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Impacts of wild fire severity and salvage harvesting on the nutrient balance of jack pine and black spruce boreal stands

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Abstract

In August of 1995, wildfires burnt over 50 000 ha of boreal forest in northwestern Quebec. A balance sheet approach was used in order to assess the long term effects of fire and subsequent salvage harvesting operations on nutrient site capital. Following a validation of burn severity indices and maps, we conducted an evaluation of soil nutrient pools in (1) lightly to moderately, (2) severely burned, and (3) unburned stands with similar biophysical characteristics. Above-ground biomass values for unburned stands, precipitation and N biological fixation inputs were drawn from the literature. Weathering rates were drawn from previous work and estimated with the PROFILE model.

Fire significantly reduced forest floor dry weight by 41% in the light/moderate class and by 60% in the severe class while forest floor total Ca concentrations increased following both types of burn. Forest floor exchangeable Ca and total Mg concentrations increased following a light/moderate burn. Fire increased exchangeable K concentrations in the 0–10 cm mineral layer but had no other effects on mineral soil concentrations or characteristics. Forest floor nutrient content was significantly reduced on severely burned areas only. Kjeldahl N content was reduced by 44%, exchangeable Mg by 53% and exchangeable K and total K by 60 and 51%, respectively. Reduction of K soil content was important enough that inputs through weathering and precipitation would take 278 years to compensate for soil losses following a severe fire. The projected effects of salvage harvesting on severely burned sites indicated that Ca, Mg and K would not return to their pre-burn level in the course of a 110-year rotation. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Wildfires; Jack pine; Black spruce; Boreal soils; Site fertility; Nutrient depletion

1. Introduction

In August 1995, wildfires burned over 50 000 ha of boreal forest in northwestern Quebec. The severity of these fires, combined with salvage harvesting operations that followed, gave rise to questions concerning their mutual effects on long-term soil fertility. Effects of fire on soils and nutrient cycling have been reviewed extensively (Ahlgren and Ahlgren, 1960; Raison, 1979; Wells et al., 1979; MacLean et al., 1983). They include losses of N through volatilization during fire (DeBell and Ralston, 1970), transfer of ammonium from the forest floor to the mineral soil (Covington and Sackett, 1992) and changes in mineralization kinetics (Prieto-Fernandez

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et al., 1993). Exchangeable base cation concentrations of surface soil increase due to ash deposition with a concomitant increase in pH and nutrient losses through leaching (Smith, 1970; Grier, 1975; Bayley et al., 1992; Williams and Melack, 1997), while consumption of the forest floor may lead to a decrease in soil nutrient reserves (Groeschl et al., 1993).

Due to site and landscape heterogeneity following wildfires, inferences of these effects are limited to any particular situation. At the site level, vegetation, microrelief, fuel distribution and moisture concur to maintain or increase soil heterogeneity after fire (Rowe and Scotter, 1973; Raison, 1979), while natural fire barriers, duff moisture and prevailing winds will affect fire severity (*sensu* Viereck and Schandelmeier, 1980) across the landscape (van Wagner, 1972; Rowe and Scotter, 1973; Johnson, 1992). Decrease of N ecosystem reserves as well as changes in mineral nutrient concentrations are proportional to the amount and type of fuels burned (Knight, 1966; Dyrness et al., 1989); leaching of base cations in the years following fire will depend on the amount of sulfate produced by the combustion and the biological oxidation of organic matter (Bayley et al., 1992). Independent of fire severity, soil chemical properties will determine the magnitude of changes a soil will undergo following fire (Viro, 1969; Wells et al., 1979).

In boreal coniferous ecosystems, a large proportion of site nutrient capital is contained in the forest floor (Weetman and Webber, 1972; Foster and Morrison, 1976; Weetman and Algar, 1983). Despite large nitrogen pools, these ecosystems are generally N limited as indicated by fertilization trials (Krause et al., 1982). Decomposition of soil organic matter is slow due to its poor quality in terms of base saturation and of N and lignin concentrations (Flanagan and Van Cleve, 1983). Accumulation of organic matter and net nitrogen immobilization commonly occur in the course of succession (Van Cleve and Viereck, 1981; Paré et al., 1993). Hence, the effects of fire, as a disturbance agent, are seen as positive (Tamm, 1991), as fire itself and conditions prevailing afterwards favor higher rates of nutrient cycling.

Our hypotheses were that (1) fire would significantly reduce nutrient pools in severely burned stands and would have little impact on moderately or lightly burned sites, (2) nitrogen would be the nutrient most affected by fire and (3) fire combined with salvage harvesting would severely reduce nutrient pools on all sites. This paper (1) reports on the validity of using a fire severity map based on forest cover combustion as a tool for assessment of impacts on site fertility, (2) reports on soil nutrient concentrations and contents one year after burns of different severity and (3) presents a preliminary balance sheet for jack pine and black spruce stands that were burned and harvested immediately after fire.

2. Study area

The study area lies between 48°45′ and 49°N, and between 76°45′ and 77°45′W. The region is part of the Cambrian shield and bedrock is mostly orthogneiss and granitic rocks (Hocq and Verpaelst, 1994). The topography is that of a flat plateau. Most of the bedrock is covered with Quaternary deposits such as till and glaciofluvial sand and gravely sand. Some coarse textured glaciolacustrine deposits are also present. Podzols (Spodosols) are the dominant soils on upland sites. The climate is continental with a mean annual temperature of 0.8–1.2°C and precipitation of 840–950 mm, falling mainly as rain (Environment Canada, 1982). The region belongs to the Gouin forest section (B.3) of the Boreal forest region of Rowe (1972). Stands of jack pine (*Pinus banksiana* Lamb.) and black spruce (*Picea mariana* (Mill.) B.S.P.) are the most abundant on coarse textured soils; while mixed stands of aspen (*Populus tremuloides* Michx), white birch (*Betula papyrifera* Marsh.), white spruce (*Picea glauca* (Moench) Voss) and balsam fir (*Abies balsamea* (L.) Mill.) can be found on upland till soils (Rowe, 1972). The extent of the study was restricted to stands formerly dominated by softwood species growing on upland (mesic) sites. Soil parent material information was provided by the Quebec Ministry of Natural Resources (MNRQ) 1:50 000 Quaternary deposit maps (Bergeron et al., 1992). Sampled soils included soil developed on shallow and deep till, on glaciofluvial sand and gravely sand and on glaciolacustrine sand. Shallow soils on upper slopes, very moist soils with a ground cover of *Sphagnum* spp. and organic soils were not included.

3. Methodology

3.1. Validation of fire severity map

Using aerial photography, fire severity was assessed immediately after fire from the state of residual forest cover. Three broad classes were retained and mapped by the MNRQ: (1) Severe: all vegetation was charred; (2) Moderate: understory and canopy leaves and twigs were singed; (3) Light: leaves and twigs were partly singed but most of the vegetation remained intact. Stands that were harvested prior to the fire were not assigned a severity class for lack of forest cover. These stands were nonetheless part of the sampling if they met our soil and pre-disturbance forest cover criteria (according to MRNQ forest cover maps). In order to validate this fire severity map as a diagnostic tool for soil fertility, correspondence between forest cover damages, forest floor combustion and soil characteristics had to be assessed.

In order to achieve this, a second burn severity classification was derived from the appearance of the litter and soil as proposed by Wells et al. (1979). A severity class was attributed to each sampled location on the basis of averaged duff and mineral soil exposure. (Lightly burned: mineral soil exposure < 10% and charred duff < 15%; Moderately burned: mineral soil exposure < 10% and charred duff > 15% or mineral soil exposure > 10% and charred duff + mineral soil exposure < 80%; Severely burned: mineral soil exposure > 10% and charred duff + mineral soil exposure > 80%.)

Eighty-seven sampling locations covering the range of severity and surficial deposit conditions were surveyed over the study area along accessible roads. At each sampling location, four 2 m^2 circular plots were sampled along a 15 m transect. For each plot, cover values were recorded for living low shrubs, herbs, grasses and mosses. Thickness of the L (litter) and FH (duff), thickness and color (hue, chroma, value) of the Ae layer, percent cover of mineral soil and duff exposure as well as cover of singed or unburned litter were noted. Soil samples were taken from the forest floor, 0–10 and 10–20 cm mineral soil and pooled by soil layer and sampling location for pH determination and for forest floor organic matter content. An additional sample was taken between 25 and 30 cm for soil texture determination (Bouyoucos hydrometer method (McKeague, 1976)). Validation of surficial deposit in the field was based on criteria outlined by Gerardin and Ducruc (1987). Finally, a disk was taken from a remaining tree stem to roughly assess stand age.

Correspondence between severity classes (forest cover and surface soil) and soil characteristics was assessed by means of discriminant analysis. A stepwise procedure was used to retain the most significant variables for discrimination (SAS Institute Inc., 1988). The misclassification rates were assessed by means of a cross-validation procedure.

3.2. Soil nutrient concentrations and contents following fires of different severity

Eighteen of the 87 stands were revisited at the end of the first growing season following fire and sampled for soil nutrient concentrations and content. Prior to fire, stand forest cover was dominated by black spruce ($n = 14$) or jack pine ($n = 4$) though both species were often found on the same sites. Stand age varied from 45 to 120 years. Three unburned stands of similar forest cover, age and soil and close to the fire perimeter were sampled as well. At each stand, twelve soil samples were taken systematically from the forest floor and in the 0–10 and 10–20 cm mineral soil layers over a 50 $\times$ 50 m area. Eight extra forest floor samples were collected using a 25 $\times$ 25 cm template for ash-free dry weight estimation. Bulk density of both mineral layers was measured on four undisturbed soil cores. A visual estimation of stone content was made at two places.

3.3. Laboratory analysis

Samples were pooled by soil layer prior to analysis to four final samples for N, C, and pH analysis and to one sample for exchangeable and total cations. Samples were air-dried, forest floor samples were ground (1.7 mm) and mineral soil samples were sieved (2 mm). Samples were analyzed for Kjeldahl N, including NO_2 and NO_3 (Bremmer and Mulvaney, 1982), and for exchangeable cations (one composite sample) (Ca_e, Mg_e, K_e, Na_e) (inductively coupled plasma atomic emission (ICP), Perkin–Elmer Plasma 40) and acidity (titration, Metler DL-40) after extraction with 1 M NH_4NO_3 (Stuanes et al., 1984).

Effective cation exchange capacity (CEC_E) was estimated by summing base cations and exchangeable acidity ($acidity_e$) and base saturation was determined by dividing total base cation concentrations by CEC_E. Soil pH was determined in 0.01 M $CaCl_2$ (McKeague, 1976). Organic matter (organic $C = 0.58 \times OM$) of forest floor samples was determined by loss on ignition and organic carbon of ground mineral samples (250 mm) by wet oxidation (Yeomans and Bremner, 1988). Forest floor samples were wet-digested (Parkinson and Allen, 1975) and total cation concentrations (Ca_t, Mg_t and K_t) measured by ICP. Soil texture determination was estimated by the Bouyoucos hydrometer method (McKeague, 1976). Soil content was the product of concentration and density of layers on a hectare basis. Soil volume was total volume minus stone content.

3.4. Statistical analysis

Homogeneity of variance was tested using Bartlett's procedure (Steel and Torrie, 1980). Variables that did not meet the requirement were transformed using a natural log or an angular transformation. Parametric analysis of variance and mean comparisons using orthogonal contrasts between unburned (control) stands and stands from each severity class were conducted.

3.5. Preliminary balance sheet of sites subjected to salvage harvesting

In order to produce a preliminary budget of site nutrient capital (Boyle, 1976) over the next rotation, we considered two nutrient pools: soil and above ground biomass (Fig. 1). Soil nutrient pool was assessed as described earlier and included forest floor exchangeable (Ca, Mg, K) and total nutrient (Ca, Mg, K, Kjeldahl N) and 0–20 cm mineral soil exchangeable base cations and Kjeldahl N contents. Above ground biomass values for unburned stands were drawn from the literature on jack pine and black spruce stands growing in similar conditions (Morrison, 1973; Foster and Morrisson, 1987). We assumed that following burning and subsequent harvesting, this pool was reduced to a minimum.

Inputs (Fig. 1) in the course of the next rotation will come from three sources: (1) precipitation (N and base

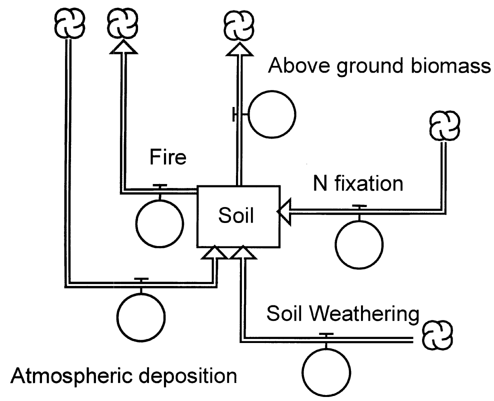

Fig. 1. Nutrient fluxes considered in the calculation of the preliminary budget for boreal forest soils.

cations); (2) N biological fixation; and (3) weathering (base cations). Precipitation inputs have been estimated from Boulet and Jacques (1993) and values from the three nearest atmospheric monitoring stations were averaged. Reports of N fixation for these ecosystems are scarce and highly variable. Knowles (1969) reported values ranging from 0 to 20 kg ha^{-1} per year from laboratory incubation of black spruce humus, but little nitrogenase activity was found in the forest floor and decaying wood from jack pine stands (Hendrickson, 1990, 1991) and in the forest floor from Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) (Nohrstedt, 1988) stands. We arbitrarily fixed these inputs at 1 kg ha^{-1} per year.

Inputs through weathering were drawn from previous work on critical load of atmospheric S and N deposition conducted in Quebec (Duchesne and Ouimet, 1996). The rate of soil base cation weathering down to 30 cm depth was estimated with the PROFILE model, version 3.2 (Alveteg et al., 1994). Values for five coniferous boreal stands growing on coarse textured soils of the Cambrian shields were averaged. Annual precipitation averaged 712 mm (range: 678–759 mm) for these sites. Mean annual soil temperature was set to 5°C. Average soil water content was estimated at 21% (range : 18–27%). Soil normative mineralogy was estimated from total elemental content (Si, Al, Fe, Mn, Ca, Mg, K, Na, P). Estimates of net nutrient immobilization in the forest biomass were (average and range, keq ha^{-1} per year): 0.1 (0.04–0.14) for N, 0.08 (0.02–0.14) for Ca, 0.02 (0.01–0.03) for Mg, and 0.02 (0.01–0.03) for K. The nitrification rate option was set to 'low', and the vegetation response to the basic cations-aluminum ratio was set to 'unspecific' in the model.

Annual inputs from all sources were summed up over a 65-year rotation for jack pine and a 110-year rotation for black spruce. These were the ages of the stands retained for the above ground biomass estimate and would be within the range of commercial forest rotation of these two species.

Table 1
Correspondence between severity classes according to canopy burn and forest floor combustion

Fire severity according to forest cover combustion	Fire severity according to forest floor combustion		
	Light	Moderate	Severe
Harvested prior to fire ($n = 23$)	3	10	10
Light ($n = 18$)	1	12	5
Moderate ($n = 21$)	0	15	6
Severe ($n = 23$)	0	6	17
Total ($n = 85$)	4	43	38

4. Results

4.1. Validation of the fire severity map

All surface deposits could be classified as coarse textured (average sand content of 71% for till ($n = 69$) and 85% for fluvioglacial ($n = 13$) and glaciolacustrine sands ($n = 4$)). Averaged clay content was 4–6% for all deposits. No further distinctions were made between deposits.

Relationships between forest cover and forest floor combustion are shown in Fig. 2 and Table 1. Exploratory discrimination analyses of the data set showed that with three cover burn severity classes, differences between classes were weak (Wilks's $\lambda = 0.3884$, $p = 0.108$, $n = 62$) and misclassification rates were high (50%). By combining the light and moderate classes, we obtained a better group differentiation and lower misclassification rates (Wilks's $\lambda = 0.622$, $p < 0.001$). Mineral soil exposure, cover of singed or unburned litter, and thickness and chroma of the albic horizon produced the best discriminant function (Table 2). Misclassification rates were 31% for the combined light/moderate class and 13% for the severe class. The overall rate was 24%.

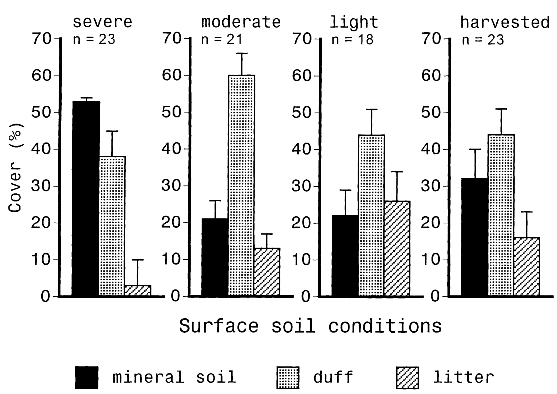

Fig. 2. Soil surface conditions according to forest cover combustion (bars = standard errors of the class mean).

Only four sampling locations were classified in the lightly burned sites based on forest floor combustion criteria, thus soil light and moderate severity classes were combined. Thickness of the L horizon and forest floor pH produced the best discriminant function (Table 3). Group differentiation was good (Wilks's $\lambda = 0.447$, $p < 0.001$, $n = 84$). Misclassification rates were 17 and 8%, respectively, for the light/moderate and the severe classes. The over all rate was 13%.

4.2. Soil nutrient concentrations and content following fires of different severity

Following the results of the validation exercise and in order to use stands that were harvested prior to fires, sampled stands were classified into two classes according to soil burn severity: light/moderate ($n = 11$) and severe ($n = 7$). Both classes were compared with control stands ($n = 3$). Fire significantly reduced forest floor dry weight (ash free) by 41 and 60%, and organic carbon concentrations by 11 and 26% in the light/moderate and in the severe classes, respectively (Fig. 3). One year following fire, forest floor base saturation and pH were higher for both severity classes than for unburned stands while acidity$_e$ was lower. The increase in base saturation was due to higher calcium saturation which increased from 35% in control stands to 56% ($p = 0.015$) and 61%

Table 2
Discriminant variables for fire severity according to forest cover classification

Variable	Partial R^2	F	p	Average values	
				Light/moderate fire ($n = 39$)	Severe fire ($n = 23$)
Mineral soil exposure	0.203	15.05	<0.001	21%	53%
A horizon chroma	0.084	5.32	0.025	1.77	1.91
A horizon thickness	0.065	3.94	0.052	6.5 cm	5.3 cm
Litter cover	0.073	4.42	0.040	19%	3%

($p = 0.006$) in lightly/moderately and severely burned stands, respectively. The effect of fire on individual forest floor base cation concentrations was less pronounced. Significant differences ($p < 0.100$) were found only for Ca_e and Mg_t following light/moderate fires and for Ca_t in both severity classes. No differences between control and burned stands were found for CEC_E (27.6 cmol(+) kg^{-1}) (Fig. 3).

In the mineral soil, fire increased K_e concentrations in the 0–10 cm layer from 0.041 cmol(+) kg^{-1} in the control (SE = 0.004) to 0.071 ($p = 0.018$) in the light/moderate class and 0.065 ($p = 0.060$) in the severe class. Fire had no significant effects on other mineral soil nutrients or characteristics. Averaged values are given in Table 4.

Forest floor nutrient content was significantly reduced on severely burned areas only (Table 5). Kjeldahl N content was reduced by 44%, Mg_e by 53% and K_e and K_t by 60 and 51%, respectively. Fire had no significant effect on mineral soil (0–20 cm) nutrient content.

4.3. Preliminary balance sheet of sites subjected to salvage harvesting

Projected annual nutrient inputs are given in Table 6. The balance sheet (Table 7) reported differences between nutrient inputs throughout the next rotation and losses caused by forest floor combustion and aboveground biomass combustion and harvesting. Theoretically, fire, with or without harvesting, would have little impact on long-term fertility if inputs in the course of the next rotation compensated for losses (positive balance) or, in the case of a negative balance, if the magnitude of the balance compared with site reserves remained small. This was the case for nitrogen. Following a severe fire, we estimated it would take 75 years to replenish soil N pools to the level they were before fire. The additional 161 kg loss caused by biomass combustion and harvesting of jack pine stands would take 27 years to be compensated for. Nevertheless, the negative balance, estimated over a 65-year jack pine rotation, represented only 10% of site reserves at the beginning of the new rotation. Over a 110-year black spruce rotation, the balance would be close to null.

The estimated replenishing time for soil Ca following a severe fire was 101 years. Losses induced by stem combustion and harvesting in black spruce stands were more profound than those incurred by severe forest floor combustion and the negative balance caused by combined disturbances represented more than half of the remaining site reserves. Following a severe fire, replenishing time of 163 and 278 years were found for soil Mg and K, respectively. In the case of Mg, harvesting severely burnt stands would create a

Table 3
Discriminant variables for fire severity according to forest floor classification

Variable	Partial R^2	F	p	Average values	
				Light/moderate fire ($n = 48$)	Severe fire ($n = 36$)
Horizon L thickness	0.395	53.49	<0.001	1.1 cm	0.1 cm
Forest floor pH	0.261	28.56	<0.001	3.5	4.5

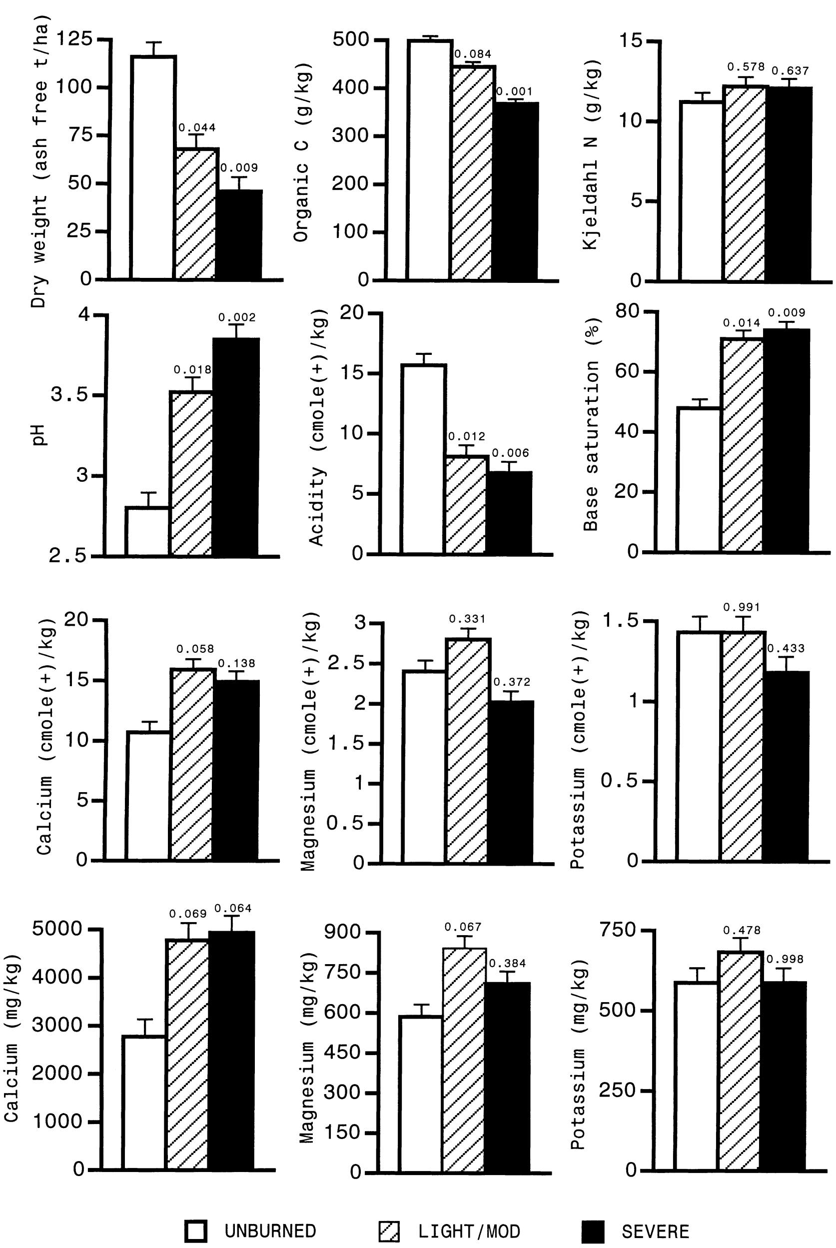

Fig. 3. Effects of fire on forest floor characteristics (bars = standard errors of population mean, 0.000 = significance of contrasts between unburned stands and individual severity class).

negative balance representing 65% of sites reserves for jack pine and 79% for black spruce. Potassium inputs (0.27 kg per year) in the course of the next rotation will not compensate for soil losses incurred by a light to moderate fire even in the case of a 110-year rotation. Following salvage harvesting, the estimated negative balance for both rotations and both severity classes were close or superior to site reserves, indicating that K will be in short supply in the course of the next rotation.

Table 4
Mineral soil characteristics and nutrient concentrations (±SE) of coarse textured boreal soils

Depth (cm)	Kjeldahl N	Organic C	Base saturation (%)	pH	
	(g kg^{-1})				
0–10	0.72 ± 0.04	18 ± 1	16 ± 2	3.84 ± 0.05	
10–20	1.02 ± 0.01	23 ± 1	17 ± 2	4.33 ± 0.04	
Depth (cm)	**Acidity**	**Ca**	**Mg**	**K**	**CEC**
	(cmol(+) kg^{-1})				
0–10	2.60 ± 0.15	0.30 ± 0.04	0.072 ± 0.007		3.09 ± 0.15
10–20	1.84 ± 0.19	0.23 ± 0.03	0.045 ± 0.003	0.053 ± 0.004	2.20 ± 0.21

Table 5
Effects of fire on forest floor and mineral soil (0–20 cm) nutrient content (kg ha^{-1}) of coarse textured boreal soils[a]

Burnt severity	Forest floor				Mineral soil	
	Exchangeable cations		Total nutrients		Kjeldahl N and exchangeable base cations	
	$\bar{x} \pm$ SE[b]	$p > F$	$\bar{x} \pm$ SE	$p > F$	$\bar{x} \pm$ SE	$p > F$
Nitrogen						
Unburned			1364 ± 96		1260 ± 137	
Light/mod			1024 ± 96	0.241	1227 ± 137	0.935
Severe			764 ± 96	0.059	1411 ± 137	0.724
Calcium						
Unburned	306 ± 33		405 ± 41		70 ± 12	
Light/mod	279 ± 33	0.782	404 ± 41	0.988	79 ± 12	0.802
Severe	189 ± 33	0.270	288 ± 41	0.368	89 ± 12	0.635
Magnésium						
Unburned	36 ± 3		76 ± 7		10 ± 1	
Light/mod	30 ± 3	0.553	71	0.797	10 ± 1	0.899
Severe	17 ± 3	0.087	45	0.133	11 ± 1	0.698
Potassium						
Unburned	73 ± 6		73 ± 6		31 ± 2	
Light/mod	48 ± 6	0.146	59 ± 6	0.475	31 ± 2	0.961
Severe	29 ± 6	0.021	36 ± 6	0.083	36 ± 2	0.456

[a]Analysis of variance, contrasts between unburned stands and individual severity classes.
[b]Standard error of the population.

Table 6
Estimated annual nutrient inputs (kg ha^{-1} per annum) through precipitation, weathering or biological fixation

Nutrient	Precipitation	Fixation or weathering
Nitrogen	5	1
Calcium	1.30	0.85
Magnesium	0.20	0.10
Potassium	0.20	0.07

5. Discussion

Soils of this region are coarse textured and frequently stony. The forest floor contains most of the soil exchangeable base cation reserves while nitrogen reserves are equally distributed between the forest floor and the mineral soil. The degree of combustion of the forest floor was found to be a good indicator of

Table 7
Effects of fire and salvage harvesting on nutrient (kg ha^{-1}) balance in boreal black spruce and jack pine stands growing on coarse textured soils

Burnt severity	Jack pine stands: age of rotation = 65 years						Black spruce stands: age of rotation = 110 years					
	Nutrient content		Losses caused by			Balance	Nutrient content		Losses caused by			Balance
	Total ecosystem	Soil	Forest floor combustion	Biomass combustion / harvesting	Total		Total ecosystem	Soil	Forest floor combustion	Biomass combustion / harvesting	Total	
Nitrogen												
Unburned	2784	2623	0	0	0	390	2857	2623	0	0	0	660
Light/mod	2251	2251	372	161	533	−143	2251	2251	372	234	606	54
Severe	2175	2175	448	161	609	−219	2175	2175	448	234	682	−22
Calcium												
Unburned	898	782	0	0	0	140	1116	782	0	0	0	237
Light/mod	762	762	20	116	136	4	762	762	20	334	354	−117
Severe	565	565	217	116	333	−193	565	565	217	334	551	−314
Magnesium												
Unburned	140	122	0	0	0	20	164	122	0	0	0	33
Light/mod	112	112	10	18	28	−8	112	112	10	42	52	−19
Severe	73	73	49	18	67	−47	73	73	49	42	91	−58
Potassium												
Unburned	257	176	0	0	0	18	298	176	0	0	0	30
Light/mod	138	138	38	81	119	−101	138	138	38	122	160	−130
Severe	101	101	75	81	156	−138	101	101	75	122	197	−167

the impacts of fire on soil characteristics and nutrient content. Canopy burn was sufficiently well correlated with forest floor combustion and soil characteristics to be used as a substitute for forest floor combustion. The severity map derived from aerial photos of canopy burn could thus be used as a diagnostic cartographic tool. Combined with forest maps indicating harvested and unharvested burned stands, it will be useful for nutrient management and site productivity monitoring. Stands harvested prior to fire were equally distributed between severity classes. As these sites could not be classified by photo interpretation, classification would require field evaluation.

Changes in pH, $acidity_e$ and base saturation induced by fire were limited to the forest floor and the magnitude of these changes was proportional to fire severity. Dyrness et al. (1989) reported higher increases in pH following wildfires in stands of white and black spruce but sampling of these soils was conducted immediately after burning. In the present study, soils were sampled one year after fire. Changes in soil characteristics and nutrient concentrations can be transient for coarse textured soils. Smith (1970) has shown that for soils similar to those of the studied area, the immediate increase in nutrient concentrations caused by fire was not apparent 15 months after burning and that base cation leaching was greatest immediately after fire.

The lack of significant differences between severity classes could be blamed on our sampling design. The study was designed to cover a large area in order (1) to validate the severity map and (2) to produce results that could be inferred over the entire area. This approach may yield less precision than a more intensive sampling scheme conducted on a smaller area. During the second part of the study, 18 stands that were sampled for the validation phase were sampled a second time for nutrient concentrations and pools. Care was taken to assure the homogeneity of soil (texture, thickness, slope) and stand (composition, age) characteristics. Moreover, sampled stands were equally distributed between three different sectors of the burnt area as in a completely random block design. As no significant effect of location in space was found, this factor was not considered any further. We believe the observed variability of the data reflects natural inter-stand variation.

Different patterns of retention were observed for divalent and monovalent cations. Forest floor concentrations of Ca_t, Mg_t, and Ca_e as well as Ca saturation remained higher in burned stands while no differences were found for K_e and K_t. On the other hand, it appeared some of the leached K had been retained in the underlying horizons. Differential effects of fire on monovalent and divalent cations have been previously reported (Viro, 1969; Smith, 1970; Grier, 1975; Chorover et al., 1994). This could be due to the lower vaporization temperatures of monovalent cations and the greater solubility of potassium oxydes, hydroxydes and carbonate compared with that of calcite (Ulery et al., 1993).

Losses of nitrogen caused by severe combustion of the forest floor amounted to only 17% of the total soil reserves. Contrary to our second hypothesis, we do not believe that fire would exacerbate existing N deficiencies. Inputs in the course of the next rotation would compensate for the observed reduction in forest floor N. Increases in Ca concentrations in the forest floor have so far compensated for a decrease in forest floor weight. Following a severe fire, reductions in forest floor exchangeable and total K concentrations and in dry weight were large enough that inputs through weathering and precipitation would not compensate for soil losses. The high solubility of potassium forms in ash materials (Ulery et al., 1993) combined with organic colloid preference for polyvalent cations (Bonn et al., 1985) could have contributed to K susceptibility to leaching and depletion following fire. Increases in mineral soil K_e concentrations following fire may somewhat compensate for these losses. Such a situation was observed by Johnson et al. (1997) following harvesting of northern hardwood forests. Potassium limitations in boreal jack pine and black spruce stands growing on coarse soils are not supported by fertilization trials (Krause et al., 1982) but lack of significant response to K fertilization in many experimental trials may be a result of insufficient treatment replication (Foster and Morrisson, 1983).

Under a natural disturbance regime characterized by an estimated fire cycle of 112 years (Bergeron, 1991), a majority of these stands would completely or partially replenish their reserves between two consecutive fires. Generalized nutrient depletions would result only from severe fires occurring at shorter intervals. Salvage harvesting of burned sites affected this nutrient balance. Harvesting of lightly to moderately burned stands was critical for K balance. The high forest cover K content compared with K soil content made it more susceptible to depletion by harvesting than N, Ca and Mg. Harvesting of severely burned sites shifted the balance towards depletion for all nutrients except N under a 110-year forest rotation.

This balance sheet was based on rough estimates of inputs and forest cover content and the estimation of nutrient fluxes by mineral weathering remains questionable. Although we believe the sampled soil depth (forest floor and mineral soil down to 20 cm) was adequate considering that in boreal soils most roots are located within these horizons (Ruess et al., 1996; Finéer et al., 1997), recent studies have indicated that the ability of vegetation to acquire nutrients from soil minerals could be grossly underestimated (Bormann et al., 1998; Kelly et al., 1998). Nonetheless, we believe this exercise provided insight into how salvage harvesting following fire could trigger nutrient limitations different in nature and magnitude from those caused by fire alone. Following late summer fires, salvage harvesting on coarse textured sites should be limited to lightly and moderately burned sites. Management of coarse textured sites should (1) favor long forest rotations and (2) aim at maintaining site organic matter for nutrient conservation and other benefits. Sands et al. (1979) have suggested that losses of soil organic matter and associated decreases in water-holding capacity and conductivity may be a possible cause for a decrease in productivity in second rotation radiata pine plantations in Australia. A slow but continuous input of organic matter through fragmentation and decomposition of standing dead trees is of particular relevance for coarse-textured soils where stabilization of organic C by clay is minimal (Oades, 1988) and where most of the soil exchange capacity depends mostly on its organic fraction (Pritchett and Fisher, 1987). This biological oxidation process may have a more gradual but longer lasting effect than fire on soil acidity (Binkley and Richter, 1987).

6. Conclusion

The effects of fire on soil nutrient status were linked to the severity of forest floor combustion. A light to moderate combustion had little impact on site nutrient status while severe combustion would induce K depletion. At the landscape level, maps of late summer fire severity based on forest cover combustion could be used as a tool for nutrient management. Combined with forest maps indicating harvested and unharvested burned stands, this information may be used as a predictive tool for nutrient depletion. We expect K depletion on all sites following salvage harvesting. Severely burned stands that were harvested will be subjected to Mg and Ca depletions as well. Because of larger soil reserves and inputs, the N budget was less affected by fire than that of other nutrients. Residual tree biomass and nutrient content is currently being estimated in order to refine this first analysis. Black spruce plantations have also been established in sampled burned stands in order to monitor stand nutrient status and validate our results.

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