Comparison of ground disturbance of frozen peatland during stump harvesting using a stump drill and rake

Simon Berg a,1, Juha Nurmi b and Robert Prinz c

aDepartment of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences, Umeå, Sweden; bNatural Resources Institute Finland, Kokkola, Finland; cNatural Resources Institute Finland, Joensuu, Finland

ABSTRACT

Tree stumps could be a source of renewable energy, contributing to a reduced dependence on fossil fuels. In Finland, stumps are currently harvested when the ground is not frozen to avoid co-removal of large amounts of soil and stones. Hence, the machinery used for stump extraction is not operated year-round. On peatlands, stumps could potentially be harvested when the ground is frozen. However, peatlands are highly sensitive to ground disturbance. There is, therefore, a need to identify equipment that causes low ground disturbance. In this study, peatland ground disturbance at stump level caused by stump harvesting using either a stump drill or a conventional stump rake was evaluated and compared in winter conditions. Results show that the stump drill caused up to 90% less ground disturbance per harvested stump than the conventional stump rake, but harvested 32–53% of the stump wood. Additionally, the size and shape of the disturbed areas changed between the harvesting year and following year, indicating that frost heaving plays a role in filling holes caused by stump extraction. The stump drill also consumed similar time to the conventional stump rake when harvesting Scots pine stumps on mineral soils, but far more when harvesting Norway spruce stumps.

Introduction

A long-term political goal in Europe is to replace fossil fuels with renewable energy sources (European Commission 2011). One such source of renewable energy is forest biomass, as the carbon that is emitted when it is burnt to generate energy will be captured again when new trees grow. Tree stumps provide one source of forest biomass. Currently, tree stumps are mainly harvested in Finland, and focused on Norway spruce (Picea abies) dominated clear cuttings on mineral soil (Laitila et al. 2019). Stump harvesting is done during the ground frost and snow-free parts of the year, after logging residues (branches and tops) have been forwarded from the site (Laitila et al. 2008, 2019; Anerud 2010). Harvesting is typically conducted using 20–25 t excavators (Kärhäs 2012) fitted with a special stump rake (Laitila et al. 2008). These excavators generally drive on the strip roads and harvest all stumps in the reach of the machine. Meanwhile, stumps directly on the strip road are left in place. The stumps and roots are uprooted and split and then shaken to remove soil before being piled into heaps next to the strip road (Laitila et al. 2008). The stumps are stored on-site, where they are cleaned by rain and dried by the sun (Laitila et al. 2008). Forwarders are then used to transport the stumps to the roadside where they are stored in windrows for several months before being transported to end-users as stumps or as chips after crushing at the landing (Asikainen 2010).

Stump harvesting on mineral soils has both advantages and disadvantages (Walmsley and Godbold 2010; Persson 2016). The main advantages are that: harvested stumps may be used as fuelwood, root rot is reduced in the next forest generation, soil scarification is improved (thereby improving seedling growth and survival rates); and an additional income for the forest owner is secured. The disadvantages of the practice are that it: causes substantial ground disturbance that can cause leaching of nutrients and heavy metals from the site, increases erosion risks (Eklöf et al. 2012; Kiikkilä et al. 2014), increases nutrient removal from the site (mainly through removal of small roots), causes soil compaction, and promotes establishment of competing vegetation (Walmsley and Godbold 2010; Hellsten et al. 2013) and limits the amount of dead wood, potentially reducing the presence of important habitats for fungi, mosses, bryophytes and insects. Additionally, concerns (Walmsley and Godbold 2010) and indications (Grelle et al. 2012) were voiced that stump-harvesting ground disturbance would increase CO₂ emissions from the forest soil. However, later studies have not found such an effect, concluding that the emissions are comparable to those occurring during harrowing (Persson 2016).

Currently, stump harvesting has limited appeal for contractors as they cannot operate year-round, which compromises their ability to maintain cash flow and profitability. There is, therefore, a need to investigate the possibility of prolonging the stump-harvesting season to include the period of the
year with ground frost and snow. Winter harvest would probably be very difficult on mineral soils as the soil would be frozen onto the stumps and difficult to remove, resulting in fuelwood of low quality with high ash content (Anerud and Jirjis 2011). However, stumps could be harvested on deep peatlands in winter conditions where the stump and roots don’t reach down to the mineral soil. This could provide high-quality fuel, as any peat residue that remains on the stumps has a high fuel value (Leckner 2007). There are many ditched peatlands planted with pine in Finland (Turuunen 2008), which could be of interest for this type of winter harvest. Ditched peatlands have a low bearing capacity, so trees at a majority of site can only be harvested when the ground is frozen to avoid severe soil rutting (Väätäinen et al. 2004). As stump harvesting and forwarding causes more severe disturbance than stemwood harvesting and forwarding the stump harvesting on ditched peatlands is only viable during the winter time. This would provide an extended operating period for contractors in winter time when extraction on mineral soils is not possible.

The main contributors to the bearing capacity of peatland are roots and vegetation that reinforce the ground (Uusitalo and Ala-Iломаки 2013). Soil disturbance on peatland are known to increase N₂O emissions, but have no effect on CO₂ emissions (Pearson et al. 2012). What the effects of stump harvesting on peatland are on the emission are unknown, but it is likely that the effects increase with increased ground disturbance. Hence, the viability of peatland stump harvesting is dependent on the minimization of adverse effects whilst the operations are conducted. The use of conventional stump rake harvesting heads is questionable on peatlands, even in winter conditions. It is known that they cause significant disturbance on mineral soils (Berg et al. 2015) that can persist for up to a decade (Kaarakka et al. 2018). It is also recognized that such disturbance can potentially be reduced if new technologies and approaches are adopted. For example, von Hofsten (2014) investigated ground disturbance on mineral soils after using a newly developed prototype head that was designed to break the roots at a certain distance from the stump centre, significantly reducing ground disturbance. However, the prototype needed modifications in order to achieve efficient stump harvesting. More recently Laitila et al. (2019) investigated a modified crusher grapple for harvesting the central part of Norway spruce stumps on mineral soil. Although, the ground disturbance of this head has not yet been assessed, the disturbance might be similar to those determined by von Hofsten (2014). Further development of harvesting techniques that leave some (or all) of the side roots in the soil is warranted, as this approach is likely to substantially reduce soil disturbance.

An alternative to conventional stump rake harvesting heads are stump drills that only harvest the central part of the stump and root system. Stump drills are used in southern Europe for harvesting in poplar (Populus sp.) plantations, e.g. when clones are rotated, and in maritime pine (Pinus pinaster) plantations when stands are re-established (Spinelli et al. 2005; Emeyriat et al. 2014). These heads, introduced more than 50 years ago (Czereyński et al. 1965) are large cylindrical saws that cut the side roots around the stump centre. Stump drills could potentially be used for harvesting stumps on ditched peatland in winter conditions as their operation is likely to reduce soil disturbance. Harvesting rates of 92–202 stumps per hour (h) of productive machine time, excluding delay time (PM0), equivalent to 4.0–13.7 t fresh weight/PM0 in poplar plantations have been reported (Spinelli et al. 2005). Productivity reported in maritime pine plantations is lower, where 33–86 stumps can be harvested per PM0 (Emeyriat et al. 2014). Stump drills have also been tested in Nordic forestry systems on mineral soils (von Hofsten and Nordén 2007), where productivity was similar to that achieved with maritime pine, reaching 36–84 stumps per PM0 (2.2–5.3 m³ solid on bark/PM0). This rate was equivalent to that achieved using a conventional stump rake in Nordic conditions, but their use is unprofitable because of a reduction in harvested volumes (von Hofsten 2010). Norway spruce stumps have 32% and Scots pine (Pinus sylvestris) 53% of the total stump-root volume in the stump centre respectively (Nilsson and Danielsson 1976). Stump drills could become profitable in Nordic forestry, but this would require raising their productivity to levels achieved in poplar plantations in southern Europe.

It is possible that the stump drill could be utilized on ditched peatland, and they might be particularly suitable as there are no stones in the soil which could hinder the extraction process. It is also possible that the stump drill could be more productive harvesting pine stumps under Nordic conditions as they have a larger part of the stump mass in the tap root and less coarse side roots (Hakkila 1972). Harvesting on peatland is likely to be feasible only during the winter when soil disturbance would be minimal, and would be advantageous as extraction ceases on mineral soils at this time, allowing contractors to continue working. However, before this practice can be adopted commercially it is necessary to: assess peatland sensitivity to ground disturbance (as it differs from that on mineral soils), investigate changes in the disturbance over time, compare the impacts of stump drill harvesting with the conventional stump rake, and evaluate the economic viability of this harvesting technique.

Therefore, the aims of the study were to: quantify and compare the ground disturbance on ditched peatland after stump harvesting caused by the operation of a stump drill and a conventional stump rake; investigate changes in ground disturbance during a winter period after frost heaving; and investigate the productivity of the stump drill.

Materials and methods

Site and equipment

The study site was located on a ditched peatland in Lappajärvi municipality, Southern Ostrobothnia, Finland (63°29’N 23°53’E). Tree species recorded at the site were Scots pine, Norway spruce and birch (Betula pendula and Betula pubescens, for which data were pooled) in proportions of 85:6:9. Spatial locations of 448 stumps were recorded on 4th and 5th of April 2013, using a Trimble GPS data collector (Trimble Inc., Sunnyvale, USA) on five 20 × 75 m (1500 m²) plots (Figure 1), and their diameter at stump height (DSH)
was determined by cross-calipering. The average DSH was 241 mm (SD 57 mm). The plots were centred along strip roads on the logging site.

An Ellettari stump drill (di Ellettari Luca & Co., Collecchio, Italy) was used to harvest stumps on Plot 3 and parts of Plot 2 on 10 April 2013 (Figure 2). The stump drill is based on the principle of a cylindrical saw that cuts the lateral roots around the stump and harvest only the stump core. The stump drill harvest was limited due to a technical malfunction of the drill (otherwise the whole of Plot 2 would have been harvested). The stump drill had a 40 cm inner diameter and was designed for machinery used in southern European conditions. For Finnish conditions, the drill was mounted on a New Holland Kobelco E 200 SR excavator which required adjustment of the drill’s hydraulic system. The operator had extensive experience of using a conventional stump rake, but limited experience with the stump drill (having only worked with the equipment for two days prior to the experiment). A conventional Terosa KK-900 stump rake (Terosa Oy, Ristijärvi, Finland) was used to harvest stumps on Plots 1, 4 and 5 on 24 April 2013. The principle of the harvesting technique with the rake was that the stump was first split in the ground. Then the pieces were lifted from the ground. Majority of the stump and root system being harvested. The rake was mounted on a Hyundai 180-9LC excavator. The operator of the stump rake had several years’ experience as a stump-harvesting operator. Ground frost was present on both harvesting occasions, whilst most of the snow had thawed.

Both machines drove on the strip road along the centre of the plot. The stump drill harvested stumps both on and outside the strip road. While the stump rake mainly harvested stumps outside the strip road. The machines operated with a total working width of 12–16 m, i.e. around 6–8 m to either side of the centreline of the plot. The stumps were at all plots piled in heaps next to the strip road by the extractor.

**Ground disturbance**

Ground disturbance (defined to include the stump hole area, soil scattered on the ground and on vegetation, and disturbed
vegetation) caused by the stump drill and the stump rake during the harvest of individual Scots pine stumps was measured. Ground disturbance was measured on 7–8 October 2013 (Year 0) and again, after the stumps had been forwarded, on 21–22 May 2014 (Year 1). The ground was free from ground frost on both measurement occasions. Overlapping ground disturbance caused by harvesting adjacent stumps was not measured. There were no disturbance overlaps when the stump drill was used, but many with the stump rake. Disturbance from harvesting old stumps from thinning, partially harvested stumps, and the forwarder (i.e. when the forwarder had driven within an area) were not included in the dataset. Due to these constraints, only a small percentage of the disturbed areas surrounding stumps harvested by the stump rake were measured. In total, the disturbed areas created by harvesting 36 and 32 stumps using the stump drill and the stump rake were analysed respectively. The mean DSH of the analysed stumps were 252 (SD 44) and 255 mm (SD 56) for the stump rake and the stump drill, respectively. Ground disturbance caused by the stump rake when harvesting a single stump was estimated by placing a net with a 0.024 m² mesh size over the disturbed area and counting all the squares in which more than 50% of the ground was disturbed (Figure 3). Ground disturbance caused by the stump drill when harvesting a single stump had distinct banks (i.e. a circular area that included hole) and both the hole and total disturbed area were measured using a ruler to the nearest cm. The depths of the holes (to the estimated edge of the soil surface prior to harvest) created by the stump drill and the stump rake were also measured to the nearest cm.

**Time study**

A time study was conducted for the stump drill. A total of 52 Scots pine stumps were harvested on Plots 2 and 3, and 47 stumps were included in the analysis while old stumps were removed, as described above. The average DSH of analysed stumps was 255 mm (SD 42). Time study data were collected from video recordings of the harvesting operations, and analysed using a continuous time study approach (Harstela 1991; Magagnotti et al. 2013). In total, 0.48 h of work was filmed. Excel-based software developed at the Natural Resources Institute Finland (Luke) was used for analysing the video material and to determine the duration of specific time elements (Niemistö et al. 2012; Nuutinen et al. 2016). Cycle time was divided into: moving machine, crane movement, drilling, stump extraction, and other (Table 1). Only productive machine time, excluding delay time (PM0) was analysed and consisted of: moving machine, crane movement, drilling, and stump extraction (priority 1 and 2). The work element “other” was not analysed due to limited data. Work elements were given different priority as some of them may otherwise overlap based on their importance where more sophisticated work elements were given higher priority. The work elements with the highest priority were used if overlaps occurred.

**Statistics**

Analysis of variance (ANOVA) was used to investigate differences between the two stump-harvesting methods with respect to ground disturbance per harvested stump and the depth of holes. ANOVA \((y_1 = \mu + \alpha + e)\) was applied separately to the data collected in Year 0 and Year 1, where \(y_1\) is the observed value, \(\mu\) the grand mean, \(\alpha\) the effect of the harvesting method and \(e\) the random variation. The Shapiro–Wilk normality test was used to determine whether the residuals

---

**Table 1. Definitions of the work elements (Element) in the time consumption study of the stump drill.**

| Element             | Start point                        | End point                        | Priority |
|---------------------|-----------------------------------|----------------------------------|----------|
| Moving machine      | Tracks start turning               | Tracks stop turning              | 2        |
| Crane movement      | Crane starts to move towards the stump | Drilling starts or crane stops moving | 1        |
| Drilling            | The head is spinning and touching the stump | Stump extraction starts | 1        |
| Stump extraction    | The stump head is pulled out from the stump hole and is above ground | Stump is pushed out from the head | 1        |
| other               | Other time (mostly delays related to unproductive work) | | 3        |
Results

The ground disturbed area per harvested stump by the stump rake and stump drill differed in both Year 0 and Year 1, but the depth of holes they created did not significantly differ in either year (Table 2). On average, the stump rake caused about 10 and 8 times more disturbance per harvested stump than the stump drill in Years 0 and 1, respectively (Table 3).

The size and depth of the holes created by the stump drill decreased significantly between Years 0 and 1, however, the change in ground disturbed area per harvested stump was not significant (Table 2). In contrast, both the holes created by the stump rake were significantly shallower and the disturbed areas per harvested stump significantly smaller in Year 1 than in Year 0 (Tables 2 and 3).

The relationships between DSH and the dependent variables were weak according to the regression analyses (Table 4). Significant least squares regression functions were obtained for stump drill time consumption and stump rake ground disturbance per harvested stump in Year 0, but regression functions for Year 1 were non-significant (Table 4; Figure 4). The proportions of time consumed during operation of the stump drill by the work elements machine movement, crane movement, drilling and stump extraction were: 10%, 26%, 50%, and 14%, respectively.

Discussion

Ground disturbance

Although our dataset was limited in size, it was still clear that the stump drill caused less ground disturbance at stump level than the stump rake. The stump rake disturbed 8–10 times larger areas of ground when harvesting a single stump than the stump drill (Tables 2 and 3). Roots and vegetation provide most of the bearing capacity on peatland (Usuitalo and Ala-Iломаки 2013), so the extensive ground disturbance (4–21 m² per stump) caused by the stump rake would probably severely reduce its bearing capacity, thereby making forwarding difficult. In contrast, harvesting by the stump drill only had a limited effect on the side roots (0.9 m² per stump), so it should have limited impact on bearing capacity. Therefore, to preserve bearing capacity, stump drills or equivalent newly developed extraction machinery could be used to minimize ground disturbance of stump harvesting on peatlands. Reductions in ground disturbance should lead to lower N₂O emissions as soil scariﬁcation increases N₂O emissions from peatlands (Pearson et al. 2012). However, effects of different types of ground disturbance on emissions of greenhouse gases from peatlands require further study.

Ground disturbance per stump caused by the stump rake was surprisingly high compared to that observed in previous

| Table 2. Summary of ANOVA to examine differences in performance between the stump rake and stump drill. |
| --- |
| **ANOVA** | **Normality test** | **T-test** |
| **Variable** | p-Value | R² adj | S-W | K-W | p-Value | t-Value |
| Y0 Ground dist. (ln (m²)) | <0.001 | 93.5 | 0.001 | <0.001 | – | – |
| Y0 Depth (cm) | 0.090 | 2.7 | 0.092 | – | – | – |
| Y1 Ground dist. (ln (m²)) | <0.001 | 93.7 | 0.678 | – | – | – |
| Y1 Depth (cm) | 0.057 | 3.8 | 0.472 | – | – | – |
| Y0 vs. Y1 Ground dist. Rake (m²) | – | – | – | – | 0.008 | 2.8439 |
| Y0 vs. Y1 Depth Rake (cm) | – | – | – | – | <0.001 | 5.1959 |
| Y0 vs. Y1 Ground dist. Drill (m²) | – | – | – | – | 0.416 | –0.8221 |
| Y0 vs. Y1 Depth Drill (cm) | – | – | – | – | <0.001 | 8.9794 |
| Y0 vs. Y1 Hole Drill (m²) | – | – | – | – | <0.001 | 4.9832 |

Notes: – indicates that the value was not calculated. P-values obtained from the Shapiro–Wilk’s normality test (S–W) of residual distributions and Kruskal–Wallis (K–W) rank sum tests when the residuals were not normally distributed for the response variables and adjusted R² values (R² adj) are shown. The response variables were the area of disturbed ground (Ground dist.) and depth of the holes (Depth) created by harvesting stumps using the stump rake (Rake) and stump drill (Drill), respectively, in the harvest year (Y0) and following year (Y1). T-tests were applied to test the significance of differences between the two years (Y0 vs. Y1) in the response variables. The areas of stump holes created by the stump drill (Hole) in the two years were also compared using a t-test (areas of holes created by the rake were not measured).

| Table 3. Areas of disturbed ground and depths of holes created by the stump rake and stump drill, respectively, and sizes of the holes created by the stump drill. |
| --- |
| **Extraction head** | **Measuring time** | **Ground disturbance (m²)** | **Hole size (m²)** | **Hole depth (cm)** |
| **Year** | **Stump rake** | **Stump drill** | **Year** | **Stump rake** | **Stump drill** | **Year** | **Stump rake** | **Stump drill** |
| Year 0 | 9.04 (4.01) | – | 36.4 (7.6) | | | | |
| Year 0 | 0.90 (0.17) | 0.31 (0.03) | 39.3 (7.1) | | | | |
| Year 1 | 7.60 (2.62) | – | 29.3 (5.5) | | | | |
| Year 1 | 0.93 (0.20) | 0.27 (0.04) | 31.9 (6.0) | | | | |

Notes: – indicates that the value was not measured. Standard deviations indicated in parentheses. Year 0 refers to the harvest year and Year 1 to the following year.
studies conducted on mineral soil. Ground disturbance following use of a stump rake harvesting a 250 mm DSH Norway spruce stumps on mineral soil is on average 5 m² (Berg et al. 2015); the corresponding disturbance in our study for Scots pine stumps was 9 m². Some difference between our study and those conducted on mineral soils was to some extent expected as peatlands are more sensitive to disturbance. However, the difference was larger than expected as the investigated Norway spruce on mineral soil has a wider root system than Scots pine (Hakkila 1972). The stump drill caused less ground disturbance (0.9 m² per stump on average) than a prototype head harvesting Norway spruce stumps on mineral soil (2.7 m² when harvesting a 350 mm DSH stump, on average) observed by von Hofsten (2014). The stump drill has a small diameter (40 cm), and our observations demonstrate that its rotation does not severely impact the soil around the stump, resulting in limited soil disturbance.

The area of disturbed ground per harvested stump caused by operation of the stump rake was smaller and the holes shallower in Year 1 than in Year 0. In contrast, Kaarakka et al. (2018) detected no change in these variables within this timeframe following harvesting using the stump rake on mineral soil. This difference indicates that peatlands could potentially return to a normal state more rapidly than mineral soils after stump harvesting, probably due to more severe frost heaving (Goulet 1995; Chimner 2011). Stump forwarding conducted between the sampling occasions may also have had a minor impact on the measurements, although disturbed areas after harvested stumps that the forwarder had directly driven over where not included in the analysis. Nevertheless, the forwarder drove close to some areas, which may have had a minor effect. Recolonization of ground vegetation could also affect the results, but this is likely to have been minimal as only one year elapsed between the two sampling occasions. We consider that frost heaving, which can be significant in both drained and undrained peatlands (Goulet 1995; Chimner 2011), was probably responsible for most of the observed differences in soil disturbance.

In contrast, we observed no significant difference in ground disturbance per harvested stump between the two sampling occasions for stump drill operations, although the stump holes were shallower in Year 1 than in Year 0 and the stump holes were also smaller. This difference was

---

**Table 4.** Least squares regression functions for time consumption in seconds per stump (Time), for the stump drill (Drill), and the ground area disturbed in m²/stump (Area), in the harvest year (Year 0) and the year after harvest (Year 1) for both the stump drill and stump rake (Rake).

| Response | Machine | Year | Corr. | Parameter | Parameter estimate | Standard error | p-Value | RMSE | Adj R² (%) |
|----------|---------|------|-------|----------|-------------------|---------------|---------|------|------------|
| Time     | Drill   | –    | 1.022 | Intercept | −2.8705           | 1.0641        | 0.0098  | 0.4407| 42.83      |
|          |         |      |       | LN(DSH)  | 1.1456            | 0.1924        | <2e−07  | −3.65 |            |
| Area     | Rake    | 0    | 1.246 | Intercept | 2.014             | 9.56e−02      | 3.65e−10| 0.3473| 9.30       |
|          |         |      |       | DSH     | 1.118e−13         | 5.46e−14      | 0.0498  | 2.64 | −3.17      |
| Area     | Rake    | 1    |       | Intercept | 7.329371         | 2.134710      | 0.00176 | 2.64 | −3.17      |
|          |         |      |       | DSH     | 0.001824          | 0.008440      | 0.83035 |      |            |
| Area     | Drill   | 0    |       | Intercept | 0.3208           | 2.71e−02      | 1.35e−13| 0.02789| −2.54      |
|          |         |      |       | DSH     | −3.878e−05       | 1.059e−04     | 0.716   |      |            |
| Area     | Drill   | 1    |       | Intercept | 2.926e−01        | 4.260e−02     | 6.56e−08| 0.04379| 2.25       |
|          |         |      |       | DSH     | −7.995e−05       | 1.663e−04     | 0.634   |      |            |

Notes: The root mean square error (RMSE), adjusted coefficient of determination (Adj R²) and correction for logarithmical bias (Corr.) of the functions are also shown. Response and Machine in bold indicate functions with significant p-values for all parameters. Abbreviation: DSH = diameter at stump height.

---

**Figure 4.** Left: observed time consumption (s/stump) and regression line. Top right: ground disturbance in Year 0 and Year 1 created by the conventional stump rake. Bottom right: ground disturbance in Year 0 and Year 1 created by the stump drill.
probably due to the stumps’ side roots remaining in the soil following operation of the stump drill, which should reduce the effect of subsequent frost heaving. If this was the case, then it should also take longer for the surrounding peat to collapse into a hole so that new vegetation can grow. Therefore, it is possible that whilst a stump drill disturbs a smaller area per harvested stump, such disturbance persists for longer than that caused by a stump rake. This possibility warrants further investigation as it could impact the viability of stump drill harvesting, unless a simple way of filling the hole can be developed.

The results indicate that the harvesting season could be extended to cover most of the year if the stump drill is utilized as it has limited ground disturbance per harvested stump. The ground disturbance per harvested stump for the stump rake was too severe to make harvest viable. Winter stump harvesting with the stump drill would minimize ground disturbance, but it would need to occur soon after roundwood harvests to avoid snowfall and drift covering stumps, which makes it difficult for an operator to locate stumps. Additionally, smaller volumes of stumps would be harvested using a stump drill rather than a conventional stump rake, so heaps would be smaller. Thus, they would be more easily covered with snow, more difficult for forwarder operators to find, and they would have to drive further to obtain full loads. Roundwood harvesting is mainly conducted on ditched peatlands when ground frost is present due to their low bearing capacity (Väätainen et al. 2004). Forwarding of stumps in the springtime may therefore not be viable, which might necessitate on-site storage of stumps until the next winter. However, an extended storage time increases the risk of both erosion and soil compaction and the growth of weed vegetation competing with planted seedlings (Walmsley and Godbold 2010). These factors should be considered when planning stump harvesting and forwarding.

Reducing ground disturbance caused by stump harvesting would be environmentally beneficial on all soil types. For example, ground disturbance caused by stump harvesting on mineral soils increases risks of both erosion and releases of nutrients and heavy metals (Egnell et al. 2007; Walmsley and Godbold 2010; Grelle et al. 2012). The stump drill could probably be operated on mineral soils with similar levels of ground disturbance to that observed on peatland. Nutrient removal should be reduced as more side roots, which have higher nutrient contents than stump centres (Hellsten et al. 2013), would remain in the soil. Reducing ground disturbance could also reduce both soil compaction and the growth of weed vegetation competing with planted seedlings (Walmsley and Godbold 2010). Additionally, habitats for fungi, mosses, bryophytes and insects are retained when using a stump drill rather than a conventional stump rake, although further study is needed to determine whether the side roots have the same habitat quality as stump centres. Harvesting with the stump drill could also improve fuel quality of extracted Scots pine stumps, as their centres have higher energy content than the side roots (Nurmi 1997). It should be noted that the opposite is evident for Norway spruce (Nurmi 1997). However, the stump drill has limited capability to remove soil from stumps (von Hofsten et al. 2012). So it’s use may increase ash contents of harvested stumps on mineral soil, unless other methods for cleaning are developed.

We estimated the ground disturbance on stump level, which is not the same as ground disturbance at site level. There were many overlapping disturbed areas after harvesting individual stumps with the stump rake. This means that its ground disturbance cannot be extrapolated to site level based on the number of stumps and their size. The stump drill had no overlapping holes and it’s disturbance did not depend on stump size. It could therefore theoretically be possible to estimate the stump drills ground disturbance at site level if the number of harvested stumps is known. However, at site level there are also additional ground disturbances from stump forwarding, roundwood harvesting, and soil preparation for regeneration. These types of disturbance are not equal in type and severity, even if the disturbed area is equal in size. Those reasons make the investigation of site-level disturbance quite complex. There is, therefore, a need for further investigations into size and severity of other types of disturbances to estimate the total disturbance and impact at site level. Particularly interesting is the impact of site preparation as the ground disturbance of the roundwood harvest under frozen winter conditions should be minimal.

**Time consumption**

To date, stump drills have not been profitable for harvesting stumps on mineral soils in Nordic forestry (von Hofsten 2010), but they are frequently used in southern Europe (Czereszycki et al. 1965; Spinelli et al. 2005; Emeryiat et al. 2014). The time consumption per kg dry substance (DS) harvested when using the Ellettari stump drill applied in our study was estimated to be lower than previously reported times for the conventional lifting of Scots pine stumps on mineral soil (Figure 5) (Athanassiadis et al. 2011). It was also lower than times recorded in a study of Norway spruce stump harvesting on mineral soils with a head similar to the one we used (von Hofsten et al. 2012). So it’s use may increase ash contents of harvested stumps on mineral soil, unless other methods for cleaning are developed.

We estimated the ground disturbance on stump level, which is not the same as ground disturbance at site level. There were many overlapping disturbed areas after harvesting individual stumps with the stump rake. This means that its ground disturbance cannot be extrapolated to site level based on the number of stumps and their size. The stump drill had no overlapping holes and it’s disturbance did not depend on stump size. It could therefore theoretically be possible to estimate the stump drills ground disturbance at site level if the number of harvested stumps is known. However, at site level there are also additional ground disturbances from stump forwarding, roundwood harvesting, and soil preparation for regeneration. These types of disturbance are not equal in type and severity, even if the disturbed area is equal in size. Those reasons make the investigation of site-level disturbance quite complex. There is, therefore, a need for further investigations into size and severity of other types of disturbances to estimate the total disturbance and impact at site level. Particularly interesting is the impact of site preparation as the ground disturbance of the roundwood harvest under frozen winter conditions should be minimal.

To date, stump drills have not been profitable for harvesting stumps on mineral soils in Nordic forestry (von Hofsten 2010), but they are frequently used in southern Europe (Czereszycki et al. 1965; Spinelli et al. 2005; Emeryiat et al. 2014). The time consumption per kg dry substance (DS) harvested when using the Ellettari stump drill applied in our study was estimated to be lower than previously reported times for the conventional lifting of Scots pine stumps on mineral soil (Figure 5) (Athanassiadis et al. 2011). It was also lower than times recorded in a study of Norway spruce stump harvesting on mineral soils with a head similar to the one we used (von Hofsten et al. 2012). So it’s use may increase ash contents of harvested stumps on mineral soil, unless other methods for cleaning are developed.

**Time consumption**

To date, stump drills have not been profitable for harvesting stumps on mineral soils in Nordic forestry (von Hofsten 2010), but they are frequently used in southern Europe (Czereszycki et al. 1965; Spinelli et al. 2005; Emeryiat et al. 2014). The time consumption per kg dry substance (DS) harvested when using the Ellettari stump drill applied in our study was estimated to be lower than previously reported times for the conventional lifting of Scots pine stumps on mineral soil (Figure 5) (Athanassiadis et al. 2011). It was also lower than times recorded in a study of Norway spruce stump harvesting on mineral soils with a head similar to the one we used (von Hofsten et al. 2012). So it’s use may increase ash contents of harvested stumps on mineral soil, unless other methods for cleaning are developed.

**Figure 5.** Estimated time consumption (s) per kg dry substance (DS) when harvesting Scots pine stumps. The DS for harvesting Scots pine stumps in the studies by Athanassiadis et al. (2011), von Hofsten et al. (2012), and Laitila et al. (2019) was calculated according to Hakkila (1972), assuming that 53% of the stump and root system was harvested by the head studied by von Hofsten et al. (2012), Laitila et al. (2019), and the stump drill in our study. The time consumption was assumed to be equal when harvesting Scots pine as when harvesting Norway spruce.
Hofsten et al. 2012). The stump drill was also faster for most stump sizes than the modified crusher grapple recently studied by Laitila et al. (2019) when harvesting Norway spruce stump on mineral soil. However, time consumption was still much higher than for Norway spruce harvesting with stump rakes on mineral soils (Kårhå 2012; Palander et al. 2015). The difference between our study and previous studies on mineral soil could partly be because there was no need to clean the stumps that is harvested on deep peatlands, which means that also other technologies are expected to be faster on peatland than on mineral soil. This could warrant studies of other technologies with low ground disturbance on peatlands. Such removal of cleaning phase could also reduce the vibrations experienced by the operator. This would potentially improve the work environment, and is something that should be studied further.

Although our data are limited, they clearly indicate that interactive effects of equipment, soil and other environmental factors on time consumption in stump-harvesting operations require further consideration. Currently, only conventional stump rake harvesting of Norway spruce dominated stands on mineral soils is profitable. However, the demand and price for stump wood should increase as the use of fossil fuels declines through replacement by biomass and other renewable sources (European Commission 2011). Further studies on the use of the stump drill for harvesting on peatlands are therefore warranted.

The technical reliability of the stump drill used in the current study was limited under the environmental conditions at the study site. A larger-scale study utilizing a reliable stump drill, that is both designed for Nordic conditions and used by an experienced operator, would be of great interest. The Elletari stump drill was originally designed for lower hydraulic pressure but was by necessity adapted to the higher pressure system used by the excavator operated in our study. The drill could not withstand the pressure applied by the excavator’s hydraulic system, and modification would be required to achieve the operational reliability required for commercial operation under Nordic conditions. Our operator had limited experience of using a stump drill and could have performed better, time wise, if a longer training period had been possible. However, at least one noted problem, the malfunctioning of the bearing housing, was most likely due to technical limitations, either due to design, poor assembly, or machine parts of low quality rather than limited experience of the operator.

Design enhancements that would increase productivity should focus on the drilling element during harvesting, which accounted for 50% of the total work time. Improved teeth and possibly faster rotation speeds could improve the operational performance of the stump drill. The potential problem that contractors might require two stump-harvesting heads, a stump drill for winter and a stump rake for summer, also requires consideration, as this would increase capital costs. Stump drills are also likely to be more costly than conventional stump rakes due to their more complex design. In addition, further study is needed to determine effects of snowfall on the potential use of stump drills, and how long the harvesting season can be extended. The potential extension of the harvesting season will be weather dependent, and vary between years.

Both the volume and bulkiness of harvested wood are reduced when using the stump drill, which will affect the forwarding’s profitability. Forwarding after stump drill harvesting has only been studied once under Nordic conditions (von Hofsten et al. 2012), when a standard stump forwarder was used. The cited authors observed that productivity was 32% lower than when handling conventionally harvested stumps, attributed to stump centres falling from the load space and being difficult to pick up. Therefore, modifications would be required for forwarders to be suitable for stump drill harvesting operations. This would add costs, but would extend potential employment to most of the year. In order to fully understand the economics of stump drill harvesting, a full system cost analysis is required. It is likely that the cost would be higher than conventional whole stump harvesting. Under current regulations, the stump drill system will probably only be used to harvest areas where conventional approaches cannot be used, such as peatland and wet mineral soil areas.

Conclusions

Ground disturbance per harvested stump was significantly lower when harvesting stumps on peatland with the stump drill than with the conventional stump rake. Use of a stump drill could reduce ground disturbance per harvested stump by up to 90%, but with a 47–68% reduction in harvested volume, depending on tree species. When using the stump rake, hole depth and disturbed area were smaller in the year after harvest than in the harvest year. The holes created by the stump drill were also smaller and shallower in the year after harvest, but no significant change in the area disturbed by the drill was detected. The between-year differences were probably due to frost heaving. Time consumption using the stump drill was lower than that observed for the conventional stump rake on mineral soil for Scots pine, but still far higher than for conventional harvest of Norway spruce. Two key technical problems with the stump drill need to be addressed before the equipment can be used under Nordic conditions: the hydraulic system must be adapted to withstand higher hydraulic pressure, and drilling must be faster to be profitable under current market conditions. Further studies on the operation of the drill in winter conditions would be worthwhile, especially if its design can be improved.

Acknowledgements

Jaakko Miettinen formerly based at Finnish Forest Research Institute research station in Kannus is acknowledged for assistance in the field work. Mikko Nivala is acknowledged for assistance during the field work and GIS work. Otto Läspä is acknowledged for assistance during the planning of field work.

Disclosure statement

No potential conflict of interest was reported by the authors.
Funding
The study was financed by the Forest Refine research project as part of the EU Interreg Botnia-Atlantica program, the European Union Seventh Framework Programme (EU FP7-KBBE-2012-6) through the INFRES project under grant number 311811, the Swedish Energy Agency, the Swedish District Heating Association, Jämtkraft AB, Skelleftekraft AB and supported by the research school FIRST.

ORCID
Simon Berg http://orcid.org/0000-0002-6033-8615
Robert Prinz http://orcid.org/0000-0002-1593-6974

References
Anerud E. 2010. Stump as a fuel – the influence of harvesting technique and storage method on fuel quality of Norway spruce [dissertation]. Uppsala: University of Agricultural Sciences, Department of Energy and Technology.

Anerud E, Jirjis R. 2011. Fuel quality of Norway spruce stumps – influence of harvesting technique and storage method. Scand J For Res. 26(3):257–266.

Asikainen A. 2010. Simulation of stump crushing and truck transport of chips. Scand J For Res. 25(3):245–250.

Athanassiadis D, Lindroos O, Nordfjell T. 2011. Pine and spruce stump harvesting productivity and costs using a Pallari KH 160 stump-lifting tool. Scand J For Res. 26(5):437–445.

Berg S, Bergström D, Nordfjell T. 2015. Effect of stump size and timing of stump harvesting on ground disturbance and root breakage diameter. Silva Fenn. 49(5):article 1312.

Chimner RA. 2011. Restoring sedges and mosses into frost heaving iron fens, San Juan Mountains, Colorado. Mires Peat. 8:article 7.

Czerkies K, Galimski J, Robel H. 1965. Rationalization of stump extraction. Geneva: FAO/ECO/LOG/158. Joint FAO/ECO/ILLO Committee on Forest Working Techniques and Training of Forest Workers.

Egnell G, Hyvönen R, Högbom L, Johansson T, Lundmark T, Olsson B, Ring E, von Sydow F. 2007. Miljökonsekvenser av stubbskörd – en sammanställning av kunskap och kunskapsbehov. [Environmental assessment of stump harvesting – compilation of knowledge and knowledge gaps]. Eskilstuna: Swedish Energy Agency. (Rapport ER 2007:40). Swedish.

Eklof K, Kraus A, Weyhenmeyer GA, Meili M, Bishop K. 2012. Forestry influence by stump harvest and site preparation on methylmercury, total mercury and other stream water chemistry parameters across a boreal landscape. Ecosystems. 15(8):1308–1320.

Emeryt R, Castagnet C, Cloarec S, Moreau J, Husson H. 2014. Harvesting of heart stump from poplar and maritime pine forest in South West France. Poster session presented at: 5th Forest Engineering Conference; Sep 23–26; Germerade, France.

European Commission. 2011. A roadmap for moving to a competitive low carbon economy in 2050. COM(2011) 112 final.

Goulet F. 1995. Frost heaving of forest tree seedlings: a review. New For. 9(1):67–94.

Grelle A, Strömgen M, Hyvönen R. 2012. Carbon balance of a forest ecosystem after stump harvest. Scand J For Res. 27(8):762–773.

Hakkilä O. 1972. Mechanized harvesting of stumps and roots: a sub-project of the joint Nordic research programme for the utilization of logging residues. Communications Instituti Forestalis Fenniae 77(1). Helsinki: Finnish Forest Research Institute. 71 p. ISBN 951-40-0035-8.

Harstela P. 1991. Work studies in forestry. Juensuu: Faculty of Forestry, University of Joensuu.

Hellsten S, Helmsaari HS, Melin Y, Skovsgaard JP, Kaakinen S, Kukkola M, Saarvalmi A, Petersson H, Akselsson C. 2013. Nutrient concentrations in stumps and coarse roots of Norway spruce, scots pine and silver birch in Sweden, Finland and Denmark. Forest Ecol Manag. 290:40–48.

Hollander M, Wolfe DA. 1973. Nonparametric statistical methods. New York: Wiley.

Jonsell M, Hansson J. 2011. Logs and stumps in clearcuts support similar saproxylic beetle diversity: implications for bioenergy harvest. Silva Fenn. 45(5):1053–1064.

Kaarakka LM, Vaithinen J, Marjalan M, Hestlen S, Kukkola M, Saarsalmi A, Palviainen MM, Helmsaari H-SM. 2018. Stump harvesting in Picea abies stands: soil surface disturbance and biomass distribution of the harvested stumps and roots. Forest Ecol Manag. 425:27–34.

Kärhä K. 2012. Comparison of two stump-lifting heads in final felling Norway spruce stand. Silva Fenn. 46(4):625–640.

Kiikkilä O, Nieminen TM, Starr M, Mäkilä M, Loukola-Ruskeeniemi K, Ukonmaanaho L. 2014. Leaching of dissolved organic carbon and trace elements after stem-only and whole-tree clear-cut on boreal peatland. Water Air Soil Pollut. 225(2):1767.

Laitila J, Paikela A, Ovaskainen H, Väätäinen K. 2019. Novel extracting methods for conifer stumps. Int J Forest Eng. DOI:10.1080/14942119.2019.1654614.

Laitila J, Ranta T, Asikainen A. 2008. Productivity of stump harvesting for fuel. Int J Forest Eng. 19(2):37–47.

Leckner B. 2007. Co-combustion: a summary of technology. Therm Sci. 11(4):4–10.

Magagnotti N, Kanzian C, Schulmeyer F, Spinelli R. 2013. A new guide for work studies in forestry. Int J Forest Eng. 24(3):249–253.

Niemistö P, Korpunen H, Laurén A, Salomäki M, Uusitalo J. 2012. Impact and productivity of harvesting while retaining young understory spruces in final cutting of downy birch (Betula pubescens). Silva Fenn. 46(1):81–97.

Nilsson PO, Danielsson B-O. 1976. Tillgängliga kvantiteter stubbrubrava [Available quantities of stump wood]. In: Alsefelt P, editor. Proceedings of Stubbdag; March 9; Stockholm (Sweden): Projekt Helträdutsnyttjande.

Nurmi J. 1997. Heating values of mature trees. Acta For Fenn. 256:1–28.

Ovaskainen H, Vahtonen J, Väätäinen K, Uusitalo J. 2016. Log quality and productivity in comminution of small-diameter tree bundles. Int J Forest Eng. 27(3):179–187.

Palander T, Kärhä K, Mehtätalo L. 2015. Work system study of three stump-lifting devices in Finland. Scand J For Res. 30(6):558–567.

Pearson M, Saarinen M, Minkkinen K, Silvan N, Laine J. 2012. Short-term impacts of soil preparation on greenhouse gas fluxes: a case study in nutrient-poor, clearcut peatland forest. Forest Ecol Manag. 283:10–26.

Persson T. 2016. Stump harvesting – impact on climate and environment. Forest Ecol Manag. 371:1–4.

Royston P. 1982. An extension of Shapiro and Wilk’s W test for normality to large samples. J R Stat Soc Ser C Appl Stat. 31(2):115–124.

Spinelli R, Nati C, Magagnotti N. 2005. Harvesting and transport of root biomass from fast-growing poplar plantations. Silva Fenn. 39(4):539–548.

Turunen J. 2008. Development of Finnish peatland area and carbon storage 1950–2000. Boreal Environ Res. 13:319–334.

Uusitalo J, Ala-Iломaki J. 2013. The significance of above-ground biomass, moisture content and mechanical properties of peat layer on the bearing capacity of ditched pine logs. Silva Fenn. 47(3):article 993.

Väätäinen K, Sikanen L, Asikainen A. 2004. Feasibility of excavator-based harvesting of two stump lifting heads, Biorex 50 and the rotary stump cutter. Uppsala: Skogforsk. (Arbetsrapport 853). Swedish with English summary.

von Hofsten H, Nordén B. 2007. Stubbfräsen – en ny och annorlunda teknik för att ta tillvara stubbar [Rotary stump cutter – a new technique for harvesting stumps]. Uppsala: Skogforsk. (Resultat 2007:18). Swedish with English summary.

Walsme JD, Godbold DL. 2010. Stump harvesting for bioenergy – a review of the environmental impacts. Forestry. 83(1):17–38.