ELSEVIER

Forest Ecology and Management 110 (1998) 35–48

Forest Ecology and Management

Impacts of mechanical site preparation on foliar nutrients of planted white spruce seedlings on mixed-wood boreal forest sites in Alberta

S. Ellen Macdonald[a,*], Margaret G. Schmidt[b], Richard L. Rothwell[a]

[a] Department of Renewable Resources, University of Alberta, Edmonton AB, T6G, 2E3, Canada
[b] Department of Geography, Simon Fraser University, Burnaby B.C., V5A, 1S6, Canada

Accepted 13 February 1998

Abstract

The impacts of different methods of mechanical site preparation (MSP) on performance and foliar nutrition of planted white spruce (*Picea glauca* (Moench) Voss) seedlings were examined at two mixed-wood boreal forest sites (Judy Creek, Fox Creek) in Alberta, Canada. The treatments included three types of MSP: disc trench, ripper plough, and bladed, the latter including thin and thick microsites (based on depth of remaining organic matter); as well as a harvested-control (no MSP). Seedlings were planted in June 1991, four months after MSP, and foliar N, P, K, Ca, Mg, S, Mn, Fe, and Al were assessed in the second and third growing seasons (13, 25, and 28 months later). Nutrient concentration and relative (among treatments) foliar nutrient content scaled up to the level of the whole seedling were examined. Following analysis of variance, significant responses were interpreted using vector analysis. MSP did not significantly affect seedling survival, height or unit needle weight. There was a non-significant trend of higher foliar biomass for seedlings in MSP areas than for control seedlings. Overall, the impact of MSP on foliar nutrient status on these sites was minimal. The only consistent positive effect of MSP on seedling nutrition was increased foliar Mg concentrations in blade-thin sites at Fox Creek. Indications of possible negative impacts of MSP include: increased Fe and Al concentrations in MSP areas at both sites; reduced P and K concentrations at both sites; and reduced Mn concentration and content at one site. The ripper treatment had the greatest positive effect on foliar nutrient status (P, K, Mn concentration). Blading (particularly blade-thin) resulted in the lowest concentrations of foliar P, K and Mn and the greatest increases in foliar Fe and Al. © 1998 Elsevier Science B.V.

Keywords: Foliar aluminum; Foliar iron; Ion toxicity; Vector analysis; Forest harvesting; Foliar biomass

1. Introduction

Upon planting, conifer seedlings must immediately begin acquiring water and nutrients in order to support photosynthesis and future growth (Margolis and Brand, 1990). The ability to do so depends upon nutrient availability in the soil, soil temperature, moisture, root growth, and mycorrhizal relationships. Mechanical site preparation (MSP) is a widely-used silvicultural tool which may be used to manipulate the first three and could, in turn, influence the latter two (McMinn and Hedin, 1990).

*Corresponding author. Tel.: 00 1 403 492 3070; fax: 00 1 403 492 1767; e-mail: ellen.macdonald@ualberta.ca

PII S0378-1127(98)00272-2

Although an important objective of MSP has been to improve nutrient availability to planted seedlings, MSP has been associated with some negative impacts on site nutrient relations including leaching of cations as a result of increased nitrification (Vitousek and Matson, 1985; Fox et al., 1986; Smethurst and Nambiar, 1990; Vitousek et al., 1992; Munson et al., 1993) and reductions in available P (Krause and Ramlal, 1987), N and C in surface soils (Tuttle et al., 1985; Munson et al., 1993). MSP may effectively improve seedling nutrition in the short term (Burger and Pritchett, 1988; Munson et al., 1993) but there is also evidence for negative effects of MSP on foliar nutrient status of seedlings in the short (Brand and Janas, 1988; Brand, 1991) or long (Weber et al., 1985) term.

On boreal sites, with cold soils, long winters and cool air temperatures, and where species are adapted to these conditions, responses to site preparation may well be less dramatic than those observed for more southerly sites and species (Munson and Timmer, 1995). There is currently no information on the effects of different methods of MSP on seedling nutrition in the mixed-wood boreal forest in Alberta, a region currently experiencing rapid increases in the extent of land under management for fibre production. In our previous paper (Schmidt et al., 1996), we demonstrated that 15 months after MSP, treated areas had either reduced or unchanged concentrations of total and mineralizable N and available P in surface mineral soils and increased or unchanged pH and exchangeable base concentrations. In this paper, we discuss the impacts of different methods of MSP on foliar concentrations and contents of N, P, K, Ca, Mg, S, Mn, Fe and Al in planted white spruce (*Picea glauca* (Moench) Voss) seedlings.

2. Materials and methods

2.1. Site description

The two study sites (Judy Creek: 54°24′N, 115°40′W, 1010 m elevation, slope: 20%, aspect: 270° and Fox Creek: 54°15′N, 116°49′W, 975 m, slope: 6%, aspect: 350°) were located in the Whitecourt Forest in west-central Alberta, Canada. Both are in the Lower Boreal Cordilleran Ecoregion (Corns and Annas, 1986). Prior to harvest, they hosted mature (≈100-year-old) mixed-wood forests dominated by white spruce (≈18–24 m in height, 50–70% crown density) and trembling aspen (*Populus tremuloides* Michx.). Both sites were sloping with relatively homogeneous topography, soils, aspect, and stand types (see Schmidt et al. (1996) for a full site description).

2.2. MSP treatments

Sites were harvested (clear cut) in November 1990 and MSP was carried out in February, 1991. Each site was divided into two blocks and, within each block, four treatments were applied in randomly assigned plots of 20 m width running up and down slope. The treatments included those commonly used in the region: disc trench, ripper plough, bladed, as well as no MSP (harvested-control). With disc-trenching, 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). During ripper ploughing, blocks of frozen soil are displaced laterally and partially turned over, creating a berm (Coates and Haeussler, 1987). In blading, the soil surface is scraped and slash and surface organic material are displaced to small central piles. MSP treatments were applied using equipment and methods customarily used in operational procedures in the region (see Schmidt et al., 1996 for details).

Nursery-grown (plug+1 stock) white spruce seedlings (2-year-old) were planted in June 1991. For the disc trench and ripper plough treatments, seedlings were planted in the hinge microsite. This 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 microsites in the bladed area were level areas of at least 0.16 m^2, where some reduction of the surface organic layer occurred. Seedlings were planted in two microsites: thin (organic-layer depth <2 cm) and thick (organic-layer depth >2 cm).

2.3. Sampling and analyses

Seedling performance was assessed twice. In early June 1992, mortality, condition of terminal bud (for live seedlings – bud alive or dead; if alive – flushing or not), and foliage colour (scaled classification, where 1=green and 3=chlorotic) were assessed for planted seedlings. Then, 10–15 seedlings were assessed along each of two transects per block (per treatment, per site). At the end of August 1993, height, terminal leader length, and caliper (diameter) of the terminal leader were measured for 10 seedlings along each of three transects per block (per treatment per site). For those data, the thin and thick microsites (within blade) were not distinguished.

Foliar samples were collected from planted seedlings in five treatments: disc, ripper, blade-thin, blade-thick, and harvested-control (no MSP). For each treatment, within a block, samples were collected along two transects corresponding to rows along which the MSP treatments were applied. Of these, five samples (10–20 m apart) were collected along each transect, each sample bearing equal amounts of current-year foliage from three adjacent (1–2 m apart) seedlings.

Foliar samples were collected at three times: July 1992, July 1993, and October 1993 (different seedlings at each time). During the dormant season (October) foliar nutrients are expected to be in equilibrium with soil availability and, by sampling during the active growing season (July), physiologically important deficiencies might be observed (van den Driessche, 1974). After oven-drying at 70°C for 48 h, needles were removed from the stem and mean needle weight was determined for each sample by counting and weighing 100 needles. Samples were then ground with a Wiley mill. Part of each sample was wet-ashed in a microwave oven in a digest of nitric acid and hydrogen peroxide (Kalra et al., 1989) and then analyzed for P, K, Ca, Mg, S, Mn, Fe, and Al using an inductively coupled plasma-atomic emission spectrometer (Anonymous, 1990). The remainder of the sample was analysed for total N by means of a micro-Kjeldahl digest (Parkinson and Allen, 1975) followed by colorimetric determination of NH_4^+ using a Technicon autoanalyser (Bremner and Mulvaney, 1982). For the purpose of statistical analysis, each block (within MSP treatment within site) is the true experimental unit, thus block means were used in all subsequent analyses.

When examining nutritional responses to treatment over time, by foliar analysis, treatment-induced changes in total foliar biomass become important. We used a procedure modified from Munson and Timmer (1995) to scale nutritional responses up to the whole seedling. Using 22 seedlings of similar size (20–40 cm in height) and age (5 years) to those sampled in the study, we developed the following relationship to estimate foliar biomass as a function of height and unit needle weight:

$$B = \left(e^{(3.7411-(61.5/H))}\right) \times (-0.227 + 1.716 \times N - 0.5437 \times N^2) \quad (1)$$

where B is the foliar biomass (g), H the height (cm), N the unit needle weight (mg), r^2=0.543 and p<0.001.

Foliar contents (mg seedling^{-1}) for the various elements were then calculated as the product of the concentration and the foliar biomass. Block means were used for height since height measurements had to be taken from seedlings other than those used for foliar sampling. For graphical presentation, foliar biomass and element contents were standardized with control=100.

2.4. Statistical analyses

For the seedling performance data, we used ANOVA to test for effects of site and treatment using the following model:

$$Y_{lijk} = u + S_i + T_j + ST_{ij} + e_{k(ij)} \quad (2)$$

where S is the site (i=1 or 2), T the treatment (k=1,2…5) and e the random error within site×treatment combination. For performance data, when treatment or site×treatment were significant, we used planned comparisons to compare harvested-control to all MSP treatments as a group. If site or site×treatment were significant, this was done for each site, separately.

For foliar element concentrations and relative foliar biomass content of each element, we used analysis of variance (ANOVA) to test for the effects of site, time, treatment and their interactions using the following model:

$$Y_{lijk} = u + S_i + Q_j + T_k + SQ_{ij} + ST_{ik} + QT_{jk} + SQT_{ijk} + e_{l(ijk)} \quad (3)$$

where S is the site (i=1 or 2), Q the time (j=1, 2, 3), T the treatment (k=1,2…5) and e the random error within site×time×treatment combination. Site, time and treatment were considered to be fixed effects. Block means were entered as the raw data into the

ANOVA. When treatment or any interaction involving treatment was significant for concentration or content, we explored the results graphically using vector analysis (Timmer and Stone, 1978). If there were any significant interactions involving site, the two sites were examined separately. When treatment or interaction involving treatment was significant, we conducted planned comparisons as follows: harvested-control vs. all MSP treatments as a group; harvested-control vs. each MSP treatment individually. If site or site×treatment were significant this was done for each site, separately.

3. Results and discussion

3.1. Site differences

Differences in seedling performance and foliar element concentrations and contents between the two study sites (harvested-control only) suggest that Judy Creek is the more productive and fertile site (Tables 1–3). Seedlings at Judy Creek had significantly higher percent flushing of the terminal bud, terminal leader length and diameter (not shown), unit needle weight and foliar biomass than seedlings at Fox

Table 1
Results (*p*) of analysis of variance testing for effects of site, time, treatment (Trmt), and interactions among these on needle weight, foliar biomass, and foliar concentration and content of N, P, K, Ca, Mg, S, Mn, Fe, and Al in planted white spruce seedlings. Results (*p*) of analysis of variance testing for effects of site, treatment, and site×treatment on seedling survival and condition in June 1992, and seedling size in 1992 and 1993

Variable	Site	Time	Trmt	Site×Time	Site×Trmt	Time×Trmt	Site×Time×Trmt
Needle weight [a]	<0.01	0.21	0.78	0.06	0.24	0.12	0.63
Foliar biomass	0.02	<0.01	0.07	0.47	0.20	0.81	0.99
N concentration	0.70	<0.01	0.16	0.99	0.82	0.80	0.89
P concentration	<0.01	<0.01	<0.01	0.03	0.18	0.04	0.94
K concentration	<0.01	<0.01	<0.01	<0.01	0.48	0.41	0.28
Ca concentration	<0.01	<0.01	0.17	0.95	0.25	0.87	0.97
Mg concentration	0.85	<0.01	0.11	0.02	<0.01	0.87	0.42
S concentration	0.59	<0.01	0.15	0.25	0.72	0.40	0.92
Mn concentration	<0.01	<0.01	<0.01	0.71	0.04	0.06	0.58
Fe concentration	0.64	0.02	<0.01	0.73	0.23	0.04	0.80
Al concentration	<0.01	<0.01	<0.01	0.75	0.49	<0.01	0.99
N content [b]	0.05	<0.01	0.14	0.66	0.41	0.75	0.99
P content	<0.01	<0.01	0.18	0.73	0.39	0.81	0.99
K content	<0.01	<0.01	0.21	0.45	0.21	0.92	0.99
Ca content	<0.01	<0.01	0.13	0.29	0.53	0.90	0.98
Mg content	0.05	<0.01	0.02	0.75	0.04	0.87	0.98
S content	0.02	<0.01	0.12	0.73	0.41	0.77	0.99
Mn content	<0.01	<0.01	<0.01	0.53	0.03	0.01	0.18
Fe content	0.69	<0.01	<0.01	0.46	0.05	0.18	0.73
Al content	0.04	0.20	0.04	0.52	0.21	0.12	0.99

	Site	Trmt	Site×Trmt		Site	Trmt	Site×Trmt
Seedling survival [c]	0.43	0.71	0.74	Height '93 [d]	0.06	0.30	0.58
Colour	0.06	0.17	0.04	Height '92	0.52	0.39	0.66
Flush	<0.01	0.09	0.22	Leader caliper	0.03	0.22	0.62
Terminal bud	0.03	0.34	0.37	Leader length	0.01	0.17	0.32

[a] Unit needle weight, foliar biomass (function of height and needle weight, see text for details)
[b] Foliar element content (seedling^{-1})
[c] Seedling survival: % survival. Colour: foliage colour. Flush: flushing of terminal bud. Terminal bud: terminal bud alive or dead.
[d] Height: seedling height in 1992 or 1993. Leader caliper: caliper of terminal leader in 1993. Leader length: length of terminal leader in 1993.

Table 2
Mean values for measures of seedling colour, height, needle weight, and foliar biomass by site and MSP treatment

Site	Colour [a]	Height '92 [b]	Height '93	Needle weight [c], 7/92	Needle weight, 7/93	Needle weight, 10/93	Foliar biomass [d], 7/92[4]	Foliar biomass, 7/93	Foliar biomass, 10/93
Judy Creek									
Control	1.38	25.1	35.6	1.48	1.99	2.01	4.07	7.74	7.64
Disc	1.43	26.4	39.9	2.07	1.91	1.88	4.08	9.50	9.73
Ripper	1.26	30.1	46.6	2.07	1.75	1.73	5.47	12.25	12.30
Blade-thick	1.29	27.6	40.3	1.78	1.80	1.93	4.97	10.03	9.64
Blade-thin	1.19			1.79	1.92	1.86	5.01	9.69	9.71
Fox Creek									
Control [e]	1.21 [f]	25.0	35.5	1.76	1.59	1.54	4.00	8.30	8.39
Disc	1.49	24.7	31.4	1.57	1.45	1.50	3.93	6.63	6.66
Ripper	1.55	26.1	37.6	2.24	1.66	1.53	2.97	9.17	9.15
Blade-thick	1.25	29.1	36.1	1.98	1.63	1.56	5.03	8.56	8.65
Blade-thin	2.17			1.63	1.73	1.66	5.73	8.18	8.61

[a] Colour: foliage colour in June 1992 (1=green, 3=chlorotic).
[b] Height (cm) in 1992 or 1993.
[c] Needle weight (mg needle^{-1})
[d] Foliar biomass (g seedling^{-1}, as a function of height and needle weight, see text for details)
[e] Results of planned comparisons.
[f] Significant difference between MSP treatments (as a group) and harvested-control; no planned comparison were conducted for height, needle weight, or foliar biomass because there were no significant effects of treatment (see Table 1).

Creek (Table 2). Foliage of seedlings at Judy Creek had significantly higher foliar concentrations of P, K and Ca, contents of N, P, K, Ca, Mg and S (not shown) and lower foliar concentrations and contents of Mn (Table 3) and Al (not shown) than seedlings at Fox Creek.

Differences in a number of soil chemical properties between the two study sites also suggest that Judy Creek is the more fertile site (Schmidt et al., 1996). 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.

Significant site×treatment interactions were found for foliar concentrations and contents of Mg and Mn (Table 1). At Fox Creek, the ripper treatment had little effect on Mg concentration or content, whereas this treatment had much larger effects at Judy Creek (Fig. 1). In October 1993, there was a tendency for foliar Mg concentrations to be lower for MSP treatments as compared to the control at Judy Creek but to be higher for MSP treatments as compared to the control at Fox Creek (Fig. 1). For Mn, the site×treatment interaction is attributable to differences in the effectiveness of the ripper and blade treatments at the two sites (Table 3, Fig. 2).

3.2. Seedling performance, foliar biomass and N, P, K, Ca, Mg and S

Overall seedling survival was >85% in all treatments and there were no significant effects of MSP on seedling survival, flushing of the terminal leader, height in 1992 and 1993, the diameter and length of the terminal leader, or unit needle weight (Tables 1 and 2). Relative foliar biomass of seedlings in MSP areas was generally higher (except disc on all sampling dates, ripper in July 1992 at Fox Creek) than for control seedlings but the effect was small and non-significant (p=0.07, Tables 1 and 2). There is little information on what limits early seedling growth on mixed-wood sites in the western boreal forest. Soil temperature, water logging, nutrient availability,

Table 3
Results of planned comparisons following significant treatment or site X treatment effects (Table 1). Data for the two sites were pooled if there were no significant interactions involving site (see Table 1). The range is given when no planned comparisons were significant. Mean foliar (a) concentrations and (b) contents for planted white spruce seedlings by site, collection time (July 1992, July 1993 and Oct. 1993), and MSP treatment (italics represent individual MSP treatment significantly different from harvested-control

(a) Concentration (mg g^{-1})

Site	Treatment	P [a]		K	Fe		Al
		July '93	Oct. '93	Oct. '93	July '92	Oct. '93	July '92
Both [1]	control	1.87	2.14 [b]	5.87 [b]	0.030 [b]	0.038	0.018 [b]
	disc	1.86	1.98	5.69	0.042	0.042	0.028
	ripper	1.78	1.97	*5.38*	0.047	0.070	0.037
	blade-thick	1.77	*1.90*	5.42	0.064	0.055	0.041
	blade-thin	*1.68*	*1.74*	*5.27*	*0.150*	*0.093*	*0.106*

Site	Treatment	Mn		Mg		
		July '93	Oct. '93	July '92	July '93	Oct. '93
Judy	control	0.20–0.34	0.76 [b]	0.92–1.07	0.77–0.81	0.86–1.07
	disc		*0.39*			
	ripper		0.57			
	blade-thick		0.59			
	blade-thin		*0.44*			
Fox	control	0.53	1.03 [b]	0.83	0.73	0.92
	disc	0.58	0.98	0.84	0.77	0.96
	ripper	0.52	0.76	0.95	0.76	1.04
	blade-thick	0.38	0.74	0.97	0.81	1.10
	blade-thin	*0.28*	*0.50*	*1.05*	*0.88*	*1.16*

(b) Contents (mg $seedling^{-1}$)

Site	Treatment	Al July '92
Both	control	0.07 [b]
	disc	0.11
	ripper	0.15
	blade-thick	0.20
	blade-thin	*0.55*

Site	Treatment	Mn			Fe		
		July '92	July '93	Oct. '93	July '92	July '93	Oct. '93
Judy	control	0.95	2.10–2.64	5.80	0.16 [b]	0.19	0.40–1.22
	disc	*0.75*		*3.81*	0.14	*0.45*	
	ripper	1.80		6.70	0.23	*0.45*	
	blade-thick	1.16		5.45	0.31	0.24	
	blade-thin	1.31		*4.20*	*0.62*	0.34	
Fox	control	1.72–2.65	4.50	8.58 [b]	0.08 [b]	0.27–0.54	0.19 [b]
	disc		3.87	6.54	0.20		0.21
	ripper		4.78	6.69	0.18		0.47
	blade-thick		3.29	6.41	0.31		0.51
	blade-thin		*2.32*	*4.29*	*0.92*		*1.08*

[a] Results of planned comparisons.
[b] Significant difference between MSP treatments (as a group) and harvested-control.

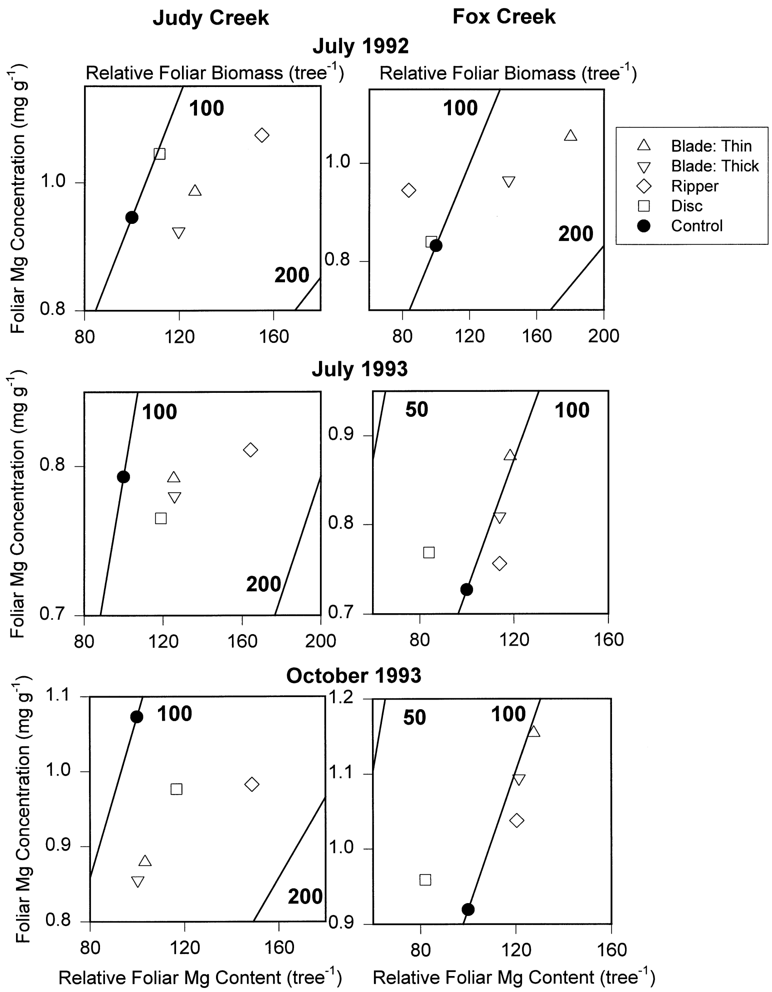

Fig. 1. Vector diagram (after Timmer and Stone, 1978) illustrating the effects of the MSP treatments on foliar Mg concentration and content and foliar biomass of planted white spruce seedlings. Values are means at each site for the three different sampling times. Mg content and foliar biomass are standardized relative to the control seedlings (control seedlings=100). (●) Control, (□) disc, (◇) ripper, (▽) blade: thick, (△) blade: thin.

climatic effects, and competition are generally considered to be important. Whatever factors limit growth on these sites, it appears they were not positively affected by MSP.

Mechanical site preparation had no significant effect on foliar concentrations or contents of N, Ca or S on either site at any sampling date (Table 1). In July 1992, the only significant treatment effect was increased foliar Mg concentrations on blade-thin sites as compared to controls at Fox Creek (Table 3) (but see discussion of Fe and Al below). By the third growing season foliar concentrations and contents of several elements for seedlings in MSP areas dropped below those of seedlings in control areas. In July 1993, foliage of seedlings in blade-thin areas as compared to untreated areas had significantly lower concentrations of P at both sites and, at Fox Creek, lower contents and concentrations of Mn, but higher concentrations of Mg. In October 1993, foliar P and K concentrations for both sites and Mn concentrations and contents at Fox Creek were significantly lower in the MSP treatments as a group as compared to the

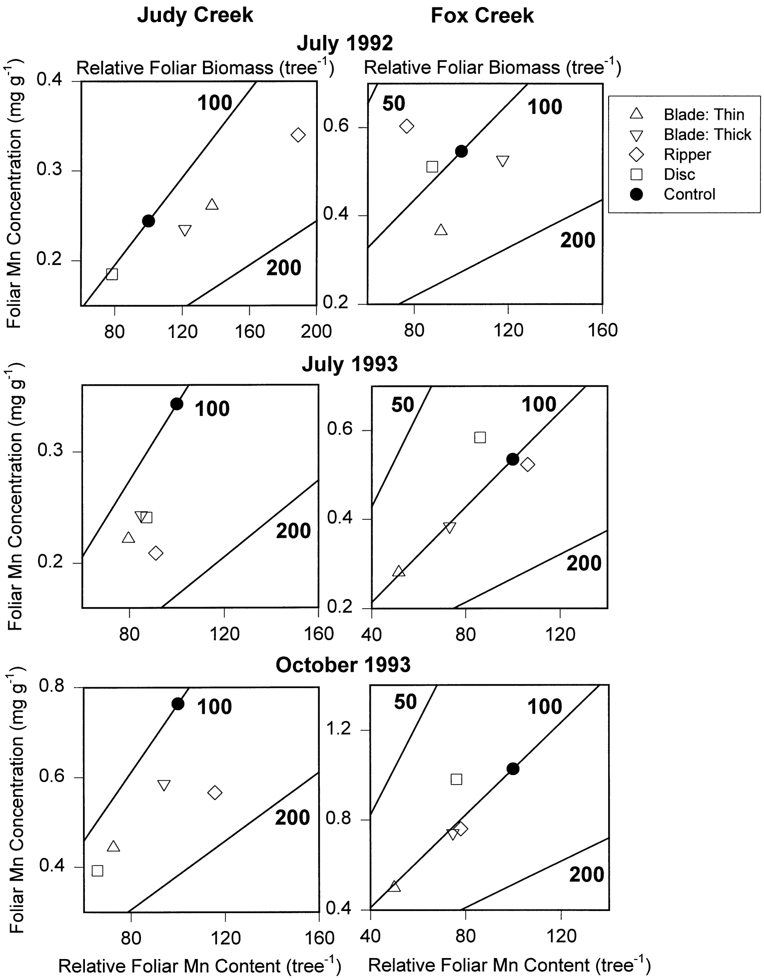

Fig. 2. Vector diagram illustrating the effects of the MSP treatments on foliar Mn concentration and content and foliar biomass of planted white spruce seedlings. Values are means at each site for the three different sampling times. See Fig. 1 legend for details.

control while foliar Mn concentrations and contents of seedlings in disc and blade-thin areas were significantly less than those in the control area at Judy Creek. In contrast, foliar Mg concentrations at Fox Creek were higher in blade-thin as compared to control plots.

The following are foliar nutrient concentrations for white spruce below which deficiencies may occur: N (15.5 mg g^{-1}), P, (1.6 mg g^{-1}), K (4.5 mg g^{-1}), Ca (1.5 mg g^{-1}), Mg (1.0 mg g^{-1}), S (1.2 mg g^{-1}), and Mn (0.025 mg g^{-1}) (Morrison, 1974; Ballard and Carter, 1986). In our study, foliar concentrations of P (1.7–1.9 mg g), K (5.3–5.9 mg g), Ca (2.65–4.0 mg g), and Mn (0.20–1.03 mg g) indicate that, probably, there were no deficiencies for these elements for the control or any of the treatments at either site at any sampling time. There were possible slight deficiencies in N (10.4–12.4 mg g) and S (0.82–0.92 mg g) for all treatments at both sites at all sampling times and these were not alleviated by MSP. There were some possible Mg deficiencies, particularly at Fox Creek (Table 3).

In general, the vector diagrams for July 1992 (Figs. 1–4) illustrate little response in foliar nutrient status to MSP treatments (Timmer and Stone, 1978). The vector diagrams for October 1993 show reduced foliar P and K concentrations in seedlings in MSP

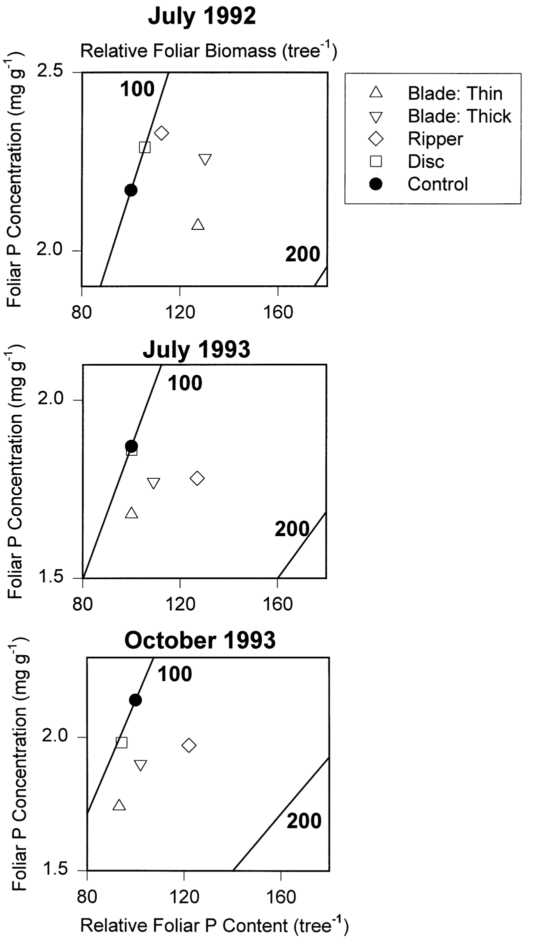

Fig. 3. Vector diagram illustrating the effects of the MSP treatments on foliar P concentration and content and foliar biomass of planted white spruce seedlings. Values are means (both sites combined) at each sampling time. See Fig. 1 legend for details.

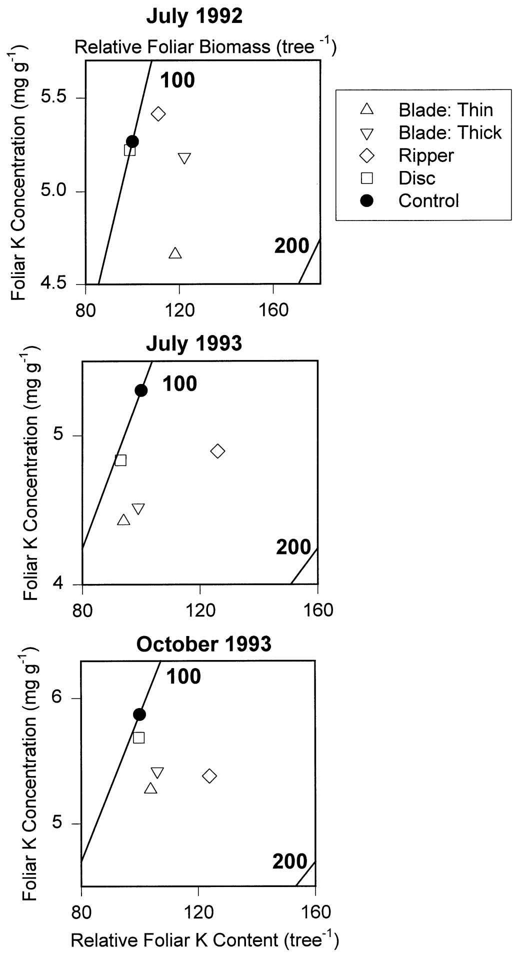

Fig. 4. Vector diagram illustrating the effects of the MSP treatments on foliar K concentration and content and foliar biomass of planted white spruce seedlings. Values are means (both sites combined) at each sampling time. See Fig. 1 legend for details.

areas as compared to controls while foliar biomass and nutrient content showed no significant differences (Table 1, Figs. 3 and 4). This suggests that supply was not sufficient to keep up with demand. For Mn in July and October 1993 the MSP-treated seedlings had lower foliar concentrations and contents than seedlings in the control areas but similar foliar biomass (Fig. 2). This pattern is the reverse of that normally interpreted as luxury consumption (Timmer and Stone, 1978) and suggests reduced availability of Mn, but that it was non-limiting. In July and October 1993, concentrations of Mg for seedlings in blade-thin areas were higher while foliar biomass was unchanged, indicating possible luxury consumption (Fig. 1).

Overall, it appears that the impact of MSP on foliar nutrient status on these sites was minimal. The only consistent positive effect of MSP on seedling nutrition was increased foliar Mg in blade-thin sites at Fox Creek (Fig. 1). In July and October 1993, there may have been luxury consumption of Mg. Indications of possible negative impacts of MSP include: reduced P and K concentrations (Figs. 3 and 4) at both sites and reduced Mn concentration (Fig. 2) and content. However, the data do not indicate any deficiencies of these elements at the two study sites.

3.3. Comparison with results of soil chemical property measurements

A comparison of soil chemical properties on these same study sites (Schmidt et al., 1996) indicated that MSP either reduced or did not change total N and C, C/N ratio and mineralizable N. Lower C/N ratios associated with MSP were considered a positive influence on site fertility, since lower C/N ratios are often associated with increased N availability. However, lower total N and mineralizable N suggested that N availability may have been reduced. The foliar N data indicate, however, that there was no significant effect of MSP on N uptake.

Burger and Pritchett (1988) found an initial positive effect of site preparation (increased foliar N concentration) in slash pine. Studies in other systems, however, have shown negative effects within a few years (reduced foliar N concentration in jack pine 8 years after scarification, Weber et al., 1985). Studies in boreal mixed-woods in Ontario have provided conflicting results. Blade scarification has been associated with reduced foliar nutrient concentrations in the first or second growing seasons following treatment on mixed aspen-white spruce stands (Brand and Janas, 1988; Brand, 1991). In contrast, Munson et al. (1993) found slightly increased foliar N concentration 4 years after scarification. Examining responses in terms of total foliar biomass and content of jack pine and white pine 6 years after scarification, Munson and Timmer (1995) found reduced foliar N concentration but slightly increased content and foliar biomass and they found no significant effects on other elements.

Munson and Timmer (1995) suggest that boreal sites and species may show less dramatic responses to MSP than observed for more southerly sites and species, particularly for N, because of climatic limitations on the more northern sites. Our results, from a boreal site more northerly than theirs, support this. On our sites, MSP was associated with reduced, rather than increased, total N, NH_4–N, and mineralizable-N in surface soils (Schmidt et al., 1996) and we found no significant effect of MSP on foliar N. Further, our treatment-induced increases in foliar biomass were quite small relative to those observed by Munson and Timmer (1995); 6 years after establishment of their boreal site, they found planted jack pine on scarified areas had seven times the foliar biomass of control trees. Our largest foliar biomass response was 1.6 times for an MSP treatment (ripper at Judy Creek) as compared to the control.

The increase in foliar Mg in the blade-thin treatment is consistent with our previous finding of higher exchangeable Mg in surface mineral soils of blade-thin areas as compared to controls (Schmidt et al., 1996). In other studies, blade scarification has been associated with reduced foliar Mg concentrations in the first growing season following treatment (Brand and Janas, 1988; Brand, 1991).

3.4. Foliar Fe and Al

In general, MSP treatments increased foliar Fe concentrations and contents (Table 3, Fig. 5). All MSP treatments as a group, and the blade-thin treatment in particular, had significantly higher foliar Fe concentrations and contents as compared to the control in July 1992 on both sites, and in October 1993 at Fox Creek (Table 3, Fig. 5). Ballard and Carter (1986) report that foliar Fe concentrations below 0.05 mg g^{-1} in white spruce may indicate an Fe deficiency. The control plots at both sites had foliar Fe concentrations below this value and thus indicate a possible deficiency in Fe (Table 3).

In a study of nutrient deficiency symptoms in container-grown white spruce seedlings, van den Driessche (1989) found that the micronutrient showing the greatest toxicity was Fe. They found that seedling dry weight declined as shoot iron concentrations increased above 0.03 mg g^{-1}, suggesting iron toxicity above this level. Although we found no evidence of toxicity in terms of reduced foliar biomass, it is possible that foliar Fe of seedlings in blade-thin areas were at levels which were potentially harmful in July 1992 (0.15 mg g^{-1}) at both sites, and in October 1993 at Fox Creek (0.12 mg g^{-1}) (Fig. 5).

Foliar Al concentrations and contents were generally higher in MSP treatments than in the control (Table 3, Fig. 6). All MSP treatments as a group and the blade-thin treatment on its own had significantly higher foliar Al concentrations and contents as compared to the control in July 1992 on both sites. We found no data which identifies the critical toxicity level for foliar Al for white spruce seedlings. Foliar Al levels of 0.065 mg g^{-1} have been associated with increases in dark respiration and declines in photo-

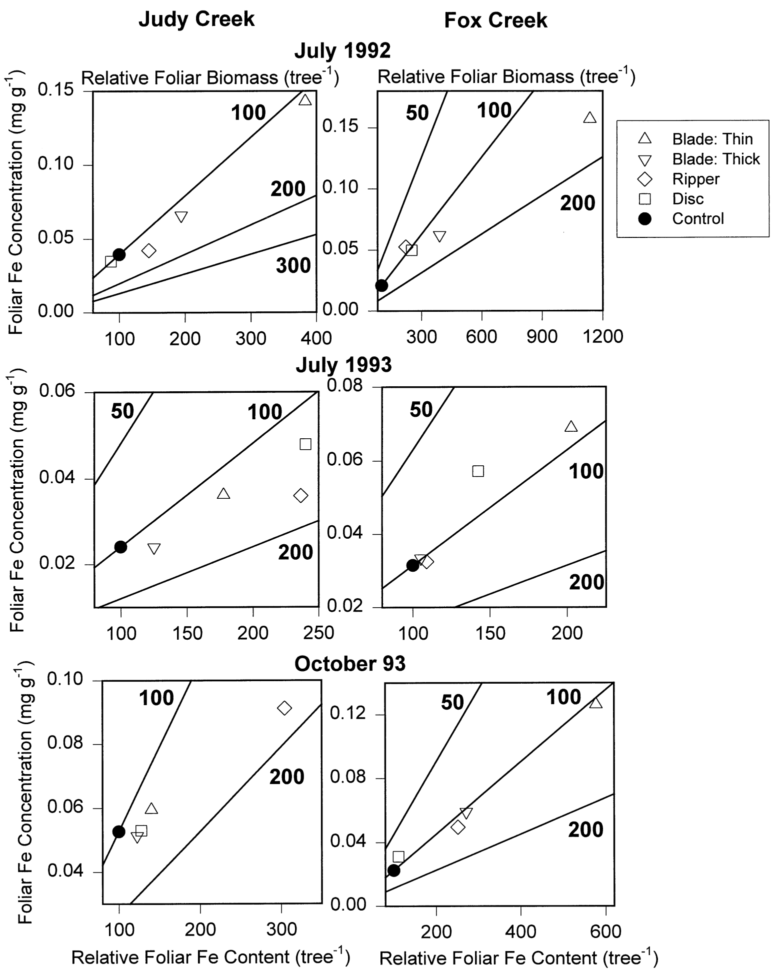

Fig. 5. Vector diagram illustrating the effects of the MSP treatments on foliar Fe concentration and content and foliar biomass of planted white spruce seedlings. Values are means at each site for the three different sampling times. See Fig. 1 legend for details.

synthesis in red spruce seedlings (McLaughlin et al., 1991). It is likely that, in July 1992, seedlings in the blade-thin area were experiencing harmful concentrations of Al (0.106 mg g^{-1}). Exposure to toxic levels of Al can reduce root growth in white spruce seedlings and this species has been reported to respond to very low concentrations in the rooting environment (Nosko et al., 1988). Nosko and Kershaw (1992) suggested that Al could limit natural regeneration of white spruce by preventing seedling establishment through effects on early shoot and root growth.

The increased chlorosis of seedlings in MSP areas at Fox Creek in 1992 may have been indicative of the high levels of foliar Fe and Al (Table 2). We observed chlorosis and loss of needles (both general symptoms of ion toxicity (van den Driessche, 1989)) in many seedlings in bladed areas in 1993 as well. The increases in foliar Fe and Al in blade-thin areas are surprising. The pH values for surface mineral soils in blade-thin sites were significantly higher than for controls (Schmidt et al., 1996) and Fe and Al availability usually decline with rising pH (Brady, 1990). The increases in Fe and Al could be attributed to an increased proportion of mineral soil in the rooting zone of planted seedlings in bladed areas. In the bladed-thin sites, seedlings were often planted directly into mineral soil with very little surface organic matter. On these same sites, we found that the forest

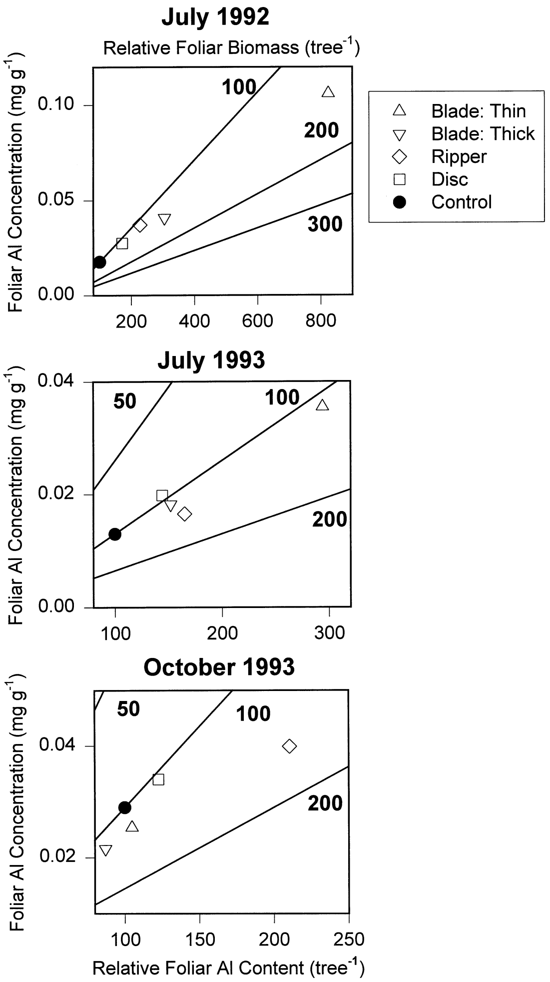

Fig. 6. Vector diagram illustrating the effects of the MSP treatments on foliar Al concentration and content and foliar biomass of planted white spruce seedlings. Values are means (both sites combined) at each sampling time. See Fig. 1 legend for details.

floor in harvested (vs. unharvested) areas had higher Fe and Al concentrations (Schmidt et al., 1996), presumably as a result of contamination by mineral soil, although we have no data on Fe and Al in mineral soils.

3.5. Comparison of MSP treatments

The various MSP treatments differed in their influence on foliar nutrient status between sites and over time. This can be attributed to differences in the effect of MSP treatments on soil physical and chemical properties, and in the time response of these and, potentially, to differences in the way MSP treatments were applied at each site. The ripper treatment had the greatest positive (but not significant) effect on tree growth and foliar nutrient status. Seedlings in the ripper areas had the highest foliar biomass and height in 1993, the highest concentrations of foliar P, K and Mn at both sites and Mg at Judy Creek in July 1992, and the highest contents of foliar P, K, and Mn at both sites and Mg at Judy Creek in October 1993. At all sampling times, blading (particularly blade-thin) was associated with the lowest concentrations of foliar P and K at both sites, the lowest Mg concentrations at Judy Creek, and the lowest Mn at Fox Creek. At the same time, blading caused the greatest initial increases in foliar Fe and Al and was associated with higher foliar Fe concentrations at Fox Creek throughout the sampling period. This is likely due to the fact that removal of the forest floor and heavy disturbance of surface soils during blading directly reduced nutrient availability (Schmidt et al., 1996).

3.6. Implications for seedling performance

Whether the reduced P, K and Mn concentrations and elevated Fe and Al concentrations will translate into effects on survival and growth remains uncertain. We would not expect to observe any effects of the declines in nutrient concentration observed in 1993 on growth or performance until subsequent growing seasons and the impact may increase over time if nutrient status remained poor as a result of the reduced nutrient supplying power of the substrate (Schmidt et al., 1996). Our results show that, for white spruce on these boreal mixed-wood forest sites, mechanical site preparation has little positive effect on seedling nutrient status and may, in time, result in reduced P, K, and Mn availability. In addition, treatments, such as blading, which greatly reduce the organic layer, may result in increases in foliar Fe and Al to potentially harmful levels.

Acknowledgements

We thank John Konwicki, David MacIntosh, Lee Martens, Kym Shreiner and Alexandra Torn for their assistance in the field and/or laboratory. The foliar analyses were carried out at the Northern Forestry Centre, Canadian Forest Service in Edmonton. Victor Lieffers and RLR initiated the field experiment and collection of the seedling mortality and performance data. Blue Ridge Lumber Ltd., Edson, Alberta, carried out the harvesting and MSP treatments. We are very grateful to them. Research funding was provided by grants from the Alberta Forest Development Research Trust Fund and the Canada–Alberta Partnership Agreement in Forestry.

References

Anonymous, 1990. Plasma Vision 60 Software Guide, ARL 3500 Series, single stand ICP spectrometer, version 2.0 B12 single user, Valencia, CA.

Ballard, T.M., Carter, R.E., 1986. Evaluating forest stand nutrient status. British Columbia Ministry of Forests, Land Management Report No. 20, Victoria, BC.

Brady, N.C., 1990. The Nature and Properties of Soils, 10th edn. MacMillan, New York.

Brand, D.G., 1991. The establishment of boreal and sub-boreal conifer plantations: An integrated analysis of environmental conditions and seedling growth. For. Sci. 37, 68–100.

Brand, D.G., Janas, P.S., 1988. Growth and acclimation of planted white pine and white spruce seedlings in response to environmental conditions. Canadian J. For. Res. 18, 320–329.

Bremner, J.M., Mulvaney, C.S., 1982. Nitrogen – total, In: Page, A.L. (Ed.), Methods of Soil Analysis, Part 2, Chemical and Microbiological Properties, Agronomy, 9, 595–624.

Burger, J.A., Pritchett, W.L., 1988. Site preparation effects on soil moisture and available nutrients in a pine plantation in the Florida Flatwoods. For. Sci. 34, 77–87.

Coates, D., Haeussler, S., 1987. A Guide to the Use of Mechanical Site Preparation Equipment in North Central British Columbia, 2nd edn. Canada–British Columbia Forest Resource Development Agreement, FRDA Handbook 001, British Columbia Ministry of Forests, Victoria, BC.

Corns, I.G.W., Annas, R.M., 1986. Field Guide to Forest Ecosystems of West Central Alberta, Canadian Forest Service, Edmonton, AB.

Fox, T.R., Burger, J.A., Kreh, R.E., 1986. Effects of site preparation on nitrogen dynamics in the southern Piedmont. For. Ecol. Manage. 15, 241–256.

Hunt, J.A., McMinn, R.G., 1988. Mechanical Site Preparation and Forest Regeneration in Sweden and Finland: Implications for Technology Transfer. Canada–British Columbia Forest Resource Development Agreement, FRDA Report 031, British Columbia Ministry of Forests, Victoria, BC.

Kalra, Y.P., Maynard, D.G., Radford, F.G., 1989. Microwave digestion of tree foliage for multi-element analysis. Canadian J. For. Res. 19, 981–985.

Krause, H.H., Ramlal, D., 1987. In situ nutrient extraction by resin from forested, clear-cut and site-prepared soil. Canadian J. Soil Sci. 67, 943–952.

Margolis, H.A., Brand, D.G., 1990. An ecophysiological basis for understanding plantation establishment. Canadian J. For. Res. 20, 375–390.

McLaughlin, S.B., Anderson, C.P., Hanson, P.J., Tjoelker, M.G., Roy, W.K., 1991. Increased dark respiration and calcium deficiency of red spruce in relation to acidic deposition at high-elevation southern Appalachian Mountain sites. Canadian J. For. 21, 1234–1244.

McMinn, R.G., Hedin, I.B., 1990. Site preparation: Mechanical and manual. In: Lavender, D.P., Parish, R., Johnson, C.M., Montgomery, G., Vyse, A., Willis, R.A., Winston, D. (Eds.), Regenerating British Columbia's Forests, University of British Columbia Press, Vancouver, BC., pp. 150–163.

Morrison, I.K., 1974. Mineral Nutrition of Conifers With Special Reference to Nutrient Status Interpretation: A Review of Literature, Dept. of the Environment, Canadian Forestry Service Publ. No. 1343, Ottawa, ON.

Munson, A.D., Margolis, H.A., Brand, D.G., 1993. Intensive silvicultural treatment: Impacts on soil fertility and planted conifer response. Soil Sci. Soc. Am. J. 57, 246–255.

Munson, A.D., Timmer, V.R., 1995. Soil nitrogen dynamics and nutrition of pine following silvicultural treatments in boreal and Great lakes – St. Lawrence plantations. For. Ecol. Manage. 76, 169–179.

Nosko, P., Brassard, P., Kramer, J.R., Kershaw, K.A., 1988. The effect of aluminum on seed germination and early seedling establishment, growth, and respiration of white spruce. Canadian J. Bot. 66, 2305–2310.

Nosko, P., Kershaw, K.A., 1992. The influence of pH on the toxicity of a low concentration of aluminum to white spruce seedlings. Canadian J. Bot. 70, 1488–1492.

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

Schmidt, M.G., Macdonald, S.E., Rothwell, R.L., 1996. Impacts of harvesting and mechanical site preparation on soil chemical properties of mixed-wood boreal forest sites in Alberta. Canadian J. Soil Sci. 76, 531–540.

Smethurst, P.J., Nambiar, E.K.S., 1990. Effects of slash and litter management on fluxes of nitrogen and tree growth in a young *Pinus radiata* plantation. Canadian J. For. Res. 20, 1498–1507.

Timmer, V.R., Stone, E.L., 1978. Comparative foliar analysis of young balsam fir fertilized with nitrogen, phosphorus, potassium, and lime. Soil Sci. Soc. Am. J. 42, 125–130.

Tuttle, C.L., Golden, M.S., Meldhal, R.S., 1985. Surface soil removal and herbicide treatment: Effects on soil properties and loblolly pine early growth. Soil Sci. Soc. Am. J. 49, 1558–1562.

van den Driessche, R., 1974. Prediction of mineral nutrient status of trees by foliar analysis. Bot. Rev. 40, 347–394.

van den Driessche, R., 1989. Nutrient Deficiency Symptoms in Container-grown Douglas-fir and White Spruce Seedlings. Canada–B.C. Forest Resource Development Agreement, FRDA Report No. 100, British Columbia Ministry of Forests, Victoria, BC.

Vitousek, P.M., Andariese, S.W., Matson, P.A., Morris, L., Sanford, R.L., 1992. Effects of harvest intensity, site preparation, and herbicide use on soil nitrogen transformations in a young loblolly pine plantation. For. Ecol. Manage. 49, 277–292.

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

Weber, M.G., Methven, I.R., Van Wagner, C.E., 1985. The effect of forest floor manipulation on nitrogen status and tree growth in an eastern Ontario jack pine ecosystem. Canadian J. For. Res. 15, 313–318.