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# Effect of stump size and timing of stump harvesting on ground disturbance and root breakage diameter

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## Highlights

- The ground disturbance and root breakage diameter during conventional stump harvesting on mineral soil were quantified.
- A function for estimating the disturbed area based on stump size was constructed.
- Many fine roots were found to be harvested.
- The total ground disturbance at the site after stump harvesting was similar to that caused by soil scarification.

## Abstract

Stump wood is a possible alternative to fossil fuel. Its harvesting, however, disturbs the ground and this has not yet been quantified at stump level. Such disturbance is likely to be dependent on stump size, type of soil and timing of stump harvesting. Therefore, we measured ground disturbance and root breakage diameter at two Norway spruce sites with sandy glacial till soil. The sites were harvested with a fork type head, 6 and 18 months after clear cutting. Measurements were made within 2 weeks of harvest. No difference was found between the two sites. The mean area of disturbed ground was 6.06 (std 3.14) m$^2$ per stump and increased exponentially with stump size. A regression function modelling the relationship was constructed. Unexpectedly, many fine roots where extracted in the harvest. The arithmetic and basal area weighted mean root breakage diameter was 4.6 (std 2.2) and 29.5 (std 17.9) mm, respectively. There seems to be a limited increase in root breakage diameter with increased stump size. The small root breakage diameter is associated with reduced fuel quality and greater nutrient removal. It appears that much of the ground disturbance is associated with the creation of ruts rather than stump harvest per se. Stump harvesting disturbs a larger percentage of the area of a harvested site than mounding. Postponing stump harvest by one year did not decrease the ground disturbance or increase the root breakage diameter. To achieve less disturbance and larger root breakage diameter, probably new stump harvesting technology is required.

**Keywords** stump harrow; Ecorex30; *Picea abies*; site impact; Sweden; glacial till soil; scarification
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# 1 Introduction

Fossil fuels are being progressively replaced by renewable fuels in Europe (European Commission 2011). Clearly, these fuels must be both economically and ecologically acceptable (Anerud and Jirjis 2011), and attractive sources are residue stumps from forestry. However, use of stumps is currently very limited in Sweden (Anerud and Jirjis 2011) as Forest Stewardship Council (FSC) members can only harvest them from 2500 hectares per year nationally, due to ecological concerns (FSC 2012). This is a tiny proportion of the average annual clear cutting area of about 200 000 ha (Christiansen 2013). Stumps are harvested after removal of logging residues (branches and tops) from the site (Anerud 2010), using excavators weighing 17–25 tonnes (Laitila et al. 2013). The stump and root systems are uprooted and split with a special stump harvesting head, shaken to remove the soil and then piled up and stored on site (Laitila et al. 2008). Subsequently, a forwarder transports the stumps to roadside storage in windrows where they remain for between several months and a few years before further transportation to the point of use, either intact or after comminution at the landing (Asikainen 2010).

There are several benefits and drawbacks to stump harvesting (Walmsley and Godbold 2010). Benefits include: fuel wood can replace fossil fuels; root rot is reduced in the next forest generation as infected wood is removed; soil scarification is more effective, as no stumps hinder the work and there is increased mineralisation due to the ground disturbance, which leads to better growth and reduced seedling death; and there is extra income for the forest owner from the stump wood. The main drawback is the ground disturbance that can cause a reduction in the carbon stored in the forest soil as decomposition is increased plus a possible increase in soil erosion, as binding roots are removed and more soil is exposed. Other drawbacks are removal of nutrients from the site, increased soil compaction, as more heavy machines traverse the site, and loss of valuable habitat for fungi, mosses, bryophytes and insects as dead wood is removed from the forest (Walmsley and Godbold 2010). In the UK an increase in non-forest vegetation (heather, rhododendron, bramble and bracken) has been feared after stump harvesting (Walmsley and Godbold 2010). With climate change, this could perhaps become a problem in southern Sweden (Tveito et al. 2000; Lind and Kjellström 2008; Jenkins et al. 2009). There are also concerns about leaching of nutrients and heavy metals, e.g. methylmercury, from sites due to the ground disturbance as it increases mineralisation (Egnell et al. 2007). The documented knowledge about ground disturbance after stump harvesting is however limited, and it has only been studied in relation to the total disturbance on the site, which can vary between 40–70% of the area (Hope 2007; Kataja-aho et al. 2012). Soil preparation is mainly performed using separate machines after the stumps have been harvested and forwarded (Kärhä 2012). It is therefore interesting to compare ground disturbance after stump harvesting to that after various possible kinds of soil preparation, including mounding, which is the most commonly used soil preparation method after stump harvesting in Finland (Rantala et al 2010; Hallongren et al 2014). For example, 14–21% of the total area is disturbed after mounding and 40–60% after disc trenching (Roturier and Bergsten 2006; Roturier et al. 2011).

From a fuel quality perspective, the nutrient contents in fuel wood are important as they are positively correlated with ash contents and $NO_x$ emissions. Compared to other tree parts, coarse roots have lower nutrient contents than foliage but higher contents than stem wood (Hellsten et al. 2013; Sicard et al. 2006). Roots contents of nutrients – especially N but also P, K, Ca Mg and Na – increase with reductions in their size. For roots below a diameter of 60–80 mm, the concentration of N can become quite high (0.05–0.35%) (Hellsten et al. 2013), compared to stemwood (0.015–0.055%) (Sicard et al. 2006). The content of N in large fine roots, 2–5 mm in diameter, is even higher (~0.7%) and the content in small fine roots < 2 mm is higher still (~1%) (Gordon and Jackson 2000). So, from both a fuel quality and a nutrient perspective, it would be good to avoid harvesting smaller roots. A limited amount of fine and small roots harvested should also lead to a limited ground disturbance. To date, no data are available about the root breakage diameter at stump harvest.

There could be a time dependent effect, with the amount of harvested fine roots being lower if the stumps are left in the soil for some time before harvest. Norway spruce (*Picea abies* [L.] Karst) roots decompose after clear cutting at a rate of 4.6% per year (Melin et al. 2009). The decomposition rate is faster for birch (*Betula* spp.) and slower for Scots pine (*Pinus sylvestris* L.) (Shorohova et al. 2012). There is a lag phase before decomposition of coarse wood (and roots) begins, because the colonisation of the wood by decomposing organisms takes time, and the length of the lag phase depends both on the species of wood involved and the habitat (Harmon et al. 1986). Fine roots decompose much faster than coarse roots and there seems to be little or no lag time before their decomposition starts, as Palviainen et al. (2004) found that 14% of spruce fine roots (<2 mm diameter) were lost within one year of clear-cutting and about 30% after 3 years.

This could lead to fewer harvested small roots if the stump harvest is postponed, perhaps for one year, and may also result in reduced ground disturbance.

The aims of the study presented here were: 1) to quantify the ground disturbance and root breakage diameter for different stump sizes at stump harvest; 2) to investigate whether the timing of uprooting after clear cutting affects the amount of the ground disturbance when lifting stumps, the depth of the stump holes and the root breakage diameter; and 3) to investigate the total ground disturbance at sites after stump harvesting as well as after subsequent soil scarification.

## 2 Material and methods

The trial took place in the municipality of Östersund, in the county of Jämtland, Sweden (63°53´N, 15°01´E). Two sites were studied: a "new" (altitude 480 m) and "old" (altitude 440 m) site, where stumps had been harvested in June and July 2012, respectively. Both sites had a fine sandy glacial till soil. The trees had been cut 18 months before the stump harvest at the old site and 6 months before harvest at the new site, there had been ground frost in the area from approximately mid November to late March during the winters of 2010–2011 and 2011–2012. On each site, 4 study plots measuring 50×20 m were marked out. Study plots were enlarged to 80×20 m if they had fewer than 50 stumps in order to ensure that an appropriate number of stumps could be harvested from each plot (Table 1). The logging residues (branches and tops) had been removed from the sites before the stump harvest. There were only Norway spruce stumps in the plots.

**Table 1.** Characteristics of the study plots. DSH is the diameter at stump height, with the standard deviation shown in parentheses.

| | Plots on Old site | | | | Plots on New site | | | |
|---|---|---|---|---|---|---|---|---|
| Properties | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Plot size (m) | 20×50 | 20×50 | 20×50 | 20×50 | 20×80 | 20×80 | 20×50 | 20×50 |
| DSH (mm) | 281 (88) | 258 (82) | 318 (113) | 258 (85) | 331 (109) | 324 (161) | 287 (104) | 289 (107) |
| No. of stumps per plot | 72 | 80 | 78 | 98 | 55 | 65 | 114 | 81 |
| No. stumps harvested per plot | 58 | 71 | 68 | 91 | 48 | 52 | 93 | 76 |
| Density (Stumps ha$^{-1}$) | 720 | 800 | 780 | 980 | 344 | 394 | 1140 | 810 |
| No. of measured stump holes | 10 | 10 | 10 | 10 | 20 | 13 | 13 | 15 |
| No. of stump heaps | 17 | 15 | 19 | 17 | 13 | 12 | 16 | 12 |

**Fig. 1.** The Ecorex30 stump harvesting head.

The stump harvesting head used was an Ecorex30 (weight 1500 kg), manufactured by UFO (Umeå försäljning AB); this is a fork-like head equipped with a knife for splitting the stumps (Fig. 1). The head was mounted on a 21-tonne Hyundai 210LC-9 excavator, 2009 model. The excavator started at the middle of a short edge of each plot assigned to stump-harvesting and moved to the opposite side of the plot, stopping at working points from which all stumps within reach were harvested. On average 4.2 stumps were harvested, and placed in a separate heap, at each working point. A stump was harvested as follows: the head was placed behind/underneath the stump and then pulled through the stump which usually split it and partly uprooted it; the stump pieces were then lifted out from the soil. Small stumps, however, were often lifted whole and then split with the knife, whilst large stumps had to be split in the ground with the knife before uprooting. Lifted stumps and stump pieces were split over the heap. In general the goal was to split the stumps into four pieces but the number of pieces produced varied according to stump size. The stump and stump pieces were shaken after being uprooted to remove some of the soil. This was mostly done over the stump hole and during the beginning of the movement towards the heap. The hole after the stumps was usually not smoothed out by the stump harvester, however a few holes after the largest stumps were smoothed out by the stump harvester. The stump harvest on the plots was conducted as a conventional stump harvesting operation. The only deviation was that stumps with a diameter at stump height (DSH) down to 72 mm were harvested; normally stumps < 200 mm DSH are left on site. Between 80% and 94% of the stumps on the plots were harvested during the work as the operator could not locate or reach all stumps (Table 1).

## 2.1 Measurements of ground disturbance and root breakage diameter after stump harvesting

In each of the study plots, a local Cartesian coordinate system was defined, with the corners of the plots as fixed points. The coordinates of each individual stump were determined using measuring tape from the fixed points and the diameter at stump height (DSH) was measured over bark by cross callipering to an accuracy of 1 mm before the harvest. After stump harvest, the coordinates were used to identify a specific stump hole with stump size and location. Overlapping holes from more than one stump were not measured and included in analysis (Table 1). The area of total ground disturbance and depth were measured for each of these stump holes. The area of disturbed ground was defined as the sum of the following: the stump hole from which vegetation and the stump had been removed and where the mineral soil was visible; soil on the ground next to the hole caused by lifting the stump; vegetation on top of *in situ* vegetation next to the hole caused by lifting the stump. No measurements of the separate types of disturbance were done. The area of ground disturbance caused by stump removals was measured by putting steel reinforcement meshes (with 15.5 × 15.4 cm, 0.024 $m^2$ grids, including half of the steel bars) over each affected area and counting all squares visually judged to contain more than 50% disturbed ground (Fig. 2). The depth of each hole was measured with a folding ruler with 1 cm accuracy from the deepest point of the hole to the estimated surface of the mineral soil prior to lifting. The depth of the hole's bottom in relation to the previous level of the soil surface was estimated by putting a reinforcement mesh over the hole and then measuring the distance between the mesh and the bottom.

The root breakage diameter was evaluated by measuring the breakage diameter for all roots of one stump piece randomly chosen from the surface of each stump heap, on the side of the heap facing the machine strip road (Table 1). The root breakage diameter was measured at the point where roots had broken off (Fig. 2). Not all roots broke, quite a large numbered slipped from the soil without breaking, and these were measured in the same way as the roots that had broken. The diameter was measured in 1 mm classes. Roots with a diameter larger than 20 mm were cross callipered, while smaller roots were callipered in one direction. Between 15 and 329 (average 70) roots were measured per stump piece. The DSH of the stump that the stump pieces belonged to was estimated visually, as shown in Fig. 2. Root breakage diameter and ground disturbance were measured in June and July, 2012.

## 2.2 Total ground disturbance at each site

On each site, two line transect inventories (Esseen et al. 2006) were used to estimate the percentage area of soil disturbed on site-scale. One transect inventory was examined directly after the stump harvesting, and another after soil scarification. The transect lines were orientated north–south, the distance between the lines was 50 m and the starting point of the first line on both occasions was a randomly chosen along the edge of the site. At the old site, soil preparation was carried out in an east–west orientation, while it was carried out in different directions on different parts of the new site. The soil preparation was conducted using a Bracke M46 mounder (Bracke Forest AB) on both the new and old sites, according to standard methods (c.f. Johansson et al. 2013). The ground surface was divided into 9 ground disturbance classes (Table 2). Using a measuring tape, the length

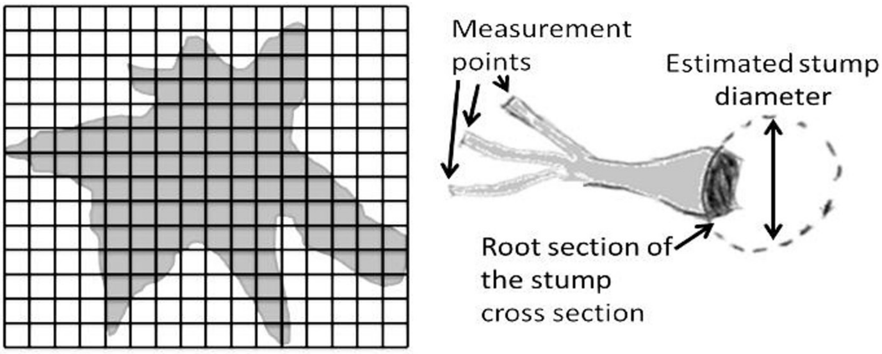

**Fig. 2.** Left: a mesh (15.4 × 15.5 cm grid size) over the disturbed ground after stump lifting. Right: the measurement points for recording root breakage diameter on one stump piece and the way in which the diameter at stump height was visually estimated from the root section.

**Table 2.** Codes and definitions for ground disturbance classes used in the line transect inventory.

| Code | Disturbance class | Definition |
|---|---|---|
| 1 | Unaffected ground | Ground unaffected by stump harvest, machine tracks or soil scarification |
| 2 | Vegetation with limited disturbance | Disturbed vegetation but no visible mineral soil |
| 3 | Vegetation on the ground | Vegetation that has been moved and put on top of other vegetation |
| 4 | Soil on the ground | Soil that has fallen onto the vegetation. |
| 5 | Tracks after machine | Tracks that penetrate down to the mineral soil |
| 6 | Stump hole | Area with removed vegetation in the location of a lifted stump |
| 7 | Unclear disturbance | Disturbance down to the mineral soil the origin of which cannot be determined |
| 8 | Soil scarification | Disturbance after soil scarification, both down to mineral soil and in the humus layer |
| 9 | Stump heap or slash pile | Slash or stumps left after forwarding or slash used to prevent rutting |

of transect section belonging to each class was recorded to an accuracy of 1 dm. The new site was measured after stump harvesting in June 2012 and after soil scarification in July 2012. The old site was measured after stump harvesting in July 2012, but the scarification was not conducted until September 2013 and the measurements after the soil scarification were collected in May 2014. On the new site, the line transects before and after the soil scarification were 706 and 615 m long, respectively. Corresponding lengths on the old site were 622 m and 827 m, respectively.

### 2.3 Statistics and comparison of the sites

The following variables were compared between the old and new sites: mean disturbed area per stump; mean disturbed area for stumps smaller and larger than 300 mm DSH; mean hole depth; arithmetic and basal area weighted (BAW) mean root breakage diameter per stump piece; and arithmetic and BAW mean root breakage diameter for different stump size intervals (100–199, 200–299, 300–399 and 400–499 mm DSH). In addition, the root breakage diameter was compared between different stump size classes. To investigate whether there were differences between the treatments, analysis of variance (ANOVA) was conducted using the following model: $y_i = \mu + \alpha_i + e_{i,}$ were $y_i$ is the observed value, $\mu$ the grand mean, $\alpha_i$ is the effect of the treatment, and $e_i$ is the random deviation. If the response variable in the ANOVA was correlated to the DSH, then the DSH was used as a covariate in an analysis of covariance (ANCOVA). Least square linear regression functions, ($y = a + b \times x$) were derived for the area of disturbed ground and for the arithmetic and BAW mean root breakage diameter with DSH as an independent variable. Data from the two sites were pooled before the regression analysis if no significant difference was found between the sites. The Shapiro-Wilk normality test was used to determine whether the residuals from the regression and ANOVA were normally distributed (Royston 1982). The Kruskal-Wallis rank sum test was used if the residuals from the ANOVA or ANCOVA were not normally distributed (Hollander and Wolfe 1973). For all statistical analysis, the level of significance was set at the 5% probability level. All statistical analysis were conducted in RStudio version 0.97.511.

## 3 Results

### 3.1 Ground disturbance and root breakage diameter at stump level

The ANOVA and ANCOVA did not reveal any difference between the old site and the new site for any of the analysed variables (Table 4). Only two ANCOVA analyses were conducted as there were

**Table 3.** Means (Value) and standard deviations (std) for variables measured on the sites and the mean (Mean) for the two sites together; Arithmetic mean root breakage diameter (Art), basal area weighted mean root breakage diameter (BAW), Area of disturbed ground (Area), and the depth of stump holes (Depth).

| | | Old | | New | | Mean | |
|---|---|---|---|---|---|---|---|
| Variable | Stump size class (mm) | Value | std | Value | std | Value | std |
| Art (mm) | All | 4.3 | 1.6 | 5.0 | 2.7 | 4.6 | 2.2 |
| | 100–199 | 3.9 | 1.0 | 3.7 | 1.3 | 3.8 | 1.1 |
| | 200–299 | 4.3 | 1.9 | 5.0 | 2.4 | 4.6 | 2.1 |
| | 300–399 | 4.3 | 1.4 | 4.0 | 1.3 | 4.2 | 1.3 |
| | 400–499 | 4.5 | 1.8 | 6.5 | 3.8 | 5.9 | 3.1 |
| BAW (mm) | All | 26.4 | 18.4 | 33.5 | 16.4 | 29.5 | 17.9 |
| | 100–199 | 13.4 | 2.4 | 14.6 | 8.1 | 14.1 | 6.0 |
| | 200–299 | 20.9 | 13.5 | 37.3 | 16.8 | 26.9 | 16.6 |
| | 300–399 | 32.5 | 21.8 | 32.9 | 11.2 | 32.7 | 18.7 |
| | 400–499 | 34.6 | 17.3 | 40.5 | 16.1 | 37.7 | 16.5 |
| Area ($m^2$) | All | 5.13 | 2.23 | 6.67 | 3.49 | 6.06 | 3.14 |
| | <300 | 4.28 | 2.17 | 4.81 | 1.77 | 4.55 | 1.97 |
| | >300 | 6.07 | 1.96 | 7.72 | 3.79 | 7.18 | 3.38 |
| Depth (cm) | All | 38.9 | 11.0 | 40.4 | 11.6 | 39.8 | 11.4 |

no strong correlations between the stump size and the response variable per plot (Table 4). The residuals were normally distributed in all but one case (Table 4), where the Kruskal-Wallis rank sum test was used and revealed no difference. The area of the disturbed ground per stump varied from 1.29 to 21.06 $m^2$ and was, on average, 6.06 $m^2$ (std 3.14). Stumps smaller than 300 mm DSH had a mean of 4.55 $m^2$ (std 1.97) and stumps above 300 mm had a mean of 7.18 $m^2$ (std 3.38) (Table 3). The arithmetic and BAW mean root breakage diameter per stump piece varied from 1.9 to 14.9 and from 4.7 to 121.3 mm, respectively, with an average of 4.6 (std 2.2) and 29.5 mm (std 17.9), respectively. The mean depth of the stump holes was 397 mm (std 11.4) ranging from 200 to 740 mm.

**Table 4.** Correlation analysis between the response variables and the diameter at stump height (DSH). Correlation coefficient = R. ANOVA and ANCOVA tests p-values, adjusted $R^2$ ($R^2$ adj) and covariate (Cov) values. Shapiro-Wilk test for normality of the residuals = S-W, Kruskal-Wallis rank sum test for situations where the residuals were not normally distributed = K-W. Tests were conducted for all stumps and for the different stump size classes: Mean root breakage diameter; arithmetic = Art and basal area weighted = BAW, area of disturbed ground = Area, depth of the stump holes = Depth.

| | | Correlation analysis | | ANOVA or ANCOVA | | | Normality test | |
|---|---|---|---|---|---|---|---|---|
| Variable | Stump size class (mm) | R | p-value | p-value | $R^2$ adj | Cov | S-W | K-W |
| Art (mm) | All | 0.20 | 0.630 | 0.084 | 31.9 | - | 0.116 | - |
| | 100–199 | –0.61 | 0.197 | 0.936 | –24.8 | - | 0.832 | - |
| | 200–299 | 0.23 | 0.621 | 0.291 | 6.1 | - | 0.033 | 0.289 |
| | 300–399 | –0.06 | 0.892 | 0.783 | –15.1 | - | 0.611 | - |
| | 400–499 | –0.20 | 0.633 | 0.752 | –14.6 | - | 0.134 | - |
| BAW (mm) | All | 0.67 | 0.067 | 0.157 | 18.7 | - | 0.228 | - |
| | 100–199 | –0.25 | 0.632 | 0.727 | –20.8 | - | 0.644 | - |
| | 200–299 | –0.12 | 0.792 | 0.068 | 42.3 | - | 0.990 | - |
| | 300–399 | –0.75 | 0.032 | 0.125 | 39.2 | 0.052 | 0.131 | - |
| | 400–499 | –0.51 | 0.192 | 0.971 | –16.6 | - | 0.318 | - |
| Area ($m^2$) | All | 0.73 | 0.042 | 0.670 | 36.4 | 0.136 | 0.096 | - |
| | <300 | 0.05 | 0.901 | 0.459 | 0.00 | - | 0.711 | - |
| | >300 | 0.42 | 0.303 | 0.309 | 3.3 | - | 0.557 | - |
| Depth (cm) | All | 0.50 | 0.211 | 0.639 | 0.00 | - | 0.944 | - |

- indicates that no values were calculated

**Table 5.** Least square regression functions for the ground disturbance area (Area) and arithmetic (Art) and basal area weighed (BAW) mean root breakage diameter (RBD) depending on diameter at stump height (DSH). The estimated variable (Estimate), the standard deviation of the estimated variable (Std estimate), the p-value for the estimated variable (p-value), the residual standard error of the function (RMSE) and the adjusted $R^2$ ($R^2$ adj) for the regression function are shown.

| Predicted variable | Response | | Estimate | Std estimate | p-value | RMSE | $R^2$ adj (%) |
|---|---|---|---|---|---|---|---|
| Area ($m^2$) | LN(Area) | Constant | 0.9720 | 0.1332 | <0.001 | 0.419 | 23.6 |
| | | DSH (mm) | 0.002203 | 0.0003902 | <0.001 | | |
| $RBD_{ART}$ (mm) | LN($RBD_{ART}$) | Constant | 1.186 | 0.1221 | <0.001 | 0.398 | 2.9 |
| | | DSH (mm) | 0.0008082 | 0.0003733 | 0.0324 | | |
| $RBD_{BAW}$ (mm) | LN($RBD_{ART}$) | Constant | 2.821 | 0.1080 | <0.001 | 0.6137 | 11.2 |
| | | DSH^2 (mm) | 0.000003493 | 0.0000008660 | <0.001 | | |

The transformed function for the area of ground disturbance ($m^2$): $1.091 \times e^{(0.972+0.002203 \times DSH)}$
The transformed function for the Art mean root breakage diameter (mm): $1.089 \times e^{(1.186+0.0008082 \times DSH)}$
The transformed function for the BAW mean root breakage diameter (mm): $1.177 \times e^{(2.821+0.000003493 \times DSH^2)}$

The data sets from the two sites were pooled before the regression analysis because no difference between them was found (Table 4). It was possible to create regression functions for the area of disturbed ground, and the arithmetic and BAW mean root breakage diameter (Table 5; Fig. 3 and 4). The Shapiro-Wilk normality test showed that the residuals from the regression analysis of the disturbed ground area, and the arithmetic and BAW mean root breakage diameter were normally distributed (Table 5). It was necessary to transform the response variables in the regression function with natural logarithms to achieve normally distributed residuals. When the values from the functions are retransformed, the following ratio corrections for logarithmic bias (Snowdon 1991) are needed: ground disturbed area = 1.091, arithmetic mean root breakage diameter = 1.089 and BAW mean root breakage diameter = 1.177, according to ration correction. Virtually non of the variation ($R^2$-adj 2.9%) in the arithmetic mean root breakage diameter was explained by DSH (Table 5). For the BAW mean root breakage diameter, the DSH explained the variation somewhat more ($R^2$-adj 11.2%).

The stump size classes for the arithmetic mean root breakage diameter in the plots differed significantly according to the ANOVA (p-value 0.027, $R^2$-adj 22.0%). The mean root breakage diameter was found to be smaller in the smallest stump size class (100–199 mm DSH) than in the largest class (400–499 mm DSH) (Tables 3 and 7). A Shapiro-Wilk test showed that the residuals were normally distributed (p-value 0.827). The BAW mean root breakage diameter in the plots differed significantly between stumps of different size classes according to the ANOVA (p-value < 0.001, $R^2$-adj 48.5%). The BAW mean root breakage diameter was found to be smaller in the smallest stump size class (100–199 mm DSH) compared to the two largest classes (300–399 and 400–499 mm DSH) (Tables 3 and 7). A Shapiro-Wilk test showed that the residuals were normally distributed (p-value 0.136).

**Table 6.** Proportion (%) of the ground disturbance classes, 1 unaffected ground, 2 vegetation with limited disturbance, 3 vegetation on the ground, 4 soil on the ground, 5 tracks after machine, 6 stump hole, 7 unclear disturbance down to mineral soil, 8 soil scarification, 9 stump heap or slash pile.

| | Ground disturbance class | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Treatment combination | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Total |
| Old site before scarification | 37.3 | 9.4 | 1.9 | 0.9 | 31.9 | 14.8 | 2.8 | NS | 1.1 | 100.0 |
| Old site after scarification | 33.8 | 7.2 | 2.2 | 1.5 | 10.2 | 13.0 | 12.0 | 19.7 | 0.4 | 100.0 |
| New site before scarification | 37.5 | 9.5 | 2.1 | 5.2 | 24.0 | 18.6 | 3.1 | NS | 0.0 | 100.0 |
| New site after scarification | 30.5 | 8.8 | 0.9 | 1.6 | 23.8 | 6.2 | 6.1 | 22.2 | 0.0 | 100.0 |

NS indicates that no value exists

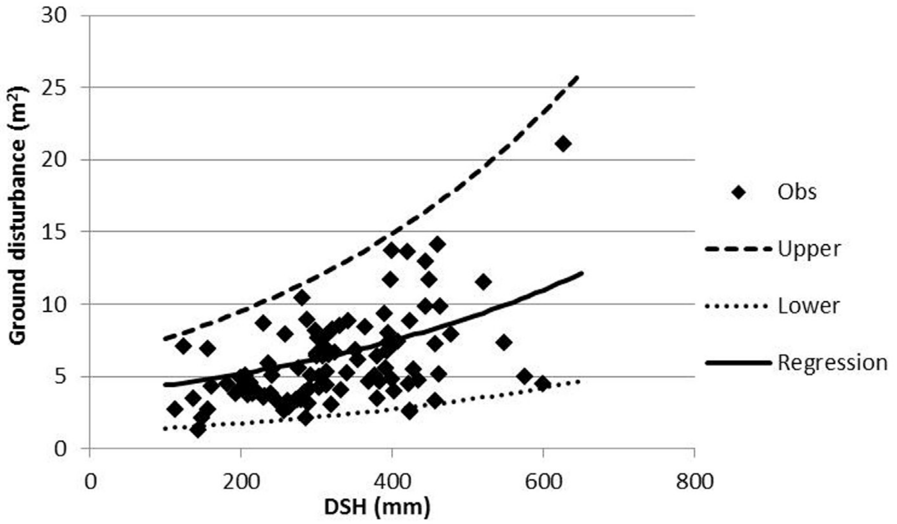

**Fig. 3.** Measured area of ground disturbance (Obs) plotted against diameter at stump height (DSH), the regression function (Regression) for predicting ground disturbance (Table 5) and the upper ($e^{(1.805+0.002238\times DSH)}$) and lower ($e^{(0.1392+0.002167\times DSH)}$) boundaries for the 95% interval when the regression function is used to predict the ground disturbance.

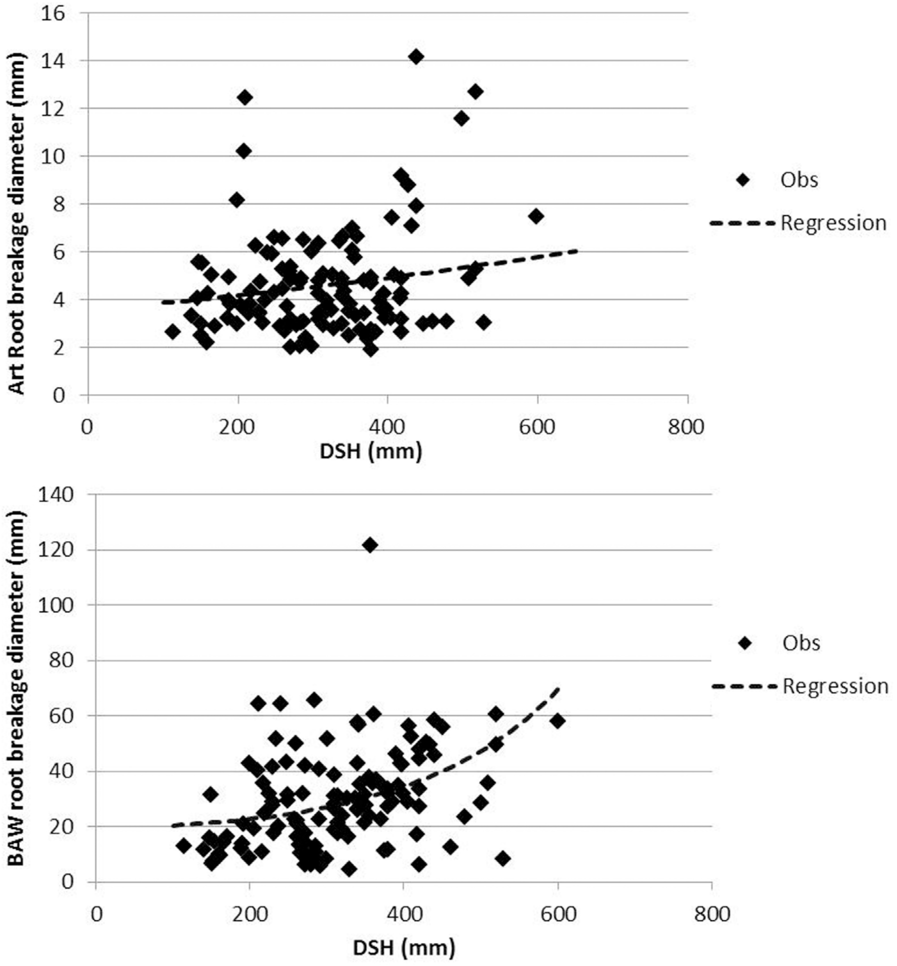

**Fig. 4.** Above: measured arithmetic (Art) mean root breakage diameter (Obs). Below: the basal area weighted (BAW) mean root breakage diameter (Obs). Both plotted against diameter at stump height (DSH) and with the transformed regression function (Regression) (Table 5).

**Table 7.** P-value for ANOVA comparing the arithmetic and basal area weighted (BAW) mean root breakage diameter between different stump size (DSH) classes.

| | Arithmetic | | | BAW | | |
|---|---|---|---|---|---|---|
| | DSH class (mm) | | | | | |
| DSH class (mm) | 100–199 | 200–299 | 300–399 | 100–199 | 200–299 | 300–399 |
| 200–299 | 0.577 | - | - | 0.067 | - | - |
| 300–399 | 0.886 | 0.922 | - | 0.006 | 0.732 | - |
| 400–499 | 0.025 | 0.295 | 0.081 | <0.000 | 0.050 | 0.309 |

### 3.2 Total ground disturbance at site level

The measured area with little or no ground disturbance (classes 1 and 2) after stump harvesting but before soil scarification was 46.7% on the old site and 47.0% on the new site (Table 6). The measured area with little or no ground disturbance after stump harvesting and soil scarification was 41.0% on the old site and 39.3% on the new site. On the new site, the measured area of the stump holes decreased after soil scarification by about 10% and the measured undisturbed area decreased by about 10% while the measured area that was scarified amounted to 20%. On the old site, the measured area of machine tracks decreased by about 20%, the measured area of "unclear disturbance" increased by about 10% and the measured area of soil scarification was about 20%. The decrease in the disturbed area of some disturbance classes was due to the face that that area had changed in to other disturbance classes. It is also worth noting that the measured area with machine tracks (24–32%) was larger than the measured area of stump holes (14–19%) before soil scarification, even if all "measured unclear disturbance" (2–4%) was assumed to be from lifted stumps, the measured area of machine tracks was still greater.

## 4 Discussion

### 4.1 Ground disturbance

We did not detect any significant difference between the sites with respect to ground disturbance. However, we found that the area of disturbance increases with increasing stump size and a regression function was constructed. The function did not include the ground disturbance associated with the rutting that is caused by the machinery used for stump harvest and round-wood harvest. In fact, the total ground disturbance caused by stump lifting depends on the type of stump harvesting head and the rutting which varies with the type of base machine. We do not believe that only considering non-overlapping ground disturbances caused by stump removal affected the results. Stumps that left overlapping holes were generally closer to each other than those that left non-overlapping holes. Thus, the stumps we measured might have been subject to less root competition from other trees and hence a larger root system. This implies that if the selection method had any impact on the results it caused a slight overestimation of the disturbed area.

The total area of disturbed ground after stump harvesting was 53–56% (Table 6) if ground disturbance classes 1 and 2 are considered to represent undisturbed ground. These are far higher proportions than those reportedly caused by mounding (14–21%; Roturier and Bergsten 2006), which is the most common method of preparing soil for spruce stands (Rantala et al. 2008; Hallongren et al. 2014). However, similar proportions are reportedly disturbed by disc trenching

(40–60%; Roturier et al. 2011). The percentages of ground disturbed in the present study after stump harvesting and mounding were 59–61%.

This indicates that the visible area of total ground disturbance after stump harvest with mounding could be comparable to the visible ground disturbance after disc trenching, although the type of ground disturbance may differ between stump harvesting, mounding and disc trenching. So, from a soil disturbance perspective, it is not possible to claim that stump harvest is suitable for all sites were disc trenching is used. This needs to be investigated further. Previous studies indicate a much higher ground disturbance after stump harvest and soil scarification (47–99%) (Hope 2007), and similar or higher levels after only stump harvesting 43–85% (Page-Dumroese et al. 1998; Hope 2007). There were also changes in the type of ground disturbance before and after soil scarification. Our results indicate that about half of the ground disturbance due to the soil scarification was allocated to previously disturbed areas (Table 6). It seems that the soil scarifier operator tried to drive in old machine tracks on the old site, and in stump holes on the new site as far as possible, this was quite evident at least at the old site. This working method is probably wise as it minimise the area of disturbed soil. It appears that at least half of the ground disturbance before soil scarification on the site was caused by machine tracks. This fact indicates that it is as important to reduce rut formation as it is to reduce ground disturbance when harvesting stumps.

## 4.2 Root breakage diameter

It was surprising to detect no significant differences between the sites in terms of root breakage diameter (Table 4). We expected to find a difference as Palviainen et al. (2004) observed little or no lag in the decay of Norway spruce fine roots in a previous study in Finland. Although fine roots decompose faster than coarse roots (Melin et al. 2009; Palviainen et al. 2004), postponing the stump harvest for one year seems too short a delay to affect the root breakage diameter. The higher altitude of the sites in the present study than those considered by Palviainen et al. (2004) might have affected the results, as this could potentially prolong the lag phase before decomposition starts, and delay the decomposition of fine roots. However there was a tendency (p-value 0.084) for the root breakage diameter on the old site (4.3 mm) to be smaller than on the new site (5.0 mm) (Table 3). This finding is contradictory to the suggestion that a longer delay would produce a larger root breakage diameter, at least initially. One explanation could be that when the roots start to decompose they slip more easily out from the soil instead of breaking (decreased friction between root and soil), leading to an initial decrease in root breakage diameter. It is likely that a study designed with more plots or a longer delay before uprooting would show a difference.

The arithmetic mean root breakage diameter was 5 mm and the BAW mean root breakage diameter was 30 mm (Table 3). It is obvious that in the prevailing conditions and with the harvesting head used in this study a large quantity of small roots was harvested. This is negative both from a nutrient and a fuel quality perspective, as the smaller roots contain more nutrients than the coarse roots (Gordon and Jackson 2000; Hellsten et al. 2013). The harvest of many small roots probably also increases the ground disturbance compared to only harvesting the coarse roots. The two regression functions for root breakage diameter (Table 5) only explain a small part of the variation in the data, which makes their usefulness in practice very limited. The study showed a difference between the smallest and largest stump size class for the arithmetic mean root breakage diameter and BAW mean root breakage diameter (Table 7). This indicates that there is some increase in root breakage diameter with increasing stump size.

## 4.3 Practical applications

The root breakage diameter and ground disturbance did not change with a delay in harvest of one year. It is probable that a much longer delay would be needed to alter these aspects, which means that regeneration would also be postponed, which is not desirable and unlikely to be considered acceptable conventionally. In addition, stumps decay over time, so there will be less stump wood left to harvest if the harvest is postponed for several years (Melin et al. 2009; Shorohova et al. 2012). A long delay in stump harvest would also mean that the stumps have been colonised by insects and fungi before they are harvested, thus acting as traps for some species. One summer old stumps have, on average, been colonised by 3.1 different insect species (Jonsell and Hansson 2011). It therefore seems that the only way to improve these aspects is to change/develop the technology used for stump harvesting. For a long time there have been techniques, currently used in other parts of Europe (Czereyski et al. 1965; Spinelli et al. 2005), for harvesting only the central part of the stump. These techniques have so far not been profitable to use in Nordic forestry (von Hofsten 2010; von Hofsten et al. 2012), but could be developed further. Another alternative is to develop technology for harvesting only the central part of the stump together with the roundwood. This type of harvest was tried in the 1970s but improvements in technology could make it a viable approach today (Koch and Coughran 1975; Nordfjell et al. 2011). Such options would lead to far less ground disturbance and probably to very few fine roots being harvested. Berg et al. (2014) have shown that such integrated stump harvesting system could be economically feasible when harvesting tree sizes above 420 mm in breast height diameter, in comparison to conventional up-rooting systems. It may also be possible to re-design/develop the stump harvesting heads currently used in Nordic forestry. One example of this is the prototype Järvinen head (Kärhä 2012). This head has a ring, which is placed around the stump and the stump is then pulled upwards; the ring breaks the roots around the stump when it is lifted. The ring can easily cut roots with diameters of 5–10 cm. Using a head like this would reduce the removal of fine roots and nutrients (Hellsten et al. 2013), but should also reduce the ground disturbance. The Järvinen head has the following drawbacks: it has difficulties harvesting large stumps; it cannot split stumps after uprooting while some are split during the uprooting; and it cannot clean the stumps at all (Kärhä 2012). These are features that would have to be improved.

A reduction in the amount of harvested small roots would lead to a lower harvested volume. If only roots above 50 mm in diameter were harvested, the harvested stump volume would decrease by 7–27% for pine and 23–28% for spruce compared to harvesting all roots down to a diameter of 5 mm (Marklund 1988; Petersson and Ståhl 2006). However it would reduce the environmental impact of stump harvesting and improve the fuel quality and should therefore be desirable. All harvested fine roots will not end up as fuel. The handling of stump material is rough (cf. Anerud 2010; Asikainen 2010), and the amount of small roots is likely to decrease along the supply chain, during storage, transportation and comminution operations.

## 4.4 Generalisation of our results

The stump harvester operator who conducted the uprooting work in the trials was an experienced professional and worked normally during the trials. Thus, it is unlikely that the operator uprooted the stumps more “carefully” than if he was not being studied. It therefore seems likely that the ground disturbance and root breakage diameter results can be somewhat generalised to medium to coarse glacial tills. The roots would probably break at similar sizes on similar soil types, but may break at much smaller sizes on sedimentary soils and peaty soils as no stones or larger particles exist there to break the roots. The breakage diameter would probably also be similar for heads that harvest the whole root system. Predicting the level of ground disturbance is probably more complicated as it could also be affected by the working technique. In this study the head was pulled through the stump which usually split it and partly uprooted it. There could also be an operator effect, i.e. there may be differences in the ground disturbance when different operators use the same working methods. It is likely that the ground disturbance would be reduced if the stumps were split in the soil and then uprooted. The ground disturbance is also likely to be greater on sedimentary and peaty soils. In addition, the form of the root system is species-dependent (Hakkila 1972; Kalliokoski et al. 2008). So, for example, removing Scots pine stumps will probably cause deeper disturbance, but over smaller areas, than removing Norway spruce stumps, as Scots pine root systems spread less widely and may include deep tap roots. There is a clear need to study the ground disturbance and root breakage diameter associated with other stump harvesting heads, partly because knowledge of the ground disturbance caused by different harvesting heads could be valuable for creating guidelines on the optimal heads to use in different situations.

The regression function for estimating the area of disturbed ground (Table 5) could be used to estimate the disturbance caused by the stump harvest on similar sites harvested with a Ecorex30 head or similar. If the regression function is used to estimate the ground disturbance on similar sites, then the 95% confidence interval will be larger than when using the function with the original data (Fig. 3). It is also important to point out that uprooting stumps often produces overlapping holes, so if the disturbed area is extrapolated at the site level it would give an overestimation. More accurate extrapolations could be obtained if the positions of the stumps were known, as this would allow consideration of the overlaps, which may account for up to 30% of the disturbed area, when the regression function is applied to the study plots in this study (Table 1).

## 4.5 Improvements to the study design

The study could have been improved by including other uprooting methods with the Ecorex30 harvesting head, and more than one operator. Another aspect that could have been improved is that the soil scarification could have been conducted nearer to the time of stump harvesting on the old site. This delay made it difficult to compare the line transect data between the sites, but is useful as different landowners have different delays between stump harvest and soil scarification. This delay probably caused the 10% increase in "unclear disturbance" which in turn seems to explain the 10% decrease in the area of stump holes at the old site.

The estimation of the DSH for stump pieces introduced some uncertainty. It is hard to improve these estimates, as long as the stump harvesting is conducted as a conventional operation. One way would be to colour-mark stumps in different size classes before uprooting and then identify them when piled in heaps. Another way would be only to harvest one stump at a time and then measure the root breakage diameter of that stump to obtain an accurate measurement of the DSH. Harvesting one stump at the time could, however, affect how the stumps are harvested and thus affect the root breakage diameter. Experienced operators would probably not consciously change their behavior but could do so unconsciously. On the other hand, such experimental harvesting should give better regression functions and also have a greater ability to detect differences between stump classes.

To obtain comprehensive knowledge of areas of disturbed ground, measures of overlapping holes are needed, and interaction effects between the stumps must be considered in order to establish predictive stump-level models for disturbed areas with stump size as an independent variable. For example, both sizes of uprooted stumps and distances between them will be influential. However, collecting sufficient data to establish such models would be extremely time consuming. An alternative option could be to count trees and determine their size distributions before harvests, and subsequently count numbers and sizes of remaining stumps and holes (single and overlapping). These data could be compiled relatively easily from vast numbers of sites and used to create predictive models.

## 5 Conclusions

The ground disturbance was, on average, 6.06 $m^2$ per stump and increased exponentially with stump size. A regression function for the area of disturbed ground as a function of stump size was constructed and could, if stump positions are known, be used to estimate the ground disturbance in similar areas when harvesting is conducted using a Ecorex30 or similar stump harrowing heads. The arithmetic mean root breakage diameter was 5 mm and the basal area weighted mean root breakage diameter was 30 mm; in both cases there was only a slight increase with stump size. A small root breakage diameter reduces the fuel quality and removes nutrients from the site as small roots have higher nutrient contents than coarse roots; the aim, therefore, should be to increase the breakage diameter. There was no effect of postponing the harvest for one year on either the ground disturbance or root breakage diameter. A long delay would probably be favourable in terms of these variables, but also allow insects to colonise the stumps (acting as ecological traps) and postpone regeneration, so long delays are unlikely to be conventionally applied. The total area of ground disturbance at the site was 53–56% after stump harvesting and 59–61% after stump harvesting and soil scarification. After stump harvesting, about half of the ground disturbance at the site was due to lifting stumps and half due to rut formation. This fact indicates that it is as important to reduce rutting as it is to reduce the ground disturbance caused by the harvest per se. In conclusion, the technology for stump harvesting must probably be developed to reduce ground disturbance and increase the root breakage diameter.

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