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Title: Torque required to twist and cut loose Scots pine stumps

Running headline: Torque required to twist pine stumps

Authors: Simon Berg*, Dan Bergström, Dimitris Athanassiadis & Tomas Nordfjell

Swedish University of Agricultural Sciences, Department of Forest Resource Management, Umeå, Sweden.

*Corresponding author: Phone: +46 90-786 81 52, email: simon.berg@slu.se

Abstract

Stump wood is a possible source of renewable energy, but before its potential as a fuel can be utilized to a high degree, new harvesting techniques should be developed to reduce the environmental impact (notably ground disturbance) of harvesting stumps. The forces required to lift and drag stumps out of the soil are known. In this study two unknown and important parameters were addressed: the torque required to uproot stumps by twisting them and the torque required to cut lateral roots around stumps. A new, improved stump-twisting rig was designed and used in trials with 28 Scots pine (*Pinus sylvestris*) trees (breast-height diameter over bark, 153-427 mm). The measured torque requirements ranged from 10 to 50 kNm. Twisting stumps required more torque than cutting lateral roots around stumps and the required torque increased with increases in stump size. The results indicate that a wrist on a big feller-buncher, but not a conventional rotator used on forest machines, should be able to generate sufficient torque to cut the roots around stumps such as those used in this study.

Keywords: bioenergy, force, cutting roots, stump harvesting, uprooting

Introduction

Fossil fuels are being replaced with renewable fuels in Sweden. Thus, it is important to find renewable fuel sources that are both economically and ecologically acceptable. A possible source is the high quality-fuel wood contained in tree stumps (Anerud & Jirjis, 2011). Therefore, stumps are currently being harvested in Sweden on a trial basis, using techniques developed in the 1970s and early 80s when stump harvesting was last conducted in the country (Jonsson, 1985). The stumps are extracted after clear-cutting, by excavators weighing 20-25 tons (metric) equipped with stump harvesting heads, then left on-site in heaps to be cleaned from soil by a combination of rainfall, drought and wind before being forwarded to roadside (Hedman, 2008; von Hofsten, 2010).

A major problem that needs to be addressed before stump wood can be used as a credible source of renewable and sustainable energy is that uprooting stumps can cause substantial ground disturbance, and thus adversely affect the environment (Walmsley & Godbold, 2010). One way to decrease the ground disturbance could be to only harvest the stump centres. Stump centres of poplar trees planted on farmland have been harvested for a long time with a tube saw (Czereyski et al., 1965), and are still harvested in some areas of Italy (Spinelli et al., 2005). A prototype tube saw stump-centre harvester for work in forest condition has been tested in the field in Sweden. To date, its productivity has been lower than for conventional whole-stump harvesting, mainly due to the decreased volume harvested per stump (von Hofsten, 2011); 7-10% of the total stem volume is harvested in stump centre harvests (Fryk, 1975), compared to 15-30 % in whole-stump harvests (Magnusson & Nylinder, 1977). An alternative solution could be to integrate stump centre and stem harvests, handling the stump centre as an extension to the butt log (Nordfjell et al., 2011) and leaving the roots in the soil, thereby reducing the ground disturbance, increasing the bearing capacity for heavy machines and decreasing the environmental impact of stump harvesting (Nordfjell, et al., 2011).

Understanding stump properties and the variations in ground disturbance associated with different uprooting methods is important for developing more environmentally-friendly machines for stump harvesting. Thus, several studies have examined the force required to vertically lift (Czereyski et al., 1965; Horváth-Szováti & Czupy, 2005; Lindroos et al., 2010) or horizontally pull (e.g. Golob et al., 1976; Liley, 1985; Peltola et al., 2000) stumps out of the ground. In addition, Anderson et al. (1989) studied the shear strength (a type of material failure) of the root plate/soil interface of Sitka spruces (*Picea sitchensis*) (Figure 1) in various soils by twisting stumps, but they did not report the torque, and there is a general lack of information about the torque required to twist stumps. Of course, if stumps were simply twisted, large proportions of the root systems could be uprooted, probably causing similar degrees of ground disturbance to current stump harvesting technology. Alternatively, in order to reduce the ground disturbance when stumps are lifted by twisting, knives could be twisted around the stumps to cut the roots. No information about torque or forces required to cut roots in such a manner appears to have been published, the only pertinent information regarding the force needed to cut wood is above ground (e.g. Wiklund, 1967). However, the increase in force required may not be high, since Gebresenbet & Jonsson (1992) found that 35 N was sufficient to pull seed drill coulters through agricultural soil, although knives would have to penetrate more deeply to cut lateral roots around trees. The forest soils also often contain more stones than agricultural soils, so the forces required would probably be higher, especially because the roots are coarser and more resistant in forests.

<Figure 1 here>

The aim of this study was to measure the torque needed to twist, and the force and torque needed to cut lateral roots around Scots pine (*Pinus sylvestris*) stumps in a sandy sedimentary soil.

Material and Methods

Study site and treatments

The study site was a clear-cutting area in Vindeln municipality (64° 13′ N 19° 48′ E) with sandy sedimentary soil and flat, even, dry ground; bearing capacity, ground roughness and slope all 1 according to the Swedish terrain classification scheme (Berg, 1982). At the time of the study, the site was supporting a stand with a mean diameter over bark at breast height (1.3 m above ground; DBH) of 179 mm, mean height of 14.3 m, a basal area of 25.9 m^2/ha and 934 stems per hectare. In August and October 2010, 19 trees were felled, and six “fresh“ stumps were twisted within three weeks. The remaining stumps (“old“ stumps, n=13) were twisted in August -September 2011, about 10 months after cutting. In 2011 another nine trees were also cut and twisted fresh. Thus, in total 28 Scots pine stumps were used in the trials (Table 1).

Three main treatments were applied in the trials: twisting stumps (T1), cutting lateral roots around stumps by rotating a single knife (T2) and cutting lateral roots around the stumps by rotating two knives on opposite sides of each stump (T3) (Table 1). In T1 the dependent variable torque required to twist stumps was measured, while in the T2 and T3 treatments the dependent variables torque and force required to cut the lateral roots were measured. In addition, the torque or force needed to overcome the rig-to-stump resistance (E) was measured by twisting the rig without any knives or chains around stumps (Table 1). This torque or force was then subtracted from the T2 and T3 measurements to exclude the rig-to-stump resistance from the results.

<Table 1 here>

Experimental rig and trial setup

A stump-twisting rig capable of twisting the stumps through an entire revolution (360°) was constructed of steel, based on the stump-twisting rig described in Smith (1986) (Figure 1), but with a circular design, enabling forces to be exerted on two sides of a stump with a constant relationship between force and torque (i.e. maintaining a constant angle) while the rig is rotating (Figure 2). To apply treatment T1 four 1.5 m long chains were fastened (one in each corner) to the inner frame (Figure 2). Holes were then dug under four major roots, one chain was placed around each of them and then reconnected to the rig. The rig rotated with the stump. To apply T2 and T3 one or two knives were attached to the rig (Figure 2), near the roots (within 10-50 mm) of the focal stump. The knives were sharpened between every repetition. The weight (ca. 300 kg) of the rig was enough to push the knives into the soil when it was placed around a stump, and the rig rotated around the stump.

Trees were cut 1-1.5 m above ground to create high stumps before the trials. The ground-covering vegetation around each stump was removed to make the lateral roots around it visible. The rig had bolts on two sides (32 in total) which were used to push plates against the stump, in order to keep the rig upright during the trials. To further stabilize the rig when it was rotating, wooden planks and wedges (numbers depending on stump size) were placed between the stump and the metal frame. After the rig was fixed to the stump the rest of the trial equipment was connected (Figure 3): a pulley reversing the direction of one cable, a triangular bar connecting the rig's cables to the winch cable, a winch applying force to the rig's cables, an anchor holding the pulley in place, a load cell between the pulley and the anchor for measuring the force applied during the trial and a rotary encoder for measuring how far the rig turned during the trial. The winding rate of the winch was about 31 mm/s, under trial conditions.

<Figure 2 here>

<Figure 3 here>

Measurements

Before the trees were cut in the trials the following variables of each individual tree were measured: tree height, DBH, crown diameter and bark thickness. After the experiment the soil temperature was measured. The root diameter of the first root cut in T2 and the first two roots simultaneously cut in T3 were measured, to calculate the cut root area.

The applied force was measured with a load cell (ID no. 264003), positioned as shown in Figure 3 and calibrated daily by lifting a 976 kg mass (validated using a Lindell 3100 scale, with accredited calibration to 3 March 2014). The distance the rig turned was measured with a modified rotary encoder (Emeta model 300-6-2000-9), with a drum diameter of 31.4 mm and resolution of 0.0493 mm. A string was wrapped around the rotary encoder's drum and was then fastened to one of the cables. The data from the load cell and rotary encoder were recorded at a resolution of one measurement per second by an Intab ACC2 data logger controlled by a computer running EasyView software version 5.5.1.5.

The rotation (R) of the rig during trials was calculated as:

$$R = \frac{P}{1540 * \pi} * 360 \text{ (degrees)} \qquad (1)$$

where P is the distance in mm that the rig turned and the constant 1540 is the rig's diameter in mm.

The maximum torque (T) during each trial was calculated as:

$$T = \frac{F}{2} * 0.77 + \frac{F}{2} * 0.77 = F * 0.77 \text{ (kNm)} \qquad (2)$$

where F is the maximum force (kN) recorded during the revolution and the constant 0.77 is the rig’s radius in m. These calculations were based on the assumption that the rig was pulled at two points with the same force (half the measured force). To calculate the required torque to overcome E the average value for an entire revolution was used.

The force required to cut through lateral roots (F_R) was calculated as:

$$F_R = F * \frac{0.77}{0.44} = F * 1.75 \text{ (kN)} \qquad (3)$$

where F is the maximum recorded force (kN) when cutting through the first root in treatment T2 or the two first roots simultaneously in T3. The constants 0.44 and 0.77 (m) are the distances from the rig's centre to the knives and the point where the force was applied on the rig, respectively, the latter acting as a lever increasing the force. To calculate the force required to overcome E the average value for an entire revolution was used.

Analyses and statistics

Linear equations (k×x+m) expressing the force and torque of E as a function of DBH (for both fresh and old stumps) was constructed, using the data presented in Table 2. The E force and torque values were then subtracted from the values measured during the T2 and T3 treatments before any further analysis of the data (Table 2).

The effects of main treatment (T1, T2 and T3) and secondary treatment (stump type, “fresh” and “old”) on the required torque were evaluated with analyses of covariance (ANCOVA) using the following general linear model (GLM, with 95% confidence intervals): $y_{ij}=\mu+\alpha_i+\beta_j+e_{ij}$, where y_{ij} is the observed torque, μ is the true value, α_i is the effect of main treatment, β_j is the effect of stump type and e_{ij} is the random deviation including the interaction effect of α and β. Tukey’s pair-wise comparison test of means was used to test the significance of differences between treatments. No interaction effects between factors were examined since T1 was not applied to “old” stumps (see Table 1). Pearson correlation tests were used to assess the strength of associations of variables with the torque (and thus whether they should be included as covariates in the ANCOVA).

The differences in required force between treatments T2 and T3 were also studied with ANCOVA, in which interaction effects of α and β could be examined, using the model $y_{ij}=\mu+\alpha_i+\beta_j+(\alpha\beta)_{ij}+e_{ij}$, where $(\alpha\beta)_{ij}$ is the interaction between the main and secondary treatments and e_{ij} is the random deviation. Again, Pearson correlation tests were used to assess the strength of associations of other variables with the force (and thus whether they should be included as covariates in the ANCOVA).

The maximum torque needed to twist stumps, the maximum torque required to cut lateral roots around stumps and the maximum force required to cut lateral roots were also modelled with least square regression functions, again applying Pearson correlation tests to identify associated variables that could be used as independent variables, considering those with p-values < 0.05 to be significant. All statistical analyses were performed using Minitab 16 (Minitab Ltd.) software.

Results

In total 28 stumps with DBH ranging from 154-427 mm (mean, 239 mm) were used in the trials (for details of these and other variables, see Table 2). The equations derived for E are shown in Table 4.

<Table 2 here>

The DBH variable that was most closely associated with torque, and was used in the ANCOVA analysis with maximum torque (n=26, Pearson's r = 0.722, p<0.001). There was a significant difference in maximum torque between treatments T1 and T2 (p<0.001) and a close to significant difference between T1 and T3 (p =0.057), but not between "fresh" and "old" stumps (p=0.758) nor between T2 and T3 (p=0.383) (Table 3). Thus, twisting stumps required higher maximum torque than cutting lateral roots around stumps with one knife and could even require higher maximum torque than cutting lateral roots with two knives simultaneously. Based on these findings, data for treatments T2 and T3 were pooled (and designated T4) for further ANCOVA analyses of the maximum torque, which detected significant differences between treatments T1 and T4 (p<0.001). The maximum torque in treatment T1 was highly correlated to DBH (n=6, Pearson's r=0.942, p=0.005), bark thickness (n=5, Pearson's r= 0.933, p=0.020) and crown diameter (n=5, Pearson's r=0.982, p=0.003), while the maximum torque in treatment T4 was highly correlated to DBH (n=20, Pearson's r=0.813, p<0.001), and crown diameter (n=16, Pearson's r=0.738, p=0.001) (Table 3). Hence, the variables DBH and crown diameter were used in the least square regression functions for treatment T1 and T4 (Table 4 and Figure 4).

The root area variable was most significantly correlated to the required force and hence was used in the ANCOVA of force which showed that there was no significant difference between the force required to treat "fresh" and "old" stumps, nor between treatments T2 and T3 (Table 3). Data for these treatments were therefore again pooled and designated T4. The force applied in treatment T4 was significantly correlated not only to root area (n=14, R^2=0.736, p=0.003), but also to DBH (n=14, R^2=0.631, p=0.016) and the torque needed to cut roots around stumps (T4) (n=14, R^2=0.637, p=0.014). Root area and the DBH were used in a least square regression functions for T4 (Table 4 and Figure 5).

<Table 3 here>

<Table 4 here>

< Figure 4 here>

< Figure 5 here>

Discussion

Our results show that twisting stumps or cutting lateral roots around stumps requires much greater torque (10-50 kNm) than any ordinary rotator mounted at the tip of a boom can generate. The largest rotator supplied by the manufacturer Indexator (Vindeln, Sweden) can only generate a torque of 7.8 kNm (L. Eriksson, Indexator AB, pers. comm., May 12, 2010). Thus, if such rotators were used only the roots around small stumps could be cut, but any efficient stump harvesting technology developed would have to be capable of harvesting stumps of all sizes. As an alternative, it could be possible to twist stumps using the wrist of a feller-buncher's felling head, which can generate a torque of 54.3 kNm and rotate through 340° (D. Barlow, Tigercat Inc., pers. comm., May 27, 2011). Two knives in combination with a feller-buncher's wrist should be able to harvest most pine stumps in soils similar to the soil at our study site, provided the boom is designed to handle such torque.

The force we found necessary for cutting lateral root wood is slightly higher than the force Wiklund (1967) reported to be required for cutting stems with 9000-71000 mm^2 basal area (Figure 6), which is not surprising since the soil’s resistance also hinders cutting through roots. This resistance was not measured in the presented study, but Gebresenbet and Jonsson (1992) found that the force needed to drag seed drill coulters through agricultural soil increases with depth and increases in speed, up to about 35 N (at 70 mm depth and 2.1 m/s). In the presented study the knives penetrated the soil more deeply (to 350-400 mm) than in Gebresenbet and Jonsson (1992), but the speed was much lower (0.03 m/s). These comparative data indicate that the force needed to pull knives through sandy sedimentary forest soil will constitute a minor fraction of the total force required to cut through the roots in such soil. It should be noted that the root size at the cutting point and DBH were correlated (n=14, R^2=0.631 p-value=0.016), because it was not possible to adjust the radial position of the knives during the trials. Hence the knives were closer to the stems of large stumps, the knives cut through larger roots attached to large stems, and the root size was not independent of DBH in the trials.

Kalliokoski *et al.* (2008) found that pines growing on a *Myrtillus* type site with a diameter at stump height of 293 mm had 21 (s.d., 6.2) proximal roots, with an average root diameter of 64 mm (s.d., 37 mm), which approximately corresponds to trees with a DBH of ca. 236 mm (Karlsson, 2007). This indicates that it should be possible to cut lateral roots around small pines. It also indicates that the root diameters measured in this study are reliable, and the generated functions could be generalized to pines growing in similar soils.

< Figure 6 here>

The time profiles of the torque differed substantially between twisting stumps (T1) and cutting lateral roots with one and two knifes pooled together (T4), as shown in Figure 7. In T1 the torque was initially high, but the required torque dropped rapidly when the roots loosened from the soil, or broke off. In contrast, in T4 the maximum torque was lower, but the torque increased every time a root was encountered. Thus, when a stump was twisted high torque had to be generated initially, but after the initial peak was reached far less torque was needed, whereas when cutting roots the maximum torque could occur at any time.

< Figure 7 here>

Only two measurements of the rig-to-stump resistance were made. In an attempt to validate the reliability of the rig-to-stump resistance equation derived from these two measurements, the torque values acquired just before the rig started to turn in treatment T4 were used. This resulted in a spread of observations above and below the rig-to-stump resistance line (Figure 8), indicating that the rig-to-stump resistance line was adequately reliable to use to remove the rig-to-stump resistance before analyzing the data, although it was based on only two measurements. However, it was not possible to be certain when the rig started to move, therefore the torque measured just before the rig started to turn was not used in any regression functions.

< Figure 8 here>

The treatments’ effects on the stems were not measured in any way, but cracks were observed in some stems in inspections following T4 (Figure 9), probably due to roots flexing before being cut. Some stumps subjected to T1 also had cracks, but they were much smaller. Therefore, twisting stumps or using torque to cut roots around stumps should not be used for integrated stem and stump harvests as it would endanger the butt log. A possible alternative for integrated harvest could be to cut off the roots in a vertical movement (from above). Koch and Coughran (1975) found that such a method did not damage the stem, but it was sometimes damaged when the tree was lifted from the ground.

< Figure 9 here>

Some T4 trials were interrupted because the knives bent before all the roots were cut, or the stump leaned so much that the cables fell off the rig (Table 2). There are two likely reasons for the knives bending: the knives hitting the roots at an angle (since the roots were not straight), and/or the roots flexing before being cut. Further, the degree of bending presumably increased somewhat as each root was cut. However, the bending in some trials is unlikely to have biased our results in any particular direction as both large and small roots had been cut before the knives bent. In addition, during most of the treatment T1 trials the rig did not rotate through 360° (Table 2), instead the four main roots usually broke after a short rotation, resulting in the stump either heavily leaning or standing straight with four broken main roots. The data obtained during these observations were not removed from the analysis since the remaining roots were smaller than those that broke off, thus the torque required to uproot them should not have been higher than the observed maximum torque, and hence the incomplete twisting is unlikely to have biased our results.

A weakness of this study is that the experiment was unbalanced (for reasons beyond our control), making it less likely to find treatment-related differences in force and torque in the ANCOVA analysis. Therefore, further trials with balanced experiments would be desirable, to enhance the reliability of the ANCOVA. If the experimental rig presented here is used in further studies it would also be desirable to make the radial positioning of the knives adjustable, to maintain the same distance between the knives and stumps (of all sizes). It would also be interesting to investigate other species and soil types, to see if they require different torque/force. Finally, functions describing the diameters of lateral roots close to the stem would be highly valuable for calculating the power required to cut them.

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Tables

Table 1. No. of replicates of treatments in fresh (cut < 3 weeks before trial) and old stumps (cut ca. 10 months before trial). T1=twisting stumps; T2=one knife used for root cutting; T3=two knives used for root cutting; E=rig-to-stump resistance.

	Stump age		
Treatments	**Fresh stumps**	**Old stumps**	**Sum**
T1	6	0	6
T2	5	6	11
T3	8	1	9
E	1	1	2
Sum	20	8	28

Table 2. Data on trees and stumps in the trials. Addrevations: T1=twisting stumps; T2=one knife used for root cutting; T3=two knives used for root cutting; E=rig-to-stump resistance; DBH=diameter at breast height over bark; BT=bark thickness; H= height of tree; Diam. C=crown diameter; Aroot=root area; Soil temp.= temperature in the soil after trial; fresh=cut < 3 weeks before trial; old=cut ca. 10 months before trial; RTSR=calculated rig-to-stump resistance; Perf.=performance in trials, where T=completely twisted, L=stump leaning during twisting, B=roots broke off (for T1), K=bent knives, degree of twisting (0-360°).

	Tree and stump variables							Trial responses and performance			
Treatment	*DBH (mm)*	*BT (mm)*	*H, Tree (m)*	*Diam.,C (m)*	A_{root} *(mm^2)*	*Soil temp. (˚C)*	*Stump age*	*RTSR (kNm)*	*Max Torque (kNm)*	*Force to cut root (kN)*	*Perf.*
T3	295	24	n.a.	n.a.	n.a.	15	Old	5.12	34.78*	n.a.	130L
T3	267	36	n.a.	n.a.	n.a.	12	Old	4.36	25.61*	n.a.	180T/K
T3	300	16	n.a.	n.a.	14421	12	Old	5.26	44.58*	49.55*	138T/K
T3	252	n.a.	n.a.	n.a.	14627	13	Old	3.96	34.57*	56.78*	145T/K
T3	167	21	14.8	3.3	n.a.	12	Old	1.65	17.19*	n.a.	142L
T3	235	28	18.5	2.5	22894	11	Old	3.49	20.83*	33.78*	196T/K
T3	243	37	17.5	3.9	n.a.	12	Old	3.72	21.46*	n.a.	180T/T
T3	211	33	1585	3.5	n.a.	11	Old	2.85	33.11*	n.a.	121L
T3	177	20	13.0	1.0	4500	8	Fresh	1.92	22.20*	50.45*	180T/T
T2	174	23	14.8	2.2	1854	9	Old	1.85	9.80*	15.14*	216L
T2	154	18	9.5	2.8	2733	9	Fresh	1.31	8.84*	10.93*	157L
T2	213	28	16.8	3.7	n.a.	11	Old	2.91	20.58*	n.a.	134K
T2	245	26	14.5	3.6	2884	10	Fresh	3.76	18.49*	37.71*	360T
T2	247	25	16.5	3.3	1272	n.a.	Fresh	3.81	16.24*	15.96*	321K

T2	200	21	13.5	2.3	803	8	Fresh	2.54	12.40*	13.23*	347L
T2	220	24	15.5	3.8	852	8	Fresh	3.10	21.55*	4.85*	360K
T2	211	21	15.5	3.2	6927	8	Fresh	2.84	25.27*	37.78*	208L
T2	286	28	16.3	4.2	12374	6	Old	4.88	34.16*	77.63*	198K
T2	320	39	17.3	5.9	9940	7	Old	5.78	49.85*	33.99*	360T
T2	327	48	15.8	5.4	31696	8	Old	5.97	35.99*	81.43*	160K
T1	184	23	12.3	3.1	n.a.	2	Fresh	n.a.	20.89	n.a.	360B
T1	229	28	15.0	4.3	n.a.	3	Fresh	n.a.	40.53	n.a.	BL
T1	279	36	17.5	5.0	n.a.	4	Fresh	n.a.	47.50	n.a.	~90BL
T1	220	27	15.5	3.8	n.a.	2	Fresh	n.a.	31.25	n.a.	360B
T1	249	35	14.3	5.1	n.a.	5	Fresh	n.a.	45.33	n.a.	BL
T1	170	n.a.	n.a.	n.a.	n.a.	n.a.	Fresh	n.a.	24.75	n.a.	360T
E	427	n.a.	n.a.	n.a.	n.a.	n.a.	Old	n.a.	8.67	n.a.	360T
E	196	n.a.	n.a.	n.a.	n.a.	n.a.	Fresh	n.a.	2.49	n.a.	360T

*Torque or force after subtracting the stump-to-rig resistance.

Table 3. Summary results of the ANCOVA. Abbreviation: T1=twisting stumps; T2=one knife used for root cutting; T3=two knives used for root cutting; T4=data in T2 and T3 pooled; Stump age=fresh or old stumps (cut < 3 weeks or ca. 10 months before trial, respectively). DBH and root area were used as covariates.

	Model factors				
Responses	**Main tretments**	**Stump age**	**Interaction**	**Covariate**	**R^2 adj (%)**
Torque (kNm)	p<0.001 (T1,T2 and T3)	p=0.758	n.a	DBH (mm) (p<0.001)	72.2
Torque (kNm)	p<0.001 (T1 and T4)	p=0.289	n.a	DBH (mm) (p<0.001)	71.1
Force (kN)	p=0.519 (T2 and T3)	p=0.583	p=0.124	Root area (mm^2) (p=0.032)	50.1

Table 4. Parameters for least squares regression functions for the torque required to twist stumps (T1), and the torque or force required to cut lateral roots around stumps with one and two knives pooled togheter (T4). Parameters of the linear equations for the rig-to-stump resistance (E) are also shown. DBH, crown diametre and root area were independent variables. Abbrevation: SE=standard error; RMSE= root mean square error.

	Independent variables	**Parameter estimate**	SE	p-value	**RMSE**	**R^2 adj (%)**	**Interval**
Torque (E) (kNm)	Intercept	-2.844					
	DBH (mm)	0.027					196-427
Force (E) (kN)	Intercept	- 4.977					
	DBH (mm)	0.047					196-427
Tourqe (T4) (kNm)	Intercept	-16.896	7.729	0.032	6.656	64.3	
	DBH (mm)	0.178	0.030	< 0.001			154.0-326.5
Tourqe (T4) (kNm)	Intercept	0.212	5.870	0.972	7.485	51.3	
	Crown diameter (m)	6.677	1.630	0.001			1.0-5.9
Tourqe (T1) (kNm)	Intercept	-22.270	10.330	0.097	4.142	86.0	
	DBH (mm)	0.259	0.046	0.005			170-278.5
Tourqe (T1) (kNm)	Intercept	-17.805	6.247	0.065	2.422	95.2	
	Crown diameter (m)	12.888	1.444	0.003			3.1-5.1
Force (T4) (kN)	Intercept	-29.800	24.320	0.244	19.495	34.8	
	DBH (mm)	0.280	0.099	0.016			154.0-326.5
Force (T4) (kN)	Intercept	99.840	28.650	0.005	14.652	63.2	

LN(Root area) (mm^2)	16.049	3.326	<0.001		803-31696

Figure legends

Figure 1. The stump twisting rig designed by Smith (1986) and used by Anderson, et al. (1989) to investigate the shear strength of Sitka spruce root plate/soil interfaces. Figure after Smith (1986).

Figure 2. Schematic Illustration of the rig and knives used in the study: from above (A), from the side, equipped with chains (B), from the side, equipped with a ring for mounting knives (C) and cross-section of knife used to cut roots (D), dimensions in mm. Knives were 14 mm thick and had an edge angle of 30°.

Figure 3. The trial setup, cables shown as lines and strings as broken lines.

Figure 4. Left panel: torque needed to cut roots around stumps with one and two knives pooled together (kNm= -16.896+0.178×DBH, DBH in mm) (T4) and the torque needed to twist stumps (kNm=-22.270+0.259×DBH in mm) (T1) as functions of diameter at breast height over bark (DBH). Right panel: torque needed to cut roots around stumps with either one or two knives (kNm=0.212+6.677×Crown diameter in m) (T4) and the torque needed to twist a stump (kNm=-17.805+12.888×Crown diameter in m) (T1) as functions of the crown diameter. In both cases, the lines shown are least squares regression lines.

Figure 5. Forces needed to cut a lateral root with one and two knives pooled together (T4) as a functions of root area (kN=-99.84+16.049×LN(Root area in mm^2)) and diameter at breast height over bark (DBH) (kN=29.80+0.28004×DBH in mm) to left and right, respectively. In both cases, the lines shown are least squares regression lines.

Figure 6. Observed force (diamonds and solid line) needed to cut lateral roots of Scots pine with one and two knives pooled together in current study and the force required to cut stems found by Wiklund (1967) (broken line).

Figure 7. Illustration of torque curves for trials in which stumps were twisted with chains (solid line) or lateral roots were cut with a single knife (broken line).

Figure 8. Rig-to-stump resistance as a function of diameter at breast height over bark (solid line) and measured values (dots) just before the rig started to rotate.

Figure 9. A stem with a crack after cutting the lateral roots around the stump (treatment T4), the stump was debarked by the rig during the trial.

Figures

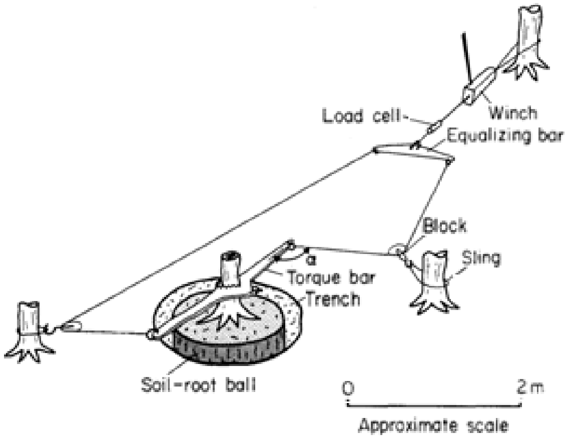

Figure 1.

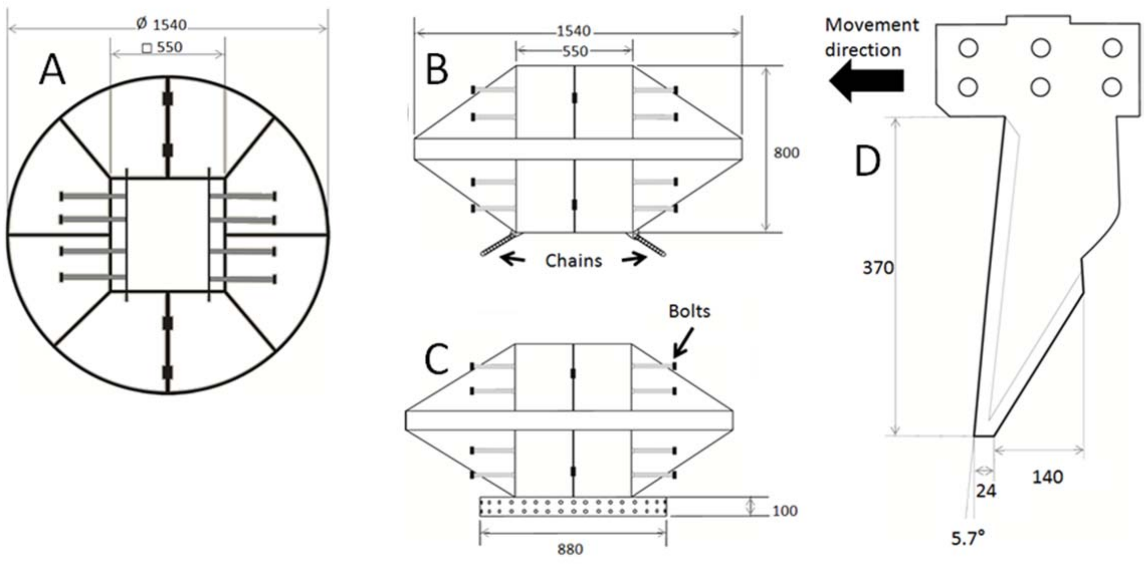
Ø 1540
□ 550
A
1540
550
B
800
Chains
Bolts
C
100
880
Movement direction
D
370
24
140
5.7°

Figure 2.

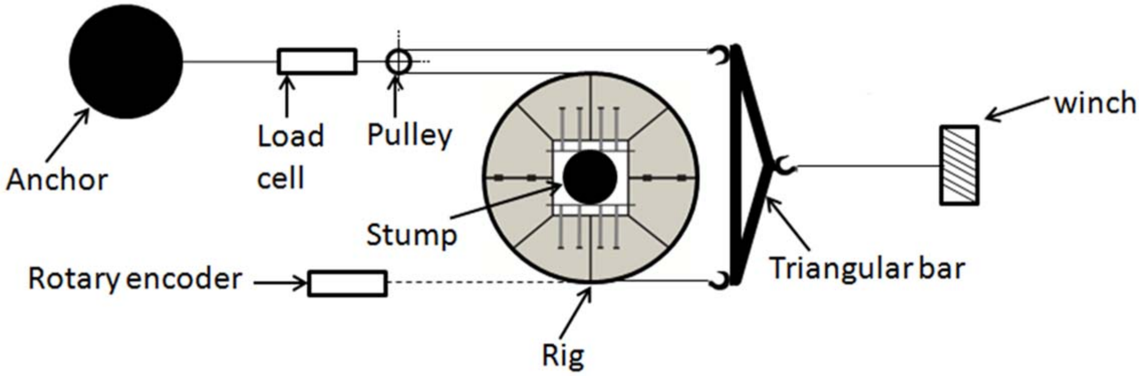
Anchor
Load cell
Pulley
winch
Stump
Triangular bar
Rotary encoder
Rig

Figure 3.

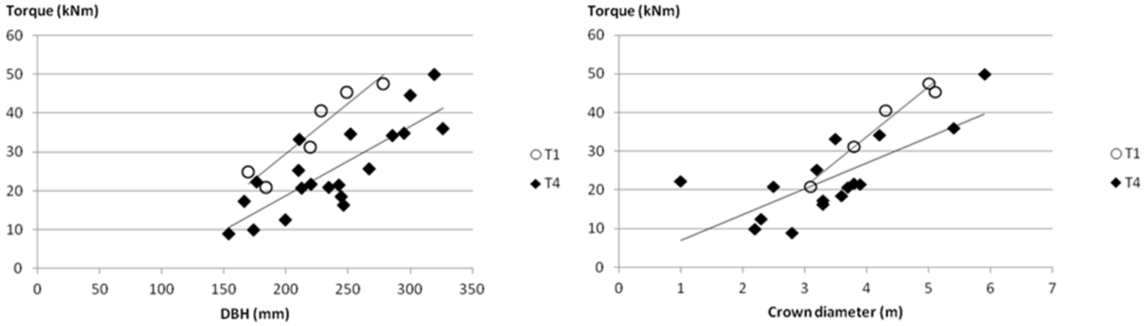
Torque (kNm)
60
50
40
30
20
10
0
0
50
100
150
200
250
300
350
DBH (mm)
○ T1
◆ T4
Torque (kNm)
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
Crown diameter (m)
○ T1
◆ T4

Figure 4.

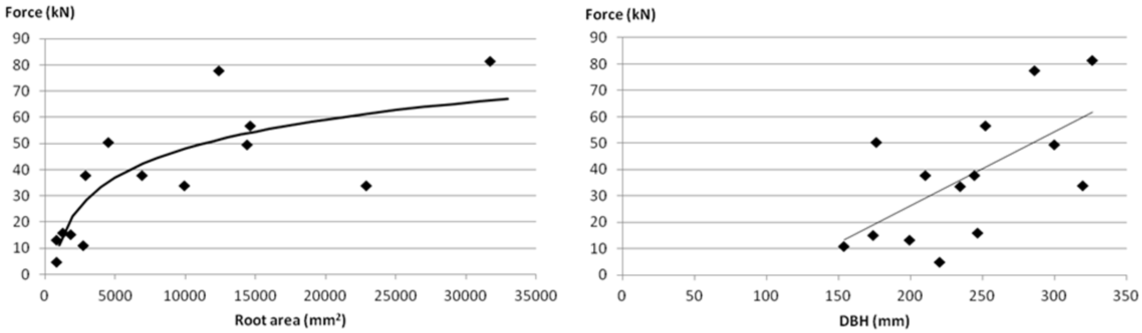
Force (kN)
90
80
70
60
50
40
30
20
10
0
0
5000
10000
15000
20000
25000
30000
35000
Root area (mm²)
Force (kN)
90
80
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
350
DBH (mm)

Figure 5.

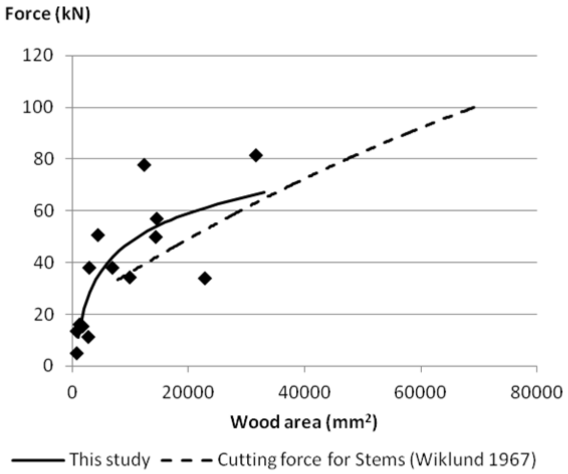
Force (kN)
120
100
80
60
40
20
0
0
20000
40000
60000
80000
Wood area (mm²)
This study
Cutting force for Stems (Wiklund 1967)

Figure 6.

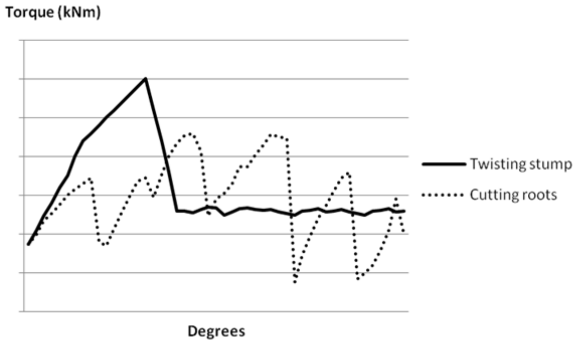

Figure 7.

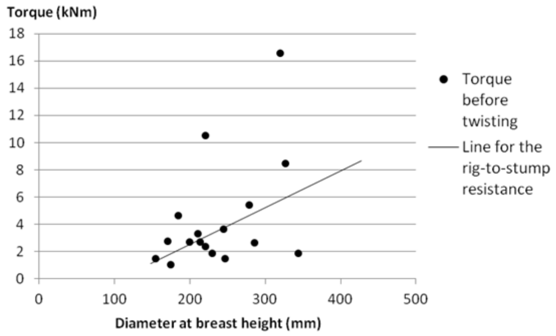
Torque (kNm)
18
16
14
12
10
8
6
4
2
0
0
100
200
300
400
500
Diameter at breast height (mm)
● Torque before twisting
Line for the rig-to-stump resistance

Figure 8.

Figure 9.