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Ten-year Results from Operational Broadcast Burning Trials in Northwestern British Columbia

J.M. Kranabetter and A.M. Macadam

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SUMMARY

We monitored logging slash and forest floor consumption by broadcast burns, as well as subsequent changes over 10 years in soil chemical properties, foliar nutrients, and tree heights across seven medium-quality sites in northwest British Columbia. An average of 45.3 tonnes/ha of logging slash and 26.4 tonnes/ha of forest floor were consumed by low- to moderate-severity broadcast burns (55 and 29% of pre-burn levels, respectively). Forest floor chemical properties were strongly affected by burning: exchangeable Mg and Ca mass, available P mass, and pH increased in the 1st year; total N and C mass decreased. After 10 years, the forest floors had significantly lower C (54% reduction), N (50% reduction), available P (71% reduction), exchangeable Mg (37% reduction), and exchangeable K (81% reduction). The upper mineral soils (0–15 cm depth) had small increases in exchangeable Ca and K mass. Overall, we could only detect significant changes in mass balance only for C in the soil profile (forest floor + 0–30 cm mineral soil) during the 10-year period. Lodgepole pine planted on the burned plots have possible N and S deficiencies, but average or better rates of growth. Results from the monitoring program demonstrate the low impacts of well-executed broadcast burns to site productivity.

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1 INTRODUCTION

Prescribed fire is sometimes used in the Prince Rupert Forest Region for wildfire hazard abatement and site preparation following clearcut logging. In the early 1980s, concerns were raised about the short- and long-term impacts of broadcast burning on soil fertility. Burning was suspected of causing nutrient losses, particularly of nitrogen (N), through volatilization and leaching (Chandler et al. 1983).

Burning effects on forest soils have been studied in many parts of the world, and soil impacts are often tied to site factors such as climate, soil mineralogy, and burn severity. However, because little information was available for interior sites of northwestern British Columbia, the B.C. Forest Service established, in 1982, a monitoring program of operational broadcast burns. Monitored plots were established across a range of forest zonal types to examine trends and consistent burning effects on average site conditions. An earlier paper (Macadam 1987) presented detailed results for two sites up to two years following burning.

This report describes the effects of broadcast burning on fuels (logging slash and forest floors) at seven sites, and summarizes the subsequent changes in forest floor and mineral soil nutrients, from pre-treatment through to post-burn years 1, 5, and 10. In addition, tree response to broadcast burning is examined through growth rates and foliar nutrient concentrations of lodgepole pine (*Pinus contorta* Dougl. ex Loud.).

2 METHODS

2.1 SITE SELECTION

Sites were selected from three major Prince Rupert Forest Region biogeoclimatic zones: the mid-elevation interior forests of the Sub-boreal Spruce Zone (SBS); the high-elevation, subalpine forests of the Engelmann Spruce–Subalpine Fir Zone (ESSF); and the transitional coastal/interior forests of the Interior Cedar–Hemlock Zone (ICH). All sites had predominantly medium moisture and nutrient regimes, with typical vegetation and surficial materials for the given biogeoclimatic unit (Banner et al. 1993). Soils were typically glacial tills with sandy loam to loam texture and moderate coarse fragment

TABLE 1 *Broadcast burn site locations and descriptions*

Site	Burned	Planted	Latitude	Longitude	Elevation	BEC*	Description
Kinskuch A	1982	1985	55°1’	128°59’	250 m	ICHmc1 01	Podzolic Gray Luvisol; morainal veneer with coarse loamy to fine loamy texture; Hemimor forest floor 1–6 cm deep
Kinskuch B	1982	1985	55°34’	129°1’	270 m	ICHmc1 01	Podzolic Gray Luvisol; morainal blanket with sandy loam texture; Hemimor forest floor 2–4 cm deep
Kinskuch C	not burned	1985	55°32’	129°1’	265 m	ICHmc1 01	Podzolic Gray Luvisol; morainal blanket with sandy loam texture; Hemimor forest floor 6–10 cm deep
Helene	1982	1983	54°16’40”	125°3’45”	1050 m	SBSmc2 01	Brunisolic Gray Luvisol; morainal blanket with loamy skeletal texture; Hemimor forest floor 4–7 cm deep
Walcott	1982	1983	54°31’20”	126°55’0”	830 m	SBSmc2 01	Orthic Dystric Brunisol; morainal blanket with loam texture; Hemimor forest floor 4–6 cm deep
Herron	1983	1985	54°20’25”	125°10’0”	1335 m	ESSFmc 01	Orthic Humoferric Podzol; morainal blanket with coarse loamy texture; Hemimor forest floor 4–6 cm deep
Echo	1984	1987	54°19’25”	125°9’50”	1250 m	ESSFmc 01	Podzolic Gray Luvisol; morainal blanket with coarse loamy texture; Hemimor forest floor 2–6 cm deep
McKendrick	1985	1986	54°52’30”	127°45’50”	1150 m	ESSFmc 01	Orthic Humoferric Podzol; colluviated morainal veneer with coarse loamy texture; Hemimor forest floor 2–5 cm deep

* Biogeoclimatic ecosystem classification.

content. Seven sites were established between 1982 and 1985: two sites in the SBSmc2, three in the ESSFmc, and two in the ICHmc1 (Table 1).

Three plots were established (non-randomly) at each site for fuel measurements and soil sampling. Each plot was 30 x 30 m, and was chosen for uniformity in surface shape and fuel loading, without any significant soil disturbance from logging. No control plots (unburned) were established. The ICH sites were an exception, where two rather than three plots were installed per site. One unburned site, Kinskuch C, was installed in the ICH as well.

2.2 FUEL SAMPLING

Quantitative assessments of slash loading and consumption were based on line transect samples (Trowbridge et al. 1986). Before burning, three 30-m transects forming a triangle were superimposed on each plot. Intersecting slash pieces <7 cm in diameter were tallied by size class along portions of each transect, and species composition was estimated. Slash pieces >7 cm in diameter were individually measured and the species identified. Forest floor depth was measured at four points along each 30-m transect. A metal depth-of-burn pin was inserted adjacent to each measurement. The sample transects were relocated and resampled within 10 days after burning.

Fuel loading and consumption were calculated using equations presented by Van Wagner (1982a, b) with some modifications (Deas and Macadam 1985). Specific gravity of slash was calculated for the major species by size class based on oven-dry weight and volume determined by displacement. A computer program was developed to calculate fuel loading and consumption from line intersect data (Deas and Macadam 1985).

2.3 SOIL AND FOLIAR SAMPLING

Soil samples were taken from the forest floor and mineral soils at depths of 0–15 cm and 15–30 cm. Before burning, soil and forest floor bulk densities were determined for each layer, through a process of excavation and displacement at four randomly chosen points per plot. The coarse fragment content of the mineral soil samples was determined by sieving out material finer than 2 mm and then weighing the remainder. Nutrient content by mass was determined by multiplying nutrient concentrations by soil bulk density adjusted for coarse fragment content. Soil bulk density was measured once, in the pre-burn sampling, and was used for calculating nutrient mass in all years.

Measurements of forest floor depths and bulk density, both pre- and post-burn (first year only), were used to determine forest floor mass. In subsequent years (using a 20 x 20 cm template) the forest floor was excavated over the exact area, oven-dried, and weighed. Solid woody materials (roots, cones, and undecomposed wood) were removed from forest floor samples. Well-decomposed wood, where plant roots could grow, was left as part of the forest floor sample.

The number of soil and forest floor chemistry samples changed during the course of monitoring as more experience was gained. In 1982, the pre-burn samples were taken in eight random locations per plot, and this increased to 15 in 1983–1985. In most post-burn sampling, the methodology was standardized to 20 random locations composited to five samples per plot. The 15- to 30-cm depth was sampled on a subset of 11 plots over the seven sites, with either one or two plots per site. Sampling took place before burning (year 0), the year after burning (year 1), and years 5 and 10 after burning.

Lodgepole pine seedlings (2 + 0 bareroot stock) were planted at 2.5-m spacing on the sites 1–3 years after burning (Table 1). Seedling height, diameter (at root collar), and leader increment were determined on planted seedlings 10 years after planting. Needles from the current year's growth were taken from main laterals of the second whorl and oven-dried at 70° C; and the needle mass (per 100 needles) was determined before the foliar samples were ground for chemical analysis.

In a separate study, average nutrient concentrations were determined for slash diameter classes in the SBSmc for lodgepole pine, subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), and white spruce (*Picea glauca* [Moench] Voss) (Trowbridge et al. 1996). These data were used to estimate nutrient mass of logging slash on the broadcast burn plots (Appendix 1).

2.4 LABORATORY ANALYSIS

Soil analysis was carried out by the Ministry of Environment laboratory in Kelowna (1982–1983) and the Ministry of Forests lab in Victoria (1984–1996). The two labs used different methods for the analysis of carbon (C) and N. In Environment's lab, organic C was determined for the mineral samples according to the Walkley Black wet combustion method, and total C content of the forest floor samples was determined using the Leco induction furnace (Bremner and Tabatabai 1971). Total N was determined by semimicro-Kjeldahl digestion and colorimetric determination of NH_4-N. In Forestry's lab, total C and total N were determined using combustion elemental analysis. Exchangeable cations (calcium [Ca], magnesium [Mg] and potassium [K]) and cation exchange capacity were determined by the neutral ammonium acetate method; available phosphorus (P) was determined with the Bray P1 procedure; and soil pH was determined in 0.01 mol $CaCl_2$ (methods described in Kalra and Maynard 1991; Carter 1993) for all years. Foliar macro- and micronutrients were analyzed by ICP-AES after microwave digestion, with concentrated HNO_3, 30% H_2O_2, and concentrated HCl.

2.5 STATISTICS

Changes in chemical properties over time were tested using a randomized block design, with sites as blocks and plots as replicates (Table 2) (SAS 1988). Interaction effects were tested according to site x year. Plot means were used in the ANOVA, so differences in sampling intensity between years were therefore not a factor in the statistical analysis. Tukey's studentized range test was used to indicate significant differences among years for each chemical property. Fuel consumption was not statistically analyzed.

TABLE 2 *ANOVA model*

Source	DF
Site	6
Year	3
Site X Year	18
Plot(Site)	12
Error	36

Soil and fuel results are presented as overall means rather than by sites, so that average impacts of broadcast burning can be examined. However, because the differences in fuels and nutrient mass between sites were sometimes large, Appendices 2–4 show the range in fuel loading and soil properties (at year 10) by site.

3.1 SLASH AND FOREST FLOOR CONSUMPTION

Broadcast burning was found to reduce forest floor mass by 29% on average, ranging from a low of 14% to a high of 39% across sites (Table 3). Total slash was consumed by 55%, ranging from 34 to 75% across sites. This translates to 71.7 tonnes/ha of organic matter, on average, consumed by the burning treatment (41% of pre-burn organic matter levels). Most of the fine slash (< 3 cm) and intermediate slash (3–7 cm) was consumed (91 and 72%, respectively). These average fuel consumption levels are comparable to the burning impacts of low to moderate fire severity reported in other studies. At Regan Creek, an SBSmc–ESSFmc transitional site, a low-impact broadcast burn reduced forest floor depths by 17% and slash by 40% (Yole and Macadam 1993). Blackwell et al. (1992), in the SBSmc subzone, found 30% losses in forest floor mass for low-severity broadcast burns, increasing to 39% on high-severity burns. They also found that total slash consumption ranged from 59% for low-severity broadcast burns to 76% for high-severity burns.

TABLE 3 *Average slash and forest floor consumption*

	Pre-burn	Post-burn	Consumed	
Slash size class		(tonnes/ha)		% loss
Forest floor	90.7	64.3	26.4	29
< 3 cm	13.2	1.2	12.0	91
3–7 cm	13.7	3.9	9.8	72
> 7 cm	55.8	32.3	23.5	42
Total slash	82.7	37.4	45.3	55

3.2 CHANGES TO FOREST FLOOR CHEMISTRY

Combustion of slash and forest floor led to increases in exchangeable Ca, exchangeable Mg, and available P in the forest floor one year after burning (Table 4). The inputs of exchangeable cations increased pH (reduced soil acidity) by 1.3 units to 5.2, on average. Exchangeable K decreased by 35% in year 1, likely through rapid leaching of released K from the ash. Volatilization of organic N resulted in losses in forest floor N that matched losses in forest floor mass (30%). Nitrogen volatilization can vary significantly, depending on fire temperatures and duration; losses from 110 to almost 1000 kg/ha have been reported (McNabb and Cromack 1990). The N loss from these operational burns (average 288 kg/ha) again suggests a low to medium fire severity. The changes in forest floor chemical properties are consistent with trends reported in the literature on fires. Increases in soil pH and the availability of such nutrients as P, Ca, and Mg, and decreases in total amounts of some elements (notably N), have been widely documented (Macadam 1987).

After burning, forest floor N and C continued to decrease from year 1 to year 10 by almost 25%. This decrease resulted from decomposition, which probably was accelerated compared to that on unburned sites because of the increased heat absorption of the black surface created by burning (Bissett and Parkinson 1980). The C:N ratio did not decrease over time, which was unexpected, given that N is usually immobilized by micro-organisms until C:N ratios reach approximately 25

TABLE 4 *Average changes in forest floor chemistry (n=76)*

Chemical property	Pre-burn (kg/ha)	Post-burn (kg/ha)			Year p<F	Interaction p<F
		Year 1	Year 5	Year 10		
Total C	42684a*	28261b	23729bc	19161c	*0.0001*	*0.4917*
Total N	948a	660b	592bc	482c	*0.0001*	*0.4916*
C:N	45	45	41	43	*0.2098*	
P	9.8b	15.2a	6.1c	2.9c	*0.0001*	*0.6479*
Ca	406bc	642a	537b	364b	*0.0001*	*0.6545*
Mg	50a	61a	37b	32b	*0.0001*	*0.4114*
K	97a	62b	24b	16b	*0.0001*	*0.0005*
pH (CaCl2)	3.90d	5.21a	4.74b	4.35c	*0.0001*	*0.0462*

* Values significantly different between columns are separated by letters ($p<0.05$).

(Brady and Weil 1996). The reason for the lack of N immobilization could be related to the change in C quality over time. With only low amounts of fresh litter inputs in clearcuts, C substrates of the forest floor decline in quality as decomposition proceeds, leaving only the most recalcitrant C types such as lignin and humus. Microbial biomass also declines, since fewer micro-organisms can use these poorer C sources. As the microbial biomass declines, the amount of immobilized N also decreases, since the microbial biomass holds much of the N in the forest floor (Prescott 1997). This results in N being mineralized at higher C:N ratios than expected, allowing either plant uptake of N or perhaps leaching of N through the rooting zone.

Another possible reason for the high C:N ratios is N translocation from forest floors to woody debris by fungi (Covington 1981). The competition for N between saprophytes removes N from the forest floor, keeping the C:N ratio higher than expected. In this case, N could be redistributed from the forest floor to woody debris without net losses to the site. Losses of forest floor N have also been found in hardwood forests after clearcutting (800 kg/ha after 20 years [Federer 1984]), so relatively large changes to forest floor N mass are perhaps unavoidable after disturbance, whether burning occurs or not.

Available P and exchangeable Ca, Mg, and K changed significantly over the 10-year period, likely leaching from the forest floor. Values of these cations had usually declined at year 10 from pre-treatment levels (with the exception of Ca). The rate of decrease in K was variable across sites at year 1, which might be related to the amount of slash consumed and the leaching rates from the forest floor (Figure 1). As well, the changes in pH were not completely consistent, which might also be related to the extent of cation inputs and leaching rates across sites (Figure 1).

3.3 CHANGES TO SURFACE MINERAL SOIL CHEMISTRY (0–15 CM)

The upper mineral soil horizons had comparably larger pools of nutrients and less exposure to extreme fire temperatures, so fewer nutrients changed significantly over time than in forest floors. Exchangeable cations and P tended to increase over time, probably due to leaching from the forest floor, but K and Ca mass showed the only statistically significant changes

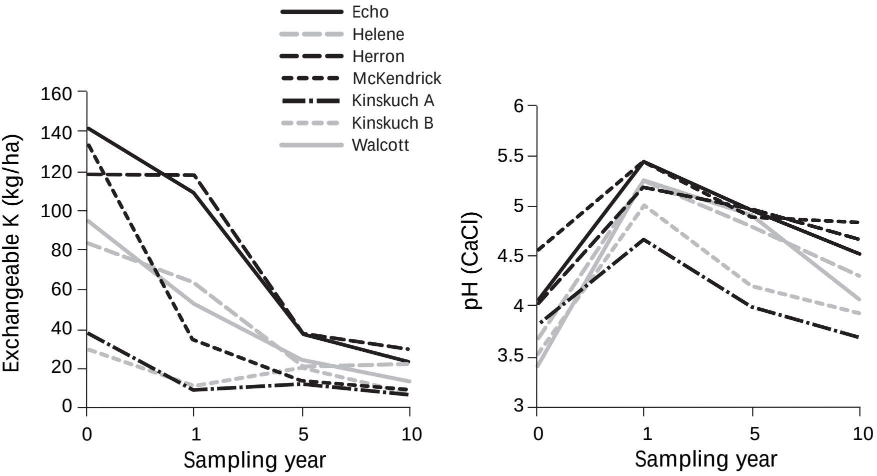

FIGURE 1 *Chemical properties of forest floors (from all sites) with significant site interactions over time.*

(Table 5). Enough basic cations entered the mineral soil over 10 years to cause a small increase in soil pH. The trends in chemical properties of mineral soils were more variable between sites (significant site interactions) than were the trends in forest floors. Changes in K were again inconsistent, perhaps because of factors such as rainfall and soil texture that influenced leaching rates. The organic matter dynamics (C, N, and C:N ratio) were sometimes significant but much too

TABLE 5 *Average changes in 0–15 cm mineral soil chemistry (n=76)*

Chemical property	Pre-burn (kg/ha)	Post-burn (kg/ha)			Year p<F	Interaction p<F
		Year 1	Year 5	Year 10		
Total C	29806a*	27374ab	29891a	24415b	*0.0087*	*0.0001*
Total N	1148	1090	1160	1221	*0.0973*	*0.0039*
C:N	25.8ab	26.4a	24.4b	19.6c	*0.0001*	*0.0001*
P	120	139	132	148	*0.2641*	
Ca	964	946	1189	1156	*0.0351*	*0.8097*
Mg	119	129	132	141	*0.3202*	
K	109b	134b	163a	131b	*0.0001*	*0.0024*
pH ($CaCl_2$)	4.23b	4.27ab	4.25b	4.36a	*0.0069*	*0.0001*

* Values significantly different between columns are separated by letters ($p<0.05$).

variable from site to site to treat as an overall trend. Figure 2 shows the inconsistencies in trends and outlier data that reflect some of the experimental errors (such as changes in laboratory methodologies) that might have occurred during the monitoring program.

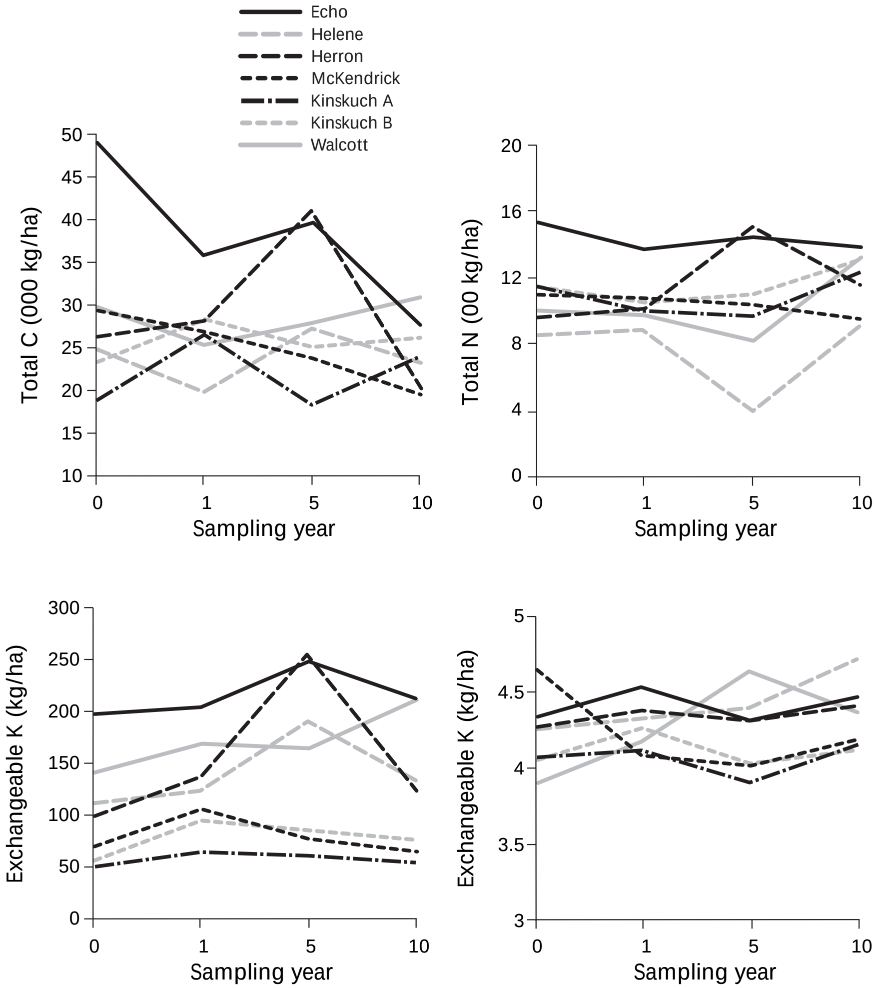

FIGURE 2 *Chemical properties of mineral soils (all sites, 0–15 cm) with significant site interactions over time.*

Logging slash, forest floors, and surface mineral soils (0–15 cm depth) represent much of the site nutrient capital that can be affected by broadcast burning. Figure 3 shows the relative changes in nutrients after 10 years across the sites.[1] The site nutrient budget is not exact because total cations and P were determined for logging slash, while exchangeable cations and available P were determined for soils. Despite this difference in methods, it is apparent that mineral soils hold the bulk of the site nutrients, and that the burning in these trials led to a redistribution of some nutrients from logging slash and forest floors to mineral soil, with little change in overall totals for P, Ca, and Mg. Net losses occurred with C and N, likely through volatilization and decomposition, and with K, likely through leaching.

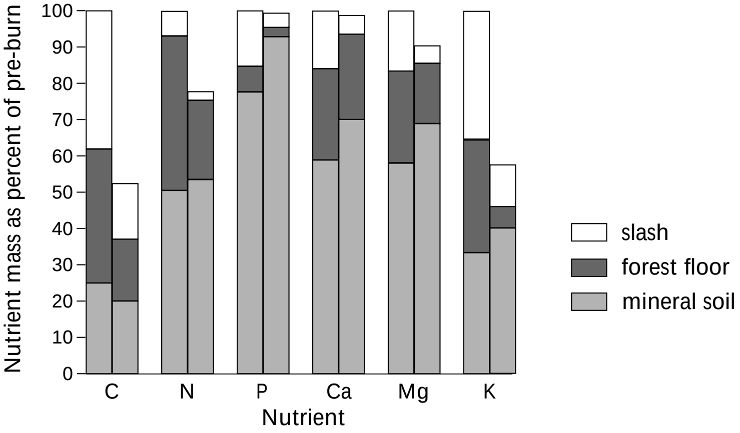

FIGURE 3 *Comparison of pre-burn (first column) and 10th year (second column) distribution of nutrient mass for logging slash, forest floor and mineral soil (0–15 cm depth). Note that total cations and P were determined for slash while exchangeable cations and available P are shown for forest floor and mineral soil.*

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[1] The post-burn slash nutrient estimate is approximate because logging slash was not remeasured at year 10. Since 91 and 72% of the smaller size classes were consumed by the fire, we assumed that only slash from the > 7 cm post-burn remained at year 10 (Appendix 1).

3.5 CHANGES IN NUTRIENT MASS OF TOTAL SOIL PROFILE

Where the deeper soil profile was monitored (on a subset of 11 plots across the seven sites), the changes in soil nutrient mass were generally found to be not statistically significant (Table 6). Carbon was the only element to be significantly reduced, although some interaction between sites affects the strength of this conclusion. The net changes in exchangeable cations and available P were not significant over the 10-year period. Total N decreased by approximately 10%, but this was not a large enough loss for a significant treatment effect.

Although the total N content of the soil profile was not greatly affected by burning, it is difficult to say whether the loss of forest floor N might nevertheless significantly alter N availability for trees. In mature forests at least, higher concentrations of mineralizable N in the forest floor than in mineral soils suggest greater biotic activity and consequently a more readily available source of N in the forest floor. On the other hand, it is possible that unburned sites might have undergone similar patterns of nutrient redistribution as had the burned sites. Without N immobilization in the forest floor, similar losses of forest floor N and cation transfer to mineral soils might have also occurred on unburned sites, through slow release by decomposition over longer periods of time rather than through the more immediate impact of broadcast burning.

3.6 TREE RESPONSE AFTER 10 YEARS

Foliar nutrient concentrations of 10-year-old lodgepole pine from the monitored sites indicate probable deficiencies in N and sulphurs (Table 7) (Ballard and Carter 1986). Sulphur,

TABLE 6 *Average changes in soil chemistry (forest floor + 0–30 cm mineral soil) (n=44)*

Chemical property	Pre-burn (kg/ha)	Post-burn (kg/ha) Year 1	Year 5	Year 10	Year p<F	Interaction p<F
Total C	90744a*	74293b	74162b	65717b	*0.0008*	*0.0917*
Total N	3039	2668	2609	2786	*0.1441*	*0.2388*
P	279	356	294	361	*0.8407*	
Ca	3008	2975	3421	3134	*0.4344*	
Mg	366	367	361	357	*0.9407*	
K	330	357	353	305	*0.2472*	

* Values significantly different between columns are separated by letters (p<0.05).

TABLE 7 *Foliar nutrient concentrations for lodgepole pine at year 10*

	N	P	S	Ca	Mg	K	B	Cu	Fe	Mn	Zn	NW**
	(%)						(ppm)					(g)
Echo	1.19	0.15	0.08	0.14	0.07	0.65	10.9	2.6	22.4	184	41.1	2.53
McKendrick	1.20	0.14	0.08	0.17	0.08	0.65	11.9	3.0	69.4	266	41.9	2.68
Herron	1.27	0.14	0.11	0.17	0.08	0.63	13.1	2.8	38.3	181	38.0	1.93
Helene	1.22	0.15	0.10	0.14	0.07	0.63	9.3	2.3	23.1	169	41.4	2.11
Walcott	1.18	0.14	0.09	0.15	0.08	0.64	12.6	2.4	24.6	208	43.1	2.28
Kinskuch A	1.22	0.13	0.09	0.19	0.10	0.61	14.2	3.4	40.5	349	32.5	1.63
Kinskuch B	1.23	0.12	0.08	0.19	0.09	0.66	15.1	3.5	40.0	414	27.8	1.66
Kinskuch C	1.23	0.12	0.08	0.18	0.09	0.56	13.8	3.5	34.4	466	27.0	1.55
deficient*	1.20	0.12	0.12	0.06	0.07	0.40	10.0	2.0	25	15	10	

* Values below which foliar nutrients are considered severely deficient for lodgepole pine (Ballard and Carter 1986).

** Average weight of 100 needles.

though known to be susceptible to losses from burning, was unfortunately not monitored in these trials (S was not part of standard soil analysis when monitoring began). Nitrogen and S deficiencies have been documented in forest ecosystems in much of western North America (Brockley et al. 1992). It is therefore possible that the long history of wildfires might be responsible for the widespread deficiencies of N and S regardless of the most recent burning event. For example, on the unburned site (Kinskuch C), the foliar N and S concentrations were as low as on the burned ICH sites. Other nutrient deficiencies—such as low levels of iron (Fe), Mg, and boron (B) found on a few sites—were less consistent. These deficiencies might be related to inherent differences in soils rather than to the impacts of broadcast burning.

Tree growth data from across the sites show reasonable heights for lodgepole pine after 10 years compared to regional averages (Table 8). On the unburned site (Kinskuch C), tree height and diameter were lower than on the burned ICH plots. Yole et al. (1997) also found better growth of lodgepole pine on burned plots than on unburned plots after five years. Good rates of tree growth on burned sites might be attributed to an "assart" effect, which is the immediate increase in nutrient availability that occurs after burning, such as the increase in exchangeable cations and P found on these sites. Broadcast

TABLE 8 *Ten-year-old lodgepole pine growth response*

Site	Location	Ht (cm)	Dia. (mm)	Inc. (cm)
ESSFmc	Echo	274	67	44
ESSFmc	McKendrick	323	80	58
ESSFmc	Herron	175	45	.
SBSmc2	Helene	281	70	43
SBSmc2	Walcott	347	72	54
Regional SBS average*		237	-	46
ICHmc1	Kinskuch A	312	72	53
ICHmc1	Kinskuch B	297	67	56
ICHmc1	Kinskuch C	258	49	43
Regional ICH average		287	-	40

* Average height (Ht) and increment (Inc.) for 10-year-old plantations in the Prince Rupert Forest Region (Pollack et al. 1985).

burning can also reduce competing vegetation, as well as temporarily cause a partial sterilization of the upper soil from the fire, which in turn can lead to a reduction in antagonistic soil organisms (Pritchett and Fisher 1987).

4 CONCLUSIONS

Broadcast burning of low to moderate severity in the Prince Rupert Forest Region resulted in effects on soils comparable to those reported in other fire studies (Viro 1974; Chandler et al. 1983; McNabb and Cromack 1990). Forest floors were immediately altered through cation release, pH increases, and N and C losses. Much of the site nutrients were redistributed from forest floor and logging slash to mineral soils over the 10-year monitoring period. There was little evidence of deleterious effects of broadcast burning on total soil nutrient mass. Nutrients released by logging slash and forest floors were apparently either retained on site by mineral soils or were lost in such small or inconsistent quantities as to be hardly detectable. Tree growth on the burned sites was better than regional averages, despite the possible deficiencies of N and S indicated by foliar analysis.

Wildfire is a natural part of forest disturbance and could have many functional roles that are not yet fully appreciated (e.g., see the ecological role of charcoal discussed by Zackrisson et al. 1996). Currently, a minimal amount of broadcast burning is occurring in the Prince Rupert Forest Region because of concerns over air quality, the potential for fire escapes, and high cost of treatment relative to mechanical treatments. The results from this operational monitoring program demonstrate the low impact that well-executed broadcast burns have on site productivity. This is reassuring, given the evidence of good tree growth on burned sites, and the likely important role of fire in forest ecology. In this regard, broadcast burning can be recommended as a tool in forest management.

APPENDIX 1

Estimated slash nutrient concentration and nutrient mass consumption after broadcast burning (average of seven sites).

Slash size (cm)	C	N	P	S	Ca	Mg	K
			Nutrient concentrations (%)				
< 3	54.7	0.47	0.073	0.041	0.60	0.069	0.24
3-7	54.3	0.17	0.024	0.014	0.26	0.040	0.14
> 7	53.5	0.14	0.017	0.011	0.25	0.034	0.12
			Pre-burn nutrient mass(kg/ha)				
< 3	7220	62	10	5	79	9	32
3-7	7439	24	3	2	36	6	19
> 7	29853	76	10	6	141	19	65
Total	44512	162	23	13	256	34	116
			Nutrient mass consumed (kg/ha)				
< 3	6564	56	9	5	71	8	29
3-7	5321	17	2	1.4	26	4	14
> 7	12573	32	4	2.6	59	8	27
Total	24458	105	15	9	156	20	70

* Nutrient concentrations from lodgepole pine, subalpine fir, and white spruce (Trowbridge et al. 1996).

APPENDIX 2

Site fuel loading pre- and post-burn. Means and (standard deviations).

	Pre-burn(tonnes/ha)					Post-burn (tonnes/ha)				
Site	FF**	< 3 cm	3–7 cm	> 7 cm	Slash*	FF	< 3 cm	3–7 cm	> 7 cm	Slash
Echo	106.2	15.7	16.4	77.3	109.4	92.3	1.5	3.9	43.7	49.1
(n=18)	(36.3)	(10.1)	(7.6)	(24.6)	(25.6)	(36.1)	(1.0)	(1.6)	(20.2)	(21.4)
McKendrick	79.1	25.7	32.8	61.1	119.6	55.8	0.05	0.6	28.9	29.5
(n=9)	(35.7)	(6.3)	(10.4)	(25.3)	(24.2)	(36.3)	(0.07)	(0.6)	(17.8)	(17.8)
Herron	118.0	18.5	8.7	48.7	75.8	102.5	3.4	5.9	31	40.3
(n=9)	(48.8)	(4.9)	(2.6)	(25.6)	(28.6)	(53.2)	(3.0)	(3.4)	(13.1)	(12.1)
Helene	104.7	6.7	7	46.1	59.8	76.0	0.6	3.7	34.8	39.2
(n=9)	(57.6)	(2.4)	(2.9)	(19.2)	(19.2)	(59.7)	(0.3)	(1.9)	(17.0)	(15.7)
Walcott	110.6	8.6	8.5	33.7	50.8	71.7	0.6	6.1	19.4	26.1
(n=9)	(46.4)	(3.2)	(2.9)	(21.0)	(21.0)	(38.7)	(0.3)	(2.0)	(11.2)	(10.5)
Kinskuch A	58.4	4.4	6.3	63	73.6	27.5	0.5	2.8	33.5	36.8
(n=6)	(32.0)	(1.5)	(2.9)	(39.4)	(37.3)	(28.2)	(0.5)	(0.8)	(29.0)	(29.1)
Kinskuch B	57.8	4.3	10.0	34.2	48.4	24.6	0.7	3.6	19.4	23.7
(n=6)	(48.5)	(1.9)	(2.6)	(11.7)	(13.8)	(41.9)	(0.4)	(2.0)	(12.9)	(11.1)

* Total slash does not include forest floor.

** FF = forest floor.

APPENDIX 3

Average 10-year soil nutrient mass (kg/ha) by site—forest floor and 0–15 cm mineral soil. Means and (standard deviations); n=15 except ICH, where n=10.

Site	Type	C	N	Ca	Mg	K	Min. N	Avail. P
ESSFmc (Echo)	FF	26241	702	644	48	23	10.2	5.7
		(5797)	(144)	(222)	(12)	(4.7)	(3.1)	(3.4)
	0–15	27763	1379	1611	221	212	13.7	118
		(6765)	(257)	(435)	(63)	(53)	(3.9)	(30)
ESSFmc (McKendrick)	FF	10298	287	233	18	8	6.9	2.5
		(2256)	(61)	(60)	(4.4)	(1.2)	(1.5)	(0.8)
	0–15	19556	945	663	84	64	19.8	34
		(5544)	(263)	(409)	(42)	(9)	(11.6)	(15)
ESSFmc (Herron)	FF	28795	878	673	60	29	23.9	3.1
		(7641)	(217)	(248)	(22)	(9.7)	(9.8)	(1.1)
	0–15	20297	1164	1452	222	125	13.2	105
		(4443)	(302)	(587)	(71)	(24)	(6.5)	(31)
SBSmc2 (Helene)	FF	26302	620	421	41	22	12.5	3.9
		(4797)	(147)	(115)	(8.6)	(7.3)	(4.0)	(2.1)
	0–15	22536	910	1039	126	132	17.4	241
		(5099)	(136)	(279)	(34)	(24)	(5.3)	(56)
SBSmc2 (Walcott)	FF	19562	346	254	25	13	6.2	2.2
		(3371)	(60)	(77)	(5.9)	(2.6)	(2.1)	(1.2)
	0–15	30957	1326	1016	158	210	8.3	324
		(8843)	(360)	(408)	(75)	(45)	(4.0)	(138)
ICHmc1 (Kinskuch A)	FF	8094	188	60	12	6	2.7	0.6
		(3998)	(93)	(28)	(6)	(4)	(1.9)	(0.3)
	0–15	24065	1231	210	55	53	21.5	49
		(5024)	(236)	(120)	(15)	(10)	(7.3)	(17)
ICHmc1 (Kinskuch B)	FF	7135	140	66	8	7	3.0	0.5
		(1818)	(33)	(22)	(2)	(3)	(1.3)	(0.3)
	0–15	26214	1312	318	67	75	20.4	127
		(5797)	(267)	(110)	(20)	(24)	(6.5)	(58)

APPENDIX 4

Average 10-year soil nutrient concentrations by site—forest floor and 0–15 cm mineral soil. Mean and (standard deviation); n=15 except ICH, where n=10.

		C	N		CEC	Ca	Mg	K	Min. N	Avail. P	
Site	Type	%	%	C:N	cmol(+)/kg soil				ppm	ppm	pH
ESSFmc	FF	40.2	1.08	38	94.5	47.9	6.0	1.1	157.5	86.4	4.53
(Echo)		(7.4)	(0.2)	(5.3)	(12.9)	(14.0)	(1.1)	(0.2)	(50.2)	(52.7)	(0.3)
	0–15	3.01	0.15	20	29.9	8.6	2.0	0.7	15.1	128.7	4.46
		(0.8)	(0.03)	(2.2)	(5.1)	(2.5)	(0.7)	(0.2)	(5.4)	(36.5)	(0.2)
ESSFmc	FF	36.8	1.03	36	77.0	40.8	5.4	0.9	249.2	91.0	4.84
(McKendrick)		(6.1)	(0.2)	(3.5)	(14.0)	(8.3)	(1.0)	(0.1)	(53.0)	(29.9)	(0.3)
	0–15	2.10	0.10	21	14.8	3.3	0.7	0.2	20.5	38.7	4.18
		(0.4)	(0.02)	(1.1)	(1.6)	(1.6)	(0.3)	(0.05)	(9.4)	(21.9)	(0.2)
ESSFmc	FF	46.8	1.44	33	110.2	52.5	7.8	1.4	386.2	49.7	4.69
(Herron)		(3.7)	(0.2)	(3.5)	(10.6)	(11.3)	(1.6)	(0.1)	(100.3)	(10.9)	(0.2)
	0–15	2.14	0.12	17	22.7	7.4	1.9	0.4	13.5	114.0	4.41
		(0.5)	(0.03)	(2.6)	(5.1)	(2.8)	(0.5)	(0.08)	(6.0)	(42.4)	(0.2)
SBSmc2	FF	42.8	1.00	43	89.6	33.7	5.5	1.1	202.6	60.1	4.30
(Helene)		(5.2)	(0.2)	(6.8)	(8.0)	(8.2)	(0.9)	(0.2)	(52.7)	(25.8)	(0.3)
	0–15	2.28	0.09	24	16.1	5.1	1.0	0.4	17.4	240.2	4.72
		(0.6)	(0.02)	(3.7)	(1.7)	(1.2)	(0.2)	(0.07)	(5.2)	(52.9)	(0.3)
SBSmc2	FF	46.3	0.83	58	91.6	30.4	5.0	1.0	149.2	52.3	4.08
(Walcott)		(4.4)	(0.2)	(12.6)	(11.1)	(11.9)	(1.1)	(0.3)	(55.0)	(27.8)	(0.3)
	0–15	2.59	0.11	23	20.4	4.3	1.1	0.6	6.9	263.6	4.36
		(0.5)	(0.01)	(3.4)	(1.8)	(1.7)	(0.4)	(0.2)	(2.9)	(62.6)	(0.1)
ICHmc1	FF	39.89	0.93	43	88.8	15.0	4.7	1.0	120.2	32.6	3.70
(Kinskuch A)		(10.5)	(0.2)	(13.7)	(22.6)	(5.0)	(1.7)	(0.3)	(52.8)	(16.2)	(0.3)
	0–15	2.78	0.14	20	18.9	1.2	0.5	0.2	25.2	56.3	4.15
		(0.6)	(0.02)	(3.8)	(2.6)	(0.6)	(0.1)	(0.04)	(10.0)	(18.8)	(0.3)
ICHmc1	FF	45.36	0.92	49	86.4	21.3	4.4	1.5	206.1	32.2	3.94
(Kinskuch B)		(5.3)	(0.3)	(20.7)	(6.9)	(8.0)	(1.2)	(0.6)	(118.1)	(14.4)	(0.4)
	0–15	2.45	0.12	20	18.4	1.5	0.5	0.2	19.5	116.4	4.12
		(0.2)	(0.01)	(1.9)	(1.1)	(0.5)	(0.1)	(0.06)	(7.0)	(39.1)	(0.1)

Ballard, T.M. and R.E. Carter. 1986. Evaluating forest stand nutrient status. B.C. Min. For. Land Manage. Handb. 20. Queen's Printer Publications, Victoria, B.C.

Banner, A., W. MacKenzie, S. Haeussler, S. Thomson, J. Pojar, and R. Trowbridge. 1993. A field guide to site identification and interpretation for the Prince Rupert Forest Region. B.C. Min. For. Field Handb. 26. Crown Publications, Victoria, B.C.

Bissett, J. and D. Parkinson. 1980. Long-term effects of fire on the composition and activity of the soil microflora of a subalpine, coniferous forest. Can. J. Bot. 58:1704–21.

Blackwell, B., M.C. Feller, and R. L. Trowbridge. 1992. Conversion of dense lodgepole pine stands in west-central British Columbia into young lodgepole pine plantations using prescribed fire. 1. Biomass consumption during burning treatments. Can. J. For. Res. 22:572–81.

Brady, N.C. and R.R.Weil. 1996. The nature and properties of soils. 11th ed. Prentice-Hall, New York, N.Y.

Bremner, J. and M.A. Tabatabai. 1971. Use of automated combustion techniques for total carbon, total nitrogen, and total sulphur analysis of soils. *In* Instrumental methods for analysis of soils and plant tissue. L.M. Walsh (editor). Soil Sci. Soc. Am., Madison, Wis.

Brockley, R.P., R.L. Trowbridge, T.M. Ballard, and A.M. Macadam. 1992. Nutrient management in interior forest types. *In* Forest fertilization: sustaining and improving nutrition and growth of western forests. H.N. Chappell, G.F. Weetman, and R.E. Miller (editors). Inst. For. Resour. 73:43–63.

Carter, M.R. (editor). 1993. Soil sampling and methods of analysis. Lewis Publishers, Boca Raton, Fla.

Chandler, C., P. Cheney, P. Thomas, L. Trabaud, and D. Williams. 1983. Fire in forestry. Vol. I: Forest fire behaviour and effects. John Wiley & Sons, New York, N.Y.

Covington, W.W. 1981. Changes in forest floor organic matter and nutrient content following clearcutting in northern hardwoods. Ecology 62:41–48.

Deas, A. and A.M. Macadam. 1985. A computer program for calculating fuel loading and consumption for prescribed fire studies. B.C. Min. For., Victoria, B.C. Res. Rep. 85004-PR.

Federer, C.A. 1984. Organic matter and nitrogen content of the forest floor in even-aged northern hardwoods. Can. J. For. Res. 14: 763–67.

Kalra, Y.P. and D.G. Maynard. 1991. Methods manual for forest soil and plant analysis. For. Can., Nor. For. Cent., Edmonton, Alta. Inf. Rep. NOR-X-319.

Macadam, A.M. 1987. Effects of broadcast slash burning on fuels and soil chemical properties in the Sub-boreal Spruce Zone of central British Columbia. Can. J. For. Res. 17 (12):1577–84.

McNabb, D.H. and K. Cromack. 1990. Effects of prescribed fire on nutrients and soil productivity. *In* Natural and prescribed fire in Pacific Northwest forests. J.D. Walstad, S.R. Radosevich, and D.V. Sandberg (editors). Oreg. State Univ. Press, Corvallis, Oreg. pp. 125–42.

Pollack, J.C., F. van Thienen, and T. Nash. 1985. A plantation performance assessment guide for the Prince Rupert Forest Region. B.C. Min. For., Land Manage. Rep. 35. Queen's Printer Publications, Victoria, B.C.

Prescott, C.E. 1997. Effects of clearcutting and alternative silvicultural systems on rates of decomposition and nitrogen mineralization in a coastal montane coniferous forest. For. Ecol. Manage. 95(3):253–60.

Pritchett, W.L. and R.F. Fisher. 1987. Properties and management of forest soils. 2nd ed. John Wiley & Sons, New York, N.Y.

SAS Institute Inc. 1988. SAS/STAT user's guide. Release 6.03 ed. Cary, N.C.

Trowbridge, R.L., B. Hawkes, A.M. Macadam, and J. Parminter. 1986. Field handbook for prescribed fire assessments in British Columbia: logging slash fuels. B.C. Min. For., Land Manage. Handb. 11. Queen's Printer Publications, Victoria, B.C.

Trowbridge, R.L., J.M. Kranabetter, A.M. Macadam, J. Battigelli, S. Berch, W. Chapman, R. Kabzems, P.M. Osberg, and P. Sanborn. 1996. The effects of soil compaction and organic matter retention on long-term soil productivity in British Columbia. B.C. Min. For., Smithers, B.C. Establishment Rep.

Van Wagner, C.E. 1982a. Practical aspects of the line intersect method. Can. For. Serv., Petawawa Natl. For. Inst. Rep. PI-X-12.

Van Wagner, C.E. 1982b. Graphical estimation of quadratic mean diameters in the line transect method. For. Sci. 28: 852–55.

Viro, P.J. 1974. Effects of forest fire on soil. *In* Fire and ecosystems. T.T. Kozlowski and C.E. Ahlgren (editors). Academic Press, New York, N.Y., pp. 7–46.

Yole, D., J.M. Kranabetter, and A.M. Macadam. 1997. Alternatives to broadcast burning in the interior: 5th year results. B.C. Min. For., Smithers, B.C. Progress Rep.

Yole, D. and A.M. Macadam. 1993. Alternatives to broadcast burning in the interior. B.C. Min. For., Smithers, B.C. Establishment Rep.

Zackrisson, O., M. Nilsson, and D.A. Wardle. 1996. Key ecological function of charcoal from wildfire in the Boreal forest. Oikos 77:10–19.