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Responses of Soil Carbon and Nitrogen Transformations to Stump Removal

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We studied in central Finland whether stump harvesting after clear felling of coniferous forest poses further short-term changes in soil carbon and nitrogen dynamics when compared to the traditional site preparation method, mounding. Exposed mineral soil patches in Norway spruce (*Picea abies*) dominated clear-cut stands were sampled 1–5 years after the treatments. The extent of the exposed mineral soil surface was significantly larger at the stump removal sites when compared to the mounding sites. No differences were found in soil pH, organic matter content or total concentration of soil C between the treatments or treatment years. Total concentration of soil N was consistently higher and C:N ratio lower in the stump removal plots than in the mounded plots. Further, both net N mineralisation and nitrification were clearly increased in the stump removal plots one year after the treatments. Soil microbial activity (CO_2 production) was higher in the stump removal plots but similar difference was not found in sieved soil samples incubated in the laboratory. Fluxes of other important greenhouse gases (CH_4 and N_2O) did not seem to be affected by stump removal. The differences between the stump removal and mounding procedures were most obviously attributed to more substantial soil disturbance by stump pulling and/or differences in the microbial communities and quality of soil organic matter in the differently treated soil.

Keywords biofuel, boreal forest, carbon, nitrogen, nutrient dynamics, stump removal
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1 Introduction

Increasing amounts of tree biomass is harvested from boreal coniferous forests to produce renewable fuel. This resource consists mainly of whole-trees from thinnings and management of young stands, and logging residues from clear felled areas. More often also stumps are harvested from clear-fellings. Modern regeneration practices including mechanical site preparation after final felling cause substantial disturbance to the soil and decomposer community that inhabit organic soil layers. Stump removal is likely to further increase the level of this disturbance.

Stump removal may affect soil processes and resources of decomposers and vegetation both directly and indirectly. Carbon (C) and nutrients are lost in stump and root biomass that is transported from the forest. On the other hand, stump harvesting operations disturb the soil heavily changing its physical structure and may thus have substantial consequences for C and nutrient reserves and mineralization processes (Walmsley and Godbold 2010).

Stump removal is a rather novel method to obtain forest biomass, and its effects on the structure and functioning of the diverse soil decomposer communities are poorly known. At present e.g. in Finland, stumps are removed mainly from Norway spruce (*Picea abies* (L.) H. Karst.) dominated stands (Halonen 2004), as well as from clear-cuts stricken by root rot (e.g. *Heterobasidion* Bref. sp.) to avoid infection of next tree generation (Thies and Westlind 2005, Müller et al. 2007, Zabowski et al. 2008).

Staaf and Olsson (1994) observed clear transient changes in nitrogen (N) mobilization after stump harvesting in a Norway spruce forest in SW Sweden. On the other hand, Zabowski et al. (2008) noticed that stump removal lead to decline in mineral N in Douglas-fir (*Pseudostuga menziesii* (Mirb.) Franco) stands over 22–29 years. Hope (2007) also found significant decreases in surface soil reserves of C and nutrients after stump removal followed by scarification after both 1 and 10 years in forests of British Columbia dominated by western redcedar (*Thuja plicata* Donn ex D. Don) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). On the other hand, C and nutrient reserves in the mineral horizon were increased in the stump removal plots (Hope 2007). Thus, it is evident that stump removal would lead to changes in soil C and nutrient cycling when applied systematically in large scale after clear-felling. Further, it has been proposed that changes in soil nutrient stocks are due to the elevated rates of decomposition of soil organic matter after physical disturbance, rather than direct removal of C and nutrients in stumps and roots (Hope 2007, Walmsley and Godbold 2010). It is also important to notice that stump removal may have negative effects on the diversity of saproxylic beetles (Hjälten et al. 2010), and possibly also on the diversity of other organism groups living in dead wood.

The main objective of the present study was to determine the short-term effects of stump removal on soil C and N transformations in clear felled boreal spruce forests because these processes may have a significant impact on the development of next tree generation and other biota at the site. Kataja-aho et al. (2011) observed that especially the extent of exposed mineral soil patches differ between the stump removal and conventionally prepared clear-fellings. As changes in nutrient transformation processes are impending just in the disturbed soil, we took soil samples from mineral soil exposed in the stump removal practice and compared those with samples taken from mineral soil in the conventionally site prepared areas. In addition, we measured fluxes of the important greenhouse gases, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) from stump removal and conventionally prepared soils. We hypothesized that increased intensity of soil disturbance leads to increased mineralization of C and N through mixing soil materials and improving environmental conditions for decomposers.

2 Materials and Methods

2.1 Study Plots and Experimental Design

The study sites were coniferous stands located in central Finland, in the area of Haukilahti (61°48´N, 24°47´E; municipalities of Jämsä and Orivesi). The warmest and the coldest months

in the area were July and February in both study years (+17.7 °C and –10.9°C in 2006 and +15.4 °C and –13.1 °C in 2007, respectively), and the mean annual precipitation was 535 mm as rain and 115 mm as snow during the study period. The snow cover lasted approximately four months (4.5 months in 2006 and 3 months in 2007). The length of the growing season was ca. 6 months in 2006 (from 24th April to 17th October) and 5 months in 2007 (from 6th May to 8th October; Finnish Meteorological Institute, the meteorological station in Halli, ca. 10 km from our study area). Soil in the study plots is podzolised moraine with a 3–4 cm thick organic layer.

Twenty 80–100 years old Norway spruce (*Picea abies*) dominated forest sites growing on the Oxalis-Myrtillus (OMT) or Myrtillus (MT) site types (Cajander 1949) at the same area with similar vegetation and approximately at the same altitude were allocated for the study. Ten of the sites were clear felled in 2002 and ten in 2005. After clear felling, ca. 70% of the slash was collected from the sites. At five randomly selected sites clear felled in 2002 and five sites clear felled in 2005, stumps were removed from the soil using a caterpillar excavator equipped with a special stump removal bucket. The rest of the sites were mechanically site prepared by mounding using a similar excavator and considered as controls. The number of replicates in each treatment (stumps removed or left on site) and time (treatment year) combination was five. One and a half years old Norway spruce seedlings from a nursery were planted at each site (1600 seedlings per ha) during the first summer after the felling and stump removal/site preparation procedures.

All the management and regeneration practices performed at the study sites were done according to the prevailing instructions followed in forestry in Finland at that moment (Metsätalouden kehittämiskeskus Tapio 2006). Total areas of the clear felled experimental sites varied between 2 and 3 hectares including surrounding buffer zones treated similarly. From each study site, one ca. 30 m x 30 m (900 m^2) plot was chosen for samplings, avoiding marshy, rocky and stony areas. The proportions (extent) of intact forest floor and mineral soil surface exposed in the treatments (either mounding or stump harvesting) were visually estimated in each plot. Soil surface consisting of mixed mineral soil and organic matter was classified as mineral soil surface.

2.2 Determination of Soil C and N Transformations and Soil Properties

Soil sampling was carried out twice, in September 2006 and September 2007. In each plot, six samples were randomly taken from the exposed mineral soil surface (exposed patches at the mounding sites) to a depth of 4 cm with a steel soil auger (25 cm^2) to form one ca. 0.5 L composite sample. Distance of the samples to the nearest seedling was more than 1 m. Samples were placed in plastic bags, and transported in coolers to the laboratory. In the laboratory, the samples were first sieved with a 4-mm mesh, and roots and other plant material together with stones etc. were removed. Then, the samples were stored at +2 ºC until further treated or analyzed.

Soil C and N transformations were studied using two laboratory replicates in each analysis. Organic matter content in the soil was measured as loss-on-ignition at 550 ºC. Soil pH was measured in a sample of soil suspended in ultrapure water (1:2.5 by volume). Total C and N were measured from air-dried samples using a CHN analyzer (Leco-1000, Leco Corp., St. Joseph, MI, USA).

The concentrations of C and N in the microbial biomass were determined using the fumigation-extraction method, as described previously (Kanerva and Smolander 2007). Briefly, soil samples were fumigated for 24 h at 28 °C with ethanol-free chloroform vapour. Carbon and N flushes from the microbial biomass were calculated by subtracting K_2SO_4-extractable organic C and N in unfumigated control samples from those in fumigated samples. Carbon and N flushes were converted to microbial biomass with the formulas of Ocio and Brookes (1990).

To determine net N mineralization and net nitrification, soil samples were incubated in 125 ml glass bottles at constant temperature (14 °C) and moisture (60% of water-holding capacity, WHC) for 6 weeks and analysed using FIA (flow injection analysis) as described previously for humus samples (Kanerva and Smolander 2007). The KCl-extractable NH_4-N and (NO_2+NO_3)-N

concentrations were measured in the beginning and at the end of the incubation. To calculate rates of net ammonification and nitrification, initial concentrations of NH_4-N and (NO_2+NO_3)-N were subtracted from the corresponding post-incubation concentrations. Net N mineralization was estimated as the sum of net ammonification and net nitrification, i.e. as the accumulation of NH_4-N and (NO_2+NO_3)-N during incubation.

In the same incubations, aerobic C mineralization was evaluated as CO_2-C production (Kanerva and Smolander 2007). To measure this, the bottles were first aerated and then closed air-tightly. After 24 h, CO_2 production was measured by sampling the head spaces of the incubation bottles and analyzing the amounts of CO_2 on a gas chromatograph. The production was measured twice during the 1–2 weeks after incubation began.

Results are expressed on organic matter basis to describe the quality of organic matter.

2.3 Field Gas Emission Measurements

Gas fluxes (CO_2, CH_4 and N_2O) were measured twice (4th October 2006 and 1st October 2007) from the exposed mineral soil at three points in each study plot treated in 2005 (five plots where stumps were removed and five where stumps were left on site). The fluxes were measured in October to get more comparable data since in October the primary production has already ceased while microbial activity is close to its maximum (high soil moisture and moderate soil temperature). Diurnal temperature variations are also tiny in October.

Collars made of metal tubes (diameter 31.5 cm) were inserted at least 10 cm deep in the soil in 22nd August 2006 and were left in place till the latter measurement in October 2007. An aluminum groove was attached on the top of each collar. Before sampling, a closed chamber (d = 0.315 m, h = 0.3 m, V = 0.024 m^3) equipped with a fan was placed on the groove filled with water to seal the chamber. At each sampling occasion, four successive samples of 30 ml were taken from the chamber with plastic syringes during a 17.5-minute measurement period at 5 minutes intervals (2.5, 7.5, 12.5, 17.5 minutes). The syringes were then taken to the laboratory and analyzed for CO_2, CH_4 and N_2O concentrations within 24h hours from sampling by a gas chromatograph (GC conditions for CO_2 see Pietikäinen and Fritze 1995 and for CH_4 and N_2O see Alm et al. 2007). Fluxes were calculated from a linear change of gas concentrations during the sampling period.

2.4 Statistical Analyses

Analysis of variance (ANOVA) for repeated measures was used to test the effects of the fixed factors (stump removal and treatment year) and time of sampling (as the within-subject factor) on the measured variables. If there was significant interaction between the samplings and the factors, two-way ANOVA was applied separately for both samplings. If the factors (stump removal and treatment year) significantly interacted with each other, the level of the factor in question was fixed and one-way ANOVA was applied to test the effect of the other factor. If assumptions for parametric tests were violated (homogeneity of variances: Levene's test; normality of the variables: Shapiro-Wilk's test and equality of covariance matrices in repeated measures ANOVA: Box's test), the data were transformed to ln(x+1) or square root. When the assumptions were not fulfilled even after transformation, non-parametric Kruskal-Wallis test was used to test the effect of the treatments. In gas emission data the mean of the three replicate samples represented each study plot. The data analyses were performed using SPSS 14.0 for Windows™.

3 Results

3.1 Soil Properties and C and N Transformations

The proportion of intact soil at the mounding sites was on average 52 ± 5.8 (S.E.) % and at the stump removal sites 32 ± 3.7% (see Katajaaho et al. 2011). Soil pH was slightly higher in 2007 than in 2006 but no differences were found between the treatments or treatment years (Tables 1–2). No differences were found in soil organic matter content between the treatments, treatment

Table 1. Soil pH (in water), organic matter content (OM, loss on ignition), total N (g N kg^{-1} OM), total C (g C kg^{-1} OM), C:N ratio, and CO_2-production (mg CO_2-C kg^{-1} OM h^{-1}) in the mineral soil in stump removal and stump retaining plots. Means (S.E., n=5) are shown.

Sampling year	2006		2007	
	Stumps retained	Stumps removed	Stumps retained	Stumps removed
Soil pH				
Treated 2002	4.8(0.01)	4.8(0.04)	4.9(0.04)	4.9(0.02)
Treated 2005	4.7(0.03)	4.7(0.04)	4.9(0.09)	4.9(0.09)
OM (%)				
Treated 2002	8.6(0.67)	6.2(0.81)	7.3(0.74)	6.9(1.98)
Treated 2005	7.7(0.64)	6.9(0.55)	7.9(0.90)	7.0(1.00)
Total soil N				
Treated 2002	19.5(1.11)	21.8(1.36)	16.8(1.30)	20.0(2.06)
Treated 2005	17.8(0.41)	20.1(1.02)	14.8(0.61)	19.04(1.39)
Total soil C				
Treated 2002	452.9(32.33)	393.1(11.47)	426.8(19.71)	429.1(39.92)
Treated 2005	404.6(13.43)	396.2(9.84)	376.8(15.09)	425.4(16.52)
C:N ratio				
Treated 2002	23.3(1.22)	18.2(0.97)	25.7(1.39)	21.8(1.44)
Treated 2005	22.7(0.61)	19.9(0.74)	25.7(1.24)	22.7(1.43)
CO_2-production				
Treated 2002	4.68(0.24)	4.42(0.52)	5.19(0.43)	6.70(1.52)
Treated 2005	2.82(0.76)	2.87(0.08)	2,70(0.24)	2.82(0.32)

Table 2. Results (values of F and p; n = 5) from the repeated measures ANOVAs for soil pH, organic matter content, total carbon and nitrogen, C:N ratio and microbial biomass N.

Variable	pH F(p)	Organic matter F(p)	C_{tot} F(p)	N_{tot} F(p)	C:N ratio F(p)	N_{mic} F(p)
Sampling year	16.7(0.001)	0.02(0.881)	0.03(0.873)	5.9(0.027)	23.4(< 0.001)	6.0(0.026)
Sampling year × treatment	0.1(0.762)	1.0(0.338)	3.0(0.103)	0.7(0.415)	0.2(0.667)	0.1(0.786)
Sampling year × treatment year	0.1(0.741)	0.3(0.605)	0.02(0.904)	0.01(0.925)	0.01(0.942)	0.8(0.389)
Sampling year × treatment × treatment year	0.1(0.762)	1.4(0.256)	0.01(0.942)	0.1(0.742)	0.3(0.599)	0.02(0.882)
Treatment	1.4(0.247)	1.6(0.228)	0.1(0.765)	11.5(0.004)	13.7(0.002)	2.4(0.144)
Treatment year	0.3(0.581)	0.01(0.918)	3.1(0.099)	3.3(0.088)	0.2(0.648)	6.5(0.022)
Treatment × treatment year	0.1(0.782)	0.1(0.779)	3.0(0.103)	0.1(0.793)	0.7(0.422)	0.01(0.928)

years or samplings (Tables 1–2). Further, there were no differences in the total concentration of soil C; it varied roughly from 380 to 450 g kg^{-1} organic matter.

Aerobic C mineralization (CO_2 production of soil samples incubated in the laboratory, mg CO_2-C kg^{-1} OM h^{-1}) did not differ between the treatments, but it appeared to be higher in the plots treated in 2002 compared to those treated in 2005 (Tables 1 & 3).

Total concentration of soil N (g N kg^{-1} OM) was consistently higher in the stump removal plots than in the mounded plots (Tables 1–2). Further, total N was higher in the sampling in 2006 than in 2007. Soil C:N ratio was higher in the mounded plots compared to the stump removal plots and higher in the sampling in 2007 than in 2006 (Tables 1–2).

Concentration of ammonium N (mg N kg^{-1} OM) was higher in the mounded plots compared

Table 3. Kruskal-Wallis test results (test value χ^2 and p; n = 5) for soil CO_2-production, NH_4 and NO_3 concentrations, net mineralization and nitrification, and microbial carbon ($C_{microbes}$).

Variable	Constant	CO_2-prod.	Soil NH_4-N	Soil NO_3-N	Net N mineral.	Net nitrific.	$C_{microbes}$
Sampling year 2006							
Treatment	Treatm. yr 2002	0.01(0.917)	7.03(0.008)	1.84(0.175)	0.54(0.465)	0.28(0.596)	2.46(0.117)
Treatment	Treatm. yr 2005	0.27(0.602)	0.01(0.917)	3.94(0.047)	3.94(0.047)	5.77(0.016)	0.54(0.465)
Treatm. yr	Mounding	2.46(0.117)	5.81(0.016)	3.94(0.047)	0.27(0.602)	2.45(0.115)	0.54(0.465)
Treatm. yr	Stump removal	6.82(0.009)	6.99(0.008)	6.82(0.009)	6.82(0.009)	6.82(0.009)	1.84(0.175)
Sampling year 2007							
Treatment	Treatm. yr 2002	0.54(0.465)	3.17(0.075)	2.45(0.118)	0.10(0.754)	0.74(0.389)	0.27(0.602)
Treatment	Treatm. yr 2005	0.10(0.754)	0.27(0.602)	6.99(0.008)	1.32(0.251)	3.17(0.075)	0.54(0.465)
Treatm. yr	Mounding	6.82(0.009)	0.10(0.754)	1.16(0.281)	0.27(0.602)	0.55(0.459)	5.77(0.016)
Treatm. yr	Stump removal	3.15(0.076)	3.17(0.075)	7.26(0.007)	1.32(0.251)	3.23(0.072)	3.94(0.047)

Table 4. Initial Ammonium and nitrate N (mg N kg^{-1} OM), rate of net mineralization and nitrification (mg N kg^{-1} OM 6 $weeks^{-1}$), and microbial biomass C and N (g kg^{-1} OM) in the mineral soil in stump removal and stump retaining plots. Means (S.E., n=5) are shown.

Sampling year	2006		2007	
	Stumps retained	Stumps removed	Stumps retained	Stumps removed
NH_4-N				
Treated 2002	15.8(2.53)	0.61(0.43)	65.1(15.7)	22.4(13.2)
Treated 2005	99.8(40.2)	81.0(18.9)	58.9(9.94)	103.1(40.4)
NO_3-N				
Treated 2002	0.29(0.08)	0.48(0.1)	0.33(0.09)	0.09(0.09)
Treated 2005	3.14(1.53)	26.3(8.74)	0.26(0.20)	12.2(10.83)
Net mineralization				
Treated 2002	–2.97(3.01)	7.17(7.15)	52.2(9.54)	66.1(35.6)
Treated 2005	–44.7(60.1)	130.9(26.8)	60.2(13.7)	82.5(12.3)
Net nitrification				
Treated 2002	0.02(0.06)	0.66(0.68)	2.64(2.76)	10.6(10.38)
Treated 2005	11.1(4.95)	111.4(23.61)	13.1(12.32)	51.4(10.43)
Microbial C				
Treated 2002	4.09(0.36)	4.92(0.37	5.60(0.38)	6.28(0.77)
Treated 2005	4.72(0.41)	4.06(0.54)	4.35(0.22)	4.07(0.25)
Microbial N				
Treated 2002	0.48(0.03)	0.57(0.05)	0.60(0.08)	0.69(0.11)
Treated 2005	0.35(0.08)	0.46(0.09)	0.42(0.04)	0.50(0.04)

to the stump removal plots, but only in the plots treated in 2002 and only in the sampling done in 2006 (Tables 3–4). In the sampling in 2006, concentration of ammonium N was clearly higher in the plots treated in 2005 compared to those treated in 2002 (Tables 3–4). No differences between the treatments were observed in the sampling in 2007.

Concentration of nitrate-N (mg N kg^{-1} OM) was clearly higher in the stump removal plots than in the mounded ones in both samplings, but only in the plots treated in 2005 (Tables 3–4). Further, in the stump removal plots nitrate-N was higher in the soil treated in 2005 than in that treated in 2002. The same difference was also found in the mounded plots, but only in the first sampling (Tables 3–4).

In the first sampling (2006), the rate of net nitrification (mg N kg^{-1} OM 6 $weeks^{-1}$) was higher in the stump removal plots compared to the mounded plots, but only in those treated in 2005 (Tables 3–4). In addition, in the first

Table 5. Gas fluxes (methane: reduction in concentration during closure of measurement chambers as μl h^{-1} m^{-2}, nitrous oxide: concentrations as μl l^{-1} in air sample and carbon dioxide: production as μl h^{-1} m^{-2}) from the mineral soil in stump removal and stump retaining plots treated in 2005. Means (S.E., n = 5) are shown.

	Stumps retained	Stumps removed
Methane:		
Sampling 2006	35.1(14.6)	59.6(4.74)
Sampling 2007	40.7(21.7)	91.0(14.8)
Nitrous oxide:		
Sampling 2006	0.42(0.004)	0.40(0.009)
Sampling 2007	0.38(0.009)	0.35(0.004)
Carbon dioxide:		
Sampling 2007	46.8(18.3)	121.4(26.5)

sampling and in the stump removal plots, the net nitrification was higher in the plots treated in 2005 than in those treated in 2002 (Tables 3–4). In the latter sampling in 2007, no significant differences between the treatments were found in the rates of net nitrification although the same tendencies were seen (Table 4).

The rate of net N mineralization (mg N kg^{-1} OM 6 $weeks^{-1}$) was higher in the stump removal plots than in the mounded plots, but only in 2006 and plots treated in 2005 (Tables 3–4). Clear N immobilization was observed in the stump retaining plots in 2006 whereas N was mineralized in the stump removal plots (Table 4). In general, variation among the samples was high. In addition, the rate of net N mineralization was clearly higher in the plots where stumps were removed in 2005 compared to those where stumps were removed in 2002. No differences between the treatments or treatment years were found in 2007 (Tables 3–4).

The concentration of C (g kg^{-1} OM) in the microbial biomass was not affected by the treatments. In the sampling in 2007, microbial biomass C was higher in the plots treated in 2002 than in those treated in 2005 in both treatments (Tables 3–4). Treatments did not affect the concentration of N (g kg^{-1} OM) in the microbial biomass, but it was consistently higher in the plots treated in 2002 than in those treated in 2005, and higher in 2007 than in 2006 (Tables 2 and 4).

3.2 Gas Emissions

Gas fluxes from the mineral soil surfaces were measured as concentrations in the chamber air only in the study plots clear felled in 2005. Concentrations of methane decreased consistently during incubations (when the chambers were closed), and no significant differences were found between the treatments or the sampling occasions (Table 5; repeated measures ANOVA: $F = 3.77$, $p = 0.088$ and $F = 3.75$ $p = 0.089$, respectively). Somewhat more N_2O was emitted from the soil in the plots where stumps were left on site (repeated measures ANOVA: $F = 10.76$, $p = 0.011$), and emissions were slightly higher in 2006 than in 2007 in both treatments ($F = 97.32$, $p < 0.001$). In general, production of N_2O was low and concentration in the chambers hardly increased during the closing time. In the latter sampling (in 2007), more CO_2 was produced from the soil in the stump removal plots (Table 5; ANOVA: $F = 5.37$, $p = 0.049$). Unfortunately, CO_2 measurements in 2006 had to be discarded because of the failure in the gas chromatograph.

4 Discussion

Our results revealed some differences in C and N transformations between the stump removal and mounded study sites. Apparently, modern forest regeneration operations already cause substantial disturbance to the forest floor and soil, and stump removal further induces additional effects on soil physical structure, chemistry and biology (see Walmsley and Godbold 2010). Clear-cutting has been shown to increase net N mineralization and either to initiate net nitrification or increase it in boreal forest ecosystems (Vitousek and Matson 1984, Dahlgren and Driscoll 1994, Smolander et al. 1998, 2001).

The most important differences between our treatments were indeed found in net N mineralisation and nitrification already after one year; both were clearly increased in the stump removal plots. Probably the lower C:N ratio and higher N concentration in the mineral soil of the stump removal plots can explain the high N mineralisation since the difference could not be explained by differ-

ences in soil acidity or amount of soil organic matter. More substantial soil disturbance by the stump removal procedure compared to mounding and/or differences in the microbial communities in the differently treated plots evidently contributed to this difference. Strong disturbance apparently changes soil physical conditions, such as temperature and moisture conditions. It is possible that the acceleration of N mineralisation in the stump removal plots have consequences on site productivity in the future. Nitrate-N is potentially leached and thus lost from the forest ecosystem. The larger extent of exposed mineral soil in the stump removal plots increases the risk of N losses. Leaching of N would be even higher after the initial immobilization period in the stump removal sites if felling residues were left on site (Staaf and Olsson 1994).

It would also be possible that mineralized N is readily immobilized by soil microbes or utilized by the recovering and developing vegetation. During the first years after clear-cutting microbial immobilization of N is most probably a more important process than N retention by the developing vegetation in preventing N losses from the clear-cuts (Vitousek and Matson 1984, Piirainen et al. 2002). Usually the growth of vegetation, including the planted conifer seedlings, is not restricted by the availability of N during the first years after regeneration (Egnell 2011). Thus, it is not very likely that only very sparse plants could utilize the excess nitrate N already one year after the disturbance. Staaf and Olsson (1994) observed elevated nitrate N concentrations after complete-tree harvesting somewhat later than we did, NH_4-N peaking during the first two years after the treatments and NO_3-N thereafter for two years. The nitrate concentration was observed to drop along with an intensive growth of ground layer vegetation (Staaf and Olsson 1994). Thus, vegetation may have potential to restrict nutrient losses from the treated stands along with its development some years after the regeneration practices.

Egnell (2011) observed that when compared to the conventional stem-wood harvesting or harvesting of above-stump biomass except needles, the whole-tree harvesting resulted in large but temporary growth reduction in Norway spruce forests in Sweden, over a 5-year period (8–12 years after regeneration) due to increased N losses. Similar nutrient losses were obviously in the background in our experiment because nutrient rich felling residues were collected to the same degree from every study plot.

In general, stump removal is unlikely to cause serious direct nutrient losses due to the relatively low nutrient concentrations of stump wood (Egnell et al. 2007) especially if the bark of the stumps and all fine roots are left on site (Hellsten et al. 2009). The total volume of coarse woody debris was observed to decrease by 20% in our stump removal study plots (Rabinowitsch-Jokinen and Vanha-Majamaa 2010). Stumps represent, however, long-term C and N reserves in boreal coniferous forests after clear-cutting, and they can be significant N sinks potentially diminishing N leaching from the stand (Melin et al. 2009, Palviainen et al. 2010). In the long run, slowly decomposing stumps form important nutrient rich microsites increasing the heterogeneity of the forest soils (Sucre and Fox 2009), thus also offering habitats for more diverse organism communities.

On the other hand, in short-term (as was our observation period in the present study) removal of slowly decomposing wood material in stumps and main roots may not have potential to influence soil nutrient dynamics. Thus, it is evident that stronger and deeper penetrating soil disturbance is attributable to the differences between the stump removal and mounding plots. The physical disturbance of soil caused by stump removal procedure induces alterations e.g. in soil temperature and moisture conditions and consequently may cause clear changes in soil nutrient transformations and decline in soil N and other nutrients (Staaf and Olsson 1994, Hope 2007, Zabowski et al. 2008). This process is evidently attributed to elevated rates of decomposition of dead organic matter in the surface soil layers (Hope 2007).

Total concentration of soil N was higher and C:N ratio lower in our stump removal sites compared to the mounded sites. However, amount of organic matter did not differ between the treatments. Thus, the increased concentration of N was obviously related to the stronger mixing of soil layers in the stump removal procedure. As the C:N ratio is usually lower deeper in the soil (Tamminen 2000), mineral soil lifted up from

the deeper soil layers during the stump pulling procedure might have affected C:N ratio and the concentration of N of the surface soils. Possible biological nitrogen fixation is very probably too low to explain any differences in soil total N.

In our study plots, CO_2 production was higher in the stump removal plots compared to the mounded plots. Also this difference between the treatments may be attributed to more efficient mixing of soil layers in the stump pulling procedure and differences in the quality of soil organic matter and soil moisture as these factors have been shown to influence soil respiration in previous studies (e.g. Mallik and Hu 1997, Smolander et al. 2005, Jaatinen et al. 2008). However, when measured in the laboratory from the sieved soil samples no differences in the soil respiration between the treatments were observed. The laboratory measurement reflects the microbial decomposition activity under controlled conditions. Since the quality and quantity of soil organic matter are the same, this result points towards soil moisture and temperature controlled differences in the field CO_2 flux.

Our soils (in both treatments) were methane sinks (except two measurement points in 2006) indicating that the activity of forest soil high-affinity methanotrophs (Jaatinen et al. 2004) living mainly in the mineral soil layer were not differently affected by the treatments. Emissions of nitrous oxide were small as also found for other well drained forest soils (Von Arnold et al. 2005, Tate et al. 2006, Matson et al. 2009). Values were slightly lower in the stump removal plots but when taking into account the difference in the extent of the exposed mineral soil between the treatments, the difference in the N_2O emissions practically disappeared. Although our gas measurement data were limited, it can be concluded that excluding CO_2 stump removal seems not to significantly affect the fluxes of the two other common greenhouse gases previously measured in boreal forests (Tate et al. 2006, Matson et al. 2009).

Higher CO_2 production in the soil taken from the plots treated in 2002 may indicate better resources for microbes in older sites as the total amount of organic matter was not increased in the mineral soil patches in three years. Developing vegetation would have produced more resources of better quality (litter and root exudates) for higher microbial biomass.

In conclusion, the most important impact of the stump removal procedure on soil C and N dynamics is derived from the fact that stump harvesting mixes soil layers stronger and in larger area when compared to the mounding. Thus, clear acceleration of N mineralization and few smaller differences between the treatments found in the exposed mineral soil may be manifested themselves at the forest stand scale. Thus, all efforts to lower the degree of soil disturbance would be beneficial for the nutrient retention and transformation in the stand. The analyses of C and nutrient status of our study plots during the development of the next tree generation will be crucial to understand the longer term environmental impacts of stump removal. On the other hand, it should be noted that there are also other kinds of disturbed soil microhabitats in the stump removal areas as studied here, e.g. heavily compacted organic layers and double organic layers below mineral soil. Increase in harvesting of forest biomass for bioenergy production can only be based on the results derived from carefully designed forest stand scale experiments.

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