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Forces Required to Vertically Uproot Tree Stumps

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Stumpwood attracts renewed interest due to increased use of forest biomass for bioenergy. In Nordic countries stumps are generally uprooted with crawler excavators, which have strong cranes (ca. 400 kNm gross lift torque), but are not designed for moving in forest terrain. Their use is based on practical experience with available and tested machine types rather than thorough examinations of requirements, partly due to limited knowledge of force requirements for uprooting of stumps. Therefore, in this work mean and maximum forces required to vertically uproot stumps of Norway spruce (*Picea abies*) and birch (*Betula* spp.) were quantified together with the effects of various soil types and uprooting methods. The used excavator's crane-mounted uprooting device enabled comparisons between usage of solely crane force, and a method in which preparatory loosening forces were applied prior to crane force.

Uprooting stumps in single pieces proved difficult; 61% split unintentionally. Force requirements were similar across tree species, increasing curve-linearly with stump diameter, and stumps uprooted in a single piece required more force than split stumps. Preparatory loosening reduced crane force requirements and, surprisingly, less force was required to uproot stumps from a mesic, till soil than from a moist, finer-textured soil. No stump required more than 60 kN crane force and functions for maximum force requirements indicate that powerful harvesters and forwarders (gross crane lifting capacity of 273 and 155 kNm, respectively) should be able to uproot all stumps with ≤61 cm and ≤32 cm diameter, respectively, in one piece. Larger stumps could be managed if it is acceptable that stumps are split before uprooting.

Keywords Stump harvesting, machine development, bioenergy, forest fuels, *Picea abies*, *Betula* spp.
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1 Introduction

Over time, stumpwood has been harvested by a multitude of techniques for a number of purposes, for instance, firewood, fibre board or pulp production, extraction of chemicals, root rot control and the facilitation of various kind of ground work (Lundberg 1918, Czereyski et al. 1965, Jonsson 1985, Vasaitis et al. 2008). In comparison to roundwood, stumpwood has received fluctuating interest following raw material shortages and changes in demand for certain products. It is currently attracting renewed interest due to increased use of forest biomass for bioenergy purposes. Consequently, the forest industry is interested in increasing the resource base for bioenergy in order to avoid competition for roundwood.

The harvesting of stumpwood after regeneration fellings could provide a considerable quantity of bioenergy since the biomass below stump cut (stump with attached root system) constitutes approximately 20% of the total living tree biomass, which exceeds the amount of logging residues (Hakkila and Parikka 2002). Given the potential of stumpwood, stump harvesting is currently performed at quite large scale in Finland (Laitila et al. 2008), at smaller scale in Sweden (Karlsson 2007, Hedman 2008) and at test scales in many other countries (Horváth-Szováti and Czupy 2005, Spinelli et al. 2005).

Harvesting stumpwood involves removal of the stump wood from the ground (the uprooting operation) and the subsequent removal of contaminants (e.g. soil and stones) and processing to obtain pieces of desired sizes (the conversion operation) (Czereyski et al. 1965). Uprooting stumps after removal of stems used to involve laborious manual digging and cutting roots, but this has been superseded by methods in which forces are mechanically exerted vertically, horizontally or in a combination of the two directions. In the Nordic countries, the currently predominant technique and work methods used were essentially developed during the last stump harvest boom in the second half of the 1970's (Jonsson 1985). Generally, 20–23 metric tonnes (t) crawler excavators are used as base machines with some kind of uprooting device attached to the end of the knuckle boom crane (Laitila et al. 2008). The device is typically equipped with a hydraulic knife that can split the stump during or after the uprooting process and has a mass of 1–2 t. After uprooting, stumps are shaken or even dropped to the ground repeatedly to remove some of the soil and stones. If not split during uprooting, stumps are finally split and stored in piles before further transport to the roadside and industrial sites. In the Nordic countries stumps are mostly harvested from Norway spruce (*Picea abies*) regeneration areas, mainly because Norway spruce commonly has a shallow root system (Kalliokoski et al. 2008) facilitating their removal relatively cost- and time-effectively (Laitila et al. 2008).

Despite being commonly used, this uprooting technique has several drawbacks. Crawler excavators are mainly designed for digging and less for moving, especially on unprepared terrain. Hence, they are not ideal for the between-stump movements that must be made, often across uneven terrain (which should be disturbed as little as possible), in stump uprooting operations. Thus, compared to specialized forest machinery the crawler excavators can only be driven at low speeds in the terrain, are difficult to maneuver and have further limitations in rough forest terrain (c.f. Laitila et al. 2008). Moreover, the operator's working conditions are far from ideal due to vibrations both when driving and (especially) when shaking the stumps to get rid of contaminating material. Despite their many shortcomings, there is a strong reason for using crawler excavators: their strong cranes. The lifting torque of a 22–23 t excavator is ca. 400 kNm (Komatsu 2009), which is considerably more than the highest torques of harvesters (ca. 270 kNm) and forwarders (ca. 155 kNm) (John Deere 2009, Komatsu Forest 2009).

However, the technique currently used has originated from practical experience, and knowledge of the relationships between the magnitude of the uprooting force and variables such as stump size, tree species, root architecture and soil conditions is limited. There has been extensive research on the lateral (horizontal) forces required for tree uprooting, mainly due to the importance of trees' anchorage for their resistance to windthrow and snow damage (e.g. Coutts 1983, Peltola et al. 2000, Lundström et al. 2007), their utility as anchors in cable logging operations (Liley 1985, Biller and Baumgras 1987, Pyles et al. 1991) and the ease of uprooting them for other purposes (Czereyski et al. 1965, Golob et al. 1976, Weidermann and Cross 1996). In contrast, there have been few studies on the forces required for vertical uprooting. However, in a review from the 1960s Czereyski et al. (1965) refer to findings that mature (5–25 years after felling) 20–35 cm diameter pine stumps require uprooting forces of 15–150 kN, and based on a study on 150 Scots pine (*Pinus sylvestris*) stumps in sandy soil, Horváth-Szováti and Czupy (2005) concluded that the force required was dependent on the stump diameter according to:

$$F = 6.542 \times (\mathrm{DSH}^{0.6369} + e^{0.041189 \times \mathrm{DSH}} - 1) \qquad (1)$$

where F is the required vertical uprooting force in kN and DSH is the stump diameter in cm. In the studied diameter interval (15–35 cm), Eq. 1 corresponds to a linear function with a constant of 11 kN and a slope of 2 kN for every centimeter increase in the diameter. Hence, a 35 cm pine stump should require a vertical force of 84 kN (Horváth-Szováti and Czupy 2005). However, knowledge of the vertical forces required for lifting stumps of Norway spruce, the most typical species currently uprooted in Nordic countries, is lacking.

To decrease the pure crane force required, stumps can be processed before uprooting. For instance, before uprooting, a stump can be split into smaller pieces (Laitila et al. 2008), have some or all roots cut (Czereyski et al. 1965, Koch and Coughran 1975, Spinelli et al. 2005), be vibrated during uprooting (Horváth-Szováti and Czupy 2005) or be allowed to decompose before uprooting (Czereyski et al. 1965). Exerting loosening forces of a different nature to the force that finally displaces the stump, e.g. by using explosives (Lundberg 1918, Czereyski et al. 1965), is yet another alternative. Other possible solutions in which "preparatory" forces are applied include the use of devices equipped with separate force actuators (e.g. hydraulic pistons) for loosening the stump, which in best cases are completely freed from the ground (Jonsson 1985).

If the force required to uproot a given stump at a given site was known, it would be possible to develop machinery capable of performing the operation efficiently or adapting currently available machinery with sufficiently powerful cranes. As machines ideally should be able to cope with most stumps of a desired stump size, the maximum required force is of relevance in this kind of study. Therefore, the main aim of this study was to quantify the mean and maximum vertical force that is required to uproot stumps in one piece. In addition, the effects of soil types and uprooting methods were addressed. The hypothesis was that increased soil moisture content and use of uprooting methods applying preparatory treatments (forces) would reduce the removal force subsequently required.

2 Materials and Methods

2.1 Methodology Applied to Vertical Force Measurements

The machine used in the study was an SRG 160 Stump harwarder (SRG Carrier Systems AB, Sweden), based on part of a Cat M316D excavator (cabin and crane) and a forwarder undercarriage, equipped with articulated steering and an eight-wheeled double bogie (Fig. 1). The machine's mass was circa 26 t and the crane had a reach of 8.1 m. The maximum hydraulic pressure allowed in the system was 37.5 MPa.

The studied crane tip-mounted device for uprooting and splitting of stumps was the prototype "Hercules" (originally patented by Hedblom (1979) and currently developed by Leif Unosen, Karlskoga, Sweden). In addition to quite conventional rake and pliers-like features, the "Hercules" also has a metal plate attached to two hydraulic cylinders (Fig. 2). When operating, the tool was placed around a stump as with similar conventional uprooting devices, but instead of using the crane immediately the plate could be used to loosen stumps by pushing the device upwards by extending the pistons with the ground as a counterweight. Since the initial phase of the uprooting was performed independently of the crane's lifting force, it was presumed that the following work would require less crane force than for uprooting stumps that had not been pre-treated. The two cylinders operating the plate could develop a nominal pressure force of 314 kN. The piston length was 0.595 m and the area of the metal

Fig. 1. The vertical force required to uproot stumps (F_S) were derived from the law of levers, based on the force developed by the crane pillar lifting cylinders (F_H), the perpendicular distance between F_H and the crane pillar fulcrum (L_H) and the horizontal distance between the crane pillar fulcrum and the stump (L_S). Photo: O. Lindroos.

plate was ca. 0.34 m^2. The mass of the "Hercules" device was ca. 1650 kg.

When the machine operator had positioned the uprooting device around the stump and was ready to start the vertical uprooting, two measurements for deducing lever lengths (L_H and L_S, see Fig. 1) were recorded. When uprooting with pure crane force, the operator slowly lifted the stump by extending the two crane pillar cylinders and stopped when it was no longer in contact with the ground or decided that the stump could not be uprooted. The highest hydraulic pressure during the uprooting work was recorded (P_T). When employing the metal plate (preparatory force), the highest hydraulic pressure during the work to uproot the stump after the plate function had been applied was recorded (i.e. pressure from the plate work was not recorded). Hydraulic pressure was recorded from the digital display of a LEO 1 pressure measuring instrument (Keller AG, Germany), which had a measurement error of $<0.2\%$. Current pressure as well as maximum and minimum pressures since the last reset were showed by the instrument, which was set to collect two measurements per second to avoid recording possible extremely short peak values. The instrument was plugged into the crane pillar lifting cylinders' common hydraulic circuit.

Based on the law of levers, the force required to uproot stumps (F_S) was derived in kN according to:

$$F_S = F_H \times L_H \times L_S^{-1} \qquad (2)$$

where L_H is the perpendicular distance in meters between F_H and the crane pillar fulcrum (located at the centre of the joint attaching the crane to the excavator) and L_S is the horizontal distance (m) between the crane pillar fulcrum and the contact point between the uprooting device and the stump (Fig. 1). F_H is the force developed by the lifting cylinders (kN), calculated according to:

$$F_H = (P_T - P_0) \times A_P \qquad (3)$$

where P_T is the hydraulic pressure (kPa) recorded in the lifting cylinder during the uprooting, P_0 is the hydraulic pressure (kPa) required to lift the weight of the crane and the uprooting device alone (calculated according to Eq. 4) and A_P is

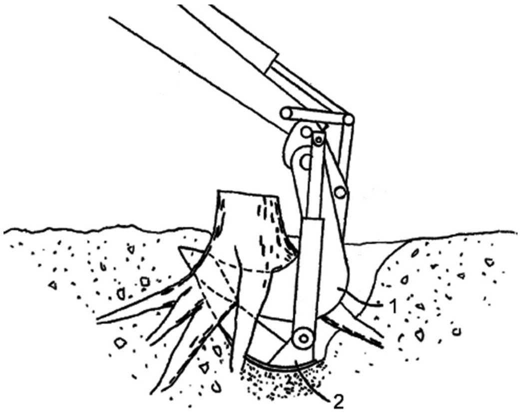

Fig. 2. Sketch illustrating the technique for preparatory uprooting, before applying crane force, using the "Hercules" device. The uprooting device (1 in the figure) is placed in the same position as when uprooting with pure crane force. Pistons attached to a metal plate (2) jointed to the tip of the uprooting device are extended and, using the ground as a counterweight, the uprooting device and the stump are pushed upwards. Picture derived from Hedblom (1979).

the internal area (m^2) of the two lifting cylinders (2×0.01021 m^2).

P_0 for the used crane and uprooting devise was measured from three crane cycles, resulting in 30 observations within a L_S distance of 3.5–7.8 m. Based on linear regression, P_0 (in kPa) was proportional to L_S (in m) according to:

$$P_0 = 5123 + 1428 \times L_S \quad (4)$$

In Eq. 4, both the intercept and coefficient contributed significantly ($p<0.001$) and the function explained 99.2% of the observed variance.

Eq. 4 was validated by slowly lifting a known weight of 2.7 kN from ground level and a weight of 16.4 kN from circa 3 m above ground (rather than ground level due to attachment practicalities). Hydraulic pressure was recorded at approximate L_S intervals of 0.4 m within a distance of 3.3–7.9 m ($n\geq10$ per calibration). The 2.7 kN weight was generally underestimated by Eq. 4 by, on average, 26% (0.7 kN, SD 0.3 kN), while the 16.4 kN weight was quite accurate; on average the weight was overestimated by 3% (0.5 kN, SD 0.8 kN) with underestimations at low L_S values and overestimations at high values. The validation indicated that measurement accuracy in relative terms decreased when F_S was low, but measurement accuracy in absolute values was rather constant over the two levels of F_S. Hence, because the levels during the actual uprooting were generally high, the values generated from Eq. 4 were considered accurate enough and used without adjustment.

2.2 Characteristics of Study Site and Stumps

The study was conducted in June 2008 in a forest stand dominated by Norway spruce (>77% of the trees) in Fagersta, central Sweden (60°05´N, 15°43´E). Prior to regeneration cutting in 2007, the area had a mean stand density of ca. 600 trees per ha and a mean stem volume of 0.73 m^3 of solid wood under bark. A Norway spruce was expected to be 30 m high at an age of 100 years (i.e. site index G30) and the stand was not trafficable during thaw or rain periods, with a smooth ground surface and less than 11° slope (i.e. GYL 2-3:2:2 according to Berg (1992)). Within the stand two flat areas with different soil drainage conditions were chosen, one of which was classified as mesic and the other as moist according to Berg (1992). The forest stand was located below the highest post-glacial coast line, and its till soil was of loamy texture in the mesic area and of silt loam texture in the moist area. In total 332 stumps were included in the experiment, of which 85% were Norway spruce and 15% birch (*Betula* spp.). Stumps were numbered, their height was recorded and the mean stump diameter under bark was calculated based on two perpendicular measurements with 0.5 cm accuracy. Prior to the study, stump records within each area and species were ordered according to mean diameter and alternating stumps were assigned to the conventional and plate uprooting methods to ensure an even and random distribution of treatments across the range of stump diameter.

The dry mass content of each test stump, including roots >5 mm in diameter, was estimated based on functions provided by Petersson and Ståhl (2006). In the mass functions, the inde-

Table 1. Characteristics of Norway spruce and birch stumps used in the field experiment

Area	Tree species	Method	n	Diameter (cm)				Height (cm)		Weight (kN)[a]	
				Mean	SD	Min	Max	Mean	SD	Mean	SD
Mesic	Spruce	Conventional	106	45.7	14.7	17.0	79.5	20.4	8.2	2.9	1.8
		Plate	70	47.5	15.2	17.0	77.0	23.3	8.8	3.2	1.9
	Birch	Conventional	14	36.2	10.0	16.0	54.5	18.5	5.8	1.6	0.9
		Plate	6	42.3	11.7	32.5	64.0	16.0	7.6	2.2	1.5
Moist	Spruce	Conventional	56	37.1	11.5	16.5	63.5	17.4	5.8	1.9	1.3
		Plate	50	37.5	10.8	13.5	61.5	18.0	6.4	1.9	1.1
	Birch	Conventional	13	30.9	7.6	17.5	43.0	17.3	6.3	1.1	0.6
		Plate	17	29.7	6.9	20.0	46.5	14.7	5.4	1.0	0.6

[a] including roots >5 mm, estimated according to Petersson and Ståhl (2006) assuming a moisture content of 35% (dry basis) (Karlsson 2007).

pendent variable was diameter at breast height (DBH = 1.3 m), which is generally 55–80% 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 and DSH relationship for the empirical data in Petersson and Ståhl (2006) were established, showing that DBH was 76.5% and 74.0% of the DSH for Norway spruce and birch, respectively (Karlsson 2007). The raw weight of each stump was acquired by assuming a moisture content of 35% (dry basis) (Karlsson 2007) and by multiplying the raw mass by $g = 9.82$ m/s^2.

2.3 Statistical Analyses

Within tree species and lifting result (stump in one piece vs. stumps that split), the dependent variable (required uprooting force, F_S) was analyzed by analysis of covariance (ANCOVA) with one treatment (uprooting methods), a fixed block effect (soil conditions of the areas) and the interaction effect between treatment and blocking. The dependent variable was transformed to the natural logarithm (Ln) or square root to meet the statistical analyses' assumptions of normality and homogeneity of variance of residuals. A general linear model (GLM) was used to analyze the ANCOVA models (Minitab 14, Minitab Ltd.). In the models, the covariate was DSH if not otherwise stated. Estimated stump weight was not tested as a covariate since it was predicted solely from DSH. The relationship between F_S and DSH was established by multiple regression analyses according to normal additive functions ($y = a + b \times x_1 + \ldots$), with treatment and blocking variables included as dummy variables when relevant. For other relations, the Pearson correlation test was used. The critical significance level was set to 5%.

Using data obtained for stumps of each of the seven diameter classes indicated in Fig. 3, the mean uprooting force and its standard deviation was found for both Norway spruce stumps that came up in one piece and stumps that split. These data were pooled over methods and soil conditions and used to calculate upper limits (maximum force requirements, F_{max}) of 95% confidence intervals (mean + 1.96 SD) within diameter classes. Consequently, 97.5% of the Norway spruce stumps in each diameter class would be expected to be uprooted by forces below those upper limits. The pooling of data instead of e.g. soil type specific of F_{max}, was motivated by the assumption that machines specially designated for uprooting stumps most likely will work under varying conditions. Moreover, without the pooling there would have been few observations in the lowest and highest diameter classes.

3 Results

3.1 Effects of Different Factors on Uprooting Forces

The intention was to uproot the stump in a single piece (i.e. stumps were not intentionally split),

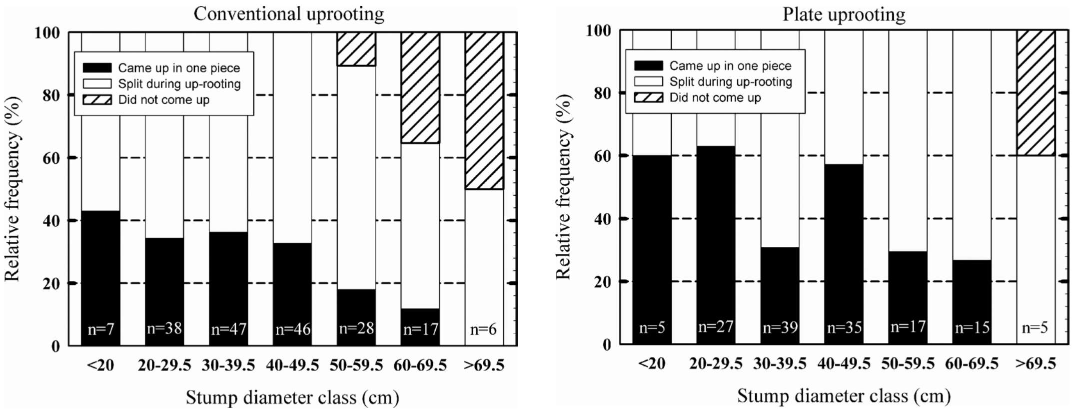

Fig. 3. Relative frequencies of outcomes in vertical uprooting trials of the conventional (left) and plate method (right), for all tree species in both areas.

but nevertheless stumps usually split during the uprooting, resulting in only one of at least two pieces being uprooted. Irrespective of soil conditions and tree species, stumps were either uprooted in one piece (35%), split (61%) or did not come up at all (4%). The proportion of split stumps was relatively constant over stump diameter, while stumps that were uprooted in one piece were more common in the smaller diameter classes (Fig. 3). In contrast, increases in stump diameter were associated with increases in frequency of stumps not coming up at all. Compared to the conventional method, a considerably larger proportion of stumps came up in one piece and fewer did not come up at all when using the plate method (Fig. 3).

The Ln-transformed force required to uproot Norway spruce stumps in one piece was significantly dependent on stump diameter and soil conditions ($p \leq 0.001$) and method ($p = 0.031$), while there was no significant interaction effect between soil conditions and method ($p = 0.876$). In total, the model explained 66.1% of the adjusted variance (R^2_{adj}). The methods were compared at a common stump diameter of 39 cm in the ANCOVA analyses.

For the ANCOVA on Ln-transformed forces for birch stumps uprooted in one piece, there were significant effects of diameter and soil conditions ($p \leq 0.044$), while the effect of method fell just outside the critical significance level ($p = 0.062$). However, due to the small sample, the method was included in the multiple regression analysis for establishing variables' relationships to uprooting force (Table 2). The analyses were based on 92 and 24 observations of Norway spruce and birch, respectively.

The square root-transformed force required to uproot Norway spruce stumps in more than one piece (i.e. stumps splitting during uprooting) was dependent on stump diameter and method ($p \leq 0.003$), while there was no significant effect of soil conditions ($p = 0.119$) nor any interaction effect between method and soil conditions ($p = 0.317$). In total, the model explained 36.8% of the adjusted variance. The methods were compared at a common stump diameter of 43 cm in the ANCOVA analyses.

For the square root-transformed uprooting forces of birch stumps that split the ANCOVA did not identify any significant effects ($p \geq 0.138$). The analyses were based on 176 and 26 observations of Norway spruce and birch, respectively. Norway spruce stump height was significantly correlated to stump diameter ($n = 282$, Pearson's $r = 0.575$, $p < 0.001$), but did not contribute to the uprooting in the 1 piece or >1 piece ANCOVA models, either as the sole covariate ($p < 0.001$, but $R^2_{adj} \leq 15.8\%$) or in conjunction with stump diameter ($p \geq 0.375$).

Table 2. Functions for mean force requirements (kN) for vertical uprooting of Norway spruce and birch stumps in one and more than one piece

Species	Uprooting case	Dependent variable	Independent variables	Parameter estimate	p-value	RMSE	R^2_{adj} (%)	Diameter interval (cm)
Spruce	1 piece	Ln(Y)	Intercept	1.904	<0.001	0.323	66.5	13.5–69.5
			DSH	0.035	<0.001			
			Mesic	–0.205	0.005			
			Plate	–0.159	0.021			
	>1 piece	$Y^{0.5}$	Intercept	1.952	<0.001	1.024	36.0	17.0–79.5
			DSH	0.057	<0.001			
			Plate	–0.416	0.010			
Birch	1 piece	Ln(Y)	Intercept	2.204	<0.001	0.341	32.9	20.0–46.5
			DSH	0.026	0.025			
			Mesic	–0.346	0.031			
			Plate	–0.299	0.058			

Note: DSH = mean diameter at stump height in cm. Mesic is a dummy variable which is assigned the value 1 if the soil was mesic (soil conditions in area 1) and 0 if moist (area 2), while Plate is a dummy variable assigned the value 1 if the preparatory uprooting force method was used and 0 otherwise. RMSE= root mean square error. R^2_{adj} = adjusted level of explained variance (%)

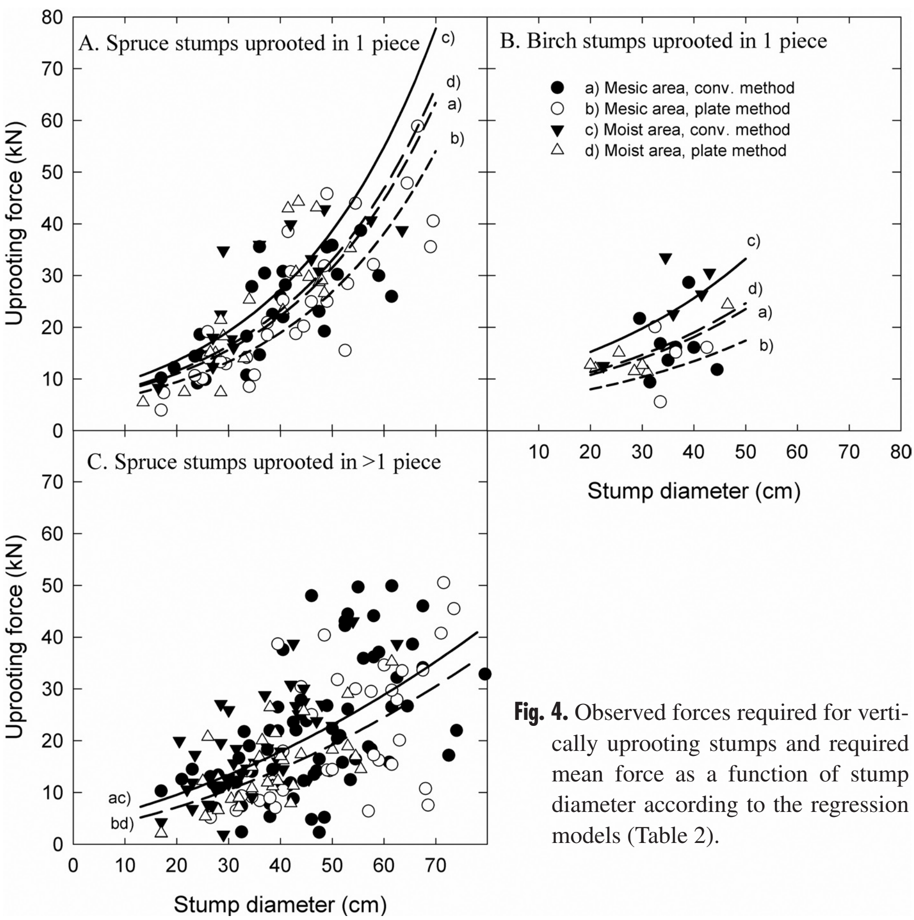

Fig. 4. Observed forces required for vertically uprooting stumps and required mean force as a function of stump diameter according to the regression models (Table 2).

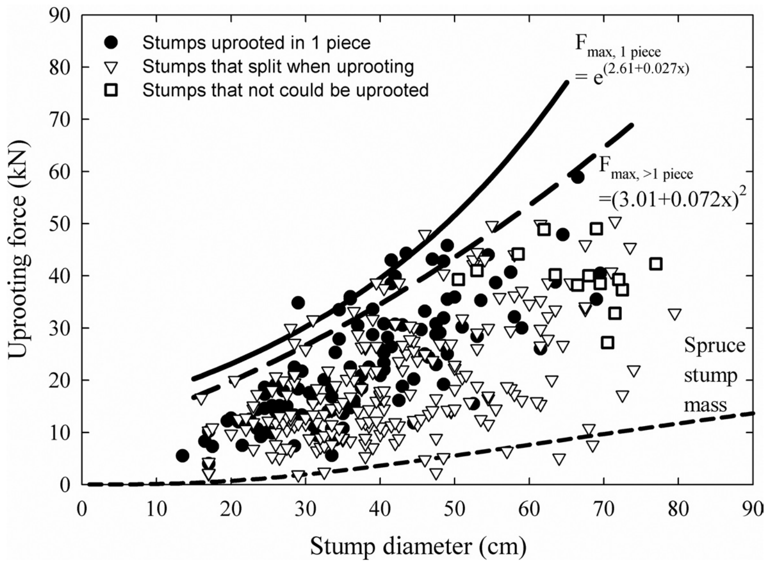

Fig. 5. Observed forces required for vertically uprooting Norway spruce stumps in one or more pieces and the recorded maximum force for stumps that could not be uprooted. In general, 97.5% of all observations should be found below the maximum force functions (F_{max}). The weight of Norway spruce stump as a function of diameter (Petersson and Ståhl 2006) at a moisture content of 35% (dry basis) is shown by a dashed line.

3.2 Predicting the Uprooting Forces

Based on the ANCOVA results, the mean forces required to uproot Norway spruce and birch stumps in one piece and Norway spruce stumps in more than one piece were predicted according to the multiple regression models summarized in Table 2. Due to the transformation of data, the mean uprooting force in kN was calculated for 1 piece stumps according to Eq. 6 and for stumps that split according to Eq. 7, in which DSH is stump diameter under bark in cm, a–d are parameter estimates (Table 2) and Mesic and Plate are dummy variables, assigned the value 1 if they applied and otherwise 0. Functions are visualized together with the observed data in Fig. 4.

$$F_{s,\,1\,\text{piece}} = e^{(a + b \times DSH + c \times Mesic + d \times Plate)} \quad (6)$$

$$F_{s,\,>1\,\text{piece}} = (a + b \times DSH + c \times Plate)^2 \quad (7)$$

Since stump weight was estimated from stump diameter, a correlation between the observed required force and stump weight was expected. Accordingly, the correlation was strong ($r = 0.760$, $p < 0.001$) for Norway spruce stumps uprooted in one piece, but weaker for stumps that split during uprooting ($r = 0.579$, $p < 0.001$) (cf. Fig. 5). The estimated weight corresponded on average to 8.3% (SD 4.0) of the observed required force for Norway spruce stumps uprooted in one piece, and to 16.0% (SD 14.4) for stumps that split. The corresponding values for birch were 9.0% (SD 5.0) and 13.0% (SD 18.4).

Linear regression analyses on transformed data showed that maximum force required for uprooting (F_{max}) of Norway spruce stumps was significantly ($p \leq 0.002$) dependent on stump diameter for both stumps that were uprooted in one piece and stumps that split (functions shown in Fig. 5). Intercepts of the functions were significantly separable from zero ($p < 0.001$) and the models explained 90.0% and 95.7% of the adjusted variance in the relationships, respectively. The inclusion of observed forces during the uprooting of birch stumps in the derivation of F_{max} limits for the diameter classes did not affect the relationships to any notable degree.

Due to the close to linear relationship between the observed maximum forces required for uprooting and diameter (Fig. 5), a linear regression of F_{max} on the diameter intervals based on untransformed data yielded an even better fit (functions not shown). According to such a construction, F_{max} for Norway spruce stumps increased by 0.924 and 0.794 kN per cm stump diameter when uprooting stumps that came up in one piece and stumps that split ($p < 0.001$ in both cases), respectively. The intercepts of the functions were not significantly separable from zero ($p \geq 0.37$) and the models explained 97.0% and 98.2% of the adjusted variance in the relationships.

4 Discussion

4.1 Required Uprooting Forces and Practical Applications

The main objective of this study was to quantify the force required to vertically uproot stumps in one piece in order to identify possible adaptations of current machinery, or facilitate the development of new machinery, for efficient uprooting. In this context it is highly relevant to assess whether or not contemporary forest machines could be used instead of crawler excavators and, thus, comparing crane capacity with the maximum force functions. A powerful harvester has a gross crane lifting capacity of 273 kNm (Komatsu Forest 2009) and assuming that stumps are uprooted at a distance of 3 m from the crane pillar, the machine has a gross lifting force of 91 kN. Equipped with an uprooting device with a mass of ca. 2 t, the net uprooting force is 71 kN, which would suffice to uproot virtually all Norway spruce stumps in one piece up to 61 cm in diameter and up to 75 cm if stumps could be split (cf. Fig. 5). A powerful forwarder crane has a gross lifting capacity of 155 kNm (John Deere 2009, Komatsu Forest 2009), and would under the same assumptions suffice for 1-piece Norway spruce stumps with a diameter up to 32 cm and up to 37 cm if stumps could be split (cf. Fig. 5). Thus, the most powerful harvesters are theoretically capable of uprooting Norway spruce stumps of most sizes that are normally harvested. Forwarders, on the other hand, seem to be restricted to the smaller stump sizes. However, the potential of forwarders would increase if lighter stump harvest devices could be developed. The theoretical findings are consistent with indications from a few small-scale practical applications of both harvesters and forwarders in Sweden and Finland. Notably, studies with a forwarder reported by Laitila et al. (2008) indicate that its productivity was poor compared to that of a crawler excavator-based stump harvester. This is in accordance with the generally limited uprooting capacity of forwarders, and especially so if it is correctly understood that a Valmet 860 was used in the study since it only has a gross crane lifting capacity of 126 kNm (Komatsu Forest 2009).

Compared to results presented in two similar previous studies, the required forces observed in this study were rather low. The previous results were within the interval of 15–150 kN required for vertically uprooting 20–35 cm diameter stumps 6–25 years after roundwood harvest (reported in Czereyski et al. 1965), but the force required in this study did not exceed 40 kN for stumps with diameters less than 35 cm and did not exceed 60 kN for stumps of any diameter within the range of the examined material (≤79.5 cm). The function obtained in this study indicates that the mean force required for uprooting Norway spruce stumps in one piece is five-fold less for 20 cm stumps and four-fold less for 35 cm stumps than Horváth-Szováti and Czupy's (2005) function (Eq. 1). In both studies a similar methodological approach was used, but Horváth-Szováti and Czupy (2005) uprooted Scots pine stumps within the diameter interval 15–35 cm on sites with homogeneous sandy soils. Consequently, differences in derived mean force requirements are likely to be attributable to differences in methods and materials between the studies.

The mechanics of vertical and lateral uprooting of stumps are quite different, since the latter involves rotation around a fulcrum located some distance from the stump centre (Coutts 1983, Stokes 2002). Nevertheless, it is of interest to briefly consider the likely relative effects of applying force in the two directions since stumps could be uprooted more or less laterally with the currently used equipment. Given that trees have evolved to withstand lateral forces but not vertical ones, it seems likely that greater forces are required for lateral uprooting of stumps than for vertical uprooting. The studies reviewed in Biller and Baumgras (1987) corroborates this hypothesis, since at least five times more force is required for laterally uprooting 25 cm stumps compared to the mean values in this study. It seems, thus, that stumps should preferably be uprooted vertically to minimize force requirements.

The effects on the mean required uprooting force by preparatory forces and soil moisture content were generally rather small (Fig. 4) in this study and even contradictory to theories in the case of soil moisture content. This is further discussed in sections 4.2 (preparatory forces) and 4.3 (soil moisture content).

4.2 The Effect of Preparatory Forces

As expected, the method in which preparatory loosening was applied, rather than brute crane force alone, required significantly less force (Fig. 4). Moreover, a smaller proportion of stumps had to be left in the ground due to the lack of capacity to uproot them (Fig. 3). The reduction in force requirement afforded by the preparatory method implies that either less powerful base machines could be used for stumps of the same size or larger stumps could be uprooted with the same base machine. However, the between-method differences in mean force requirements were small and there was considerable within-method variation.

The nominal preparatory uprooting force (314 kN) was more than five times the highest recorded required uprooting force, but differences in required crane force were relatively small. Moreover, some stumps could not be uprooted at all even after applying preparatory force. At least two interacting factors could contribute to this apparent discrepancy. Firstly, most of the force was probably wasted in compression of the soil beneath the stump instead of lifting the stump. Forest soils have been found to be vertically compacted 5–30 cm by pressures of some 300–500 kPa (Wästerlund 1990, Horn et al. 2004). Given its area and the applied force, the plate exerted about twice as much pressure (ca. 900 kPa) on the soil and, hence, it seems reasonable to assume that there was substantial vertical compaction before the soil started to act as a counterweight for the applied uplifting force. Secondly, the limited effect of the preparatory forces might be due to the elastic properties of the anchoring root and soil systems (Coutts 1983). In addition to purely material-related factors, the lateral forces that inevitably affect trees (e.g. rocking by wind) also create elasticity in the system due to root breakage and soil compaction (Coutts 1983). Hence, even stumps that are considered to be firmly anchored have a certain level of movability. In fact, it has been found that roots move vertically almost constantly due to the lateral forces exerted by wind (Hintikka 1972). Due to the lack of a distinct yield point at which failure in the anchorage system occurs (Pyles et al. 1991), the uprooting force has to result in sufficient movement (i.e. deformation) to be successful (Timoshenko and Goodier 1970). Hence, the lifting height of the preparatory force applied in the study might not have been sufficient to exceed the root system's elasticity limits, especially if the actual lifting height was reduced due to soil compaction. Elasticity also provides a plausible explanation for observed lack of effects in previous attempts to reduce uprooting force requirements by vibrating the stump (Horváth-Szováti and Czupy 2005). Given all the factors that increase elasticity, extending the pistons and the surface area of the plate of the studied preparatory uprooting device could be advantageous. Moreover, the applied preparatory force could then be decreased to increase the speed of the operation and thus save time when expanding pistons.

Another possible means to decrease the required uprooting force is to prolong the delay between the cutting and stump harvest times. For trees that lack capacity to sprout from stumps and roots, stumps start to decompose when trees are cut and roots decompose quite rapidly (Palviainen et al. 2004, Melin et al. 2009) and thus loose strength rapidly (O'Loughlin and Watson 1979). This, together with the shrinkage of large roots due to drying, reduces uprooting force requirements with time (Czereyski et al. 1965). However, decomposition also results in reductions in the recoverable amount of biomass with time. Moreover, stump harvesting is usually performed, as in this study, within a year of roundwood harvesting to avoid undesirable delays in forest regeneration operations (Laitila et al. 2008).

4.3 Evaluation of Applied Methodology and Materials

The methodology applied in this study has several advantages as well as drawbacks. Most importantly, it only requires standard equipment (a pressure measuring instrument and measuring tapes) and is quite easy to apply to most machinery used in conventional stump uprooting. However, indirect measurements are subject to various measuring and calculation errors that are likely to aggregate in the process of deriving the required force. Nevertheless, validation of the method used indicated that it provided satisfactory accuracy, although the relative accuracy decreased with small loads. A higher level of accuracy would probably be provided by a method capable of directly measuring the required force, and the most feasible way would probably be to attach a load cell between the crane-tip and the uprooting device.

In this study, the somewhat low level of measurement accuracy is considered acceptable given the inevitably strong sources of variation related to stump anchorage, which is influenced by complex interactions between the root and soil systems. Variations in root morphology (e.g. depth, length, size distributions and branchiness) and soil characteristics (e.g. moisture content and texture) result in a wide spectrum of anchorage levels. Further contributions to these variations are made by differences in soil strengthening by the roots of neighboring trees and levels of decay, making force requirements even more difficult to predict. Since root and soil anchorage systems are hidden beneath the ground, their properties are difficult to determine and were not addressed in this study. However, some general relationships are known. For instance: root morphology varies between species (due to genetic differences), but is also dependent on soil conditions (von Zoth and Block 1992); trees develop wider and more superficial root systems in poorly drained soils (Stokes 2002); and the shear strength of soils decreases with increases in moisture content (Coutts 1983, Stokes 2002). Moreover, the friction between soil and root decreases with increases in soil moisture content, thus in moist soils fine roots could slide up instead of having to break during uprooting (Coutts 1983, Stokes 2002). Hence, many factors indicate that there should theoretically be an inverse relationship between force requirements and the moisture content of soils. Therefore, it was surprising that in this study stumps in mesic soil required less force to uproot than those in moist soils (Fig. 4). However, this might be because moisture content was confounded with other soil properties (e.g. texture).

Some stumps could not be uprooted at all in the study (Figs. 3 and 5). However, it was surprising that the recorded maximum forces during the uprooting attempts did not reach the highest recorded force levels for successfully uprooted stumps. Hence, it seems that those uprooting attempts were aborted by the operator before the hydraulic system's pressure relief valve was activated. Unfortunately, the occasions and reasons for premature abortion of uprooting trials could not be recalled by the operator. A possible explanation is that the operator actively aborted in response to cues indicating that it was pointless to continue the uprooting attempts due, for instance, to insufficient lifting force or risk of overturning the machine. However, irrespective of the reason, only minor proportions of the total number of stumps studied were not uprooted (4%) and excluding them from analyses of force requirements is not considered to have affected the results to any relevant degree.

In the study, two kinds of data transformations were used to ensure that presumptions of linear analysis were met. Both resulted in curvelinear functions indicating that force requirements accelerate with increases in stump diameter, in accordance with expectations since there are similar relationships between stump diameter and both root (anchorage) area and stump weight. The functions could presumably have been forced to pass through zero, since when the stump diameter approaches zero, so should the required uprooting force (cf. Peltola et al. 2000). However, for analytical reasons (the level of explained variance cannot be validly analyzed using a function that has been forced through zero) and since the functions used here are only valid for the studied diameter interval (13.5–79.5 cm), such a theoretically correct approach was not applied.

4.4 Future Research

In future research, it would be of interest to both increase and diversify the amount of data on forces required for vertical uprooting. The influence of, for instance, root morphology and soil characteristics warrant further studies. The multitude of influential factors observed in this study indicates, however, that substantial research would be needed to thoroughly elucidate the effects of the complex interactions involved in stump uprooting. Given the emerging potential of large-scale stump harvests for bioenergy purposes, development of models capable of accurately predicting vertical stresses on root systems would be beneficial for efficient stump uprooting. Development of such models could probably be facilitated by the abundant data on the effects of lateral forces on root systems (e.g. Coutts 1983, Coutts et al. 1999, Peltola et al. 2000, Stokes 2002, Lundström et al. 2007).

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