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Pine and spruce stump harvesting productivity and costs using a Pallari KH 160 stump lifting tool

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Abstract

Even though stumpwood may become a significant part of the future fuel mix for combined heat and power plants in Sweden the harvesting of stumps after regeneration fellings is still only performed on a trial basis. Results from time studies on two, 23 tonne, excavators fitted for stump lifting; together with follow-up data on stump lifting and forwarding are presented. Lifting, splitting and piling the stumps accounted for 17 %, 32 % and 32 %, respectively, of the total productive work time. A predictive model was developed to estimate operational times and productivities when lifting pine and spruce stumps. Stump diameter, species and terrain conditions contributed significantly to the fit of the model. The model predicts that productivity of stump lifting in spruce sites with easy terrain conditions and average stump diameters of 20 and 40 cm will be 1.23 and 4.19 oven-dry tonnes (ODT) per productive work hour respectively. This is 43% higher than in pine sites with difficult terrain conditions and the same diameters. In the follow-up data the productivity in stump lifting varied from 1.5 to 2.9 ODT per productive work hour while the cost for lifting and extraction to roadside varied from 37.8 to 59.4 € per ODT.

Keywords: excavator, forest fuels, Norway spruce, Scots pine, time study.

Introduction

The harvesting of stumps after felling trees in regeneration of forest stands could have a number of benefits by providing a considerable quantity of biomass for the energy sector (Swedish Forest Agency 2008), hindering the spread of root-rot (Vasaitis et al. 2008), and helping to prepare sites for subsequent planting due to the scarification associated with harvesting stumps (Saarinen 2006). The total annual potential of stumpwood in final-cut stands in Sweden is 11.7 million oven-dry tonnes (ODT) (Athanassiadis et al. 2009). One tonne is equivalent to 1000 kg. After subtracting the amount situated in areas where ecological restrictions apply, and in areas with rough terrain and steep slopes, the remaining available potential of stumpwood amounts to 4.2 million ODT (Athanassiadis et al. 2009). Assuming a net energy content of 5.2 MWh per ODT (Anerud & Jirjis 2011), the available potential is circa 22 TWh, which corresponds to circa 20 % of the annual biomass based energy consumed in Sweden (Swedish Energy Agency 2009).

Currently, most stump harvesting is performed in stands of Norway spruce (*Picea abies*), mainly because it has a shallow root system, but also due to the fact that spruce tends to be grown on richer soils that are less sensitive to nutrient leaching and any future decrease in site productivity. According to Kärhä & Mutikainen (2009), 14 % (ca. 1.2 TWh or 0.23 million ODT) of wood-chip production in Finland was derived from stumpwood in 2008. In Sweden, stump harvesting is still performed on an experimental basis in order to field-test different forest management concepts and harvesting machinery (Lindroos et al. 2010).
In the past, stumps were commonly used for tar production in Sweden (Jonsson 1985). In the beginning of the 20th century, explosives were trialed as a method for

harvesting stumps, but manual techniques were generally used (Lundberg 1918). In 1980, the use of stumps for pulp production became locally rather common in Sweden, with about 200 000 m^3 of solid stumpwood being used in 1982 (Jonsson 1985). High costs, combined with problems associated with soil contamination, brought this business to an end in the late 1980s. The growing public awareness of climate change, the establishment of international obligations to decrease greenhouse gas emissions and the scarcity of fossil fuels have led to renewed interest in stumps, this time as a renewable energy source. The technique used today is principally similar to that used 25 years ago (cf. Jonsson 1985, Karlsson 2007). Typically, a stump-lifting tool attached to an excavator uproots the stumps and splits them, either during or after the uprooting process. The stumps are then shaken to remove most of the attached soil and stones, and piled for subsequent transport to the roadside and on to the receiving plant. As only one scientific paper (Laitila et al. 2008) and some conference contributions (Kärhä & Mutikainen 2009; Lazdinš et al. 2009; Jouhiaho et al. 2010) have appeared presenting recent time studies on stumpwood harvesting there is a need for further research in order to get a better understanding on the factors that have an impact on the productivity of stumpwood harvesting operations.

In this paper, we present the results of two time studies carried out on two excavators fitted with stump–lifting tools, and we provide accounting data on stump lifting and forwarding. The aim of the paper is to demonstrate the influence that factors such as stump size, species and terrain conditions have on equipment productivity and stump harvesting costs.

Materials and Methods

Two separate stump-harvesting operations were studied. The first field time study took place near Nordmaling (N 63°35', E 19°29') in northern Sweden in August 2006 (Karlsson 2007). The second field time study took place near Norrköping in southern Sweden (N 58° 30.55', E 16° 12.06') in May/June 2007 (Hedman 2008). Weather conditions were favorably dry and clear with good visibility during both study periods. For the time studies, we examined operations on a total of 1119 stumps distributed over eight plots each of between 0.19 ha and 0.36 ha (Table 1).

(Table 1 here)

On basis of there being differences in ground conditions, roughness and slope among the plots, we formed the plots into three blocks (Table 1). Due to a small sample size (n = 66), deciduous stumps were excluded from the analysis, which finally focused on 862 spruce and 191 pine *(Pinus sylvestris)* stumps. In all plots, except plot 2:1(block:plot), 90 - 95 % of the stumps were lifted (Table 1). In plot 2:1 only 60 % of the stumps were lifted due to rough ground and slopes that rendered stumps in some areas inaccessible to the heavy equipment. The final number of harvested stumps corresponded to densities of 256-575 stumps/ha in the southern Sweden study and 500-989 stumps/ha in the northern Sweden study.

The two field studies were similarly designed. First, harvesting residues (branches and tops) were collected and forwarded to the roadside prior to the initiation of the studies. In each plotthe boundaries were marked out, each stump was numbered, and its diameter, height and species were recorded. Soil moisture conditions around each stump were assessed visually and noted as being either mesic (with a groundwater depth between 1 m and 2 m) or moist (with groundwater depth < 1 m). Mean ground roughness, soil bearing capacity, and slope in the plots were also visually assessed and recorded on a five-point scale (Berg 1992). In this classification scheme 1 stands for very easy and 5 for very difficult conditions. All stump-harvesting operations were recorded with a digital video recorder in order to be able to perform the time studies at a later date on the recorded material using a Husky Hunter equipped with Siwork 3 time study software. Data were recorded in centi-minutes but were subsequently transformed into seconds. In each study a Pallari KH 160 stump-lifting tool (Fig. 1) was used. The tool had a mass of ca. 2000 kg, a gap opening of circa 135 cm and a cutting force of ca. 500 kN (Tervolan Konepaja 2010) and was attached to a tracked, 23- tonne excavator; a Hyundai 210 LC in northern Sweden and a Volvo EC 210 in southern Sweden).

(Figure 1 here)

Different personnel operated the machinery in each study. In the study in southern Sweden the machine operator had been operating forest machines for 40 years, had used excavator-based equipment for 6 months, and had been involved in stump lifting for one week. The machine operator in the study in northern Sweden was also experienced in forestry work and had been working with excavator based stump harvesting for approximately six weeks.

For each time study, the stump harvester working cycle was divided into six work elements that together covered the harvesting of a single stump (Table 2). LIFT, SPLIT and PILE together comprised the work category PROCESS, for which time consumption was recorded for most stumps, as they were the stump dependent variables. FILL, MOVE and OTHER together comprised the work category COMPLEM, for which times were recorded for only a fraction of the stumps. For those elements, the mean time required per stump was calculated as the sum of observed time in each plot, divided by the number of lifted stumps. Thus, the number of observations for FILL, MOVE, OTHER, and hence COMPLEM, was equal to the number of plots, i.e. eight. Only productive work time in hours (PWh) or seconds (PWsec) excluding any delay time was used in the analyses.

(Table 2 here)

In addition, follow up data on stump lifting and forwarding operations in three stands located in southern Sweden, were obtained by a forest company. The characteristics of the stands before the operations began are presented in Table 3. The same stump harvester was used in the time study in northern Sweden (Hyundai 210 LC with the Pallari KH 160). The Timberjack 1710 forwarder's crane scale was used to measure the raw mass of the stumps forwarded to the roadside. Stump lifting and forwarding times were reported as delay-free productive work time in hours (PWh).

(Table 3 here)

In the time studies, the dry mass of each stump, including roots > 5 mm in diameter, was estimated from functions provided by Petersson and Ståhl (2006). In the mass functions, the independent variable was diameter at breast height ($DBH_{1.3}$), which is generally 75 - 80 % of the diameter at stump height (DSH) for the tree species in question (Ager et al. 1964). To ensure accurate input in mass estimations, the $DBH_{1,3}$ and DSH relations for the empirical data in Petersson and Ståhl (2006) were established, showing that $DBH_{1.3}$ was 76.5 and 80.6 % of the DSH for spruce and pine, respectively (Karlsson 2007). The raw mass of each stump was estimated by assuming a moisture content of 35 % (wet weight basis). The energy content of the stumps was set to 5.2 MWh/ODT assuming a calorific value of 20.0 MJ/ODkg (Anerud & Jirjis 2011) and natural ash content of 1.0%

(dry weight basis). In the follow up study, an arbitrary contamination share of the stump raw mass was set to 10 % in order to account for the mass of the soil and stones that remained on the stumps after the lifting operation, and which was thus transported to the roadside.

For cost estimations a stump harvester was assumed to cost 77 €/PWh and a forwarder to cost 92 €/PWh (Athanassiadis et al. 2009). Technical availability was set at 90 % for both the stump harvester and the forwarder.

Time consumption per stump for the work elements LIFT, SPLIT and PILE and the work category PROCESS, was analyzed by analysis of covariance (ANCOVA), based on the model:

$y_{ijk}= \mu+\alpha_i+\beta_j+(\alpha\beta)_{ij}+\gamma_k(_j)+bx_{ijk}+\varepsilon_{ijk.}$ [1]

where y_{ijk} is the dependent variable, μ is the grand mean, α_i is the fixed effect of tree species, β_j is the fixed block effect, $(\alpha\beta)_{ij}$ is the fixed interaction effect, $\gamma_k(_j)$ is the random effect of the plots nested within blocks, b is the slope for covariate x (DSH if not otherwise stated), and ε_{ijk} is the random error term, assumed NID $(0,\sigma^2)$.

Time consumption per unit area for the work elements FILL, MOVE and OTHER together with work category COMPLEM were analyzed with a one-way ANCOVA model with the fixed block effect, and with stump density (no. stumps per ha) as a covariate.

The dependent variable data were transformed to natural logarithms (Ln) to meet the assumptions of normality and homogeneity of variance of residuals required by the statistical tests. A general linear model (GLM) was used to analyze the

ANCOVA models. During the GLM procedure, pairwise differences were analyzed with Tukey's simultaneous test of means. Relationships were established by regression analyses according to normal additive functions ($y = a + b \times x_1 + \ldots$), with treatment variables included as dummy variables when relevant. Logarithmic bias was corrected by adding $RMSE^2/2$ to the constant for PROCESS. In the analysis the critical significance level was set to 5 %.

Results

Time study

Lifting, splitting and piling the stumps accounted for 17 %, 32 % and 32 %, respectively, of the total productive work time (PWh_{TOTAL}). The work elements comprising the work category COMPLEM together accounted for 19 % of the PWh_{TOTAL} (Table 4).

(Table 4 here)

The ANCOVA showed that the productive work time required per stump for the work elements LIFT, PILE and SPLIT was significantly ($p < 0.001$) dependent on stump diameter (Table 5). Similarly, the work category PROCESS was dependent on stump diameter ($p < 0.001$). For all work elements, the required mean work time required per stump was higher for pine than for spruce, but the difference was only statistically significant for the splitting element. However, on a work category scale there was a significant mean difference between the processing times required for the two species (Table 5).

(Table 5 here)

For the work elements SPLIT and PILE, the time required per stump was significantly shorter in block 1 than in the other two blocks. A significant interaction effect between species and block was observed for time required for the work element LIFT and the work category PROCESS (Table 5). Thus, although pine stumps required significantly more time than spruce stumps in all plots, the difference was less in block 3 than in the other blocks. However, in the creation of the time consumption models it was decided not to take this interaction effect into account because it is most likely the result of the somewhat unbalanced sample of pine stumps between blocks (c.f. Table 3). This unbalance with rather few pine stumps in some plots is probably also the reason to the significant differences in time consumption between plots within blocks. (Table 5). The ANCOVA analyses were performed at a common DSH of 30 cm.

Stump species (pine or spruce) and diameter, explained 38 % of the observed variance (R^2-Adj.), and the RMSE was 0.207. The models without logarithmic transformations, with compensation for logarithmical bias added to the coefficient, were $T_{pp} = e^{3.50 + 0.03x}$ for pine and $T_{ps} = e^{3.38 + 0.03x}$ for spruce, where T_{pp} = Productive work time consumption (s) for PROCESS for pine, T_{ps} = Productive work time consumption (s) for PROCESS for spruce and x = DSH (cm). Figure 2 shows time consumption (s) per stump for spruce and pine stumps.

(Figure 2 here)

There was a significant block effect on the mean time consumption per stump for the work elements FILL ($p \leq 0.048$), OTHER ($p \leq 0.002$) and COMPLEM ($p \leq 0.008$). However, for OTHER it was the mean time required in block 2 that was significantly higher than in the other blocks ($p \leq 0.015$), whereas for COMPLEM it was the mean time required in block 3 that was significantly lower than that in block 2 ($p=0.009$). Stump density contributed significantly to the model for

OTHER ($p = 0.04$) but not for other work elements ($p \geq 0.189$). The ANCOVA analysis was conducted at a common stump density of 629 stumps / ha. There were four degrees of freedom for the error term, and the level of explained variance (R^2 – Adj.) was 73 %, 46 %, 94 % and 90 % for FILL, MOVE, OTHER and COMPLEM, respectively.

The significantly lower mean time consumption per stump for COMPLEM in block 3 compared to block 2 was probably caused by the easier terrain conditions in block 3. A dummy variable was therefore created to indicate difficult terrain conditions (i.e. 0 if block 3 and 1 otherwise; however, for general use we suggest that it should be interpreted as indicated below). Stump density was excluded from the relationship analysis due to its having no significant effect as a covariate in the ANCOVA analysis. For the relationships between mean time consumption per stump for COMPLEM, both the constant and the dummy variable contributed significantly to the model ($p < 0.001$). The model explained 87 % of the observed variance (R^2 – Adj.) and the RMSE was 3.5. The model was $T_C = 11.8 + 10.6 \times S$, where T_C = Productive work time consumption (s) for COMPLEM and S = dummy variable for terrain conditions, which is taken to be 1 if the value for ground roughness or slope value according to Berg (1992) =3, and 0 if the Berg value ≤ 2.

The total time consumption in seconds per stump is predicted by adding T_C to T_{pp} and T_{ps}, respectively, whereas the productivity in terms of stumps per PWh is achieved by dividing 3600 by the total time consumption per stump (Table 6). For instance, the number of spruce stumps harvested per hour (P_{ss}) in an area with ground condition, roughness and slope values ≤ 2 is predicted by:

$$P_{ss} = \frac{3600}{11.8 + 10.6 \times S + e^{3.38+0.03x}} \qquad [2]$$

(Table 6 here)

As shown in Figure 3, stump harvest productivity (ODT/PWh_{TOTAL}) is higher for spruce than for pine stumps. Consequently stump lifting is more cost efficient for spruce (Fig. 4).

(Figure 3 and 4 here)

Follow-up study

The productivity of the operations that are reported in the accounting data is presented in Table 7. Lifting productivity in Stand 1 and Stand 2 were in accordance with productivity in the time study. However, productivity in Stand 3 was lower than in the other two stands and in the time study (Table 7). Here stump mass was much lower than in the other stands (0.12 raw tonnes per stump). Productivity of the extraction varied from 6.67 to 10.94 ODT/PWh (Table 7). The total cost for lifting and extraction to roadside amounted to 37.8 €/ODT in stand 1, 42.3 €/ODT in stand 2, and 59.4 €/ODT in stand 3. Extraction represented 30 %, 33 % and 14 % of the costs in stands 1, 2 and 3, respectively.

(Table 7 here)

Discussion

The results of the present study largely agree with those of Laitila et al. (2008) and Kärhä & Mutikainen (2009), especially concerning the amount of productive time spent in different activities. Splitting stumps and shaking off impurities (SPLIT), and stump piling (PILE) proved to be the most time consuming work elements with the widest spread of values around the means (Table 4). This large standard deviation is mainly due to the fact that the two operators employed different working techniques, which in one study made splitting of the stumps appear in at least two work elements (SPLIT and PILE). In the study in southern Sweden (plots 1:1 – 1:4) the stumps were mainly split while they were being transported to the pile, or when they were at the pile, while in the study in northern Sweden (plots 2:1, 2:2, 3:1, 3:2) the stumps were split directly after they were lifted. This does not affect the accuracy of the productivity function presented here, which is at a work category level. Splitting stumps and shaking off impurities is an important part of stump harvesting *per se*, not only because it represents a large part of the processing time. Split and cleaned stumps, being less bulky, can increase the productivity of transportation and comminution. It is preferable for stumps to be split and shaken above or in the vicinity of the extraction hole, so that the extraction hole is filled. This process can, however, be associated with lower productivity since the boom has to move sideways from the hole to the stump pile many times while carrying parts of split stumps. Recent results imply, however, that a substantial part of the cleaning process depends on the transportation, handling and storage of the stumps and that the initial shaking might not be as important (cf. Anerud & Jirjis 2011). Less initial shaking of the stumps should increase stump harvesting productivity.

Kärhä and Mutikainen (2009) studied the Väkeva stump processor, which is similar to the tool used in the present study. Its productivity when lifting spruce stumps of 40 cm in diameter proved to be very close to that of the Pallari tool used in the present study. It is interesting to notice that productivity in this study is roughly at the same level as for 25 years ago concerning stumps of a DSH of 20 cm but up to 25 % higher for stumps of 40 cm (Jonsson 1985).

The productivity function for spruce proposed by Laitila et al. (2008), indicates that the 17- tonnes excavator with the fork-like stump-lifting tool used in that study, needed less time to process stumps up to 47 cm diameter, and more time for stumps with diameters greater than 47 cm. For instance, according to Laitila et al., 51 seconds are required to process a stump with a DSH of 35 cm, which is 40 % less than the time it would take according to the productivity function determined in the present study. However, for a stump with a 55 cm DSH, our model predicts 14 % less time consumption than the 178 seconds in Laitila et al.'s model. It should be noted, however, that the function described by Laitila et al. (2008) also included the time taken to smooth the holes, although that operation only accounted for 3 % of the processing time.

Stump lifting productivity (ODT/PWh) for stands 1 and 2 in the accounting data fits well in the predictive model presented here. The lower productivity in stand 3 was mainly due to a lower mass/stump ratio (57% and 70% of the mass in stands 1 and 2 respectively) and, consequently, less stump-mass per unit area.

Tracked excavator-based forest machinery does not have the same mobility and working capacity of purpose built forestry machinery, although it is used in a number of different forest operations, e.g. road construction, soil preparation, tree planting and, currently, stump lifting. Its use is motivated by low operating and maintenance costs and great lifting power (Lindroos et al. 2010). Purpose built wheeled forest machinery is environmentally and technically more adapted for working in a forest environment. It has better stability and higher working capability in uneven terrain and provides better ergonomics for the operator. It is expected that in the future stump-lifting tools will be developed in accordance with the lifting capacity of the forest machine cranes (cf. Jonsson 1985; Lindroos et al. 2010).

Stump harvesting is not without controversy. For a review of the research on environmental impacts of stump harvesting on different sites, see Walmsley and Godbold, (2009). Therefore, it has been found necessary to develop guidelines in order to reduce the risk of potentially serious environmental consequences of the operations (e.g. Nisbet et al. 2009; Swedish Forest Agency 2009,). These include limiting the intensity of harvesting (stumps per hectare), and restricting activities to certain forest and soil types, tree species, slope classes and regions of important conservation potential. In addition to the analysis of current methods there is, therefore, also need for development of methods that decrease soil disturbance.

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Figure legends

Figure 1. The Pallari KH 160 stump-lifting tool.

Figure 2. Processing time per stump as a function of stump diameter.

Figure 3. Productivity of stump lifting. Spruce and pine stumps in easy (ground condition, roughness and slope ≤ 2 (Berg 1992)) and difficult (ground condition, roughness and slope = 3 (Berg 1992)) terrain conditions.

Figure 4. Cost of stump lifting. Spruce and pine stumps in easy (ground condition, roughness and slope ≤ 2 (Berg 1992)) and difficult (ground condition, roughness and slope = 3 (Berg 1992)) terrain conditions.

Figure 1.

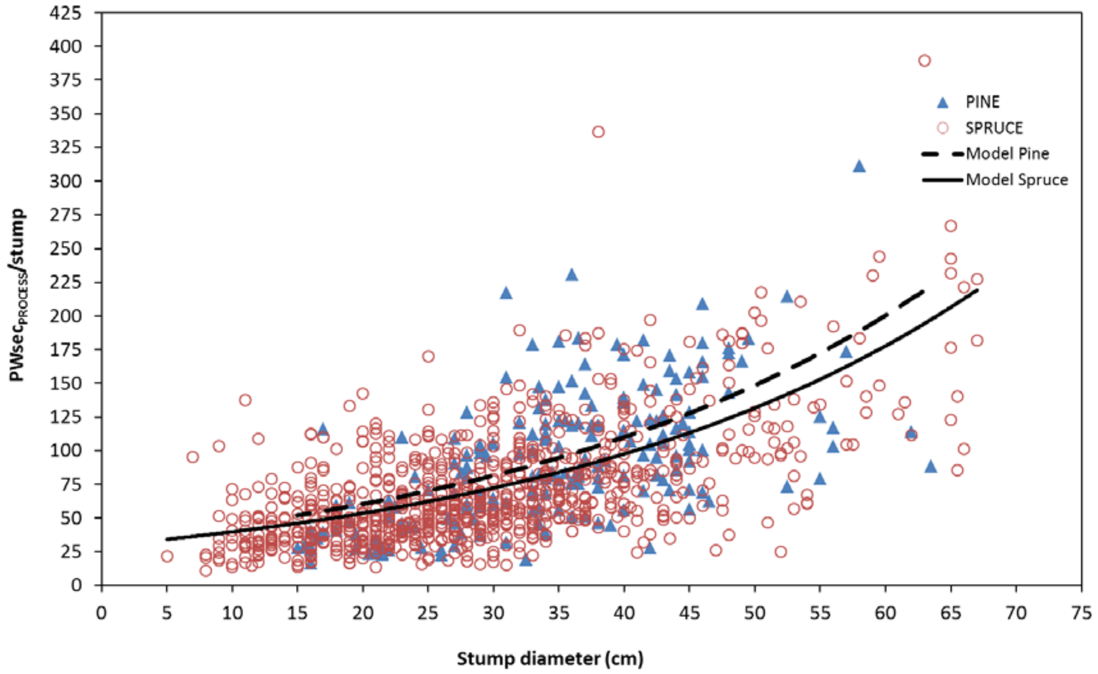
425
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
PWsec$_{PROCESS}$/stump
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
Stump diameter (cm)
PINE
SPRUCE
Model Pine
Model Spruce

Figure 2.

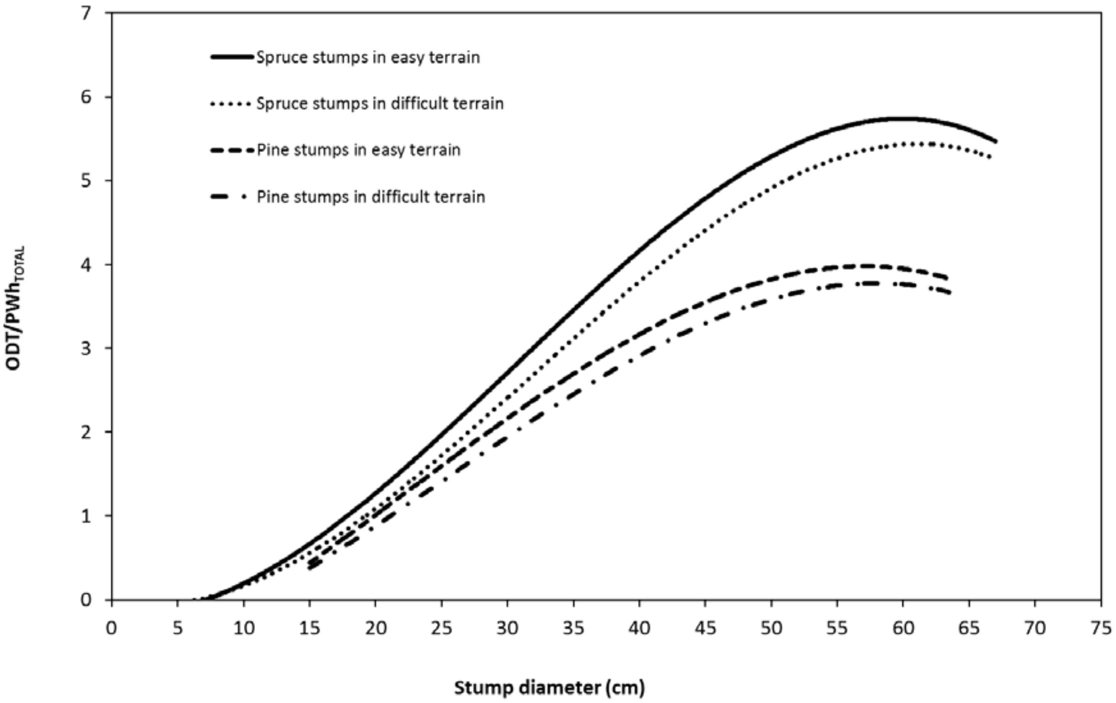
Spruce stumps in easy terrain
Spruce stumps in difficult terrain
Pine stumps in easy terrain
Pine stumps in difficult terrain
ODT/PWh$_{TOTAL}$
Stump diameter (cm)
0
1
2
3
4
5
6
7
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75

Figure 3.

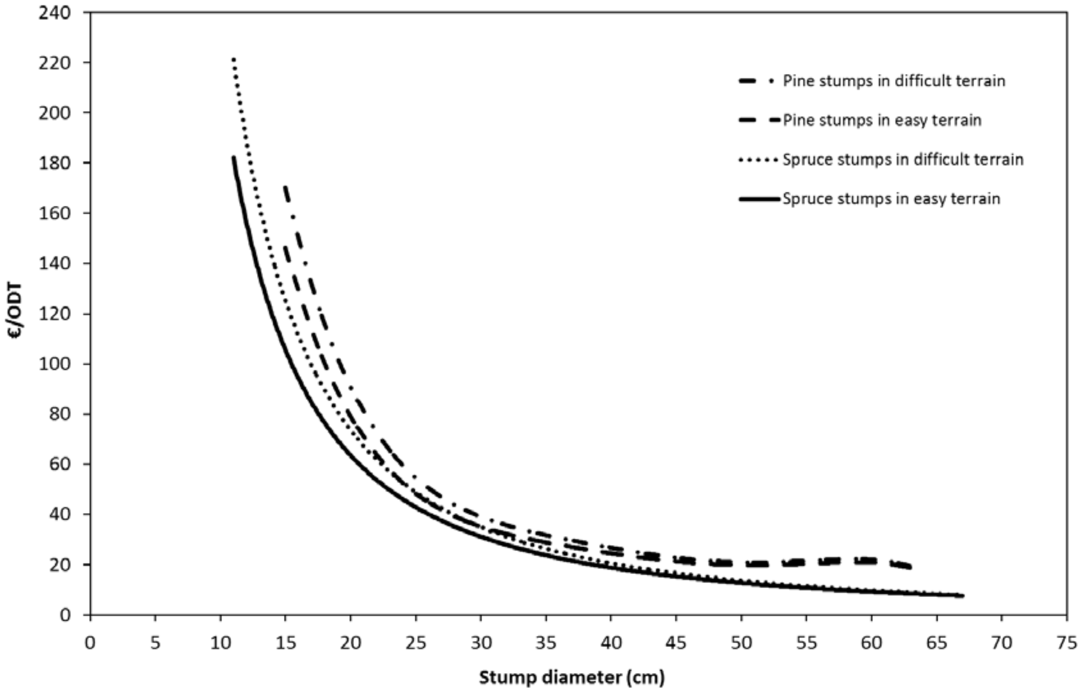
240
220
200
180
160
140
120
100
80
60
40
20
0
€/ODT
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
Stump diameter (cm)
Pine stumps in difficult terrain
Pine stumps in easy terrain
Spruce stumps in difficult terrain
Spruce stumps in easy terrain

Figure 4.

Table 1. Characteristics of the time study plots

	Southern Sweden				**Northern Sweden**			
Blocks	**1**				**2**		**3**	
plotPlots	**1**	**2**	**3**	**4**	**1**	**2**	**1**	**2**
Size (ha)	0.19	0.20	0.20	0.36	0.25	0.19	0.25	0.22
Number of lifted stumps	94	99	115	92	125	188	226	180
Pine/spruce/deciduous (%)	19/67/14	41/52/7	38/56/6	20/74/6	1/97/2	7/93/0	21/66/13	4/96/0
Ground condition[*]	3	3	3	3	2	2	2	2
Ground roughness[*]	1	1	1	1	3	3	1	1
Ground inclination[*]	1	1	1	1	3	3	1	1
Average stump height (cm)	29.4	20.6	18.4	28.2	22.6	21.2	22.8	28.1
Average pine stump diameter (cm) (SD)	40.6(8.1)	34.3(8.7)	35.4(10.1)	41.9(10.9)	34.0(-)	29.8(7.2)	30.5(8.2)	42.3(12.5)
Average spruce stump diameter (cm)	37.6(10.8)	34.1(9)	35.4(11.7)	46.7(12.3)	32.2(9.8)	23.3(7.2)	19.7(6.7)	26.7(8.2)
Lifted stump mass (ODT biomass/ha)	50	41	54	42	42	40	28	48

[*] Terrain classification (Berg 1992).

Table 2. Work elements and their priority. If multiple work elements were performed simultaneously, time consumption was recorded for the work elements with highest order of priority (lowest number).

Work category	Work Element	Definition	Priority
PROCESS	LIFT	The stump-lifting tool is positioned at the stump and the stump is lifted. It begins when the boom starts moving towards a stump and ends when the stump (or part of the stump) is lifted and the boom is located at its highest position.	1
	SPLIT	The stump is shaken and split. It begins when the boom is at its highest position and ends when the boom starts moving sideways to the pile. Shaking of either stumps or stump parts is included in this work element.	2
	PILE	The stump or stump parts are put on a pile. Begins when the boom starts moving sideways to the pile and ends when the stump or all stump parts have been moved to the pile.	2
COMPLEM	FILL	The stump hole is filled in. Begins when PILE ends and ends when the hole is filled. FILL does not necessarily mean that adequate site preparation has been performed (even if a good number of planting spots have been created).	3
	MOVE	The machine moves. Begins when the excavator’s wheels starts to move to the next processing position and ends when the wheels stop.	3
	OTHER	Other work relevant activity.	3

Table 3. Stand characteristics for the follow-up study.

	Stand 1	Stand 2	Stand 3
Stand size (ha)	47	22	7
Cut roundwood volume (m^3sub[*]/ha)	200	192	192
Average tree size (m^3sub)	0.20	0.31	0.25
Average DSH (cm)[**]	26	32	31
Stand density (trees/ha)	1025	619	768
Ground condition[***]	2	2	3
Ground roughness [***]	2	2	2
Ground inclination [***]	2	3	1

[*] Solid under bark.

[**] Estimated by $DBH_{1.3}$ using a coefficient of 1.24 (Ager et al. 1964).

[***] Terrain classification (Berg 1992).

Table 4. Proportion of the total work time (PWh_{TOTAL}) for each work element in each of the plots (%). SD denotes standard deviation of the mean value.

Block:Plot	**Work Element**						
	LIFT	**SPLIT**	**PILE**	**FILL**	**MOVE**	**OTHER**	**TOTAL**
1:1	18	18	43	7	8	6	100
1:2	19	19	43	7	6	6	100
1:3	19	22	41	7	6	5	100
1:4	17	21	45	5	7	5	100
2:1	15	42	19	5	8	11	100
2:2	16	42	17	7	9	9	100
3:1	18	43	22	8	6	3	100
3:2	14	47	24	4	7	4	100
Mean	**17**	**32**	**32**	**6**	**7**	**6**	**100**
SD	**1.8**	**12.7**	**12.2**	**1.4**	**1.3**	**2.7**	

Table 5. Levels of significance (p-values), explained variance (R^2 – Adj.) and degrees of freedom for the error term (Df) from the analysis of covariance of a treatment's effect on the logarithmically transformed time consumption for stump dependent elements. DSH is the covariate stump diameter.

Work element	Species (S)	Block	S×Block	Plot nested in Block	DSH	R^2 – Adj	Df
LIFT	0.872	0.074	0.003	<0.001	<0.001	27.62	1041
SPLIT	0.021	<0.001	0.716	0.241	<0.001	24.63	949
PILE	0.290	<0.001	0.055	0.232	<0.001	49.81	1034
PROCESS[a]	0.042	0.29	0.032	0.012	<0.001	40.05	1041

[a] Process = Lift+Split+Pile

Table 6. Prediction of the number of spruce stumps (P_{ss}) and pine stumps (P_{ps}) that would be lifted per hour in areas with easy (ground condition, roughness and slope ≤ 2. (Berg 1992)) or difficult terrain conditions (ground condition, roughness and slope = 3). Diameter at stump height (cm) is denoted by *x*.

	Species	
Terrain conditions	Spruce	Pine
Easy	$P_{ss} = \frac{3600}{11.8 + e^{3.38+0.03x}}$	$P_{ps} = \frac{3600}{11.8 + e^{3.50+0.03x}}$
Difficult	$P_{ss} = \frac{3600}{22.4 + e^{3.38+0.03x}}$	$P_{ps} = \frac{3600}{22.4 + e^{3.50+0.03x}}$

Table 7. Follow-up data on stump harvesting in three stands

	Stand 1	Stand 2	Stand 3
Lifting			
Follow-up hours (PWh)	463	219	79
Lifted stumps (no)	11123	5944	1720
Lifted stumps (no/ha)	237	270	245
Mass/stump (raw tonnes/stump)	0.21	0.17	0.12
Mass/stump (ODT biomass/stump)*	0.12	0.10	0.07
Mass/ha (ODT biomass/ha)*	28	27.2	13
Productivity (stumps/PWh)	24.0	27.2	21.6
Productivity (raw tonnes/PWh))	5.0	4.6	2.6
Productivity (ODT biomass/PWh)*	2.9	2.7	1.5
Productivity (MWh/ PWh) **	15.1	14.0	7.8
Time consumption (PWh/ha)	9.9	9.9	11.4
Cost (€/ODT biomass)***	26.5	28.5	51
Forwarding			
Follow-up hours (PWh)	164	88	11
Loads (no)	177	83	15
Average load (raw tonnes)	12.9	12.1	13.7
Average load (ODT biomass)*	7.5	7.1	8
Productivity (loads/PWh)	1.08	0.95	1.36
Productivity (raw tonnes/ PWh)	13.9	11.4	18.7
Productivity (ODT biomass/PWh)	8.15	6.67	10.94
Productivity (MWh/PWh)**	42.3	35.0	56.6
Time consumption (PWh/ha)	3.5	2.9	1.6
Cost (€/ODT biomass)****	11.3	13.8	8.4

* Estimated by assuming an impurity level (soil content) of 10 % that was subtracted by the raw mass and a moisture content of 35 %.

** 1 oven-dry tonne equals to 5.2 MWh, assuming a calorific value of 20.0 MJ/ODkg for stumps with a natural ash content of 1.0% (cf. Anerud & Jirjis 2011) and a moisture content of 35%.

***The excavator cost is assumed to be 77 €/PWH.

**** The forwarder cost is assumed to be 92 €/PWH.