

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

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5 Lilli Kaarakka¹, Riitta Hyvönen², Monika Strömgren³, Marjo Palviainen¹, Tryggve Persson²,
6 Bengt A. Olsson², Erno Launonen¹, Birgitta Vegerfors⁴ and Heljä-Sisko Helmisari¹

7
8 ¹Department of Forest Sciences, University of Helsinki, P.O. Box 27, 00014 Helsinki,
9 Finland

10 ²Swedish University of Agricultural Sciences, Department of Ecology, P.O. Box 7044, SE-
11 750 07 Uppsala, Sweden

12 ³Swedish University of Agricultural Sciences, Department of Soil and Environment, P.O.
13 Box 7014, SE-750 07 Uppsala, Sweden

14 ⁴Swedish University of Agricultural Sciences, Department of Energy and Technology, Unit
15 of Applied Statistics and Mathematics, P.O. Box 7032, SE-750 07 Uppsala, Sweden

16
17 Corresponding author:

18 Lilli Kaarakka

19 University of Helsinki, Department of Forest Sciences

20 P.O. Box 27, FI-00014 University of Helsinki, Finland

21 lilli.kaarakka@helsinki.fi

22 +358503759776

23

24

25 **Abstract**

26 The use of forest-derived biomass has steadily increased in Finland and Sweden during the
27 past decades leading to more intensive forest management practices in the region, such as
28 whole-tree harvesting, both above- and belowground. Stump harvesting results in a direct
29 removal of stump and coarse-root carbon (C) from the stand and can cause extensive soil
30 disturbance, which in turn can result in increased C mineralization. In this study, the effects
31 of stump harvesting on soil C and nitrogen (N) mineralization, and soil surface disturbance
32 were studied in two different clear-felled Norway spruce (*Picea abies*) sites in Central
33 Finland. The treatments were whole-tree harvesting (WTH, removal of stems and logging
34 residues), and WTH and stump harvesting (WTH+S). Both sites, Honkola (2 stands) and
35 Haukilahti (6 stands) were mounded. In both treatments, soil samples were taken from
36 different soil layers down to a total depth of 20 cm from (i) mounds, (ii) undisturbed soil and
37 (iii) pits. The sampling was performed 11–12 years after treatments. Soil C and N
38 mineralization rates were determined in laboratory incubation experiments. In addition, total
39 C and N pools (g m^{-2}) were estimated for each disturbance class and soil layer. Soil C and N
40 pools tended to be lower following stump harvesting, but no statistically significant treatment
41 effect was detected. Stump harvesting increased soil mixing as indicated by a significant
42 decrease in C concentration in the mound disturbance class. There was no significant effect
43 of stump harvesting on soil C mineralization rates. A combination of mineralization rates and
44 soil pool data showed that field C mineralization ($\text{g CO}_2\text{-C m}^{-2} \text{ yr}^{-1}$) did not significantly
45 differ between stands where stumps were removed or were retained. Further, stump
46 harvesting did not seem to have any stimulating effect on soil CO_2 efflux 11–12 years after
47 treatment.

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

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52

53 1 Introduction

54 The European Union has set ambitious targets to reduce greenhouse gas emissions and
55 increase the use of renewables by 2020. The targets for the proportion of renewable energy
56 sources used for energy production in Finland and Sweden are 38% and 49%, respectively
57 (EU, 2009). In order to reach these goals, both countries have increased the utilization of
58 forest-derived biomass and thus intensified the current logging operations. Consequently, the
59 use of forest-derived biomass as an energy source has steadily increased in the region during
60 the past 20 years (Ericsson et al., 2004; Helmisaari et al., 2014). In 2013, 8.7 million m³ of
61 forest chips were used in Finland, out of which 1.2 million m³ came from stumps and 2.8
62 million m³ from logging residues (Torvelainen, 2014). Stumps are annually harvested from
63 17 000–20 000 ha, which corresponds to approximately 10% of the annual clear-felling area
64 in Finland (Juntunen, 2011; Asikainen et al., 2014).

65

66 Boreal forest vegetation and soil represent one of the largest pools of carbon (C) in the world
67 (Strömberg and Mjöfors, 2012). Stumps and coarse roots contain 20% of the biomass C and
68 10–15% of the major nutrients (N, P, K, and Ca) found in tree biomass in mature boreal
69 forests (Hellsten et al., 2013; Merilä et al., 2014). Stumps are the largest coarse woody debris
70 (CWD) component in a managed boreal forest (Palviainen et al., 2010; Rabinowitch-Jokinen
71 and Vanha-Majamaa, 2010). Due to their relatively slow decomposition, coarse roots and
72 stumps represent a long-term C and N pool, which has a vital role in the nutrient cycling of
73 forest stands (Sucre and Fox, 2009; Palviainen et al., 2010). Decomposing stumps contribute
74 to the soil organic matter (SOM) pool, which in turn acts as a driver for several soil-
75 benefiting qualities such as cation exchange capacity, aeration and water-holding capacity
76 (Sucre and Fox, 2009). In addition, stumps provide habitat for a variety of saproxylic species
77 (Hjältén et al., 2010; Anderson et al., 2015; Hämäläinen et al., 2015).

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

82

83 The most obvious consequence of stump harvesting is that it reduces the volume and
84 composition of deadwood remaining in the stand (Eräjää et al., 2010; Anderson et al., 2015).

85 Secondly, harvesting in combination with site preparation causes a disturbance of the forest
86 floor and will expose the mineral soil (Finér et al., 2003). Previous studies have shown that
87 stump harvesting significantly increases soil surface disturbance when compared to site
88 preparation (Kataja-aho et al., 2012; Strömgren and Mjöfors, 2012; Saksa, 2013; Strömgren
89 et al., 2013). Although stump harvesting causes a sizeable change in the micro-topography of
90 the soil surface, additional site preparation is practically always needed to create more
91 favorable planting spots for seedlings (Saarinen, 2006; Laitila et al., 2008; Rantala et al.,
92 2010; Saksa, 2013). In site preparation, the organic humus layer is mixed with mineral soil
93 material and mineral soil is exposed to various depths. The preparation thus changes the
94 temperature and moisture conditions of the soil surface layers by creating mounds of soil and
95 shaded pits which have a different microclimate and organic matter (OM) distribution than
96 that of undisturbed soil (Pumpanen et al., 2004). This combined procedure is likely to cause
97 greater direct effects on forest soil structure than either of these practices alone, leading into
98 exposing, mixing and redistributing as well as compaction of the soil. Mounding is the most
99 commonly used site preparation method for re-establishing Norway spruce stands in Finland
100 (Uotila et al., 2010), while both mounding and disc trenching are common in Sweden
101 (Hallsby and Örlander, 2004).

102

103 Relatively little is known about the effects of stump harvest on soil C and nitrogen (N)
104 dynamics. There are only a handful of studies that have determined the effect of stump
105 harvesting on soil surface disturbance (Kataja-aho et al., 2012; Tarvainen et al., 2015) and
106 soil CO₂-fluxes (Grelle et al., 2012; Strömngren et al., 2012; Strömngren and Mjöfors, 2012;
107 Mjöfors et al., 2015; Uri et al., 2015). None of them have reported longer-term changes in C
108 dynamics or pools in different soil disturbance classes that are created as a result of
109 mounding and stump harvesting. In Finland, Kataja-aho et al. (2012) studied exposed mineral
110 soil surfaces post-mounding and stump harvesting and found that N mineralization was
111 initially higher on stump harvested sites. They also observed a higher CO₂-flux from stump
112 harvested sites in the field, however this effect was not observed in the *in vitro* samples
113 (Kataja-aho et al., 2012).

114

115 In Sweden, Strömngren et al. (2012) and Strömngren and Mjöfors (2012) examined the soil
116 CO₂-flux the first few years following stump harvest in comparison to conventional site
117 preparation. They found no significant differences between soil CO₂-fluxes after mounding
118 and stump harvesting. Grelle et al. (2012) observed a reduction in CO₂ emissions measured
119 by the Eddy-covariance technique on stump harvested plots owing to the decrease in
120 decomposable substrate during the first year after stump harvesting; the decrease was
121 however followed by an increase in CO₂-efflux. Similarly, a recent study by Mjöfors et al.
122 (2015) found that stump harvesting, when compared to site preparation treatment, did not
123 lead to increased CO₂-fluxes or soil decomposition immediately after harvesting.

124

125 Mjöfors et al. (2015) concluded that although mixing favors decomposition it does not
126 necessarily lead to higher CO₂-emissions from the whole profile, but rather creates SOM
127 cohorts in various soil depths, which then decompose at different rates.

128

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

136

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

143 Our specific hypothesis was: mixing of the soil layers (incorporation of OM into the mineral
144 soil and *vice versa*) caused by stump harvesting will increase decomposition of SOM and will
145 therefore increase C and N mineralization rates of SOM in topsoil layers (per unit C).

146 Furthermore, the highest fluxes of CO₂ were expected from the surfaces with high SOM
147 content (e.g., mounds) and the lowest fluxes from the pits.

148

149 2 Materials and methods

150 2.1 Experimental sites

151 Two experimental sites located in Central Finland (Honkola and Haukilahti) were used in this
152 study, both sites belonging to the southern boreal zone (Ahti et al., 1968) (Table 1). Two
153 stands were studied in Honkola, and six in Haukilahti. The stands were clear-cut in 2001–
154 2002. Logging residues were harvested in all clear-cuts, so all clear-cuts were subject to
155 whole-tree harvesting (WTH). Stump harvesting (WTH+S) was performed in half of the
156 clear-cuts. Site preparation in the form of spot mounding was carried out in all clear-cuts,
157 also where the stumps were removed, to ensure suitable planting spots. Seedlings of Norway
158 spruce, *Picea abies* (L.) Karst., were planted the year following harvesting. At the time of
159 sampling, each experimental clear-cut (from now on called plots) included three 30 m x 30 m
160 subplots, altogether 6 at Honkola and 18 at Haukilahti. All treatments carried out were done
161 according to the current Finnish forestry management guidelines (Äijälä et al., 2014).

162

163 2.2 Soil disturbance

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

167

168 2.3 Soil sampling

169 In October 2012 (Honkola) and October 2013 (Haukilahti) soil samples were taken for
170 respiration and N-mineralization studies. Soil samples were collected with a soil corer ($d=28$
171 mm). Samples were collected from all three disturbance classes separately. Samples from
172 undisturbed soil surfaces were divided into humus layer (organic layer) and three mineral soil

173 layers; 0-5 cm, 5-10 cm and 10-20 cm. Samples from the pits, lacking a humus layer, were
174 divided into 0-5 cm, 5-10 cm and 10-20 cm mineral soil layers. Soil material from the
175 mounds was divided into top layer, humus layer, and three mineral soil layers; 0-5 cm, 5-10
176 cm and 10-20 cm. The top layer consisted of a heap of soil placed on top of the humus layer
177 and mostly consisted of both organic and mineral soil. The thickness of the humus layer, if
178 present, was measured at each sample point. Soil material from five points of each
179 disturbance class was sampled in each subplot and the samples were pooled to form three
180 composite samples per plot, disturbance class and soil layer.

181

182 2.4 Laboratory analyses

183 Soil samples were stored at +5 °C before further treatment. To homogenize the soil material,
184 the humus samples were sieved through a 6-mm sieve and the mineral soil through a 2-mm
185 sieve. This method also removes live roots, mycorrhizal mycelia and coarse plant remnants.
186 Soil pH was measured by mixing 10 ml of soil with 25 ml of deionized water. The
187 suspension $\text{pH}_{(\text{H}_2\text{O})}$ was measured with a glass electrode the next day. C and N concentrations
188 in the samples were measured directly from a subset of dried samples by a VarioMax CN-
189 analyzer (Elementar Analysensysteme GmbH, Germany). Total pools of N and C were
190 calculated using the formula:

191

192 $\text{Pool (g m}^{-2}\text{)} = \text{Concentration (mg g}^{-1}\text{ soil)} \times \text{BD}_{<2} \text{ (g cm}^{-3}\text{)} \times \text{layer thickness (cm)} \times 100,$

193

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

197

198 For the incubation, humus and mineral soil sub-samples (corresponding to 15–30 g and 100 g
199 dry weight, respectively) were placed in 466 ml plastic containers made of styrene/acryl
200 nitrile as described in Persson et al. (1989) and Olsson et al. (2012). Water content was
201 adjusted to 60% of water holding capacity (WHC) and the soil samples were then incubated
202 at a constant temperature of 15 °C for 26 days. Lids with 5 mm aperture were put on these
203 soil microcosm containers during incubation to allow gas exchange. CO₂-measurements were
204 performed once every week and averaged for the 26-day period. During each measurement,
205 the container was closed with a gas-tight lid equipped with closable stopcocks. The CO₂
206 concentration in the chamber container was obtained by connecting an infrared gas analyzer
207 (EGM-4, PP-systems, Hitchin, Hertfordshire, UK). Respiration rate was calculated on the
208 basis of the slope of the linear CO₂ concentration increase within the chamber and circulating
209 air between container and analyzer approximately every 10 to 15 minute for organic and
210 mineral soil, respectively. If the increase of CO₂ to time had an r² below 0.99, the procedure
211 was repeated a fourth or a fifth time. Calculations of respiration were performed according to
212 Persson et al. (1989) with correction of values for the measured pH.

213

214 At the start and end of the 26-day incubation, an analysis of inorganic N was performed to
215 estimate net N mineralization for the samples from Honkola. Each soil sub-sample (20 g of
216 mineral soil or 10 g of humus for samples) was extracted with 100 ml of 1 M KCl for 2 hours
217 and stored in a fridge (+5 °C) until it was analyzed for ammonium (NH₄⁺)-N and nitrate
218 (NO₃⁻)-N on a TRAACS™ 800 (Technicon (Bran+Luebbe), Elmsford NY, US). Net
219 mineralized N was calculated from the sum of (NH₄⁺-N) and (NO₃⁻-N) accumulated during
220 the period of incubation. Both soil respiration and net N mineralization were normalized to
221 the C content in the soil.

222

223 2.5 *Heterotrophic field respiration*

224 The estimates of C mineralization rates obtained from the laboratory measurements were
225 extrapolated to the field by multiplying C mineralization rates (expressed per g of C)
226 obtained at 15 °C and 60% WHC for each plot by: (1) the amount of C per plot and soil layer
227 and (2) the number of days per year (365). This calculation made it possible to estimate the
228 amount of CO₂-C evolved m⁻² yr⁻¹ in the field (at laboratory temperature and moisture).

229 Because the C mineralization rates were obtained after removing live roots and mycorrhizal
230 fungi by sieving, followed by a stabilization period, we consider the result as an estimate of
231 heterotrophic respiration.

232

233 2.6 *Statistical analyses*

234 Honkola and Haukilahti belong to the same region, and we considered this region as a unit
235 for the statistical analysis and compared the stump-harvested stands (WTH+S) with the non-
236 harvested stands (WTH) independent of sites. Because the disturbance classes (mounds,
237 undisturbed soil and pits) contained different numbers of soil layers, each disturbance class
238 was analyzed separately. The statistical analysis was made as a split-plot ANOVA, in which
239 treatment (WTH and WTH+S), soil layer (top, humus layer, 0-5, 5-10 and 10-20 cm mineral
240 soil) and soil layer within treatment were considered as fixed factors, and plot (treatment x
241 soil layer) as a random factor. To obtain (approximately) normally distributed data in the
242 statistical tests, plot data showing large variation were log-transformed (ln x), but in other
243 cases log transformation was not needed. When significant interactions between treatment
244 and soil layer were indicated, pair-wise comparisons were made between the treatment means
245 for individual soil layers according to the Bonferroni correction. Only some variables were

246 common for both Honkola and Haukilahti (pH, respiration rate, C conc., N conc., C/N ratio)
247 (n=4), others were only present for Haukilahti (C pools, N pools and R_H =heterotrophic
248 respiration) (n=3), while net N mineralization and net nitrification were only present at
249 Honkola (n=1). Consequently, treatment effects could not be evaluated at Honkola. However,
250 by using the subplots at Honkola as replicates, it was possible to get an idea of the treatment
251 effects assuming no plot differences. Differences between treatments were considered
252 statistically significant when $P < 0.05$.

253

254 **3 Results**

255 *3.1 Soil C and N pools, and soil pH*

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

263

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

269

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

273

274 There was a significant interaction between treatment and soil layer in the mound class. Pair-
275 wise comparisons per soil layer showed significantly higher pH in WTH+S than in WTH in
276 the humus layer ($P<0.05$). Soil pH was low in the humus layer and generally higher with
277 increasing soil depth (Fig. 2). The “top” layer was an exception in having similar pH as the 0-
278 5 cm mineral soil layer in the mound disturbance class.

279

280 3.2 *C mineralization rate*

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

284

285 3.3 *Heterotrophic soil respiration*

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

292

293 3.3 3.4 *Net N mineralization and nitrification rate*

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

299

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

304

305 **Discussion**

306 4.1 *Soil C and N pools*

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

312

313 In this study, performed 11-12 years after site preparation and stump removal, total C and N
314 soil pools had a slight tendency to be lower after stump harvesting, but there were no
315 significant differences between treatments. The tendency of decrease was restricted to the

316 humus layer, both in the “mound” and in the “undisturbed” disturbance class. The humus
317 layer had lower C concentration, lower C/N ratio and higher pH after stump removal, all
318 factors indicating that the humus layers had partly been mixed with materials from other soil
319 layers at stump harvesting. This was probably also the case in the “undisturbed” spots,
320 although it was not possible to discern a soil-surface disturbance during the initial inspection.

321

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

332

333 Other studies on soil C and N pools made 10–12 years after stump harvesting are very scarce,
334 the study by Hope et al. (2007) in British Columbia, Canada, being an exception. Hope et al.
335 (2007) found that the amount of total C and N was not significantly affected by stump
336 harvesting (“O+ treatment”) in the forest floor, but total C showed a significant increase
337 (using $P < 0.1$ as accepted value of significance) in the mineral soil in comparison with the
338 undisturbed treatment (NT) ten years after soil treatment. Total C in the whole soil profile to
339 a depth of 20 cm in the mineral soil was very similar, 5.2 (O+) and 4.9 (NT) kg m⁻²,

340 respectively, which indicated no effect of stump harvesting. On the other hand, Hope (2007)
341 found that stump harvesting followed by complete scarification of the forest floor (by
342 removal or mixing with mineral soil) reduced the forest floor C and N pools.

343

344 Other studies performed 25–39 years after logging and stump harvesting, show modest
345 effects. Strömngren et al. (2013) reported significantly lower C pools in the humus layer 25
346 years after stump harvesting than after stem-only harvesting in a study involving four forest
347 stands in Sweden, but because the C pools in the 0-20 cm mineral soil were not negatively
348 affected by stump harvesting, there was no significant difference between treatments in the
349 whole soil profile. In another study of eight forest stands in Sweden, Jurevics et al. (2016)
350 found that there was no general effect of harvest treatment on the total C, soil C (humus layer
351 + 0-10 cm mineral soil) or tree biomass C pools across all sites 32–39 years after clear-
352 cutting. In a third long-term study (33 years), Karlsson and Tamminen (2013) found that
353 stump harvesting had no or minimal effects on C and N pools in the organic and 0-10-cm
354 mineral soil layers. In contrast to the above-mentioned studies, Zabowski et al. (2008)
355 reported about 20% lower C and N pools in both humus layer and the 0-15 cm mineral soil
356 22–29 years after stump harvesting at five sites in Oregon and Washington, USA. A possible
357 reason for the discrepancy between this study and the others can be that in the Zabowski et al.
358 (2008) study, the stumps were removed with the intention to reduce root diseases, and the
359 stump removal was done by pushing with a bulldozer equipped with a brush blade.

360

361 The lack of significant differences in the total soil C and N pools at Haukilahti between WTH
362 and WTH+S treatments are thus in agreement with other comparable studies. It is possible
363 that increased disturbance after stump harvesting can have accelerated SOM decomposition

364 (see also below), but the most reasonable explanation to the differences in OM concentrations
365 in comparable soil layers is soil mixing.

366

367 4.2 *C mineralization*

368 There was no general effect of stump harvesting on soil C mineralization rates. Data on rates
369 give an indication of the quality (decomposability) of the OM but cannot alone be used to
370 draw conclusions about the quantity of CO₂ evolution per m². The high C mineralization rate
371 in the pits (Fig. 3) was unexpected, because the null hypothesis was that these mineral soil
372 layers should resemble the corresponding layers in the mound and undisturbed disturbance
373 class. It is possible that the pits acted as collectors of fresh litter from the clearcut vegetation,
374 and although all visible litter was removed at sampling, fragmented litter from the 11–12
375 year-period after soil treatment might have created an influx of high quality SOM to the the
376 top layer in the pit. It is also possible that the pits also could be filled with water after heavy
377 rains and after snowmelt. During litter decomposition, fragmented litter and dissolved
378 organic C (DOC) was probably formed, and could penetrate into the underlying soil layer and
379 act as a C source for the decomposers. The early dynamics of CO₂ efflux from soil pits was
380 studied by Pumpanen et al. (2004), who reported low soil CO₂ efflux from both exposed E
381 horizon and exposed C horizon during the first year after clear-cutting, followed by a steady
382 increase in CO₂ efflux during the following two years which they suggested to be caused by
383 the colonization of pit vegetation.

384

385 The top layer of the mounds contained extra SOM (an inverted humus layer plus attached
386 mineral soil on top of the original humus layer). This top layer seemed to have similar C
387 mineralization rates as the underlying humus layer. As this study was done in the laboratory

388 under controlled temperature and moisture, this was expected. To our knowledge, field
389 studies on CO₂ fluxes in 11–12 year-old stands after stump harvesting are lacking, but studies
390 on 1-2 year-old clear-cuts show that CO₂ fluxes from mounds, despite the addition of a top
391 layer, can be lower than those from undisturbed soil (Strömgren and Mjöfors, 2012). In
392 another study, Mjöfors et al. (2015) noted that CO₂ fluxes from plots with double humus
393 layer (DHL) were initially higher than from control plots with an undisturbed humus layer.
394 However, during the second year, the soil CO₂ fluxes from DHL plots decreased and equaled
395 those from control plots. A possible reason for the occasionally very low fluxes from DHL
396 plots is that high moisture levels in layers containing much of the OM may have suppressed
397 decomposition and/or gas fluxes (Mjöfors et al., 2015).

398

399 *4.3. Heterotrophic respiration in the field*

400 When combining the plot data of soil C pools and C mineralization rates at Haukilahti, soil
401 layer by soil layer, the total heterotrophic respiration (R_H) ranged between 1000 and 1400 g
402 CO₂-C m⁻² yr⁻¹ for mounds and undisturbed soils, given the temperature (15 °C) and moisture
403 (60% WHC) conditions in the laboratory (Fig. 4). These data can be extrapolated to the field
404 situation (e.g. Olsson et al., 2012; Bergholm et al., 2015), but because we lack data on field
405 soil temperature and moisture for the actual sites, we avoided this.

406

407 The R_H estimates showed that there were no significant differences between stump harvesting
408 and non-harvesting treatments. Thus, the hypothesis that increased soil mixing by stump
409 harvesting will increase C mineralization rates could not be supported. The significantly
410 lower R_H in the WTH+S than in the WTH treatment in the humus layer rather showed that
411 soil mixing can change the proportion of CO₂ efflux from different soil layers.

412

413 4.3 4.4. *Net N mineralization and nitrification rate*

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

428

429 **5. Conclusions**

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

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

437

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