Soil microclimate and nitrogen availability 10 years after mechanical site preparation in northern British Columbia

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Abstract: Mechanical site preparation (MSP) changes the distribution and character of forest floor and mineral soil and may affect soil nutrient availability, soil water content, and soil temperature. The effects of different kinds of MSP were compared to a control in the tenth growing season at two research sites in northern British Columbia. To compare MSP results with those of the natural disturbance regime, a burned windrow treatment was also included in the analysis. The bedding plow, fire, and madge treatments all had significantly greater crop-tree growth compared to the control. The bedding plow and madge treatments had significantly lower soil bulk density, higher soil temperature, and lower soil water throughout the growing season compared with that of the control. The bedding plow also resulted in significantly higher concentrations of total carbon, total nitrogen, NH_4^+, and NO_3^- than that of the control, at both the 0–10 and 10–20 cm depths. The madge rotoclear resulted in significantly greater potential mineralizable N than that of the control. Ionic resins bags, installed for one growing season, did not show any significant treatment differences in available soil nitrogen. MSP did not reduce soil fertility on these sites when compared with an untreated control, but it is difficult to say that it improved it.

Résumé : La préparation mécanique de terrain modifie la distribution et les caractéristiques de la couverture morte et du sol minéral, et peut affecter la disponibilité des nutriments, la teneur en eau et la température du sol. Les effets de différents types de préparation mécanique ont été comparés à un témoin au cours de la dixième saison de croissance après leur application dans deux stations de recherche du nord de la Colombie-Britannique. Afin de comparer les résultats des préparations mécaniques à ceux du régime de perturbations naturelles, l'analyse a aussi tenu compte d'un traitement impliquant le brûlage d'andains. Le labour de surface, le brûlage et le rotoculteur madge ont tous significativement augmenté la croissance des arbres d'avenir par rapport au témoin. Pour toute la durée de la saison de croissance, le labour de surface et le rotoculteur madge ont significativement diminué la densité apparente, augmenté la température et diminué la teneur en eau du sol comparativement au témoin. Le labour de surface a aussi provoqué une augmentation significative des concentrations de carbone total, d'azote total, de NH_4^+ et de NO_3^- comparativement au témoin et ce, à des profondeurs de 0 à 10 et 10 à 20 cm. Le rotoculteur madge a entraîné une augmentation significative de l'azote minéralisable comparativement au témoin. Des sacs de résines d'échanges ioniques, installés pendant une saison de croissance, n'ont pas permis d'observer de différences significatives dans la disponibilité en azote du sol entre les traitements. La préparation mécanique de terrain n'a pas diminué la fertilité des sols de ces stations par rapport à un témoin non traité, mais il est difficile d'affirmer qu'elle l'a améliorée.

[Traduit par la Rédaction]

Introduction

Mechanical site preparation (MSP) is used extensively in North America to promote seedling survival and growth on harvested and reclaimed forestlands. MSP may involve one or more of the following: removing the forest floor to expose mineral soil, inverting forest floor and mineral soil, raising mineral soil, and mixing forest floor with mineral soil (McMinn and Hedin 1990). The objectives of MSP are to increase nutrient availability, improve soil microclimate, increase early crop-tree performance, create planting microsites, and facilitate planter access. Canadian forest surveys indicate that the use of MSP has increased in the recent past. In 1986, 7% of the land replanted in British Columbia (B.C.) received some form of MSP, while in 1991, 54% of the land replanted had some form of MSP (Anonymous 1993; Runyon

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Table 1. Summary of the site characteristics for the Bednesti and Inga Lake sites.

Site characteristics	Bednesti	Inga Lake
Slope (%)	0–2	0–5
Aspect (°)	0–5	350–355
Elevation (m)	700	845
Soil classification	Orthic Humo-ferric Podzol	Orthic Gleyed Luvisol
Textural class	Silty clay loam to sandy loam	Clay loam to silty clay
Biogeoclimatic zone	SBSdw3	BWBSmw1
Nutrient regime	Submesotrophic, B[a]	Mesotrophic, C[a]
Moisture regime	Mesic (4[a])	Mesic (4[a])

[a] Nutrient and moisture regime designations from the BC Biogeoclimatic Ecosystem Classification (DeLong and Tanner 1993).

1991). Unfortunately, scientific knowledge of the long-term effects of MSP is generally lacking in boreal regions (Munson and Timmer 1995; Orlander et al. 1996; Schmidt et al. 1996).

MSP has the potential to change soil microclimate and soil nutrient turnover (Burger 1996; Munson and Timmer 1995). MSP generally increases nitrogen (N) mineralization and nitrification, but may reduce fertility, because increased nitrification may lead to net N loss (NO_3^- leaching) and cation losses (Krause and Ramlal 1987). Some forms of MSP have been shown to lower the concentration of total carbon (C) and total N in surface soils (Tuttle et al. 1985). Over time, this may reduce the concentration of available phosphorus and reduce plant uptake (Krause and Ramlal 1987; Munson et al. 1993; Tew et al. 1986).

In 1987, the B.C. Ministry of Forests established a series of permanent plots in the northern interior that have become some of the oldest and best documented plots in B.C. The project was established as a means of examining methods to combat the growing backlog of not satisfactorily restocked forestlands. The effects of MSP on soil properties and tree growth were assessed in 1997, 10 years after MSP treatment, and the results represent the mid- to long-term (10–20 years) nutrient dynamics in a forest regenerated with MSP.

The objectives of this study are to examine the potential differences created by various MSP techniques on tree growth and soil properties at two sites in northern B.C. Therefore, in this paper we report on the impacts of MSP on soil properties including bulk density, soil microclimate (temperature and soil water), soil pH, cation exchange capacity (CEC), percent base saturation, total C, total N, NH_4^+ and NO_3^- concentrations, and potential mineralizable N (PMN). We also used ion-exchange resin bags to measure in situ organic matter (OM) mineralization over the growing season. Crop-tree height will be included as a means of comparing treatment effectiveness.

Materials and methods

Study sites

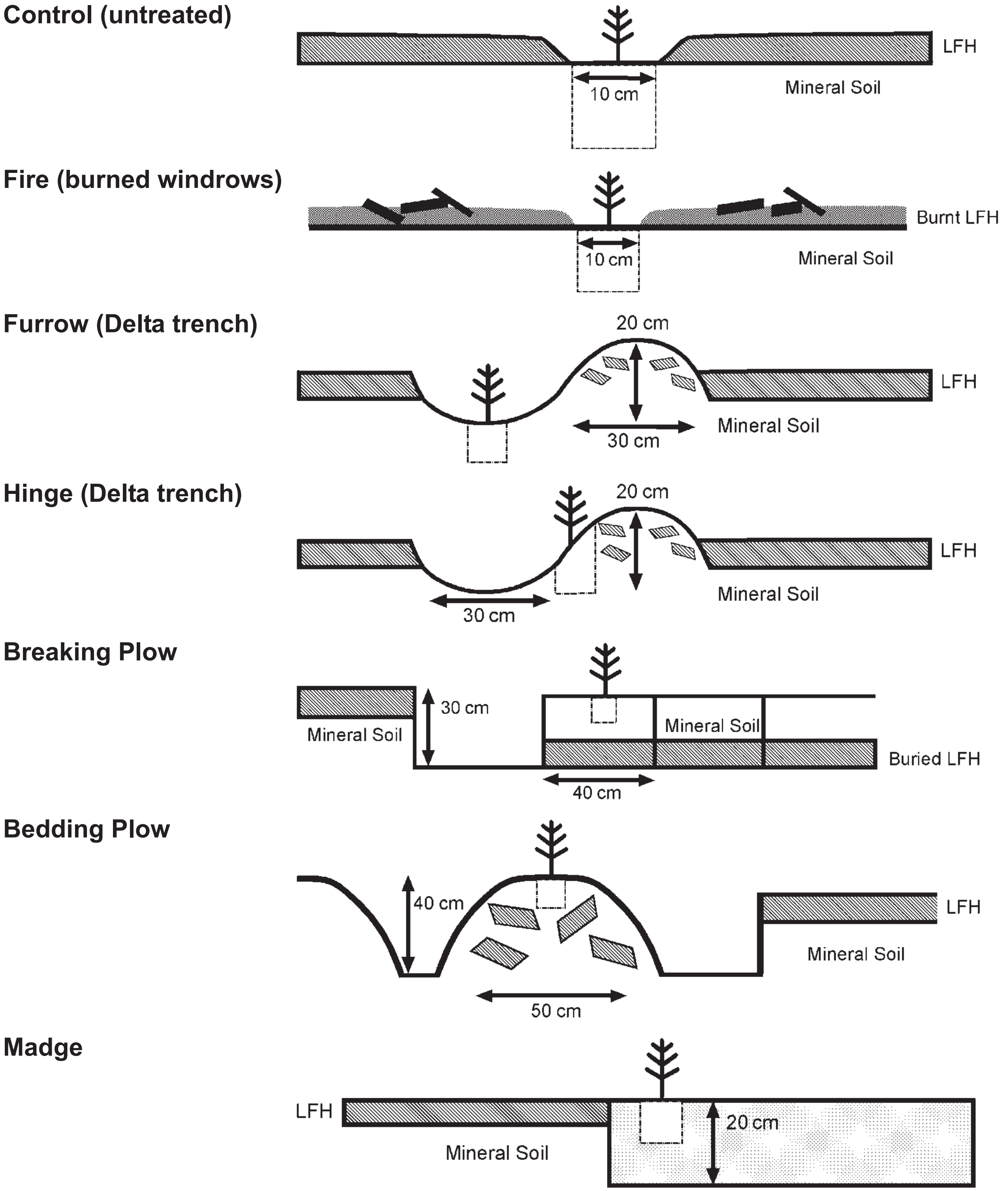
The study was conducted at two sites located in northern B.C. (Table 1). The Bednesti site is in the Sub-boreal Spruce biogeoclimatic zone, at 53°52′N and 123°29′W, in the Prince George Forest District (DeLong and Tanner 1993). The climate is subtemperate, with long cold winters and summers with a short growing season, hot days, and cool nights (Haeussler et al. 1999; McMinn and Bedford 1989). The total annual precipitation is 614 mm, and the mean annual temperature is 3.7 °C, with a maximum temperature of 22.1 °C in July and a minimum temperature of –14.1 °C in January. Soils of the Bednesti site are classified as Orthic Humo-ferric Podzols, with a texture of sandy loam to loam, a poor nutrient regime, and a mesic moisture regime. The loamy parent material consists of coarsely stratified basal till that is slightly stony and water modified (Haeussler et al. 1999; McMinn and Bedford 1989). The previous stand of lodgepole pine (*Pinus contorta* Dougl.) and black spruce (*Picea mariana* (Mill.) B.S.P.) was strip-logged in 1963, with the residual strips logged in 1971. In 1986, a stocking survey determined the block to be not satisfactorily restocked. The Ministry of Forests chose to use this site to study MSP the following year. Rehabilitation consisted of shearing all regeneration, piling stems into windrows, and burning. Disturbance to the forest floor and mineral soil was minimized by shearing and piling in January, when the soil was frozen. MSP treatments were completed that fall (see Experimental design), and lodgepole pine was planted in the spring (McMinn and Bedford 1989).

The Inga Lake site is in the Boreal White and Black Spruce biogeoclimatic zone, at 56°35′N and 121°36′W, in the Fort St. John Forest District (DeLong and Tanner 1993) (Table 1). The overall climate is subtemperate, again with long cold winters and a short growing season characterized by warm days and frequent thunderstorms. The total annual precipitation is 492 mm, and the mean annual temperature is 1.3 °C, with a maximum temperature of 21.9 °C in July and a minimum temperature of –21.9 °C in January. The soil is classified as an Orthic Gray Luvisol, has a texture of silty loam to clay loam, a moderate nutrient regime, and a mesic moisture regime. The parent material here is made up of clayey to loamy basal till (McMinn et al. 1989). There is no history of logging on this site, but in 1950 a wildfire led to aspen (*Populus tremuloides* Michx.) and willow (*Salix* L. sp.) regeneration. In 1987, the Ministry of Forests decided to use this block in the MSP study, and it was also sheared, piled, and burned in January. In the fall, MSP treatments were implemented (see Experimental design), and blocks were planted with hybrid spruce in the spring (*Picea glauca* (Moench) Voss × *Picea engelmannii* Parry) (McMinn et al. 1989).

Experimental design

A randomized block design was used to compare the soil properties of untreated (control) plots to those created by various MSP treatments. Seven treatment plots (approximately 40 m × 35 m), including the control, were established and examined within each of five blocks. The MSP treatments ex-

Fig. 1. Mechanical site preparation schematics for the treatments carried out at the Bednesti and Inga Lake sites. Diagrams show the basic treatment morphology, the crop-tree planting microsite, and the location from where soil samples were removed. The black plates on the fire treatment represent large pieces of charcoal, and the grey plates on the bedding plow, hinge, and furrow treatments represents large pieces of forest floor at a given depth.



amined in this study were delta trench (furrow and hinge microsites), bedding plow, breaking plow, and madge rotoclear (Fig. 1). A burned windrow treatment (fire) was included to compare with MSP results. Orlander et al. (1990) and Sutherland and Foreman (1995) have classified MSP techniques into the following categories: blading, trenching, mixing, inverting, and raising the planting microsite. These categories can be used to describe the five MSP treatments examined here. Delta trenching creates three distinct microsites: a low microsite in the furrow, one on the hinge of the furrow and the berm, and one on top of the berm. The furrow represents a bladed microsite, while the hinge is on the edge of a raised and mixed microsite. The breaking plow creates a continuous bed of mineral soil on top of forest floor by cutting out strips of forest floor and mineral soil and flipping them side by side to produce an inverted microsite. The bedding plow incorporates a series of discs that break up the forest floor, mix it with the mineral soil, and deposit the material for a mixed and raised microsite. The madge rotoclear consists of a toothed cylindrical drum that rotates at 300 r/min. In one pass the madge mixes the forest floor and mineral soil to a depth of 12–15 cm and a width of 1.75 m producing a homogeneously mixed microsite. Bedford and Sutton (2000) provide full descriptions of all treatments established at both sites.

Tree growth

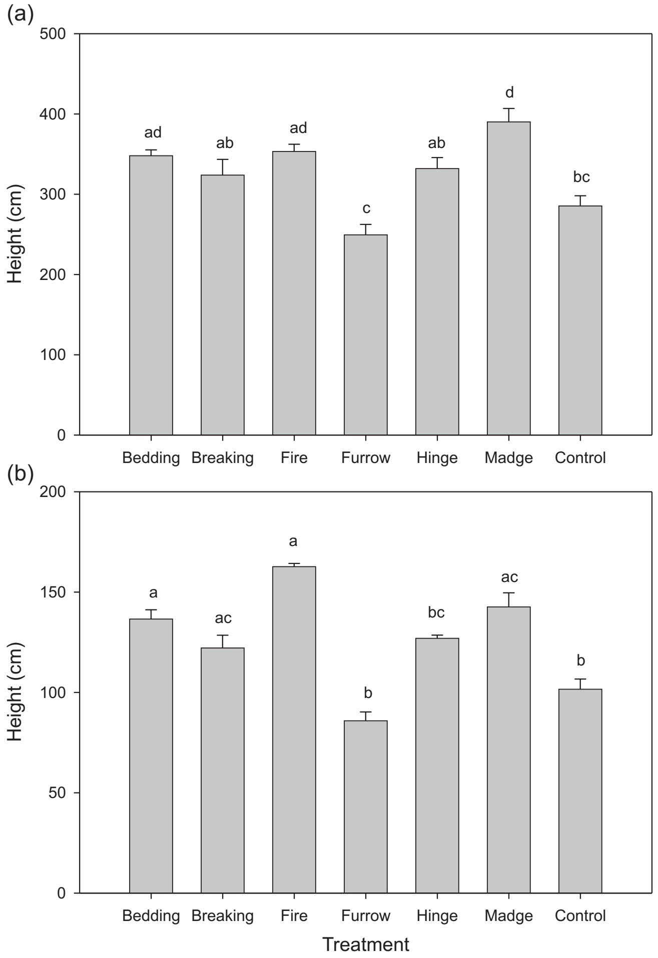
Tree height and basal diameter have been measured every year since establishment at both the Bednesti and Inga Lake sites. Towards the end of the growing season (late July), the height and basal diameter of each tree were measured for all treatments, at both sites. Tenth-year height data are presented for treatment comparisons, but a more detailed analysis of the growth trends for all ten growing seasons is available from Bedford and Sutton (2000) and Haeussler et al. (1999).

Soil sampling and physical analysis

Soil samples were collected in June and July 1997 (approximately 10 years after the crop trees were planted). All crop trees were individually numbered, and a list of random numbers was generated to locate sampling spots. All soil samples were taken 0.5 m away from these randomly chosen crop trees. Since treatments differ with regard to how they bury or mix OM, samples were taken from the planting microsite of each treatment. A round 10 cm × 10 cm core and core hammer were used to remove all samples. Eight samples per plot were collected from the upper mineral soil (0–10 cm), and six samples per plot were collected from the lower mineral soil (10–20 cm), except on the furrow and hinge treatments. At both depths, half of the samples were composited for physical analysis and the other half for chemical analysis. Samples set aside for physical analysis were oven dried at 105 °C for 24 h. When dry, the samples were sieved to 2 mm and both the coarse and fine fractions weighed. Bulk density (D_b) was calculated for both the fine fraction and the total soil as soil mass divided by soil volume.

The spring and summer soil water and soil temperature were measured for the control, furrow, hinge, bedding plow, and madge treatments. Soil temperature measurements were made with copper-constantan thermocouples installed at 10 cm depths in the planting microsite. An Omega digital temperature meter was used to take the readings. In an attempt to measure maximum daily temperatures, soil temperature measurements were made in late afternoon because of the lag time involved in atmospheric–soil heat transfer. Volumetric field water content was determined with a Delta T probe and meter at the same time as soil temperature. The Delta T probe measures an apparent change in the dielectric constant of a soil, similar to a time-domain reflectometry process (Whalley 1993; White et al. 1994). The probe measures soil water from an area of 3 cm in diameter and 6 cm in depth created by four steel prongs inserted into the ground. Soil water and temperature data were collected at 2-week intervals for the growing season and then once a month for the rest of the frost free season.

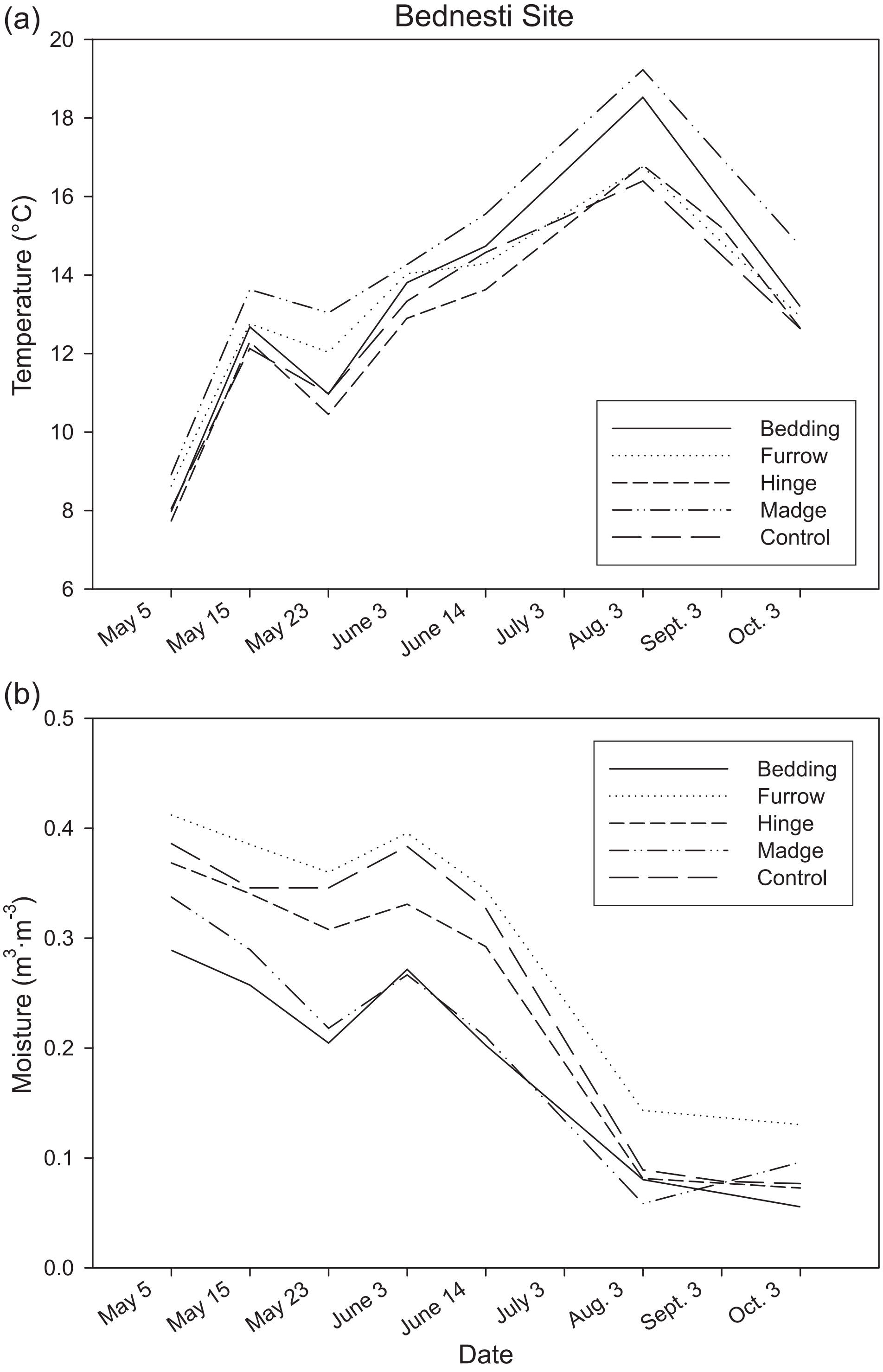
Fig. 2. The average height and standard error of trees for (*a*) the Bednesti site and (*b*) the Inga Lake site from 1997. Different letters indicate statistically significant differences at p = 0.100. Adapted from Bedford and Sutton (2000) and Haeussler et al. (1999).



Soil chemical analysis

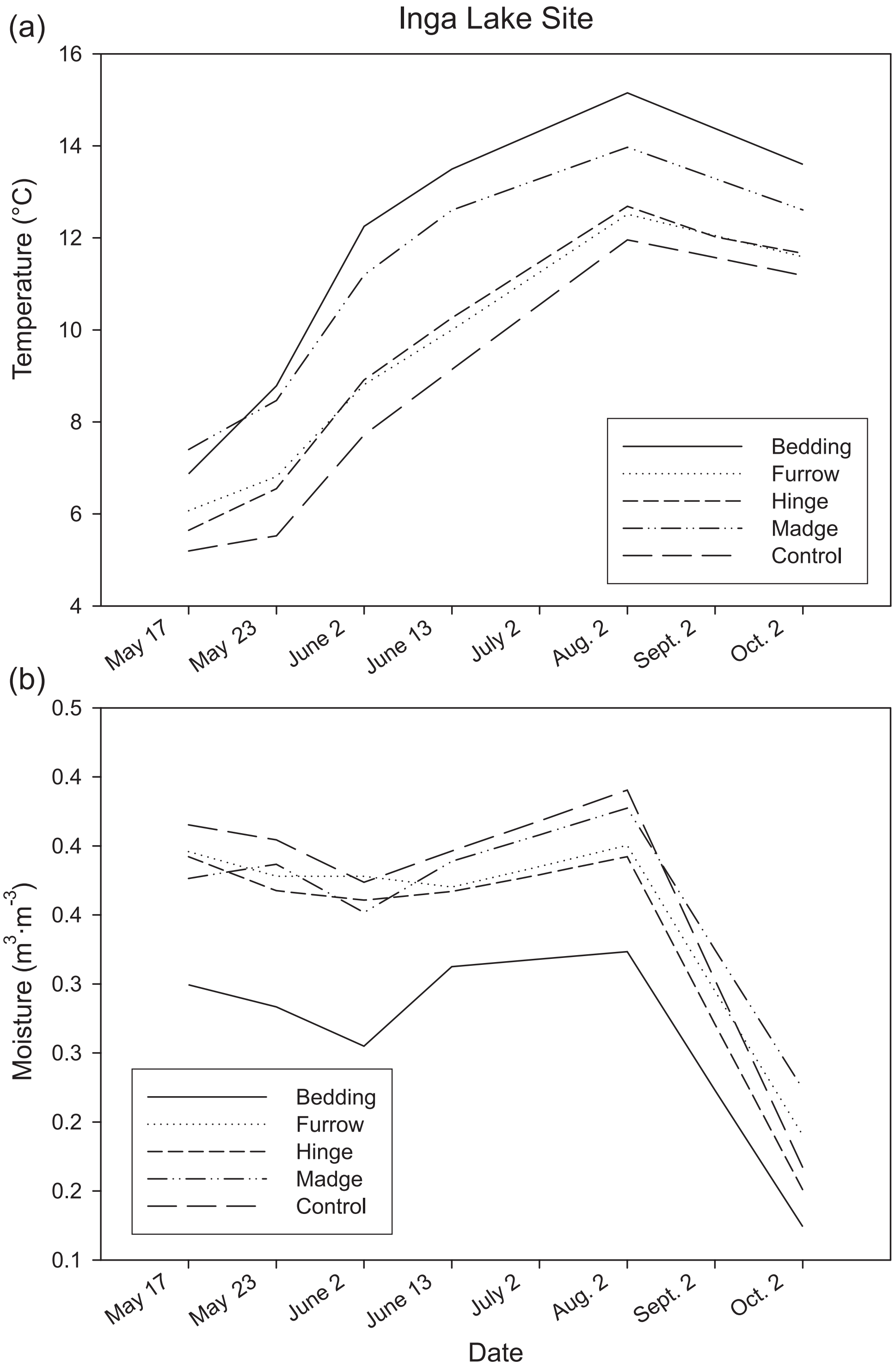
Soil pH was determined in a 2:1 slurry of 0.01 mol/L $CaCl_2$ and soil. The slurry was left to stand for 30 min, and pH was measured on a Fischer Scientific Accumet pH meter (McLean 1982). CEC was measured using the manual leaching and vacuum extraction method (Kalra and Maynard 1991). Exchangeable bases were measured by extraction with 1 mol/L NH_4OAc adjusted to pH 7.0, and base cation concentration was determined by atomic absorption spectophotometry (Thomas 1982). Percent base saturation (%BS) was then calculated as base cation concentration divided by CEC. Total C was measured using a LECO induction furnace (Nelson

Fig. 3. (*a*) Average seasonal soil temperature and (*b*) soil moisture for mechanical site preparation treatments at the Bednesti site. Data were collected in 1997 on the dates indicated.



and Sommers 1982). Total N was determined using a semimicro Kjeldahl digest followed by colorimetric determination of N concentration using a Technicon II autoanalyzer (Bremner and Mulvaney 1982). The C:N ratio was calculated from the total C and total N data. Twenty-five grams of field-fresh soil was extracted with 50 mL of 2 mol/L KCl. NH_4^+-N concentrations were determined by the salicilate–nitroprusside method, while NO_3^--N concentrations were determined by the cadmium reduction method, and both were analyzed on a Technicon II autoanalyzer (Keeney and Nelson 1982). Potential mineralizable N (PMN) was determined by incubating soil samples in 20 mL of deionized water under a head space of N_2 gas for 2 weeks at 30 °C (Bremner and Mulvaney 1982). Samples were then extracted with an equal amount of 4 mol/L KCl, and NH_4^+-N was determined by the same colorimetric analysis described previously.

Fig. 4. (*a*) Average seasonal soil temperature and (*b*) soil moisture for mechanical site preparation treatments at the Inga Lake site. Data were collected in 1997 on the dates indicated.



Ion-exchange resin analysis

To measure seasonal nutrient availability we used ion-exchange resins (IER) following the methods of Binkley and Matson (1983), Krause and Ramlal (1987), Munson et al. (1993), and Munson and Timmer (1995). The IER method was selected because it is sensitive to changing field conditions throughout the growing season and provides an accurate estimate of in situ mineralizable N. A mixed-bed resin was obtained from JTBaker Laboratory Inc. and was prepared by adding approximately 8 g of resin to 5 cm × 5 cm nylon bags. The bags were first rinsed in deionized water for 24 h, loaded with 1 mol/L NaCl (25 mL per bag) for 24 h, and rinsed in deionized water again for 24 h (Krause and Ramlal 1987). Four IER bags were installed at each block on 5 May at the Bednesti site and on 17 May at the Inga Lake site. The resin bags were installed individually by creating a straight slit in the ground with a shovel at a 45° angle, as described by Munson and Timmer (1995). The resin bags were then placed horizontally at a depth of 10 cm. The resin bags were collected on 2 October at Inga Lake and on 3 October at Bednesti. After removal from the field, the resins were extracted using 0.1 mol/L NaCl, and the concentrations of NH_4^+-N and NO_3^--N were determined using the same methods described previously.

Foliar N analysis

Foliar samples were collected at both sites in October 1997, from the top third of dominant trees for each replicate. Samples from 15 trees were composited to one sample per replicate per treatment and oven dried at 65 °C (Ballard and Carter 1986). Samples were then ground in a Wiley Mill and used to determine foliar N concentration by Kjeldahl digest (Parkinson and Allen 1975) and colorimetric analysis as described previously.

Statistical analysis

Two-way analysis of variance (ANOVA) tests were performed to compare the effect of treatment and block on different variables. Each plot was considered an experimental unit. Differences that resulted between treatments were analyzed using Tukey multiple comparison tests. Repeated measures ANOVA was used to test the time-series data that were collected for soil water and soil temperature and measure the changing temperature or soil water (within subjects) with regard to the different MSP treatments (between subjects). Specifically, we report the time × treatment interaction to determine whether MSP treatments affected these soil properties through the growing season (Underwood 1997; Wilkinson 1997). In all cases, the data were tested to ensure that they met the assumptions of parametric statistics. All analyses were conducted with the SYSTAT 7.0 statistical package (Wilkinson 1997). As a means of increasing the power of statistical analysis, results were considered statistically significant when $p \leq 0.10$.

Results

Tree growth

MSP significantly influenced mean crop-tree height at both sites (Bedford and Sutton 2000; Haeussler et al. 1999). At Bednesti, the control had a mean tree height and standard error of 285 ± 37 cm (Fig. 2*a*). Treatments that were significantly greater than the control ($n = 35$, df = 6, F ratio = 10.508, $p \leq 0.000$) included the bedding plow, fire, hinge, and madge, which were anywhere from 20% to 25% taller. Tree height differences were more dramatic between MSP treatments and the control at Inga Lake (Fig. 2*b*). There, the control had a mean tree height and standard error of 139 ± 26 cm. Treatments that were significantly greater than the control ($n = 35$, df = 6, F ratio = 30.778, $p \leq 0.000$) were the breaking plow, bedding plow, fire, and madge, whose trees were all approximately twice as tall as those of the control.

Soil microclimate and physical properties

MSP had a significant effect on soil microclimate as shown by an increase in soil temperature and a general decrease in soil water as the growing season progressed (Figs. 3 and 4). At the Bednesti site, soil temperature was not significantly different among treatments according to repeated measures ANOVA ($n = 25$, df = 24, F ratio = 0.947, $p = 0.413$) (Fig. 3*a*). Although not statistically significant, the madge was the fastest to warm up in the spring and stayed the warmest throughout the growing season. Soil water was significantly different among treatments for the sampling period according to repeated measures ANOVA ($n = 25$, df = 24, F ratio = 1.538, $p = 0.066$) (Fig. 3*b*). Water content was significantly lower in the bedding plow and madge treatments, possibly allowing the soil to heat more quickly. The control, hinge, and furrow treatments retained more water throughout the growing season and theoretically did not warm very quickly.

The seasonal soil water and temperature trends at the Inga Lake site (Fig. 4) were similar to those at Bednesti. Soil temperature (Fig. 4*a*) and soil water (Fig. 4*b*) were both significantly different among treatments ($n = 25$, df = 24, F ratio = 2.442, $p = 0.001$; $n = 25$, df = 24, F ratio = 1.739, $p = 0.028$, respectively) for the entire period of measurement according to repeated measures ANOVA. Soil temperature of the bedding plow and madge treatments both increased rapidly in the spring and remained high throughout the growing season. The control, furrow, and hinge did not warm quickly, with the control having the lowest seasonal soil temperature. The bedding plow treatment had the lowest soil water content, which persisted through the growing season, while the control, furrow, hinge, and madge treatments had similar soil water contents throughout the sampling period.

Bulk density (D_b) was significantly altered by MSP at both sites (Table 2). At both Bednesti and Inga Lake, the bedding plow had significantly lower D_b than the control at both the 0–10 and 10–20 cm depths. At Inga Lake, the madge also had significantly lower bulk density than the control at both depths. The furrow was the only treatment that significantly increased D_b when compared to the control, where the 0–10 cm D_b of the furrow is similar to the D_b of the 10–20 cm depth of the control.

Soil chemical properties

MSP significantly affected pH, CEC, and %BS at both sites (Table 3). At the 0–10 cm depth at Bednesti, the fire had significantly higher pH than the control, and the CEC of the bedding plow was significantly greater than that of the control. No treatments differed significantly from the control in %BS; however, fire and furrow had significantly greater %BS than the bedding plow. At 10–20 cm, the pH of the fire treatment was still elevated, but no longer significantly different from the control, the CEC of the bedding plow remains significantly greater than the control, and the %BS of the fire and %BS of the control treatment are still significantly greater than that of the bedding plow. There were similar trends at Inga Lake between the fire, bedding plow, and control for pH, CEC, and %BS (Table 2). The soil pH for fire was significantly greater than that of the control at both the 0–10 and 10–20 cm depths. The CEC of the bedding plow was significantly greater than that of the control at both 0–10 and 10–20 cm; however, the hinge microsite had the highest CEC of all treatments. The %BS was not significantly different from the control for any treatment at either depth, but fire had the highest value at 10–20 cm.

Table 2. Bulk density (D_b) values at two different depths at the Bednesti and Inga Lake sites.

	D_b (Mg/m^3)	
Treatment	Depth 0–10 cm	Depth 10–20 cm
Bednesti		
Bedding	0.76(0.04)a	1.00(0.04)a
Breaking	0.98(0.03)b	1.11(0.03)a
Control	1.20(0.04)c	1.54(0.04)b
Fire	1.16(0.07)c	1.39(0.06)bc
Furrow	1.37(0.03)d	—
Hinge	1.01(0.04)b	—
Madge	1.10(0.03)bc	1.29(0.02)c
n	35	35
df	6	6
F ratio	16.565	26.321
p value	<0.000	<0.000
Inga Lake		
Bedding	0.74(0.03)a	0.81(0.07)a
Breaking	1.15(0.08)b	0.90(0.03)a
Control	1.20(0.03)b	1.43(0.02)b
Fire	1.18(0.07)b	1.40(0.04)b
Furrow	1.37(0.02)c	—
Hinge	0.73(0.04)a	—
Madge	0.99(0.04)d	1.36(0.01)b
n	35	35
df	6	6
F ratio	31.134	52.600
p value	<0.000	<0.000

Note: Mean and standard error are reported for five replicates. ANOVA statistics include number of samples (*n*), degree of freedom (df), *F* ratio, and *p* value. Letters refer to treatment differences of a given depth based on post hoc Tukey multiple comparison tests of the ANOVA results. Different letters indicate treatment differences at $p \leq 0.100$.

MSP significantly influenced total C, total N, and the C:N ratio at both sites (Table 4). The bedding plow had significantly greater total C, total N, and C:N ratio compared to the control, at both depths and both sites, indicating that OM had been incorporated to the full depth in this treatment. However, the bedding plow had a C:N ratio much greater than 30:1 at Bednesti, which is generally considered a threshold for N mineralization (Sutherland and Foreman 1995), indicating that N availability might be reduced in this treatment. In fact, all treatments at Bednesti had C:N ratios greater than 30:1 except for the control, fire, and furrow treatments at the 0–10 cm and the control and fire treatments at 10–20 cm depth. At Inga Lake, the C:N ratio is less than 20:1 for most treatments except for the bedding plow and hinge at 0–10 cm and the bedding and breaking plow at 10–20 cm, indicating that N mineralization should not be inhibited.

MSP had a significant effect on NH_4^+, NO_3^-, and PMN at both sites (Table 5). At Bednesti, no treatments differed significantly from the control at the 0–10 cm depth. However, the bedding plow had significantly greater NH_4^+ than the madge at both the 0–10 and 10–20 cm depths and significantly greater NO_3^- than the furrow at the 0–10 cm depth and the control at 10–20 cm depth. Potential mineralizable N was also significantly higher for the bedding plow than for all other treatments at 10–20 cm. The results for Inga Lake were similar, but concentrations were much higher. The hinge microsite was significantly greater than the control for NH_4^+, NO_3^-, and PMN at 0–10 cm, while the bedding and breaking plow had significantly higher concentrations of NH_4^+, NO_3^-, and PMN than the control at 10–20 cm. Nutrient contents were not significantly different from the control for any treatment and are not reported here.

Seasonal N availability

Seasonal N availability, as collected by IER, was not significantly altered by MSP at either site (data not shown). At Bednesti, the control had mean concentrations of 38.5 ± 19.8 µg/bag for NH_4^+ and 2.11 ± 0.46 µg/bag for NO_3^- (n = 25, df = 4, F ratio = 1.606, p = 0.212; n = 25, df = 4, F ratio = 1.370, p = 0.280, respectively). At Inga Lake, the control had mean concentrations of 53.0 ± 15.3 µg/bag for NH_4^+ and 3.90 ± 0.90 µg/bag for NO_3^- (n = 25, df = 4, F ratio = 2.125, p = 0.110; n = 25, df = 4, F ratio = 1.325, p = 0.295, respectively). However, the IER data do show that a large amount of NH_4^+ accumulated in the control treatment as compared with the mineral soil grab samples, while there was little difference between IER-collected NO_3^- and mineral soil grab sample NO_3^-.

Foliar N analysis

There were no significant differences in foliar N concentrations among treatments at either site (data not shown). The control at Bednesti had an average foliar N concentration of 13.7 ± 0.49 mg/g (n = 35, df = 6, F ratio = 1.699, p = 0.160), while the control at Inga Lake had an average foliar N concentration of 13.0 ± 0.40 mg/g (n = 35, df = 6, F ratio = 0.695, p = 0.656). Both of these values are considered to be slightly deficient for the lodgepole pine and hybrid spruce, respectively, planted on these sites (Ballard and Carter 1986).

Discussion

Soil physical properties and tree growth

Results indicate that fertility on these sites has not been reduced (in some cases it has been improved), but there was no clear connection between increased N availability and increased crop-tree performance. Therefore, we must consider the impact of soil microclimate as an alternative explanation. Seasonal soil moisture and temperature regimes are critical factors affecting growth on most forest plantations (Bulmer et al. 1998; Macadam and Bedford 1998). At Bednesti, the bedding plow and madge treatments reduced soil water compared to the control, and the madge increased soil temperature. These treatments also had the best crop-tree performance, with trees 35% and 130% taller than those of the control at Bednesti and Inga Lake, respectively. The bedding plow and madge also had lower D_b than that of the control at both sites. These treatments had bulk densities lower than 1.00 g/cm^3, which may indicate that a large amount of OM was incorporated into the surface mineral soil of these treatments, an amount of OM that was still evident 10 years later. The total C data indicated that the bedding plow had significantly greater OM than the control at both sites and that the madge, although not statistically different at either site, had almost double the C concentration of the control. Given the treat-

Table 3. pH, cation exchange capacity (CEC), and percent base saturation (%BS) at two different depths at the Bednesti and Inga Lake sites.

	Depth 0–10 cm			Depth 10–20 cm		
Treatment	pH	CEC (cmol$_c$/kg)	%BS	pH	CEC (cmol$_c$/kg)	%BS
Bednesti						
Bedding	4.8(0.1)a	20.9(1.48)a	46.6(3.81)a	4.8(0.1)a	14.6(1.12)a	50.4(2.51)a
Breaking	4.9(0.1)a	15.4(0.63)b	54.1(4.48)ab	4.9(0.0)ab	13.2(0.45)ac	55.1(2.51)a
Control	4.9(0.1)a	12.7(0.31)b	53.9(3.14)ab	5.2(0.1)bc	8.24(0.31)b	75.0(3.45)b
Fire	5.4(0.1)b	13.5(1.26)b	66.4(4.84)b	5.4(0.0)c	10.7(0.76)bc	74.9(3.54)b
Furrow	5.5(0.1)c	12.3(0.75)b	67.2(4.45)b	—	—	—
Hinge	5.0(0.1)a	14.5(1.61)b	58.5(6.05)ab	—	—	—
Madge	5.0(0.0)a	15.0(1.80)b	54.1(8.12)ab	5.1(0.0)ab	9.9(0.61)b	64.5 ab (7.62)
n	35	35	35	25	25	25
df	6	6	6	4	4	4
F ratio	8.197	4.587	1.789	9.662	13.061	4.955
p value	<0.000	<0.000	0.093	<0.000	<0.000	0.006
Inga Lake						
Bedding	4.9(0.0)a	23.9(1.57)ac	50.8(2.38)	5.0(0.1)ab	21.8(3.36)a	58.4(2.78)ab
Breaking	4.9(0.0)a	12.4(0.90)b	60.8(5.78)	4.9(0.0)ab	19.6(1.61)a	56.1(3.90)a
Control	4.9(0.1)a	11.1(1.35)b	68.9(4.71)	4.8(0.0)a	9.3(0.94)b	59.3(5.52)ab
Fire	5.9(0.2)b	18.0(3.81)ac	68.2(6.99)	5.1(0.1)b	9.8(1.08)b	73.5(5.02)b
Furrow	5.1(0.1)a	10.0(1.21)b	67.1(4.71)	—	—	—
Hinge	5.0(0.1)a	27.1(3.68)c	59.1(7.85)	—	—	—
Madge	5.1(0.0)a	16.2(2.02)a	62.4(4.35)	4.9(0.1)ab	9.4(0.63)b	65.9(3.68)ab
n	35	35	35	25	25	25
df	6	6	6	4	4	4
F ratio	11.151	7.740	1.348	2.750	11.675	2.765
p value	0.000	0.000	0.270	0.057	0.000	0.056

Note: Means and standard errors are reported for five replicates. ANOVA statistics include number of samples (*n*), degree of freedom (df), *F* ratio, and *p* value. Letters refer to treatment differences of a given depth based on post hoc Tukey multiple comparison tests of the ANOVA results. Different letters indicate treatment differences at $p \leq 0.100$.

ment morphology, low D_b and high C concentrations in the surface soil of the bedding plow and madge, it is likely that these treatments have increased drainage of excess soil water in the spring, allowing soil heating to begin earlier in the season. Increasing soil temperature has been shown to improve net photosynthetic rate and nutrient mobilization by stimulating microbial activity and OM decomposition (Munson et al. 1993). The increased soil temperature on the madge treatment may have led to increased nutrient uptake (Munson and Timmer 1995).

The positive effect of fire on height growth at both sites may also be related to temperature. Fire increases soil temperature for a short period of time by replacing the forest floor with a thin layer of ash, which allows more solar radiation to penetrate the soil (Kimmins 1996; MacKenzie et al. 2004).

MSP techniques that raise and invert the forest floor and mineral soil, such as the bedding plow, have been shown to significantly increase crop-tree growth in other studies (Attiwill et al. 1985; Macadam and Bedford 1998), as have trenching and ripping techniques, such as Delta trench (Sutton and Weldon 1993, 1995). The hinge microsite improved tree growth, but after 10 years it is not clearly related to soil microclimate, D_b, or soil chemistry (discussed in next section). Blading the forest floor, which is similar to the furrow treatment, has been shown to reduce tree growth by as much as 30% when compared with untreated plots in eastern Ontario (Weber et al. 1985), and a similar reduction in crop-tree performance has been shown for these sites.

Nontarget species competition can be a severe problem for MSP techniques that create continuous and open microsites (Glover and Zutter 1993). At Inga Lake, crop-tree height differences between treatments have been influenced by competition from other species (Glover and Zutter 1993; Haeussler et al. 1999). Competing vegetation is far more abundant at Inga Lake than at Bednesti and is likely reducing the amount of resources available to crop trees. Heavy competition may be reducing plant growth potential on certain blocks of the control, hinge, and furrow treatments at both sites (Haeussler et al. 1999).

Soil chemical properties and N availability

One goal of this project was to evaluate the soil fertility of different treatments in the tenth growing season. It has been shown that certain nutrients (mainly N) may be insufficient or unavailable in the soil environment several years after disturbance and could begin to affect crop-tree growth at this time (Prescott et al. 1992). For most treatments, soil fertility was the same or slightly enhanced when compared with the control. However, treatments with the best growth at both sites (bedding plow, madge, and fire) were not consistently different from the control for any of the measured chemical properties. Of course it is possible that multiple variables are having synergistic effects on crop-tree growth, but this does

Table 4. Total C (TC) and total N (TN), and the C:N ratio at two different depths at the Bednesti and Inga Lake sites.

	Depth 0–10 cm			Depth 10–20 cm		
Treatment	TC (g/kg)	TN (g/kg)	C:N	TC (g/kg)	TN (g/kg)	C:N
Bednesti						
Bedding	60.8(6.41)a	1.3(0.09)a	47(3.8)a	32.4(7.44)a	0.84(0.08)a	38(7.8)a
Breaking	37.6(5.47)b	0.82(0.07)b	47(7.6)a	21.2(1.35)a	0.60(0.03)b	36(3.0)ac
Control	21.6(1.78)bc	0.82(0.05)bc	26(1.0)b	6.2(0.67)b	0.32(0.02)c	19(1.4)b
Fire	18.2(2.15)bc	0.70(0.09)c	26(2.0)b	9.4(1.70)ab	0.44(0.05)bc	21(2.8)b
Furrow	12.0(1.26)c	0.48(0.02)c	25(1.9)b	—	—	—
Hinge	30.0(7.04)bc	0.90(0.17)bc	32(4.2)ab	—	—	—
Madge	34.2(7.71)bc	0.84(0.08)bc	32(5.3)ab	11.4(0.94)ab	0.46(0.05)bc	25(0.9)a
n	35	353	35	25	25	25
df	6	6	6	4	4	4
F ratio	9.235	6.736	4.880	9.349	16.197	4.726
p value	<0.000	<0.000	<0.000	<0.000	<0.000	0.006
Inga Lake						
Bedding	49.6(3.50)ac	2.16(0.14)ac	23(1.4)a	48.0(9.64)a	2.04(0.18)a	23(2.6)a
Breaking	17.0(2.19)b	1.12(0.07)b	15(1.2)b	44.6(5.38)a	1.88(0.15)a	24(1.4)a
Control	16.2(2.74)b	1.06(0.11)b	15(0.8)b	8.60(0.98)b	0.66(0.04)b	13(1.8)b
Fire	20.8(4.26)b	1.22(0.21)b	17(1.2)b	9.4(1.70)b	0.88(0.13)b	12(1.4)b
Furrow	12.6(1.61)b	0.94(0.09)b	13(0.7)b	—	—	—
Hinge	71.4(13.4)c	2.90(0.39)c	24(2.2)a	—	—	—
Madge	31.0(2.60)ab	1.68(0.16)ab	19(0.9)ab	11.8(0.85)b	0.88(0.04)b	15(2.2)b
n	35	35	35	25	25	25
df	6	6	6	4	4	4
F ratio	14.286	13.796	10.659	16.858	28.043	13.649
p value	<0.000	<0.000	<0.000	<0.000	<0.000	<0.000

Note: Means and standard errors are reported for five replicates. ANOVA statistics include number of samples (*n*), degree of freedom (df), *F* ratio, and *p* value. Letters refer to treatment differences of a given depth based on post hoc Tukey multiple comparison tests of the ANOVA results. Different letters indicate treatment differences at $p \leq 0.100$.

not help managers identify easily measurable characteristics for determining long-term productivity.

The bedding plow and breaking plow both deposit forest floor to a given depth in the mineral soil, and this has reduced the rate of decomposition, perhaps making N more available through time, where both treatments have elevated N indices compared to the control. However, at Bednesti the breaking plow crop-tree performance was not significantly different from that of the control, while at Inga Lake it was significantly greater. This is the first indication that something other than N availability is controlling tree growth at these northern sites. The madge treatment, which mixes the forest floor and mineral soil into a homogeneous layer, did not differ from the control in terms of soil pH, CEC, or %BS, has the lowest N values of all treatments at Bednesti, and yet has very good crop-tree growth. This is perhaps the best example that MSP has not depleted N availability sufficiently to compromise tree growth for the first 10 years after planting and that in northern climates, soil microclimate and D_b are the most important factors for increasing productivity.

Schmidt et al. (1996) showed that fire improved site fertility marginally by increasing pH and CEC, and these results are corroborated here. However, the fire treatment did not show increased N availability after 10 years. Fire has been shown to increase N availability in the short term, but levels return to predisturbance within 2–5 years (DeLuca and Zouhar 2000). For all treatments, including fire, it is possible that the improved crop-tree growth resulted from increased nutrient supply after disturbance, which has since returned to untreated levels. Some studies have indicated that burned windrows may result in excess N being concentrated in one area directly after treatment, while the rest of the site suffers from lower N availability (Fox et al. 1986; Pye and Vitousek 1985). This does not seem to be the case after 10 years, where N concentrations in the soil of the fire treatment are, for the most part, not statistically different from that of the control or other treatments.

Differences in N availability created by delta trench microsite selection are very important. The furrow and hinge microsites, created by the same equipment and within 0.5 m of each other, continue to exhibit differences in N availability after 10 years. The furrow microsite is lower in the soil profile and seems to have reduced fertility due to lower OM content (data not shown) and has poor crop-tree growth. This supports the blading results of Weber et al. (1985) and Munson and Timmer (1995). In contrast, the hinge treatment enhanced many soil fertility factors, but did not improve tree growth beyond that of the control. It is possible that roots proliferate through the furrow and hinge microsites and into control-like surroundings within a few years of establishment. Root development into control-like microsites (untreated) may reduce nutrient availability compared to treatments with more continuous distributions, such as the bedding plow, madge, and fire.

Seasonal N availability was not significantly different between treatments. It appeared that the overall N availability

Table 5. NH_4^+-N, NO_3^--N, and potential mineralizable N (PMN) concentrations at two different depths at the Bednesti and Inga Lake sites.

	Depth 0–10 cm			Depth 10–20 cm		
Treatment	NH_4^+-N (mg/kg)	NO_3^--N (mg/kg)	PMN (mg/kg)	NH_4^+-N (mg/kg)	NO_3^--N (mg/kg)	PMN (mg/kg)
Bednesti						
Bedding	10.2(1.3)a	4.3(0.6)a	28.4(3.36)	6.6(1.1)a	2.8(0.4)a	30.0(5.02)a
Breaking	8.6(0.8)ab	3.0(0.3)ab	26.0(3.00)	6.2(0.9)a	2.6(0.2)ab	17.4(1.17)b
Control	7.2(0.7)ab	3.0(0.1)ab	31.0(2.51)	4.4(0.7)ab	1.9(0.2)b	12.2(1.93)b
Fire	5.6(0.9)ab	2.5(0.3)ab	25.8(5.69)	4.6(0.9)ab	2.2(0.3)ab	14.8(2.82)b
Furrow	6.5(1.4)ab	2.0(0.2)b	27.5(0.58)	—	—	—
Hinge	9.6(2.2)ab	4.2(1.0)ab	30.0(2.83)	—	—	—
Madge	4.8(0.4)b	3.2(0.5)ab	21.8(3.05)	3.2(0.2)b	2.4(0.4)ab	14.8(1.48)b
n	35	35	35	25	25	25
df	6	6	6	4	4	4
F ratio	2.849	2.596	0.832	2.975	1.591	6.186
p value	0.030	0.041	0.556	0.040	0.039	0.026
Inga Lake						
Bedding	17.0(1.88)ab	15.6(3.7)a	80.2(7.94)ac	14.2(2.38)a	13.1(3.50)a	74.2(13.9)a
Breaking	12.4(1.08)a	6.0(2.0)a	29.6(5.47)b	19.6(2.60)ab	14.5(4.35)a	78.2(8.97)a
Control	11.0(2.56)a	4.1(1.7)a	43.2(8.74)b	5.2(0.6)c	1.6(0.1)b	12.8(1.35)b
Fire	11.4(3.09)a	3.5(0.3)a	33.8(5.11)b	8.2(1.8)ac	2.2(0.3)b	14.6(3.23)b
Furrow	13.0(2.02)a	4.4(1.9)a	28.4(5.18)b	—	—	—
Hinge	24.8(2.65)b	51.3(12.2)b	107.8(13.0)c	—	—	—
Madge	15.0(5.20)ab	5.5(0.8)a	81.4(10.6)ab	9.2(1.1)ac	3.1(0.8)b	22.4(4.26)b
n	35	35	35	25	25	25
df	6	6	6	4	4	4
F ratio	2.798	12.417	13.969	9.384	6.300	17.884
p value	0.030	<0.000	<0.000	<0.000	<0.000	<0.000

Note: Means and standard errors are reported for five replicates. ANOVA statistics include number of samples (*n*), degree of freedom (df), *F* ratio, and *p* value. Letters refer to treatment differences of a given depth based on post hoc Tukey multiple comparison tests of the ANOVA results. Different letters indicate treatment differences at $p = 0.100$.

was the same for all treatments at both sites; however, it is unlikely that N availability was consistently the same throughout the study period. It is likely that treatments which allowed for improved drainage and warmer soil temperatures, such as the bedding plow and madge, have better early-season N availability than treatments that stay cold and wet. The resolution of the data would have increased by including a biweekly analysis of resin bags. It may also be more appropriate to extract IER with 2 mol/L KCl (DeLuca et al. 2002) rather than the 0.1 mol/L NaCl used in this study, which may not have removed all cation and anions from the exchange material.

The difference between IER N values and mineral soil grab sample N values merits further discussion. The results showed that NO_3^- was not accumulating on the IER as quickly as NH_4^+. A lack of resin-collected NO_3^- is possibly an indication of inhibition of nitrification (MacKenzie et al. 2004; Rice and Pancholy 1972; White 1994) which may occur as a result of late secondary succession. If this is the case, it appears that the anthropogenic disturbance of MSP is not enough to reinitiate nitrification, as fire has been demonstrated to do (DeLuca et al. 2002; MacKenzie et al. 2004). Unfortunately, the fire treatment was not included in the IER analysis. Another possible explanation is that NO_3^- turnover and immobilization is occurring rapidly on these sites (Stark and Hart 1997), possibly because of the preferential use of NO_3^- by the herbaceous species establishing on these sites as a result of MSP (Haeussler et al. 1999; Kronzucker et al. 1997; Persson et al. 2003). Future work with IER that incorporates better sampling resolution and experiments to differentiate between NO_3^- inhibition versus immobilization will prove invaluable, given the obvious benefits of analyzing in situ mineralization with IER.

Foliar N concentrations were not significantly different for any treatment at either site, but the average values for each treatment were slightly below 15.5 mg/g, which has been determined to be the minimum for healthy crop trees of the species used in this study (Ballard and Carter 1986). Again, it is possible that when this trial was initiated, MSP may have had an effect on foliar N concentration, but 10 years after treatment, there is no evidence for this except for different crop-tree heights. These results also suggest that MSP has not reduced N fertility in the mid-term, and it will be interesting to examine the long-term results from these sites.

Results from this study are different from those reported for studies located in the southern United States and Australia. Results from these locations report reduced organic residues and increased N losses after different kinds of MSP techniques have been performed (Burger and Pritchett 1984; Smethurst and Nambiar 1990*a*, 1990*b*; Vitousek et al. 1992). However, our results are similar to those for adjacent boreal locations. A study from northern Alberta suggests that 2 years after treatment, nutrient availability was only reduced by MSP techniques that removed the forest floor completely, such as blading and the furrow microsite associated with trenching (Schmidt et al. 1996). A retrospective study from interior B.C. found that nutrient availability was not reduced by fire or MSP when compared to a control 15 to 20 years after treatment (Bulmer et al. 1998), and the authors hypothesized that it may take upwards of 20–30 years to determine the cumulative effects of MSP on fertility. Finally, a study from northern Ontario showed that seasonal N availability, measured with IER, was lowest early in the season and varied substantially for each period that it was measured (Munson and Timmer 1995).

Conclusions

Results from this study indicate that 10 years after MSP, soil N availability is not the primary limiting factor for these treatments when compared to an untreated control. N availability on MSP blocks was not reduced, and in some cases enhanced, compared with control blocks. Seasonal N availability was not statistically different between treatments, but was only measured once for the entire growing season. Soil temperature (Inga Lake) and soil water (both sites) were significantly different between treatments throughout the growing season; soil microclimate better explained differences in crop-tree height among treatments.

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