Soil Nutrient Dynamics after Harvesting and Slash Treatments in Boreal Aspen Stands

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ABSTRACT

The effects of harvesting and slash treatments on soil nutrient dynamics were assessed in boreal aspen stands growing on mesic clayey sites. Stem-only harvested stands were compared with unharvested controls according to a complete block design with three replications. Within harvested areas, four slash treatments (stem-only harvesting [SOH], whole-tree harvesting [WHT], wood chip application, and slash burns) were compared. Treatments created a gradient of slash that ranged from 52.3 Mg ha^{-1} in stem-only to 13.8 Mg ha^{-1} in control stands. The amount of slash had no effect on wood decomposition rates but was strongly associated with higher forest floor organic C, Kjeldahl N and base cation concentrations (Ca_e and Mg_e), base saturation, pH, and effective cation exchange capacity (CEC) and lower microbial C/N when control stands were compared with stem-only harvested stands. Slash burn severity was too low to significantly reduce slash loads and induce base cation release but severe enough to reduce forest floor microbial C and N concentrations (−48 and −55%, respectively) for at least one complete growing season. Slash burn also induced increases in forest floor available P (54%) concentration compared with other slash treatments. Chipping reduced forest floor microbial N concentration by 25% and increased microbial C/N by 28% but had no impact on nutrient availability. Differences between WTH and SOH were linked to the abundance of slash. Finally, the results illustrate that whatever the treatment, the amount of slash left on the ground is the main factor found to affect soil microbial community characteristics and soil nutrient availability.

Forest harvesting of nutrient-demanding species such as trembling aspen (*Populus tremuloides* Michx.) may induce large reductions in ecosystem nutrient pools (Mann et al., 1988; Stevens et al., 1995; Paré et al., 2002) and changes in nutrient dynamics (Brais et al., 1995, 2002; Bélanger et al., 2003). Stem-only harvesting, where branches and tree tops are left on the ground, can limit nutrient export (Paré et al., 2002), but after harvesting, the contribution to nutrient dynamics of slash left on the ground still needs to be investigated. Slash has been shown to increase nitrogen net mineralization rates (O'Connell et al., 2004), but slash can also induce nutrient leaching by preventing vegetation growth (Fahey et al., 1991a) or may favor nutrient immobilization by microorganisms (Vitousek and Matson, 1985; Fahey et al., 1991b). Changes in substrate quality and soil moisture and temperature after harvesting have also been shown to affect microorganism biomass and activities (Pietikäinen and Fritze, 1993; Baldock and Nelson, 1999). In boreal forests of western Quebec, where wildfires are the major natural disturbance (Bergeron, 1991; Payette, 1992), control or slash burns could partially mimic the immediate effects of wildfires on soil (MacLean et al., 1983; Brais et al., 2000) and, as such, could induce processes that are of the same magnitude and direction as those observed after a natural disturbance. Because rate of slash decomposition is dependent on slash amount, size, composition, and proximity to soil (Harmon et al., 1986; Fahey et al., 1991b), chipping of slash should increase decomposition and present a safer alternative to slash burns. Proper slash management could contribute to maintaining productivity of forest ecosystems (Niemelä, 1999) by limiting nutrient losses and would allow for synchronism between nutrient release and stand requirements (Stevens et al., 1995).

This study reports on short-term effects of clear-cut harvesting and four slash treatments on net mineralization rates, parameters of soil microorganism community, and soil nutrient status of boreal aspen stands growing on mesic clayey sites. We compared (i) unharvested control stands with stem-only harvested stands and (ii) three slash treatments after SOH (stem harvesting without further slash manipulation, slash chipping, and slash burn) and a whole-tree harvested treatment where branches with a diameter smaller than 7 cm were removed by hand after harvesting. An abundant aspen sprouting and rapid growth after disturbance (Peterson and Peterson, 1992; Brais et al., 2004) combined with high soil clay content should contribute to nutrient retention after harvesting. We also expected higher nutrient mineralization rates after slash burn and chipping than under untreated SOH and WTH treatments and higher soil nutrient inputs from slash decomposition under SOH than under WTH.

MATERIALS AND METHODS

Study Area

The study area is located in the Lake Duparquet Research and Teaching Forest in the Abitibi region of northern Quebec, 45 km northwest of Rouyn-Noranda, Quebec (48°86′–48°32′ N, 79°19′–79°30′ W). The region is situated in the mixed-wood zone of the boreal shield. The climate is continental, with mean annual temperature of 0.6°C. Annual precipitation is 823 mm, of which 639 mm falls as rain from April to November. The average frost-free period is 64 d (Environment Canada, 1993). Soils are Gray Luvisols (Cryalfs) (Agriculture Canada Expert Committee on Soil Survey, 1987) originating from glaciolacustrine clay deposits left by proglacial Lake Ojibway (Vincent and Hardy, 1977). Soil texture is that of heavy clay (>75% clay), and the forest floor is a thin mor of 27 cm.

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Abbreviations: CEC, effective cation exchange capacity; CHT, chipping harvesting treatment; PCA, principal component analysis; SB, slash-burn treatment; SOH, stem-only harvesting treatment; WTH, whole-tree harvesting treatment.

Experimental Design and Treatments

The study was conducted in aspen stands of fire origin dating from 1923 (Dansereau and Bergeron, 1993) and located on fresh clayey upland sites. Aspen represented 93% of stand basal area (see Brais et al. [2004] for a complete description of harvested stands). In the winter of 1998–1999, two levels of forest harvesting (no-harvest and SOH) were applied according to a complete-block design with three replications of each treatment (Fig. 1). Control stands and stem harvesting experimental plots were 1 and 2.5 ha, respectively (Fig. 1). In the spring of 1999, nine additional 50 × 50 m plots were located within stem-only harvested plots for slash treatments according to a complete–block, randomized design with three replications.

The slash treatments consisted of (i) SOH treatment with no additional slash manipulation, (ii) a WTH treatment where all debris between 3 and 7 cm in diameter was removed, (iii) a chipping harvesting treatment (CHT) where all debris between 3 and 7 cm in diameter was removed, and (iv) a slash-burn treatment (SB). The slash burn was conducted over the 50 × 80 m plots at the end of August 1999 by Quebec's Société de protection des forêts contre le feu. At the time of burning, air temperature was 26°C, relative air moisture was 37–42%, wind speed was 9–10 km h^{-1}, and forest floor moisture content (w/w) varied between 166 and 220%. According to the Canadian forest fire weather index system, the fine fuel moisture code was 89, and the buildup index was 24. The rate of spread was 0.5 m m^{-1}, and flame length was between 0.5 and 0.7 m. Similar conditions were observed for the three burns.

Field Methods

Five permanent circular ($r = 11.28$ m) sampling plots were located in all experimental units. Most nondestructive sampling (soil temperature and moisture, decomposition bags, and mineralization rates) was conducted within each permanent plot of each experimental unit. Destructive sampling (soil and vegetation biomass) was conducted close to but outside of each of the five permanent sampling plots. Slash inventory was conducted over the whole experimental unit.

Slash volume and mass (load) was estimated by the triangular-transect method (McRae et al., 1979) in 1999 after harvesting and slash treatments. One 30-m side triangle was sampled in each experimental plot. Along each transect, the frequency of wood pieces was recorded by species, diameter class (0–0.49, 0.5–0.99, 1–2.99, 3–4.99, 5–6.99, >7 cm) and five decomposition classes (Daniels et al., 1997). Samples of slash were brought back to the laboratory for estimates of density for each combination of species/decomposition and diameter class. In SB treatment, sampling for slash or fuel load (McRae et al., 1979) was performed before and after fire and along two triangles (30-m sides). Total slash loads are the summation of all slash included in decomposition classes 1 to 3 and summed up over all species.

Soil Moisture and Temperature

Soil was sampled for moisture content once every 2 wk from the end of May to the end of September. Bulk samples were taken from the forest floor and the 0- to 10-cm mineral soil. Soil temperatures were measured at the same time and for

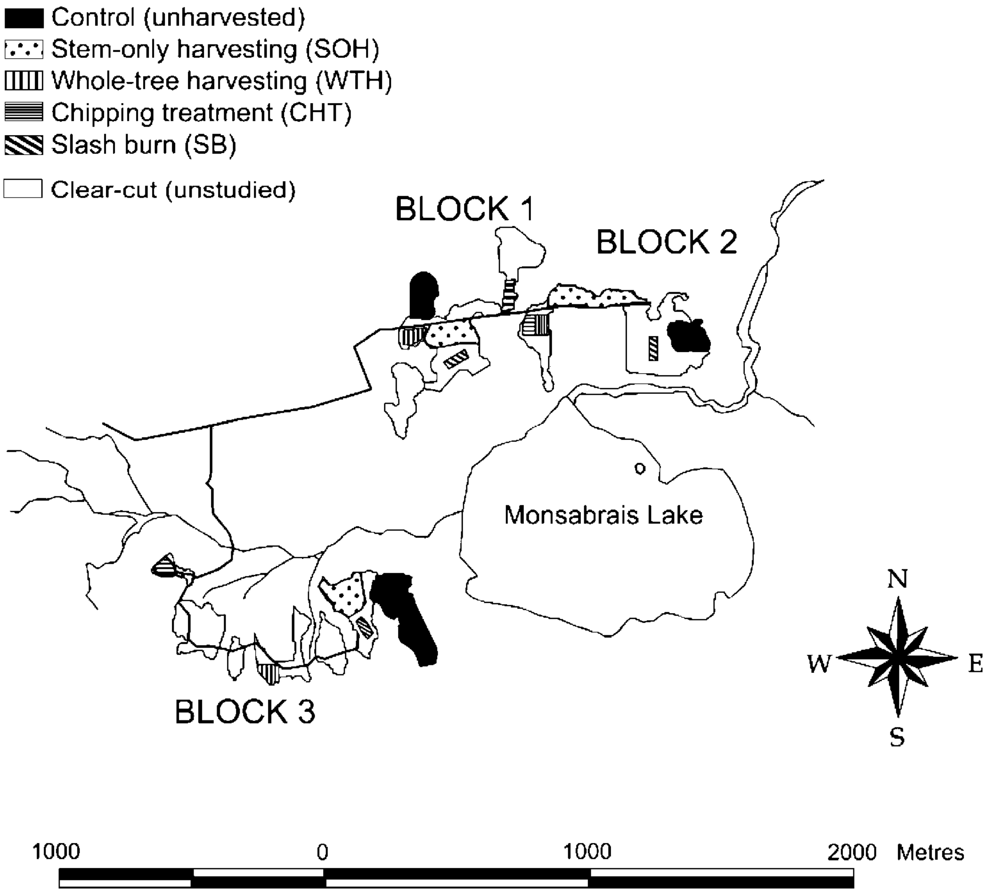

Fig. 1. Experimental design.

the same soil layers. Air temperature 1 m above the ground was measured.

Decomposition Rates

To estimate wood decomposition rates, five litter bags containing aspen wood blocks of 10 by 5 by 4 cm, and, in the chipping treatment only, five litter bags containing chips from the chipping treatment were set on the ground (Trofymow, 1998) in the summer of 1999 in each of the permanent sampling plots. A bag of each litter type was collected 1 yr later in each sampling plot for a total of five in each experimental unit. To estimate loss of organic matter from slash, wood blocks and chip dry weight losses were applied to slash and chip loads.

Understorey Vegetation Biomass Increment

Annual increment of understorey vegetation biomass (above ground) was estimated from two 0.5-m^2 quadrats located outside each sampling plot (10 per experimental unit). All vegetation within each quadrat was clipped at the base and grouped into the following categories: herbaceous plants, shrub annual growth (stem and branch yearly increments and leaves), and aspen annual growth (stem and branch yearly increments and leaves from aspen suckers <2 m tall). Different quadrats were sampled every year. Each category was weighed in the field, and a sample was kept for oven-dry weight conversion.

Soil Nutrient Concentration and Content

In the fall of 1999 and 2000 and close to each sampling plot, two forest floor samples were collected using a 25 by 25 cm template for ash-free dry weight estimation of forest floor and nutrient concentration. The forest floor samples did not include slashes or wood chips associated with slash treatments. In the chipping treatment, wood chips were collected in the same micro-quadrat and weighed separately from the rest of the forest floor. Three bulk soil samples were taken from the 0- to 10-cm mineral soil and pooled, leading to one sample per plot for mineral soil nutrient concentrations. Two undisturbed soil cores were taken from the 0- to 10-cm mineral soil for bulk density estimates.

Net Nitrogen Mineralization Rates and Microbial Parameters

Nitrogen mineralization rates were estimated by the closed top cores in situ incubation technique (Raison et al., 1987). Two cores were positioned in pairs in each sampling plot. Soils were incubated from mid-July to late October in 1999 (15 wk), from late October 1999 to late May 2000 (32 wk), and from late May 2000 to late October 2000 (23 wk). ABS cores, 30 cm long and 4.5 cm in diameter, were driven through the forest floor to a depth of 10 cm in the mineral soil. Tubes were covered with plastic to prevent rain from entering. At the beginning of each incubation period, forest floor and 0- to 10-cm mineral samples were collected beside each pair of cores for determination of initial NO_3^- and NH_4^+ concentrations and, in the fall, for additional laboratory measurements of soil microbial biomass and respiration. At the end of each period, the soil was removed from the core and forest floor material was separated from mineral soil. Samples from core pairs were pooled in the field.

Laboratory Analysis

Forest floor samples were ground (1.7 mm), and mineral soil samples were sieved (2 mm). Samples were analyzed for Kjeldahl N, including NO_2^- and NO_3^- (Bremner and Mulvaney, 1982) and for exchangeable cations (Ca_e, Mg_e, K_e, Na_e) (inductively coupled plasma atomic emission) (PerkinElmer Plasma 40) and acidity (titration; Metler DL-40) after extraction with NH_4Cl–$BaCl_2$ (Amacher et al., 1990). Effective cation exchange capacity was estimated by summing base cations and exchangeable acidity. This method allows determination of CEC at field pH and was found preferable for use on acid forest soils (Pritchett and Fisher, 1987). Extractable phosphorus BRAY II (P_{ext}) was estimated using a spectrophotometer (McKeague, 1976). Soil pH was determined in 0.01 *M* $CaCl_2$ (Hendershot et al., 1993). Organic matter (organic C = 0.58 × OM) of forest floor samples was determined by loss of ignition and organic carbon of ground mineral samples (250 μm) by wet oxidation (Yeomans and Bremner, 1988). Forest floor samples were wet-digested (Parkinson and Allen, 1975), and total phosphorus and cation concentrations (Ca_t, Mg_t, and K_t) were measured by inductively coupled plasma atomic emission. Samples from incubation cores were dried and extracted with *2M* KCl. Mineral N concentrations in KCl extractions were determined using an autoanalyzer (Kalra and Maynard, 1991).

Microbial biomass was determined on fresh samples collected in the fall by the fumigation-extraction method (Voroney et al., 1993). Microbial C was determined on K_2SO_4 extracts acidified to pH 2 with a Shimadzu carbon analyzer. Microbial N was determined according to Cabrera and Beare (1993). Correction factors were $k_{EC} = 2.86$ (Sparling et al., 1990) and $k_{EN} = 1.85$ (Brookes et al., 1985; Joergensen and Mueller, 1996).

Soil basal respiration was estimated in the laboratory on fresh samples. Ten grams of forest floor and 50 g of mineral soil were incubated in closed jars at 21°C for 24 h. Respiration was estimated from the amount of CO_2 absorbed in NaOH and determined by HCl titration (Skoog and West, 1965; Alef and Nannipieri, 1995). Jars containing NaOH but no soils were used as control.

Downed wood density was estimated from two sections from each of the 330 samples. The first section was weighed (fresh) and coated in hot paraffin before its volume was measured by water displacement. The second section was weighed (fresh) and oven dried for moisture content estimation. The density was estimated from the first section after its fresh weight was corrected for moisture content.

Statistical Analyses

Data analyses were done using GLM, MEANS and CORR, and PRINCOMP procedures of the SAS statistical package (SAS Institute Inc., 1988). Homogeneity of variance between treatments was tested using Bartlett's procedure (Steel and Torrie, 1980). Data that did not meet the requirements were log (P_{ext}, mosses, herbaceous, and shrub stem biomass) or arc sinus (base saturation) transformed. In a parallel study, Brais et al. (2004) compared control and clear-cut stands with partially harvested stands. No direct comparison was made between control and clear-cut stands. To avoid duplication, only significant results of simple ANOVA between control and clear-cut stands are presented in the next section. To assess the effects of slash treatments, a second ANOVA was conducted according to a completely randomized design with four treatments and three replications per treatment. Orthogonal contrasts between treatments were used to compare slash treatments: (i) SB was compared with the three other treatments, and (ii) chipping treatment with WTH and SOH treatments and (iii) SOH and WTH were compared together. To summarize relationships between changes induced by treatments and soil characteristics, a principal component analysis (PCA) was computed from the correlation matrix between forest floor chemical and microbial characteristics (dependent variables). Correlations between principal component scores and independent variables (slash loads and decomposition, understorey biomass, soil humidity, and temperature) were assessed.

RESULTS

As presented in Brais et al. (2004), the first growing season after harvesting (1999) was relatively hot and dry compared with the second one. In 1999, mean forest floor and mineral soil temperatures remained over 10°C from the end of May to September, and maximum soil temperatures were reached in June. In 2000, soil temperatures over 10°C were reached only in June for the forest floor and in July for the mineral layer. Maximum temperatures, observed in July, were 16.3 and 15°C for the forest floor and mineral soil, respectively. Soil moisture was higher in 2000 than in 1999.

Effects of Harvesting

In response to harvesting, we observed a significant increase ($p = 0.04$) in annual above-ground understorey vegetation biomass increments, which were 3210 ± 294 (mean ± SE) and 2520 ± 113 kg ha^{-1} in harvested stands in 1999 and 2000, respectively, and 450 and 554 kg ha^{-1} in control stands for the same years. Harvesting increased slash loads. Mean slash dry weights immediately after harvesting were 52.3 ± 4.1 and 13.8 Mg ha^{-1} for stem-only harvest and uncut control stands, respectively ($p = 0.05$). Wood block dry weight losses were 32% in harvested stands and 26% in control stands during the first growing season after harvesting. Applying wood block weight losses to initial slash loads led to estimated losses of slash dry matter of 16.2 ± 1.7 and 3.7 Mg ha^{-1} for stem-only harvested plots and control plots, respectively ($p = 0.06$).

During the first year after harvesting, a decrease in forest floor C_{mic}/N_{mic} from 8.06 ± 0.14 to 6.88 ($p = 0.05$) was observed in harvested stands. Net in situ N immobilization was observed in the forest floor of both treatments during the first growing season (control stands = −7.7 ± 30.1; harvested stands = −74.0 mg N kg^{-1} soil wk^{-1}) and in the 0- to 10-cm mineral soil (average = −7.11 ± 0.9 mg N kg^{-1} soil wk^{-1}). Net immobilization was observed again during the winter season (results not shown) and in the forest floor during the second growing season with somewhat higher values in the harvest treatment (control stands = −27 ± 0.3; harvested stands = −7.2 mg N kg^{-1} soil wk^{-1}). Low rates of net mineralization were measured in the 0- to 10-cm mineral soil. Little nitrification was observed in any of the treatments during the study period.

In the first year after harvesting, a small but significant decrease in K_T (from 1.21 ± 0.01 to 1.11 g kg^{-1}, $p = 0.05$) and a large increase in extractable P (from 60.5 ± 0.1 to 80.5 mg kg^{-1}, $p < 0.01$) were observed in harvested stands. During the second growing season, harvesting increased forest floor organic C, Kjeldahl N and base cation concentrations (Ca_e and Mg_e), base saturation, pH, and effective CEC (Table 1). Two years after harvesting, no significant changes in mineral soil characteristics were observed.

Table 1. Significant changes in forest floor nutrient characteristics 2 yr after stem-only harvesting of aspen stands on clayey soils.

	Control	Clear-cut	SE	$p > F$
Soil parameters	$\bar{X}(n = 3)$			
Total nutrients				
C_{org}, g kg^{-1}	440.72	506.85	10.30	0.085
N_T, g kg^{-1}	14.71	17.39	0.35	0.062
Extractable nutrients				
Ca_e, cmol(+) kg^{-1}	53.39	86.60	1.97	0.014
Mg_e, cmol(+) kg^{-1}	6.65	9.06	0.08	0.004
Acidity and related parameters				
pH	5.0	5.9	0.07	0.020
CEC_e, cmol(+) kg^{-1}	62.89	97.94	1.93	0.012
SB, %	98.87	99.90	0.15	0.079

Effects of Slash Treatments

Overall, burns affected 70% of SB area. Compared with pre-burn values, burns decreased forest floor dry weight (ash free) by 6.74 ± 1.24 Mg ha^{-1} ($P > T = 0.161$) or 15% and fine debris (0–0.99 cm diameter) loads by 12% but had no effect on medium and coarse slash loads (Belleau, 2002). Overall, compared with pre-burn values, total slash loads were reduced by 4 Mg ha^{-1}. Nonetheless, slash burn had on average higher medium (3.0–6.99 cm diameter) slash loads than the three other treatments (Table 2). Decreases in medium slash loads after chipping were compensated for by chips returned to the sites (Table 2). Total slash load after WTH was 34% lower than under SOH.

No significant differences in soil temperature and moisture content were observed among slash treatments, and no significant differences in decomposition rates (wood block dry weight losses) were observed the first

Table 2. Forest floor and fresh slash loads after slash treatments in harvested aspen stands. A priori comparisons by means of orthogonal contrasts ($p > F$).

	Slash burn‡	Chipping	Stem-only harvest	Whole-tree harvest	SE
	$\bar{X}$ ($n = 3$)				
Contrasts§	**A**	**b**	**c**	**c**	
Ash-free forest floor dry weight, Mg ha^{-1}	37.7	62.0	46.4	33.4	5.5
Slash loads by diameter class, Mg ha^{-1}					
Fine (0–2.99 cm)	15.8	12.5	18.9	12.7	1.3
Medium (3.0–6.99 cm)	14.2***	5.8	11.1*	2.9	0.5
Coarse (>7 cm)	20.2	18.3	22.4	15.8	3.0
Total slash load, Mg ha^{-1}	50.1	36.6	52.3†	31.4	3.5
Chip load, Mg ha^{-1}		8.9			
Wood decomposition rates, % of dry weight					
Blocks	33.8	31.5	31.2	31.2	1.2
Chips		33.7			
Slash dry weight loss, Mg ha^{-1}	16.9	14.7¶	16.2	9.9	1.3

* Significant at the 0.05 probability level.
*** *Significant at the* 0.001 probability level.
† Significant at the 0.1 probability level.
‡ Residue loads have been evaluated after burn.
§ See statistical analyses for description of orthogonal contrasts.
¶ Includes chip weight losses.

year after implementation of the treatments (Table 2). No significant differences in slash dry weight losses were observed among any of the slash treatments.

In the second year after treatments, understorey vegetation biomass increment amounted to 3230, 2520, 2459, and 2425 kg ha^{-1} under WTH, SOH, CHT, and SB, respectively. No significant differences between treatments were observed. Slash burn biomass increment was delayed in 2000, the first growing season after fire, with decreases of 73 ± 86.4% ($p = 0.07$) and 92 ± 0.25% ($p < 0.01$) respectively, in shrub and moss biomass relative to other treatments. However, herbaceous biomass was 30% higher in SB than in the other treatments.

Slash burn induced immediate and significant decreases in forest floor organic concentrations of C (−14%, Fig. 2) and microbial C and N (−48 and −55%, respectively) (Fig. 3) and in forest floor basal respiration (−37%), whereas the microbial biomass respiratory quotient increased by 20% (Fig. 3). Differences in microbial C and N concentrations and basal respiration between SB and other slash treatments remained significant throughout the next growing season, and SB also resulted in positive

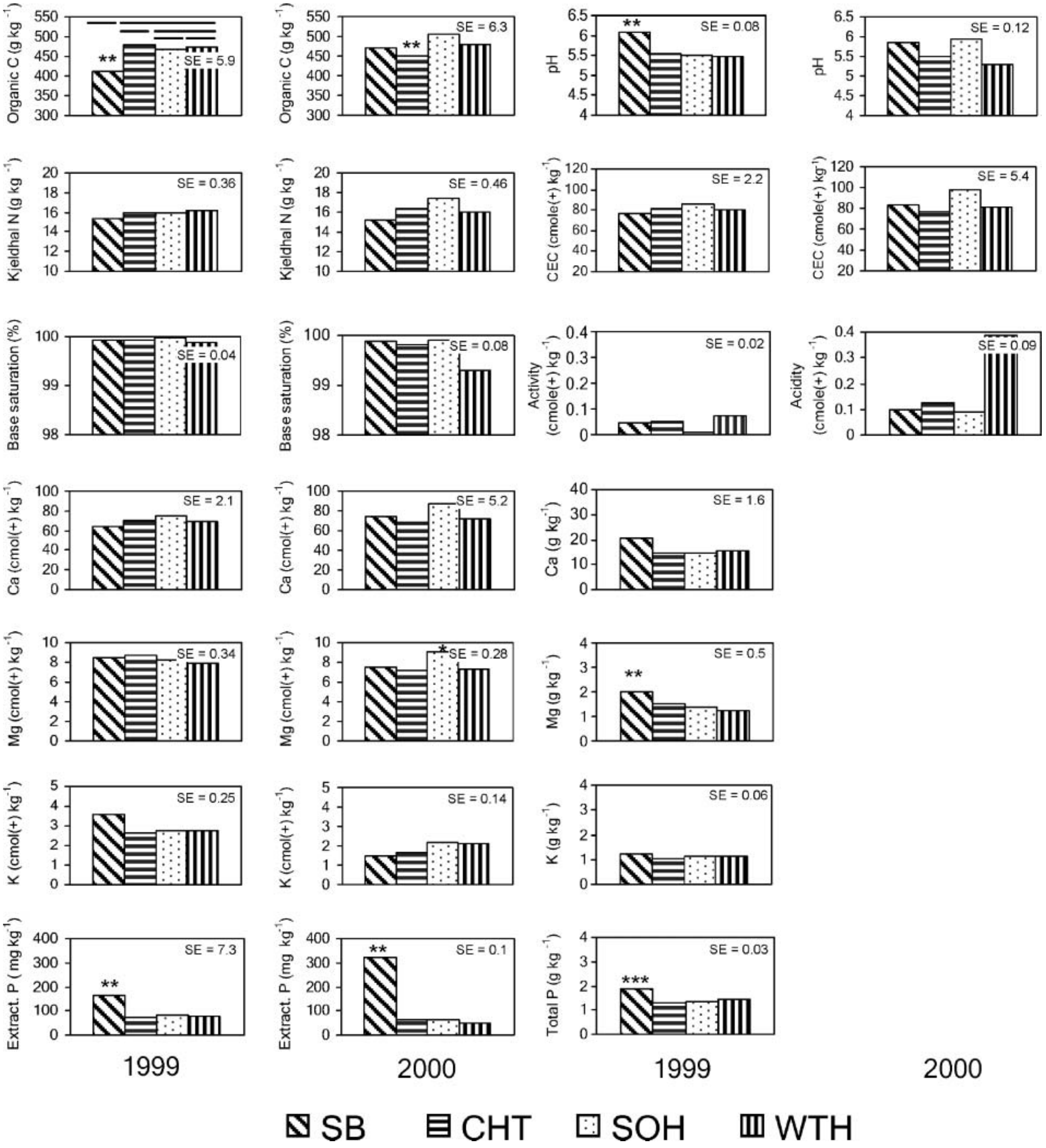

Fig. 2. Slash treatment effects on forest floor characteristics. SB, slash burn; CHT, chipping; SE, population standard error; SOH, stem-only; WHT; whole-tree harvesting. Lines = orthogonal contrast between treatments. See Methods section for contrast descriptions. Contrast significance levels: $*p = 0.1$; $**p = 0.05$; $***p = 0.001$ ($n = 12$).

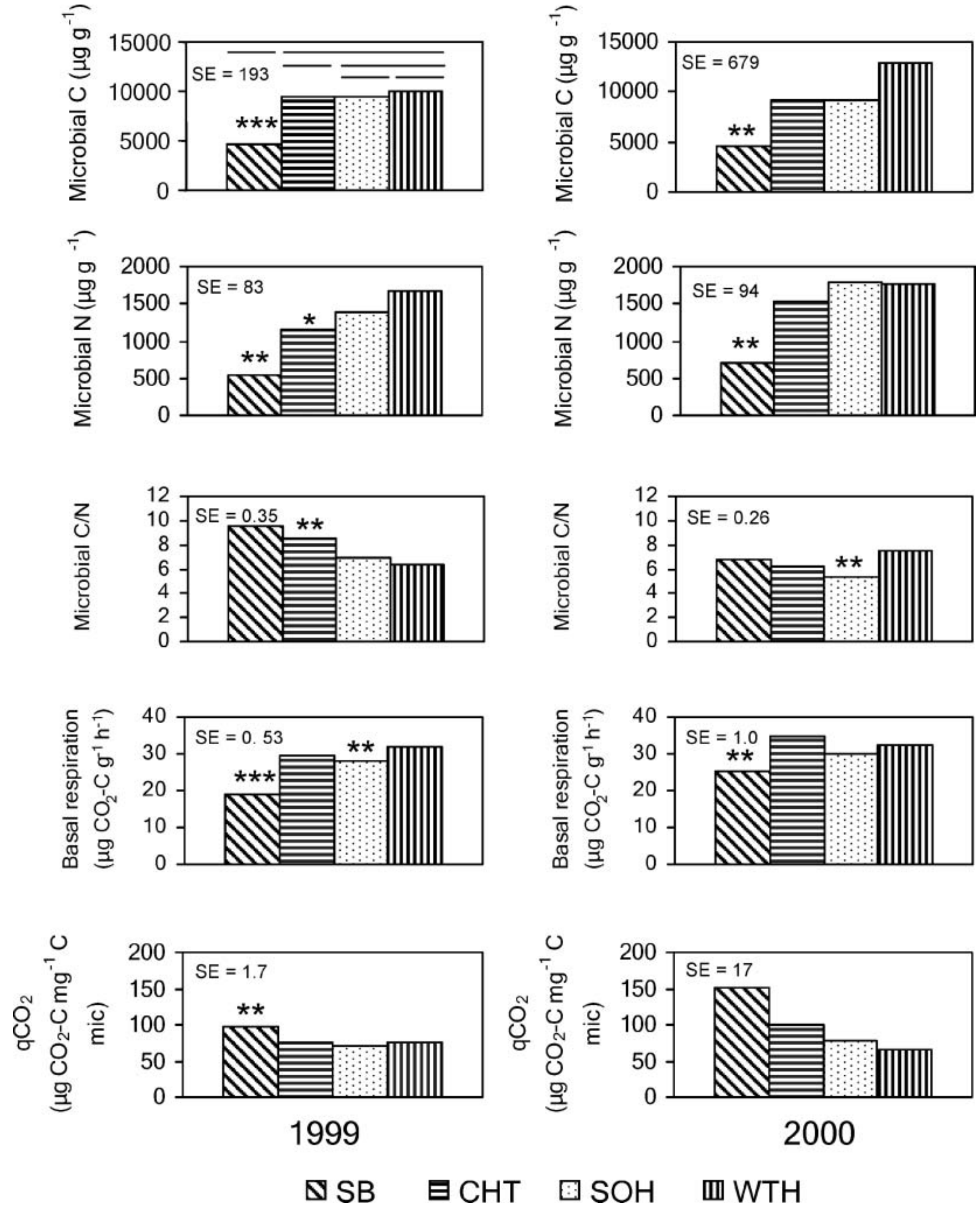

Fig. 3. Slash treatment effects on forest floor microbial community. SB, slash burn; SE, population standard error; CHT, chipping; SOH, stem-only; WHT, whole-tree harvesting. Lines = orthogonal contrast between treatments. See Methods section for contrast descriptions. Contrast significance levels: *p = 0.1; **p = 0.05; ***p = 0.001 (n = 12).

net N mineralization in the forest floor (Table 3). Immediately after SB, forest floor–extractable P, total P, and total Mg concentrations increased by 54, 27, and 40%, respectively, and forest floor pH increased by 0.6 units (Fig. 2). Extractable P forest floor concentrations remained higher throughout the year after burning. Slash burn had no significant effects on extractable base cation concentrations (Fig. 2).

Chipping induced temporary changes in forest floor microbial N and C/N ratio (Fig. 3). At the end of the first growing season, forest floor microbial N concentration was 25% lower and microbial C/N 28% higher than average values observed under SOH and WTH. A small decrease in organic C was also observed at the end of the second growing season (Fig. 2). Chipping had no effect on forest floor N net mineralization rates (Table 3) or on extractable base cation and P concentrations (Fig. 2).

Besides a slight but significant higher basal respiration rate under WTH, no differences in forest floor microbial community characteristics (Fig. 3) and nutrient concentrations (Fig. 2) were observed between SOH and WTH during the first growing season (Fig. 2). In the following year, forest floor microbial C/N increased while extractable base cation concentrations decreased under WTH,

Table 3. Slash treatment effects on in situ net N mineralization rates 1 and 2 yr after harvesting of aspen stands. A priori comparisons by means of orthogonal contrasts ($p > F$).†

	Net N mineralization rates $[\mathrm{mg\ N_{(NH4+NO3)}\ kg^{-1}\ soil\ wk}]^{-1}$				
	SB	CHT	SOH	WTH	SE
	$\bar{X}$ (n = 3)				
Forest floor					
Contrasts	a	B	c	c	
Summer 1999	n/a	−1.5	−74.0	−1.8	25.7
Winter 1999–2000	0.1	1.2	−0.5	−0.6	0.4
Summer 2000	0.7*	−5.8	−7.2	−6.6	0.7
Mineral soil (0–10 cm)					
Summer 1999	n/a	−0.25	−8.80	−0.41	1.75
Winter 1999–2000	−1.76	−1.61	−1.10	−1.68	0.15
Summer 2000	−0.13	0.03	0.03	−0.12	0.08

* Significant at the 0.05 probability level.

† CHT, chipping harvesting treatment; SB, slash-burn treatment; SE, standard error; SOH, stem-only harvesting treatment; WTH, whole-tree harvesting treatment.

although the reduction was only significant for exchangeable Mg (Fig. 2).

Slash treatments had little immediate effect on nutrient dynamics in the 0- to 10-cm mineral soil. Nonetheless, higher exchangeable acidity values were observed for both growing seasons (p = 0.06; p = 0.02) under WTH (1.65 and 1.78 cmol[+] kg^{-1} for 1999 and 2000) than under SOH (0.76 and 0.72 cmol[+] kg^{-1} for 1999 and 2000).

Overall Effects of Slash Treatments on Forest Floor Nutrient Status and Microbial Community

The first component of PCA (Component 1; Fig. 4 and Table 4) explained 32% of forest floor characteristic variance and was correlated to forest floor pH; effective CEC; and concentrations of organic C, Kjeldahl N, exchangeable Ca, and exchangeable Mg. The second component explained 29% of forest floor variance and was positively correlated to microbial respiratory coefficient, extractable P, net N mineralization rate, and pH and was negatively correlated to forest floor–exchangeable K, microbial N, and microbial C concentrations. Ordination of experimental units on the two first principal components (Fig. 4) showed a clear differentiation between control unharvested plots (negative values on Component 1, lower nutrient and C concentrations and pH) and stem-only harvested units (positive values on Component 1, higher nutrient concentrations and pH). Slash burn and chipping experimental plots were found at the center or to the left of Component 1. Component 2 differentiated between SB (low microbial N and C and high respiratory coefficient, high extractable P, net N mineralization) and all of the other treatments. The first component was correlated to slash loads, slash dry weight loss, and forest floor average water content. The second component was not correlated to any of the independent variables but was clearly linked to slash combustion. No significant correlations were found between soil temperature or biomass increment and any of the components.

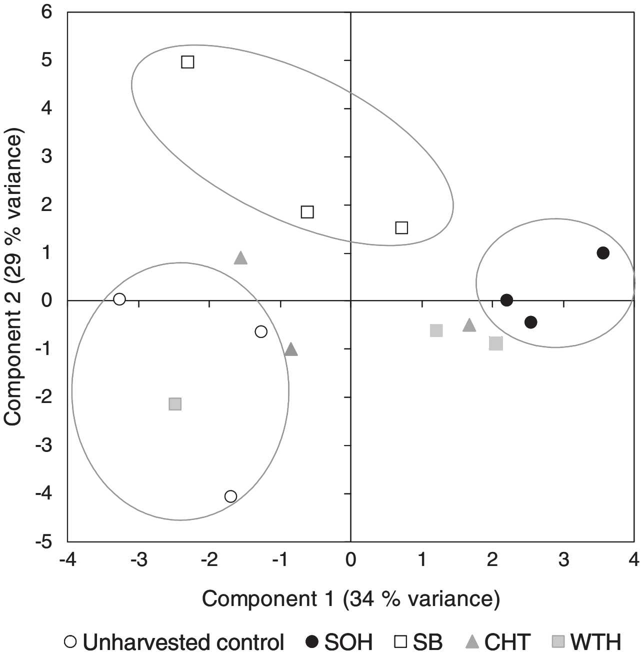

Fig. 4. Principal component analysis of forest floor properties after harvesting and four slash treatments. Gray ellipses show the influence zone of segregate treatment types. SB, slash burn; CHT, chipping; SOH, stem-only; WHT, whole-tree harvesting.

Table 4. Correlation between forest floor characteristics and principal components (see Fig. 4) derived from these characteristics and between principal components and independent variables.

	Component 1 (32% of variance)		Component 2 (29% of variance)	
	r value	p value	r value	p value
Forest floor characteristics				
pH	0.70	0.004	0.64	0.011
Effective CEC†	0.91	<0.001	0.30	0.273
Organic C concentration	0.73	0.002	−0.03	0.908
Kjeldahl N concentration	0.76	0.001	−0.31	0.257
Exchangeable Ca concentration	0.89	<0.001	0.32	0.249
Exchangeable Mg concentration	0.76	0.001	0.39	0.147
Exchangeable K concentration	0.19	0.497	−0.55	0.035
Microbial N concentration	0.44	0.099	−0.68	0.005
Microbial C concentration	0.13	0.638	−0.83	<0.001
Microbial C/N	−0.33	0.232	−0.47	0.078
Basal respiration	0.01	0.978	−0.28	0.305
Microbial respiratory coefficient	−0.24	0.383	0.70	0.004
Extractable P concentration	−0.31	0.258	0.77	<0.001
N net mineralization rate	−0.47	0.080	0.55	0.032
Independent variables				
Forest floor average temperature	0.07	0.811	−0.02	0.941
Forest floor average moisture content	0.63	0.012	−0.07	0.797
Slash load	0.53	0.040	0.50	0.059
Decomposition rate	0.34	0.210	0.46	0.086
Slash weight losses	0.53	0.042	0.48	0.073
Understorey vegetation biomass increment	0.38	0.161	0.16	0.577

† CEC, cation exchange capacity.

DISCUSSION

Effects of Harvesting

Short-term changes in forest floor nutrient dynamics after harvesting can be attributed to a number of factors, including increases in decomposition and mineralization rates, decreases in plant and microbial uptake, or nutrient leaching from woody debris (Abbott and Crossley, 1982; Burger and Pritchett, 1984; Keenan and Kimmins, 1993; Prescott, 1997). Despite increases in forest floor temperature and water content (Brais et al., 2004), decomposition rates were not affected by harvesting, and, contrary to what would be expected after disturbance (Mann et al., 1988), net N immobilization was observed in harvested stands. Net nitrogen immobilization was consistently higher after harvesting, although not significantly so. Nitrogen leaching from fresh logging slash and subsequent forest floor immobilization could have induced the observed increase in forest floor total organic (Kjeldahl) N. The latter process is plausible because aspen branches release N during the first years of decomposition (Miller, 1983). Such increases have also been reported by Adams and Boyle (1982), Hornbeck and Kropelin (1982), Silkworth and Grigal (1982), and Titus et al. (1997). Leaching of water-soluble organic C from fresh slash, an easily accessible source of energy for soil microorganisms (Huang and Schoenau, 1996), coupled with a reduction in tree root exudation (Bååth, 1980) and root capacity to support ectomycorrhizae (Harvey et al., 1980) and changes in forest floor acidity, could have induced the observed changes in the microbial C/N ratio. The decrease in microbial C/N ratio that we observed after harvesting is believed to reflect a change toward a community where the ratio of bacteria to fungi is higher (Marumoto et al., 1982). Hassett and Zak (2005) observed similar changes in community structure 8 yr after harvesting of aspen stands in Michigan. Changes in community structure did not affect the community's ability to function because no changes in basal respiration or respiratory coefficient were observed after harvesting.

Increases in forest floor Mg and Ca concentrations observed after harvesting were also linked to the amount of slash left on the ground (Fig. 4). No mechanism can be provided for the short-term increase in extractable phosphorus. Higher forest floor effective CEC and understorey vegetation biomass increment after harvesting contributed to nutrient immobilization, and, with the absence of forest floor disturbance, may account for the lack of changes in mineral soil properties. On the other hand, slash decomposition in harvested stands is of short duration, whereas a continuous input of organic matter from coarse woody debris is expected to take place in unharvested stands. Long-term reductions in soil C and N content were observed after harvesting of stands of similar composition growing on fine-textured soils in western Canada (Pennock and van Kessel, 1997).

Slash Treatment Effects

Slash burn severity was low, and burns did not significantly reduce the amount of slash when compared with amounts left by other slash treatments. Nonetheless, combustion induced changes in soil microbial community as shown by the distinct position of slash burns on the second PCA axis. Forest floor microbial biomass was reduced by combustion and presented a higher respiratory coefficient. Similar decreases in microbial biomass after burning have been reported for boreal forests (Pietikäinen and Fritze, 1993). Short-term changes in the forest floor microbial community resulted in a reduced net N immobilization rate after fire, although no significant differences have been observed between slash burns and other slash treatments in forest floor Kjeldahl N concentrations. Increases in Ca and Mg availability were observed when forest floor pre-burn values were compared with post-burn values (Belleau, 2002), but post-burn values were within the range of those observed under other slash treatments. Sudden increases in phosphorus after fire have been reported by Romanyà et al. (1994), Cade-Menun et al. (2000), Giardina and Rhoades (2001), and Simard et al. (2001). High P concentrations after fire may be linked to high concentrations of P in fine ashes that are rapidly returned to the soil surface (Carter and Foster, 2004). Response of herbaceous species after fire, notably pyrophilous *Geranium bicknellii* (Britton), was swift, as indicated by the high herbaceous biomasses observed in slash burns. Higher P availability and reduced microbial competition for N may have contributed to herbaceous vegetation response.

The effects of slash chipping or of residual understorey vegetation on soil have been studied by Brais et al. (1996), Corns and Maynard (1998), Scherer et al. (2000), and Zabowski et al. (2000). Differences in techniques and amount of chips spread on the ground make comparisons difficult. In this study, slash fragmentation did not result in increased decomposition rates and nutrient release. However, a higher C_{mic}/N_{mic} ratio under the chipping treatment than under WHO and SOH suggested changes in soil microbial community composition shifting toward a higher proportion of fungi. Fungi colonizing chip surfaces could have acted as a sink for soluble organic C (Harmon et al., 1986), explaining the lower forest floor C concentration observed under this treatment. Chip C and N concentrations were not measured in this study, but Corns and Maynard (1998) have observed N immobilization within aspen chips in a similar study.

Slash loads under WTH were intermediary between that of SOH and control stands, and differences between WTH and SOH in forest floor microbial community structure and basic cation concentrations were linked to the abundance of slash loads and forest floor water content (Fig. 4), with higher forest floor concentrations under higher loads. Higher forest floor organic C and base cation concentrations are often reported for SOH when compared with WTH (Bélanger et al., 2003), whereas WTH harvesting may show little difference in nutrient dynamics when compared with unharvested stands (Hendrickson et al., 1989). Results from Bélanger et al. (2003) were obtained in black spruce stands, indicating that rapid nutrient leaching from slash is not limited to faster decomposing species. Increases in vegetation biomass and plant nutrient uptake under WTH could account for differences in nutrient availability between WTH and SOH (Stevens et al., 1995; Titus et al., 1997), but this was not the case here.

The rapid increase in mineral soil exchangeable acidity under WTH could not be linked solely to slash decomposition dynamics or nutrient uptake. Mineral soil changes in acidity after WTH may reflect complex interactions between slash loads and decomposition, vegetation uptake, and disruption of root networks induced by harvesting.

In our experimental design, the level of replication was low, which is inherent to large experimental designs that are made to study the effect of forest practices on ecosystem processes (e.g., Emend: Volney et al., 1999; North American Long-Term Soil Productivity: Powers, 1999; Hubbard Brook Experimental Forest: Likens and Bormann, 1995). The low level of replication generated a low power and a high probability for type II error. Therefore, the effects that were significant in the present study were strong, and we could have missed some moderate effects of treatment. On the other hand, because the study was conducted immediately after treatment, it is likely that weaker effects vanished with increasing time since disturbance. A longer-term follow-up is required to determine the effects that are persistent throughout a forest rotation cycle.

CONCLUSIONS

Slash burns had distinct effects on nutrient dynamics that none of the other treatments could mimic. We do not know if these effects are critical for long-term soil fertility. Slash burn application in aspen stands on rich sites may be limited by slash humidity immediately after harvesting and vegetation growth early in the growing season. Burning also killed most aspen suckers, and its applicability to naturally regenerating aspen stands is limited. Independently from combustion, the amount of slash left on the ground was the main factor driving forest floor base nutrient dynamics in the years immediately after harvesting. Slash reduced forest floor acidity and increased basic cation availability. Although SOH may leave large amounts of slash on these upland mesic sites, slash did not reduce soil temperature and limit aspen growth. Rapid understorey biomass response and effective CEC limited nutrient leaching after SOH. Although it is not clear if base cation availability is a limiting factor in the early phase of aspen stand establishment, in the longer term, SOH could alleviate nutrient losses induced by harvesting (Paré et al., 2002). Chipping did not improve nutrient availability or reduce vegetation competition, and its application did not result in any tangible immediate advantage. On the other hand, with SOH, slash is often piled in skidding trails, and chipping might improve its distribution in cutovers.

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REFERENCES

Abbott, D.T., and D.A. Crossley, Jr. 1982. Woody litter decomposition following clear-cutting. Ecology 63:35–42.

Adams, P.W., and J.R. Boyle. 1982. Soil fertility changes following clearcut and whole-tree harvesting and burning in central Michigan. Soil Sci. Soc. Am. J. 46:638–640.

Agriculture Canada Expert Committee on Soil Survey. 1987. The Canadian system of soil classification. 2nd ed. Agriculture Canada, Publ. No. 1646.

Alef, K., and P. Nannipieri. 1995. Methods in applied soil microbiology and biochemistry. Academic Press Limited, London.

Amacher, M.C., R.E. Henderson, M.D. Breithaupt, C.L. Seale, and J.M. LaBauve. 1990. Unbuffered and buffered salt methods of exchangeable cations and effective cation-exchange capacity. Soil Sci. Soc. Am. J. 54:1036–1042.

Baldock, J.A., and P.N. Nelson. 1999. Soil organic matter. p. B-25–B-84. *In* M.E. Sumner (ed.) Handbook of soil science. CRC Press, Boca Raton, Florida.

Bååth, E. 1980. Soil fungal biomass after clear-cutting of a pine forest in central Sweden. Soil Biol. Biochem. 12:495–500.

Bélanger, N., D. Paré, and S.H. Yamasaki. 2003. The soil acid-base status of boreal black spruce stands after whole-tree and stem-only harvesting. Can. J. For. Res. 33:1874–1879.

Belleau, A. 2002. Impacts de divers traitements de résidus ligneux sur les sols de peuplements de peuplier faux-tremble. Mémoire présenté comme exigence partielle à M. Sc. Biologique, Université du Québec en Abitibi-Témiscamingue, Rouyn-Noranda, Québec.

Bergeron, Y. 1991. The influence of island and mainland lakeshore landscapes on boreal forest fire regimes. Ecology 72:1980–1992.

Brais, S., C. Camiré, and D. Paré. 1995. Impacts of whole-tree harvesting and winter windrowing on soil pH and base status of clayey sites of northwestern Quebec. Can. J. For. Res. 25:997–1007.

Brais, S., B. Harvey, and F. Tremblay. 1996. Étude des relations entre l'intensité de la préparation de terrain et les impacts sur les sols, la végétation compétitive et la croissance des plants. Projet EETTF no. 4010, Service Canadien des Forêts, Ressources Naturelles Canada.

Brais, S., D. Paré, and R. Ouimet. 2000. Impacts of wild fire severity and salvage harvesting on the nutrient balance of jack pine and black spruce boreal stands. For. Ecol. Manage. 137:231–243.

Brais, S., D. Paré, C. Camiré, P. Rochon, and C. Vasseur. 2002. Nitrogen net mineralization and dynamics following whole-tree harvesting and winter windrowing on clayey sites of northwestern Quebec. For. Ecol. Manage. 157:119–130.

Brais, S., B.D. Harvey, Y. Bergeron, C. Messier, D. Greene, A. Belleau, and D. Paré. 2004. Testing ecosystem management in boreal mixed woods of northwestern Quebec: Initial response of aspen stands to different levels of harvesting. Can. J. For. Res. 34:431–446.

Bremner, J.M., and C.S. Mulvaney. 1982. Nitrogen-total p. 505–624. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. Agron. Monogr. No. 9, ASA and SSSA, Madison, WI.

Brookes, P.C., A. Landman, G. Pruden, and D.S. Jenkinson. 1985. Chloroform fumigation and the release of soil nitrogen: A rapid direct extraction method to measure microbial biomass nitrogen in soil. Soil Biol. Biochem. 17:837–842.

Burger, J.A., and W.L. Pritchett. 1984. Effects of clearfelling and site preparation on nitrogen mineralization in a southern pine stand. Soil Sci. Soc. Am. J. 48:1432–1437.

Cabrera, M.L., and M.H. Beare. 1993. Alkaline persulfate oxidation for determining total nitrogen in microbial biomass extracts. Soil Sci. Soc. Am. J. 57:1007–1012.

Cade-Menun, B.J., S.M. Berch, C.M. Preston, and L.M. Lavkulich. 2000. Phosphorus forms and related soil chemistry of podzolic soils on northern Vancouver Island. II. The effects of clear-cutting and burning. Can. J. For. Res. 30:1726–1741.

Carter, M.C., and C.D. Foster. 2004. Prescribed burning and productivity in southern pine forests: A review. For. Ecol. Manage. 191: 93–109.

Corns, I.G.W., and D.G. Maynard. 1998. Effects of soil compaction and chipped aspen residue on aspen regeneration and soil nutrients. Can. J. Soil Sci. 78:85–92.

Daniels, L.D., J. Dobry, K. Klinka, and M.C. Feller. 1997. Determining year of death of logs and snags of *Thuja plicata* in southwestern coastal British Columbia. Can. J. For. Res. 27:1132–1141.

Dansereau, P.-R., and Y. Bergeron. 1993. Fire history in the southern boreal forest of northwestern Quebec. Can. J. For. Res. 23:25–32.

Environment Canada. 1993. Normales climatiques au Canada, 1961–1990. Service de l'environnement atmosphérique, Ottawa, ON.

Fahey, T.J., P.A. Stevens, M. Hornung, and P. Rowland. 1991a. Decomposition and nutrient release from logging residue following conventional harvest of Sitka spruce in North Wales. Forestry 64: 289–301.

Fahey, T.J., M.O. Hill, P.A. Stevens, M. Hornung, and P. Rowland. 1991b. Nutrient accumulation in vegetation following conventional and whole-tree harvest of Sitka spruce plantations in North Wales. Forestry 64:271–288.

Giardina, C.P., and C.C. Rhoades. 2001. Clear cutting and burning affect nitrogen supply, phosphorus fractions and seedling growth in soils from a Wyoming lodgepole pine forest. For. Ecol. Manage. 140:19–28.

Harmon, M.E., J.F. Franklin, F.J. Swanson, P. Sollins, S.V. Gregory, J.D. Lattin, N.H. Anderson, S.P. Cline, N.G. Aumen, J.R. Sedell, G.W. Lienkaaemper, K. Cromack, and K.W. Cummins. 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. 15: 133–302.

Harvey, A.E., M.F. Jurgensen, and M.J. Larsen. 1980. Clearcut harvesting and ectomycorrhizae: Survival of activity on residual roots and influence on a bordering forest stand in western Montana. Can. J. For. Res. 10:300–303.

Hassett, J.E., and D.R. Zak. 2005. Aspen harvest intensity deceases microbial biomass, extracellular enzyme activity, and soil nitrogen cycling. Soil Sci. Soc. Am. J. 69:227–235.

Hendershot, W.H., H. Lalande, and M. Duquette. 1993. Soil reaction and exchangeable acidity. p. 141–145. *In* M.R. Carter (ed.) Soil sampling and methods of analysis. Canadian Society of Soil Science, Lewis Publishers, London.

Hendrickson, O.Q., L. Chatarpaul, and D. Burgess. 1989. Nutrient cycling following whole-tree and conventional harvest in northern mixed forest. Can. J. For. Res. 19:725–735.

Hornbeck, J.W., and W. Kropelin. 1982. Nutrient removal and leaching from a whole-tree harvest of northern hardwoods. J. Environ. Qual. 11:309–316.

Huang, W.Z., and J.J. Schoenau. 1996. Distribution of water-soluble organic carbon in an aspen forest soil. Can. J. For. Res. 26:1266–1272.

Joergensen, R.G., and T. Mueller. 1996. The fumigation-extraction method to estimate soil microbial biomass: Calibration of the k_{EN}–value. Soil Biol. Biochem. 28:33–37.

Kalra, Y.P., and D.G. Maynard. 1991. Methods manual for forest soil and plant analysis. Forestry Canada, Northern Forestry Centre. Inf. Rep. NOR-X-319.

Keenan, R.J., and J.P. Kimmins. 1993. The ecological effects of clearcutting. Environ. Rev. 1:121–144.

Likens, G.E., and F.H. Bormann. 1995. Biogeochemistry of a forested watershed. Springer, New York.

MacLean, D.A., S.J. Woodley, M.G. Weber, and R.W. Wein. 1983. Fire and nutrient cycling. p. 111–132. *In* R.W. Wein and D.A. MacLean (ed.) The role of fire in northern circumpolar ecosystems. John Wiley & Sons Ltd, New York.

Mann, L.K., D.W. Johnson, D.C. West, D.W. Cole, J.W. Hornbeck, C.W. Martin, H. Riekerk, C.T. Smith, W.T. Swank, L.M. Tritton, and D.H. Van Lear. 1988. Effects of whole-tree and stem-only clearcutting on postharvest hydrologic losses, nutrient capital, and regrowth. For. Sci. 34:412–428.

Marumoto, T., J.P.E. Anderson, and K.H. Domsch. 1982. Decomposition of ^{14}C- and ^{15}N-labelled microbial cells in soil. Soil Biol. Biochem. 14:461–467.

McKeague, J.A. 1976. Manual of soil sampling and methods of analysis. Canadian Society of Soil Science, Ottawa, ON.

McRae, D.J., M.E. Alexander, and B.J. Stocks. 1979. Measurement and description of fuels and fire behavior on prescribed burns: A handbook. Great Lakes Forest Research Centre, Canadian Forestry Service. Inf. Rep. O-X-287.

Miller, W.E. 1983. Decomposition rates of aspen bole and branch litter. For. Sci. 29:351–356.

Niemelä, J. 1999. Management in relation to disturbance in the boreal forest. For. Ecol. Manage. 115:127–134.

O'Connell, A.M., T.S. Grove, D.S. Mendham, and S.J. Rance. 2004. Impact of harvest residue management on soil nitrogen dynamics in *Eucalyptus globulus* plantations in south western Australia. Soil Biol. Biochem. 36:39–48.

Paré, D., P. Rochon, and S. Brais. 2002. Assessing the geochemical balance of managed boreal forests. Ecol. Indic. 1:293–311.

Parkinson, J.A., and S.E. Allen. 1975. A wet oxidation procedure suitable for the determination of nitrogen and mineral nutrients in biological material. Commun. Soil Sci. Plant Anal. 6:1–11.

Payette, S. 1992. Fire as a controlling process in the North American boreal forest. p. 144–169. *In* H.H. Shugart et al. (ed.) A systems analysis of the global boreal forest. Cambridge Univ. Press, Cambridge, UK.

Pennock, D.J., and C. van Kessel. 1997. Clear-cut forest harvest impacts on soil quality indicators in the mixedwood forest of Saskatchewan, Canada. Geoderma 75:13–32.

Peterson, E.B., and N.M. Peterson. 1992. Ecology, management, and use of aspen and balsam poplar in the Prairie Provinces, Canada. Special Report 1. Forestry Canada, Northwest Region, Northern Forestry Centre, Edmonton, Alberta.

Pietikäinen, J., and H. Fritze. 1993. Microbial biomass and activity in the humus layer following burning: Short-term effects of two different fires. Can. J. For. Res. 23:1275–1285.

Powers, R.F. 1999. If you build it, will they come? Survival skills for silvicultural studies. For. Chron. 75:367–373.

Prescott, C.E. 1997. Effects of clearcutting and alternative silvicultural systems on rates of decomposition and nitrogen mineralization in a coastal montane coniferous forest. For. Ecol. Manage. 95:253–260.

Pritchett, W.L., and R.F. Fisher. 1987. Properties and management of forest soils. 2nd ed. J. Wiley and Son, New York.

Raison, R.J., M.J. Connell, and P.K. Khanna. 1987. Methodology for studying fluxes of soil mineral-N *in situ*. Soil Biol. Biochem. 19: 521–530.

Romanyà, J., P.K. Khanna, and R.J. Raison. 1994. Effects of slash burning on soil phosphorus fractions and sorption and desorption of phosphorus. For. Ecol. Manage. 65:89–103.

SAS Institute Inc. 1988. SAS/STAT user's guide, Release 6.03 ed. Cary, NC.

Scherer, G., D. Zabowski, B. Java, and R. Everett. 2000. Timber harvesting residue treatment. Part II. Understory vegetation response. For. Ecol. Manage. 126:35–50.

Silkworth, D.R., and D.F. Grigal. 1982. Determining and evaluating nutrient losses following whole-tree harvesting of aspen. Soil Sci. Soc. Am. J. 46:626–631.

Simard, D.G., J.W. Fyles, D. Paré, and T. Nguyen. 2001. Impacts of clearcut harvesting and wildfire on soil nutrient status in the Quebec boreal forest. Can. J. Soil Sci. 81:229–237.

Skoog, D.A., and D.M. West. 1965. Analytical chemistry: An introduction. Holt, Rinehart and Winston, Austin, TX.

Sparling, G.P., C.W. Feltham, J. Reynolds, A.W. West, and P. Singleton. 1990. Estimation of soil microbial C by a fumigation-extraction method: Use on soils of high organic matter content, and a reassessment of the $k_{\mathrm{ec}\text{-}factor}$. Soil Biol. Biochem. 22:301–307.

Steel, R.G.D., and J.H. Torrie. 1980. Principles and procedures of statistics. 2nd ed. McGraw-Hill, New York.

Stevens, P.A., D.A. Norris, T.G. Williams, S. Hughes, D.W.H. Durrant, M.A. Anderson, N.S. Weatherley, M. Hornung, and C. Woods. 1995. Nutrient losses after clearfelling in Beddgelert Forest: A comparison of the effects of conventional and whole-tree harvest on soil water chemistry. Forestry 68:115–131.

Titus, B.D., B.A. Roberts, and K.W. Deering. 1997. Soil solution concentrations on three white birch sites in Central Newfoundland following different harvesting intensities. Biomass Bioenergy 13: 313–330.

Trofymow, J.A. 1998. The Canadian intersite decomposition experiment (CIDET): Project and site establishment report. Pacific Forestry Centre, Victoria, British Columbia. Inf. Rep. BC-X-378.

Vincent, J.-S., and L. Hardy. 1977. L'évolution et l'extension des lacs glaciaires Barlow et Ojibway en territoire québécois. Géogr. Phys. Quat. 31:357–372.

Vitousek, P.M., and P.A. Matson. 1985. Disturbance, nitrogen availability, and nitrogen losses in an intensively managed loblolly pine plantation. Ecology 66:1360–1376.

Volney, W.J.A., J.R. Spence, M.G. Weber, D.W. Langor, K.I. Mallett, J.D. Johnson, I.K. Edwards, G.R. Hillman, and B.E. Kishchuk. 1999. The Alberta EMEND project: Recipe and cooks' argument. p. 244–249. *In* T. S. Veeman et al. (ed.) Science and practice: Sustaining the boreal forest. SFM Network. 14–17 Feb. 1999. Edmonton.

Voroney, R.P., J.P. Winter, and R.P. Beyaert. 1993. Soil microbial biomass C and N. p. 277–286. *In* M.R. Carter (ed.) Soil sampling and methods of analysis. Canadian Society of Soil Science. Lewis Publishers, London.

Yeomans, J.C., and J.M. Bremner. 1988. A rapid and precise method for routine determination of organic carbon in soil. Commun. Soil Sci. Plant Anal. 19:1467–1476.

Zabowski, D., B. Java, G. Scherer, R.L. Everett, and R. Ottmar. 2000. Timber harvesting residue treatment: Part 1. Responses of conifer seedlings, soils and microclimate. For. Ecol. Manage. 126:25–34.