

Prescribed fire-induced changes in properties of sub-boreal forest soils

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Abstract

Pile and windrow burning of logging slash are important silvicultural practices in sub-boreal forests, yet, little is known about their effects on soil properties. We investigated the physical, chemical, and mineralogical properties of soils collected 2 years after prescribed pile and windrow burning treatments of clearcut forest site in the central interior of British Columbia. We also used scanning electron microscopy to investigate the effects of fire on soil morphology, particularly, soil aggregate and sand fraction. We observed higher soil pH, exchangeable Ca, Mg, K and Na and base saturation in burnt plots compared to unburnt plots. The concentrations of total and available N were similar in all treatments. In general, pile burning had more significant effects on soil properties than windrow burning. Pile and windrow burning reduced the amount of 2:1 expanding clays (vermiculite) but not kaolinite in the clay fractions of Ae and Bm horizons indicating that the temperature < 500 °C. Prescribed burns may also have caused the cracks in sand-sized amphibole, perhaps reducing their sizes into silt fraction and finer. The prescribed burns may also be responsible for the cracking patterns observed in soil aggregates and sand fraction potentially contributing to increased weathering rates.

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1. Introduction

Prescribed fire (or burn) is the knowledgeable application of fire to a specific land area to achieve predetermined forest management or other land use objectives (Merrill and Alexander, 1987). From a forest management perspective, prescribed fire has been commonly used as a tool for site preparation following logging operations (Hawkes et al., 1990). Fires (wildfires and prescribed burns) result in short and long-term changes in properties of forest soils such as the supply of essential nutrients (e.g., calcium (Ca), potassium (K) and magnesium (Mg)) that are essential to the long-term sustainability of forest productivity. Fires dramatically alter nutrient cycling through volatilization, substrate transfer, in the form of particulate matter, smoke and ash, as well by inducing nutrient losses and leaching (Grier, 1975; Feller, 1982; Macadam, 1989; DeBano et al., 1998). Some of the immediate physical effects of fire on boreal forest ecosystems include significant increases in soil temperature (Macadam, 1989; Agee, 1993) and reduced water infiltration rates into soils (DeBano et al., 1998; Robichaud, 2000). These changes enhance the rate of chemical processes involved in mineral weathering, hence the long-term nutrient supply of Ca, K and Mg.

Fires influence long-term nutrient supply through loss organic matter (OM) and cations bound to burned forest floor. Forest floors contain as much as 0.79% Ca, 0.11% K, and 0.06% Mg (Goetz et al., 1976). Brais et al. (1995) reported that Ca and Mg in the 0–10 cm layer of mineral soil was reduced by 60% and 55%, respectively, following the removal of forest floor. Equilibrium K concentration and potential K buffering capacity of soils is a function of soil organic matter content (Evangelou et al., 1986). Removal of forest floor may also change the amount of organic acids (e.g., oxalic, citric, vanillic, syringic). These organic acids are active agents of mineral weathering because of their high complexing capability (Barnhisel and Bertsch, 1989; Lapeyrie, 1988). For example, high amounts of oxalate are shown to extract the Fe and Al from andesite (Cromack et al., 1979). While several studies on the effects of prescribed fires on soil chemical properties have been conducted elsewhere (e.g., in Oregon by Minroe, 1986; in Washington by Friend, 1989; and in Utah by Harvey et al., 1979), very limited (e.g., Ballard and Hawkes, 1989) studies had been previously undertaken in boreal forests such as those of central interior British Columbia (BC).

In BC, the use of broadcast burning is declining due to public concerns regarding air quality and related health issues, the potential cost of the suppression of escaped fires and liability, changes in forest harvesting systems, and the lack of experienced and qualified forest managers to conduct prescribed burns. Thus, it is likely that pile burning or windrow burning will continue to become the site preparation of choice for many forest managers. Compared to broadcast burning, little is known about the effects of pile and windrow burning on the properties of forest soils (e.g., Morris et al., 1983; Ballard and Hawkes, 1989). At the same time, broadcast burning may represent a use of fire that more closely mimics natural disturbance in these boreal ecosystems.

The focus of this paper is to investigate the effects of fires on soil properties to better understand the influence of prescribed fires on nutrient supply in sub-boreal forests soils. In this paper, we define the use of prescribed fires to achieve silvicultural objectives (e.g., site preparation, and disposal of logging slash) as an intentional burning of logging slash

(debris) on a designated unit of land where the fuel has been piled (pile burning), windrowed (windrow burning), or spread freely over the entire area (broadcast burning). Site preparation is undertaken to: (1) increase the success of forest regeneration because logging debris are obstacles for tree planters; and (2) improve the quality of microsites for artificial or natural regeneration. Our main objective was to compare the properties of soils from sites that were subjected to pile burning, and windrow burning treatments. We hypothesized that prescribed fires significantly altered the soil physical, chemical, and mineralogical properties.

2. Materials and methods

2.1. Study area

The study area (Fig. 1) is located ($53^{\circ}34'45''\text{N}$; $123^{\circ}33'30''\text{W}$) in the dry warm Sub-Boreal Spruce (SBSdw3) biogeoclimatic unit (Reynolds, 1989) in the central

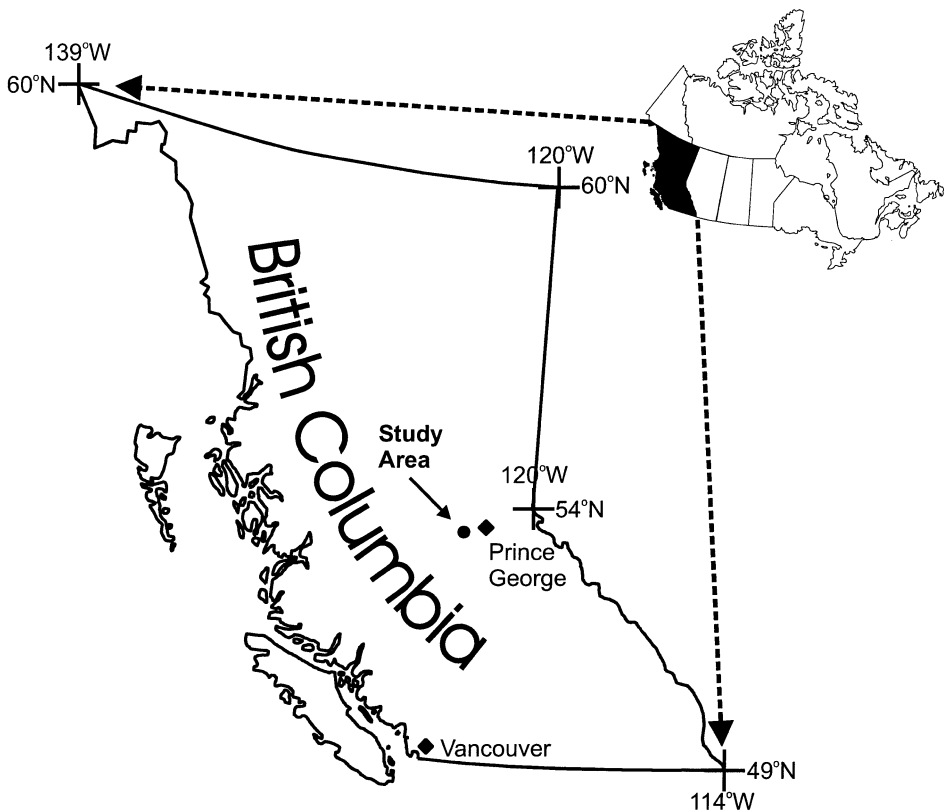


Fig. 1. Location of the study area.

interior of British Columbia, Canada. The landscape is generally rolling, with elevation ranging from 750 to 1100 m asl. Mean annual rainfall ranges from 500 to 800 mm, and mean annual air temperature is 2.6 °C, with a range from 1.3 to 3.5 °C. The mean growing season precipitation is 259.4 mm, and ranges from 224.1 to 298.4 mm. Snowpack is generally <2 m in depth. The soil is Dystric Brunisols developed from loam to fine sandy loam morainal materials containing 10–15% coarse fragment deposited from a mixture of volcanic, sedimentary and metamorphic rocks carried by the east- and westward flowing glaciers between 10 and 20 ka BP (Kodama, 1979). The study area, ~ 45 ha, was clearcut in August 1997 using conventional feller–buncher and grapple skidder technique. In October 1997, about 0.6 ha (1.3%) of the study area was subjected to pile and windrow fires (Canadian Forest Products (CANFOR), 2000) according to the regulation outlined in Forest Practices Code of British Columbia Act (FPC, 1995).

2.2. Experimental design and sample collection

The design consisted of four treatments: Burnt Pile (BP), Control Pile (CP), Burnt Windrow (BW), and Control Windrow (CW). These treatments were replicated three times. The BP and BW plots were selected based on the presence of ash and burnt soils (i.e., reddish color). The size of each BP and CP plot was 6 m in diameter, while that of each BW and CW plot was 6 m wide and 13 m long. The BP and BW plots were randomly selected from the 0.6 ha (1.3%) of the study area that was subjected to pile and windrow fires. Three soil profiles were dug in each plot where composite soil samples were taken from Ae, Bm, and C horizons. The soil profiles were located in each plot as follows: one profile at the centre of the plot, and the other two profiles occupied opposite positions, but of equal distances, from the plot centre. The soil samples were put in plastic bags (identified by treatment type, and soil horizon) and taken to the laboratory for analyses. Thicknesses of the Ae and Bm horizons were measured in each profile. Because we were not able to do any pre-burn measurements (fuel and soil properties) of the study area, the control (unburnt) plots were chosen side by side within 6 m along the burnt plots to minimize inherent variations in soil properties, and thus ensures a robust comparisons between the control and burnt treatments. Soil sample collection was conducted in May 1999.

2.3. Particle size analysis

Particle size analysis was conducted on <2-mm air-dried samples using the pipette method (Kalra and Maynard, 1991). Separation of clay, silt and sand was done after ultrasonic dispersion for 6 min at 400 W. We did not use H₂O₂ pre-treatment to remove organic matter because the soil samples contained <5% organic matter (Kalra and Maynard, 1991). Clays were separated from sand and silt through successive dispersion and gravity sedimentation following the principles of Stoke's Law. Clay samples were then saturated with Ca and K for mineralogical analyses. The sand fraction from each sample was separated from the silt fraction by wet sieving on a 53- μ m sieve.

2.4. Chemical analyses

Chemical analyses were conducted following Kalra and Maynard (1991). Soil pH in 0.01 M CaCl_2 was determined using a 1:2 soil to solution ratio and an electronic pH meter. Total carbon (C) and nitrogen (N) were determined on samples ground to pass a 100-mesh sieve using a Carlo Erba NA1500 Elemental Analyzer (Milan, Italy) where atropine was used for standard calibration. Available nitrogen ($\text{NO}_3^- \text{N} + \text{NH}_4^+ \text{N}$) was extracted using 2.0 M KCl method, where a 1:10 soil to extractant ratio was shaken for 30 min and filtered through WhatmanTM filter paper #42 and the extracts were analyzed for $\text{NO}_3^- \text{N} + \text{NH}_4^+ \text{N}$ using a micro-distillation apparatus. Exchangeable cations and the cation exchange capacity (CEC) were determined using 1 M NH_4OAc buffered at pH 7.0. Exchangeable Ca, K, Mg and Na in NH_4OAc -extract were analyzed using inductively coupled plasma-atomic emission spectroscopy (Kalra and Maynard, 1991). Available phosphorus was estimated using the Bray P1-method (Kalra and Maynard, 1991).

2.5. Mineralogical analysis

Clay mineral identification was conducted on Ca- and K-saturated slides, prepared by the paste method (Theisen and Harward, 1962), by X-ray diffraction (XRD) analysis. Potassium-saturated clays were scanned from 3 to $36^\circ 2\theta$ in the K-0% relative humidity (RH) treatment, and from 3 to $19^\circ 2\theta$ in 54% RH, K-300 and K-550 °C treatments. Calcium-saturated clays were scanned from 3 to $36^\circ 2\theta$ in the Ca-54% RH treatment, and from 3 to $19^\circ 2\theta$ after ethylene glycol (Ca-EG) and glycerol (Ca-Gly) solvations. Kaolinite and chlorite were recognized by the reflections at 0.71 and 1.4 nm, respectively, that were not affected by various RH and solvation treatments. In addition, kaolinite in the presence of chlorite was identified by the doublet reflections at 0.357 and 0.354 nm as suggested by Bradley (cited in Barnhisel and Bertsch, 1989). Mica was identified from the 1.0 nm reflection in all XRD treatments. Low-charge swelling clay (smectite) was recognized by the 1.7 nm reflection from the Ca-Gly and Ca-EG treatments. The presence of high-charge clay (vermiculite) was based on 1.7 nm reflection in Ca-EG treatment and on its absence in Ca-Gly treatment.

X-ray diffraction analysis of the sand fractions was determined on samples back-packed in an aluminum sample holder against a filter paper to minimize preferred orientation. The powder mount was scanned from 3 to $90^\circ 2\theta$ at ambient condition. Identification of the minerals in the sand fraction was based on the following criteria: (1) quartz—0.425, 0.334, 0.245, 0.228 and 0.182 nm reflections, (2) feldspars—0.635, 0.404–0.420, 0.315–0.325 nm reflections, (3) amphiboles—0.833, 0.310–0.312, and 0.270 nm reflections.

2.6. Morphological analysis

We used a Philips XL30 scanning electron microscope equipped with energy dispersive analyzer (SEM–EDS) to determine the effects of thermal shock (heating) from fires on soil morphological properties, specifically on aggregates and sand fraction. Random samples of sand and sand-sized aggregates from all treatments were mounted on aluminum stubs and sputter-coated with gold for 60 s prior to SEM–EDS analysis.

2.7. Statistical analysis

We used non-parametric (SAS NPARIWAY procedure) Kruskal–Wallis test for equality of treatments and for equality of true means (SAS, 1996) for two reasons. First, normality and homoscedasticity were not achieved even after data transformations. Second, the efficiency of non-parametric methods relative to parametric ones is quite high for small samples, with a number of observations < 10 (Steel and Torrie, 1980). Differences in treatment means were compared at $p=0.05$ and post hoc comparison of significantly different means was made using planned Least Square Difference test statistics.

3. Results

Visual examination of exposed soils under pile and windrow burnt areas revealed the following characteristics: completely consumed duff layer and exposed grayish brown (10YR 5/2 d) mineral soil. These characteristics occur due to intense soil heating from high fire severity, with soil temperatures, at 1 cm below the duff layer, $>250^{\circ}\text{C}$ (DeBano et al., 1998).

3.1. Chemical and physical properties

Non-parametric (SAS NPARIWAY) results based on the general analysis of the treatments only, not the soil horizons, revealed that the two controls (CP and CW) were not significantly ($p>0.05$) different in soil properties. However, we found that burnt pile (BP) was significantly different from its control (CP), burnt windrow (BW) was significantly different from its control (CW), and BP was significantly different from BW. Thus, we pooled the data of the two controls (CPW) in one data set, and then compared the treatments BP, BW and CPW in similar soil horizons.

Table 1 shows the means of the selected physical and chemical properties of soils collected from BP, BW and CPW plots. Mean thickness in Ae horizons in the BP plots was significantly thinner than in the BW plots. Mean pH in the horizon Ae in the BP plots was significantly higher than in the CPW. In Bm horizons, mean pH was significantly higher (as much as 2 pH units) in BP plots and BW plots, as compared to the CPW plots. For almost all soil horizons, there were no significant differences in particle size analyses, and in total C and N concentrations. Mean C/N ratio of the horizon Bm in the BP was significantly lower than in the CPW plots. Available P concentrations were not affected by prescribed burning and ranged from 2 to 6 mg kg⁻¹ with the highest concentration in the Bm horizons. Available N in the C horizon in the BP plots was significantly higher than in the BW and CPW plots. Cation exchange capacity in all horizons was not affected by prescribed burning. Exchangeable Na, Mg, K, and Ca concentrations in the Ae and Bm horizons in the BP plots were significantly higher than in CPW plots (and the BW plots in some cases). Mean base saturation in Ae and Bm horizons was significantly higher in BP plots than in BW and CPW plots.

Table 1

Means (and standard deviations) of selected physical and chemical properties of soils collected from burnt pile, burnt windrow and control plots

Sample	Thickness (cm)	pH	Sand (%)	Silt (%)	Clay (%)	Total N (%)	Total C (%)	C/N ratio	Bray 1-P (mg kg ⁻¹)	Avail N (mg kg ⁻¹)	CEC (cmol _c /kg)	Na (cmol _c /kg)	Mg (cmol _c /kg)	K (cmol _c /kg)	Ca (cmol _c /kg)	Base saturation (%)
<i>Burnt pile (BP) (n = 3)</i>																
Ae	1.33b (0.58)	5.22a (1.10)	52.52 (5.00)	41.43 (5.00)	6.05 (1.00)	0.08 (0.50)	1.50 (0.08)	18.17 (2.00)	2.91 (1.29)	19.53 (7.00)	6.93 (0.83)	0.10 (0.03)	2.98a (2.49)	0.76a (0.50)	4.79a (0.87)	100a (65)
Bm	6.00a (2.00)	6.23a (0.50)	51.33 (3.00)	42.33 (5.00)	6.35 (2.00)	0.08 (0.01)	1.17b (0.27)	15.31b (5.00)	4.56 (0.50)	35.25 (20.90)	8.74 (3.39)	0.13a (0.02)	3.30a (2.13)	1.39a (0.23)	4.24a (1.36)	100a (10)
C	nd	5.40a (1.00)	55.68 (3.00)	37.77 (2.00)	6.54 (2.00)	0.05 (0.03)	0.84 (0.54)	15.74 (2.00)	2.59 (3.02)	12.83a (1.98)	8.27 (2.80)	0.11a (0.02)	1.47 (0.90)	0.30 (0.13)	3.72 (1.61)	66 (15)
<i>Burnt windrow (BW) (n = 3)</i>																
Ae	3.67a (0.58)	4.93a (0.20)	55.16 (4.00)	39.29 (3.00)	5.55 (1.00)	0.07 (0.02)	1.23 (0.32)	17.83 (2.00)	4.04 (0.99)	31.68 (35.70)	6.33 (1.18)	0.13 (0.07)	1.40ab (0.94)	0.78ab (0.49)	2.93b (0.44)	82a (9)
Bm	8.33a (0.58)	4.50b (0.50)	56.11 (7.00)	37.51 (5.00)	6.38 (2.00)	0.07 (0.03)	1.39ab (0.45)	19.19b (1.00)	5.41 (1.12)	18.59 (15.80)	6.40 (1.07)	0.10a (0.02)	0.59b (0.41)	0.87ab (0.86)	1.74b (0.82)	49b (23)
C	nd	5.40a (0.50)	60.93 (5.00)	34.13 (4.00)	4.94 (1.00)	0.04 (0.02)	0.61 (0.31)	14.64 (2.00)	2.21 (1.88)	6.36b (4.70)	5.72 (1.07)	0.10ab (0.03)	0.83 (0.19)	0.33 (0.27)	2.71 (0.67)	69 (12)
<i>Control pile and windrow (CPW) (n = 6)</i>																
Ae	2.17ab (1.17)	3.48b (0.20)	51.17 (2.00)	43.17 (3.00)	5.66 (1.00)	0.08 (0.01)	1.48 (0.25)	19.58 (3.00)	2.50 (1.37)	17.51 (14.00)	6.77 (1.12)	0.06 (0.02)	0.75b (0.22)	0.32b (0.07)	2.91b (1.11)	59b (14)
Bm	7.17a (2.14)	3.91c (0.20)	54.38 (2.00)	38.20 (2.00)	7.42 (3.00)	0.09 (0.03)	2.03a (0.59)	22.35a (3.00)	6.30 (1.21)	13.88 (10.50)	7.86 (1.34)	0.04b (0.01)	0.52b (0.14)	0.35b (0.12)	2.05ab (0.81)	37b (8)
C	nd	4.82a (0.40)	58.76 (7.00)	35.90 (6.00)	5.34 (1.00)	0.04 (0.01)	0.63 (0.27)	16.19 (2.00)	2.04 (1.66)	3.75b (1.90)	6.43 (1.99)	0.08b (0.02)	0.83 (0.15)	0.22 (0.05)	2.65 (0.48)	61a (13)

n = Number of observations.For each column and similar soil horizon, means followed by different letters are significantly different ($p < 0.05$). nd = Not determined.

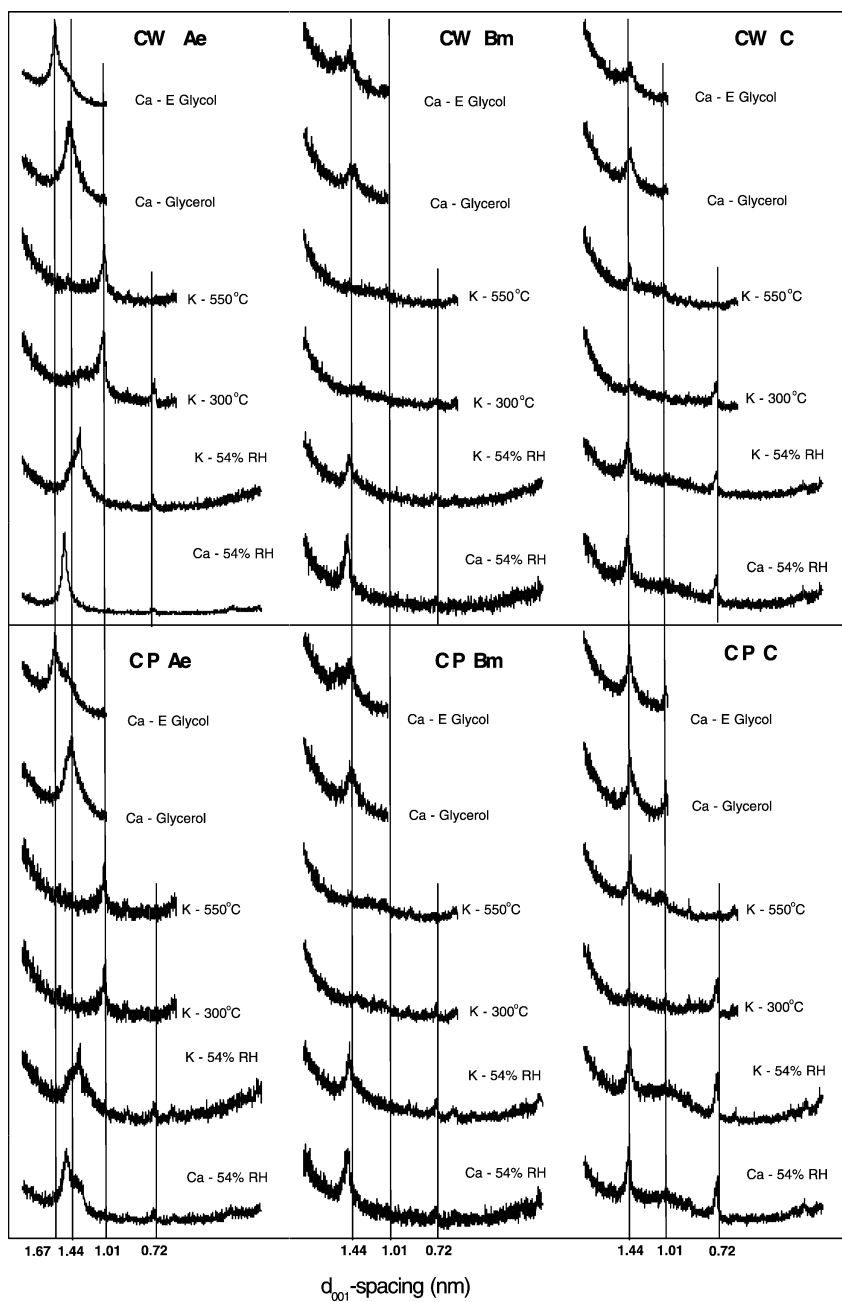


Fig. 2. X-ray diffraction patterns for the clay fractions of various soil horizons collected from control treatments (CW and CP). Only representative samples from different replicates are illustrated. Treatment designations refer to various K and Ca saturation, ethylene glycol (EG) and glycerol (Gly) solvations, heat treatment and relative humidity (RH).

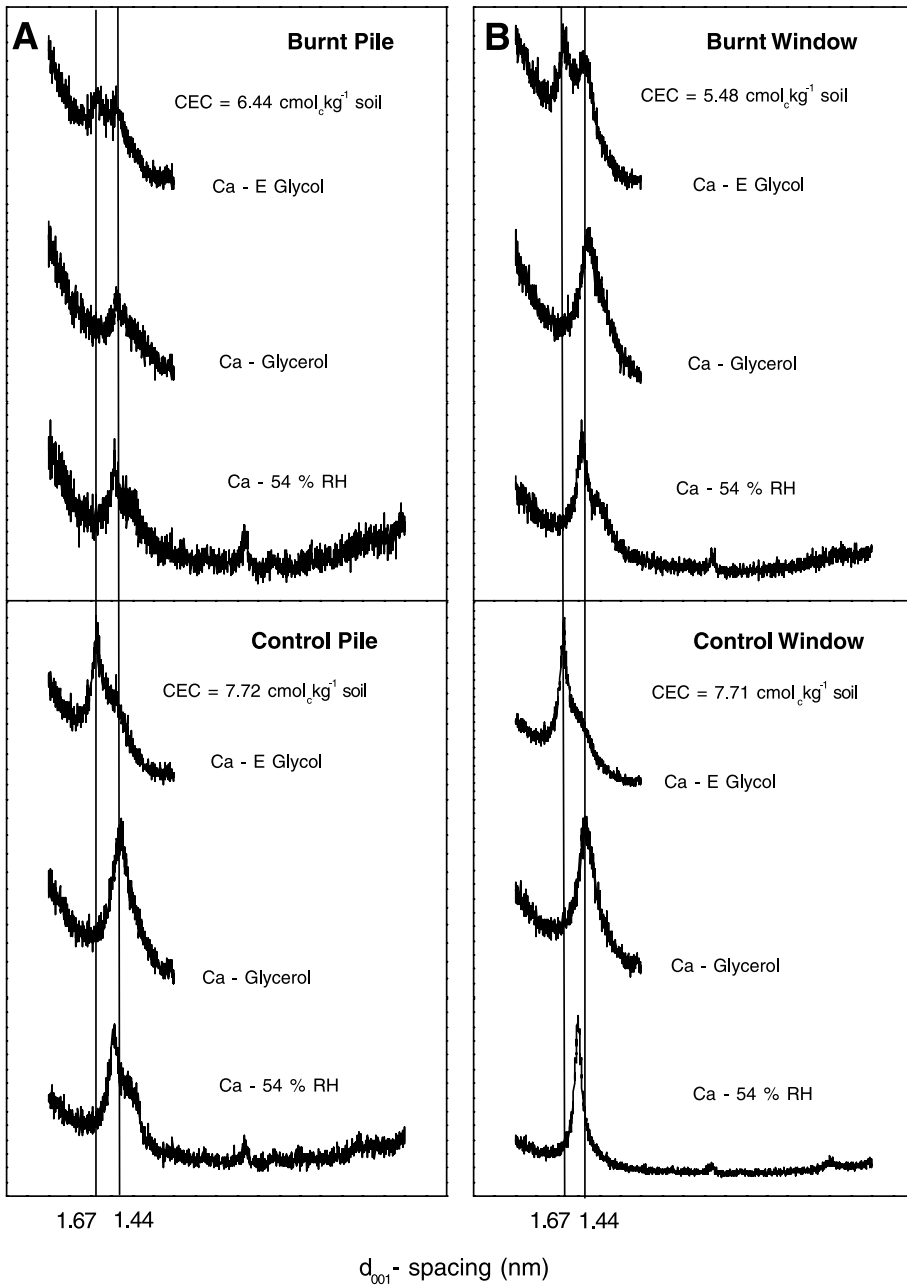


Fig. 3. X-ray diffraction patterns for the clay fractions from Ae horizons collected from (A) BP—Burnt Pile and CP—Control Pile, and (B) BW—Burnt Windrow and CW—Control Windrow treatments. Only representative samples from different replicates are illustrated. Treatment designations refer to various K and Ca saturation, ethylene glycol (EG) and glycerol (Gly) solvations, and relative humidity (RH).

3.2. Mineralogical properties

The clay fractions in CP and CW plots consist of chlorite ((Mg₅Al)(Si₃Al)O₁₀(OH)₈), mica (KSi₃Al₃O₁₀(OH)₂), 2:1 expanding clays, kaolinite (Al₂Si₂O₅(OH)₄) and possibly fine-grained quartz (SiO₂) as indicated by the X-ray diffraction patterns (Fig. 2). The presence of X-ray reflection at 0.50 nm indicated that muscovite (a dioctahedral mica) is the main species of micaceous mineral in the study area. In Ae and Bm horizons, the presence of 2:1 expanding clay is shown by the presence of X-ray reflection at 1.67 nm in Ca-EG treatment but not in Ca-Gly treatment (Fig. 2). This high-charged 2:1 clays could be low-charged vermiculite ((MgFe)₃(Al_xSi_{4-x})O₁₀(OH)₂·4H₂O Mg_x with $x = 0.6$ to 1.5) or high-charged smectite such as beidellite (Ca_{0.25}(Si_{3.5}Al_{0.5}Al₂)O₁₀(OH)₂) or nontronite ((Ca_{0.25}(Si_{3.5}Al_{0.5}Fe₂)O₁₀(OH)₂).

The effects of heating from prescribed fires on soil clays are shown in Fig. 3. First, the intensity of the X-ray reflection at 1.67 nm (Ca-EG) with respect to 1.44 nm reflection decreased significantly in BP and BW plots when compared to CP and CW plots (Fig. 3). Moreover, the decrease in the intensity of 1.67 nm reflection was more pronounced in the

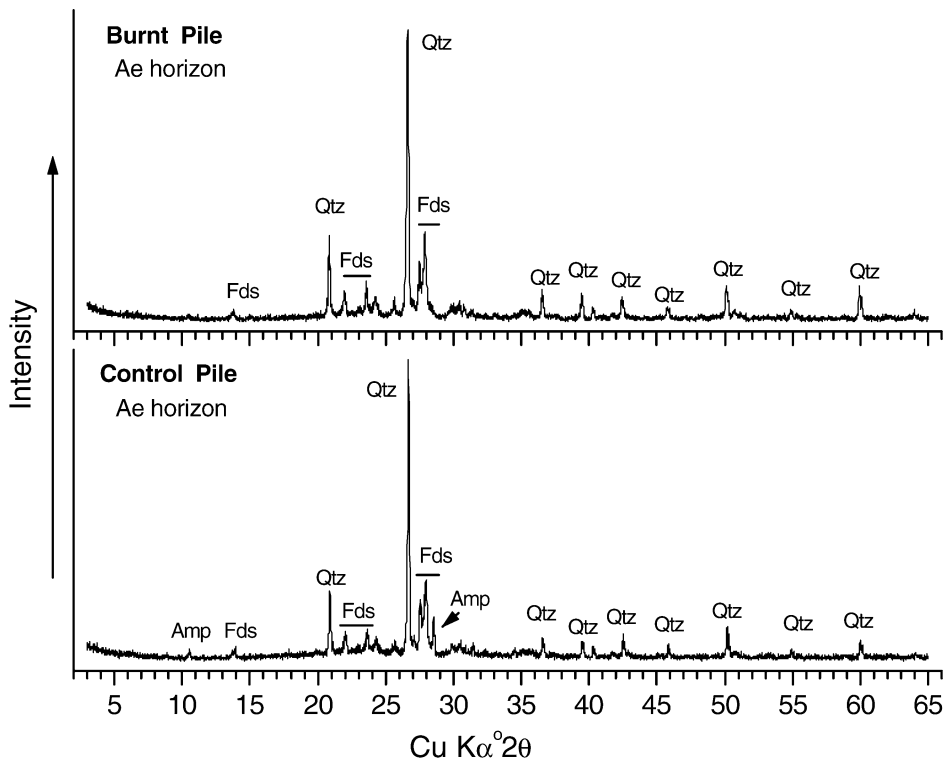


Fig. 4. X-ray diffraction patterns for the sand fraction of Ae horizons from Burnt Pile and Control Pile treatments. Only representative samples from different replicates are illustrated. Qtz—quartz, Fds—feldspars, Amp—amphiboles.

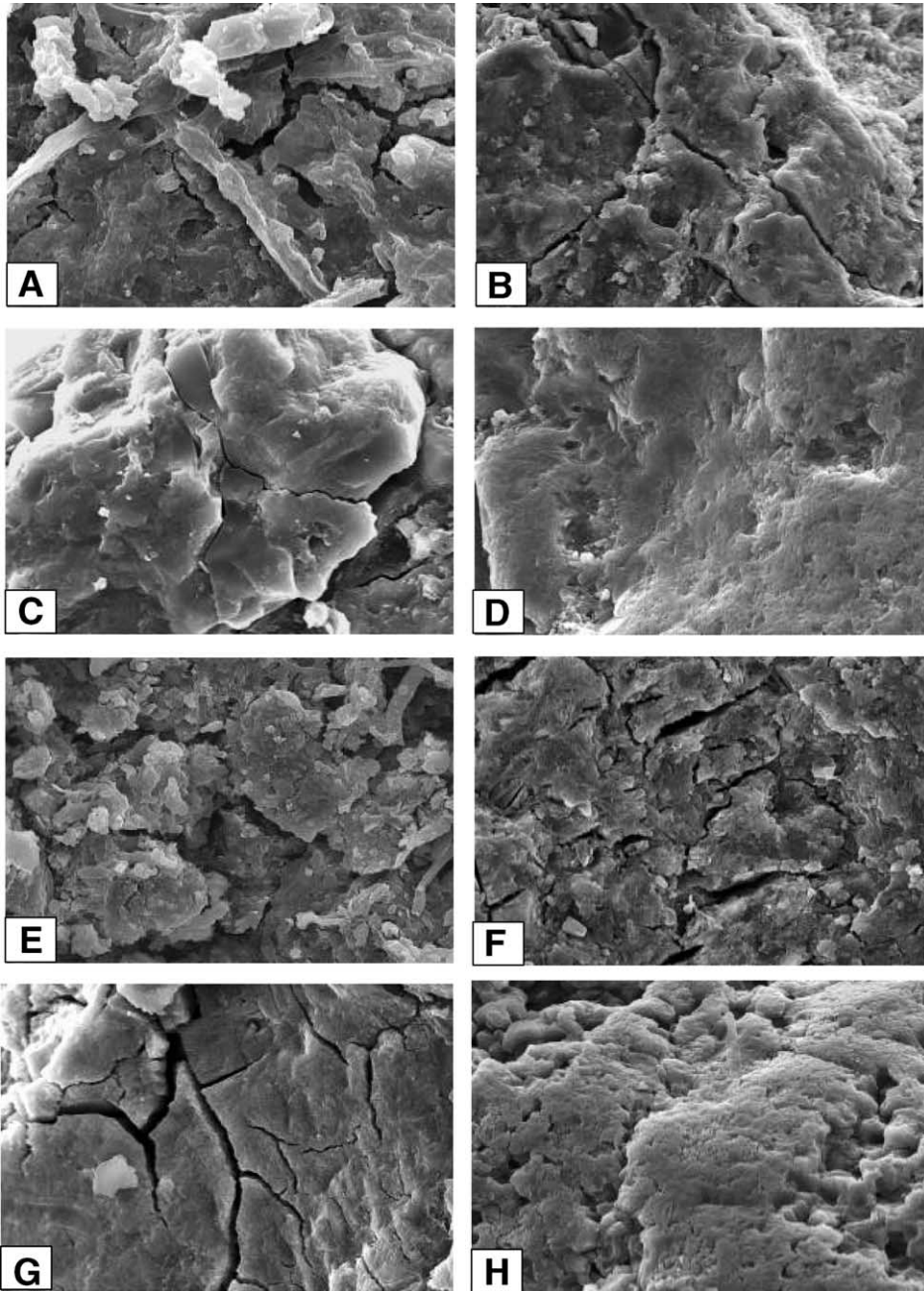


Fig. 5. Scanning electron micrographs of soil aggregates and sand fractions. (A) Soil aggregate, Burnt Pile, Frame Length (FL)=40 µm; (B) feldspars grain, Burnt Pile, FL=86 µm; (C) feldspars grain, Burnt Pile, FL=48 µm; (D) feldspar grain, Control Pile, FL=64 µm; (E) soil aggregate, Burnt Windrow, FL=63 µm; (F) feldspar grain, Burnt Windrow, FL=64 µm; (G) Iron oxide, Burnt Windrow, FL=64 µm, (H) feldspar grain, Control Windrow, FL=64 µm.

Ae horizon compared to the Bm horizon. The decrease in the intensity of the 1.67 nm reflection is accompanied by CEC reduction from 7.72 in CP to 6.44 cmol_c kg⁻¹ soil in BP, and from 7.71 in CW to 5.48 cmol_c kg⁻¹ in BW (Fig. 2).

The sand fraction of the Ae, Bm and C horizons of the study area is dominated by quartz, feldspars such as albite (NaAl₃Si₃O₈) with minor amount of amphiboles such as hornblende (Ca₂Na(MgFe)₄(Al,Si)₈(OH,F)₂) (Fig. 4). The effect of heat from prescribed burns is shown by the decreased/disappearance of the X-ray reflections at 0.833 and 0.312 nm regions (Fig. 4). Morphologically, the results of our SEM–EDS observations show the presence of cracks on soil aggregates in BP and BW (Fig. 5A); while Fig. 5D and H show the intact aggregates from CP CW plots. Fig. 5B, C, and F illustrate the cracks that we observed on sand-sized minerals in BP and BW plots. Iron oxides also exhibit crack in BW plots (Fig. 5G).

4. Discussion and implications

Our study showed higher soil pH, and availability of K, Ca, Na and Mg in Ae, Bm and C horizons of BP and BW compared to CPW plots. In most cases, higher concentrations of exchangeable cations were observed in soils under BP compared to soils under BW. These apparent differences between pile and windrow fires could be due to the differences in fuel load prior to the burn and the severity of the burn. These factors determine depth of burn, quantity of ash, and the amount of Mg, K, and Ca in the exchange complex of soils (Grier, 1975). The concentration of logging slash into a pile (which has a higher fuel load and occupies a smaller surface area than a windrowed logging slash) results into more severe burning, increased fuel consumption and pH, and generally higher concentrations of exchangeable cations than windrow burning. Our findings are consistent with the effects of pile and windrow burning on soil chemical properties reported in similar studies (Lindeburg, 1990). Calcium, magnesium, and sodium are rendered soluble (Wells et al., 1979) and major components of ash (DeByle, 1976; Feller, 1982; Agee, 1993; DeBano et al., 1998). The high Ca, Mg, and K contents of ash, over time, can increase the pH of the soil by displacing the H and Al ions adsorbed on the negative charge of the soil colloids. The increase in pH is probably one of the most beneficial effects of prescribed burning because it influences the availability of most essential nutrients (Ahlgren and Ahlgren, 1960; Wells et al., 1979) especially in soils of low pH. In high pH soils, burned soils had pH >8 for more than 3 years after fire; promoting clay illuviation and mineral weathering (Ulery et al., 1993).

In general, similar studies indicated that quick combustion of organic matter during pile and windrow burning resulted in nutrient (especially nitrogen) losses through volatilization (Minroe, 1986; Friend, 1989; Harvey et al., 1979; Ballard and Hawkes, 1989). Although losses in nitrogen caused by fire are not immediately replaceable by natural sources, from precipitation and free-living nitrogen fixation (Binkley, 1991), our results showed no significant differences in the total and available N in the Ae and Bm horizons. This may indicate that loss of N during prescribed burning was confined mainly in the forest floor. The other possibility may be that, although overall there were losses of total N, some atmospheric N deposition might have compensated for the losses. In a related study in the

sub-boreal forest, Driscoll et al. (1999) showed that a period of less than 4 years is long enough to restore the level of N in burnt areas (wildfire) to pre-fire levels in the mineral horizons. However, De Luca and Zouhar (2000) indicated that the effect of prescribed fire on extractable NH_4^+ and NO_3^- was not observable 2 years after the treatment and Choromanska and DeLuca (2001) found that after 9 months, NO_3^- concentration in Ponderosa pine soils subjected to prescribed burns was not significantly different from unburned site.

Another significant effect of prescribed fires on soil properties is on soil minerals. The reduction in the intensity of 1.67 nm reflection in Ca-EG treated samples indicate a reduction in the amount of 2:1 expanding type of clay. This is in agreement with the observed reduction in CEC because clay fraction is one of the major sources of negative charges in soils. The reduction in the amount of high-charged 2:1 clays might be related to the irreversible dehydration of K-saturated vermiculite (Douglas, 1986). Our results were consistent with Ulery et al. (1996) who reported the dehydroxilation of vermiculite in California soils. However, kaolinite in our study area was not decomposed by the prescribed fire as reported by Ulery et al. (1996). This could mean that the temperature in the mineral horizon in the study plots did not exceed 550 °C, where the structure of kaolinite would be completely destroyed and most 2:1 clays would be irreversibly transformed into non-expanding clays (Douglas, 1986). Clays lose OH H_2O at temperature >300 °C but temperature >850 °C results to the formation of anhydrous minerals (Neary et al., 1999; Giovanni et al., 1988; Borchardt, 1986). In sand fraction, the cracks often observed in feldspars grains and other soil aggregates may be the results of thermal shock associated with heat from prescribed fires because of their characteristic pattern of crack propagation orthogonal to each other. Royer-Carfagni (1999) presented a theoretical explanation of the stresses related to the development of cracks in marble subjected to temperature fluctuations. The disappearance of X-ray reflections at 0.833 and 0.312 nm regions indicate the removal of amphibole in the sand fraction. This disappearance could be due to the reduction of its particle size into silt or smaller sizes resulting from the physical breakdown initiated by the thermal shock due to heating from prescribed fires. This phenomenon increases the surface area and might accelerate the breakdown and the release of essential elements from those amphiboles. Hornblende and feldspars could follow a similar fate following induced heating wherein enhanced release of Ca, Mg, Na, Fe might result from physical fragmentation.

4.1. Implications

While short-term benefits of prescribed fires such as increased levels in pH and available nutrients are ideal, there are concerns about long-term loss in nutrients and impaired site productivity (Tiedemann et al., 2000). For instance, the reduction in CEC and the generation of thermal cracks in feldspars and other soil aggregates could accelerate weathering due to increased surface area and may result to loss of K, Ca and Mg through leaching. Our results suggest that fire severity during pile and windrow fires must be closely monitored to prevent irreversible breakdown of soil minerals because of their influence on chemical and physical processes (Ulery et al.,

1996) and site productivity. To accomplish this, fuel load and moisture content should be monitored. In addition, we suggest that future studies should investigate the changes in the nature of organic acids present in soil solution resulting from prescribed burns because of their significant implications to the weathering rates of soil minerals.

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References

- Agee, J.K., 1993. Environmental effects of fire. *Fire Ecology of Pacific Northwest Forests*. Island Press, Washington, DC, pp. 151–475.
- Ahlgren, I.F., Ahlgren, C.E., 1960. Ecological effects of forest fires. *Bot. Rev.* 26, 483–533.
- Ballard, T.M., Hawkes, B.C., 1989. Effects of Burning and Site Preparation on Growth and Nutrition of Planted White Spruce. Forestry Canada, Pacific and Yukon Region, Victoria, BC BC-X-309.
- Barnhisel, R.I., Bertsch, P.M., 1989. Chlorite and hydroxy interlayered vermiculite and smectite. In: Dixon, J.B., Weed, S.B. (Eds.), *Minerals in Soil Environments*, 2nd ed. SSSA Book Series, vol. 2, Madison, USA, pp. 729–788.
- Binkley, D., 1991. Connecting soils with forest productivity. In: Harvey, A.E., Neuenschwander, L.F. (Eds.), *Proceedings—Management and Productivity of Western-Montane Forest Soils*. Boise, Idaho, April 10–12, 1990. General Technical Report INT-280. USDA Forest Service Intermountain Research Station. Ogden, UT, pp. 66–69.
- Borchardt, G., 1986. Smectites. In: Dixon, J.B., Weed, S.B. (Eds.), *Minerals in Soil Environments*, 2nd ed. SSSA Book Series, vol. 2, pp. 675–727. Madison, USA.
- Brais, S., Camiré, C., Paré, D., 1995. Impacts of whole-tree harvesting and winter windrowing on soil pH and base status of clayey sites of northwestern Quebec. *Can. J. For. Res.* 25, 997–1007.
- Canadian Forest Products (CANFOR) 2000. Silviculture prescription for Little Bobtail operating area, Vanderhoof District. Amendment, Permit 434, Block 172.
- Choromanska, U., DeLuca, T.H., 2001. Prescribed fire alters the impact of wildfire on soil biochemical properties in a Ponderosa pine forest. *Soil Sci. Soc. Am. J.* 65, 232–238.
- Cromack Jr., K., Sollins, P., Graustein, W.C., Speidel, K., Todd, A.W., Spycher, G., Li, C.Y., Todd, R.L., 1979. Calcium oxalate accumulation and soil weathering in mats of the hypogeous fungus *Hysterangium crassum*. *Soil Biol. Biochem.* 11, 463–468.
- DeBano, L.F., Neary, D.G., Ffolliott, P.F., 1998. *Fire's Effects on Ecosystems*. Wiley, New York.
- DeByle, N.V., 1976. Fire, logging and debris disposal effects on soil and water in northern coniferous forests. In 1976 Proc. XVI IUFRO World Congr., International Union of Forest Research Organizations Div. 1 Oslo, Norway. College of Life Sciences and Agriculture, Orono, Maine, pp. 201–212.
- De Luca, T.H., Zouhar, K.L., 2000. Effects of selection harvest and prescribed fire on the soil nitrogen status of Ponderosa pine forests. *For. Ecol. Manag.* 138, 263–271.

- Douglas, L.A., 1986. Vermiculites. In: Dixon, J.B., Weed, S.B. (Eds.), *Minerals in Soil Environments*, 2nd ed. SSSA Book Series, vol. 2, pp. 635–674. Madison, USA.
- Driscoll, K.G., Arocena, J.M., Massicotte, H.B., 1999. Post fire nitrogen contents and vegetation composition in sub-boreal forests on British Columbia's central interior. *For. Ecol. Manag.* 121, 225–236.
- Evangelou, V.P., Karathanis, A.D., Blevins, R.L., 1986. Effect of soil organic matter accumulation on potassium and ammonium quantity–intensity relationships. *Soil Sci. Am. J.* 50, 378–382.
- Feller, M.C., 1982. The ecological effects of slash burning with particular reference to British Columbia: a literature review. Land Management Report No. 13. Province of British Columbia Ministry of Forests.
- Forest Practices Code of British Columbia Act (FPC), 1995. Forest Fire Prevention and Suppression Regulation. Ministry of Forests Victoria, BC.
- Friend, A.L., 1989. Differences in Nutrient Distribution Between Adjacent Cut and Uncut East-Slope Cascade Forest Stands Suggest Nutrient Losses. Forestry Sciences Laboratory, PNW Research Station, Wenatchee, WA.
- Giovanni, G., Luchessi, S., Giachetti, M., 1988. Effects of heating on some physical and chemical parameters related to soil aggregation and erodibility. *Soil Sci.* 146, 255–262.
- Gozs, J.R., Likens, G.E., Bormann, F.H., 1976. Organic matter and nutrient dynamics of the forest and forest floor in the Hubbard Brook Forest. *Oecologia (Berl.)* 22, 305–320.
- Grier, C.E., 1975. Wildfire effects on nutrient distribution and leaching in a coniferous ecosystem. *Can. J. For. Res.* 5, 599–607.
- Harvey, A.E., Jurgensen, M.F., Larsen, M.J., 1979. Role of forest fuels in the biology and management of soil. USDA Forest Service, General Technical Report INT-65, Intermountain Forest and Range Experimental Station, Ogden, UT.
- Hawkes, B.C., Feller, M.C., Meehan, D., 1990. Site preparation: fire. In: Lavender, D.P., Parish, R., Johnson, C.M., Montgomery, G., Vyse, A., Willis, R.A., Winston, D. (Eds.), *Regenerating British Columbia's Forests*. UBC Press, Vancouver, BC, pp. 131–149.
- Kalra, P., Maynard, D.G., 1991. *Methods Manual for Forest Soil and Plant Analysis*. Information Report. NOR-X-319 Forestry Canada, Edmonton, AB.
- Kodama, H., 1979. Clay minerals in Canadian soils: their origin, distribution and alteration. *Can. J. Soil Sci.* 59, 37–58.
- Lapeyrie, F., 1988. Oxalate synthesis from soil bicarbonate by the mycorrhizal fungus *Paxillus involutus*. *Plant Soil* 110, 3–8.
- Lindeburg, S.B., 1990. Effects of prescribed fire on site productivity: a literature review. Land Management Report, vol. 66. Province of British Columbia Ministry of Forests, Victoria. ISSN 0702-9861.
- Macadam, A., 1989. Effects of prescribed fire on forest soils. BC Ministry of Forests Research Report 89001-PR, Victoria.
- Merrill, D.F., Alexander, M.E., 1987. *Glossary of Forest Fire Management Terms*. National Research Council of Canada, Ottawa.
- Minroe, D., 1986. Effects of site preparation on seedling growth: a preliminary comparison of broadcast burning and pile burning. USDA For. Ser. Res. Note PNW-RN-452.
- Morris, L.A., Pritchett, W.L., Swindel, B.F., 1983. Displacement of nutrients into windrows during site preparation of a flatwood forest. *Soil. Sci. Soc. Am. J.* 47, 591–594.
- Neary, D.G., Klopatek, C.C., DeBano, L.F., Ffolliott, P.F., 1999. Fire effects on belowground sustainability: a review and synthesis. *For. Ecol. Manag.* 122, 51–71.
- Reynolds, G., 1989. Climatic Data Summaries for the Biogeoclimatic Zones of British Columbia. Province of British Columbia Ministry of Forests, Research Branch, Victoria.
- Robichaud, P.R., 2000. Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA. *J. Hydrol.* 231, 220–229.
- Royer-Carfagni, G.F., 1999. On the thermal degradation of marble. *Int. J. Rock Mech. Min. Sci.* 36, 119–126.
- SAS, 1996. *SAS for Windows*, Release 6.12, Copyright© SAS Institute, Cary, NC, USA, 1989–1996.
- Steel, R.G.D., Torrie, J.H., 1980. *Principles and Procedures of Statistics: A Biometrical Approach*, 2nd ed. McGraw-Hill, New York.
- Theisen, A.A., Harward, M.E., 1962. A paste method for preparation of slides for clay mineral identification by X-ray diffraction. *Proc.-Soil Sci. Soc. Am.* 26, 90–91.

- Tiedemann, A.R., Klemmedson, J.O., Bull, E.L., 2000. Solution of forest health problems with prescribed fire: are forest productivity and wildlife at risk? *For. Ecol. Manag.* 127, 1–18.
- Ulery, A.L., Graham, R.C., Amrhein, C., 1993. Wood-ash composition and soil pH following intense burning. *Soil Sci.* 156, 358–364.
- Ulery, A.L., Graham, R.C., Bowen, L.H., 1996. Forest fire effects on phyllosilicates. *Soil Sci. Soc. Am. J.* 60, 309–315.
- Wells, C.G., Campbell, R.E., DeBano, L.F., Lewis, C.E., Fedriksen, R.L., Franklin, E.C., Froelich, R.C., Dunn, P.H., 1979. Effects of fire on soil: a state-of-knowledge review. USDA Forest Service General Technical Report WO-7. Washington, DC.