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Effects of burning and mechanical site preparation on growth and nutrition of planted white spruce

T.M. Ballard and B.C. Hawkes

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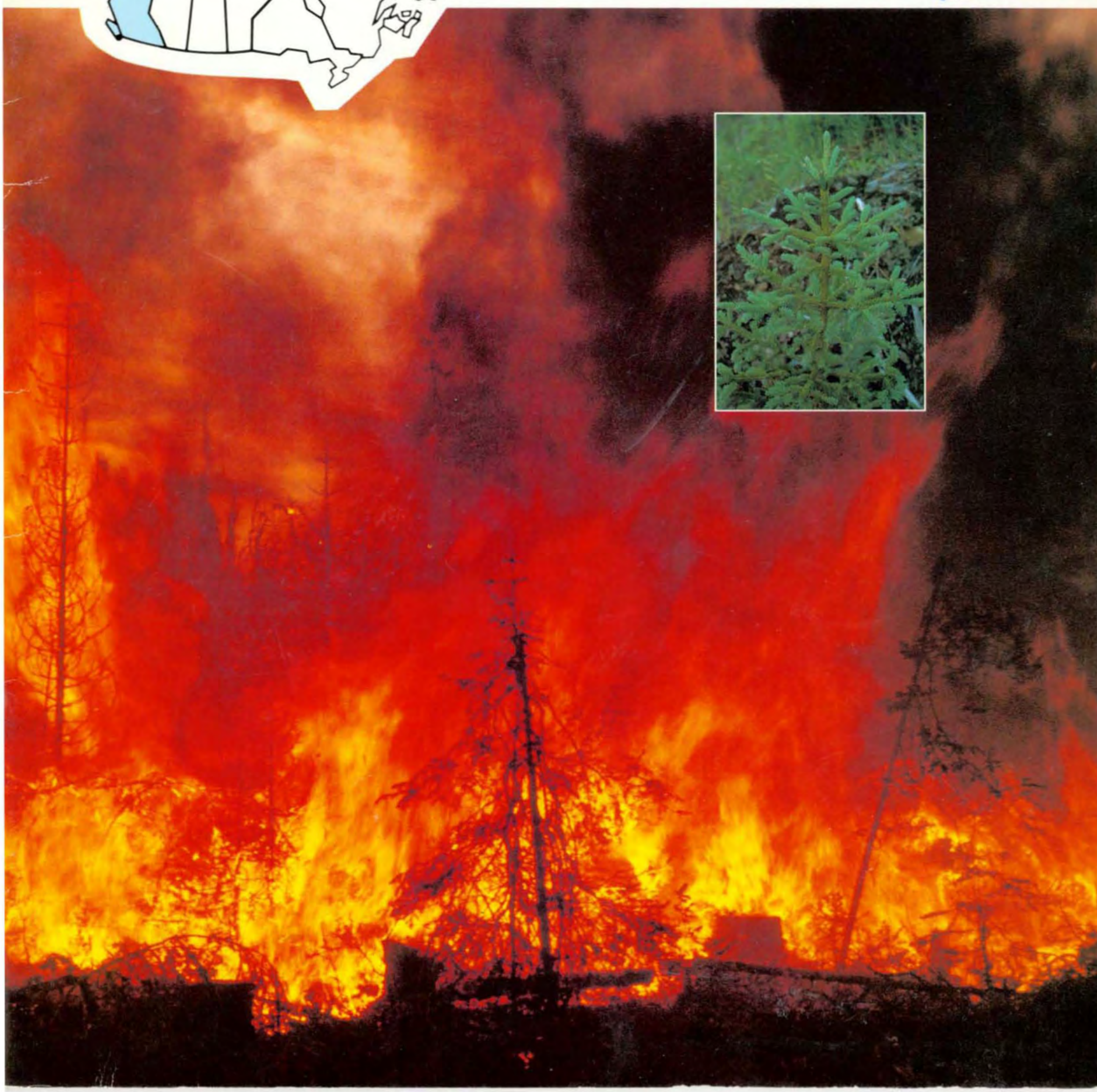

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Abstract

Established operational plantations were examined to determine the effect of burning and mechanical site preparation on growth and nutrition of planted white spruce.

Growth and nutrition of planted white spruce near the Willow and Bowron Rivers, east of Prince George, have been dramatically affected by prescribed burning. Five growing seasons after planting, unburned areas had an average leader length 36% lower and concentrations of foliar N, active Fe, and Cu 27, 66, and 41% higher, respectively.

At the McLeod Lake plots, north of Prince George, which were burned in 1967, no relationship of growth or nutrition of spruce with levels of burn impact was found in a group of plots which varied in stock type, time of planting, drainage, soil parent material, slope, and aspect. In plots where these factors were similar, foliar N and Cu and soil mineralizable N were positively correlated with residual duff depth and negatively correlated with the extent of bare mineral soil. Total tree height and 1983 leader length were negatively correlated with residual duff depth and positively correlated with the extent of bare mineral soil.

Near Boomerang Lake, spruce growth and foliar concentrations of several nutrients were significantly higher within burned windrows than in the scalped areas between windrows. In lodgepole pine, foliar concentrations of several nutrients, although not necessarily the same nutrients, were higher within than between windrows. At Carp Lake, in areas where alder has invaded scalped areas between windrows, N status of spruce foliage and current height growth of spruce exceeded those of areas between windrows with no alder, and were comparable to those within the burned windrows. These results suggest the potential usefulness of shrubby alder in silviculture on sites in central interior British Columbia that have low levels of nitrogen.

Résumé

Des plantations exploitées depuis un certain temps ont été étudiées afin de déterminer les effets du brûlage et de la préparation des sites par des machines sur la croissance et la nutrition des épinettes plantées.

Un brûlage dirigé a eu des effets spectaculaires sur la croissance et la nutrition d'épinettes plantées près des rivières Willow et Bowron, à l'est de Prince George. Cinq saisons de végétation après la plantation, la longueur moyenne des pousses apicales des épinettes ne se trouvant pas dans les brûlis était 36 % plus faible et les concentrations foliaires de N, de Fe actif et de Cu étaient respectivement plus élevées de 27, 66 et 41 %.

Aucune relation entre la croissance et la nutrition et l'impact du degré de brûlage n'a pu être établie dans un groupe de parcelles du lac McLeod, au nord de Prince George, où des brûlages ont été effectués en 1967, parcelles dont la composition, la période de plantation, le drainage, les matériaux originels, la déclivité et l'aspect variaient. Dans les parcelles où ces facteurs étaient similaires, le N et le Cu foliaire et le N minéralisable du sol étaient corrélés positivement à l'épaisseur de la couche d'humus brut résiduelle et négativement à l'étendue du sol minéral dénudé. La hauteur totale de l'arbre et la longueur de la pousse apicale de 1983 étaient corrélées négativement a la couche d'humus brut résiduelle et positivement à l'étendue du sol minéral.

La croissance et les concentrations foliaires de plusieurs éléments nutritifs d'épinettes situées près du lac Boomerang étaient beaucoup plus fortes dans les andains brûlés que dans les entrandains dégazonnés. Chez le pin tordu, les concentrations foliaires de plusieurs éléments nutritifs, mais non pas nécessairement des mêmes éléments nutritifs, étaient plus élevées dans les andains que dans les entrandains. Au lac Carp, dans les parties des entrandains envahies par les aulnes, la teneur en N des aiguilles et la croissance en hauteur courante des épinettes étaient plus élevées que celles des parties des entrandains dépourvues d'aulnes, et comparables à celles mesurées dans les andains brûlés. Ces résultats démontrent que les arbustes d'aulnes pourraient être utiles à la sylviculture des sites pauvres en azote de la région intérieure centrale de la Colombie-Britannique.

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Introduction

Site preparation by prescribed burning or mechanical means is often used to facilitate planting and to enhance survival and early growth of white spruce (*Picea glauca* (Moench) Voss). Such site preparation also has implications for spruce nutrition. A problem analysis of prescribed burning research needs indicated that prediction of fire behavior, nutrient release, and tree growth response was necessary for the development of prescribed fire prescriptions (Auclair 1982). However, initial modeling research indicated that more research was needed in the area of nutrient release during burning and subsequent nutrition of spruce (Blackhall 1983a and 1983b). In addition, it must be determined whether growth is substantially influenced by the nutritional effects of fire, or whether other fire effects may be more influential on growth.

A broad survey of nutritional problems in planted white spruce was recently completed in the Prince George and Cariboo Forest Regions of British Columbia (Ballard 1984). Results of this survey indicated the following:

1) N, Mg, Fe and Cu often are seriously deficient in young, planted white spruce, and S often becomes growth-limiting if the N deficiency is relieved.

2) Both the frequency and severity of N, Fe and Cu deficiencies are greater where burning or mechanical site preparation have been carried out.

3) Although nutrition tends to be poorer, height growth tends to be better where site preparation has been done.

Thus, if site preparation is responsible for poorer nutrition, this detrimental effect is outweighed by beneficial effects on other growth-limiting factors such as soil temperature and competition. However, because the survey design did not allow distinction of cause and effect from mere correlation, one could not conclude that site preparation was necessarily responsible for the differences.

The objective of this study is to evaluate, by means of foliar analysis and internode measurement, the effects of prescribed burning and associated mechanical site preparation on spruce nutrition and height growth, and to develop practical models to predict these effects.

There was insufficient time in this study to impose treatments, establish plantations, and evaluate results. Instead, it was necessary to evaluate established plantations where different treatments have previously been done on adjacent or nearby sites. Comparisons are valid if there are no significant differences, in terms of stock type, seed lot, time of planting, or pre-treatment site conditions between the treatment sites being compared. Because only a few sites allowed such comparative evaluations and the range of operational site preparation methods was limited, sampling for the present study was limited ultimately to three kinds of areas:

1) Adjacent burned and unburned sites. One area was found between the Willow and Bowron Rivers south of Highway 16 (Figure 1). Quantitative fire impact (slash and fuel consumption) of the burn had not been measured, but the site was useful because it had an unburned area to serve as a control.

2) An area divided into plots subject to different, measured impacts of burning. These are Forestry Canada plots at McLeod Lake, which do not include an unburned (control) plot (Figure 1). These plots were used in the initial development of a prescription model for prescribed fire (Muraro 1975) and later by Lawson and Taylor (1986) for prediction of fire behavior and fuel consumption in white spruce-subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) fuel types.

3) Areas where growth and nutrition can be evaluated within and between burned windrows. To the extent that soil thermal and moisture regime and vegetation competition may be similar under both conditions, growth differences might be directly related to nutritional differences caused by windrowing and burning. Plantations near Boomerang and Carp Lakes were selected for this purpose (Figure 1). The Boomerang Lake plantation included lodgepole pine (*Pinus contorta* Dougl.), as well as spruce, enabling some indication of species differences. Because the Carp Lake plantation had some Sitka alder (*Alnus viridis* ssp. *sinuata*) encroachment between windrows, it allowed an evaluation of effects of alder on spruce growth and nutrition.

Study areas and sampling methods

Locations and characteristics of the sampling sites are listed in Table 1. Foliage sampling was based on guidelines summarized by Ballard and Carter (1986); current-year needles from the more exposed branches were used, generally from the upper part of the seedling, but in all cases the uppermost whorl was avoided. Obviously unhealthy trees were avoided (e.g., trees suppressed by aspen (*Populus tremuloides* Michx.) competition), but no other stratification for sampling was done except as noted in this report or in the guidelines cited. The soil taxa described in this paper follow the classification defined by the Canada Soil Survey Committee (1978).

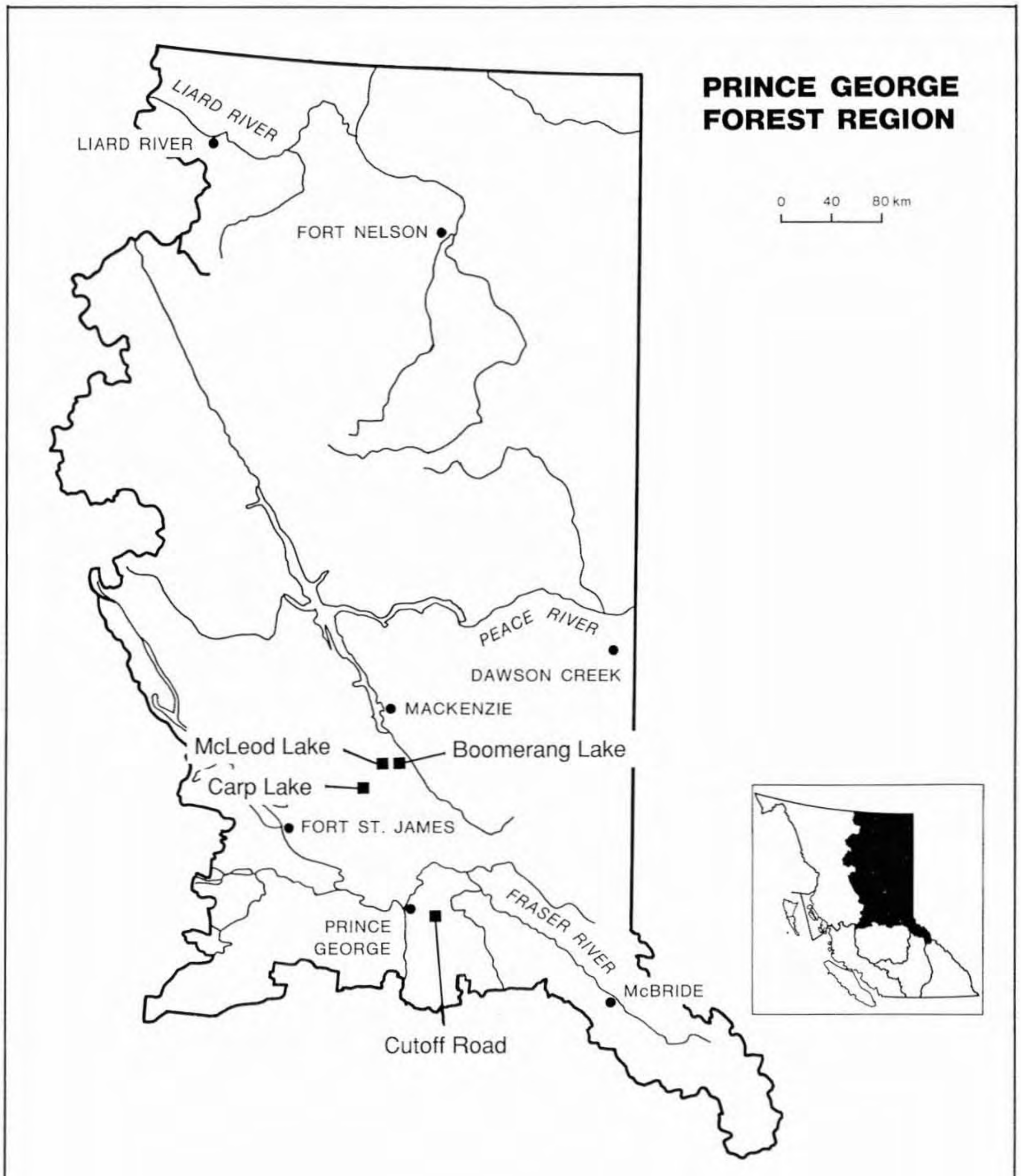

Figure 1. Study area locations in the Prince George Forest Region.

Table 1. Locations and characteristics of study areas

Year sampled and Treatment block no.	location	Year planted	treatment
83-/TB36	Cutoff/Coalmine Jct	1979	unburned
83-/TB37	Cutoff/Coalmine Jct	1979	burned
83-/TB11	McLeod Lk. Plot 33	1971	burned
83-/TB12	McLeod Lk. Plot 32	1971	burned
83-/TB13	McLeod Lk. Plot 36	1971	burned
83-/TB14	McLeod Lk. Plot 37	1971	burned
83-/TB15	McLeod Lk. Plot 17	1971	burned
83-/TB16	McLeod Lk. Plot 47	1971	burned
83-/TB01	McLeod Lk. Plot 23	1968	burned
83-/TB08	McLeod Lk. Plot 41	1968	burned
83-/TB02	McLeod Lk. Plot 02	1968	burned
83-/TB10	McLeod Lk. Plot 19	1968	burned
83-/TB13	McLeod Lk. Plot 03	1970	burned
83-/TB16	McLeod Lk. Plot 12	1968	burned
83-/TB12	McLeod Lk. Plot 13	1969	burned
83-/TB11	McLeod Lk. Plot 14	1968	burned
84-/TB15	McLeod Lk. Plot 24	1969	burned
84-/TB14	McLeod Lk. Plot 29	1969	burned
83-/TB17	Boomerang Lk. (spruce)	1979	scalped by windrowing
83-/TB18	Boomerang Lk. (spruce)	1979	burned windrows
83-/TB41	Boomerang Lk. (pine)	1979	scalped by windrowing
83-/TB42	Boomerang Lk. (pine)	1979	burned windrows
83-/TB04	Carp Lk.	1975	burned windrows
83-/TB05	Carp Lk.	1975	scalped, no alder
83-/TB19	Carp Lk.	1975	scalped, alder invasion
83-/TB06	Carp Lk.	n.a.	unlogged

Adjacent burned and unburned sites - the Cutoff Road site

This comparison was made on one site east of Prince George. Plantations in adjacent burned (83-/TB37) and unburned (83-/TB36) blocks between the Willow and Bowron Rivers were sampled in the fall 1983. These are located just east of the junction where the Cutoff Road (south from Highway 16) meets the Coal Mine Road (which extends from the Willow Forest Road east toward and along the Bowron River (lat. 53° 52' N, long. 122° 0' W, elevation 715 m). This area will be referred to as the Cutoff Road Site.

The study site is located within the Wet Cool Central Sub-Boreal Spruce biogeoclimatic subzone (SBSj1) (DeLong et al. 1987b). The soil is variable due to micro-relief, ranging from Dystric Brunisols to Gleyed Dystric Brunisols. The parent material is a loamy lacustrine veneer over till. The area was logged in 1974, and after prescribed burning of the eastern part of the area, the whole area was planted with 2+0 white spruce stock in 1976. Replicated foliage sampling (10 randomly located trees in each of the burned and unburned areas) was carried out in the fall of 1983, and the 1983 stem internode lengths (15 randomly located trees in each area) were measured in 1984. Foliage samples were analyzed individually for foliar nutrient levels.

Burning over a range of fire impacts - the McLeod Lake plots

Plots (approximately 0.3 to 1.5 ha in size) near McLeod lake (lat. 54° 48' N, long. 122° 57' W, elevation 900 m) were established by the Canadian Forestry Service in

1967, when these plots were subject to different, measured slash and forest floor reductions. Total slash consumption ranged from 2.4 to 8.5 kg/m^2 or 13 to 60% of the pre-burn fuel loading. The reduction in the depth of the forest floor ranged from 3.0 to 8.4 cm or 35 to 95% of the pre-burn depth on the plots used in this study (Table 1). More information on fire weather conditions and fire impact are reported in Lawson and Taylor (1986). Some plots were subsequently planted for research purposes, some remained unplanted, and some were planted operationally by the British Columbia Forest Service. Not all were planted to white spruce. Lodgepole pine, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and black spruce (*Picea mariana* (Mill.) B.S.P.) were included in the research plantings, and only pine was used on many of the most severely burned, operationally planted plots. Some planted spruce differed in terms of stock type and time of planting. The site is not uniform physiographically: slope, aspect, drainage and soil parent material vary among plots, and in some cases, within plots. These variations limited the number of plots which could be evaluated simply in relation to fire intensity and forest floor reduction; it was possible to sample only a few groups of plots for analysis.

The study area is about 4 km southwest of the southern end of McLeod Lake, British Columbia on a generally flat portion of a gently rolling plateau. The area is located in the SBSe2 subzone (DeLong et al. 1987a). The soil types and textures are variable over the entire study area; the measured plots in this study have Humo-Ferric Podzols to Gray Luvisols developed in till. The soil texture ranges from sandy clay to sandy clay loam. There is also strong gleying in some local depressions.

In 1983, six operationally planted plots and four British Columbia Forest Service research plots were sampled. The first six were selected for similarity of slope (relatively level), drainage (imperfectly drained and associated drainage classes), and parent material (till), stock type (2+0 bare-root) and time of planting (spring). The remaining group of four plots had a different type of stock (plug) and was planted at a different time of year (summer) because the British Columbia Forest Service used the McLeod Lake plots for stock, species, and planting time trials.

Replicate soil samples (15 or more random locations per plot, to a depth of 15 cm, and associated forest floor samples where forest floor was present) were collected in summer, and replicate foliage samples (15 or more randomly located trees per plot) were collected in the fall. Foliage samples from each tree were analyzed individually for nutrient concentrations. Leader length (1983) or 1983 internode length (1984) and total height measurements were made at the time of foliage sampling. In some cases, fewer samples were taken; this occurred where planted trees or various stock types could not be identified with certainty, or when an insufficient number of trees were present which met the criteria (Ballard and Carter 1986) for foliar nutrient evaluation.

Soil temperature was measured in each plot at a depth of 50 cm using a sensor probe inserted in the wall of a freshly excavated soil pit. This depth was chosen for these single measurements because of the damping effect of depth on diurnal and short-term seasonal temperature fluctuations which are more pronounced at shallower depths. The measurements of soil temperature were taken at various locations between August 7 and 25, 1983.

Windrow and burning - Boomerang and Carp lakes

At Boomerang Lake (lat. 54° 52' N, long. 122° 50' W, elevation 915 m) after windrowing and burning, bareroot white spruce and lodgepole pine stock had been planted in adjacent areas in 1979. The study area is located in the SBSj1 subzone (DeLong et al. 1987b). The soil is an Orthic Humo-Ferric Podzol, derived from very gravelly loamy sand in a glacial outwash deposit.

In fall 1983, replicate samples were collected within and between burned windrows. Both within and between windrows, 15 spruce trees were randomly sampled, 15 soil samples were taken at random locations, and 15 pine trees were randomly sampled. In both the spruce and the pine areas of the plantation, sampling was associated with three windrows and adjacent between-windrow areas using a grid sampling layout within a 120 x 160 m plot for spruce and a 80 x 260 m plot for pine. The foliage samples were analysed individually for nutrient levels.

The Carp Lake study area (lat. 54° 46' N, long. 123° 14.5' W, elevation 914 m) was windrowed and burned in 1974, and planted in spring of 1975 with 2+0 bareroot white spruce. The windrowing resulted in scalping of organic layers down to the mineral soil, but left at least a remnant of the Ae horizon over much of the area. The study area is located in the SBSe2 subzone (DeLong et al. 1987a). The soil is an Orthic Humo-Ferric Podzol, derived from very gravelly glacial outwash material in which micaceous schist fragments are prominent.

At the end of the 1983 growing season, trees were selected for sampling as follows. One rectangular plot with the long axis (200 m) centered on a burned windrow was chosen. Twenty spruce trees were randomly selected in each of three microsite conditions: burned windrow; scalped areas with no alder within two tree lengths of the spruce; and scalped areas with at least two alders within one tree length of the spruce. (Scalped microsites lacking alder accounted for most of the clearcut area.) Total height and 1983 leader length were measured and current-year foliage samples were taken from the sample trees. Twenty soil samples (0-15 cm depth) were collected at randomly located points in each of the three microsite conditions during 1983. In addition, forest floor and 0-15 cm soil samples were taken from a comparable soil in a small unlogged area remaining at the clearcut margin, and the thickness of the forest floor was measured at 15 randomly selected points within this unlogged area.

Laboratory methods and statistical analysis

Soil and foliage samples were taken to the Forest Soils Laboratory at the University of British Columbia for preparation and analysis. Needles were stripped from the shoots, dried at 70°C for 48 hours, and ground (approximately 20 mesh) for analysis. One-gram samples were digested by the method of Parkinson and Allen (1975) using concentrated sulfuric acid, 30% hydrogen peroxide, lithium sulfate, and selenium in a block digestor. After dilution to 100 mL (with demineralized water), the digests were analyzed colorimetrically for N and P, using the Berthelot (phenol-hypochlorite) reaction (Weatherburn 1967) and the unreduced vanado-molybdate complex (Jackson 1958), respectively, in a Technicon R Autoanalyzer. The solutions were also analyzed for Mn, Zn and Al, and (after further 25-fold dilution) for K, Ca and Mg using atomic absorption spectrophotometry. Previous work, using reference samples from the U.S. National Bureau of Standards, had shown that such methods gave good results for most of these elements (with Ca and Mn recovery being a bit low). A nitric acid digestion was carried out with subsequent atomic absorption analysis for Cu and Fe. This method gives excellent Cu recovery, but Fe recovery is usually poor (Ballard 1982), though it is better than that obtained with the Parkinson and Allen digestion or with dry ashing.

Active Fe was determined by a modification of the method of Oserkowsky (1933) using extraction in 1M HCl and atomic absorption spectrophotometry. After dry ashing, boron (B) was determined by the azomethine H method described by Gaines and Mitchell (1979). Previous work with the National Bureau of standards reference sample indicated excellent precision and accuracy with this method (Ballard 1985). Sulfur was determined with a Fisher Sulfur Analyzer, using the procedures of Guthrie and Lowe (1984).

Soil samples were air dried, and the fraction passing a 1-mm sieve was retained for chemical analysis. Soil pH was determined in water and in 0.01 M calcium chloride. Organic C concentration was estimated by the Walkley-Black wet oxidation method (Jackson 1958). Total N was estimated by semi-micro Kjeldahl digestion, without a preliminary reduction step to include nitrite and nitrate (Black 1965), using colorimetric analysis on the Technicon R Autoanalyzer. Mineralizable N was evaluated by the anaerobic incubation method of Waring and Bremner (1964), without deducting the initial mineral N level, for reasons discussed by Powers (1980).

Statistical analysis of data was carried out using regression, correlation, and t-test software on a microcomputer and an analysis-of-variance program (MIDAS, a statistics package from the University of Michigan) on the mainframe computer at the University of British Columbia. Diagnosis of white spruce nutrient status, based on foliar analysis data, was carried out with a recently modified version of the computer program DIAGPIGL (Ballard 1982), which uses diagnostic criteria developed by Swan (1971) and others.

The various statistical approaches used in the data analysis indicate trends in the data, but attribution of these trends to the burning and mechanical treatment effects is often problematic. This study took a survey approach on a number of sites where replicates of treatments were not available, a common limitation in retrospective surveys of unreplicated operational treatments. Care was taken in picking study sites to ensure there were few differences in topography, soil morphology, and nutrient and moisture regimes. This increases the probability that significant differences between treatment areas are due to treatment effects, but it does not overcome the problem that the probability may not be quantifiable by statistical tests. If similar growth and nutritional relationships are associated with these operational treatments then we can be more confident that burning was responsible. However, statistical confirmation of some apparent relationships would require experimental design rather than sampling of unreplicated treatment areas.

Table 2. Spruce height increment and foliar nutrient concentrations on a burned and unburned site at Cutoff Road

Variable	Burned			Unburned	
1983 Leader length (cm)	27.3	(7.0)	***	17.4	(4.7)
Foliar:					
N (%)	1.08	(0.12)	***	1.37	(0.24)
P (%)	0.19	(0.19)		0.22	(0.02)
K (%)	0.63	(0.12)		0.57	(0.10)
Ca (%)	0.54	(0.11)		0.47	(0.12)
Mg (%)	0.09	(0.01)		0.11	(0.02)
S (%)	0.09	(0.01)		0.10	(0.02)
Mn (ppm)	580	(200)		780	(270)
active Fe (ppm)	23	(2.7)	***	38	(8.0)
Zn (ppm)	67	(9.6)		76	(27)
Cu (ppm)	1.7	(0.26)	***	2.4	(0.45)
B (ppm)	15	(4.3)		14	(3.2)

*** significant at P=0.01 using a "T" test
Numbers in parentheses are standard deviations.
N=15 for leader lengths, N=10 for foliar analyses.

Results and discussion

Adjacent burned and unburned sites - the Cutoff Road site

At Cutoff Road five growing seasons after planting, average leader length was 36% lower, and foliar N, active Fe, and Cu were 27, 66 and 41% higher, respectively, on the unburned (83-/TB36) site than on the burned (83-/TB37) site; the differences between burned and unburned sites for all four variables were highly significant (Table 2). Other less significant differences were also observed. These findings are in agreement with the findings of a regional survey of spruce plantations in the central interior (Ballard 1984) which found that N, Fe and Cu deficiencies tend to be more frequent and more severe on burned than on unburned sites, while tree growth tends to be better. These newer results strengthen the inference that this is probably an effect of burning and not merely fortuitous correlation. However, replication of the burn treatment on a similar ecosystem would be desirable in future research to confirm that the differences are attributable to burning.

Mechanisms to account for these results might include the following. As much as 80% of the N contained in forest fuels may be volatilized during combustion (DeBell and Ralston 1970). Mroz et al. (1980) found that burning increased the available N in mineral soils, perhaps in part because of downward movement of residual N from the forest floor. One can visualize different effects on N nutrition, depending on the net effects of various processes. If the increase in availability of residual N (including the increase through post-fire mineralization) is sufficient to compensate for loss of available N through volatilization, there may be no short-term detrimental effect of burning on the N status of seedlings. However, in some cases mineralization may be insufficient to prevent a detrimental effect. Moreover, regardless of short-term effects, the long-term effect on the availability of N in soil may be detrimental. The site N capital may be so reduced by volatilization that the available N pool eventually declines seriously due to gradual redistribution of the small N capital among soil biota, soil organic matter, and vegetation. Increased mineralization may exacerbate this effect by causing the reduced pool to be used at a more rapid rate.

Copper and iron tend to be complexed to some extent by some constituents of soil organic matter, such as fulvic acids (Schnitzer and Skinner 1966). In fact, Cu deficiency is sometimes associated with accumulation of organic matter because of complexing (Mortvedt et al. 1972). Both Fe and Cu tend to be more available at low than at high pH because the latter promotes formation of insoluble oxides or hydroxides or both (Mortvedt et al. 1972). A substantial increase in soil pH commonly results from prescribed burning (Beaton 1959) because of hydrolysis of the base oxides which dominate ash. Recently, the role of hydroxamate siderophores in iron nutrition of plants has been investigated. These organic compounds, produced by some soil organisms, mobilize oxidized iron and allow it to be absorbed by the root. Perry et al. (1984) have demonstrated the importance of siderophores in tree nutrition and have shown that soil disturbance, such as prescribed burning, can greatly reduce the abundance of siderophores. Recent work by Majid (1984), using foliar analysis and fertilizer trials, showed that Fe deficiency may occur in some lodgepole pine stands of interior British Columbia. Perhaps because most of these stands originated after fire, both high pH and a reduction of siderophore production may be implicated. Such observations may be relevant to prescribed burning effects on spruce, but more specific research in these areas is needed.

Burning over a range of fire impacts - the McLeod Lake plots

Relationships of fire impact to spruce growth and nutrition were examined using combinations of the McLeod Lake plots. Linear regressions and correlations were carried out for several variables (Table 3). Six of the plots sampled in 1983 were similar in terms of physiographic variables, as previously noted. These are identified as 1983-6 in the Data Set column of Table 3, where the number following the year indicates the number of plots used in the analysis. Ideally, the most useful indications of fire effect relationships would be derived from examination of these data. Because other sampled plots were planted at other times, tree height comparisons involving other groups of plots would not be meaningful. Consequently, relationships involving total tree height as a variable are restricted to this data set. Because current or recent height increment and several other relationships might be meaningfully compared (if increment is for the same year), the other variables are analyzed comparably for various data sets. The second data set, identified as 1983-9, includes the first data set plus three research plantations sampled in 1983. Because of significant differences between plug stock and bare-root stock in terms of one or more measured variables, only the data for bare-root stock have been included in the analysis. (The operationally planted seedlings represented by data set 1983-6 were bare-root stock.) An additional research plantation which was sampled has been omitted from the analysis because of significant differences between planted groups of bare-root stock within the plot, which resulted in a bimodal distribution. Since this factor was associated with the stand rather than the soil, this additional plot could be used for evaluating relationships involving soil mineralizable N, but not stand characteristics; thus it is included in data set 1983-10 of Table 3. The data set identified as 1984-6 represents six research plantations (sampled in 1984) with dissimilar physiography and different planting dates.

Some preliminary evaluations (not shown) indicated that duff reduction was more weakly related to growth and nutrition than variables more representative of conditions immediately after the fire, namely residual duff thickness or the percentage of the total area occupied by exposed mineral soil. The values used for these variables are those cited by Blackhall and Auclair (1982).

In data set 1983-6, tree height is strongly and negatively related to residual duff, essentially unrelated to foliar N and only weakly (and positively) related to exposed mineral soil (Table 3). Foliar N and Cu are positively related to residual duff, soil mineralizable N is also positively (but more weakly) related, and leader length (1983) is negatively related to residual duff. These findings agree with the inference obtained from a regional survey (Ballard 1984) and the data from the Cutoff Road site: growth tends to be better, although stand nitrogen status tends to be poorer, on prescribed burned sites. These results from other sites strengthen the inference that these relationships are the result of burning, rather than mere correlation, and that effects on growth and nutrition are not merely related to whether burning has occurred, but can be affected by the severity of fire impact.

Foliar N concentrations in these plots range from 1.04 to 1.09% lying well below the critical level of about 1.5%, identified by Swan (1971). Thus the spruce on all six plots represented by data set 1983-6 were severely deficient in N. The paradoxical association of better growth with N deficiency in this and other data sets indicates that other important limiting factors are being relieved by burning. Because no significant relief of severe nutrient deficiencies has been noted on burned (vs. unburned) sites (Ballard 1984), the beneficial effects of burning may be physical rather than nutritional.

Dobbs and McMinn (1977) inferred that the beneficial effects of scalping on growth of planted white spruce were attributable to reduced competition and warmer soil. Their data suggest that the warming of the soil may be due partly to reduced shading by competing vegetation and partly to the higher thermal diffusivity of mineral material compared to that of organic material. They showed that soil temperature of 10°C is sufficiently low to be severely limiting for the growth of white spruce seedlings. Benefits analogous to those of

Table 3. Linear regressions and correlations of some variables (plot averages) for various groups of Mcleod Lake plots

Data set	Y	X	a	d	r^2
1983-6	1983 Tree height (m)	Residual duff (cm)	2.520	-0.090	0.593*
1983-6	1983 Tree height (m)	Foliar N (%)	3.469	-1.150	0.042
1983-6	1983 Tree height (m)	Exposed min. soil (% of area)	1.964	0.013	0.177
1983-6	Foliar N (%)	Residual duff (cm)	1.067	0.012	0.340
1983-6	Foliar Cu (ppm)	Residual duff (cm)	2.425	0.066	0.417
1983-6	1983 Leader length (cm)	Residual duff (cm)	36.335	-1.230	0.408
1983-6	Soil mineralizable N (ppm)	Residual duff (cm)	51.885	4.984	0.163
1983-6	Foliar N (%)	Exposed min. soil (% of area)	1.179	-0.004	0.493
1983-6	Foliar Cu (ppm)	Exposed min. soil (% of area)	2.943	-0.015	0.335
1983-6	1983 Leader length (cm)	Exposed min. soil (% of area)	26.655	0.270	0.321
1983-6	Soil mineralizable N (ppm)	Exposed min. soil (% of area)	90.996	-1.322	0.268
1983-9	Foliar N (%)	Residual duff (cm)	1.081	0.010	0.188
1983-9	Foliar Cu (ppm)	Residual duff (cm)	2.178	0.108	0.498**
1983-9	1983 Leader length (cm)	Residual duff (cm)	39.802	-1.810	0.431*
1983-9	Soil mineralizable N (ppm)	Residual duff (cm)	39.198	7.780	0.331
1983-9	Foliar N (%)	Exposed min. soil (% of area)	1.163	-0.002	0.498*
1983-9	Foliar Cu (ppm)	Exposed min. soil (% of area)	2.924	-0.170	0.723***
1983-9	1983 Leader length (cm)	Exposed min. soil (% of area)	32.116	0.106	0.087
1983-9	Soil mineralizable N (ppm)	Exposed min. soil (% of area)	81.665	-0.755	0.465**
1983-10	Soil mineralizable N (ppm)	Residual duff (cm)	33.763	8.755	0.346*
1983-10	Soil mineralizable N (ppm)	Exposed min. soil (% of area)	82.686	-0.847	0.522**
1984-6	Foliar N (%)	Residual duff (cm)	1.057	0.011	0.014
1984-6	Foliar Cu (ppm)	Residual duff (cm)	2.521	0.032	0.008
1984-6	1983 Leader length (cm)	Residual duff (cm)	38.050	1.163	0.027
1984-6	Soil mineralizable N (ppm)	Residual duff (cm)	4.156	8.058	0.607*
1984-6	Foliar N (%)	Exposed min. soil (% of area)	1.030	0.001	0.050
1984-6	Foliar Cu (ppm)	Exposed min. soil (% of area)	2.434	0.004	0.032
1984-6	1983 Leader length (cm)	Exposed min. soil (% of area)	41.881	-0.045	0.013
1984-6	Soil mineralizable N (ppm)	Exposed min. soil (% of area)	36.280	-0.501	0.576*

$Y = a + dX$;
*P<0.10, **P<0.05, ***P<0.01

scalping can be obtained from prescribed burns which remove most of the organic layer of the soil. Because blackening from burning reduces the albedo, leading to more absorption of short-wave radiation, burning may further raise soil temperatures as long as the soil remains exposed to solar radiation. Viro (1974) and Endean and Johnstone (1974) have shown moderate increases in soil temperatures during the summer (3-5°C) at the forest floor mineral soil interface following prescribed burns on spruce cut-overs.

Soil temperatures were measured in 1983 at a depth of 50 cm at the McLeod lake study area, and were evaluated in relation to a model of annual soil temperature variation. (Some considerations used in evaluation of single temperature measurements are described in detail in Appendix 1). From this, it was estimated that the mean summer soil temperatures generally lie between 5 and 10°C. (August soil temperature at 50 cm under an uncut stand adjacent to the McLeod Lake plots was 6°C.) These temperatures are far below the optimum of about 20°C indicated by Dobbs and McMinn (1977), and suggest that duff reduction (and perhaps associated fire effects on seral vegetation) may have been an important factor in warming the soil.

Where growth is enhanced without increasing the ability of the soil to supply N, greater N deficiency can be expected, because the stand's demand for N is greater. The lower concentration of N in foliage is at least partly a reflection of dilution of N by increased biomass production; it does not necessarily indicate that the availability of N has been reduced by burning. However, it is evident from Table 3 that soil mineralizable N, an index of N availability, is positively correlated with residual duff, i.e., that it is adversely affected by burning and by burns of greater fire impact, presumably as a result of loss through volatilization.

Although the results cited above for the first six operational plots can be plausibly explained, quantitatively different results were obtained where data from other plots were analyzed or included with data set 1983-6 for analysis. When 1983 data for three research plots were included (data set 1983-9), correlations of foliar N with residual duff and of leader length with exposed mineral soil were weak (Table 3). Foliar N and Cu were more strongly (and negatively) correlated with exposed mineral soil, and leader length was negatively correlated with residual duff. In data sets 1983-9 and 1983-10, mineralizable N is positively correlated with residual duff and negatively correlated with exposed mineral soil. These results are consistent with the rationale presented to explain the data previously discussed; however, regression coefficients differ and some correlations are not very strong.

Extremely poor correlations were obtained with the 1984 data (Table 3). It is tempting to infer, but it cannot be proven, that this reflects the variation in site conditions and planting associated with this data set.

Windrow and Burning - Boomerang and Carp lakes

Comparisons within and between burned windrows are of interest, partly because plant competition and soil thermal behavior may be fairly similar under the two microsite conditions, so that the influence of nutritional differences on growth might be tentatively inferred. Some accumulation of nutrients occurs through windrowing, and although some nutrients may be lost by volatilization, some may become substantially more available because of ashing. If growth is better within burned windrows, it may mean that growth could be improved if nutritional limitations were ameliorated on sites prepared by blade scarifying or other mechanical means which result in extensive scalped areas.

Windrow effects on white spruce and lodgepole pine nutrition at Boomerang Lake

At Boomerang Lake, average spruce leader length is significantly higher ($P = 0.06$) within burned windrows than between burned windrows (Table 4). Spruce foliar concentrations of P, K, S, active Fe, and Zn are significantly higher ($P<0.05$) within than between windrows (Table 4). Presumably this is largely a result of accumulation of nutrients by windrowing and release if nutrients by combustion. It is interesting that, although considerable amounts of N and S are lost through volatilization during combustion (Allen 1964; DeBell and Ralston 1970), the foliar concentrations of both elements are not significantly lower within the burned windrows. This indicates that accumulation of N and S during windrowing, together with their release in available form in the ash, can more or less compensate for loss of these elements through volatilization. Only Mn has a significantly lower concentration within than between burned windrows, perhaps because of decreased solubility caused by the highly significant ($P<0.01$) increase of soil pH (Table 4) (Mortvedt et al. 1972). Growth data and the general trend of the nutrient data are consistent with the hypothesis that severe nutrient deficiencies are associated with scalped sites and that relief of these deficiencies could be expected to increase growth. Thus, although mechanical site preparation tends to improve growth, e.g., by effects on competition and soil temperature, even greater improvement of growth might be achieved if nutrient loss could be avoided or if deficient nutrients could be added. Small scalps or mounding, leaving nutrients within reach of extending seedling root systems, represent one of several alternatives which might have such beneficial effects.

At the Boomerang Lake site, foliage of planted lodgepole pine, like that of spruce, has significantly ($P<0.05$) higher concentrations of P, K, and S within than between burned windrows (Table 4). Unlike spruce, pine foliage within burned windrows also had significantly higher levels of N, Ca, and B, but not of active Fe and Zn (Table 4). Such results may reflect species differences in relative ability to exploit nutrients under different soil conditions.

Table 4. White Spruce Growth, Foliar Nutrients in White Spruce and Lodgepole Pine and Soil pH at Boomerang Lake

Variable	Spruce					Pine				
	Within windrows			Between windrows		Within windrows			Between windrows	
Leader (cm)	23.5	(6.9)		18.8	(6.2)					
Foliar:										
N (%)	1.22	(0.18)		1.20	(0.15)	1.26	(0.11)	*	1.17	(0.15)
P (%)	0.22	(0.04)	***	0.18	(0.02)	0.14	(0.02)	**	0.13	(0.01)
K (%)	0.64	(0.12)	***	0.52	(0.05)	0.58	(0.05)	**	0.54	(0.06)
Ca (%)	0.39	(0.12)		0.35	(0.15)	0.18	(0.03)	**	0.15	(0.05)
Mg (%)	0.10	(0.02)		0.09	(0.02)	0.08	(0.01)		0.11	(0.16)
S (%)	0.10	(0.01)	**	0.09	(0.01)	0.11	(0.01)	*	0.10	(0.01)
Mn (ppm)	310	(130)	***	670	(330)	380	(130)		460	(156)
Fe (ppm)	27	(9.7)		25	(5.2)	30	(4.4)		28	(5.9)
active Fe (ppm)	27	(4.6)	***	20	(4.7)	20	(6.2)		20	(4.7)
Zn (ppm)	71	(9.1)	**	60	(13)	63	(9.2)		59	(12)
Cu (ppm)	2.2	(0.82)		2.3	(0.47)	3.4	(0.69)		3.4	(0.64)
B (ppm)	7.6	(5.3)		5.9	(2.0)	14	(3.5)	**	12	(3.0)
Soil pH (in water)	5.30	(0.62)	***	4.52	(0.35)					

* P <0.10, **, P <0.05; ***, P <0.01
Numbers in parentheses are standard deviations.
N=15 for all analyses.

Table 5. Spruce growth within and between burned windrows at Carp Lake

Variable	Burned windrows	Between windrows		P levels		
		No alder	Alder	A-B	A-C	B-C
	A	B	C			
Height (m)	2.19	1.65	2.01	.00	.11	.00
Leader (cm)	40.5	28.4	42.5	.00	.37	.00

P levels indicate significance of differences between columns, as estimated by analysis of variance and Scheffé multiple comparisons.

Table 6. Some soil properties within and between burned windrows at Carp Lake.

Variable	Burned windrows	Between windrows		P levels		
		No alder	Alder	A-B	A-C	B-C
	A	B	C			
Organic C (%)	3.01	2.84	3.13	.72	.79	.54
Total N (%)	0.105	0.071	0.109	.03	.80	.01
pH (in water)	5.66	5.04	4.57	.00	.00	.00

P levels indicate significance of differences between columns, as estimated by analysis of variance and Scheffé multiple comparisons.

Table 7. Spruce foliar nutrients within and between burned windrows at Carp Lake.

Variable	Burned windrows	Between windrows		P levels		
		No alder	Alder	A-B	A-C	B-C
	A	B	C			
N (%)	1.01	0.94	1.19	.15	.00	.00
P (%)	0.20	0.20	0.20	.95	.56	.51
K (%)	0.71	0.64	0.61	.03	.00	.20
Ca (%)	0.49	0.44	0.46	.20	.45	.27
Mg (%)	0.10	0.10	0.09	.67	.07	.03
S (%)	0.09	0.09	0.09	.31	.62	.60
Mn (ppm)	760	650	670	.14	.20	.89
Fe (ppm)	22	25	25	.23	.18	.89
active Fe (ppm)	21	20	21	.44	.96	.41
Zn (ppm)	65	63	52	.59	.00	.01
Cu (ppm)	1.7	1.6	2.1	.48	.01	.00
B (ppm)	15	11	8	.01	.00	.03

P levels indicate significance of differences between columns, as estimated by analysis of variance and Scheffé multiple comparisons.

Windrow effects and alder effects on spruce at Carp Lake

The Carp Lake site offers an opportunity for checking the above windrow effects on spruce, and an opportunity for assessing alder effects on spruce growth and nutrition on a scalped soil. Data from the Carp Lake site were evaluated by analysis of variance, results of which are summarized in Tables 5, 6, and 7.

Tree growth data for the Carp Lake site are summarized in Table 5. Leaders were significantly shorter in scalped areas without alder than in the other two kinds of microsites. Leaders were somewhat longer, but not significantly so, on alder microsites than in burned windrows. Trees were also significantly shorter on scalped areas that were free of alder than on the other two microsites. Trees were tallest within burned windrows and were of intermediate height where alder was present (significant at P = 0.11). The ratio of leader length to total height was highest where alder was present, and intermediate within burned windrows. The data thus suggest that although spruce on the whole scalped area presumably got a slow start, growth on the alder microsites has been catching up, and these microsites might eventually outstrip the burned windrows in terms of total tree height.

Soil data are summarized in Table 6. It had been expected that the concentration of organic C in soil between windrows would be higher under alder as a result of litter production by alder. Although the data suggest this, it is not statistically significant. Limited litter production by the small alder shrubs and rapid decomposition might be responsible for the small, insignificant differences. Where alder has invaded between windrows, it has significantly increased the concentration of N in the soil, thus reducing the C/N ratio. This implies an increased availability of N in soil, although relative N availability cannot always be inferred from C/N ratios (Tisdale and Nelson 1966; Zöttl 1960, 1968). Further, the pH of the soil was lowest where alder had invaded the scalped areas; this also suggests that N is more available in these areas. The low pH presumably reflects nitrification of the available ammonium, accumulated as a result of N fixation. Soil pH is highest in burned windrows, presumably because of ash bases.

During sampling, no soil morphological evidence was found to indicate substantial incorporation of surface humus into mineral soil between windrows during site preparation. In the undisturbed remnant stand area, the concentration of N was 0.73 percent in the 5-cm-thick mor humus. One may assume, based on data of Gessel and Balci (1965), that such humus has a bulk density of about 130 kg/m^3. These figures yield 475 kg of N per hectare as an approximate estimate of the humus N which may have been lost from the area between windrows during site preparation.

Assuming a bulk density of 900 kg/m^3 for the surface mineral soil, to 15 cm in depth, the accumulation of N in soil attributable to alder invasion amounts to about 500 kg/ha within the alder microsites. Assuming that this represents about 8 years' accretion, it represents an annual accumulation comparable to some reported elsewhere with alders (Sprent 1979). Rapid N accumulation may continue for several more years.

Concentrations of nutrients in spruce foliage are presented in Table 7. The concentration of N in foliage is highest on alder microsites and intermediate on burned sites; however, the difference in N concentration between the burned sites and the scalped areas that were free of alder is not highly significant. Concentrations of K and B in foliage are significantly higher in burned windrows than elsewhere, presumably because of ash effects. Concentrations of K, Mg, and Zn in foliage are lowest on alder microsites. Ion exchange and acid leaching under alder might account for this, and acid leaching might also account for lower foliar B on alder microsites. Foliar Cu is significantly higher on alder microsites than elsewhere, perhaps because of the pH effect on availability. Slightly lower foliar Fe in burned windrows may be attributable to the pH effect on availability (Mortvedt et al. 1972), which can outweigh the importance of Fe inputs by windrowing. However, as noted previously, the numbers and activity of siderophore-producing microbes may also affect the Fe nutrition of plants and may be reduced by windrowing and burning (Perry et al. 1984). It is noteworthy that scalping, burning and alder invasion have not led to any difference in foliar P among the three sites. Windrowing and burning might have been expected to increase total P and the potentially soluble P content of the soil because the soil pH in the burned windrows currently seems near the optimum for maximizing the solubility of soil phosphate (Tisdale and Nelson 1966). However, ash and charcoal within the windrow may reduce phosphate availability by allowing more adsorption (Beaton et al. 1960).

Foliar nutrient concentrations in burned windrows and scalped areas that were free of alder at Carp lake resembles that at Boomerang Lake only in that higher K concentrations are associated with burned windrows in both cases. At Carp Lake, unlike Boomerang Lake, foliar N and Mn are higher (but not significant at $P = 0.10$) within burned windrows than in scalped microsites that were free of alder, and P, S, and active Fe concentrations do not differ between the two kinds of microsites. Such differences show that generalization about windrowing and burning effects on foliar nutrient concentrations would be inappropriate without controlled field experiments and additional sampling in other areas of the region. One may reasonably assume, however, that higher biomass production in foliage was associated with the increased lengths of shoots. Thus, one may reasonably infer that, even at Carp Lake, the total uptake of such nutrients as P and S, among others, was greater within windrows, because the concentrations of these nutrients are diluted by the greater foliar biomass. Thus, in terms of nutrient content rather than concentration, the differences between burned and unburned sites at both Boomerang and Carp lakes may be similar.

Of the eleven foliar nutrients evaluated at Carp lake, B, Fe, Cu, Mg, and N deserve particular discussion. Where alder has invaded, foliar concentration of B is somewhat low. Although not clearly deficient, it is near (if not at) a level where B deficiency might occur intermittently with climate fluctuations, insofar as work with other conifers may be applicable as a guide to white spruce nutrition (Stone 1968; Braekke 1979). Foliar Fe seems low. Although total Fe recovery by the analytical method used may be incomplete, the active Fe levels in Table 7 are sufficiently low to suggest possible Fe deficiency, based on data obtained for other species by Zech (1970) and Majid (1984). Also, the Mn/Fe ratios appear rather high, which may be a factor in Fe deficiency (Mortvedt et al. 1972). Copper concentrations are sufficiently low to suggest deficiency, based on data of Benzian and Warren (1956) for Sitka spruce seedling tops and on foliar data for other species reviewed by Morrison (1974). Magnesium appears deficient, judging from criteria of Swan (1971), and this may limit growth.

Average concentrations of N in spruce foliage in the three site conditions range from 0.94%, in scalped areas lacking alder, to 1.19%, on scalped areas with alder. Swan (1971) suggested that the "transition zone from deficiency to sufficiency" is at 1.3 to 1.5% for white spruce. Thus as soil N status continues to improve under the alder due to continued N fixation, further enhancement of growth of the associated spruce can be expected. Leaders on spruce in the alder areas should soon be significantly longer than those in the burned windrows, and spruce should also soon become the tallest trees on the alder microsites.

In summary, the foliar data suggest deficiencies of several nutrients. The evidence confirms that N, in particular, is a seriously growth-limiting factor at the Carp lake site. Some of the N that was accumulated in the form of windrowed material was doubtless lost by volatilization during burning, but the soil and spruce N status and tree growth are better within burned windrows than in the microsites without alder which dominate the scalped area. Windrowing stripped a large amount of N from most of the clearcut. A 27% increase in the concentration of N in spruce foliage and a recent 50% increase in height increment were associated with the substantial restoration of soil N on those microsites of the scalped area where alder has invaded.

Conclusions

The McLeod Lake plots varied in terms of species, stock types, planting dates, drainage, slope, aspect, soil parent material, and doubtless other less obvious characteristics. Presumably as a result of this variation, statistical relationships observed between spruce growth or nutrition and levels of fire impact were weak and not wholly consistent. The low number of suitable plots for regression analysis also affected the statistical relationships.

It is clear from the sampling at Cutoff Road and from the 1983 sampling at McLeod Lake that, although burning reduces the concentration of N in foliage, it results in increased growth. A plausible explanation for the increase in growth is that removal of vegetation cover and of the insulating forest floor warms the underlying soil. Another possible explanation might be that the reduced vegetation competition for nutrients, light, and water resulted in better tree growth. Foliage at the McLeod Lake plots was deficient in N to various degrees. The lower nitrogen concentrations in foliage might partly reflect dilution by the increased biomass produced. However, there also appears to be a reduction, by burning, of soil mineralizable N (an index of N availability). It seems likely that although the growth of spruce is enhanced by burning, or by more severe burning, the growth would be further improved if the N deficiency were relieved.

Although physical factors would be expected to be overwhelmingly important in the early stages of plantation establishment, it is noteworthy that the improvement in growth, despite nutritional impairment, has persisted for about 15 years at the McLeod Lake plots.

The predictive equations of Table 3 fall far short of what was visualized when this study was initiated. The scheme suggested by Auclair (1982), of modeling growth and nutrition as a function solely of fire behavior and impact, is not wholly vitiated by the results. However, it appears that greater emphasis would have to be placed on modeling fire effects on (and growth implications of) soil temperatures and perhaps some other physical factors. The dissimilarities in growth among different stock types at McLeod Lake also indicate that any predictions of absolute growth will have to take planting stock variables into account. The scope of relationships which must be quantified for effective modeling exceeds what can be determined from evaluation of plantations which happen to be present with some documentation of the fire treatment. A special experimental design would be required to meet the needs of such modeling. One can reasonably infer that the development of a generally useful predictive model for quantitative prediction of burning effects on white spruce growth lies rather far in the future. Yet, the results of this study would seem to justify some useful qualitative predictions. There is substantial qualitative agreement in the data obtained by Ballard (1984, 1986), in the evidence from the Cutoff Road site, and in the data from the 1983 sampling at McLeod Lake. One can generalize that, in comparison with unburned sites, spruce planted on burned sites in the Sub-Boreal Spruce subzones tends to grow faster and to be deficient (or more deficient) in N, Cu, and Fe. In many cases, N is less deficient, but height growth is poorer, where more residual duff remains or where there is less exposed mineral soil after burning.

There are two important caveats for the land manager who might view these results as evidence in favor of severe burning. First, because the short-term growth improvement is at the expense of N status and the status of other nutrients, it is conceivable that there may be some longer-term impairment of growth as a result of burning. Whether such impairment does occur, and if so, whether it is serious, remain to be determined. Moreover, some alternative site preparation methods might be equally or more effective in the short and longer term (e.g., mounding or small patch scarifying). Second, the beneficial effects of fire are at least partially attributable to temperature improvement effected by removing thick humus layers from the surface of cold soils. Consequently, one cannot necessarily expect similar beneficial effects of fire on warmer soils, on soils with thin humus layers, or where water holding capacity may be critical.

Comparison of results from the Boomerang and Carp Lake sites indicates that growth and nutrition of young planted spruce are better within burned windrows than in scalped areas between windrows lacking alder. While increases in the concentrations of nutrients in foliage that were attributable to burning were not consistent for the two sites, a general enhancement of foliar nutrient content (associated with increased growth) is inferred. Moreover, a comparison of pine with spruce at the Boomerang Lake site suggested some species differences in relative ability to take up nutrients under different soil conditions. Alder invasion of scalped areas at Carp lake resulted in improved N status of spruce and changes in the status of some other nutrients, and dramatically improved the height growth of spruce. Although tall alder might be detrimental from the standpoint of competition, the benefits observed with small, shrubby alder suggest its potential usefulness in silviculture on sites in central interior British Columbia that have low levels of nitrogen.

References

Allen, S.E. 1964. Chemical aspects of heather burning. J. Appl. Ecol. 1:347-367.

Auclair, A.N.D. 1982. The use, effects and research needs of prescribed burning in British Columbia ecosystems: A problem analysis and recommendation for research *In* Auclair, A.N.D. 1982. Problem analysis of prescribed burning: A synthesis text. 1217 p. Unpublished file report.

Ballard, T.M. 1972. Subalpine soil temperature regimes in southwestern British Columbia. Arct. Alp. Res. 4:139-146.

Ballard, T.M. 1982. Foliar analysis research (E.P. 889). Contract Res. Report to the Researcy Branch, B.C. Ministry of Forests. 19 p + appendices.

Ballard, T.M. 1984. Nutrition of planted white spruce. Contract Res. Report to Research Branch, B.C. Ministry of Forests. 23 p + appendices.

Ballard, T.M. 1985. Foliar analysis for deficiency diagnosis and fertilizer prescription in forestry: variability considerations. Pages 142-153 *in* The role of soil analysis in resource management. Proceedings of the 9th B.C. soil science workshop. B.C. Ministry of Environment Technical Report 16.

Ballard, T.M. 1986. Slashburning effects on growth and nutrition of planted white spruce in interior British Columbia. Pages 69-78 *in* Proceedings of a fire management symposium held at Prince George, British Columbia, April 8-9, 1986. Sponsored by the Central Interior Protection Committee.

Ballard, T.M.; Carter, R.E. 1986. Evaluating forest stand nutrient status. B.C. Minist. For. Land Manage. Rep. No. 20. 60 p.

Beaton, J.D. 1959. The influence of burning on the soil in the timber range area of Lac le Jeune, British Columbia. II. Chemical properties. Can. J. Soil Sci. 39:6-11.

Beaton, J.H.D.; Peterson, H.B.; Bauer, N. 1960. Some aspects of phosphate adsorption by charcoal. Soil Sci. Soc. Am. Proc. 24:340-346.

Benzian, B.; Warren, R.G. 1956. Copper deficiency in Sitka spruce seedlings. Nature 178:864-865.

Black, C.A. (ed.) 1965. Methods of soil analysis. Agronomy 9. American Society of Agronomy, Madison, Wisconsin.

Blackhall, J.W. 1983a. The application of NIP: a simulation of nutrient losses due to harvest and prescribed burning based on real and hypothetical data sets. Contract Res. Report to Pacific For. Res. Centre (Can. For. Serv.). 26 p. + appendices. *In* Auclair, A.N.D. 1983. Research in prescribed burning: a synthesis text. Can. For. Serv., Pacific Forestry Centre, Victoria, B.C. Unpublished report.

Blackhall, J.W. 1983b. The Nutrient Impact Predictor (NIP). Contract Res. Report to Pacific For. Res. Centre (Can. For. Serv.). 18 p. + appendices. *In* Auclair, A.N.D. 1983. Research in prescribed burning: a synthesis text. Can. For. Serv., Pacific Forestry Centre, Victoria, B.C. Unpublished report.

Blackhall, J.W.; Auclair, A.N.D. 1982. Best solution models of prescribed fire impact and fire behavior in subalpine Picea glauca-Abies lasiocarpa forests of British Columbia. ms., Pacific For. Res. Centre, Can. For. Serv., Victoria. 183 p. *In* Auclair, A.N.D. 1983. Research in prescribed burning: a synthesis text. Can. For. Serv., Pacific Forestry Centre, Victoria, B.C. Unpublished report.

Braekke, F.H. 1979. Boron deficiency in forest plantations on peatland in Norway. Medd. Fra Norsk Inst. f. Skogsforskning 35: 213-236.

British Columbia Ministry of Environment. 1980. Climate of British Columbia 1977. Air Studies Branch. 830 p.

British Columbia Ministry of Environment. 1982. Climate of British Columbia 1978. Air Studies Branch. 365 + 371 p.

Canada Soil Survey Committee. 1978. The Canadian system of soil classification. Can. Dept. Agric. Publ. 1646, Supply and Services Canada, Ottawa. 164 p.

Carslaw, H.S.; Jaeger, J.C. 1959. Conduction of heat in solids.

2nd Ed. Clarendon Press, Oxford. 501 p.

DeBell, D.S.; Ralston, C.W. 1970. Release of nitrogen by burning light forest fuels. Soil Sci. Soc. Am. Proc. 34:936-938.

DeLong, C.; Hope, G.; McLeod, A. 1987a. A field guide for the identification and interpretation of ecosystems of the SBSe2 in the Prince George Forest Region, Second Approx., Ecology Section, Prince George Region, B.C. Ministry of Forest and Lands. 47 p.

DeLong, C.; Jenvey, S.; McLeod, A. 1987b. A field guide for the identification and interpretation of ecosystems of the SBSj1 in the Prince George Forest Region, Second Approx., Ecology Section, Prince George Region, B.C. Ministry of Forests and Lands. 47 p.

Dobbs, R.C.; McMinn, R.C. 1977. Effects of scalping on soil temperature and growth of white spruce seedlings. Pages 66-73 *in* 6th B.C. Soil Science Workshop. B.C. Ministry of Agriculture, Victoria.

Endean, F.; Johnstone, W.D. 1974. Prescribed fire on clearcut spruce-fir sites in the foothills of Alberta. Environ. Can. Can. For. Serv. Northern For. Res. Cent. Inf. Rep. NOR-X-126. 33 p.

Gaines, T.P.; Mitchell, G.A. 1979. Boron determination in plant tissue by the azomethine H method. Comm. Soil Sci. Plant Anal. 10: 1099-1108.

Gessel, S.P.; Balci, A.N. 1965. Amount and composition of forest floors under Washington coniferous forests. Pages 11-23 *in* C.T. Youngberg (ed.). Forest-soil relationships in North America. Oregon State Univ. Press, Corvallis.

Guthrie, T.F.; Lowe, L.E. 1984. A comparison of methods for total sulphur analysis of tree foliage. Can. J. For. Res. 14: 470-473.

Jackson, M.L. 1958. Soil chemical analysis. Prentice-Hall, Englewood Cliffs, New Jersey. 498 p.

Lawson, B.D.; Taylor, S.W. 1986. Preliminary evaluation of prescribed fire impact relationships and predictors for spruce-balsam slash. Pages 48-68, *in* Proceedings of a fire management symposium held at Prince George, British Columbia, April 8-9, 1986. Sponsored by the Central Interior Fire Protection Committee.

Majid, N.M. 1984. Some aspects of boron, copper and iron nutrition of lodgepole pine and Douglas-fir, Ph.D. Dissertation, Dept. of Soil Science, University of British Columbia, Vancouver. 172 p.

Morrison, I.K. 1974. Mineral nutrition of conifers with special reference to nutrient status interpretation: a review of the literature. Can. For. Serv. Publ. No. 1343. 74 p.

Mortvedt, J.J.; Giordano, P.M.; Lindsay, W.L. (eds.). 1972. Micronutrients in agriculture. Soil Science Society of America, Madison, Wisconsin. 666 p.

Mroz, G.D.; Jurgensen, M.F.; Harvey, A.E.; Larsen, M.J. 1980. Effects of fire on nitrogen in forest floor horizons. Soil Sci. Soc. Am. J. 44:395-405.

Muraro, S.J. 1975. Prescribed fire predictor. Pacific Forest Research Centre, Victoria, B.C. [slide rule]. (Reprinted 1980).

Olson, R.A.; Clark, R.B.; Bennett, J.H. 1981. The enhancement of soil fertility by plant roots. Am. Scientist 69:378-384.

Oserkowsky, J. 1933. Quantitative relation between chlorophyll and iron in green and chlorotic pear leaves. Plant Physiol. 8:449-468.

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

Perry, D.A.; Rose, S.L.; Pilz, D.; Schoenberger, M.M. 1984. Reduction of natural ferric iron chelators in disturbed forest soils. Soil Sci. Soc. Am. J. 48:379-382.

Powers, R.F. 1980. Mineralizable soil nitrogen as an index of nitrogen availability to forest trees. Soil Sci. Soc. Am. J. 44:1314-1320.

Schnitzer, M.; Skinner, S.I.M. 1966. Organo-metallic interactions in soils. 5. Stability constants of Cu++, Fe++, and Zn++ - Fulvic acids. Soil Sci. 102: 361-365.

Sprent, J.L. 1979. The biology of nitrogen-fixing organisms. McGraw-Hill, London. 196 p.

Stathers, R.J. 1983. A study of soil temperature and seedling survival in a forest clearcut. M.Sc. thesis, Dept. of Soil Science, University of British Columbia, Vancouver. 131 p.

Stone, E.L. 1968. Microelement nutrition of forest trees: a review. Pages 132-175 *in* G.M. Bengtson (ed.) Forest fertilization theory and practice. TVA, Muscle Shoals, Alabama.

Swan, H.S.D. 1971. Relationships between nutrient supply, growth and nutrient concentrations in the foliage of white and red spruce. Pulp Paper Res. Inst. Can. Woodlands Pap. No. 29. 27 p.

Tisdale, S.L.; Nelson, W.L. 1966. Soil fertility and fertilizers. 2nd Ed. Macmillan, Toronto. 694 p.

van Wijk, W.R.; de Vries, D.A. 1966. Periodic temperature variations in a homogeneous soil. Pages 102-143 *in* W.R. van Wijk (ed.) Physics of plant environment. 2nd Ed. North Holland Publ. Co. Amsterdam.

Viro, P.J. 1974. Effects of forest fire on soil. *In*: Fire and Ecosystems. *Edited by*: T.T. Kozlowski and C.E. Ahlgren. Academic Press, New York. pp. 7-46.

Waring, S.A.; Bremner, J.M. 1964. Ammonium production in soil under waterlogged conditions as an index of nitrogen availability. Nature 201: 951-952.

Weatherburn, M.W. 1967. Phenol-hypochlorite reaction for determination of ammonia. Analyt. Chem. 39:971-974.

Zech, W. 1970. Nadelanalytische Untersuchungen über die Kalkchlorose der Waldkeifer (Pinus silvestris). Z. f. Pflanzenernähr. u. Bodenk. 125:1-6.

Zöttl, H. 1960. Dynamik der Stickstoffmineralisation im organischen Waldbodenmaterial. II. Einfluss des Stickstoffgehaltes auf die Mineralstickstoffnachlieferung. Plant and Soil 13: 183-206.

Zöttl, H. 1968. Die Nachlieferung von Stickstoff aus dem Bodenvorrat. Stikstof 12:8-16.

Appendix

Interpretation of single soil temperature measurements at a depth of 0.5 metres

A single soil temperature measurement, made at an appropriate depth, time of day, and time of year, can be interpreted so as to estimate T_{max}, the maximum temperature attained by the smoothed trend of annual temperature fluctuation at that depth. (T_{max} may also be calculated for other depths.) The following explains how such an estimate has been made for the soil beneath an unharvested white spruce stand at the McLeod Lake plots (lat. 54° 48' N, long. 122° 57' W) in the Prince George Forest Region. There, a temperature of 6°C was measured 50 cm below the soil surface on the morning of August 10, 1983, during routine soil description. The pedon lacks permafrost and has a surface layer of mor humus 8 cm thick.

The effect of daily temperature fluctuations on the temperature at a depth of 50 cm must be considered in order to determine whether the measured temperature was below the daily mean, making it an underestimate of the daily mean. $T_{(z,t)}$, the temperature at depth z and time t, can be roughly approximated by

$$[1] \qquad T_{(z,t)} = T_m + [A_{T_o} \exp(-z/D)\sin(\omega t - z/D + \phi)]$$

where T_m is the mean temperature, A_{T_o} is the surface temperature amplitude, D is the damping depth, ω is the angular frequency of periodic temperature variation, ϕ is a phase angle, and the angles are expressed in radians (Carslaw and Jaeger 1959; van Wijk and deVries 1966). Observations at various locations indicate that the daily temperature trough at the surface occurs at some time around 06:00 (van Wijk and deVries 1966; Ballard 1972; Stathers 1983), so that ϕ is about π, for daily temperature variation where t is expressed as Standard Time.

$$[2] \qquad D = [2\lambda/(C\omega)]^{0.5}$$

where λ/C is thermal diffusivity. For mineral soil, λ/C ranges between about 0.19 and 0.85 cm²/s; for organic layers, λ/C is about 0.12 cm²/s, so that, for diurnal temperature variation, where $2\pi/\omega$ is 86400 s, D ranges from about 7.2 to 15.3 cm for mineral soil (and is approximately 5.7 cm for organic layers)(van Wijk and deVries 1966). For August at latitudes higher than 50° N, under vegetation cover, it would be very remarkable if A_{T_o} were as high as 20°C. However, if one assumes that the largest possible value of A_{T_o} is 20°C, and one uses this to calculate the largest value by which T_m might exceed $T_{(z,t)}$, where z=50 cm and D ranges from 7.2 to 15.3 cm, and where the range of t corresponds to times from 07:00 to 12:00 Standard Time, the answer obtained is approximately 0.02°C. Although some error results from the assumptions in this analysis, 0.02°C is so small that such error is not quantitively important. (The timing of temperature measurement is important: later in the day, the amount by which T_m exceeds $T_{(z,t)}$ could be as high as 0.76°C).

Errors in calibration and reading of the soil thermometer are likely to be less than 1°C, so adding both sources of error, one can estimate that the upper limit of the true value of T_m is about 7.02°C. (For purposes of the analysis, more significant figures than normally justified by measurement accuracy are retained.)

In order to estimate T_{max}, the relationship of T_{max} to T_m must be estimated by extrapolating from annual temperature variation at the closest suitable stations for which soil temperature data are available. In order to do this, modelling of annual temperature variation is necessary. Periodic soil temperature fluctuation may be described by a Fourier series:

$$[3] \quad T_{(t)} = T_a + \sum_{k=1}^{\infty} A_k \sin(k\omega t + \phi_k)$$

where $T_{(t)}$ is the temperature at time t, T_a is average temperature over the period P corresponding at 2π radians, A_k is the amplitude of the k_{th} harmonic, ϕ_k is the phase shift of the k_{th} harmonic, and $2p/P = \omega$, the angular frequency of periodic temperature fluctuation (Carslaw and Jaeger 1959; van Wijk and deVries 1966). This series approximation of an integral can deteriorate (through insertion of high-amplitude, high-frequency waves, producing large fluctuations between data points) if calculation of higher-order harmonics is attempted from only a few data points. For this reason, it is often inappropriate to attempt fitting more than two or three harmonics to soil temperature data if one wishes to obtain a realistic simulation of the periodic trend.

Soil temperature data (in approximately monthly intervals) from 1977 for a depth of 50 cm were obtained for some of the interior soil temperature stations closest to McLeod Lake (Table 1) for which a fairly complete record has been published (British Columbia Ministry of Environment 1980, 1982). Fourier analysis of the data was conducted for each station, yielding annual T_a and the annual amplitudes and phase angles of several harmonics. However, only the first one or two harmonics (Table A2) were used for subsequent calculations, because inclusion of higher-order harmonics was not justified by the number of data points available for each station.

The annual T_a, amplitudes, and phase angles of Table 2 were used with Equation [3] to calculate two

Table A1. Location data for some meteorological stations and the McLeod Lake site

Location	Latitude	Longitude	Elevation (m)
Desaiko	54°16'	121°34'	655
Ice Mountain	54°29'	121°13'	959
Kiskat	55°02'	120°58'	917
Lower Moose	55°13'	121°16'	974
Murray	55°08'	121°05'	835
Oetco	55°30'	121°38'	590
Parsnip	54°37'	122°09'	798
Red Rock	53°54'	122°43'	620
McLeod Lake	54°48'	122°57'	900

Table A2. Annual T_a, and amplitudes (A) and phase angles (ϕ) for the first two Fourier harmonics at a depth of 50 cm at the stations

Location	T_a	A_1	A_2	ϕ_1	ϕ_2	Year
Desaiko	5.84	6.60	1.52	3.97	0.06	1977
Lower Moose	3.27	4.87	1.56	3.96	6.26	1977
Oetco	4.98	7.61	1.47	4.30	0.36	1977
Parsnip	5.28	5.30	1.47	4.36	0.88	1977
Red Rock	6.50	10.14	0.90	4.32	1.28	1977
Desaiko	6.30	7.50		4.05		1978
Ice Mountain	4.34	5.40	1.67	4.24	1.24	1978
Kiskat	5.03	6.64	2.06	4.19	0.76	1978
Murray	3.60	5.05	1.28	3.85	6.09	1978
Oetco	4.33	6.70		4.25		1978

Note: Some stations had excessively incomplete records in one year; for two stations in 1978, the second harmonic was ignored, because it contributed little or no improvement in simulation.

Table A3. Values of f for various sites on August 10 at 50 cm

Year	Desaiko	Ice Mountain	Lower Kiskat	Red Moose	Murray	Oetco	Parsnip	Rock
1977	0.996			0.992		0.975	0.911	0.927
1978	1.000	0.887	0.959		0.971	0.976		

values of T_m for each site: T_{max} and T_c, where the latter designates the calculated temperature at a depth of 50 cm on August 10. For each site, an f value was calculated:

$$[4] \qquad f = \frac{T_C - T_a}{T_{max} - T_a}$$

Thus, the f values (Table A3) are the fractions of $(T_{max}-T_a)$ attained as of August 10. (They are analogous to the sine factor of Equation [1], except that they represent the combined effect of two Fourier harmonics, yielding an improvement over the estimate given by the single harmonic of Equation [1].)

The daily mean temperature T_m, on August 10 at 50 cm, should be approximated by T_c. That is, the expected value of T_m is

$$[5] \qquad T_m = T_a + Af$$

where T_a is the mean annual temperature and

$$[6] \qquad A = (T_{max} - T_a)$$

It may be assumed that for T_m on August 10 at the McLeod Lake site:

$$[7] \qquad 0 < T_a < T_m$$

The basis for this assumption has two parts:

1) No permafrost is present, so presumably $T_a > 0$.

2) The large, positive f values in August (Table A2) indicate that $T_a < T_m$.

An estimate of T_{max} may be obtained by considering the possible range of T_a values suggested by [7]. If T=0, then $T_{max} = A = T_m/f$, from [5] and [6]. If the lowest (rather than the average) value of f (0.887, from Table 3) and the highest estimate of T_m, 7.02°C, are used, one can hope to avoid underestimating T_{max}. This yields an estimated T_{max} of 7.02/0.887 = 7.91°C.

Because higher-order harmonics are damped out at depth (as is evident from inspection of Equations [1] and [2], it can be problematic to estimate the real maximum temperature at shallower depth. However, because the first harmonic is overwhelmingly dominant, and because T_{max} has been defined as the maximum temperature attained by the smoothed trend of annual temperature fluctuation (rather than a transient peak), approximations of T_{max} for shallower depths can reasonably be estimated from the amplitude relationship of [1]:

$$[8] \; A_{Tz} = A_{To} \exp(-z/D)$$

In this case, A_{Tz} is the annual amplitude at depth z, A_{To} is annual amplitude at the surface, and D is annual damping depth (which according to Equation [2] must be about 19 times as large as diurnal damping depth, because the square root of 365.25 is about 19). Again assuming $T_a = 0$ so as to maximize the estimate of T_{max} (as in the discussion relating to Equation [7]), and using the extremes of mineral soil thermal diffusivity values, calculations yield the T_{max} data of Table A4.

The minimum λ/C value occurs when the soil is dry; the maximum occurs when the soil is at about field capacity. Calculations for Table A4 assume homogeneity of thermal diffusivity in the mineral soil. (Upward extrapolation above the 8-cm depth to calculate amplitudes and T_{max} near the surface would not be justified, because thermal properties of the 8-cm-thick organic layer over the mineral soil would require use of a two-layer model.)

From calculations culminating in the data of Table A4, it appears that maximum values of the annual smoothed temperature trends in the McLeod Lake stand are very unlikely to exceed 7.9, 9.8, and 10.6°C at depths of 50, 20 and 10 cm, respectively. Such upper-limit estimates are useful: Dobbs and McMinn (1977) found that a soil temperature of 10° C was extremely limiting for growth of white spruce seedlings, and that 20°C was near the optimum.

T_{max} values probably lie somewhat below these upper-limit estimates. If one repeats the calculation of T_{max}, using the measured temperature as an estimate of T_m (6°C), the average f value from Table A2 (0.959), the range of the two extremes in [7] and damping depths for mineral soil at somewhat less than half of field capacity or wetter [9.7 to 15.3 cm, based on data of van Wijk and deVries (1966)], the range of calculated T_{max} values at 50 cm is 6 to 6.3° C; at 20 cm, 6 to 7.4° C; and at 10 cm, 6 to 7.8° C. These ranges might be considered to bracket the most likely T_{max} values.

Table A4. T_{max} (°C) at the McLeod Lake site, for depths of 10 and 20 cm, calculated by using extreme values of thermal diffusivity for mineral soil

Depth (cm)	T_{max} with minimum λ/C	T_{max} with maximum λ/C
10	10.6	9.1
20	9.8	8.8