Forwarding of Whole Trees After Manual and Mechanized Felling Bunching in Pre-Commercial Thinnings

Juha Laitila

Antti Asikainen*

Yrjö Nuutinen

ABSTRACT

This paper examines the forwarding productivity of energy wood thinnings. The objectives of the study were to: compare the forwarding productivity following either manual or mechanized felling of whole trees and create productivity models for forwarding. The time consumption of the work phases in forwarding, following manual and mechanized cutting, was formulated by applying a regression analysis, in which the independent variables were cutting removal (m^3/ha) and forwarding distance (m). The final calculation unit for time consumption in each of the work elements was second (s) per solid cubic meter (m^3). Time studies were carried out using two Timberjack 810B forwarders. According to these results, forwarding productivity following mechanized energy wood cutting was significantly higher compared to productivity after manual cutting. Mechanized cutting by the harvester enables the felling and bunching of whole trees into large grapple loads close to the side of the strip road, which clearly improves the output of forwarding thereby helping to reduce costs. When the forwarding distance was 250 m, accumulation of energy wood was 60 m^3/ha, and load size was 6 m^3, the forwarding productivity following mechanized cutting was 11.9 m^3/E_0h and 7.1 m^3/E_0h after manual cutting.

Keywords: *forwarding, energy wood, young stand thinning, productivity functions*

Introduction

In Finland, timber procurement is based on the cut-to-length (CTL) method both in thinnings and regeneration cuttings. In the CTL-method, both delimbing and cross-cutting into assortments are carried out at the stump (Hakkila 2004) and timber is transported, off the ground, to the roadside landing by load-carrying tractors (Hakkila 1995). In Finland the degree of mechanization in roundwood cuttings is nearly 97 percent (Örn and Väkevä 2005), and the modern CTL method normally uses two machines: a harvester and a forwarder. Exceptions are forest owner operations and birch (*Betula pendula* or *pubescens*) veneer log harvesting, where cutting is almost invariably performed manually with a chainsaw.

Haulage to the roadside, where the timber is temporarily stored, sorted, and piled for secondary transport, is commonly performed using a medium-size forwarder weighing 11 to 13 tonnes (Sirén and Aaltio 2003) with a payload capacity of 10 to 12 tonnes. Purpose-built forwarders are normally equipped with a 10-m hydraulic crane. The width of the 6- or 8-wheel machine is about 2.7 m. A 4-wheel drive farm tractor equipped with a hydraulic crane and trailer is most commonly used for off-road transport of timber in delivery sales from private forests. In 2004, 1,620 purpose-built forwarders were operating in Finland's forests (Metsätilastollinen vuosikirja 2005). The purpose-built forwarder is also used for hauling energy wood from thinnings or logging residues and stumps from clear cutting areas.

Whole tree harvesting is the most commonly applied method in early thinning of a young forest for energy purposes in Finland. Harvesting small trees with branches increases the size of the cutting unit and yield of energy wood thus resulting in a lower harvesting cost (Hakkila 2004). Felling of whole trees is carried out either manually or mechanically, subsequently felled trees are hauled to the roadside landing by load-carrying forwarders. The development of chipping methods, fuel receiving and handling systems, and combustion technology has enabled the use of whole-tree chips instead of delimbed-tree chips. In Finland the use of forest chips in heating and power plants was 2.6 million m^3 per year in 2005, and the whole-tree chips share of the total volume was 17 percent and delimbed-tree chips 4 percent (Ylitalo 2006).

In the manual felling of whole trees, the chainsaw is equipped with a felling frame, which enables the user to make use of the kinetic energy of the falling tree in moving the stem in the desired direction and allowing the lumberjack to keep their back straight. After cross cutting, the lumberjack puts the chainsaw on the ground and grasps the falling tree. Using the momentum of the tree, he guides it onto the stack, placing the butt toward the strip road (Harstela and Tervo 1977, Hakkila et al. 1978). Piles can be located obliquely forwards,

backwards, or at right angles to the strip road, and they are located on both sides of the strip road (**Fig. 1**). Non-delimbed trees are gathered into sufficiently large piles (usually 2 to 6 stems) within a forwarder's crane reach and bucked to 6 to 8 m in length (Metsäteho 1991). When the distance between strip roads is 20 m, the most distant piles are located 8 or 9 m away from the strip road. The primary goal of the working technique is to combine felling and bunching instead of moving

Figure 1. ~ *Piling in mechanized and manual felling.*

fallen trees to the bunch. Combined felling and bunching is applicable only for small-tree operations when the majority of the trees are smaller than 12 cm at breast height (Hakkila 1989).

Mechanized energy wood harvesting in thinnings is rapidly becoming more common since it enables the full year employment of forest machinery. Development in the cutting attachments and pressure to decrease the high felling cost of small trees has sped up mechanization. Mechanized energy wood cutting is commonly carried out by thinning harvesters which utilize the multi-tree processing technique. Simultaneous processing of several trees in the harvester's grip decreases handling time per tree and improves productivity especially in small tree operations (Myhrman 1989, Lilleberg 1997, Brunberg 1998, Johansson and Gullberg 2002, Bergkvist 2003, Kärhä et al. 2005, Laitila and Asikainen 2006). The tree bundle, which is processed, normally consists of 2 to 6 trees ($d_{1.3} < 10$ cm), and the number of small-diameter stems can be even higher. Removed trees are bunched alongside the strip road (**Fig. 1**) with piles consisting of several accumulated felling head bunches. The distance from the pile butt to the strip road is within 1 m. After mechanized felling, piles are located obliquely forwards to the strip road.

In energy wood harvesting from pre-commercial thinnings, felling and hauling are a part of processing chain, where one step affects the following step. Time consumption per loading cycle in hauling is dependent on differing conditions. Gullberg (1997) has listed some of these factors from the short wood loading point of view, and these observations are also valid for loading whole trees:

- pile characteristics (distance from strip road, volume, shape, etc.)
- loading method (multiple pile loading, etc.)
- loading conditions (remaining trees, etc.)
- machine characteristics (net lifting force, grapple area, stability, etc.)

This paper examines the forwarding productivity of energy wood thinnings following manual or mechanized felling. The findings are based on the results of "Cost factors and supply logistics of fuel chips from young forests" project (Laitila et al. 2004) which was a part of the National Wood Energy
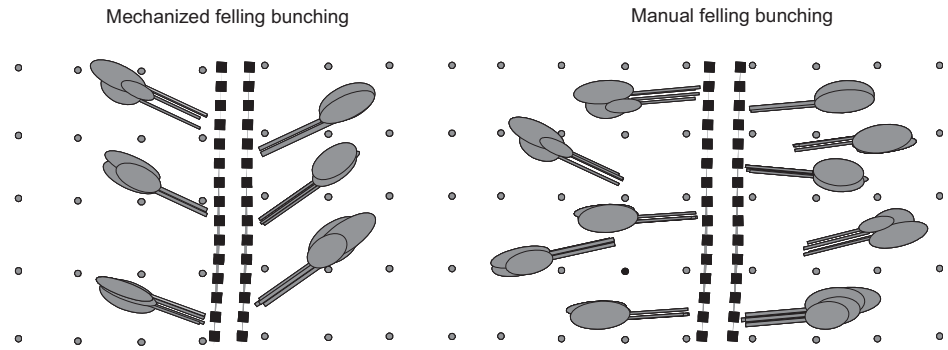
Technology Programme (Hakkila 2004). The forwarding of industrial roundwood (Kuitto et al. 1994, Väkevä et al. 2003, Brunberg 2004) or logging residues (Asikainen et al. 2001, Ranta 2002, Rieppo 2002, Kärhä et al. 2004) have been studied in several research projects and productivity models have been published. Earlier studies related to the forwarding of energy wood in thinnings have primarily concentrated on farm tractor-based technology (Ihonen 1998, Mutikainen 1999, Nätt and Mutikainen 2001) or the studies have been quite limited (Hakkila et al. 1975, Metsäteho 1984, Mäkelä et al. 2003, Kärhä 2004, Heikkilä et al. 2005). The productivity functions of energy wood hauling in thinnings by a forwarder have not been previously published.

The objectives of this study were to:

1. compare the forwarding productivity following manual and mechanized felling of whole trees and
2. create productivity models for forwarding as above.

Material and Methods

Forwarders

Time studies were carried out using two Timberjack 810B forwarders. The weight of the 8-wheeled forwarder was 10.4 tonnes and the load rating was 8.5 tonnes. The diesel engine was a 4-cylinder turbo charged Perkins 1004-40T with a power output of 81 kW. The crane model was the TJ 51 F 96 and its reach was 9.60 m with a gross lifting torque of 99 kNm. The grapple area was 0.25 m² for both forwarders and the grapple type was a normal timber grapple. The forwarder's length was 7.96 m, width 2.66 m, height 3.70 m, and ground clearance of 0.60 m. The overall length of the load space was 3.84 m and the external width was 2.60 m. The load space's cross-sectional area was 4 m² (Timberjack Sales Oy, 2002). The forwarder, which hauled trees felled by a harvester, was equipped with a load scale manufactured by Ponsse Ltd.

Time Study

The data collection procedure consisted of a set of time studies. The time study data was comprised of 97 forwarder loads of which 46 loads were hauled following manual cutting and 51 loads were hauled following mechanized cutting. The

time studies of forwarding, following manual cutting, were carried out during the period October 10 through 23, 2002, at Tohmajärvi (23°25′N, 62°16′E) in Eastern Finland. The forwarded energy trees were felled and bunched by professional lumberjacks. It was not possible to determine the load size of each individually, therefore, an average and constant load size value was used. The average load size was determined when the hauled trees were chipped at the roadside landing and delivered to the heating plant, where the delivered volumes were measured. The estimation of material losses during storing and after chipping was based on visual observations. According to the measurements, the average load size of manually felled trees was 5.7 m^3.

Time studies of forwarding, following mechanized cutting, were carried out during the period April 7 through 17, 2003, at Kannus (23°53′N, 63°53′E) in Western Finland. Trees at the study sites were felled and bunched by the Timberjack 720 accumulating felling head (formerly EnHar), which was attached to a Valmet 901 harvester. Bunches were not covered by snow; however, the snow cover of the ground at the time of forwarding was approximately 10 cm. The load size was estimated using a load scale, and the scale value was converted to solid cubic meters using a density factor of 850 kg/m^3 fresh wood. The density factor was based on Biowatti Oy's follow up studies and chipping tests (Finne pers. comm.). The load size of mechanized felled trees varied between 5.5 and 8.2 m^3, with 6.2 m^3 being the average.

Both forwarder operators in Tohmajärvi and Kannus were motivated, experienced (20 and 2 years working experience) workers. In addition to the above-mentioned energy wood hauling experience, the operators had several years of work experience in other forest machine work. Stand circumstances were comparable; the nature and slope of the ground surface was normal (flat) and similar for both felling methods including the bearing capacity of the mineral soil ground. The time studies were carried out in natural light during the daytime, with lighting conditions being similar for both felling methods. The distance between strip roads was 20 m on average, and the width of the strip road was approximately 4 m. The cutting removal from time study stands was frequently composed of broadleaf trees, mostly birch (*Betula pendula* or *pubescens*). Stand characteristics are detailed in **Table 1**. Due to limited resources, it was not possible to survey the number and volume of removed and remaining trees, but the variation range of remaining trees after pre-commercial thinning is 1,000 to 1,500 trees per hectare in Finland, and the time studied stands were not an exception to that rule.

The time study was carried out manually by the continuous time method using a hand-held data recorder. Driving distances when driving unloaded, during loading, and with load were measured using a thread meter. Each of the forwarders' working cycles (clock time) was divided into effective working time (E$_0$h) and delay time (Haarlaa et al. 1984, Mäkelä 1986). The accuracy of data recorder was 0.6 seconds (1 cmin). Delay times were measured but not included in the

Table 1. ~ *Characteristics of time studied stands and loads.*[a]

	Loads following manual felling	Loads following mechanized felling
Number of loads	46	51
Driving unloaded, avg. distance (m)	171 (20 to 456)	270 (30 to 775)
Driving during loading, avg. distance (m)	66 (19 to 154)	91 (30 to 340)
Driving with load, avg. distance (m)	130 (10 to 410)	240 (35 to 662)
Average grapple load size in the loading (m^3)	0.10 (0.07 to 0.15)	0.22 (0.05 to 0.35)
Average size of loading stop (m^3)	0.35 (0.23 to 0.57)	0.54 (0.19 to 1.1)
Average driving distance between loading stops (m)	4 (2 to 6)	6 (4 to 11)
Avg. energy wood concentration on strip road (m^3/100 m)	10.11 (3.7 to 20.4)	9.9 (2.0 to 25.6)
Average load size (m^3)	5.7 (5.7 to 5.7)	6.2 (5.5 to 8.1)
Average grapple load size in the unloading (m^3)	0.69 (0.44 to 1.14)	0.59 (0.30 to 1.03)

[a] Range is shown in parentheses.

analysis, since the studies were too short to obtain an accurate estimate of a general delay time of forwarder work and because a follow-up study was not carried out in this study. If multiple work elements were performed at the same time, the time for the work element with the highest priority was recorded. Effective working time, including auxiliary time of each work phase (e.g., work planning and preparations), was divided into the following work phases:

- *Driving unloaded* (begins when the forwarder leaves the landing area and ends when the forwarder starts loading)
- *Loading* (begins when the forwarder starts to load felled trees and ends when the forwarder is ready to move to the next loading stop)
- *Driving during loading* (forwarder moves between loading stops. The loading stop is the working location on the strip road where the loading work is carried out. Material is loaded from both sides of the machine by one stop)
- *Driving with load* (begins when the load is full and ends when the forwarder stops to begin unloading at the landing area)
- *Unloading* (begins when the forwarder raises the boom for unloading and ends when the load is empty and the forwarder is ready to return to the stand)

Data Analysis

The recorded time study data and the measured data of stand and load characteristics were combined as a data-matrix. The time consumption (E$_0$h) of each work phase in forwarding, following manual and mechanized cutting, were formulated by applying a regression analysis. Different transformations and curve types were tested to get the residuals of the regression models as symmetrical as possible and to achieve the best values for the coefficients of determination to

final models. The regression analysis was carried out by using the SPSS-statistical package.

Those work phases in which the felling method does not affect the time consumption were modelled by using the whole time study data. It was assumed that the time consumption of driving unloaded, driving with load, and unloading were independent of felling method. Time consumption for loading and driving during loading were individually modelled for manual and mechanized felling, since remarkable differences were noted in average grapple load sizes, sizes of loading stops, and driving distances between loading stops between felling methods (**Table 1**).

Regression analysis, with the variables and appropriate transformation of variables, was used for modelling the time consumption of the work phases. For example, time consumption of driving unloaded and driving with load was explained by the forwarding distance. Energy wood concentration on the strip road ($m^3/100$ m) was derived by the driving distance during loading and the load size in the work cycle. The size of loading stop (m^3) was calculated dividing the load size by the number of movements between loading locations in the work cycle. Grapple load sizes in the loading and the unloading work were based on average values per load. The final calculation unit for time consumption for every work element was second (s) per solid cubic meter (m^3).

Finally for all time elements, statistically significant variables were analyzed in order to examine the goodness-of-fit of regression models. Characteristics of regression models are detailed in **Table 2**.

Results

Driving Unloaded

The forwarding distance was the independent variable for time consumption when driving without load using a forwarder.

$$T_{Empty\,load} = \frac{10.868 + 1.241 l_e}{v_1}$$

where:

$T_{Empty\,load}$ = time consumption of driving without load (s/m^3)

l_e = forwarding distance without load (m)

v_l = load size (m^3)

The speed of the forwarder was 0.78 m/s with empty load, when the forwarding distance was 250 m. The driving speed was slightly slower for shorter distances and higher for longer distances.

Table 2. ~ *Statistical characteristics of regression models.*

Work phase model	Dependent variable	R^2	F-test F-value p	N	Term	Constant/coefficient Estimate	Std. error	t-test t-value	p
Driving unloaded	$T_{Empty\,load}$	0.96	2063.643	97	Constant	10.868	7.053	1.541	0.127
			< 0.001		l_e	1.241	0.027	45.427	< 0.001
Loading, mech. felling	$T_{Loading\,Mech.}$	0.65	92.597	51	Constant	−81.429	22.311	−3.650	0.001
			< 0.001		$v_{Grapple\,Mech.}^{-1}$	43.906	4.563	9.623	< 0.001
	$v_{Grapple\,Mech.}$	0.62	78.961	51	Constant	0.678	0.017	3.893	< 0.001
			< 0.001		$\sqrt{LStop_{Mech.}}$	0.210	0.024	8.886	< 0.001
	$LStop_{Mech.}$	0.74	137.683	51	Constant	0.138	0.039	3.545	0.001
			< 0.001		z	0.04107	0.003	11.734	< 0.001
Loading manual felling	$T_{Loading\,Manual}$	0.58	59.664	46	Constant	28.113	38.007	0.740	0.464
			< 0.001		$v_{Grapple\,Manual}^{-1}$	27.323	3.537	7.724	< 0.001
	$v_{Grapple\,Manual}$	0.14	7.226	46	Constant	0.04607	0.019	2.430	0.019
			0.01		$\sqrt{LStop_{Manual}}$	0.08652	0.032	2.688	0.010
	$LStop_{Manual}$	0.62	72.979	46	Constant	0.174	0.022	8.042	< 0.001
			< 0.001		z	0.01704	0.002	8.543	< 0.001
Driving during loading, mech.	$T_{Moving\,Mech.}$	0.88	358.107	51	Constant	4.925	2.030	2.427	0.019
			< 0.001		z^{-1}	233.094	12.318	18.924	< 0.001
Driving during loading, manual	$T_{Moving\,Manual}$	0.65	80.020	46	Constant	8.626	2.777	3.106	0.003
			< 0.001		z^{-1}	193.525	21.634	8.945	< 0.001
Driving with load	$T_{Driving\,L}$	0.94	1465.856	97	Constant	3.990	9.024	0.442	0.659
			< 0.001		l_l	1.493	0.039	38.287	< 0.001
Unloading	$T_{Unloading}$	0.28	33.304	90	Constant	15.154	4.809	3.151	0.002
			< 0.001		$v_{U\text{-}Grapple}^{-1}$	16.689	2.892	5.771	< 0.001

Loading

In this study, loading denoted the time consumption of energy wood loading work at the loading stop. An increase in the energy wood accumulation per hectare increased the energy wood density on the strip road and thus enlarged the amount of material which could be loaded from one location by one stop. In mechanized felling, the harvester collects trees within the crane's reach and piles them on the sides of the strip road, which increase the size of loading stop compared to manual felling. Following manual felling, the average driving distance between the loading stops during loading was 4 m; following mechanized felling, the average moving distance was 6 m (**Table 1**). An increase in the energy wood accumulation increased the average size of the pile and also the size of the grapple load, because it enables the driver to load full or almost full grapple loads. The grapple load size effects the productivity of the loading work.

The grapple load size was the main independent variable of time consumption in the loading work (**Fig. 2**). Regression models were constructed to express loading time consumption after manual and mechanized felling of whole trees. The grapple load size was formulated by the size of the loading stop (**Fig. 3**). The size of the loading stop was calculated on the basis of energy wood concentration, m³ per 100 m strip road (**Fig. 4**).

The grapple load size and loading productivity was significantly higher after mechanized felling (**Figs. 2 and 3**). This can be explained by the fact that the bunches, after mechanized harvesting, were considerably larger compared to bunches after manual harvesting (**Fig. 3**) and were piled at the trail side, making them more accessible for the forwarder. The loading of well-arranged piles with an optimal size gives the highest productivity. After manual felling, the bunches of wood were small and scattered over a larger area. The operator had to pick up one bunch of wood, paying attention to standing trees, reposition the bunch on top of another bunch, regrapple both bunches, and place the grapple load either on
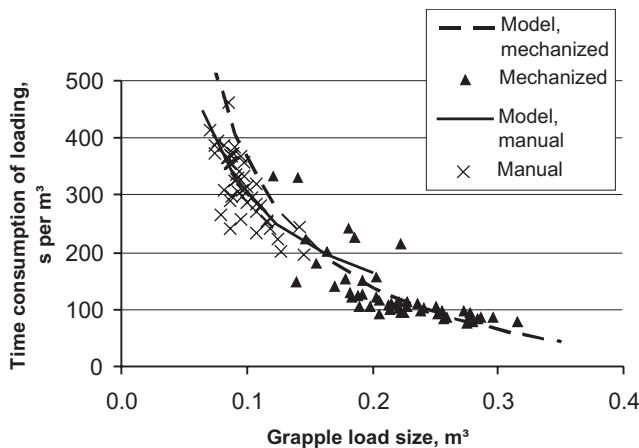
the machine or on the top of the next bunch of wood. Multiple-pile loading far from the strip road decreases the loading productivity after manual felling.

Time consumption of loading after mechanized felling bunching was formulated as:

$$T_{Loading\ Mech.} = -81.429 + \frac{43.906}{v_{Grapple\ Mech.}}$$

where:

$T_{Loading\ Mech.}$ = time consumption of loading after mechanized felling bunching (s/m³)

$v_{Grapple\ Mech.}$ = grapple load size after mechanized felling bunching (m³)

Time consumption of loading after manual felling bunching was formulated as:

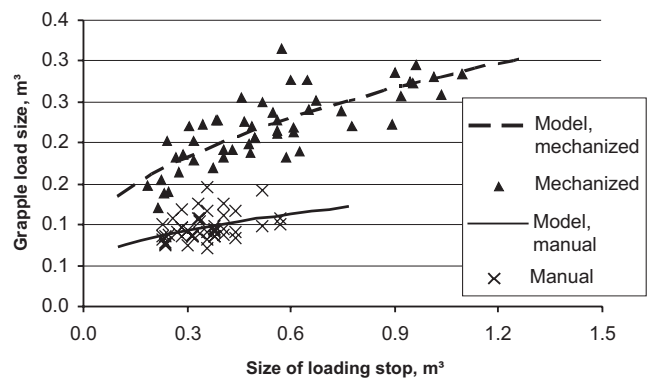$$T_{Loading\ Manual} = 28.113 + \frac{27.323}{v_{Grapple\ Manual}}$$

Figure 3. ~ *The grapple load size as a function of the size of loading stop after manual and mechanized felling.*

Figure 2. ~ *Time consumption of loading as a function of grapple load size after manual and mechanized felling.*
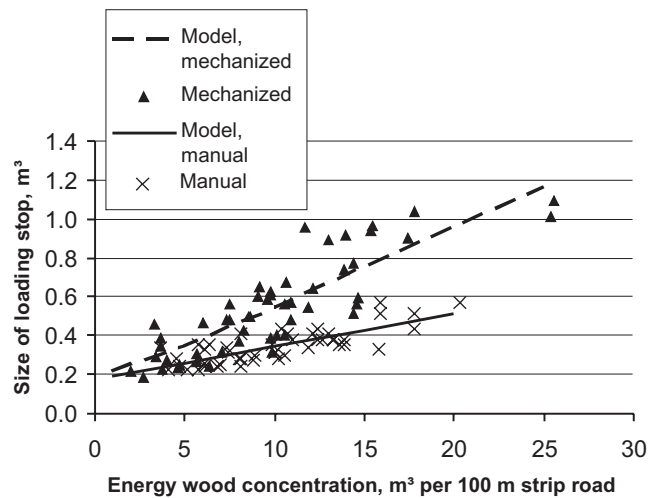

Figure 4. ~ *The size of loading stop as a function of the energy wood concentration, m³ per 100 m strip road, after manual and mechanized felling.*

where:

$T_{Loading\,Manual}$ = time consumption of loading after manual felling bunching (s/m³)

$v_{Grapple\,Manual}$ = grapple load size after manual felling bunching (m³)

Grapple load size after mechanized felling bunching, m³, was formulated as:

$$v_{Grapple\,Mech.} = 0.0678 + 0.21 * \sqrt{LStop_{Mech.}}$$

where:

$v_{Grapple\,Mech.}$ = grapple load size after mechanized felling bunching (m³)

$LStop_{Mech.}$ = size of loading stop after mechanized felling bunching (m³)

Grapple load size after manual felling bunching, m³, was formulated as:

$$v_{Grapple\,Manual} = 0.04607 + 0.08652 * \sqrt{LStop_{Manual}}$$

where:

$v_{Grapple\,Manual}$ = grapple load size after manual felling bunching (m³)

$LStop_{Manual}$ = size of loading stop after manual felling bunching (m³)

The size of the loading stop as a function of the energy wood concentration after mechanized felling bunching was formulated as:

$$LStop_{Mech.} = 0.138 + 0.04107z$$

where:

$LStop_{Mech.}$ = the size of the loading stop after mechanized felling bunching (m³)

z = energy wood concentration (m³/100 m strip road)

The size of the loading stop as a function of the energy wood concentration after manual felling bunching was formulated as:

$$LStop_{Manual} = 0.174 + 0.01704z$$

where:

$LStop_{Manual}$ = the size of loading stop after manual felling bunching (m³)

z = energy wood concentration (m³/100 m strip road)

Driving During Loading

The number of times and the distance moved depended on the accumulation of harvested energy wood. An increase in the energy wood density on the strip road shortened the driving distance required to get a full load and correspondingly a decrease in the energy wood density on the strip road lengthened the driving distance to get the load full.

The driving time between loading locations was modelled according to the energy wood concentration, m³ per 100 m strip road (**Fig. 5**). Regression models were made for both manual and mechanized felling bunching. The move time during loading decreased when the energy wood concentration increased (**Fig. 5**). Moving times during loading were at the same level after mechanized and manual cutting, since the average driving distances between loading stops was just a few meters (**Table 1**).

Forwarders moving time after mechanized felling bunching was formulated as:

$$T_{Moving\,Mech.} = 4.925 + \frac{233.094}{z}$$

where:

$T_{Moving\,Mech.}$ = time consumption of moving after mechanized felling bunching (s/m³)

z = energy wood concentration (m³/100 m strip road)

Forwarders moving time after manual felling bunching was formulated as:

$$T_{Moving\,Manual} = 8.626 + \frac{193.525}{z}$$

where:

$T_{Moving\,Manual}$ = time consumption of moving after manual felling bunching (s/m³)

z = energy wood concentration (m³/100 m strip road)

Driving with Load

The forwarding distance was the independent variable for time consumption when driving with load. Load size was excluded from the model as a second independent variable, since the bulk density of the whole trees is low and thus the weight of the load does not exceed the forwarder's engines or
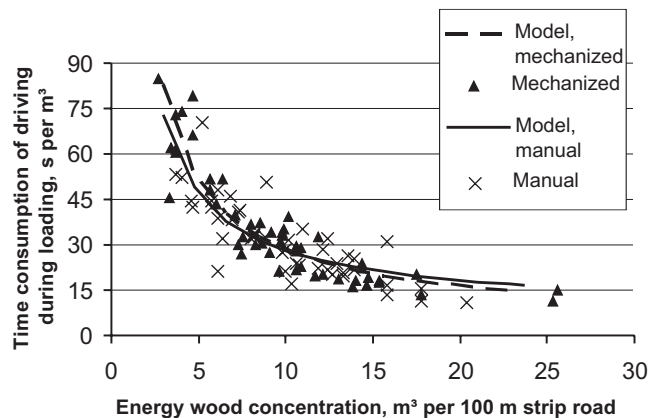
Figure 5. ~ *Moving time during loading as a function of energy wood concentration after manual and mechanized felling.*

transmission systems design power. Furthermore, the frame volume of the whole tree load does not complicate the forwarder's normal stability.

$$T_{Driving\,L} = \frac{3.99 + 1.493l_l}{v_1}$$

$T_{Driving\,L}$ = time consumption of forwarding with load (s/m³)

l_l = forwarding distance with load (m)

v_l = load size (m³)

The speed of the forwarder was 0.66 m/s with a full load, when the forwarding distance was 250 m. The driving speed was slightly lower for shorter distances and higher for longer distances. In addition, driving speed was somewhat higher when driving without load than driving with load.

Unloading

When modelling the time consumption for unloading whole trees, the average grapple load size was the independent variable. In the time studies, the grapple load size for unloading was 0.63 m³ on average. Unloading of whole trees is quicker compared to industrial roundwood since there is no need to sort the timber assortments at the landing area. Controlling of impurities during unloading decreases the productivity and also the average grapple load size. Impurities are easier to note when grapple loads are smaller than usual.

Time consumption of unloading was formulated as:

$$T_{Unloading} = 15.154 + \frac{16.689}{v_{U-Grapple}}$$

where:

$T_{Unloading}$ = time consumption of unloading (s/m³)

$v_{U\text{-}Grapple}$ = grapple load size for unloading (m³)

Review of Results

The effective forwarding time of whole trees by the forwarder T_{Tot}, s per m³, is the sum of the main working elements:

$$T_{Tot} = T_{Empty\,load} + T_{Loading} + T_{Moving} + T_{Driving\,L} + T_{Unloading}$$

The time consumption per forwarder load, T_{Load}, is calculated by multiplying the time consumption per cubic meter (T_{Tot}) with the forwarders load size (v_l).

$$T_{Load} = T_{Tot} \times v_l$$

Statistical analysis was made for each regression model in order to examine the goodness-of-fit of regression models and to test the significance of coefficients. Results of the analysis were detailed in **Table 2**.

Figure 6 shows the relative time consumption by the main working elements of forwarding after manual or mechanized cutting. In **Figure 6**, the forwarding distance was 250 m, load size was 6 m³, and accumulation of energy wood was 60 m³/ha. The loading time was 63 percent of the forwarder's effective
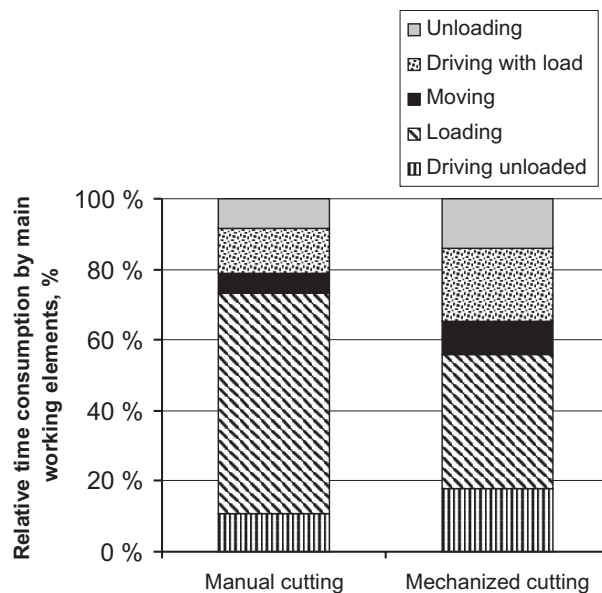

Figure 6. ~ *Relative time consumption by main working elements when forwarding whole trees after manual and mechanized cutting. Forwarding distance is 250 m, load size 6 m³, and accumulation of energy wood 60 m³/ha.*

Figure 7. ~ *Absolute time consumption by main working elements, when forwarding whole trees after manual and mechanized cutting. Forwarding distance is 250 m, load size 6 m³, and accumulation of energy wood 60 m³/ha.*
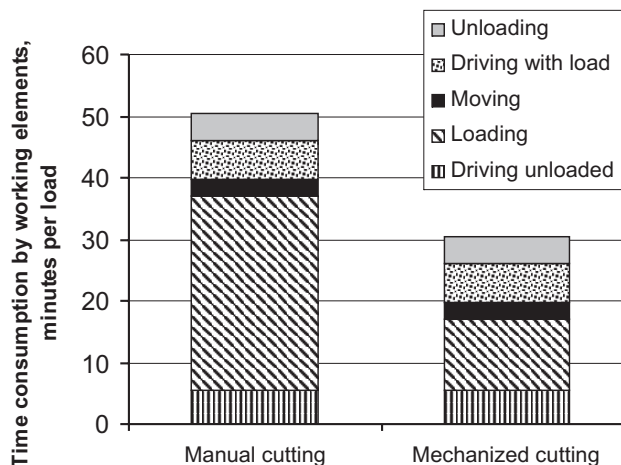
working time after manual cutting and 38 percent after mechanized cutting. The relative time consumption of moving, unloading, and driving with or without load was thus higher after mechanized cutting compared to manual cutting (**Fig. 6**).

Figure 7 illustrates the absolute time consumption by load and main working elements. The stand factors are similar to those in **Figure 6**, and calculation unit for time consumption was effective working time (E_0). For assessing the time consumption, driving with load, driving with empty load, and unloading were set as constant for both cutting alternatives. **Figure 7** shows that mechanized cutting clearly enables faster

loading, and the absolute time benefit per load is 20 minutes 9 seconds as interruption free working time.

Figures 8 and 9 show the sensitivity analysis of forwarding productivity after manual and mechanized felling according to forwarding distance, load size, and cutting removal. The output in forest haulage following mechanized cutting increased by 1.7 m³ per effective hour, when the load size grew from 4 to 9 m³ and forwarding distance was set at 50 m (**Fig. 8**). When the forwarding distance was 450 m, output in forest haulage improved 3.9 m³ per effective hour, due to the increase in load size from 4 to 9 m³. Corresponding values for forwarding productivity after manual felling were 0.4 and 1.7 m³ per effective hour, respectively. The load size is more important when cutting is mechanized since the relative time consumption of driving with or without load is greater compared to relative time consumption after manual cutting (**Fig. 6**). In **Figure 8** cutting removal was set at 60 m³/ha.

The increase in cutting removals from 30 m³/ha to 75 m³/ha improved forwarding productivity by 5 m³ per effective working hour, when the forwarding distance was 50 m and cutting was mechanized (**Fig. 9**). When the forwarding distance was 450 m, the increase in the energy wood concentration improved forest haulage output by 1.5 m³ per effective working hour. After manual felling bunching of whole trees, a clear increase was shown in the cutting removal from 30 m³/ha to 75 m³/ha, improved forwarding productivity at the 50 m forwarding distance by 1 m³, and at the 450 m forwarding distance by 0.5 m³ per effective hour (**Fig. 9**). Cutting removal has a moderate effect on forwarding productivity after manual felling. This can be explained by the fact that although the yield increases, the forwarder must collect trees from smaller bunches and some of the trees were far from the strip road. On the other hand, in mechanized felling, the increase in cutting removal makes the piles bigger, which speeds up loading.

Figure 8. ~ *Forwarding productivity after manual and mechanized felling according to load size and forwarding distance. The cutting removal is 60 m³/ha.*

Figure 9. ~ *Forwarding productivity after manual and mechanized felling according to cutting removal and forwarding distance. The load size is 6 m³.*

Discussion and Conclusions

Mechanized cutting enables the felling and bunching of whole trees into large grapple loads. In addition the bunching takes place closer to the strip road, which clearly improves the output of forwarding thereby helping to reduce costs. The importance of the grapple load size is well known also from the earlier roundwood forwarding studies (Nordström 1985, Kahala 1979, Väkevä et al. 2003, Väätäinen et al. 2005, Nurminen et al. 2006). According to Nurminen et al. (2006), loading is most effective with high timber volumes and from large piles, because it makes it possible for the operator to load full
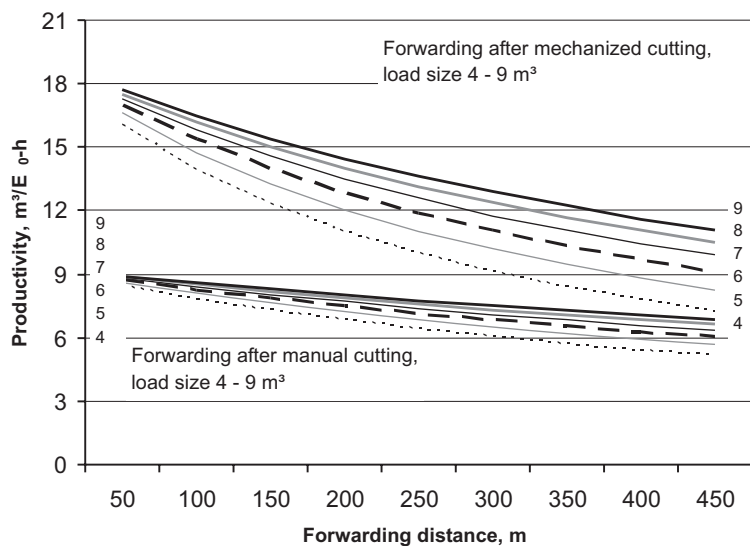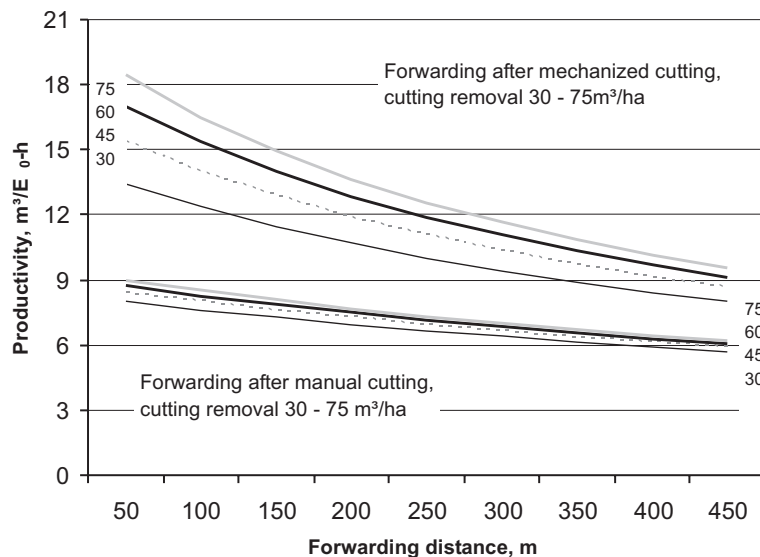
or almost full grapple loads of timber. When the timber volume at the loading stop increase enough, the loading conditions become rather optimal as the whole capacity of the grapple load can be utilized. The importance of pile and grapple volume to loading is emphasized in thinnings where the volume of removed timber is typically small and piles are scattered alongside the strip road (Nurminen et al. 2006).

The findings presented in this study are in line with earlier research in regard to differences of forwarding productivity after mechanized or manual cutting. Forest haulage of softwood saw logs following mechanized cutting was 11 to 14 percent faster than following manual cutting in summer condi-

tions and 9 to 17 percent faster in winter time (Kuitto et al. 1994). A terrain chipper's productivity in early thinnings of pine (Hakkila et al. 1978) was 7.7 m³/h after manual felling and 9.0 m³/h after feller-buncher.

Kahala (1984) found that forwarding productivity of part trees after manual cutting was 28 percent lower compared to forwarding productivity after mechanized felling. In the mechanized harvesting chain, cutting was done by the Kockums 81-11 feller-buncher, and trees were bucked by a grapple saw during loading. Melkko and Taipale (1975) noted when the forwarder has to pick up part of the trees far from the trail, its hauling productivity decreased by 10 to 15 percent.

Forwarding productivity of whole trees, when the energy wood cutting was done by the accumulating Keto Forst Energy and Valmet 945 shearhead harvester heads, was slightly below 13 m³ per effective hour (Kärhä 2004). In the study, load size was 8 m³, the forwarding distance 250 m, and energy wood concentration 20 m³ per 100 m strip road. Time study data was limited, since it consisted of only five loads and thus impacted the results. According to this paper's productivity functions, the corresponding productivity after mechanized felling is somewhat higher, 15.9 m³ per effective hour.

Heikkilä et al. (2005) studied forwarding productivity of mechanically harvested whole trees and delimbed energy wood. In that research, forwarding productivity of whole trees was 14.7 m³ per effective hour, when the cutting removal was 50 m³/ha, load size 7.7 m³, and hauling distance 300 m. Productivity was slightly higher than this paper's findings, which were 11.7 m³ per effective hour in similar circumstances. Heikkilä et al. (2005) noted also that the forwarding productivity of delimbed wood was 10 to 20 percent higher than forwarding of whole trees. The main reasons were improved efficiency in the loading and unloading work, especially the increase in load size.

When the forest transporting of whole trees is done using a farm tractor, productivity is understandably lower compared to forwarding using a purpose-built forwarder. Productivity per effective hour in forest haulage varied between 3.2 and 5.3 m³, when the work was done using a Valmet 905 4-wheel drive farm tractor equipped with a RKP-3400 hydraulic crane with a maximum reach of 7.5 m (Mutikainen 1999). The bogie trailer was equipped with driving wheels. In the study, the forwarding distance varied between 103 and 736 m and load volume was between 4.0 and 5.2 m³. In the study, manually felled trees were piled within an 8-m zone from the strip road (Mutikainen 1999).

According to Ihonen's results (1998), forwarding productivity of small-diameter whole trees was 4.1 to 5.4 m³ per effective hour, when manually felled trees were piled at the trailside and the forwarding distance varied between 100 and 400 m. The base machine was a Valmet 6600 4-wheel drive farm tractor, and the hydraulic cranes maximum reach was 6.5 m. The bogie trailer used was homemade. The average

load size was 3.3 m³, and the energy wood concentration was 4.4 m³ per 100 m strip road.

Forwarding productivity of loose logging residues (Asikainen et al. 2001), thinning roundwood (Väkevä et al. 2003), and whole trees after mechanized felling were at the same level, about 12 m³ per effective hour, when the forwarding distance was 250 m and material concentration was 10 m³ per 100 m strip road. In the comparison assessment, based on the productivity functions, the load volume of logging residues was 8 m³, roundwood 7.6 m³, and whole trees 6 m³. Furthermore the average stem volume in thinnings was 90 l and the length of the softwood pulpwood 5 m. The forwarding productivity of logging residue logs was considerably higher, as a result of using a bigger loading unit. Corresponding productivity was about 20 m³ per effective hour with a standard medium weight forwarder (load size 5.2 m³) and slightly over 30 m³ per effective hour with a heavy-duty forwarder equipped with a larger load capacity (load size 12.5 m³) (Kärhä et al. 2004).

Björheden (1997) notes that tree sections should be as long as possible in order to maximize load size. Load size is one of the most important productivity and cost factors in off-road transportation, and the lengthening of the hauled trees is the easiest way to increase its size. Disadvantages are that the lengthening of hauled trees complicates the cornering and loading work; furthermore, the forwarders tend to become tail-heavy.

In this study, load size after manual cutting was somewhat lower compared to load size after mechanized cutting. The difference might be explained by the fact that trees are bucked shorter in manual felling than in mechanized felling. According to research conducted in Sweden, loading work after mechanized cutting became complicated when trees exceed 7 to 8 m in length (Brunberg et al. 1994). After manual felling, multiple pile loading far from the strip road in the middle of remaining standing trees is, however, a challenging task, even with shorter trees. Thus, it might be that lumberjacks have been requested by the drivers to make shorter tree bunches, which decreases the grapple's and forwarder's load size.

A minor explaining factor of the differences in the load size might be the two different measurement methods, which were used to estimate hauled energy wood volumes in this study. Kärhä (2006) emphasises that the load size increase along with increasing average size of whole-tree stems in the stand. The increase in load size evens out when the average stem size of the stand reaches 20 to 30 l; from this value, the load size did not significantly increase as the average stem size increased. In this study this phenomenon was eliminated, since the average stem volume in the time studied stands was, based on visual observations, 20 to 30 l for both felling methods.

Results presented in this paper are based on the output of two forwarder operators. The differences between productivity levels after manual or mechanized felling might be partially explained by human factors, such as the drivers' motoric skills, work planning, and the decision-making process at the

worksite (Ovaskainen et al. 2004). An accurate comparison of the two methods, when using different drivers, is not feasible. The research findings, however, are supported by findings from earlier productivity studies in regard to differences of productivity after mechanized or manual cutting and especially the importance of grapple load size. Presented regression models provide accurate productivity estimates in typical Finnish energy wood thinning conditions as well as for cost calculations and different types of simulation and modelling purposes.

Literature Cited

Asikainen, A., T. Ranta, J. Laitila, and J. Hämäläinen. 2001. Hakkuutähdehakkeen kustannustekijät ja suurimittakaavaisen hankinnan logistiikka (Cost factors and large scale procurement of logging residue chips). University of Joensuu, Faculty of Forestry, Research Notes 131. 107 pp.

Bergkvist, I. 2003. Flerträdshantering höjer prestationen och ökar nettot i klen gallring. (Multi-tree handling increases both productivity and profitability in smallwood thinning). Skogforsk Resultat 5/2003.

Björheden, R. 1997. Studies of large scale forest supply systems. Dissertation. Acta Universitatis Agriculturae Sueciae/Silvestria 31.

Brunberg, T. 2004. Underlag till produktionsnormer för skotare (Productivity norm data for forwarders). Redogörelse från skogforsk, nr 3/2004. 12 pp.

_____. 1998. New techniques and methods in an expanding wood-fuel market. *In:* Wood Fuels from Conventional Forestry. The Finnish Forest Research Institute. Research Papers 680, pp. 57-68.

_____, S. Frohm, B. Norden, J. Persson, and C. Wigren. 1994. Projekt Skogsbränsleteknik – slut rapport (Forest-Fuel Technology Project: Final Report) Redogörelse nr 5, 1994. Skogforsk.

Finne, K. 2003. Forest foreman. Biowatti Oy. Personnel communication.

Gullberg, T. 1997. A deductive time consumption model for loading shortwood. J. of Forest Engineering. 8(1): 35-44.

Haarlaa, R., P. Harstela, E. Mikkonen, and J. Mäkelä. 1984. Metsätyöntutkimus (Forest work study). Department of Logging and Utilization of Forest Products. Research Notes No. 46. 50 pp.

Hakkila, D. 2004. Developing Technology for Large-Scale Production of Forest Chips. Wood Energy Technology Programme 1999–2003. Technology Programme Report 6/2004. National Technology Agency. 98 pp.

_____. 1995. Procurement of Timber for the Finnish Forest Industries. The Finnish Forest Research Institute. Research Papers 557. 73 pp.

_____. 1989. Utilization of Residual Forest Biomass. Springer Series in Wood Science. 568 pp.

_____, H. Kalaja, and M. Mäkelä. 1975. Kokopuunkäyttö pienpuuongelman ratkaisuna (Full-tree utilization as a solution to the problem of small-sized trees). Folia Forestalia 240. 78 pp.

_____, _____, M. Salakari, and P. Valonen. 1978. Whole-tree harvesting in the early thinning of pine. Folia Forestalia 333. 58 pp.

Harstela, P. and L. Tervo. 1977. Männyn taimikon ja riukuasteen metsikön korjuun tuotos ja ergonomia (Work output and ergonomical aspects in harvesting of sapling and pole-stage stands (Scots pine)). Folia Forestalia 294. 23 pp.

Heikkilä, J., J. Laitila, V. Tanttu, J. Lindblad, M. Sirén, A. Asikainen, K. Pasanen, and K.T. Korhonen. 2005. Karsitun energiapuun korjuuvaihtoehdot ja kustannustekijät (Harvesting alternatives and cost factors of delimbed energy wood). Working Papers of the Finnish Forest Research Institute 10.

Ihonen, M. 1998. Rangan ja pienkokopuun metsäkuljetus maataloustraktorilla (Forest haulage of longwood and small-diameter whole trees using an agricultural tractor). TTS Institute Forestry Bulletin 595.

Johansson, J. and T. Gullberg. 2002. Multiple tree handling in the selective felling and bunching of small trees in dense stands. International J. of Forest Engineering. 13(2): 25-34.

Kahala, M. 1984. Osapuunakorjuu eteläsuomalaisissa harvennusmetsäolosuhteissa (Part-tree harvesting in thinnings in southern Finland). Metsäteho report 386.

_____. 1979. Puutavaran kuormatraktorikuljetus ja siihen vaikuttavat tekijät (Forwarder transport of timber and factors influencing it). Metsäteho report 355.

Kuitto, P-J., S. Keskinen, J. Lindroos, T. Oijala, J. Rajamäki, T. Räsänen, and J. Terävä. 1994. Puutavaran koneellinen hakkuu ja metsäkuljetus (Mechanized cutting and forest haulage). Metsäteho report 410.

Kärhä, K. 2006. Whole-tree harvesting in young stands in Finland. Forest Studies / Metsandusli-kud Uurimused 45: 118-134.

_____. 2004. Keto Forst Energy ja Valmet 945 saksi hakkuulaitteet energiapuun hakkuussa (Keto Forst Energy and Valmet 945 shear-head harvester heads in energy wood harvesting). Metsäteho Review 1/2004.

_____, A. Jouhiaho, A. Mutikainen, and M. Mattila. 2005. Mechanized energy wood harvesting from early thinnings. International J. of Forest Engineering. 16(1): 15-26.

_____, T. Vartiamäki, R. Liikkanen, S. Keskinen, and J. Lindroos. 2004. Hakkuutähteen paalauksen ja paalien metsäkuljetuksen tuottavuus ja kustannukset (Productivity and costs in the slash bundling and bundle forwarding). Metsäteho report 179. 94 pp.

Laitila, J. and A. Asikainen. 2006. Energy wood logging from early thinnings by harwarder method. Baltic Forestry. 12(1): 94-102.

_____, _____, L. Sikanen, K.T. Korhonen, and Y. Nuutinen. 2004. Pienpuuhakkeen tuo-tannon kustannustekijät ja toimituslogistiikka. (Cost factors of the production of small-sized wood chips and supply logistics). Working Papers of the Finnish Forest Research Institute 3.

Lilleberg, R. 1997. New techniques for small-tree harvesting. *In*: Forest Management for Bioenergy. The Finnish Forest Research Institute. Research Papers 640, pp. 65-70.

Melkko, M. and J. Taipale. 1975. Marttiini liukupuomi harvennuspuun korjuussa (Marttiini's slide boom for the harvesting of thinnings. Metsäteho Review 22/1975.

Metsäteho, (Ed.) 1984. Energiapuun korjuu teollisuuspuun korjuun yhteydessä (Harvesting of energy wood in connection with the harvesting of industrial roundwood). Metsäteho report 383

Metsäteho, (Ed.) 1991. Metsurin puutavaranhakkuun työ- ja suunnitteluopas (Guide for motor-manual cutting). 148 pp.

Metsätilastollinen vuosikirja 2005 (Finnish Statistical Yearbook of Forestry 2005). Finnish Forest Research Institute, Forest Information Service. 424 pp.

Mutikainen, A. 1999. Maataloustraktorin uusi perävaunu energia ja kuitupuun metsäkuljetuksessa (New trailer for agricultural tractor for forest haulage of energy wood and pulpwood). TTS Institute Forestry Bulletin 602.

Myhrman, D. 1989. Teknik för flerträdshantering på engrepsskördare. (Technology for multiple-tree handling with single grip harvester). For. Op. Inst. Sweden. Resultat. No. 20. 4 pp.

Mäkelä, M. 1986. Metsäkoneiden kustannuslaskenta (Guide for forest machines cost calculation). Metsätehon monisteita. 21 pp.

_____, A. Poikela, and R. Liikkanen. 2003. Energiapuun korjuu harvennusmetsistä (Energy wood harvesting from thinnings). Metsäteho report 161. 31 pp.

Nordström, S. 1985. Griplastarvagnar-84. Studie av kranarbete mm (Grapple boom log trailers-84. A study of loading boom equipped log trailers). Swedish University of Agricultural Sciences, Dept. of

Operational Effiency, Garpenberg, Sweden. Research Notes No. 14.

Nurminen, T., H. Korpunen, and J. Uusitalo. 2006. Time consumption analysis of the mechanized cut-to-length harvesting system. Silva Fennica. 40(2): 335-363.

Nätt, H. and A. Mutikainen. 2001. Uusi maataloustraktoripohjainen metsäkuljetusyksikkö ener-giapuun korjuuseen (New agricultural-tractor-based-forest-haulage unit for harvesting energy wood). TTS Institute Forestry Bulletin 643.

Ovaskainen, H., J. Uusitalo, and K. Väätäinen. 2004. Characteristics and significance of a harvester operators' working technique in thinnings. International J. of Forest Engineering. 15(2): 67-77.

Ranta, T. 2002. Logging residues from regeneration fellings for biofuel production – a gis based availability and cost analysis. Acta Universitatis Lappeenrantaensis 128. 182 pp.

Rieppo, K. 2002. Hakkuutähteen metsäkuljetuksen ajanmenekki, tuotttavuus ja kustannukset (Time consumption, productivity and costs in the forwarding of logging residues). Metsäteho report 136. 47 pp.

Sirén, M. and H. Aaltio. 2003. Productivity and cost of thinning harvesters and harvester-forwarders. International J. of Forest Engineering. 14(1): 39-48.

Timberjack Sales Oy. 2002. Timberjack 810B kuormatraktori (Timberjack 810B forwarder). A brochure.

Väkevä, J., A. Kariniemi, J. Lindroos, A. Poikela, J. Rajamäki, and K. Uusi-Pantti. 2003. Puutava-ran metsäkuljetuksen ajanmenekki (Time consumption of roundwood forwarding). Metsätehon raportti 123.

Väätäinen, K., H. Ovaskainen, P. Ranta, and A. Ala-Fossi. 2005. Hakkuukonekuljettajan hiljaisen tiedon merkitys hakkuutulokseen työpistetasolla (The significance of harvester operator's tacit knowledge on cutting with single-grip harvester). Finnish Forest Research Institute Research Notes 937.

Ylitalo, E. (Ed.). 2006. Puupolttoaineiden käyttö energiantuotannossa 2005. (Use of wood fuels for the production of energy in 2005). Finnish Forest Research Institute, Forest Statistical Bulletin 820.

Örn, J. and J. Väkevä. 2005. Puunkorjuu ja kaukokuljetus vuonna 2004. (Timber harvesting and long distance transportation in 2004). 4 pp.