Productivity of Stump Harvesting for Fuel

J. Laitila, T. Ranta, and A. Asikainen

Abstract

The productivity of harvesting stump and root wood was studied in Norway spruce (*Picea abies*) stands. The objective was to create productivity models (m^3/E_0h) for stump wood extraction, stump wood forwarding, and site preparation, in addition to identifying work phases and improvement opportunities in the extraction and forwarding chain. Productivity models were based on time studies with professional operators. The independent variables in stump wood extraction were stump diameter (cm) and the number of stumps per hectare. For forwarding, the independent variables were volume of stump wood removed (m^3/ha) and forwarding distance (m). When removing 350 stumps per ha with an average diameter of 40 cm, productivity was estimated at 7.9 m^3/E_0h. Increasing the number of stumps removed from 350 to 800 stumps per ha, increased productivity to 10.8 m^3/E_0h. Forwarding productivity was 7.8 m^3/E_0h with a forwarding distance of 250 m and a load size of 7.0 m^3 when removing 60 m^3 of stumps per ha.

Keywords: *forestry residues, harvesting, stumps, time consumption models, forwarding, final fellings, productivity*

Introduction

In Finland, the utilization of stump wood for energy purposes is rapidly moving from the testing phase to practice as a result of the positive experiences from the pioneering combined heat and power (CHP) plants in Central Finland (Hakkila 2004). In 2005 the use of stump wood chips by heating and power plants totaled 0.4 million m^3 (solid), triple the consumption of 2004, which corresponds to approximately 14 percent of the total consumption of forest chips in Finland (Ylitalo 2006).

Due to the fast growing use of stumps for energy production, the need for information on stump wood harvesting in the Nordic Region has increased. The results of many earlier studies are published in reports that are unavailable to all readers (Laitila and Asikainen 2004), or the data are quite old, from the 1970s (Mäkelä 1972, Hakkila and Mäkelä 1974, Fryk and Nylinder 1974, Nylinder 1977) or early 1980s (Kuitto 1984). Knowledge of the productivity of the machinery, availability of raw material, and cost factors associated with the harvesting and transport of forest fuels is essential when designing the procurement systems for forest fuels.

Stumps are harvested from spruce regeneration areas since spruce stumps have a high wood content as well as its roots being loosely anchored in the ground (Hakkila 2003). Stump and root wood are dry and homogenous raw materials; storage improves their quality. During storage stump wood does not absorb water as readily as logging residues, therefore, the consumption of stump wood chips is concentrated during the cold winter period when the need for energy is at its highest. Stones, sand, and other impurities might cause problems during comminution and combustion if the harvesting work is not performed properly (Hakkila 2003). The splitting of stump wood into pieces accelerates its drying, increases bulk density during transportation, and increases the speed of the comminution work. Furthermore, the risk of impurities is higher when the stump is not split properly.

Stump wood extraction is completed in conjunction with forest regeneration operations, when site preparation work is integrated with stump harvesting (Saarinen 2006a). Recovery of logging residues and stumps also creates a favorable environment for forest regeneration by reducing the difficulty of the regeneration work and improving the quality and productivity of site preparation and planting work (Saksa et al. 2002). As a result of stump removal, mechanized planting might be used as a cost efficient method of forest regeneration (Saarinen 2006a). In addition, removing stumps helps to prevent the spread of the root and butt rot (*Heterobasidion annosum*) that causes decay in conifers (Lipponen 2007).

The stumps are uprooted and broken up using an excavator that is equipped with a special stump rake extraction-splitting device. Processed stump and root wood is piled into small heaps in the stand so that the rain can wash off any soil still clinging to the roots while the sun and wind can dry the woody material. Site preparation for forest regeneration is usually combined with stump wood extraction and is performed using a mounding blade, which is a part of the extraction rake. After drying and cleaning, the piled stump wood pieces are forwarded by the forwarder to the roadside for storage. After seasoning at the roadside, the stumps are transported to the terminal or end-use facility for comminution by the truck-and-trailer unit which is specifically developed for transporting uncomminuted biomass. In 2005 the procurement of stump wood chips was mainly based on comminution to the end use facility (80%) or to the terminal (20%) (Kärhä 2007a). The typ-

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This paper was received for publication in December 2007.

International Journal of Forest Engineering 19(2): 37-47.

ical consumer of stump wood chips is a large CHP plant utilizing modern fluidized bed boiler technology and equipped with an efficient fuel handling and receiving system suitable for different types of solid fuel fractions.

This study estimates the productivity and cost of stump wood harvesting. The objective was to create productivity models for stump wood extraction and forwarding. Stump extraction was combined with site preparation and work was performed using a crawler excavator. Productivity models were based on empirical time studies with professional operators.

Material and Methods

Time Study of Stump Extraction and Site Preparation

The time study of combined stump extraction and site preparation was conducted using a JCB JS 160 L crawler excavator equipped with a "Kantokunkku" extraction-splitting and mounding device. The "Kantokunkku" stump harvester is a forklike stump hook. The splitting of the stumps is either made with the two tines of the fork or by pressing the stump-root system against the shear blade of the extraction-splitting device. The stump harvester is anchored to the boom. The excavator weighed 17 tonnes (tonne = 1000 kg) and was manufactured in 2001. The turning circle of the excavator and the boom was 360°. The machine was purpose built for earth moving work and is commonly used, especially in forest drainage and site preparation operations in Finland.

The time study took place June 26 through 28, 2006 in Mikkeli (61°41′N, 27°16′E). It was conducted manually by the continuous time method using a hand-held data recorder. The accuracy of the data recorder was 0.6 s (1 cmin). The excavator working time was divided into effective working time (E_0h) and delay time (Haarlaa et al. 1984, Mäkelä 1986), which is a common method employed in Nordic work studies. Auxiliary times (e.g., planning of work and preparations) were included in the work phases in which they were observed. Effective working time was divided into the following work phases:

- positioning boom to the stump
- lifting of stump
- splitting of stump and shaking to rid impurities
- piling of stump pieces onto small heaps
- site preparation
- smoothing of stump holes and
- moving

Positioning to the stump began when the boom started to swing toward a stump and ended when the extraction device was resting on a stump and the lifting and splitting began. Lifting ended when the operator started to shake or drop the stump for cleaning. The stump was split into pieces either on the ground by crushing it or during the cleaning process by pressing the wood material against the shear blade of the extraction-splitting device. Lifting, splitting, and cleaning of the stump and root system were, thus, often done concurrently. Small stumps (diameter < 30 cm) were split into two pieces while larger stumps were split into three or four pieces. Processed stump and root wood was piled into small heaps in the stand.

Site preparation involved mounding with the upper tongue of the extraction-splitting device. Mounds were compacted by pressing with the extraction-splitting device. Stump extraction holes were smoothed after stump processing by the movements of the boom and extraction device before moving to the next working location. Moving began when the excavator started to move from one working location to another and ended when the excavator stopped moving to perform another activity.

The time studies took place on plots measuring 25 by 13.9 m (the measured width of the excavator's working strip in the study). The diameter of each stump (cm) including bark was marked on both sides of the stump (**Fig. 1**) before beginning extraction. Stump diameters recorded in the time studies were from these markings. The diameters of the stumps were measured at the cutting surface. The stand had been harvested in April 2006 by a single-grip harvester and the logging residues recovered after logging. The harvested stands were pure Norway spruce (*Picea abies*). The heights of the extracted stumps were rated as normal and representative of Nordic conditions when using mechanized cutting. The stump height rating was based on visual observation and researcher's earlier experience about logging operations in Finland. The time study material was compromised of 410 spruce stumps from 22 time study plots and two blocks. The soil type of the stands was a sandy till while the nature and slope of the ground surface was classified as "easy conditions" according to the Finnish classification (Tavoiteansioon perustuvan puutavaran ... 1990). Stand characteristics are presented in **Table 1**.

Time Study of Stump Forwarding

The time study of the forwarding of stumps involved observing a 6-wheel Ponsse Bison S15 B1 forwarder (year 2000 model). The forwarder weighed 13.8 tonnes and was rated to carry a load of 12 tonnes. The Ponsse Bison forwarder was

Figure 1. ~ *An example of a Norway spruce stump in the time study plot. The cross cutting diameter of the stump (43 cm) was marked prior to time study.*

Table 1. ~ *Characteristics of time study plots in the stump extraction.*

	Range
Diameter of stumps on the plot (cm)	19 to 60
Average stump diameter on the plot (cm)	34
Volume of stumps on the plot (*l*)	31 to 477
Average volume of stumps on the plot(*l*)	140
Number of stumps on the plot	10 to 30
Average number of stumps on the plot	18
Number of stumps per hectare	318 to 863
Average number of stumps per hectare	577
Site preparation, time consumption per hectare (hr)	1.26 to 7.14
Average site preparation time (hr/ha)	3.24

Table 2. ~ *Characteristics of the time studied stands.*

	Range
Number of loads	48
Driving unloaded (m)	34 to 345
Average driving distance with empty load (m)	156
Driving during loading (m)	15 to 145
Average driving distance (m)	50
Grapple load size in the loading (m^3)	0.11 to 0.19
Average grapple load size in the loading (m^3)	0.14
Size of loading stop (m^3)	0.61 to 2.87
Average size of the loading stop (m^3)	1.32
Driving distance between loading stops (m)	3.0 to 14.7
Average driving distance (m)	7.2
Stump wood concentration on the strip road (m^3/100 m)	5.9 to 57.3
Average concentration on the strip road (m^3/100 m)	21.2
Average load size (m^3)	8.6
Grapple load size in the unloading (m^3)	0.18 to 0.32
Average grapple load size in the unloading (m^3)	0.25
Driving with load	15 to 340
Average driving distance with loaded (m)	136

equipped with owner-constructed side bars to allow the carrying of larger loads while the grapple was a purpose-built logging residue grapple instead of a normal timber grapple.

The forwarder time study was carried out by the continuous time method again using a hand-held data recorder. Driving distances when driving unloaded, during loading, and with load were measured using a thread meter. The accuracy of the data recorder was 0.6 s (1 cmin). Each of the forwarder's working cycles (clock time) was divided into effective working time (E_0h) and delay time (Haarlaa et al. 1984, Mäkelä 1986). Effective working time, including auxiliary time of each work phase (e.g., planning of work and preparations), was divided into the following work phases:

- driving unloaded, distance m
- loading, number of grapple loads per load
- driving during loading, distance m
- reversing and turning around in the stand
- driving with load, distance m
- unloading, number of grapple loads per load
- moving during unloading at the roadside storage and
- cleaning of the roadside storage

Driving unloaded began when the forwarder left the landing area and ended when the forwarder stopped at the first loading stop and began to load stumps. Loading began when the operator started to move the crane from the bunk and ended when the last grapple load of the loading stop was loaded and the crane with the grab was rested on the bunk. Stumps were loaded from one side of the forwarder due to the location of stump piles or line-heaps. Driving during loading started when the stump loading was finished and the forwarder began to move to the next loading stop. A loading stop was the working location on the strip road where the loading work was carried out. Driving during loading ceased when the forwarder stopped at the next loading stop to begin loading. Driving with load began when the load was full and ended when the forwarder stopped at the landing area to begin unloading. The unloading phase began when the forwarder raised the crane for unloading and ended when the load was empty and the forwarder was ready to return to the stand or perform another activity. When the pile at the roadside landing was high enough, the forwarder moved to the next unloading point during unloading at the roadside storage. Before returning to the stand, the roadside landing was cleaned of material that had been dropped while unloading.

It was not possible to determine the size of each load individually. An average load size was estimated after the forwarded stumps were crushed at the terminal and delivered to the Pursiala CHP plant in Mikkeli where the delivered volumes were measured. Using this approach, the average load size of stump wood pieces was 8.6 m^3 with the time study data consisting of 48 full forwarder loads of stump and root wood.

The characteristics of the time studied stands are detailed in **Table 2**. The time study of the stump forwarding was carried out during the period of August 26 through September 6, 2006 in Juva (61°54′N, 27°52′E). The stumps had been extracted and piled to the line-heaps using a 20 tonnes excavator (a different excavator than in time studies) with the average spacing of strip roads of 20 m in the stand. The nature and slope of the ground surface, including the bearing capacity of the mineral soil ground, were classified as "easy conditions" according to the Finnish classification (Tavoiteansioon perustuvan puutavaran ... 1990).

Data Analysis of Time Studies

The recorded time study data and the measured data of the stand, stump, and load characteristics were combined as a datamatrix. The time consumption (E_0h) of each work phase in stump extraction and in forwarding was formulated by applying regression analysis. Delay times were not included in the analysis, since the studies were too short to obtain an accurate estimate of the general delay time of the machines and because a follow-up study was not performed (Haarlaa et al. 1984). Different transformations and curve types were tested to obtain the best possible symmetrical distribution of residuals of the regression models and to achieve the best values for the coefficients of determination of final models. The regression analysis was performed using the SPSS statistical package.

For forwarding, the independent variables were volume of stump wood removed (m^3/ha) and forwarding distance (m). In stump wood extraction, the independent variables were stump diameter (cm), number of stumps per hectare, and average site preparation time per hectare. The final calculation unit for time consumption for all of the work elements was second (s) per solid cubic meter (m^3) or seconds per stump.

To combine stump extraction and site preparation, time consumption models were created for the moving, stump processing as well as for the site preparation work. The stump processing time consumption model included the following work phases:

- positioning boom to the stump,
- lifting of stump,
- splitting of stump and shaking off impurities,
- piling of stump pieces onto small heaps, and
- smoothing of stump extraction holes.

The forwarding models included driving unloaded, loading, moving during loading, driving with load, and unloading. In the time consumption models, reversing and turning around in the stand was included in the moving time during loading. The moving time during unloading and the cleaning time at the roadside storage were included in the time consumption model of unloading work. Stump wood concentration on the strip road (m^3/100 m) was derived using the driving distance during loading and the load size in the work cycle. The size of loading stop (m^3) was calculated by dividing the load size by the number of movements between loading locations in the work cycle. Grapple load sizes in loading and unloading work were based on average values per load.

Results

Combined Stump Extraction and Site Preparation

Splitting of stumps and shaking off impurities represented 42 percent of the crawler excavator's effective working time in the time study (**Fig. 2**), while stump lifting accounted for 18 percent. Site preparation and piling of stump pieces to small heaps accounted for 15 percent and 11 percent, respectively. Positioning the boom to the stump, smoothing of stump holes, and moving represented 3 to 7 percent of the work cycle (**Fig. 2**). The extracted stumps were free of impurities, and stumps were split into pieces. Stumps were accepted as clean when the stones, loose soil, and most of the attached soil had fallen off.

Moving

The moving time model for the excavator in the stump wood extraction was a function of density of extracted stumps per hectare. An increase in the number of extracted stumps per hectare decreased the moving time per stump when it was possible to process several stumps from one working location.

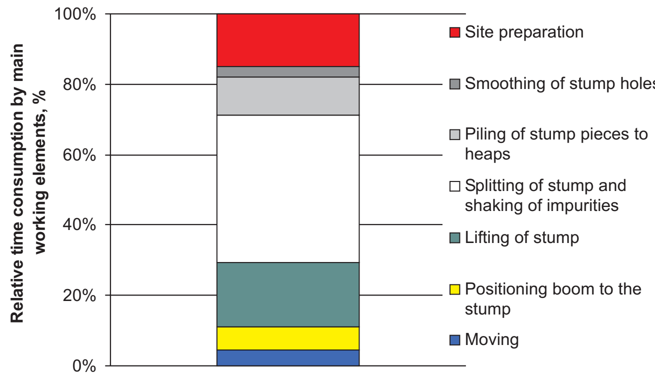

Figure 2. ~ *The main elements of the excavator's effective working time in the combined stump extraction and site preparation in the time study conditions.*

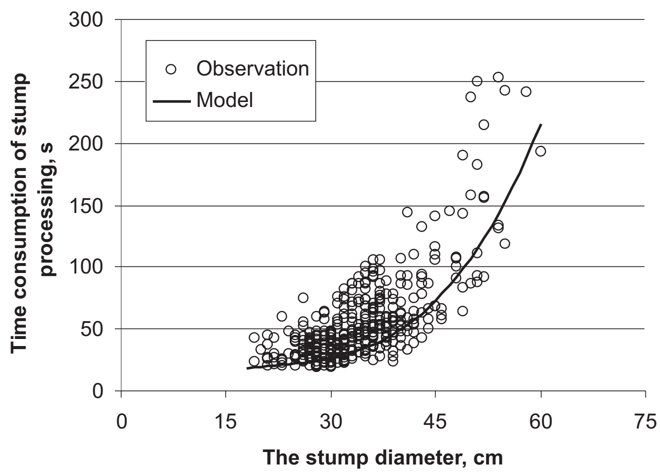

Figure 3. ~ *Processing time of stumps according to the stump diameter.*

$$T_{Moving\ E} = -1.630 + 3{,}838.892 \times \frac{1}{x}$$

where:

$T_{Moving\ E}$ = Moving time during extracting of stumps by excavator, s/stump

x = Number of extracted stumps per ha

Processing

Processing time for stumps was represented by a third-degree polynomial function with stump diameter as the independent variable. An increase in stump diameter increased stump processing time geometrically (**Fig. 3**). Large stumps are more tightly attached to the ground due to their larger root system. Additionally, larger stumps have to be split into several pieces which also affects piling and splitting time. An increase in stump diameter also increases stump height (Hakkila 1972), which will aggravate the splitting work.

$$T_{Processing} = -18.474655 + 4.944438d - 0.189565d^2 + 0.002995d^3$$

where:

$T_{processing}$ = Uprooting and splitting time of the spruce stump (s/stump)

d = Diameter of the extracted stump (cm)

Site Preparation

The average effective time consumption (E_0h) of site preparation work was 3.24 hours per hectare during the time study (**Fig. 4**). The maximum was 7.14 hours per hectare while the minimum was 1.26 hours per hectare. The variation in time consumption between time study plots was considerable. When the study began, the operator performed more site preparation than was required. The average site preparation time per hectare was 2.84 hours, if plots 3, 4, and 5 were excluded from the field study data (**Fig. 4**).

Time consumption in site preparation per stump ($T_{Mounding}$) was derived by dividing the average site preparation time per hectare ($T_{Area\ of\ mounding}$) by the number of extracted stumps per hectare. Site preparation time per hectare was set to constant since the need of mounds per hectare is constant in forest regeneration when planting, for example, Norway spruce.

$$T_{Mounding} = \frac{T_{Area\ of\ mounding}}{x}$$

$T_{Mounding}$ = Site preparation time per stump, s

$T_{Area\ of\ mounding}$ = Average site preparation time per hectare, hours per hectare (3.24 hr/ha)

x = Number of extracted stumps per hectare

Forwarding of Stumps

Loading consumed 57 percent of the forwarder's effective working time in the time study while unloading constituted 25 percent of the time (**Fig. 5**). Driving unloaded and with load took 5 percent and 6 percent, respectively. Driving during loading accounted for 3 percent, reversing and turning around in the stand, moving during unloading, and cleaning of the roadside storage were 1 percent each.

Driving Unloaded

Distance was the independent variable when driving unloaded. Time consumption was modeled as a linear function of the forwarding distance.

$$T_{Empty\ load} = \frac{14.599 + 1.042 l_{without\ load}}{v_{load}}$$

where:

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

$l_{without\ load}$ = Forwarding distance without load, m

v_{load} = Load size, m^3

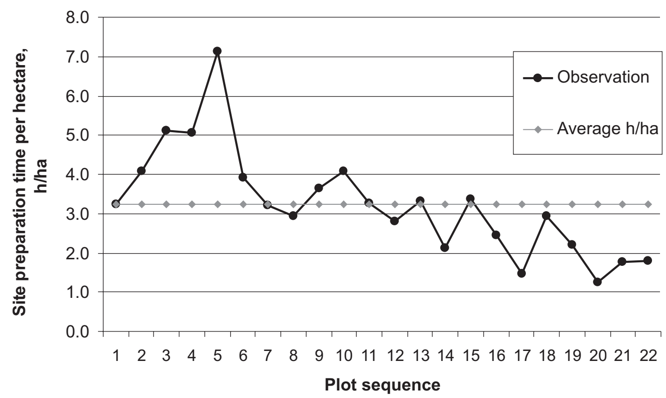

Figure 4. ~ *Time consumption of site preparation in the time study plots.*

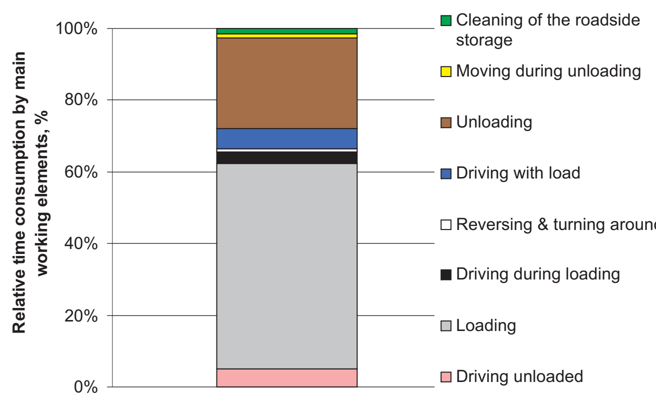

Figure 5. ~ *Elements of the forwarder's effective working time when forwarding stumps.*

Loading

In this study loading denoted the time used for loading activities at the loading stop. Higher volumes of stump wood per hectare increased the stump wood concentration beside the strip road and thus enlarges the amount of material that could be loaded in one movement of the forwarder. In this study, during loading, the average distance between loading stops was 7.2 m (**Table 2**). Increased stump wood concentration per 100 m of strip road increased the size of each loading stop. Larger loading stop size increases, to some degree, the average grapple load, because it enables the operator to increase the grapple loads per m^3 from one working location. The grapple load size is further linked to the time consumption of loading work and to the effective working time productivity m^3/E_0h. In the time study, the average number of grapple swings per load was 62 (standard deviation [SD] 8.2, min 45, max 80) while the average time of grapple swing was 32.5 s (SD 3.6, min 24.3, max 40.0).

The average grapple load size was used as the independent variable for time consumption in the loading work (**Fig. 6**). With small grapple loads the loading time consumption per m^3 was more than with larger grapple loads. The relation of loading time to grapple load size was considered to be linear (**Fig. 6**).

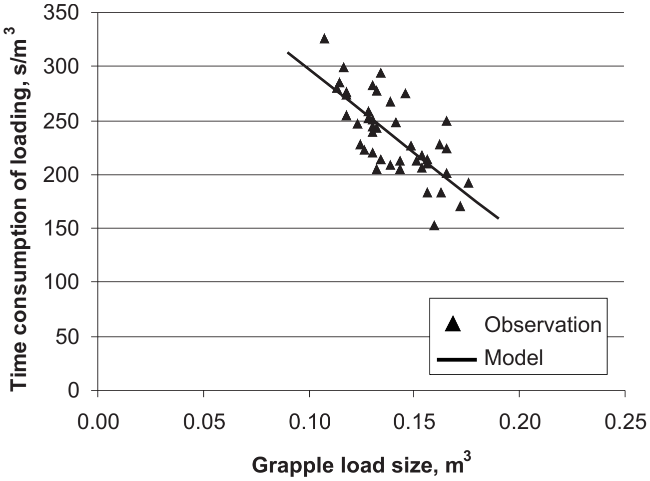

Figure 6. ~ *Time consumption of loading as a function of grapple load size.*

Loading Time Consumption

$$T_{Loading} = 451.347 - 1{,}539.249 \times \nu_{Grapple}$$

where:

$T_{Loading}$ = Time consumption of stump wood loading, s/m^3

$\nu_{Grapple}$ = Grapple load size when loading stump wood, m^3

The grapple load size (m^3) was derived from the volume per loading stop (m^3) which was calculated from the stump wood concentration (m^3) per 100 m strip road. The relation was considered to be linear for both models.

Grapple load size was formulated as:

$$\nu_{Grapple} = 0.127 + 0.0101 \times L_{Stop}$$

where:

$\nu_{Grapple}$ = Grapple load size when loading stump wood, m^3

L_{Stop} = Size of loading stop when loading stump wood, m^3

Size of loading stop was formulated as:

$$L_{Stop} = 0.510 + 0.03947z$$

where:

L_{Stop} = The size of the loading stop, m^3

z = Stump wood concentration alongside the strip road, m^3/100 m strip road

Driving During Loading

The driving time between loading stops was modelled according to stump wood concentration, m^3 per 100 m strip road. The number of times and distance the forwarder moved depended on the accumulation of the stump wood beside the strip road. Move time during loading decreased when the energy wood concentration increased. An increase in stump wood accumulation on the strip road shortened the driving distance required to collect a full load. The average time spent reversing and turning around in the stand during loading was set as a constant value (a) in the time consumption formula.

$$T_{Moving\ F} = 1.540 + \frac{214.224}{z} + a$$

where:

$T_{Moving\ F}$ = Moving time of the forwarder during loading, s/m^3

z = Stump wood concentration alongside the strip road, m^3 per 100 m strip road

a = Constant miscellaneous time, 3 s/m^3

Driving with Load

Driving distance was used as the sole independent variable when modelling driving with load time. Load size could have served as a second independent variable but each individual load was not measured directly. Time consumption was best modelled as a linear function of the forwarding distance. Time consumption while driving with load was somewhat higher compared to time consumption when driving without load.

$$T_{Driving\ with\ load} = \frac{31.354 + 1.280 l_{with\ load}}{\nu_{load}}$$

where:

$T_{Driving\ with\ load}$ = Time consumption of forwarding with load, s/m^3

$l_{with\ load}$ = Forwarding distance with load, m

ν_{load} = Load size, m^3

Unloading

Time consumption of unloading was modeled as a function of grapple load size. An increase in the grapple load volume while unloading reduced the unloading time per m^3. In the time study the average number of grapple swings per load was 35.3 (SD 5.6, min 27, max 46) while the average time of grapple swing was 25.4 s (SD 2.7, min 19, max 32). Average cleaning and moving time during and/or after unloading at the roadside storage was 11 s/m^3 and that value was added to the time consumption formula as a constant value (b).

$$T_{Unloading} = 243.905 - 281.272 \times \sqrt{\nu_{U-Grapple}} + b$$

where:

$T_{Unloading}$ = Time consumption of stump wood unloading, s/m^3

$\nu_{U\text{-}Grapple}$ = Grapple load size when unloading stump wood, m^3

b = Constant miscellaneous time of unloading, 11 s/m^3

Review of Results

Effective time consumption for the combination of stump extraction and site preparation T_{Stump} (s/stump) was the sum of the main working elements:

$$T_{Stump} = T_{Moving\ E} + T_{Processing} + T_{Mounding}$$

The productivity (m^3/E_0h) of the combined stump wood extraction and site preparation were solved by estimating the volume of the harvested stump. Stump volume was determined from stump diameter by using stump mass models from Hakkila (1976) and basic densities of stump wood (Hakkila 1975). Stump volume was further increased by the coefficient 1.17, since Hakkila's mass model excluded roots with a diameter of less than 5 cm. The coefficient used is based on operational observations of the yield of stump wood from harvested stands (Hakkila 2004).

The effective forwarding time of the stumps by the forwarder $T_{S\ Forwarding}$ (s/m^3) is the sum of the main working elements:

$$T_{S\ Forwarding} = T_{Empty\ load} + T_{Loading} + T_{Moving\ F} + T_{Driving\ with\ load} + T_{Unloading}$$

Time consumption per forwarder load, T_{Load}, was calculated by multiplying the time consumption per solid cubic meter ($T_{S\ Forwarding}$) by the load size of the forwarder (ν_{load}). The average load size of stump wood was determined to be 8.6 m^3 in this study. The total length of the strip road network was 500 m/ha in stump harvesting stands based on an average strip road spacing of 20 m.

$$T_{Load} = T_{S\ Forwarding} \times \nu_{load}$$

Statistical analysis was made for each regression model to examine the goodness-of-fit of regression models and to test the significance of coefficients. Results of the analysis are detailed in **Tables 3 and 4**. F-value of the model indicates that the model fits well with the data ($p < 0.001$). Stump diameter is the key independent variable in stump processing, and it would explain 53 percent of the processing time's variation. But, the model underestimates the time consumption of lifting very small and very large stumps. Therefore, d^2 and d^3 were added to the model (**Table 3**). Although their *p*-value is small due to multicollinearity, they considerably improve the prediction power and fit of the model (**Table 3**). In forwarding, the models for work elements had good fits, and *p*-values indicated that independent variables were very significant (**Table 4**). Only the model for the grapple load size had a higher *p*-value (0.091).

Figure 7 illustrates the productivity (m^3/E_0h) of combined stump extraction and site preparation for varying values of

Table 3. ~ *Statistical characteristics of regression models of stump extraction.*

Work phase model	Dependent variable	R^2	F-test F-value *p*	N	Term	Constant/coefficient Estimate	Constant/coefficient Std. error	t-test t-value	t-test *p*
Moving	$T_{Moving\ E}$	0.74	50.396	20	Constant	–1.630	1.094	–1.490	0.153
			< 0.001		x^{-1}	3,838.892	540.764	7.099	< 0.001
Processing of stump	$T_{Processing}$	0.63	213.646	374	Constant	–18.475	72.553	–0.255	0.799
			< 0.001		d	4.944	6.103	0.810	0.418
					d^2	–0.189	0.166	–1.141	0.255
					d^3	0.003	0.001	2.050	0.041

Table 4. ~ *Statistical characteristics of regression models of forwarding.*

Work phase model	Dependent variable	R^2	F-test F-value *p*	N	Term	Constant/coefficient Estimate	Constant/coefficient Std. error	t-test t-value	t-test *p*
Driving unloaded	$T_{Empty\ load}$	0.89	372.512	46	Constant	14.599	9.392	1.554	0.127
			< 0.001		l_e	1.042	0.054	19.301	< 0.001
Loading	$T_{Loading}$	0.53	47.066	42	Constant	451.347	31.587	14.289	< 0.001
			< 0.001		$\nu_{Grapple}$	–1,539.429	224.366	–6.860	< 0.001
	$\nu_{Grapple}$	0.68	2.991	42	Constant	0.127	0.008	16.25	< 0.001
			0.091		L_{Stop}	0.0101	0.006	1.729	0.091
	L_{Stop}	0.70	102.309	44	Constant	0.510	0.091	5.613	< 0.001
			< 0.001		z	0.03947	0.004	10.115	< 0.001
Driving while loading	$T_{Moving\ F}$	0.68	96.673	47	Constant	1.540	1.403	1.097	0.278
			< 0.001		z^{-1}	214.224	21.788	9.832	< 0.001
Driving with load	$T_{Driving\ L}$	0.92	511.897	47	Constant	31.345	9.331	3.359	0.002
			< 0.001		l_1	1.280	0.057	22.625	< 0.001
Unloading	$T_{Unloading}$	0.56	57.394	46	Constant	173.797	9.348	18.59	< 0.001
			< 0.001		$\sqrt{\nu_{U-Grapple}}$	–280.220	36.988	–7.576	< 0.001

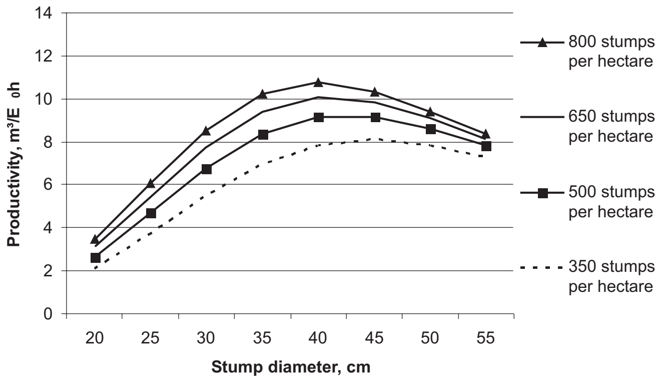

Figure 7. ~ *The productivity (m^3/E_0h) of combined stump extraction and site preparation according to the stump diameter and number of stumps per hectare.*

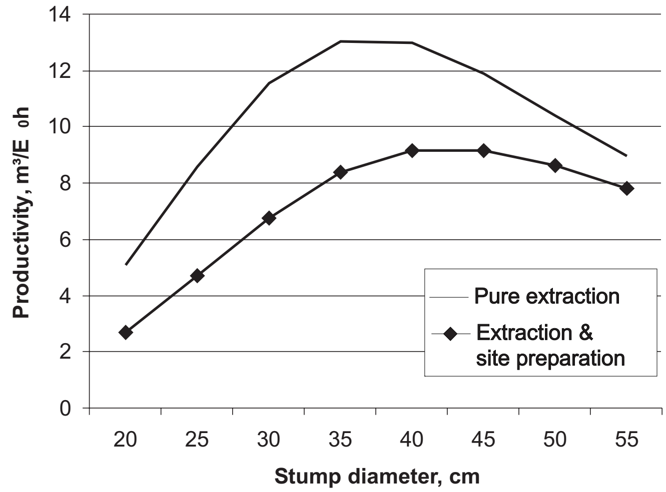

Figure 8. ~ *Productivity of pure extraction compared with extraction and site preparation (m^3/E_0h) as a function of stump diameter, assuming a stump density of 500 per hectare.*

stump diameter and number of removed stumps per hectare. The productivity curves were drawn using the time consumption models developed in this study. Productivity of stump harvesting increased rapidly until stump diameter reached 35 cm. When stump diameter exceeded 40 cm, productivity declined steadily because the stump volume and mass exceeded the excavator's stability in the lifting work (**Fig. 7**). Stump extraction time increased as a function of stump diameter faster than the stump volume correspondingly increased. The 17 tonnes excavator was relatively small for stump harvesting work. In stump extraction in Finland, the excavator's weight is usually about 21 tonnes or more (Kärhä 2007b).

The crawler excavator is quite clumsy compared to the forwarder or the harvester and, therefore, moving time from stump to stump clearly affected productivity in stump extraction. When stump diameter was 40 cm and 350 stumps were removed per hectare, productivity was 7.9 m^3/E_0h (**Fig. 7**). An increase in stump removal from 350 to 800 stumps per hectare increased productivity to 10.8 m^3/E_0h.

Figure 8 illustrates the effect of the site preparation work on the productivity of stump extraction and splitting. The example assumes 500 stumps per hectare with stump diameters ranging from 20 to 55 cm. The results indicate that the productivity of the combined stump extraction and site preparation work ranged between 52 and 87 percent of the productivity of the pure stump extraction and splitting work depending on stump diameter (**Fig. 8**).

Forwarding productivity was 7.8 m^3/E_0h, when the forwarding distance was 250 m, load size was 7.0 m^3, and stump removal was 60 m^3 per hectare (**Fig. 9**). An increase in the load size from 7 to 13 m^3 improved forwarding productivity by 1 m^3/E_0h. Forwarding productivity responded modestly to the increase in load size because the proportion of driving with load or without load was a relatively small part of the total effective working time consumption in the forwarding of stumps (**Fig. 5**).

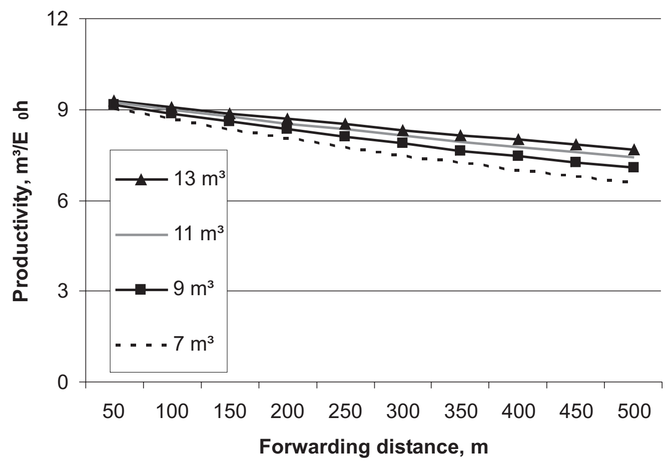

Figure 9. ~ *Forwarding productivity according to load size (7 to 13 m^3) and forwarding distance, when stump removal is 60 m^3/ha.*

Discussion and Conclusions

The 17 tonnes excavator used in this study was equipped with the "Kantokunkku" extraction-splitting and mounding device. It was determined that it was an efficient unit for stands where spruce stump diameter did not exceed 40 cm. Operating on larger stumps would require a heavier machine with more stability and power. Excavators around the size of 21 tonnes are more commonly used for stump harvesting in Finland (Fredriksson 2004, Kärhä 2007b). Big excavators also have greater boom reach which increases their ability to process more stumps per location. The longer reach also improves site preparation productivity.

Figure 10 includes collected comparison material about stump processing time according to stump diameter, when the extraction work was done either by the 20 tonnes excavator or by a forwarder based stump harwarder (Laitila and Asikainen

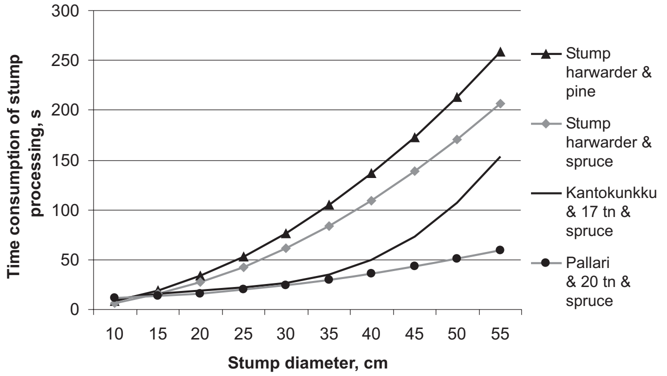

Figure 10. ~ *Time consumption of stump processing according to stump diameter when using different extraction methods or tree species (Laitila and Asikainen 2004).*

2004). The stump harwarder includes an extraction and splitting device mounted on the crane of the forwarder. The extraction and splitting device, which was anchored to the boom of the 20 tonnes crawler excavator, was a Pallari KH-160 (www.tervolankonepaja.fi).

Figure 10 shows that stump processing time of the 17 tonnes excavator, equipped with "Kantokunkku", and the 20 tonnes excavator, equipped with "Pallari", are the same up to a stump diameter of 35 cm. After that diameter the stump processing time of the 17 tonnes excavator starts to increase more than that of the 20 tonnes excavator. Stump processing time is significantly higher for the stump harwarder compared to the excavator-based machine (**Fig. 10**). The main reason is that the excavators are constructed solely for this kind of work. Larger production series also makes the excavator a less expensive base machine for stump extraction than the forwarder or harvester. Therefore, in Finland stump harvesting is currently based on excavator technology.

Shaking off the impurities from the extracted stumps took a relatively large proportion of the excavator's working time, and stump shaking by the crane movements also causes stress to the driver. A vibrator device in the stump extraction device could improve the working efficiency and might also result in stumps that have even less impurities.

Maturation of stumps after cutting decreases the cohesion between roots and the soil when the fine roots (diameter < 2 mm) start to decompose and larger roots start to dry and shrink. Understandably decomposition and drying after logging and before stump extraction makes stump lifting faster and cleaning easier. According to Palviainen et al. (2004), the mass loss of spruce fine roots was 10 percent after 1 year and 30 percent after 3 years. In Finland stumps are usually harvested within 1 year after roundwood harvesting to speed up forest regeneration operations.

Stand selection criteria and harvesting schedule is an important factor affecting the amount of loose soil in the recovered stump-root system. According to Jonsson (1985), the quantity of contaminants is strongly influenced by soil type, harvesting season, and moisture content. According to Spinelli et al. (2005), removal of impurities takes longer if the soil has a significant clay component; clay tends to stick to the root surface more than sand.

Proper stump harvesting is a precondition for the utilization of stumps for fuel since the impurities might cause serious problems in comminution, particularly in combustion. The control and cleaning of impurities is essential in all stages of the stump procurement chain from the stand to the end-use facility, especially in stump extraction and forwarding. To improve cleaning the stump-root system, a vibrating screen-bunk which was developed in the 1970s in Sweden by Ösa (Jonsson 1978, 1985) can be used. The vibrating screen-bunk is mounted on the forwarder and impurities are loosened while driving in the stand.

Stump extraction work is restricted when the ground is frozen and not free of snow. The forced down time for the excavator in winter increases the capital cost per unit if substitute work is not available. Forwarding is possible during the winter season if the stump and root pieces are properly piled into heaps. Large and high stump heaps remain visible even after heavy snowfalls. Stump wood frozen to the ground might increase the loss of useable volume somewhat and increase harvesting costs.

The measurement of the stump volumes is very problematic in stump harvesting (e.g., Hakkila 2006). One reasonable solution would be to integrate stump diameters and the number of harvestable stumps into the harvester's measurement system when cutting the stand. Having this information available would facilitate the better organization of the harvesting activities and allocation of the machine resources in stump wood procurement.

Unloading, and other related operation stages at the roadside landing, took a surprisingly large amount of operating time in forwarding. The share of the roadside storage operations were 27 percent of the relative time consumption in the time studies (**Fig. 5**). In the time study, stump pieces were loaded and unloaded by crane. The benefit of crane handling is that the number of stump contacts increases which assists in the removal of impurities during the loading or unloading process. An alternative method for improving unloading productivity would be to convert the bed to a dump body with a solid bottom and sides. The landing area is usually crowded and the material must be put in high piles, making it necessary to use a crane. The simplest way to improve unloading productivity is to increase the grapple load, but a larger grapple might be clumsy in loading.

Forwarding productivity of stump and root wood is lower compared to the forwarding productivity of loose logging residues (Asikainen et al. 2001, Ranta 2002), thinning roundwood (Väkevä et al. 2003), or whole trees after mechanized felling bunching (Laitila et al. 2007). When the forwarding distance was 250 m and material concentration was 10 m^3 per 100 m strip road, forwarding productivity was about 12 m^3 of logging residues, roundwood, or whole trees per effective working hour. In the comparison assessment, the load volume of logging residues was 8 m^3, roundwood 7.6 m^3, and whole trees 6 m^3. In corresponding stand circumstances, forwarding productivity of the stump and root wood were 7.9 m^3 per effective working hour, when the load size was 8.6 m^3. This productivity difference is a result of smaller grapple load size, variable piece size, and the form and removal of impurities during crane work.

The average effective working time (E_0) of site preparation was 3.24 hours per hectare in this study. According to the preliminary results of Saarinen (2006b), time consumption of mounding was about 2 effective working hours per hectare in the combined stump extraction and mounding. Saarinen (2006a) states that combining stump extraction and mounding seems to be promising, but a comparison should also be made of the mound quality with separate mounding and combined stump wood removal and mounding. Combining site preparation with stump extraction increase the risk that some of the mounds will be destroyed by flattening and mixing humus and mineral soil during the forwarding phase. The quality of pure mineral soil mounds is crucial for preventing pine weevil (*Hylobius abietis*) damage in forest regeneration areas (Heli Viiri, Finnish Forest Research Institute, Joensuu Unit - personal communication 2/9/08).

An interesting solution for improving stump harvesting productivity could be to integrate the forwarding of stumps with the site preparation work as it is done in the recovery of logging residues (e.g., Von Hofsten and Norden 2002, Laitila et al. 2005). The forwarder is equipped with a mounder between the front and rear bogies on both sides with soil being prepared while driving in the stand and collecting logging residues. According to the results, integration decreases the cost of site preparation and residue recovery by about 10 percent when compared to separate operations with two machines (Laitila et al. 2005).

A detailed field study was made with the goal of capturing information concerning stump and root wood harvesting productivity and improvements opportunities. Time consumption models provide recent, valid, and accurate productivity estimates in Finnish stump and root wood harvesting conditions when using a medium-sized excavator and forwarder. The results of this study may help guide machine selection and system improvements, as well as cost calculations and comparisons for simulation and modeling purposes. Results presented in this paper were based on the output of one forwarder operator and one excavator operator and, therefore, do not represent the full Nordic range of productivity of stump root system extraction and forwarding. Nevertheless the reported results give novel trends and estimates for the performance characteristic of stump and root wood harvesting for fuel.

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