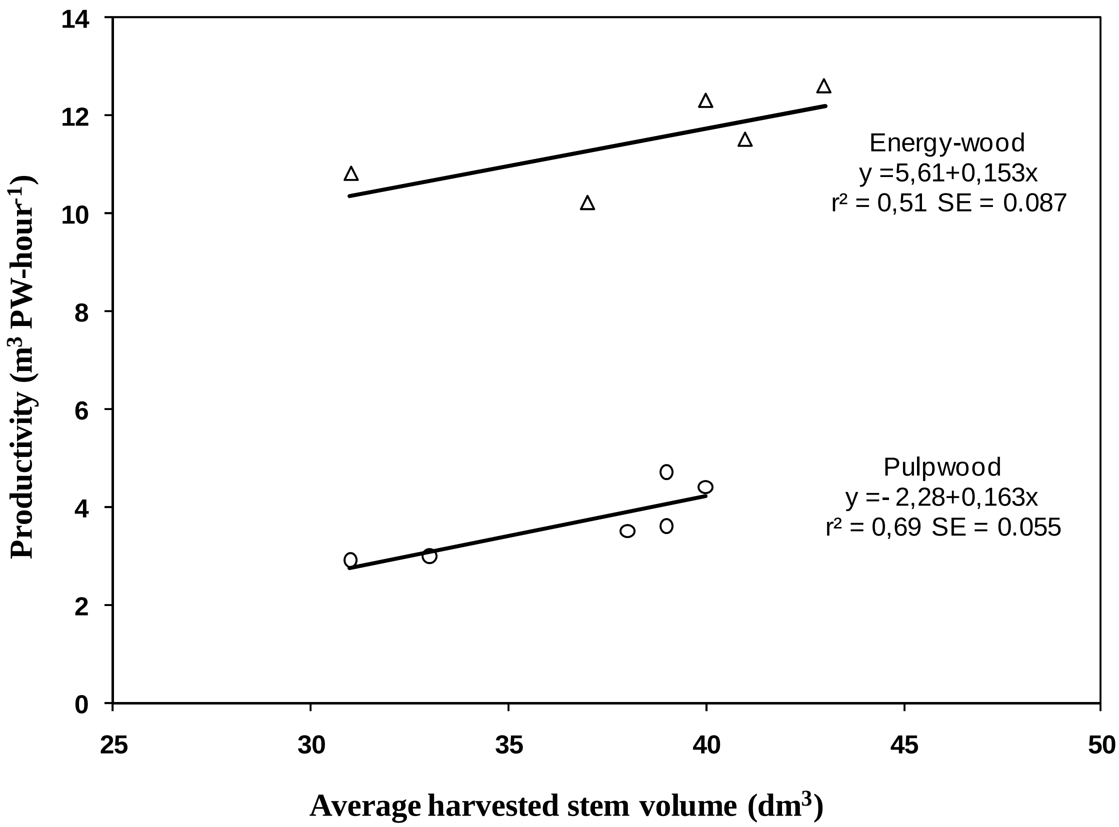

Figure 1. Productivity as a function of harvested stem-volume for the energy-wood (m^3 biomass) and pulpwood (m^3 o-b) treatments.

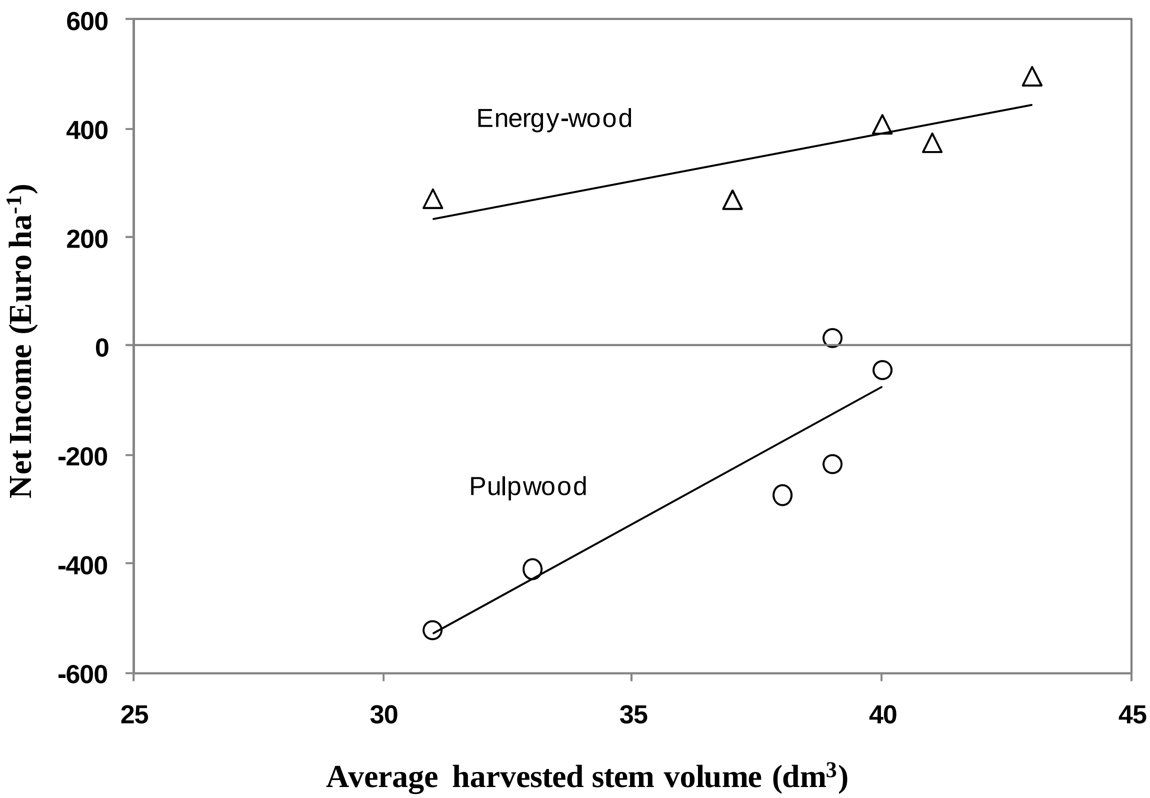

Figure 2. The net income as a function of the harvested stem-volume for the energy-wood and pulpwood treatments.

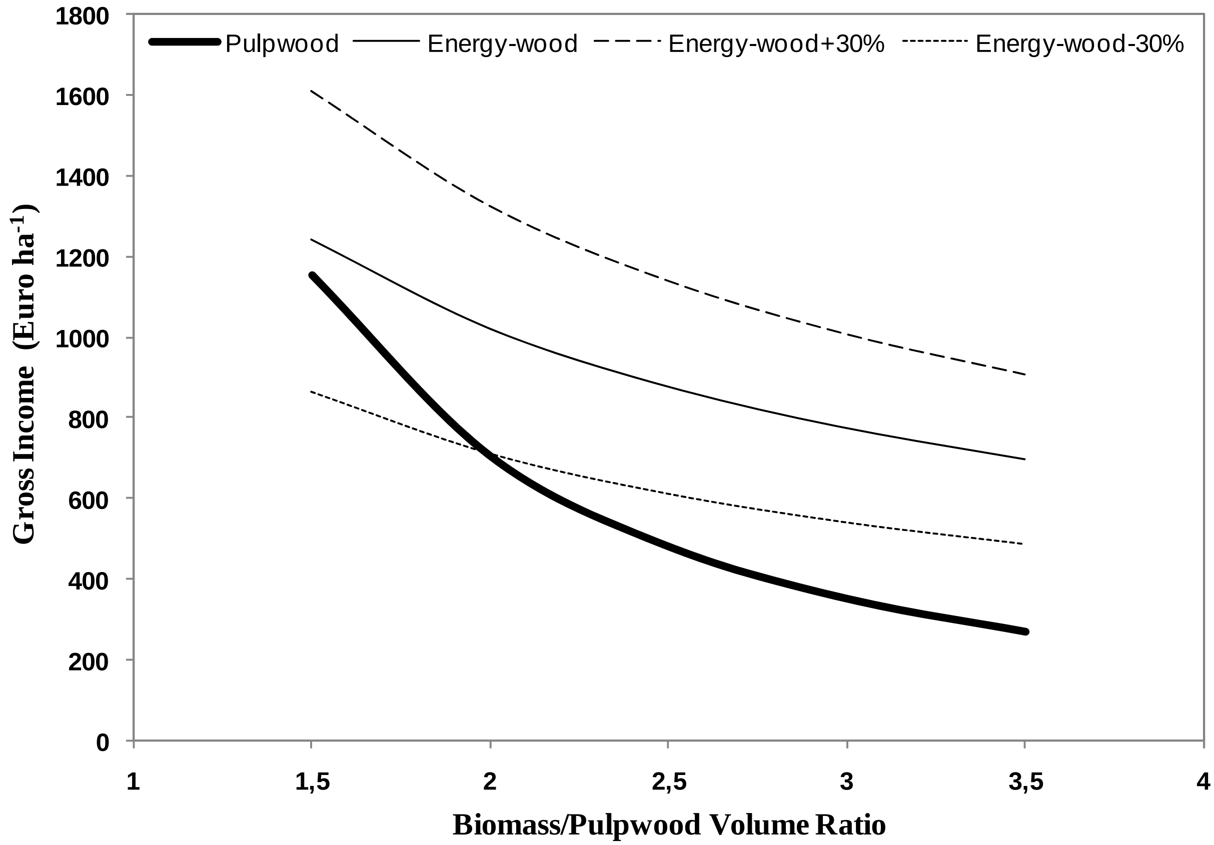

Figure 3: Gross income for different energy-wood prices as a function of the biomass to pulpwood volume ratio. The curves are based on the three types of stand, each with three thinning intensities (9 cases per curve). Energy-wood + 30 % means a 30 % higher energy-wood price. Energy-wood -30 % means a 30 % lower energy-wood price.