

# Impacts of harvesting and mechanical site preparation on soil chemical properties of mixed-wood boreal forest sites in Alberta

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<sup>1</sup>Department of Geography, Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6, e-mail: margaret\_schmidt@sfu.ca; and <sup>2</sup>Department of Renewable Resources, University of Alberta, Edmonton, Alberta, Canada T6G 2H1. Received 28 August 1995, accepted 20 June 1996.

Schmidt, M. G., Macdonald, S. E. and Rothwell, R. L. 1996. **Impacts of harvesting and mechanical site preparation on soil chemical properties of mixed-wood boreal forest sites in Alberta.** *Can. J. Soil Sci.* **76**: 531–540. We examined the impacts of harvesting and **mechanical site preparation (MSP)** on soil chemical properties of mixed-wood boreal forest sites in west central Alberta. Treatments included: 1) disc trencher, hinge, and trench microsites; 2) ripper plow, hinge, and trench microsites; 3) blading, thin (organic layer depth <2 cm), and thick (organic layer depth >2 cm) microsites; 4) harvested with no site preparation; and 5) unharvested. Twenty months after harvesting, the forest floor of harvested areas with no MSP (vs. unharvested) had higher carbon:nitrogen ratios, lower pH, and lower concentrations of total and mineralizable nitrogen, available phosphorus, and exchangeable bases. Fifteen months after MSP, treated areas had either reduced or unchanged concentrations of total nitrogen and carbon, available phosphorus, and mineralizable nitrogen in the surface mineral soil, compared with harvested sites with no site preparation. The MSP-treated areas also had increased or unchanged pH, base saturation, and exchangeable base concentrations. Microsites adjacent to the displaced forest floor (hinge for disc and ripper treatments) or with a thicker organic layer (thick for blading) generally had higher concentrations of total nitrogen and carbon, and mineralizable nitrogen in the surface mineral soil as compared to trench and thin microsites.

**Key words:** Forest soils, mechanical site preparation, harvesting, N, P, mixed-wood boreal forest

Schmidt, M. G., Macdonald, S. E. et Rothwell, R. L. 1996. **Incidences de la coupe forestière et de la préparation mécanique du terrain (PMT) sur les propriétés chimiques des sols de forêts boréales mixtes dans le centre-ouest de l'Alberta.** *Can. J. Soil Sci.* **76**: 531–540. Nous avons examiné les incidences de la coupe forestière et de la préparation mécanique du terrain (PMT) sur les propriétés chimiques du sol à 2 emplacements sous forêt boréale mixte dans le centre ouest de l'Alberta. Les traitements comparés étaient 1) trancheuse à disques: microplacettes en fond ou en rebord de sillon; 2) défonceuse à dent: microplacettes en fond ou en rebord de sillon; 3) décapeuse: microplacettes à couche organique mince (< 2 cm) ou épaisse (> 2 cm); 4) coupe sans préparation du terrain et 5) forêt laissée sur pied. Vingt mois après l'abattage, la litière forestière des placettes coupées sans PMT manifestait, par rapport à celles des microplacettes non récoltées, un rapport C/N plus large, un pH plus bas et des plus faibles concentrations d'azote total et minéralisable, ainsi que de P biodisponible et de bases échangeables. Quinze mois après PMT, les placettes traitées manifestaient des concentrations plus faibles ou inchangées de N et de C totaux, de P assimilable et de N minéralisable dans le sol minéral de surface que les placettes récoltées sans PMT ultérieur. Elles avaient en outre des valeurs égales ou supérieures pour le pH, pour le taux de saturation en bases et pour les concentrations de bases échangeables. Les microplacettes adjacentes à la litière forestière déplacée (traitement en rebord de sillon) ou à couche organique peu épaisse après décapage avaient en général des concentrations plus élevées de N et de C totaux, et de N minéralisable dans le sol minéral de surface que les microplacettes en fond de sillon et à couche organique mince.

**Mots clés:** Sols forestiers, préparation mécanique du terrain, coupe, N, P, forêts boréales mixtes

Mechanical site preparation is widely used in North America in an attempt to ensure prompt and successful regeneration of harvested forest lands. For example, MSP was carried out on 70% of the area reforested in Alberta, Canada for the period 1966–1990 and on 97% for the 1990–1991 period (Alberta Forest Service 1991). MSP typically involves the removal or reduction of the litter layer, exposure of mineral soil, and mixing of soil and organic material to provide a better growing environment for planted seedlings (Lavender et al. 1990). Objectives of MSP include slash reduction, increased soil warming, improved planter access, and increased nutrient availability.

Both harvesting and MSP have the potential to signifi-

cantly affect soil nutrient dynamics (Likens et al. 1970; Morris et al. 1983; Attiwill et al. 1985; Pye and Vitousek 1985; Tuttle et al. 1985; Tew et al. 1986; Johnson et al. 1988; Munson et al. 1993). Of particular interest is the impact on N (Burger and Pritchett 1984; Vitousek and Matson 1984; Weber et al. 1985; Robertson et al. 1987). Both harvesting and MSP are associated with increased N-mineralization and nitrification (Vitousek and Melillo 1979; Krause 1982; Vitousek and Matson 1985; Fox et al. 1986; Smethurst and Nambiar 1990a,b; Vitousek et al. 1992; Munson et al. 1993). Increased nitrification leads to increased availability of hydrogen ions which replace cations on the exchange complexes of the soil and can lead

to cation leaching (Likens et al. 1970; Krause and Ramlal 1987). Harvesting may result in elevated available P due to increased organic matter decomposition and P release at raised temperature (Krause and Ramlal 1987). MSP has been shown to cause reductions in available P (Tuttle et al. 1985; Krause and Ramlal 1987; Munson et al. 1993) as well as reduced N and C in surface soils (Tuttle et al. 1985; Munson et al. 1993) due to the displacement of forest floors.

Little information on the impacts of forest management practices on soil chemical properties and nutrient availability is available for mixed-wood boreal forest sites in west central Alberta. This is of concern, since large areas of forest in this region are increasingly subject to harvesting and MSP. In 1990, a study was initiated to examine the impacts of harvesting and MSP on mixed-wood boreal sites in this area. Montero (1994) reported on the impacts of these forest practices on soil physical properties. In this paper, we report on the impacts of harvesting and MSP on soil chemical properties including: total N and C, C/N, mineralizable N, available P, exchangeable bases, and pH. Specific study objectives were to examine the impact of harvesting on chemical properties of the forest floor and surface mineral soil, to evaluate the impact of four types of MSP on chemical properties of surface mineral soil, and to compare soil chemical properties between microsites within a particular MSP treatment. A separate paper will examine nutrient dynamics in planted seedlings.

### STUDY SITES

The two study sites (Judy Creek at 54°24'N and 115°40'W; Fox Creek at 54°15'N and 116°49'W) are located in the Whitecourt Forest in west-central Alberta, Canada (Table 1). Both sites have sloping terrain with relatively homogeneous topography, soils, aspect, and stand types. The climate of the area is humid continental, with long cold winters and cool summers. Mean annual precipitation is 550 to 600 mm and the mean annual temperature is 0°C. Mean daily temperature for the warmest month (July) is 15°C and for the coldest (January) is -14°C.

The bedrock strata are non-marine deposits consisting of thick, pale grey, crossbedded sandstones interbedded with grey siltstone, silty mudstone, and local coal seams (Knapik and Lindsay 1983). Surficial materials in the area are clay loam textured till and glaciolacustrine material. Soil landscapes are dominated by Orthic Grey Luvisols with a general profile of organic surface horizons (LFH), light-coloured eluvial horizons (Ae), and illuvial horizons with accumulations of clay (Bt). Excavated profiles revealed an Orthic Grey Luvisol at Judy Creek and a Gleyed Grey Luvisol at Fox Creek. Forest floors are classified as mor humus form and are 5 to 7 cm in depth.

The sites are in the Lower Boreal Cordilleran Ecoregion as described by Corns and Annas (1986). Prior to harvest the sites hosted a mature (approximately 100-yr old) mixed-wood forest dominated by white spruce (*Picea glauca* (Moench) Voss, approximately 18–24 m height, 50–70% crown density) and aspen (*Populus tremuloides* Michx.). Characteristic ground cover vegetation on the sites includes: prickly rose (*Rosa acicularis* Lindl.), thimble berry (*Rubus*

**Table 1. Characteristics for Judy Creek and Fox Creek study sites**

Site Characteristics	Judy Creek	Fox Creek
Slope (%)	20	6
Aspect (°)	270	350
Elevation (m)	1010	975
Soil classification	Orthic Grey Luvisol	Gleyed Grey Luvisol
Textural class of B horizon	Clay loam	Clay loam
Forest humus form	Mor	Mor
Stand type	White spruce/aspen	White spruce/aspen

*parviflorus*), low bush cranberry (*Viburnum edule*), blueberry (*Vaccinium myrtilloides*), wild sarsaparilla (*Aralia nudicaulis*), wild strawberry (*Fragaria virginiana*), pea vine (*Lathyrus ochroleucus*), twin flower (*Linnaea borealis* L.), wild lily-of-the-valley (*Mainthemum canadense*), bishop's cap (*Mitella nuda*), bunch berry (*Cornus canadensis*), and feather moss (*Pleurozium schreberi* and *Ptilium cristacastrensis*).

The study sites were chosen to represent the Luvisols found in the Lower Boreal Cordilleran Ecoregion.

## MATERIALS AND METHODS

### Experimental Design

The sites were clearcut in November 1990 and MSP was carried out in February and March 1991. Harvesting was carried out by a feller-buncher with trees skidded to a central landing prior to delimiting. Harvested volumes from the sites were as follows: Judy Creek, 287 m<sup>3</sup> ha<sup>-1</sup> white spruce; Fox Creek, 261 m<sup>3</sup> ha<sup>-1</sup> white spruce, 52 m<sup>3</sup> ha<sup>-1</sup> aspen. Each site was divided into two blocks and, within each block, four MSP treatments were applied in randomly assigned rows of 20 m width running up and down slope. The treatments included those commonly used in the region: disc trencher, ripper plow, and blading, as well as no MSP (harvested control). Part of the original forest stand was left unharvested and two plots of 20 m width running up and down slope were randomly located within the uncut forest at each site. The uncut forest plots were not part of the randomized blocks but were sampled from adjacent forest of the same stand type, slope, position and aspect as the area where the treatments were applied.

Disc trenching was carried out with a Donaren 180D powered disc trencher mounted on a John Deere 640 skidder. The trencher consisted of two toothed discs mounted on two separate, articulating arms hydraulically activated to vary downward pressure at an angle to the direction of travel. As the discs turn, the soil surface is ripped and mineral soil is exposed in a trench bordered on the upper side by a berm (Hunt and McMinn 1988). Ripper plowing was carried out with a modified standard ripper tooth mounted on the back of a tractor. The ripper tooth digs into the frozen ground and the plow displaces blocks of frozen soil laterally and partially turns them over, creating a trench and a berm (Coates and Haeussler 1987). Blading was carried out with a front-mounted straight-blade which was scraped over the soil surface, displacing slash and surface organic material to small central piles.

Potentially plantable microsites were classified as hinge and trench for disc trenched and ripper plowed areas and as thin and thick for blading. The hinge is a level planting spot at the junction of the mineral soil exposed at the furrow and the surface organic layer at the edge of the berm. The trench is a depressed planting spot located in the bottom of the furrow. The disc trencher generally produced trenches 20 cm deep and 60 cm wide, while the ripper plow produced deeper (30 cm) and wider trenches (80 cm). The microsites in the bladed area were level areas of at least 0.16 m<sup>2</sup> (i.e. 40 cm × 40 cm) where some reduction of the surface organic layer occurred. Organic layer depth was <2 cm for the thin microsite and ≥2 cm for the thick microsite.

No vegetation control (herbicide or brushing) was carried out on the study sites and at the time of sampling the amount and type of ground vegetation did not differ substantially among the various harvested treatments.

### Soil Sampling and Analyses

Soil sampling was carried out in July of 1992 (20 mo after harvesting; 15 mo after MSP treatment). In each block at both sites five samples of surface soil (0–7 cm) and two of soil from depth (20–27 cm) were collected along each of two transects for each treatment and microsite combination: disc-hinge, disc-trench, ripper-hinge, ripper-trench, blade-thin, blade-thick, harvested-control, and unharvested. Individual samples were composited from three cores (5 cm diameter, 7 cm deep). Five forest floor samples were collected along each of the two transects in the harvested-control and unharvested areas. Each forest floor sample consisted of three equal volumes (100 cm<sup>3</sup>) of forest floor material (LFH).

Air-dried mineral soil samples were crushed and passed through a 2-mm sieve. Subsamples were ground to <0.25 mm with an electric soil grinder for C determination. Dried forest floor samples were ground to <0.5 mm in a Wiley mill. The analyses were carried out in the Department of Renewable Resources at the University of Alberta, except where otherwise indicated.

Total nitrogen was determined by a micro-Kjeldahl digest followed by colorimetric determination of NH<sub>4</sub><sup>+</sup> using a Technicon autoanalyzer [Bremner and Mulvaney (1982) Industrial Method 334-74/B+]. Total carbon was determined using a LECO Induction Furnace (Tabatabai and Bremner 1970). Ten-gram portions of each mineral soil sample and 2.5-g portions of each forest floor sample were extracted with 50 mL of 2 M KCl (Keeney and Nelson 1982) and analyzed for concentrations of NH<sub>4</sub>-N (Industrial Method 98-70W) and NO<sub>3</sub>-N on a Technicon autoanalyzer (Industrial Method 487-77A).

Mineralizable N availability was assessed using an anaerobic incubation procedure (Powers 1980). Soil samples were incubated under water in stoppered test tubes for 14 d at 30°C. Released NH<sub>4</sub><sup>+</sup> was determined colorimetrically using a Technicon autoanalyzer (Industrial Method 98-70W). Mineralizable N was estimated as the NH<sub>4</sub>-N pool after incubation. Available P was determined by extracting 10-g portions of each mineral soil sample and 2.5-g portions of each forest floor sample with Bray P-1 (dilute acid

ammonium fluoride) solution (Bray and Kurtz 1945) and analyzing for extractable PO<sub>4</sub>-P on a Technicon autoanalyzer (Industrial Method 155-71W).

The pH in 0.01 M CaCl<sub>2</sub> was determined potentiometrically using a pH meter on a 1:2 soil-solution suspension for mineral soil and a 1:4 suspension for forest floor (McKeague 1978). Exchangeable cations and **cation exchange capacity (CEC)** were measured for forest floor and mineral soils at 0–7 cm, using the methods of Lavkulich (1981). Exchangeable cations were extracted using 1 M NH<sub>4</sub>OAc at pH 7 and determined by atomic absorption spectroscopy. Dissolved ammonium was rinsed with isopropanol and CEC was determined by leaching the ammonium ions from exchange positions with NaCl solution and determining NH<sub>4</sub>-N in the extract on a Technicon autoanalyzer (Industrial Method 98-70W).

A constant mass of each forest floor sample was wet-ashed in a microwave oven in a digest of nitric acid and hydrogen peroxide (Kalra et al. 1989). The following elements were determined simultaneously using an inductively coupled plasma-atomic emission spectrometer (Anonymous 1990): P, K, Ca, Mg, S, Cu, Fe, Mn, Zn, and Al (work conducted at Canadian Forest Service, Northern Forestry Centre, Edmonton).

### Statistical Analyses

We analyzed the data with the aid of the SPSS-PC computer package (SPSS Inc. 1994). For the purposes of statistical analysis we considered each transect to be an experimental unit. Thus, means were calculated for chemistry variables by depth (forest floor, 0–7 cm, 20–27 cm) for each transect. To test for depth (fixed) and site (fixed; Judy Creek, Fox Creek) effects, data from the unharvested and harvested-control sites were analyzed using analysis of variance (ANOVA). The Tukey HSD test was used to determine significant differences among the forest floor and mineral soils at 0–7 and 20–27 cm. A significance level of *P* = 0.05 was used.

Since depth and site effects were found to be significant for many variables, we carried out separate ANOVAs for each chemistry variable at each depth and site to test for treatment (fixed) effects. The block (within site) effect was included in the ANOVAs. Contrasts were used to test the following planned comparisons: unharvested vs. harvested control, control vs. each of the site preparation treatments, disc-hinge vs. disc-trench, ripper-hinge vs. ripper-trench, and blade-thick vs. blade thin.

## RESULTS

### Site and Depth Effects

Differences in a number of soil chemical properties between the two study sites (Table 2) suggest that Judy Creek is the more fertile site. The forest floor at Judy Creek had significantly higher mineralizable N, pH, exchangeable bases, base saturation, and total concentrations of K, Ca, Mg, and Mn than at Fox Creek. The mineral soil at 0–7 cm at Judy Creek had higher mineralizable N, available P, pH, exchangeable bases, and base saturation than at Fox Creek.

Table 2. Differences in mean values of chemical properties among forest floor (FF) and mineral soil at two depths and between the two study areas for harvested and unharvested sites

	Judy Creek			Fox Creek			Differences between two study areas (F-test)		
	FF	0-7 cm	20-27 cm	FF	0-7 cm	20-27 cm	FF	0-7 cm	20-27 cm
Total N (g kg <sup>-1</sup> )	12.4a (1.2)	1.0b (0.06)	0.5c (0.03)	12.0a (1.1)	0.9b (0.04)	0.5c (0.02)	NS	NS	NS
Total C (g kg <sup>-1</sup> )	405a (12)	16.6b (1.1)	6.5c (0.4)	415a (11)	15.9b (0.8)	5.9c (0.3)	NS	NS	NS
C/N	35.0a (2.3)	17.2b (0.5)	12.8c (0.2)	37.2a (3.1)	16.8b (0.4)	11.7c (0.2)	NS	NS	**
NH <sub>4</sub> -N (mg kg <sup>-1</sup> )	68.2a (10.5)	3.6b (0.2)	2.1c (0.2)	71.5a (8.3)	7.1b (1.4)	3.6c (0.6)	NS	**	*
NO <sub>3</sub> -N (mg kg <sup>-1</sup> )	5.6a (0.5)	0.6b (0.03)	0.7b (0.2)	4.7a (0.5)	0.5b (0.1)	1.0c (0.1)	NS	NS	*
Min.-N (mg kg <sup>-1</sup> )	721a (115)	28.0b (3.3)	6.2c (0.3)	582a (78.5)	17.7b (1.9)	5.4c (0.5)	**	*	NS
Avail. P (mg kg <sup>-1</sup> )	80.9a (6.7)	33.4b (5.8)	5.6c (1.9)	95.8a (14.0)	10.2b (1.0)	3.4c (0.9)	*	**	NS
pH	4.1a (0.2)	4.3b (0.07)	4.7c (0.07)	3.7a (0.1)	3.8a (0.07)	4.2b (0.05)	**	**	**
CEC (cmol <sub>c</sub> kg <sup>-1</sup> )	99.4a (6.3)	15.2b (1.1)	—	108.5a (5.1)	13.6b (0.9)	—	NS	NS	—
Exch. Ca (cmol <sub>c</sub> kg <sup>-1</sup> )	42.3a (6.6)	6.4b (0.6)	—	28.2a (5.1)	3.4b (0.5)	—	**	**	—
Exch. K (cmol <sub>c</sub> kg <sup>-1</sup> )	3.2a (0.2)	0.8b (0.1)	—	2.6a (0.4)	0.3b (0.02)	—	*	**	—
Exch. Mg (cmol <sub>c</sub> kg <sup>-1</sup> )	6.5a (0.6)	1.2b (0.1)	—	5.0a (0.4)	0.9b (0.1)	—	**	NS	—
Exch. Bases (cmol <sub>c</sub> kg <sup>-1</sup> )	52.0a (7.3)	8.4b (0.7)	—	35.8a (5.9)	4.6b (0.6)	—	**	**	—
Base Satn. (%)	53.3a (6.7)	57.6a (2.6)	—	33.7a (5.5)	35.1b (4.5)	—	**	**	—
P (mg kg <sup>-1</sup> )	1090 (82)	—	—	1100 (92)	—	—	NS	—	—
K (mg kg <sup>-1</sup> )	1220 (93)	—	—	1000 (150)	—	—	*	—	—
Ca (mg kg <sup>-1</sup> )	10700 (1807)	—	—	7220 (1253)	—	—	**	—	—
Mg (mg kg <sup>-1</sup> )	1090 (64)	—	—	853 (71)	—	—	*	—	—
S (mg kg <sup>-1</sup> )	1360 (110)	—	—	1350 (114)	—	—	NS	—	—
Cu (mg kg <sup>-1</sup> )	2.5 (0.7)	—	—	5.6 (0.8)	—	—	**	—	—
Fe (mg kg <sup>-1</sup> )	2640 (351)	—	—	3030 (540)	—	—	NS	—	—
Mn (mg kg <sup>-1</sup> )	1330 (148)	—	—	934 (104)	—	—	**	—	—
Zn (mg kg <sup>-1</sup> )	47 (5)	—	—	57 (5)	—	—	NS	—	—
Al (mg kg <sup>-1</sup> )	1980 (144)	—	—	2070 (231)	—	—	NS	—	—

\*, \*\* Significantly different value for chemical property for a given depth between study sites;  $P < 0.05$  and  $P < 0.01$ , respectively; NS, nonsignificant. Values in parentheses are standard errors.

a-c For each site, values in the same row and at the same site followed by a different letter are significantly different according to Tukey's test ( $P < 0.05$ ).

At 20–27 cm, the pH value was significantly higher at Judy Creek than at Fox Creek. Values of some chemical properties, however, were higher at Fox Creek than at Judy Creek: available P in the forest floor, NH<sub>4</sub>-N at 0–7 cm, and NH<sub>4</sub>-N and NO<sub>3</sub>-N at 20–27 cm.

Not surprisingly, the chemical properties of the forest floor, of the mineral soil at 0–7 cm, and of the mineral soil at 20–27 cm differed substantially (Table 2). Compared with

the mineral soil at 0–7 cm, the forest floors at both Judy and Fox Creek had higher values of all soil chemical properties except pH (lower at Judy Creek and not significantly different at Fox Creek) and base saturation (not significantly different at Judy Creek). Compared with the mineral soil at 0–7 cm, the soil at 20–27 cm at both study sites had lower total N, total C, C/N, NH<sub>4</sub>-N mineralizable N, and available P and higher pH.

**Harvesting Effects**

Values for a number of chemical properties were lower in the forest floor of the harvested plots as compared to the unharvested plots at both sites: total N, NO<sub>3</sub>-N, mineralizable N, available P, pH, exchangeable bases, base saturation, and concentrations of P, K, Ca, S, and Mn (Table 3). In addition, the forest floor of the harvested plots at Judy Creek had lower total C and NH<sub>4</sub>-N concentrations. C/N was higher for harvested plots at both sites.

For mineral soils at 0–7 cm, the harvested control areas had lower values than the unharvested plots for total N, pH, and exchangeable bases at Judy Creek and for base saturation at Fox Creek. NH<sub>4</sub>-N concentrations were higher in the harvested sites (vs. unharvested) at Fox Creek. The only significant effects of harvesting on soils at 20–27 cm were higher

NO<sub>3</sub>-N at harvested sites at Judy Creek ( $P < 0.01$ ) and higher NH<sub>4</sub>-N values for harvested sites at Fox Creek ( $P < 0.05$ ).

**Mechanical Site Preparation Effects**

MSP treatments had significant effects on more chemical properties at Judy Creek than at Fox Creek (Table 4). At both sites, MSP treated areas (as a group compared to harvested-control) resulted in lower NH<sub>4</sub>-N and higher pH and base saturation at 0–7 cm. MSP areas also had lower total C, C/N ratio, and higher exchangeable bases (at Judy Creek) and lower total N and mineralizable N (at Fox Creek).

At Judy Creek, individual MSP treatments (compared to harvested-control) had significantly higher values for 3 to 8 of 14 measured soil properties at 0–7 cm (Table 5). All treatments had significantly higher pH and all, except

**Table 3. Effect of harvesting on chemical properties of the forest floor and mineral soil at 0–7 cm depth; U = unharvested, H = harvested control; at Judy and Fox Creek**

	Judy Creek					Fox Creek				
	U		H		F-test	U		H		F-test
<i>Forest floor</i>										
Total N (g kg <sup>-1</sup> )	15.4	(0.4)	9.4	(0.8)	**	13.9	(0.8)	10.0	(1.6)	**
Total C (g kg <sup>-1</sup> )	425	(10)	385	(6)	*	424	(5)	410	(23)	NS
C/N	27.9	(0.8)	42.1	(2.0)	**	31.2	(2.2)	43.3	(4.1)	**
NH <sub>4</sub> -N (mg kg <sup>-1</sup> )	92.1	(9.7)	44.3	(6.7)	*	77.7	(5.2)	65.4	(16.4)	NS
NO <sub>3</sub> -N (mg kg <sup>-1</sup> )	6.4	(0.8)	4.8	(0.6)	**	5.8	(0.2)	3.5	(0.6)	*
Min.-N (mg kg <sup>-1</sup> )	1000	(72)	438	(61)	**	692	(86)	472	(115)	*
Avail.P (mg kg <sup>-1</sup> )	95.5	(68)	66.3	(5.2)	**	130	(10)	62.1	(7.0)	**
pH	4.6	(0.1)	3.6	(0.1)	**	3.9	(0.2)	3.4	(0.03)	*
CEC (cmol <sub>c</sub> kg <sup>-1</sup> )	102	(1)	95	(13)	NS	109	(2)	108	(11)	NS
Exch. Ca (cmol <sub>c</sub> kg <sup>-1</sup> )	55.7	(2.3)	23.2	(2.9)	**	38.6	(7.1)	17.8	(1.0)	**
Exch. K (cmol <sub>c</sub> kg <sup>-1</sup> )	3.7	(0.1)	2.5	(0.1)	**	3.5	(0.3)	1.7	(0.2)	**
Exch. Mg (cmol <sub>c</sub> kg <sup>-1</sup> )	7.6	(0.5)	5.0	(0.3)	**	5.9	(0.7)	4.2	(0.1)	*
Exch. Bases (cmol <sub>c</sub> kg <sup>-1</sup> )	67.0	(2.3)	30.7	(3.4)	**	48.0	(8.0)	23.7	(1.1)	**
Base Satn. (%)	66.3	(2.4)	34.7	(3.8)	**	44.5	(8.0)	22.9	(1.4)	*
P (mg kg <sup>-1</sup> )	1300	(1)	875	(38)	**	1270	(88)	920	(105)	**
K (mg kg <sup>-1</sup> )	1460	(43)	990	(39)	**	1360	(129)	641	(60)	**
Ca (mg kg <sup>-1</sup> )	15400	(300)	6000	(763)	**	9770	(1700)	4660	(296)	**
Mg (mg kg <sup>-1</sup> )	1220	(55)	965	(71)	NS	887	(107)	820	(105)	NS
S (mg kg <sup>-1</sup> )	1640	(21)	1090	(65)	**	1570	(63)	1140	(160)	**
Cu (mg kg <sup>-1</sup> )	3.8	(0.5)	1.1	(1.0)	*	6.7	(1.5)	4.6	(0.2)	NS
Fe (mg kg <sup>-1</sup> )	2140	(474)	3150	(425)	*	2140	(357)	3930	(836)	NS
Mn (mg kg <sup>-1</sup> )	1650	(108)	1005	(140)	**	1090	(159)	780	(94)	*
Zn (mg kg <sup>-1</sup> )	39.1	(5.5)	55.8	(5.2)	NS	62.4	(8.7)	52.2	(4.7)	NS
Al (mg kg <sup>-1</sup> )	1740	(204)	2210	(137)	*	1780	(264)	2350	(356)	NS
<i>Mineral soil, 0–7 cm</i>										
Total N (g kg <sup>-1</sup> )	1.1	(0.07)	0.8	(0.04)	*	1.0	(0.04)	0.9	(0.06)	NS
Total C (g kg <sup>-1</sup> )	18.0	(1.8)	15.1	(1.0)	0.09	16.1	(1.6)	15.6	(0.9)	NS
C/N	16.7	(0.9)	17.8	(0.6)	NS	16.6	(0.9)	17.1	(0.3)	NS
NH <sub>4</sub> -N (mg kg <sup>-1</sup> )	3.4	(0.2)	3.8	(0.4)	NS	4.0	(0.3)	10.2	(1.4)	**
NO <sub>3</sub> -N (mg kg <sup>-1</sup> )	0.5	(0.02)	0.6	(0.05)	NS	0.4	(0.3)	0.5	(0.1)	NS
Min.-N (mg kg <sup>-1</sup> )	31.5	(4.2)	24.4	(4.8)	NS	17.9	(2.2)	17.6	(2.5)	NS
Avail.P (mg kg <sup>-1</sup> )	25.6	(7.6)	41.3	(7.6)	0.09	9.4	(1.7)	11.0	(1.1)	NS
pH	4.5	(0.06)	4.2	(0.07)	*	3.8	(0.1)	3.7	(0.06)	NS
CEC (cmol <sub>c</sub> kg <sup>-1</sup> )	16.9	(0.8)	13.3	(1.7)	NS	12.0	(0.6)	15.7	(1.2)	NS
Exch. Ca (cmol <sub>c</sub> kg <sup>-1</sup> )	7.5	(0.7)	5.1	(0.44)	*	4.1	(0.6)	2.6	(0.6)	0.09
Exch. K (cmol <sub>c</sub> kg <sup>-1</sup> )	0.9	(0.1)	0.7	(0.06)	*	0.3	(0.02)	0.3	(0.04)	NS
Exch. Mg (cmol <sub>c</sub> kg <sup>-1</sup> )	1.3	(0.1)	1.0	(0.1)	NS	0.9	(0.1)	0.9	(0.2)	NS
Exch. Bases (cmol <sub>c</sub> kg <sup>-1</sup> )	9.7	(0.7)	6.8	(0.5)	*	5.3	(0.8)	3.8	(0.8)	NS
Base Satn. (%)	58.2	(3.8)	56.8	(4.0)	NS	44.1	(4.9)	23.5	(3.5)	*

\* \*\*Significantly different value for chemical property for a site between unharvested and harvested control sites;  $P < 0.05$  and  $P < 0.01$ , respectively; NS, nonsignificant.

Values in parentheses are standard errors.

Table 4. Effects of MSP on chemical properties of the mineral soil at 0–7 cm depth

	Harvested control	Disc		Ripper		Blade		Pooled standard error
		Hinge	Trench	Hinge	Trench	Thick	Thin	
<i>Judy Creek</i>								
Total N (g kg <sup>-1</sup> )	0.84	0.73	0.51**	0.99	0.67	0.74	0.67	0.06
Total C (g kg <sup>-1</sup> )	15.1	11.2*	6.7**	15.8	9.8**	11.6	10.3**	1.0
C/N	17.8	14.9	12.9**	16.2	15.0	15.6	15.0	0.9
NH <sub>4</sub> -N (mg kg <sup>-1</sup> )	3.84	3.05	2.06**	4.63	2.55*	2.28**	2.86	0.35
NO <sub>3</sub> -N (mg kg <sup>-1</sup> )	0.57	1.14*	0.67	1.21*	0.81	0.70	0.77	0.14
Min.-N (mg kg <sup>-1</sup> )	24.4	18.6	10.2*	34.6	17.9	21.7	15.9	3.8
Avail.P (mg kg <sup>-1</sup> )	41.3	29.3	16.9**	51.0	35.6	24.1	18.4**	5.6
pH	4.19	4.51**	4.59**	4.71**	4.80**	4.49**	4.59**	.08
CEC (cmol <sub>c</sub> kg <sup>-1</sup> )	13.3	10.3	10.8	16.7	12.6	10.8	15.4	1.6
Exch. Ca (cmol <sub>c</sub> kg <sup>-1</sup> )	5.05	6.32	7.00	7.81**	7.79**	6.01	7.71*	0.75
Exch. K (cmol <sub>c</sub> kg <sup>-1</sup> )	0.65	0.62	0.52	0.85*	0.71	0.53	0.49	0.05
Exch. Mg (cmol <sub>c</sub> kg <sup>-1</sup> )	1.01	1.22	1.55	1.47	1.57*	1.08	1.61*	0.16
Exch. Bases (cmol <sub>c</sub> kg <sup>-1</sup> )	6.71	8.16	9.07	10.1**	10.1**	7.62	9.81*	0.90
Base Satn. (%)	56.8	80.0**	84.6**	63.6	80.7**	71.6*	71.9**	4.3
<i>Fox Creek</i>								
Total N (g kg <sup>-1</sup> )	0.92	0.91	0.78	0.74	0.67*	0.91	0.58**	0.07
Total C (g kg <sup>-1</sup> )	15.6	19.9	15.5	14.4	13.1	17.6	8.6*	2.0
C/N	17.1	21.5*	20.0	18.5	18.9	18.3	14.4	1.4
NH <sub>4</sub> -N (mg kg <sup>-1</sup> )	10.2	5.66**	5.31**	3.38**	2.94	3.68**	2.76**	0.75
NO <sub>3</sub> -N (mg kg <sup>-1</sup> )	0.50	0.52	0.54	0.47	0.46	0.76	1.32**	0.10
Min.-N (mg kg <sup>-1</sup> )	17.6	12.5	12.2	9.61**	9.38**	15.8	7.18**	1.78
Avail.P (mg kg <sup>-1</sup> )	11.0	11.7	10.9	7.98	7.01	6.73	4.38**	1.51
pH	3.71	3.69	3.76	3.87	4.01*	4.01*	4.16**	0.07
CEC (cmol <sub>c</sub> kg <sup>-1</sup> )	15.7	16.7	14.4	13.6	12.5	13.3	11.7*	1.2
Exch. Ca (cmol <sub>c</sub> kg <sup>-1</sup> )	2.55	2.55	2.29	3.79	3.74	4.01	4.48*	0.5
Exch. K (cmol <sub>c</sub> kg <sup>-1</sup> )	0.31	0.32	0.30	0.32	0.31	0.26	0.25	0.02
Exch. Mg (cmol <sub>c</sub> kg <sup>-1</sup> )	0.87	0.82	0.77	1.29*	1.35*	1.16	1.49**	0.14
Exch. Bases (cmol <sub>c</sub> kg <sup>-1</sup> )	3.73	3.69	3.36	5.40	5.40	5.43	6.22*	0.64
Base Satn. (%)	23.5	23.1	25.5	40.0**	44.8**	41.4*	54.5**	4.6

\*,\*\*Significantly different value for chemical property for a given MSP treatment as compared to the harvested control, according to contrasts;  $P < 0.05$  and  $P < 0.01$ , respectively.

Table 5. Effects of MSP on chemical properties of the mineral soil at 20–27 cm depth at Judy Creek

	Harvested control	Disc		Ripper		Blade		Pooled standard error
		Hinge	Trench	Hinge	Trench	Thick	Thin	
<i>Judy Creek</i>								
Total N (g kg <sup>-1</sup> )	0.47	0.53	0.44	0.42	0.42	0.46	0.49	0.03
Total C (g kg <sup>-1</sup> )	6.13	6.16	4.56**	5.18	4.23**	5.31	4.94*	0.31
C/N	13.1	11.6	10.5**	12.3	10.1**	11.8	10.1**	0.61
NH <sub>4</sub> -N (mg kg <sup>-1</sup> )	2.20	1.93	1.86	1.75	2.28	1.81	2.42	0.33
NO <sub>3</sub> -N (mg kg <sup>-1</sup> )	1.14	0.69*	0.44**	0.79	0.89	0.64*	0.40**	0.13
Min.-N (mg kg <sup>-1</sup> )	5.86	6.38	3.90*	4.58	4.09*	6.04	4.65	0.46
Avail.P (mg kg <sup>-1</sup> )	8.14	16.16*	9.74	8.18	6.53	4.76	4.20	2.20
pH	4.76	4.65	4.57	4.64	4.65	4.73	4.54	0.14

\*,\*\*Significantly different value for chemical property for a given MSP treatment as compared to the harvested control, according to contrasts;  $P < 0.05$  and  $P < 0.01$ , respectively.

ripper-hinge, had higher base saturation. In addition: disc-hinge had lower total C and higher NO<sub>3</sub>-N; disc-trench had lower total N, total C, C/N, NH<sub>4</sub>-N, mineralizable N and available P; ripper-hinge had higher NO<sub>3</sub>-N; ripper-trench had lower total C and NH<sub>4</sub>-N and higher exchangeable bases; blade-thick had lower NH<sub>4</sub>-N; and blade-thin had lower total C, available P and higher exchangeable bases.

At Fox Creek, the blade-thin treatment affected most (12 out of 14) of the measured soil properties, while the other treatments affected fewer (1 to 6 out of 14) properties. All

treatments had significantly lower NH<sub>4</sub>-N than the harvested-control and all, except the disc hinge and trench treatments, had higher base saturation. In addition, disc-hinge had higher C/N; ripper-hinge had lower mineralizable N; ripper-trench had lower total N, mineralizable N and higher pH; blade-thick had higher pH; and blade-thin had lower total N, total C, mineralizable N, available P, and CEC and higher NO<sub>3</sub>-N, pH and exchangeable bases.

At 20–27 cm at Judy Creek, MSP treatments as a group (compared with harvested-control) resulted in lower total C,

C/N, and  $\text{NO}_3\text{-N}$  (Table 5). Compared with the control: disc-hinge had lower  $\text{NO}_3\text{-N}$  and higher available P; disc-trench had lower total C, C/N,  $\text{NO}_3\text{-N}$ , and mineralizable N; ripper-hinge had no significant differences; ripper-trench had lower total C, C/N, and mineralizable N; blade-thick had lower  $\text{NO}_3\text{-N}$ ; and blade-thin had lower total C, C/N, and  $\text{NO}_3\text{-N}$ . No significant differences associated with MSP treatments were noted for the 20–27 cm depth at Fox Creek.

### Microsite Effects

Microsite effects varied by site. Several soil properties differed significantly between hinge and trench microsites for disc and ripper treatments at Judy Creek only and between thick and thin microsites at Fox Creek only (Table 5). For the disc treatment at Judy Creek, the hinge microsite had higher total N, total C, and mineralizable N ( $P < 0.05$  for all) than the trench microsite at 0–7 cm and higher total C ( $P < 0.05$ ) and mineralizable N ( $P < 0.01$ ) at 20–27 cm. The ripper-hinge microsite had higher total N, total C,  $\text{NH}_4\text{-N}$ , and mineralizable N ( $P < 0.01$  for all) and lower base saturation ( $P < 0.05$ ) at 0–7 cm than the ripper-trench microsite. For the blade treatment at Fox Creek, the thick microsite had higher total N, total C, and mineralizable N and lower  $\text{NO}_3\text{-N}$  ( $P < 0.01$  for all) than the thin microsite.

### DISCUSSION

The results clearly indicate that forest harvesting and mechanical site preparation can have a significant influence on soil chemical properties. It appears that the impact of harvesting and MSP increased with disturbance and removal of the forest floor and decreased significantly with depth. This was not surprising since much of the disturbance associated with harvesting and MSP occurs near the surface.

### Impact of Harvesting

Harvesting had a significant impact on soil chemical properties of the forest floor and, to some extent, the surface mineral soil but had minimal impact at 20–27 cm. Higher C/N and lower total N, mineralizable N, available and total P at 20 mo after harvesting indicate that the N and P supplying power of the forest floor in harvested areas was reduced compared to unharvested areas. At both sites, forest floors in harvested areas had lower exchangeable bases, pH, base saturation, and total concentrations of K, Ca, S, and Mn, all indicators of a poorer substrate quality.

We propose the changes in forest floor chemical properties following harvesting were the result of the following processes: addition of woody material and foliage at time of harvesting; the disruption of tree litter input and canopy wash; changes in ground vegetation; mixing of forest floor and mineral soil induced by logging machinery; and accelerated decomposition and leaching.

The higher C/N ratio and lower total P concentrations of the forest floor in harvested areas most likely resulted from additions of high C/N, low P content materials (twigs and needles) at the time of harvesting and from the disruption of tree litter input and canopy wash. Over time, the C/N ratio is expected to decrease as decomposition of the original substrate takes place and as the added litter of early

successional plants, with a low C/N ratio, is added and decomposes (Cromack 1981). Lower total N concentrations in the forest floor at both sites, and in the mineral soil at Judy Creek (0–7 cm), were attributed to the addition of low N content materials at the time of harvesting, the disruption of tree litter input and canopy wash and to increased decomposition, and initial rapid mineralization and leaching of N. The decreased total C concentration of the forest floor in the harvested area at Judy Creek may be due to mixing of mineral soil with the litter layer during harvesting as reported by Johnson et al. (1991a).

Since mineralizable N was assessed by means of a laboratory incubation, we cannot say that N mineralization was reduced under field conditions where soil temperature and water would also be affected by harvesting. Most studies show an increase in net N mineralization associated with increased soil temperatures in cleared areas (Vitousek and Melillo 1979; Smethurst and Nambiar 1990a; Vitousek et al. 1992). Thus, even though substrate quality appears lower in our study, net N mineralization could have been higher in the harvested areas due to higher temperatures.  $\text{NH}_4\text{-N}$  and  $\text{NO}_3\text{-N}$  concentrations in the forest floor at the time of sampling suggest, however, that mineralization was lower for harvested areas at Judy Creek and nitrification was lower for harvested areas at both sites. It is important to note that it is difficult to judge levels of mineralization and nitrification from concentration data only.  $\text{NH}_4\text{-N}$  concentrations at the 0–7 cm depth were higher for harvested areas which indicates mineralization was enhanced in the mineral soil, or  $\text{NH}_4\text{-N}$  was leached from the forest floor into the mineral soil.

The reductions in pH and base saturation of the forest floor at both sites and in the mineral soil (0–7 cm) at Judy Creek likely resulted from organic acid production from harvest residues and from accelerated decomposition of the forest floor. Acidification may also have been enhanced by accelerated nitrification after harvesting (Likens et al. 1970; Johnson et al. 1991b). Nitrification is a strong acidifying process that can displace nutrient bases from the exchange complex and mobilize Al into solution (Sposito 1989). Acidification may result in decreased P availability and/or Al toxicity.

### Impact of Mechanical Site Preparation

Results indicated that MSP may reduce N and P availability but, at the same time, increase pH and exchangeable bases. Organic-matter-related properties (total N and C, C/N ratio,  $\text{NH}_4\text{-N}$ , mineralizable N, and available P) were either reduced or were unaffected by MSP. On the other hand, soil properties related to pH (pH, exchangeable bases and base saturation) were either increased or were unaffected by MSP.

Changes in soil chemical properties associated with MSP are probably due to a combination of the original impact of the treatments and processes which occurred following treatment. Much of the change is likely related to the displacement of forest floor and surface mineral soil and the mixing of soil layers during the application of MSP. The comparison of soil chemical properties by depth (Table 3)

showed organic matter-related properties were lower and pH-related properties were higher at the greater depth. Since the treatments we studied tended to displace surface mineral soil and/or mix mineral soil from below, we expected the organic matter-related properties to be lower and pH-related properties to be higher than for sites that were not treated. The results generally supported this expectation. Since the amount and type of ground vegetation did not vary greatly among treatments, it is unlikely that differences in ground vegetation had a significant influence on soil chemical properties.

A further process which would contribute to the reduction in total N and C and mineralizable N concentrations for some MSP treatments is accelerated decomposition of organic matter following treatment. Accelerated decomposition in MSP areas could also account for the lower C/N ratios found at both depths at Judy Creek.

Other studies have also reported decreases (not always significant) in total N, total C, C/N ratio and/or available P in surface soils after MSP [Tuttle et al. (1985) on P, Krause and Ramlal (1987) on N, Burger and Pritchett (1988) Munson et al. (1993)]. These decreases are generally associated with the displacement of forest floor and surface mineral soil. Smethurst and Nambiar (1990b), on the other hand, found plowing incorporated litter into the surface soil such that C and N increased shortly after treatment but decreased within 48 mo. We expected some incorporation of organic matter into the hinge microsites for disc and ripper treatments. It appears that either little mixing actually occurred, or the organic matter content decreased rapidly in the time since MSP treatment.

The low mineralizable N found in our study for some MSP treatments (disc-trench at Judy Creek; ripper-hinge, ripper-trench and blade-thin at Fox Creek) was probably associated with relatively low organic matter and total N contents. Fox et al. (1986) also found lower available nitrogen reserves following site preparation. Since our data were obtained from laboratory incubations rather than field incubations, we cannot say how MSP influenced N mineralization under field conditions. It is possible that increased temperatures in MSP-treated sites increased N mineralization rates, as reported by Smethurst and Nambiar (1990b). However, we also found significantly lower  $\text{NH}_4\text{-N}$  in the surface soil of MSP treated areas which supports the idea that MSP reduced N mineralization. It was surprising that lower mineralizable N in the surface mineral soil for some MSP treatments in our study was not associated with higher C/N ratios, as would be expected.

Mechanical site preparation increased  $\text{NO}_3\text{-N}$  in surface soil for disc-hinge and ripper-hinge at Judy Creek and blade-thin at Fox Creek, but decreased  $\text{NO}_3\text{-N}$  at depth for MSP treatments at Judy Creek. The enhanced nitrification in the surface soil for some microsites was probably due to a better environment for microbial activity (higher temperature and higher pH). Increased nitrification after MSP is also reported in other studies (Vitousek and Matson 1985; Fox et al. 1986; Munson et al. 1993). Leaching of  $\text{NO}_3\text{-N}$  from the forest floor to the greater depth may account for the larger

$\text{NO}_3\text{-N}$  concentrations of the harvested-control at Judy Creek.

The finding of increased pH, base saturation and exchangeable Ca and Mg in the mineral soil for MSP-treated areas varies from previous studies which show reduced (not always significant) mineral soil pH after blading (Munson et al. 1993) and reduced Ca, Mg, and K after surface mineral soil removal (Tuttle et al. 1985). Reduced pH and exchangeable base content are often associated with increased nitrification and leaching of bases. In our study, the mixing of the forest floor and surface mineral soil with deeper soils, that have a higher pH, appears to have prevented the decrease in pH and exchangeable base content usually associated with increased nitrification.

The effects of MSP treatments varied by site. For example, the disc-trench treatment had a major impact at Judy Creek (8 of 14 variables significantly different from the control), but a minimal impact at Fox Creek (1 of 14 variables significantly different). On the other hand, the blade-thin treatment had a greater impact at Fox than at Judy Creek. This variability may be due to inherent differences between the sites, the way they responded to MSP, and/or to differences in the treatment applications. Visual inspection and measurement of soil disturbance by Montero (1994) indicated the blade treatment removed more surface mineral soil at Fox Creek than at Judy Creek.

The variable impact of the same MSP treatment on soil chemical properties at different sites highlights the importance of consistency in treatment application when carrying out MSP. In addition this suggests that the extrapolation of results from one site to another should be made with caution. Ideally, similar studies should be based on a large number of replications at many sites. Unfortunately, such large experiments are very expensive.

Overall, the blade-thin areas showed the greatest differences in soil chemical properties. The most extreme impact occurred at Fox Creek where all of the forest floor and up to 3 cm of surface mineral soil was removed by the blading treatment. As expected, the hinge and thick microsites generally were less affected than the trench and thin microsites. In terms of nitrogen availability, the hinge and thick microsites appear to be preferable planting sites (higher total N and C and mineralizable N for disc-hinge and ripper-hinge at Judy Creek and blade-thin at Fox Creek at 0–7 cm).

The decreases in organic matter-related properties (except C/N ratio) for some MSP treatments on one or both sites were considered a negative impact on site fertility. For example, seedlings planted in sites with lower mineralizable N and available P (such as blade-thin at Fox Creek) may show deficiencies in nitrogen and/or phosphorus. On the other hand, the increased levels of pH-related properties and decreased C/N ratios associated with some treatments at one or both sites were considered a positive influence on site fertility. The higher pH values should enhance the environment for soil microorganisms and have a positive influence on P availability, mineralization, and nitrification. Since N and P are often limiting nutrients in boreal sites (Van Cleve et al. 1983), the negative impact on site fertility (decreased N- and



P-supplying power) probably outweighs the positive impact (increased cation availability).

### CONCLUSIONS

In summary, MSP on a group basis and for some individual treatments, in comparison to untreated areas, affected soil chemical properties by reducing the availability of nitrogen and phosphorus, and increasing the pH and base saturation. These results were expected given the mixing of surface soils with deeper soil material of higher pH and lower organic matter content. Harvesting resulted in a forest floor with higher C/N ratios and lower nutrient concentrations and this was mainly attributed to mixing of twigs, needles and other organic debris at the time of harvesting and the disruption of tree litter input and canopy wash.

The impacts of MSP on soil chemical properties were attributed to the displacement and mixing of soil during treatment. A smaller component of the observed changes was also likely due to the processes of decomposition and mineralization. The degree of change in soil properties followed a trend of increasing with the level of disturbance and removal of the forest floor, and decreasing with depth into the soil profile.

The impacts of MSP and harvesting were evaluated 15 mo after MSP treatment. These results in terms of tree establishment and growth should be considered as short term. Longer-term observations are necessary to more fully understand what happens on these boreal sites as the new forest stand and forest floor develop and as soil formation occurs.

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