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Carbon and nitrogen pools and mineralization rates in boreal forest soil after stump harvesting

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Abstract

The use of forest-derived biomass has steadily increased in Finland and Sweden during the past decades leading to more intensive forest management practices in the region, such as whole-tree harvesting, both above- and belowground. Stump harvesting results in a direct removal of stump and coarse-root carbon (C) from the stand and can cause extensive soil disturbance, which in turn can result in increased C mineralization. In this study, the effects of stump harvesting on soil C and nitrogen (N) mineralization, and soil surface disturbance were studied in two different clear-felled Norway spruce (*Picea abies*) sites in Central Finland. The treatments were whole-tree harvesting (WTH, removal of stems and logging residues), and WTH and stump harvesting (WTH+S). Both sites, Honkola (2 stands) and Haukilahti (6 stands) were mounded. In both treatments, soil samples were taken from different soil layers down to a total depth of 20 cm from (*i*) mounds, (*ii*) undisturbed soil and (*iii*) pits. The sampling was performed 11–12 years after treatments. Soil C and N mineralization rates were determined in laboratory incubation experiments. In addition, total C and N pools (g m^{-2}) were estimated for each disturbance class and soil layer. Soil C and N pools tended to be lower following stump harvesting, but no statistically significant treatment effect was detected. Stump harvesting increased soil mixing as indicated by a significant decrease in C concentration in the mound disturbance class. There was no significant effect of stump harvesting on soil C mineralization rates. A combination of mineralization rates and soil pool data showed that field C mineralization (g CO_2-C m^{-2} yr^{-1}) did not significantly differ between stands where stumps were removed or were retained. Further, stump harvesting did not seem to have any stimulating effect on soil CO_2 efflux 11–12 years after treatment.

Keywords: stump harvest, bioenergy, Norway spruce, forest soil, soil carbon

1 Introduction

The European Union has set ambitious targets to reduce greenhouse gas emissions and increase the use of renewables by 2020. The targets for the proportion of renewable energy sources used for energy production in Finland and Sweden are 38% and 49%, respectively (EU, 2009). In order to reach these goals, both countries have increased the utilization of forest-derived biomass and thus intensified the current logging operations. Consequently, the use of forest-derived biomass as an energy source has steadily increased in the region during the past 20 years (Ericsson et al., 2004; Helmisaari et al., 2014). In 2013, 8.7 million m^3 of forest chips were used in Finland, out of which 1.2 million m^3 came from stumps and 2.8 million m^3 from logging residues (Torvelainen, 2014). Stumps are annually harvested from 17 000–20 000 ha , which corresponds to approximately 10% of the annual clear-felling area in Finland (Juntunen, 2011; Asikainen et al., 2014).

Boreal forest vegetation and soil represent one of the largest pools of carbon (C) in the world (Strömgren and Mjöfors, 2012). Stumps and coarse roots contain 20% of the biomass C and 10–15% of the major nutrients (N, P, K, and Ca) found in tree biomass in mature boreal forests (Hellsten et al., 2013; Merilä et al., 2014). Stumps are the largest coarse woody debris (CWD) component in a managed boreal forest (Palviainen et al., 2010; Rabinowitch-Jokinen and Vanha-Majamaa, 2010). Due to their relatively slow decomposition, coarse roots and stumps represent a long-term C and N pool, which has a vital role in the nutrient cycling of forest stands (Sucre and Fox, 2009; Palviainen et al., 2010). Decomposing stumps contribute to the soil organic matter (SOM) pool, which in turn acts as a driver for several soil-benefiting qualities such as cation exchange capacity, aeration and water-holding capacity (Sucre and Fox, 2009). In addition, stumps provide habitat for a variety of saproxylic species (Hjältén et al., 2010; Anderson et al., 2015; Hämäläinen et al., 2015).

Climate benefits of stump combustion have been questioned (Zanchi et al., 2012) as stump harvest can cause both direct (combustion of biomass) and indirect (induced decomposition) emissions of C from the stand (Hope, 2007; Sucre and Fox, 2009; Repo et al., 2011), thus potentially reducing the stand C pool.

The most obvious consequence of stump harvesting is that it reduces the volume and composition of deadwood remaining in the stand (Eräjää et al., 2010; Anderson et al., 2015). Secondly, harvesting in combination with site preparation causes a disturbance of the forest floor and will expose the mineral soil (Finér et al., 2003). Previous studies have shown that stump harvesting significantly increases soil surface disturbance when compared to site preparation (Kataja-aho et al., 2012; Strömgren and Mjöfors, 2012; Saksa, 2013; Strömgren et al., 2013). Although stump harvesting causes a sizeable change in the micro-topography of the soil surface, additional site preparation is practically always needed to create more favorable planting spots for seedlings (Saarinen, 2006; Laitila et al., 2008; Rantala et al., 2010; Saksa, 2013). In site preparation, the organic humus layer is mixed with mineral soil material and mineral soil is exposed to various depths. The preparation thus changes the temperature and moisture conditions of the soil surface layers by creating mounds of soil and shaded pits which have a different microclimate and organic matter (OM) distribution than that of undisturbed soil (Pumpanen et al., 2004). This combined procedure is likely to cause greater direct effects on forest soil structure than either of these practices alone, leading into exposing, mixing and redistributing as well as compaction of the soil. Mounding is the most commonly used site preparation method for re-establishing Norway spruce stands in Finland (Uotila et al., 2010), while both mounding and disc trenching are common in Sweden (Hallsby and Örlander, 2004).

Relatively little is known about the effects of stump harvest on soil C and nitrogen (N) dynamics. There are only a handful of studies that have determined the effect of stump harvesting on soil surface disturbance (Kataja-aho et al., 2012; Tarvainen et al., 2015) and soil CO_2-fluxes (Grelle et al., 2012; Strömgren et al., 2012; Strömgren and Mjöfors, 2012; Mjöfors et al., 2015; Uri et al., 2015). None of them have reported longer-term changes in C dynamics or pools in different soil disturbance classes that are created as a result of mounding and stump harvesting. In Finland, Kataja-aho et al. (2012) studied exposed mineral soil surfaces post-mounding and stump harvesting and found that N mineralization was initially higher on stump harvested sites. They also observed a higher CO_2-flux from stump harvested sites in the field, however this effect was not observed in the *in vitro* samples (Kataja-aho et al., 2012).

In Sweden, Strömgren et al. (2012) and Strömgren and Mjöfors (2012) examined the soil CO_2-flux the first few years following stump harvest in comparison to conventional site preparation. They found no significant differences between soil CO_2-fluxes after mounding and stump harvesting. Grelle et al. (2012) observed a reduction in CO_2 emissions measured by the Eddy-covariance technique on stump harvested plots owing to the decrease in decomposable substrate during the first year after stump harvesting; the decrease was however followed by an increase in CO_2-efflux. Similarly, a recent study by Mjöfors et al. (2015) found that stump harvesting, when compared to site preparation treatment, did not lead to increased CO_2-fluxes or soil decomposition immediately after harvesting.

Mjöfors et al. (2015) concluded that although mixing favors decomposition it does not necessarily lead to higher CO_2-emissions from the whole profile, but rather creates SOM cohorts in various soil depths, which then decompose at different rates.

Considering that the stand rotation times for conifers in Finland and Sweden are typically more than 65 years, maintaining a longer time perspective on soil changes is imperative. That being said, there are a few studies that have reported treatment effects on soil total C pools over 20 years after stump harvesting. Karlsson and Tamminen (2013) found no treatment effect on soil C and N pools 30 years after stump harvesting, while Zabowski et al. (2008) reported decreased C and N stores 22-29 years after stump removal. Strömgren et al. (2013) and Egnell et al.{*Egnell:2015us} found that the effects were site-specific.

The aim of this study was to determine if stump harvesting causes qualitative and quantitative changes in the SOM stock in different soil-surface disturbance categories 11–12 years after stump harvesting. We used *in vitro* measurements of C and N mineralization (expressed per g of C) as a proxy of quality and estimates of C and N pools for quantity. Since mounding is the most common site preparation method used to regenerate Norway spruce in Finland, mounding sites were used as control references for stump harvesting.

Our specific hypothesis was: mixing of the soil layers (incorporation of OM into the mineral soil and *vice versa*) caused by stump harvesting will increase decomposition of SOM and will therefore increase C and N mineralization rates of SOM in topsoil layers (per unit C). Furthermore, the highest fluxes of CO_2 were expected from the surfaces with high SOM content (e.g., mounds) and the lowest fluxes from the pits.

2 Materials and methods

2.1 *Experimental sites*

Two experimental sites located in Central Finland (Honkola and Haukilahti) were used in this study, both sites belonging to the southern boreal zone (Ahti et al., 1968) (Table 1). Two stands were studied in Honkola, and six in Haukilahti. The stands were clear-cut in 2001–2002. Logging residues were harvested in all clear-cuts, so all clear-cuts were subject to whole-tree harvesting (WTH). Stump harvesting (WTH+S) was performed in half of the clear-cuts. Site preparation in the form of spot mounding was carried out in all clear-cuts, also where the stumps were removed, to ensure suitable planting spots. Seedlings of Norway spruce, *Picea abies* (L.) Karst., were planted the year following harvesting. At the time of sampling, each experimental clear-cut (from now on called plots) included three 30 m x 30 m subplots, altogether 6 at Honkola and 18 at Haukilahti. All treatments carried out were done according to the current Finnish forestry management guidelines (Äijälä et al., 2014).

2.2 *Soil disturbance*

During soil sampling disturbance classes were identified visually and confirmed with a soil corer to identify the mixing and relocation of the soil layers. Three disturbance classes were identified; (*i*) mound, (*ii*) undisturbed soil surface and (*iii*) pit (Table 2).

2.3 *Soil sampling*

In October 2012 (Honkola) and October 2013 (Haukilahti) soil samples were taken for respiration and N-mineralization studies. Soil samples were collected with a soil corer (d=28 mm). Samples were collected from all three disturbance classes separately. Samples from undisturbed soil surfaces were divided into humus layer (organic layer) and three mineral soil layers; 0-5 cm, 5-10 cm and 10-20 cm. Samples from the pits, lacking a humus layer, were divided into 0-5 cm, 5-10 cm and 10-20 cm mineral soil layers. Soil material from the mounds was divided into top layer, humus layer, and three mineral soil layers; 0-5 cm, 5-10 cm and 10-20 cm. The top layer consisted of a heap of soil placed on top of the humus layer and mostly consisted of both organic and mineral soil. The thickness of the humus layer, if present, was measured at each sample point. Soil material from five points of each disturbance class was sampled in each subplot and the samples were pooled to form three composite samples per plot, disturbance class and soil layer.

2.4 Laboratory analyses

Soil samples were stored at +5 ^{o}C before further treatment. To homogenize the soil material, the humus samples were sieved through a 6-mm sieve and the mineral soil through a 2-mm sieve. This method also removes live roots, mycorrhizal mycelia and coarse plant remnants. Soil pH was measured by mixing 10 ml of soil with 25 ml of deionized water. The suspension $pH_{(H2O)}$ was measured with a glass electrode the next day. C and N concentrations in the samples were measured directly from a subset of dried samples by a VarioMax CN-analyzer (Elementar Analysensysteme GmbH, Germany). Total pools of N and C were calculated using the formula:

$$\text{Pool (g m}^{-2}\text{)} = \text{Concentration (mg g}^{-1}\text{ soil)} \times BD_{<2}\text{ (g cm}^{-3}\text{)} \times \text{layer thickness (cm)} \times 100,$$

where $BD_{<2}$ is the measured bulk density of the 0-2 mm fraction. Pools were corrected for the field estimated soil stone content (Viro, 1952). Total pools were only determined for the six plots at Haukilahti, because sample volume was not recorded at Honkola.

For the incubation, humus and mineral soil sub-samples (corresponding to 15–30 g and 100 g dry weight, respectively) were placed in 466 ml plastic containers made of styrene/acryl nitrile as described in Persson et al. (1989) and Olsson et al. (2012). Water content was adjusted to 60% of water holding capacity (WHC) and the soil samples were then incubated at a constant temperature of 15 °C for 26 days. Lids with 5 mm aperture were put on these soil microcosm containers during incubation to allow gas exchange. CO_2-measurements were performed once every week and averaged for the 26-day period. During each measurement, the container was closed with a gas-tight lid equipped with closable stopcocks. The CO_2 concentration in the chamber container was obtained by connecting an infrared gas analyzer (EGM-4, PP-systems, Hitchin, Hertfordshire, UK). Respiration rate was calculated on the basis of the slope of the linear CO_2 concentration increase within the chamber and circulating air between container and analyzer approximately every 10 to 15 minute for organic and mineral soil, respectively. If the increase of CO_2 to time had an r^2 below 0.99, the procedure was repeated a fourth or a fifth time. Calculations of respiration were performed according to Persson et al. (1989) with correction of values for the measured pH.

At the start and end of the 26-day incubation, an analysis of inorganic N was performed to estimate net N mineralization for the samples from Honkola. Each soil sub-sample (20 g of mineral soil or 10 g of humus for samples) was extracted with 100 ml of 1 M KCl for 2 hours and stored in a fridge (+5 °C) until it was analyzed for ammonium (NH_4^+)-N and nitrate (NO_3^-)-N on a TRAACS^{TM} 800 (Technicon (Bran+Luebbe), Elmsford NY, US). Net mineralized N was calculated from the sum of (NH_4^+-N) and (NO_3^--N) accumulated during the period of incubation. Both soil respiration and net N mineralization were normalized to the C content in the soil.

2.5 Heterotrophic field respiration

The estimates of C mineralization rates obtained from the laboratory measurements were extrapolated to the field by multiplying C mineralization rates (expressed per g of C) obtained at 15 °C and 60% WHC for each plot by: (1) the amount of C per plot and soil layer and (2) the number of days per year (365). This calculation made it possible to estimate the amount of CO_2-C evolved m^{-2} yr^{-1} in the field (at laboratory temperature and moisture). Because the C mineralization rates were obtained after removing live roots and mycorrhizal fungi by sieving, followed by a stabilization period, we consider the result as an estimate of heterotrophic respiration.

2.6 Statistical analyses

Honkola and Haukilahti belong to the same region, and we considered this region as a unit for the statistical analysis and compared the stump-harvested stands (WTH+S) with the non-harvested stands (WTH) independent of sites. Because the disturbance classes (mounds, undisturbed soil and pits) contained different numbers of soil layers, each disturbance class was analyzed separately. The statistical analysis was made as a split-plot ANOVA, in which treatment (WTH and WTH+S), soil layer (top, humus layer, 0-5, 5-10 and 10-20 cm mineral soil) and soil layer within treatment were considered as fixed factors, and plot (treatment x soil layer) as a random factor. To obtain (approximately) normally distributed data in the statistical tests, plot data showing large variation were log-transformed (ln x), but in other cases log transformation was not needed. When significant interactions between treatment and soil layer were indicated, pair-wise comparisons were made between the treatment means for individual soil layers according to the Bonferroni correction. Only some variables were common for both Honkola and Haukilahti (pH, respiration rate, C conc., N conc., C/N ratio) (n=4), others were only present for Haukilahti (C pools, N pools and R_H=heterotrophic respiration) (n=3), while net N mineralization and net nitrification were only present at Honkola (n=1). Consequently, treatment effects could not be evaluated at Honkola. However, by using the subplots at Honkola as replicates, it was possible to get an idea of the treatment effects assuming no plot differences. Differences between treatments were considered statistically significant when $P< 0.05$.

3 Results

3.1 Soil C and N pools, and soil pH

Total soil C pools were estimated to be 6.9 and 5.6 kg m^{-2} in the WTH and WTH+S treatments in “undisturbed” soil at Haukilahti, and the corresponding estimates for N pools were 0.30 and 0.26 kg m^{-2} (Fig. 1). However, the total C and N pools did not differ significantly between treatments in any of the disturbance classes. The amounts of C and N differed between soil layers, and after mounding, the “top” and humus layers had higher C and N amounts than any of the mineral soil layers (Fig. 1). In the undisturbed soil, the humus layer contained more C and N than any of the mineral soil layers.

C concentrations were significantly lower in WTH+S compared to WTH in the mound disturbance class, whereas C and N concentrations in other disturbance classes only showed differences between soil layers (Table 3). The humus layer had higher C and N concentrations than any of the other soil layers, including the “top” layer, which consisted of a mixture of organic and mineral soil.

C/N ratios had a tendency to be lower after stump harvesting, *P*=0.08 and *P*=0.11 for the mound and undisturbed classes, respectively, but the only significant differences were found between soil layers (Table 3).

There was a significant interaction between treatment and soil layer in the mound class. Pair-wise comparisons per soil layer showed significantly higher pH in WTH+S than in WTH in the humus layer ($P<0.05$). Soil pH was low in the humus layer and generally higher with increasing soil depth (Fig. 2). The “top” layer was an exception in having similar pH as the 0-5 cm mineral soil layer in the mound disturbance class.

3.2 C mineralization rate

Stump harvesting did not significantly affect C mineralization rate in any of the disturbance classes or soil layers (Fig. 3). The differences in C mineralization rates (per g of C) between treatments were relatively small.

3.3 Heterotrophic soil respiration

Annual heterotrophic respiration (at laboratory temperature and soil moisture) (R_H lab) was estimated to range between 1000 and 1400 g CO_2-C in the undisturbed and mound soil profiles (Fig. 4). R_H for the whole soil profile did not differ significantly between the WTH+S and WTH treatments, but in the mound disturbance class, R_H was significantly lower ($P<0.01$) in the WTH+S than in the WTH humus layer. The “top” and humus layers had significantly higher R_H than the mineral soil layers.

3.3 3.4 Net N mineralization and nitrification rate

Net N mineralization rate was only determined for the Honkola samples. Net N mineralization rates varied between -1 and 16 µg N (g C)$^{-1}$ day^{-1} with the lowest rates in the mound tops and in the pits at 10-20 cm depth (Fig. 5). No significant differences between treatments were found, but stump harvesting had a tendency (*P*=0.053) to increase net N mineralization in the pits.

Net nitrification rates were low in comparison with the net N mineralization rates in the Honkola samples. No significant differences in net nitrification rates were found for the main treatments or for the soil layers (Fig. 6). Presence of negative values for both nitrification and net N mineralization rates indicated net immobilization during the incubation.

4 Discussion

4.1 Soil C and N pools

Changes in C and N pools after stump harvesting has been suggested to depend on (*i*) removal of stumps and coarse roots, which will reduce SOM formation, (*ii*) increased SOM decomposition as a consequence of soil disturbance, (*iii*) changed litter inputs depending on the establishment of plant cover, and (*iv*) soil mixing, which means redistribution of SOM within the soil profile but without a net loss of organic C and N.

In this study, performed 11-12 years after site preparation and stump removal, total C and N soil pools had a slight tendency to be lower after stump harvesting, but there were no significant differences between treatments. The tendency of decrease was restricted to the humus layer, both in the “mound” and in the “undisturbed” disturbance class. The humus layer had lower C concentration, lower C/N ratio and higher pH after stump removal, all factors indicating that the humus layers had partly been mixed with materials from other soil layers at stump harvesting. This was probably also the case in the “undisturbed” spots, although it was not possible to discern a soil-surface disturbance during the initial inspection.

The estimates of soil C/N ratios were consistently lower in the same soil layer after stump harvesting (WTH+S) than after WTH only (Table 3). This might indicate that SOM from deeper soil layers had been intermixed with more superficial soil layers, because C/N ratios normally decrease with increasing soil depths in boreal forests (Persson et al., 2000; Hyvönen et al., 2016). Similar results have been reported by Kataja-aho et al. (2012), who found lower C/N-ratios post-stump harvesting, and accounted it to the increased mixing caused by the harvest. The C concentration was significantly reduced by stump harvesting in the mound disturbance class, which could also be explained by both soil mixing and increased decomposition of SOM. The pits had (insignificantly) higher C concentration after stump harvest, which would indicate a down-mixing of topsoil materials.

Other studies on soil C and N pools made 10–12 years after stump harvesting are very scarce, the study by Hope et al. (2007) in British Columbia, Canada, being an exception. Hope et al. (2007) found that the amount of total C and N was not significantly affected by stump harvesting (“O+ treatment”) in the forest floor, but total C showed a significant increase (using $P<0.1$ as accepted value of significance) in the mineral soil in comparison with the undisturbed treatment (NT) ten years after soil treatment. Total C in the whole soil profile to a depth of 20 cm in the mineral soil was very similar, 5.2 (O+) and 4.9 (NT) kg m^{-2}, respectively, which indicated no effect of stump harvesting. On the other hand, Hope (2007) found that stump harvesting followed by complete scarification of the forest floor (by removal or mixing with mineral soil) reduced the forest floor C and N pools.

Other studies performed 25–39 years after logging and stump harvesting, show modest effects. Strömgren et al. (2013) reported significantly lower C pools in the humus layer 25 years after stump harvesting than after stem-only harvesting in a study involving four forest stands in Sweden, but because the C pools in the 0-20 cm mineral soil were not negatively affected by stump harvesting, there was no significant difference between treatments in the whole soil profile. In another study of eight forest stands in Sweden, Jurevics et al. (2016) found that there was no general effect of harvest treatment on the total C, soil C (humus layer + 0-10 cm mineral soil) or tree biomass C pools across all sites 32–39 years after clear-cutting. In a third long-term study (33 years), Karlsson and Tamminen (2013) found that stump harvesting had no or minimal effects on C and N pools in the organic and 0-10-cm mineral soil layers. In contrast to the above-mentioned studies, Zabowski et al. (2008) reported about 20% lower C and N pools in both humus layer and the 0-15 cm mineral soil 22–29 years after stump harvesting at five sites in Oregon and Washington, USA. A possible reason for the discrepancy between this study and the others can be that in the Zabowski et al. (2008) study, the stumps were removed with the intention to reduce root diseases, and the stump removal was done by pushing with a bulldozer equipped with a brush blade.

The lack of significant differences in the total soil C and N pools at Haukilahti between WTH and WTH+S treatments are thus in agreement with other comparable studies. It is possible that increased disturbance after stump harvesting can have accelerated SOM decomposition (see also below), but the most reasonable explanation to the differences in OM concentrations in comparable soil layers is soil mixing.

4.2 C mineralization

There was no general effect of stump harvesting on soil C mineralization rates. Data on rates give an indication of the quality (decomposability) of the OM but cannot alone be used to draw conclusions about the quantity of CO_2 evolution per m^2. The high C mineralization rate in the pits (Fig. 3) was unexpected, because the null hypothesis was that these mineral soil layers should resemble the corresponding layers in the mound and undisturbed disturbance class. It is possible that the pits acted as collectors of fresh litter from the clearcut vegetation, and although all visible litter was removed at sampling, fragmented litter from the 11–12 year-period after soil treatment might have created an influx of high quality SOM to the the top layer in the pit. It is also possible that the pits also could be filled with water after heavy rains and after snowmelt. During litter decomposition, fragmented litter and dissolved organic C (DOC) was probably formed, and could penetrate into the underlying soil layer and act as a C source for the decomposers. The early dynamics of CO_2 efflux from soil pits was studied by Pumpanen et al. (2004), who reported low soil CO_2 efflux from both exposed E horizon and exposed C horizon during the first year after clear-cutting, followed by a steady increase in CO_2 efflux during the following two years which they suggested to be caused by the colonization of pit vegetation.

The top layer of the mounds contained extra SOM (an inverted humus layer plus attached mineral soil on top of the original humus layer). This top layer seemed to have similar C mineralization rates as the underlying humus layer. As this study was done in the laboratory under controlled temperature and moisture, this was expected. To our knowledge, field studies on CO_2 fluxes in 11–12 year-old stands after stump harvesting are lacking, but studies on 1-2 year-old clear-cuts show that CO_2 fluxes from mounds, despite the addition of a top layer, can be lower than those from undisturbed soil (Strömgren and Mjöfors, 2012). In another study, Mjöfors et al. (2015) noted that CO_2 fluxes from plots with double humus layer (DHL) were initially higher than from control plots with an undisturbed humus layer. However, during the second year, the soil CO_2 fluxes from DHL plots decreased and equaled those from control plots. A possible reason for the occasionally very low fluxes from DHL plots is that high moisture levels in layers containing much of the OM may have suppressed decomposition and/or gas fluxes (Mjöfors et al., 2015).

4.3. Heterotrophic respiration in the field

When combining the plot data of soil C pools and C mineralization rates at Haukilahti, soil layer by soil layer, the total heterotrophic respiration (R_H) ranged between 1000 and 1400 g CO_2-C m^{-2} yr^{-1} for mounds and undisturbed soils, given the temperature (15 ºC) and moisture (60% WHC) conditions in the laboratory (Fig. 4). These data can be extrapolated to the field situation (e.g. Olsson et al., 2012; Bergholm et al., 2015), but because we lack data on field soil temperature and moisture for the actual sites, we avoided this.

The R_H estimates showed that there were no significant differences between stump harvesting and non-harvesting treatments. Thus, the hypothesis that increased soil mixing by stump harvesting will increase C mineralization rates could not be supported. The significantly lower R_H in the WTH+S than in the WTH treatment in the humus layer rather showed that soil mixing can change the proportion of CO_2 efflux from different soil layers.

4.3 4.4. Net N mineralization and nitrification rate

Potential net N mineralization rate obtained in the laboratory did not show clear differences between the treatments (Fig. 5) and net nitrification was very low (Fig. 6). Net N mineralization rates had a tendency to be higher (P=0.053) after stump harvesting than after mounding only in the pits. Pits act as collectors of fresh litter, and especially the number of birch seedlings increase after stump harvesting (Hyvönen et al., 2016). The lack of treatment effects 11-12 years after stump harvesting in our study is in agreement with the findings by Kataja-aho et al. (2012), who also studied net N mineralization and nitrification rates in an incubation study 1–5 years after stump harvesting. They showed that the rate of net N mineralization and net nitrification was significantly higher in stump removal plots than in mounded plots one year after harvesting. However, the difference in net N mineralization and net nitrification rate between treatments decreased by year and no differences between the treatments were found five years after stump harvesting. The increases in net N mineralization and nitrification after stump harvesting, thus, seem to be of short-term nature, but more studies are needed to validate this.

5. Conclusions

There were no clear effects of stump harvesting on soil C and N dynamics 11–12 years after harvesting. In agreement with the hypothesis, stump harvesting increases soil mixing, down-mixing of organic layers and up-mixing of mineral soil from deeper layers, as indicated by significant effects on C concentrations and near-significant effects on pH and C/N ratios. There was no evidence of increased C mineralization rates or heterotrophic soil respiration.

The lower R_H in the mound humus layer after stump removal seems to be an effect of soil mixing.

Acknowledgements

This study was funded by Maj and Tor Nessling Foundation and Niemi-foundation. It was also a part of the research program “Tree-stump harvesting and its environmental consequences” conducted by the Swedish University of Agricultural Sciences with the support of grants from the Swedish Energy Agency, the NL faculty at Swedish University of Agricultural Sciences and a consortium of forest companies. We would like to thank Marjut Wallner, Saska Lohi, Jan Fiedler, Oscar Olsson, Tommi and Minna Helmisaari for helping with field and laboratory work. We would like to extend our thanks to Christine Furuhjelm who gave us access to her property at Honkola to perform the field investigations, to UPM for providing study sites in Haukilahti and to Jari Haimi, who guided us to the appropriate field sites.

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