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**EFFECTS OF HARVESTING, PRESCRIBED BURNING  
AND WILDFIRE ON SOIL CHEMICAL PROPERTIES  
IN NORTHWESTERN ONTARIO**

by

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**A Thesis Submitted**

**In Partial Fulfillment of the Requirements**

**for the Degree of Master of Science in Forestry**

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## ABSTRACT

Stronach, R. W. 1996. Effects of harvesting, prescribed burning and wildfire on soil chemical properties in northwestern Ontario. 150 pp. Advisor: Dr. M. H. Johnston.

Key Words: fire severity, full-tree harvest, prescribed fire, soil chemistry, wildfire

Soil chemistry responses to disturbances were quantified and compared at two dates by sampling the organic, 0-5 cm and 5-10 mineral soil layers in a northwestern Ontario boreal mixedwood site. The disturbance treatments were as follows: (1) **Control**, 70 year old mixedwood stand dominated by white spruce (*Picea glauca* (Moench) Voss) and balsam fir (*Abies balsamea* L. Mill.); (2) **Harvest**, full- tree logged cutovers in winter; (3) **Prescribed Burn**, cutovers which were burned in early spring; (4) **Reburn**, cutovers which were prescribed burned and subsequently experienced a wildfire; (5) **Wildfire**, crown fire in vegetation similar to that of the Control. The severity level of the three fire treatments, as determined by depth of organic layer mineralized, was lowest for the Wildfire, moderate for the Prescribed Burn and high for the Reburn. The hypotheses under investigation were that the magnitude of change in soil chemical properties is greater following fire than full-tree harvesting and increasing fire severity increases the degree of change in soil chemical properties.

Organic layer soil reaction was significantly higher by one pH unit, in the three fire treatments than in the Harvest treatment for June and in the Harvest and Control treatments in August. All three fire treatments had a significantly higher amount of available phosphorus than the Harvest and Control treatments in the organic layer sampled in June. Elevated amounts of calcium and potassium in the organic layer sampled in June of the fire treatments resulted in significant differences between them and the Harvest treatment while the difference in magnesium was significant among the fire treatments and Harvest and Control. These significant differences among treatments in available phosphorus and cation levels did not persist to the August collection period.

There were no significant differences among fire treatments for the organic layer sampled in June but variables that the ordination suggested were responsible for separating the fire treatments included organic matter content and total nitrogen. Cation exchange capacity was significantly higher in the Wildfire and Control treatments than in the Prescribed Burn, Reburn and Harvest treatments for the organic layer sampled in August. The cation exchange capacity and total nitrogen for the Wildfire increased significantly between June and August and may be the result of a delay in the addition of ash and particulate organic matter to the forest floor from combustion which occurred in the tree crowns. Organic matter content, as estimated by loss on ignition, was significantly lower in the Reburn treatment compared to the Control in August; suggesting greater volatilization of carbon occurred in this treatment than in the other two fire treatments.

Potassium, the cation with the highest solubility, was significantly lower in the Control than the other treatments for the 0 - 5 cm mineral soil layer sampled in June. The Reburn treatment had the highest amount. For the 5 - 10 cm layer sampled in June there was not a significant difference in the level of potassium. In August the level of potassium in the 5 - 10 cm mineral soil layer was significantly higher in the Control and Wildfire treatments compared to the Harvest, Prescribed Burn and Reburn treatments. The amount of potassium in the Wildfire treatment increased significantly between dates.

Calcium was significantly lower in the Control than in the Harvest, Prescribed Burn and Reburn treatments in the 0 - 5 cm mineral soil layer sampled in August.

*Disturbance characteristics* affected the amount and timing of nutrient inputs into the soil profile as well as the amount lost from the site. Differences were most evident in the organic layer because it was directly affected by the disturbances. The full-tree harvest treatment was most similar to the Control at both sample dates than were the fire treatments. Severity and type of fire had an impact on the differences among fire treatments and among them and Harvest and Control. The results indicate that full-tree harvesting alone did not result in the same magnitude of change as fire in its effects on soil chemistry. Increasing fire severity affected the amount of organic matter and total nitrogen lost and the levels of cations released. Type of fire affected the timing of nutrient inputs and affected cation exchange capacity and total nitrogen concentrations. These differences need to be considered when trying to emulate natural disturbances in forest management activities.

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## INTRODUCTION

Ontario entered a new era of forest management when the Crown Forest Sustainability Act replaced the Crown Timber Act in 1994. One of the guiding principles included in the Act was the following:

“the long term health and vigour of Crown forests should be provided for by using forest practices that, within the limits of silvicultural requirements, **emulate natural disturbances** and landscape patterns while minimizing adverse effects on plant life, animal life, water, soil, air, and social economic values” (p.1, emphasis added).

In boreal forest ecosystems, fire is the primary source of natural disturbance (Heinselman, 1981).

Due to the frequent occurrence of fire on the landscape and the prevailing cold climate, boreal forest ecosystems have developed a dependence upon fire for a major portion of their nutrient cycling requirements and vegetative composition (Rowe and Scotter, 1973; Wright and Heinselman, 1973; Ward and Tithecott, 1993). Plants evolved regeneration and survival strategies in response to repeated fire events (Rowe and Scotter, 1973). Fire effects on soils include changes in chemical, physical and biological properties (Ahlgren and Ahlgren, 1960; Wells *et al.*, 1979). Both the structure and function of boreal forest ecosystems are influenced by fire.

The ecological impacts of fire are dependent upon many factors such as season, weather, site conditions, and fuel characteristics which influence fire behavior (Ahlgren and Ahlgren, 1960; Wells *et al.*, 1979). These factors interact before, during and after fire to create a unique disturbance event and associated ecological impacts.

Timber harvesting, however, has become a major agent of disturbance in the intensively managed zone of Ontario's boreal forest (Ward and Tithecott, 1993). A combination of increased



fire suppression and development of mechanical harvesting systems has led to the increase. The ecological consequences of this disturbance agent are not fully understood.

In order for forest management to emulate fire disturbances on the landscape, resource managers require quantitative information concerning the ecological impacts of fire over the range of fire disturbances that occur in the boreal forest. In addition, they need to know what the ecological effects of present management activities are. Only when both disturbance agents are understood will emulation of natural disturbances be possible.

Soil chemistry is a critical ecosystem property that is affected by harvesting and fire (Ahlgren and Ahlgren, 1960; Stone, 1973). Presently, limited information exists concerning the quantitative effects of these disturbances on soil chemistry and their duration in northwestern Ontario.

Although fire ecology research has been limited, there is a substantial knowledge base of fire behavior under various weather, site and fuel conditions (Chandler *et al.*, 1983; Johnson, 1992; Van Wagner, 1990). The reason for extensive fire behavior research was the need to suppress fire to protect the forest resource. Research into the ecological effects of fire should be correlated with quantified disturbance characteristics and fire behavior so the results may be extrapolated to other burning conditions and also be useful for fire effects prediction (Alexander, 1989; Whelan, 1995).

In response to the need for fire ecology and forest management impact research on soil chemistry, this research project was initiated and a study site identified near Radio Lake in northwestern Ontario. This site was selected for the following reasons: (1) the area had experienced a range of disturbances: mechanical harvesting, wild fire, prescribed fire in cutover and multiple fires in cutover; (2) there were uncut stands remaining that matched the vegetation present before the disturbances occurred; (3) information was available concerning fuel consumption and fire behavior; (4) comprehensive weather data were available; (5) all disturbances occurred on similar soil types.

The study site offered the opportunity to investigate four questions: (1) Are the effects of harvesting and fire on soil chemistry similar? (2) How do fires of varying severity and type affect soil chemistry? (3) How do disturbances change soil chemistry as compared to conditions in a mature stand? (4) Does the disturbance affect which soil chemical properties change with time and how much?

The objectives of this study were as follows: (1) to quantify the soil chemical properties on a site which had been subjected to a range of disturbances and relate that information to the characteristics of the disturbance events; (2) to compare all disturbances to a mature stand (Control) to determine how much change each disturbance caused; (3) to compare soil chemistry among disturbances to identify relative differences; (4) to compare the soil chemistry of each disturbance between sample dates to determine changes over time.

The hypotheses which were investigated include: (1) the magnitude of change in soil chemical properties resulting from fire disturbance is greater than that from full-tree harvesting; (2) the degree of change in soil chemical properties increases with increasing fire severity.

## LITERATURE REVIEW

The purpose of this chapter is to review the literature on the effects of disturbance on soil chemistry in the boreal forest and the environmental factors which influence these effects.

Emphasis is given to studies which quantify the disturbance and the resulting short term changes to soil chemistry.

Disturbances indirectly and directly affect soil chemistry (Raison *et al.*, 1990). Indirect effects are those that result due to changes in soil physical and biological properties by disturbance and subsequently from the modified environmental conditions (Raison *et al.*, 1990). Direct effects are the immediate changes in soil chemistry which result from disturbance. These changes are first evident in the organic layer of a soil profile because it is in direct contact with the disturbance. Depending on the extent of the disturbance, the A-horizon of the mineral soil may also be directly affected. With time, the effects of disturbance are measurable deeper in the mineral soil profile because of the movement of nutrients and organic matter in soil water (MacLean *et al.*, 1983).

The soil chemical properties affected by disturbances include: (1) cation exchange capacity (CEC); (2) plant available nutrient capital; (3) soil reaction (pH); and (4) base saturation (BS) (Ahlgren and Ahlgren, 1960; Wells *et al.*, 1979). These soil chemical properties are not independent, therefore, changes in one affect the others. The extent, duration and significance of changes in these soil chemical properties are dependent upon (1) soil characteristics; (2) disturbance event; and (3) post-disturbance environment (Ralston, 1971; Raison, 1979).

## CATION EXCHANGE CAPACITY

Cation exchange capacity (CEC) is a measure of the ability of a soil to adsorb cations (Brady, 1990). Cation exchange capacity is a function of the amount of negative charge present on clay and humus in the soil. These particles are colloidal in nature and have a large surface area to volume ratio, with humus having a greater CEC than clay on a per weight basis (Brady, 1990). The level of CEC of a soil as well as the base saturation helps determine the amount of nutrients which can be retained following disturbance.

There is also an anion exchange capacity associated with soil that is responsible for the retention of nutrients which occur as anions, such as phosphorus ( $\text{H}_2\text{PO}_4^-$ ,  $\text{H}_2\text{PO}_4^{2-}$ ) and nitrate nitrogen ( $\text{NO}_3^-$ ). In comparison to CEC it is much smaller (Brady, 1990).

The strength with which dissolved nutrient ions are held on exchange surfaces depends on their ionic potential (monovalent versus divalent), the charge of the ion (positive or negative), and the relative amounts of each ion in solution (Wiklander, 1980). Nutrients may be replaced on exchange sites by: (1) mass action: excess cations will take precedence and occupy exchange sites; (2) hydrogen ions generated from the formation of acids; (3) preferential adsorption when present in equal quantities: the order according to valence is  $\text{H}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+ = \text{NH}_4^+ > \text{Na}^+$  (Brady, 1990)

Fire disturbance initially affects CEC by causing a reduction and redistribution of organic matter and changes in soil reaction. Cation exchange capacity usually increases with pH because hydrogen is ionized and becomes replaceable (Brady, 1990). Conversion of undecomposed organic matter, to stable humus by microorganisms also results in changes in CEC; this can occur following either harvesting or fire (Woodmanese, 1981).

## BASE SATURATION

Base saturation is the proportion of the cation exchange capacity occupied by cations other than  $H^+$  and  $Al^+$  (Brady, 1990). The addition of nutrients in cation form to the soil following disturbance affects the base saturation level. A strong correlation exists between base saturation and pH. As base saturation decreases, the pH is usually lowered and the buffering capacity is increased due to the increased level of hydrogen on the exchange sites (Brady, 1990). The active acidity of the soil is very sensitive to change when the base saturation is high. Retention of cations released by disturbance on exchange sites is also dependent on the soil's buffering capacity.

## SOIL REACTION

There are two major kinds of soil reaction: active acidity and reserve acidity. Active acidity refers to the pH of the soil solution while reserve acidity refers to the pH of the soil colloids (Brady, 1990). As hydrogen ions in the soil solution are depleted, they are replaced by hydrogen ions held on exchange sites of soil colloids. Changes in active acidity require a large shift in the ratio of cations to hydrogen ions to overcome the buffering capacity of the soil (Wells, *et al.*, 1979).

The addition of cations to the soil following a disturbance may result in pH increases. The magnitude of change in pH is much greater following fire because of the large amount of cations rapidly added to the soil solution following the event. The active acidity is affected first followed by the reserve acidity if the concentrations of cations is sufficient. Increases in soil pH alter soil nutrient availability because of its effect on solubility and decomposition rates (Raison *et al.*, 1980; MacLean *et al.*, 1983; Kimmins, 1987).

## AVAILABLE NUTRIENT CAPITAL

The release of unavailable nutrients by disturbance is of great consequence to boreal forest ecosystems. In mature boreal forests, soil nutrient availability is low because of slow decomposition, fixation and weathering rates (Kozłowski *et al.*, 1991). Boreal forest soils tend to be acidic and low in phosphorus and nitrogen availability (Viro, 1974.). Nutrients which often increase in availability following disturbance include nitrogen, phosphorus and metallic cations, such as sodium, calcium, potassium and magnesium (Ahlgren and Ahlgren., 1960; Likens *et al.*, 1970). Retention of nutrients within the soil body depends upon the CEC, BS and pH (Woodmanese and Wallach., 1981).

Disturbances such as fire and harvesting often decrease total site nutrient capital but increase the amount of available nutrient capital (Kimmins, 1987; MacLean *et al.*, 1983). In the case of fire the increase in available nutrients is usually rapid and of a greater magnitude than that resulting from the increase in organic matter decomposition after harvesting (Wells, 1971).

Mass action is the exchange principle at work when this initial pulse of nutrients enters the soil solution following a fire disturbance. In addition to the immediate release of nutrients from the mineralization of organic matter by fire, there is an increased rate of organic matter decomposition following fire due to more favorable environmental conditions (Woodmanese and Wallach, 1981). Preferential adsorption in the mineral soil becomes important when the nutrients are released at a slower rate from microbial decomposition after harvesting and fire.

## SOIL CHARACTERISTICS

Soil characteristics important in determining the effects of disturbance on soil chemical properties include: depth and makeup of organic layer (proportions of litter, fermented material and humus); organic matter content in mineral soil horizons; nature of mineral soil horizons (textures, parent material, depths and horizon designations); secondary soil structure; and pre-disturbance soil chemical properties (buffering capacity, BS, pH, CEC, anion exchange capacity) (Grier, 1975; Wells *et al.*, 1979; Raison *et al.*, 1980). These soil characteristics affect infiltration rates, drainage, water storage capacity, fertility, nutrient retention and resistance to changes in soil chemistry (Wells *et al.*, 1979; Brady, 1990).

The effects of a disturbance on soil chemical properties are dependent upon the particular soil being affected and the severity of the disturbance event. Soils low in organic matter and nutrient availability are usually much more sensitive to disturbance than are nutrient rich sites (Raison *et al.*, 1990).

## DISTURBANCE EVENT

The nature of the site and the characteristics of the disturbance event determine the extent of the resulting changes in soil chemistry (Christensen, 1987; MacLean *et al.*, 1983). The interaction of all the variables involved creates a unique disturbance event and its associated results. The following sections discuss the specific disturbance factors which determine how and to what degree fire and harvesting affect soil chemistry. In addition studies which provide particular examples of the effects of fire and full-tree harvesting on soil chemistry are reviewed.

## Fire

The central issues when considering the effects of fire on soil chemistry are the degree of combustion and the amount and type of organic material being mineralized. Combustion is the oxidation of organic matter into its inorganic constituents with light and heat as by-products of the reaction (Chandler *et al.*, 1983). The degree of combustion refers to the completeness of the mineralization process and determines the proportions of organic and inorganic residues remaining after a fire. Factors affecting combustion include: fuel and site characteristics, season, climate, and weather (Ahlgren and Ahlgren., 1960; Johnson, 1992). The interaction of these factors, both before and during burning, affect the type and severity of fire that occurs.

Types of fire include ground, surface and crown fires, and refer to the location of combustion (Kozlowski, *et al.*, 1991). Within each type of fire there are head, flank and back fires which refer to the direction of fire movement relative to the wind. The type and direction of fire affects how long a fire burns in one spot (residence time), the rate of heat energy released (intensity), and the kind of fuel being combusted (LFH layer, surface fuels or standing vegetation) (Chandler *et al.*, 1983).

Fire severity may be defined in several ways but it is often used to characterize the ecological impacts of fire. Fire severity is usually expressed in terms of the amount of forest floor organic matter mineralized by fire. Viereck *et al.* (1979) and Dyrness and Norum (1983) defined forest floor fire severity classes as follows: (1) heavily burned (deep ash layer, forest floor material consumed to mineral soil, no discernible plant parts remaining); (2) moderately burned (organic layer partially consumed, shallow ash layer present); (3) lightly burned (forest floor charred but original form of mosses and twigs visible); (4) scorched (moss and other plants brown or yellow but species identifiable) These classes of forest floor fire severity are subjective in nature and do



not give any indication of the amount of forest floor mineralized. Wells (1971) notes that forest floor weight loss is a more accurate measure of burn severity.

Fire intensity is a term which is often confused with fire severity. The intensity of a fire refers to the rate of energy released in the form of heat per unit length of flaming front (Byram, 1959). The severity of a fire is affected by the fire intensity but the degree depends on other variables that determine the residence time of the flaming front.

### Fuel Characteristics

Fuel characteristics affect the rate and amount of combustion that occurs during a fire and also the nutrient content of the ash. Important characteristics include: type, elemental composition of vegetation, quantity of biomass, moisture content, arrangement, and size class distribution (Rothermel, 1972; Woodmanese and Wallach, 1981; Chandler *et al.*, 1983; Johnson, 1992).

Types of fuel available for combustion include woody material lying on forest floor, forest floor vegetation, forest floor organic matter (LFH layer), and shrub and tree vegetation (dormant, living and dead) (Wright and Heinselman 1973). The vegetative composition of these fuels also has an impact on combustion due to the chemical nature and moisture storage capacity of foliage of different species (Chandler *et al.*, 1983).

The chemical composition of the fuel determines its flammability as well as the elemental composition of the ash resulting from mineralization (Chandler *et al.*, 1983). In general needles are more flammable than leaves and foliage has a higher concentration of nutrients than wood (Alban *et al.*, 1978; Chandler *et al.*, 1983).

The quantity of fuel is measured in kilograms per square metre ( $\text{kg m}^{-2}$ ). To quantify surface and ground fuels, the line intersect sampling method developed by Van Wagner is used (Van Wagner, 1982; McRae *et al.*, 1979). The quantity of standing fuel is determined by using

species-specific individual tree biomass equations (e.g. Alemdag, 1982). The total amount of fuel present determines the maximum energy available to a fire (Whelan 1995); areas of high fuel accumulation tend to burn with greater severity (Dyrness 1989).

Moisture content is an important fuel characteristic because before fuel can burn the moisture must be driven off. Fuel moisture depends on the type, size, and state of the fuel (living, dead, rotten) as well as the length of time since the last rainfall and the weather conditions which control drying (Chandler *et al.*, 1983).

The spatial arrangement of fuels affects the potential spread of a fire. The horizontal arrangement of fuels determines whether or not a fire will continue to carry across the surface. Vertical arrangement of fuels affects the potential for fire to climb into tree crowns (Chandler *et al.*, 1983).

The size class distribution of the fuels affects the residence time of the fire and its ability to spread. Fine fuels have a higher surface to volume ratio which means they dry faster, burn quicker and more completely. Larger diameter fuel pieces take longer to dry, burn less completely but burn for a longer period of time (Chandler *et al.*, 1983).

### Site Characteristics

The topography of a site in combination with wind speed and direction determines how fast a fire will spread and in which direction. Fire spreads quicker upslope because of the convective properties of hot air which result in the preheating of fuels upslope (Chandler *et al.*, 1983). Slope aspect and elevation affects daily air temperature and moisture relations on the site, as well as determining when the site “greens up” in the spring and becomes dormant in the fall (Whelan, 1995).

## Weather

Weather variables of importance to the behavior and severity of a fire include temperature, precipitation, wind speed and direction, and relative humidity. These variables have an effect before, during and after a fire event. Before and during a fire they affect the moisture content of the fuel which influences the combustion process. Precipitation increases moisture content while solar radiation, air temperature, wind speed and relative humidity affect the rate at which fuels dry (Chandler *et al.*, 1983). During the fire event, wind speed and direction affects fire spread rates and residence times while air temperature and relative humidity continue to affect fuel drying.

The Canadian Forest Fire Weather Index (FWI) System uses air temperature, relative humidity, precipitation, wind speed and wind direction as variables. It is one module of the Canadian Forest Fire Danger Rating System (Stocks *et al.*, 1989). The FWI System was developed to provide a national system for rating fire danger and consists of three codes and three indices that account for the effects of fuel moisture and wind on fire behavior (Stocks *et al.*, 1989).

The three codes and three indices of the FWI System include: Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), Drought Code (DC), Initial Spread Index (ISI), Buildup Index (BUI) and Fire Weather Index (FWI) (Stocks *et al.* 1989). Fine fuel moisture code, DMC and DC represent the fuel moisture content of fine surface fuel, loosely compacted duff of moderate depth and deep compacted organic matter, respectively (Stocks *et al.* 1989). The fuel moisture codes are numerical ratings expressed on scales related to actual fuel moisture (Van Wagner, 1977). Initial Spread Index, BUI and FWI are fire behavior indices and represent rate of fire spread, fuel available for combustion and frontal fire intensity, respectively (Stocks *et al.*, 1989). The ISI combines the effects of wind and fuel moisture as represented by the FFMC while BUI combines DMC and DC. The FWI, which combines ISI and BUI, represents a relative

measure of the potential intensity of a single spreading fire in a standard fuel complex (Stocks *et al.*, 1989).

Critical values for the fuel moisture codes include: if the FFMC is less than 74, fire will not spread in surface fuels; DMC must be greater than 20 for the duff layer to contribute to frontal fire intensity; DC must be greater than 400 for subsurface fire activity to persist (Stocks *et al.*, 1989). In Ontario fire danger classes are based on FWI values as follows: low, 0-3; moderate, 4-10; high, 11-22; extreme, 23+ (Alexander, 1982).

### Products of Combustion

The products of combustion which affect soil chemical properties directly and indirectly are as follows: (1) heat; (2) volatilized gases; (3) ash (inorganic and organic particulate matter); (4) reduction and redistribution of soil organic matter (5) blackening of forest floor surface and (6) death of standing timber (MacLean *et al.*, 1983). Unique fuel, site and weather conditions, present at a point in time and space, all interact to create burning conditions which result in these impacts to varying degrees.

The heat released during combustion raises adjacent fuel to the ignition temperature and breaks down fuel chemical structure, which may result in volatilization loss of nutrients from a site (Rundel, 1978). Volatilization is the change of a solid to a vapor, and each element and compound has an associated temperature at which this occurs. The relative amount of each element volatilized is dependent upon the temperatures reached during the fire and the length of time the fuel remains above a critical threshold (Raison, 1979).

Approximate volatilization temperatures for elements of interest include: 200 °C for H, O, C, N and S, approximately; 774 °C for P and K; 880 °C, Na; 1107 °C, Mg; 1484 °C, Ca (Raison *et*

*al.*, 1990). Lower molecular weight compounds and lighter atomic elements are volatilized first. If combustion is nearly complete then most of the C, H, O, N and organic S and P are transferred to the air (Raison, 1979). The high volatilization temperatures of the cations explains why they make up the greatest proportion of ash.

Nutrient loss from a site from volatilization is significant to soil chemistry because nutrient replacement from biological fixation, atmospheric deposition and mineral weathering may be very slow. The amount of nutrients lost to volatilization is directly correlated with percent fuel weight lost and depth of forest floor consumed (Raison *et al.*, 1985; Feller, 1988). Grier (1975) reported nutrient losses due to volatilization and ash convection of 855 kg ha<sup>-1</sup> N, 75 kg ha<sup>-1</sup> Ca, 33 kg ha<sup>-1</sup> Mg, 282 kg ha<sup>-1</sup> K, and 698 kg ha<sup>-1</sup> Na following a fire which deposited an ash layer of 2900 kg ha<sup>-1</sup>. The low volatilization temperature of nitrogen makes it subject to substantial losses. This is significant because nitrogen is the element most limiting to growth in the boreal forest (MacLean *et al.* 1983). Phosphorus is also of significance because it is also limiting to growth. Replacement of phosphorus lost to the atmosphere is often slow due to low input from precipitation and weathering (Raison *et al.*, 1985).

Before fire, nutrients contained in organic matter are generally unavailable. After fire, nutrients in the ash become available in highly concentrated amounts (Wright and Heinselman, 1973). The degree to which mineralization is complete determines the relative proportions of inorganic and organic particulate matter remaining. The amount and mineral content of the ash depends on the following: quantity, species and type of fuel; degree of combustion and the amount of elements volatilized (Raison and McGarity, 1980).

Oxides of metallic cations are the most abundant compounds found in ash but some calcium carbonate is also formed during fire (Woodmanese and Wallach., 1981). Calcium is the dominant cation in ash because of its high volatilization temperature and its relatively high

abundance in nature (Ulery *et al.*, 1993.). Various amounts of silicate ( $\text{SiO}_4^{4-}$ ), phosphates (calcium polyphosphates; low solubility), sulfates ( $\text{SO}_4^{2-}$ ) and ammonium ( $\text{NH}_4^+$ ) are also found in ash but amounts are much smaller in comparison to the metallic cations (Ulery *et al.*, 1993.). The oxide compounds in ash are highly reactive and conversion to hydroxides and carbonates takes place in the absence of precipitation (Etiegni and Campbell, 1991).

The solubility of ash compounds in water is determined in part by the strength of the bonds holding the elements together. The order of solubility for the metallic elements is as follows:  $\text{Na} > \text{K} > \text{Mg} > \text{Ca}$ , with carbonate compounds being less soluble than hydroxides which are less soluble than oxides (Bohn *et al.*, 1989). Sodium and K compounds are all very soluble and are the first ones to dissociate into solution when it rains thereby causing initial soil pH increases (Woodmanese and Wallach, 1981).

The reduction and redistribution of forest floor organic matter directly affects the CEC of soil, as well as indirectly affecting other chemical properties. Conversion of the organic layer to ash by combustion produces particulate organic matter which is highly mobile (Wells, 1971). Percolation of this particulate organic matter into the mineral soil increases mineral soil CEC while decreasing the CEC of the organic layer (Smith, 1970). However, if fire is severe enough, previously incorporated organic matter in the upper mineral soil layers may also be consumed (Dymess, *et al.*, 1957).

Exposure of mineral soil from the complete loss of the forest floor and the subsequent increase in precipitation reaching the soil surface may cause blockage of macropores because of the direct impact of raindrops (Ralston, 1971). This often results in decreased aeration, water infiltration rate, and water storage capacity which may lead to increased overland flow and erosion (Wells *et al.*, 1979).

The reduction in organic matter, blackening of the soil surface, addition of charcoal and death of standing timber from fire changes soil temperature and moisture relations (Wells *et al.*,

1979; Woodmanese and Wallach, 1981). After fire, the minimum and maximum soil temperatures are greater because of the loss of soil insulation, greater insolation received by the soil, and the decreased albedo of the soil surface (Ahlgren and Ahlgren 1960; Armson 1979; Kimmins, 1987). Increased soil temperature results in higher evaporation rates and greater microbial decomposition which is an ongoing source of available nutrients (Wright and Heinselman 1973; MacLean *et al.* 1983).

### Fire Studies

Research into the effects of fire severity on the organic soil layer in experimental plots of black spruce (*Picea mariana* (Mill.) B.S.P.) forest in the interior of Alaska has measured forest floor depth before and after fire ignition (Viereck *et al.*, 1979). Their study found that increases in available phosphorus were related to the amount of forest floor reduction and that prefire moisture content was the fuel characteristic most responsible for determining fire severity. Table 1 shows the relationship between forest floor reduction and available phosphorus content in the organic layer (Viereck *et al.*, 1979). The study also reported high variability in the amount of forest floor consumed during the experimental fires which affected the amount of area in each burn severity

Table 1. Relationship between forest floor depth reduction and increase in available phosphorus. (adapted from Viereck *et al.*, 1979)

	Control	Plot 1	Plot 2	Plot 3	Plot 4
Thickness before burning (cm)		21.6 ± 0.67	19.8 ± 0.57	23.2 ± 0.66	22.4 ± 0.67
Thickness after burning (cm)		11.6 ± 0.68	14.9 ± 0.72	7.8 ± 0.55	7.2 ± 0.49
Reduction in thickness (%)		43	24	61	62
Available Phosphorus (mg kg <sup>-1</sup> )	44.2	448.1	173.6	314.2	433.4

class. The amount of area heavily burned ranged from 2 % to 49 % (Viereck *et al.*, 1979). In a study by Dymess (1957) 8% of a Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) cutover area was heavily burned during a prescribed burn.

In northern Ontario, a study of the concentration of soil nutrients before and after a fire was conducted on a sandy podzol which had been subjected to a surface fire (Smith, 1970). Details of fire behavior and severity were not reported. Samples collected 36 days after the fire from the organic, 0-2 cm and 2-6 cm layers are of most relevance to this study. Precipitation between the fire and first sampling date was 60 mm.

Organic matter losses were greatest in the organic layer; the decrease was on the order of 50 - 60 % following the fire with a further decrease of 5- 10 % between the two post-fire sampling dates. In the 0 - 2 cm mineral soil layer reduction in organic matter was on the order of 1 % following the fire and remained so at the second post-fire sample collection. An increase of



approximately 1 % in organic matter was recorded for the 2 - 6 cm layer following the fire (Smith, 1970).

A decrease in CEC of the organic layer was measured four days after the fire and at the same time an increase was reported in the 0-2 cm mineral soil layer. The lower mineral soil layers showed an increase in CEC five weeks after the fire (Smith, 1970).

The pH of the organic layer (ash + unburned organic matter) increased from 3.9 - 4.1 to 5.2 - 6.1 after the fire and remained above 5.0 at the second sampling date. Increases in soil pH at the 0 - 2 cm and 2 - 6 cm mineral soil levels were not evident at the first post fire sampling date but had increased by 0.1 to 0.3 pH units by the second sampling date (Smith, 1970).

Potassium and Ca levels increased 395 % and 271 %, respectively in the organic layer four days after the fire. Five weeks after the fire K and Ca levels decreased but remained above preburn levels. At 0-2 cm depth, the level of K and Ca increased 132 % and 240 %, respectively four days after the fire. Increases in Ca at soil depths between 2 and 12 cm occurred between 3 and 10 months after burning. Base saturation increased immediately following the fire in the organic and 0 -2 cm layers. A similar pattern was evident lower in the mineral soil profile, five weeks and three months later (Smith, 1970).

Iron increased by 192 % over preburn levels immediately after the fire but declined below preburn levels at subsequent sampling dates in the organic layer. Increases in available P were 488 % and 123 % for the organic and 0 - 2 cm layers, respectively. At the second sampling date decreases in organic layer available P coincided with increases in phosphorus in the upper 0 -12 cm of mineral soil (Smith, 1970).

In a study of a wildfire which passed through stands of white spruce (*Picea glauca* (Moench) Voss), black spruce, paper birch (*Betula papyrifera* Marsh.) and quaking aspen (*Populus tremuloides*, Michx.) in the interior of Alaska, Dymess *et al.* (1989) quantified soil chemical properties one to three weeks after. Fire behavior measurements were not reported and

subjective burn severity classes were used. The organic layer and mineral soil layer (0 - 5 cm) were sampled.

Dymess *et al.* (1989) reported increases in forest floor pH under the four stand types. Surface mineral soil pH under the white spruce stands that were heavily burned also increased. Severity of fire was related to the increase in forest floor pH. In the case of the white spruce stand the following pH values were reported: control, 5.4; lightly burned, 6.0; heavily burned, 8.3. Increases in pH were proportional to the amount of organic matter reduction and cation addition (Dymess *et al.*, 1989).

In white spruce plots that were heavily burned, the amount of total N in the forest floor was reduced by 50 % while N in the surface mineral soil layer remained about the same (Dymess *et al.*, 1989). Available P increased in lightly burned white spruce plots but remained about the same in heavily burned. Increases in exchangeable K, Ca, and Mg in the organic layer were related to burn severity; in the white spruce plots increases ranged from four to 13 fold. The 0 - 5 cm mineral soil layer on the heavily burned white spruce plots also experienced increases in cation levels (*e.g.* K increased by 100 %). Ash from burned tree crowns and bark were an additional source of cations. Areas of high forest floor consumption were located under tree crowns and next to tree boles where organic matter accumulated (Dymess *et al.*, 1989).

Viro (1974) found that pH increased from 4.0 to 6.0 after fire in the forest floor and by 0.4 units in the underlying mineral soil on a boreal forest site in Finland. The increase in pH persisted for 50 years in the forest floor and for 20 years in the mineral soil.

Wells (1971) studied the effects of repeated prescribed burning over a period of twenty years and found that although there was a loss of forest floor organic matter, the organic matter content of the 0-5 cm and 5-10 cm mineral soil layers increased. Annual burning resulted in a greater decrease than periodic burning, and summer burning resulted in greater forest floor reduction than winter burning (Wells, 1971).

### Harvesting

Harvesting may affect soil chemistry by removing nutrient capital, adding logging slash to the forest floor, disturbing and compacting the soil, decreasing nutrient and water uptake by plants, and modifying soil moisture regime and temperature (Weetman and Webber, 1971; Stone, 1973; Bormann *et al.*, 1974; Alban *et al.*, 1978). The extent of these effects is dependent upon the harvesting system and equipment used, vegetation being harvested, and the time of year cutting is completed (Brown, 1973). These modified environmental conditions most often favour soil organic matter decomposition and nutrient mineralization (Waring and Schlesinger, 1985; Likens *et al.*, 1978).

Full-tree clearcut harvesting removes a large proportion of the nutrient capital contained in tree biomass (Waring Schlesinger, 1985; Weetman and Webber, 1972). Season of logging determines the physiological state of the vegetation being logged, which in turn affects where nutrients are concentrated and how much is removed. Season also affects the amount of physical disturbance to the forest floor by logging equipment which in turn affects soil structure and porosity. Changes in these soil characteristics may lead to decreased infiltration, aeration and water storage capacity as well as increasing the potential for surface soil erosion (Brown, 1973).

Harvesting does not result in the same magnitude of change in soil chemical properties as fire. There is not the initial pulse of nutrients added to the soil that occurs following a fire. However, the mineralization of organic matter by microbes does increase due to higher soil temperatures and the addition of logging slash which contains high concentrations of nutrients (Waring and Schlesinger, 1985).

The flush of nutrients resulting from the increased rate and amount of decomposition after harvesting is known as the "assart effect" and begins one to two years following harvesting

(Kimmins, 1987). It continues until the microclimatic conditions at the soil surface approach those in a closed canopy stand or when organic matter has been mineralized or humified or contained in stable microbial biomass (Covington, 1981; Anderson, 1985; Kimmins, 1987).

### Full-Tree Harvesting Studies

Soil nutrient availability in the forest floor was compared between mature a white spruce stand and one that had been harvested less than a year before sampling in the interior of Alaska (Pare and Van Cleve, 1992). The only statistically significant differences between the two sites was cumulative soil temperature and the concentration of exchangeable K (Pare and Van Cleve, 1992).

A study comparing pH and cation levels between standing timber (230 year old balsam fir, white birch and white spruce) and full-tree harvested cutovers on clayey sites (dry to fresh and moist) was completed in northern Quebec by Brais *et al.* (1995). Sampling was done five to twelve years after harvesting. The pH and concentration of available bases of the forest floor and 0 - 10 cm mineral soil on dry to fresh sites were not significantly different between uncut and cut sites. Harvesting reduced forest floor weight which resulted in significant decreases in the reserve amounts of exchangeable and total Ca and total K (Brais *et al.*, 1995).

Nykvist and Posen (1985) examined the effects of clear-felling and clear-felling with slash removal on soil chemistry on spruce sites in Sweden one year after harvesting. Both clear-felling and clear-felling with slash removal resulted in pH increases in the forest floor. However, the increase was less in the clear-felling with slash removal treatment: control pH = 3.8; clear-felling with slash removed pH = 4.1; clear-felling pH = 4.15. Differences in mineral soil pH were less evident one year after harvesting.

Johnson *et al.* (1991) studied the effects of whole-tree logging on exchangeable cations and soil acidity by sampling immediately before and three years after harvesting in a northern hardwood forest. In the humus layer, CEC decreased 23 %, BS decreased from 49 % to 39 % and pH decreased 0.11 units. However, dilution of this layer with mineral soil is the suspected reason for the declines. In the A horizon, CEC declined by 24 %, BS decreased from 22 % to 17 % and pH declined by 0.32 units. The B horizon showed an increase in CEC of 67 % which explained why the CEC of the entire soil body did not appreciably decline. Base saturation of the B horizon decreased from 14 % to 11 % and pH decreased by 0.32 units. Johnson *et al.* (1991) suggested the acidification of the mineral soil horizons was due to the increased production of  $H^+$  through nitrification and mobilization of Al. Overall site fertility was not affected because of the nutrient retention of exchangeable cations by the B horizon (Johnson *et al.*, 1991).

Covington (1981) found that organic matter decreased in the forest floor during the first 15 years after clear cutting in a northern hardwood forest. The decrease in organic matter content was attributed to lower leaf and wood litterfall and to more rapid decomposition resulting from higher temperature, moisture content and nutrient levels (Covington, 1981).

Bormann *et al.* (1974) reported a 41 % decrease in organic matter content in the 0-9 cm soil layer following harvesting of a hardwood forest. They noted that the first response of a “deforested” ecosystem was the mobilization of nutrients from the available nutrient and organic matter compartments. This was followed by leakage of these mobilized nutrients in stream water and finally by erosion which increases particulate matter output from the system (Bormann *et al.*, 1974).

## POST DISTURBANCE WEATHER

The weather immediately following a fire event is of more significance to soil chemistry than weather following harvesting. The low density ash particles are highly mobile and may be lost from a site by the action of wind and overland water flow (MacLean *et al.*, 1983). Ash particles are chemically reactive so the timing and amount of rainfall after a fire determines what reactions have taken place and the concentration of nutrients in the ash leachate that enters the soil (Grier, 1975).

Precipitation following harvesting may lead to increased runoff and leaching losses (Bormann *et al.*, 1974; Anderson, 1985). This was evident in the Hubbard Brook ecosystem study in which the dissolved nutrient content in stream water increased several fold following deforestation (Likens *et al.*, 1970).

The longer-term weather affecting soil moisture and temperature following both fire and harvesting determines decomposition, nitrification and vegetation recovery rates (Likens *et al.*, 1970). Once a site is revegetated, the soil temperature and moisture levels are moderated.

## SUMMARY

Previous research has identified the soil chemical properties affected by disturbance, and the factors and processes that initiate and control these changes. However, there has not been adequate documentation of factors such as disturbance, site and weather characteristics and resulting soil chemistry responses. Therefore, caution must be used in interpreting these results (Raison, 1979). Studies that quantify and describe the above factors and the resultant soil chemistry responses are required so that reliable comparison of disturbances occurring at different points in time and space can be made and predictions tested (Wright and Heinselman 1973; MacLean *et al.*, 1983; Christensen, 1987; Whelan 1995).

The high degree of variability in the chemical and physical properties of soil also makes it necessary to sample at high intensities and use sufficient replication to obtain reliable results (Raison, 1979; MacLean *et al.*, 1983).

## METHODS AND MATERIALS

### STUDY AREA DESCRIPTION

The Radio Lake research site is located approximately 240 km north-northwest of Thunder Bay at 49° 25' north latitude and 90° 19' west longitude. Figure 1 shows the study area location in relation to northwestern Ontario.

The study area is approximately 900 hectares in size and consists of cutover blocks surrounded and separated by mature boreal mixedwood stands. The research plots were distributed over the area. Figure 2 shows the relative locations of the plots of each treatment.

The surficial geology of the site consists of two landform types both formed during the Wisconsin Glaciation period. The northern portion is part of an esker complex and is made up of sand, gravel and boulders. The southern part is an aeolian deposit of fine sand and silt. Laboratory textural analysis of the mineral soil layers (0-5 cm and 5 -10 cm) investigated showed no significant differences in texture between the two landforms and both were classified as loamy fine sands. However, horizon development may have been affected by landform differences. This was evident from the presence of a Bf horizon in the mineral soil profile of the esker complex.

The aeolian deposit was classified as an S2 while the esker complex was an SS5, according to the FEC system for northwestern Ontario (Sims *et al.*, 1989). Both soil types are well to rapidly drained and have a fresh to dry moisture regime. The humus form of both soils was a fibrimor. The topography of the area varies from gently rolling to hummocky with the low lying areas containing organic deposits (OMNR, 1994).



fibrimor. The topography of the area varies from gently rolling to hummocky with the low lying areas containing organic deposits (OMNR, 1994).

The study area escaped the last two major fires in the region which occurred in 1934 and 1980. Charcoal found in the soil profile provided evidence of past fire events and the stands likely originated from a disturbance prior to 1934.

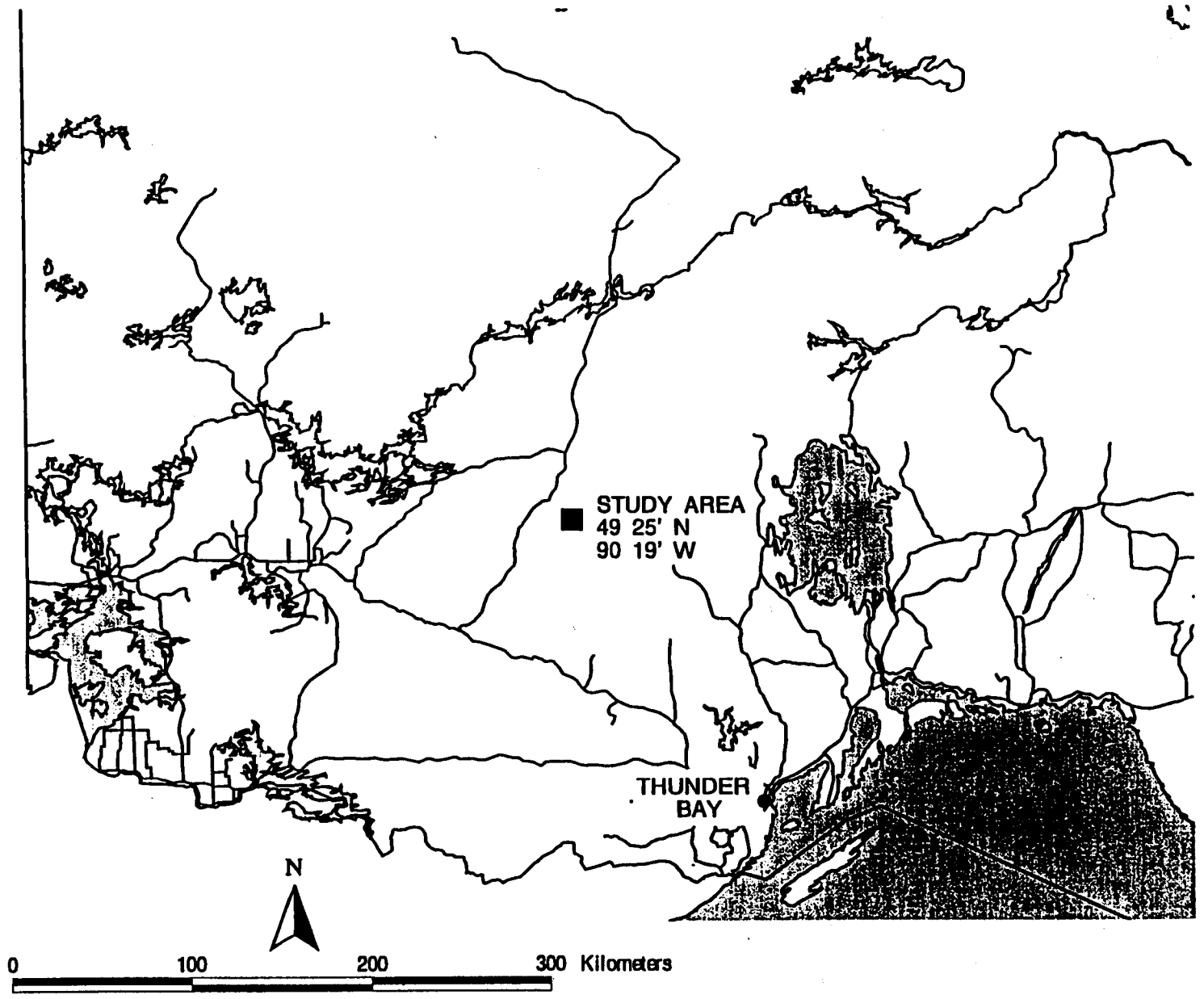


Figure 1. Location of study area in relation to northwestern Ontario.

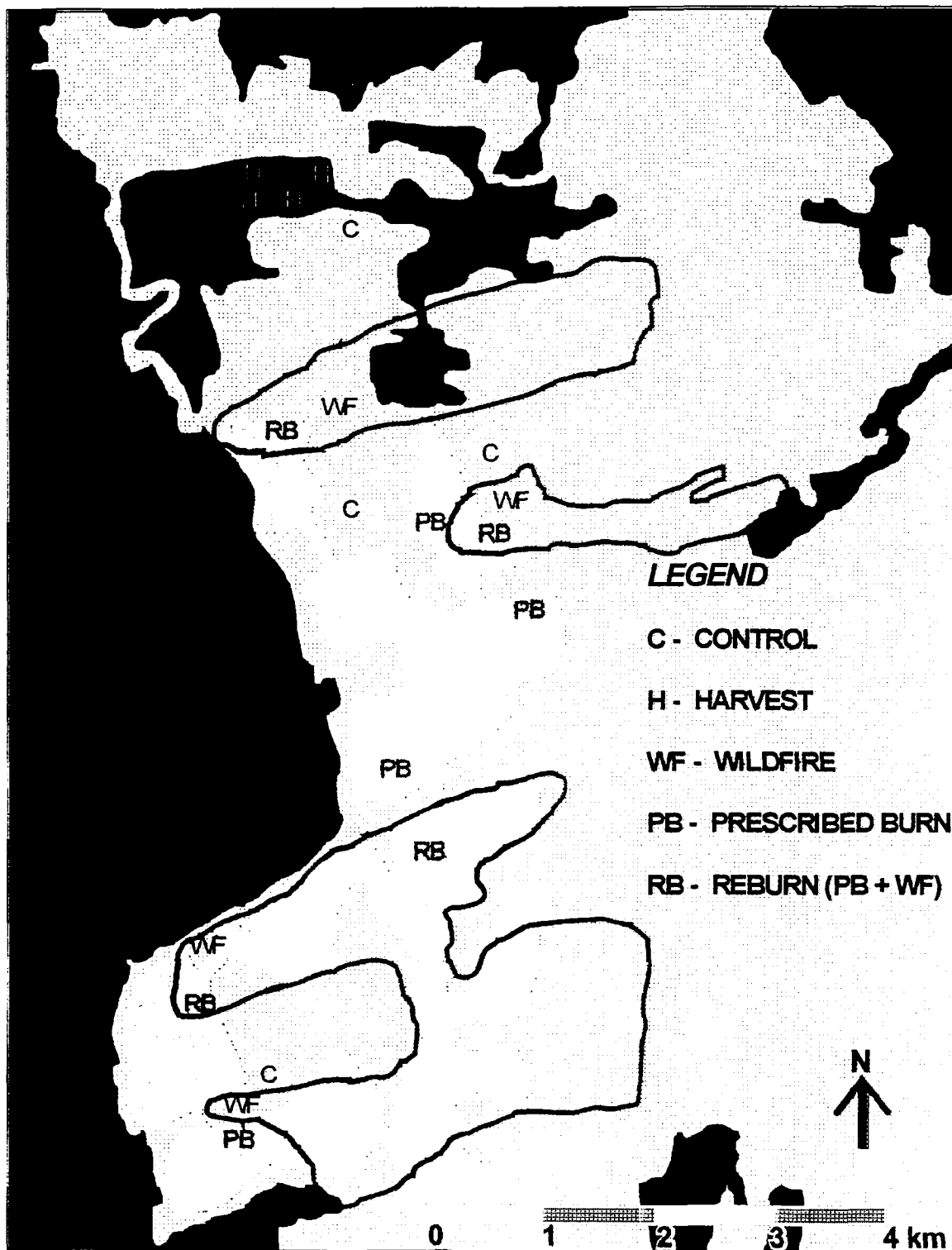


Figure 2. Location of treatment plots within the study area.

## EXPERIMENTAL DESIGN

A completely randomized experimental design was adapted to the circumstances found at the Radio Lake prescribed burn site. Five treatments were identified at the study site and four replicate plots were established randomly in each, with the restriction that they be in proximity to fuel sample locations (see below). The soil layers sampled included the organic layer (LFH), 0-5 cm mineral and 5-10 cm mineral. At every plot four sets of samples were collected. The 10 by 10 metre quadrats used for vegetation sampling served to define the plot boundary. One set of samples was taken from each side of the quadrat, with the position located randomly along the plot boundary.

Soil sampling was done in June and August. The August samples were collected next to the June sample location. Care was taken to avoid digging where the ground had been disturbed by the previous sample collection.

In total 480 soil samples were collected:

2 collection periods x 5 treatments x 3 layers x 4 replicate plots x 4 samples.

Treatments were chosen to represent a range of natural and human-caused disturbances (full-tree harvesting, prescribed fire and wildfire). A Control was included to see how the disturbances diverged from it with respect to their effect on soil chemistry. No predisturbance baseline data could be collected; thus the remaining standing timber served as a Control. The fuel triangles established as part of the prescribed burn planning process were utilized as the anchor points for locating the plots for two of the five treatments (Prescribed Burn and Reburn). The triangles provided data about fuel loading and duff depth before and after the fire and allowed for the resulting soil chemistry responses to be related to fire behavior and severity. The other two treatments included in the study were Wildfire and Full-tree Harvesting.

## Treatments

### (1) Control:

The Control consisted of 70 year old standing timber composed mainly of white spruce, balsam fir (*Abies balsamea* L. Mill.) and a minor amount of white birch. It corresponded to Vegetation Type 25 of the FEC System for Northwestern Ontario (Sims *et al.*, 1989). Mortality caused by budworm (*Choristoneura fumiferana* (Clemens)) was evident in the stands. Feathermoss (*Pleurozium schreberi* (Brid.) Mitt.) dominated the forest floor. The average depth of the organic layer was 7.7 cm. The Control plots were established in the cut buffers and moose corridors left during the logging operations and represented the stand condition and soil chemical properties before any of the disturbances investigated happened. One of the Control plots occurred on the esker complex landform.

### (2) Harvest:

The Harvest treatment represents one of the forest management practices used in the boreal forest. The Radio Lake site was mechanically harvested using a full-tree system with delimiting done at roadside. Harvesting operations were completed during the winter of 1992 -3 which minimized physical soil disturbance. The Harvest treatment was included to investigate the effects of canopy removal and slash addition to the forest floor on soil chemistry. The slash was predominantly coniferous in composition.

Cutovers were site-prepared in spring of 1994 using a Bracke scarifier. The Bracke scalps the organic layer to expose mineral soil and create planting or seeding microsites. The soil was sampled between the site prepared rows, however the effects of the machine disturbance to the ground were included in the samples to varying degrees. The average organic matter depth was 6.1 cm.

ground were included in the samples to varying degrees. The average organic matter depth was 6.1 cm.

The Harvest treatment plots were on the esker complex landform type previously described.

The harvest blocks were entering their second summer when the first soil sampling was completed.

(3) Prescribed Burn (PB):

The PB treatment was a surface fire and represents the forest management practice of burning cutovers. The objectives of the Radio Lake prescribed burn plan were to: prepare the site for artificial regeneration; reduce the fine slash fuel component; reduce the competing vegetation and reduce the residual competition and unmerchantable tree species.

The slash on the cutovers had been curing for 2 years when the Radio Lake prescribed burn was ignited on 7-8 May, 1995 using an aerial ignition device. The ignition pattern was strip headfire and backfire. The pre- and post- fire fuel levels for the plots (triangles 4, 10 and 14) in the PB treatment are presented in detail in Appendix I. A summary of this information appears in Table 2. The weather and fire indices under which the burn took place are included in Appendix II and the fire behavior measurements are in Appendix III.

(4) Reburn (RB):

Part of the cutover areas prescribed burned early in May were burned again when the fire re-ignited on 31 May and 1 June. Forest floor and woody fuel consumption was highest in this surface fire treatment. The RB treatment was therefore the most severe of the three fire treatments identified. Appendix I presents the pre- and post-fire fuel data for the plots (triangles 5, 9, 12, 13) which experienced the two burns. A summary these data is included in Table 2. Fire weather and indices for the Reburn treatment are presented in Appendix II and the fire behavior data are presented in Appendix III.

(5) Wildfire (WF):

The WF treatment represented an example of a natural disturbance in this stand type. The Control vegetation was breaking up due to mortality and had a high percentage of conifer in its composition and was therefore susceptible to fire. The wildfire was a stand replacing crown fire with a surface fire component that scorched the moss on the forest floor. The average organic layer depth for the treatment was 4.5 cm. The majority of fuel consumption in the WF was believed to have taken place in the tree crowns. Evidence to this assertion is the fact the forest floor was only scorched and the standing trees present were charred. Fuel consumption was affected by the vertical fuel arrangement, fuel loading and moisture content of the standing timber. The surface fire in the WF consumed less of the forest floor than in the PB and RB.

The weather data and fire indices for the dates of the WF treatment are presented in Appendix II and the fire behavior information is presented in Appendix III. The Wildfire occurred on May 31 and June 1, 1995. The first sample collection took place between June 20-23, 1996 and the second between August 14-18, 1996. The amount of rainfall which fell between these events as well as the other fire treatments and sample collections is presented in Appendix IV.

Table 2. Summary of fuel loading and consumption by treatment. Treatment abbreviations: PB, Prescribed Burn; RB, Reburn.

Treatment	Location	Slash Loading ( $\text{kg}\cdot\text{m}^{-2}$ ) & Percent Consumed by Size Class				Total Slash Loading & Percent Consumed		Duff Loading & Percent Consumed		Duff Depth & Percent Reduced	
		0 - 6.99 cm		7+ cm		$(\text{kg m}^{-2})$		$(\text{kg m}^{-2})$		(cm)	
PB	triangle # 4	1.8	49%	6.3	30%	8.1	34%	8.5	8%	8.0	20%
PB	triangle # 10	1.2	16%	3.5	16%	4.6	16%	18.9	17%	13.4	32%
PB	triangle # 14	1.4	0%	2.7	57%	4.1	35%	24.9	5%	16.0	14%
Mean		1.5	22%	4.1	34%	5.60	28%	17.41	10%	12.5	22%
RB	triangle # 5	3.2	62%	8.8	39%	11.9	45%	6.3	23%	6.6	39%
RB	triangle # 9	2.0	58%	3.1	23%	5.2	37%	7.8	29%	7.6	45%
RB	triangle # 12	1.3	74%	2.9	40%	4.3	50%	22.5	33%	15.0	49%
RB	triangle # 13	1.8	67%	3.9	45%	5.7	52%	10.2	44%	9.0	59%
Mean		2.1	65%	4.7	37%	6.8	46%	11.7	32%	9.6	48%



## DATA COLLECTION

Data collected at the research site consisted of weather information, fuel loading data and soil samples for laboratory analysis.

### Weather

Two weather stations were used through the course of the summer to collect weather data. During the prescribed burn a weather station was set up on site (May 6-8). After that, weather data were collected from the Wawang station which was approximately 15 kilometres west of the study site.

Weather data collected included air temperature, relative humidity, wind speed, wind direction and precipitation. The weather data were used to calculate the moisture codes and fire indices for the dates of the fires; these included: fine fuel moisture code (FFMC), duff moisture code (DMC), initial spread index (ISI), buildup index (BUI) and fire weather index (FWI).

### Fuel Loading

Fuel loadings on the cutover blocks were quantified before and after the treatments using the line intersect fuel sampling method (McRae *et al.*, 1979). Each fuel sampling plot consisted of three lines laid out as three sides of an equilateral triangle. Seven fuel triangles were utilized in this study, three for the PB treatment and four for the RB treatment.

The fuel types quantified on the site using this method consisted of three categories: woody slash, foliage retained on the slash, and duff. The woody slash measured was divided into six diameter size classes (0-0.49 cm, 0.5-0.99 cm, 1.0-2.99 cm, 3.0-4.99 cm, 5.0-6.99 cm and 7.0 + cm), according to the methodology of McRae *et al.* (1979).

Once field measurements had been made the slash fuel loading was calculated by first dividing the totals for each size class into amounts based on the species composition. There are constants for each species and size class for fresh slash and older slash which the totals are multiplied by depending on the circumstances (Blake, 1994). The year old slash constants were used. In the case of the 7 + cm class the diameters for each species tallied were squared then summed and multiplied by the appropriate species constant.

The amount of slash calculated was referred to as the uncorrected slash loading and had to be corrected for slope (McRae *et al.*, 1979). Correction factors which correspond to the percent slope measurements taken in the field were determined. The three correction factors for each triangle were averaged then multiplied by the uncorrected slash loading value to give the corrected slash loading for the triangle.

The duff loading for the triangle was found by calculating the average duff depth by type, feathermoss in this case, and inputting it to the equation for the appropriate site (McRae *et al.*, 1979). The upland black spruce equation was used;  $y = 0.3328x^{1.1021}$ , where  $y$  is the duff loading ( $\text{kg m}^{-2}$ ) and  $x$  is the average duff depth (cm).

The foliage loading was calculated by estimating the percent of foliage retained using a relationship between percent retention and slash age and multiplying it by the weight of the 0-0.49 cm size class and then multiplying by the needle to slash weight ratio (2.03 for jack pine and 1.61 for balsam fir) (McRae *et al.*, 1979).

The loadings for the three fuel types were added together to give an estimate of the total fuel loading ( $\text{kg m}^{-2}$ ). The measurements and calculations were done before and after the fire and the amount and type of fuel consumed by the fire conditions were determined by subtraction.

### Fire Behavior

Fire behavior measurements for the three fire treatments were made indirectly using the computer program Fire Behavior Prediction (FBP93; REMSOFT 1993). Frontal fire intensity and forward rate of fire spread were calculated for the three fire treatments. The inputs for this program included the weather for the burning days, fuel type (spruce, balsam slash for the cutovers and dead balsam, mixed green for the wildfire) and the amount of fuel consumed for the PB and RB treatments.

Frontal fire intensity is a measure of the rate of heat energy released per metre of fire front. It is calculated by the following equation (Alexander, 1980):  $I = H w r$ , where  $I$  = frontal fire intensity ( $\text{kW m}^{-1}$ );  $H$  = heat of combustion of fuel ( $\text{kJ kg}^{-1}$ );  $w$  = weight of fuel consumed;  $r$  = forward rate of spread ( $\text{m sec}^{-1}$ ).

### Soil Sampling

Eighty soil pits were excavated during each collection period and three layers sampled from each, which equals 240 soil samples per collection period.

Soil pits were randomly located along each side of the vegetation quadrat. The organic layer (LFH) was collected before the soil pit was dug by removing approximately a 28 by 28 cm sample and excavating down to the organic-mineral interface. The living vegetation was removed from the organic matter sample. The sample was placed and sealed in a plastic bag and labeled appropriately. In the case of the Prescribed Burn, Reburn and Harvest treatments intact organic samples were not always present. In those situations loose remaining organic matter was collected.

Next a soil pit roughly 50 cm long on each side was excavated to a depth of approximately 20 cm. The sides of the pit were cleaned and the 0-5 cm and 5-10 cm mineral soil layers were delineated on the faces of the pit. Being careful to avoid contamination, soil from the 0-5 cm layer was extracted from the sides of the pit and mixed together to give a composite sample for the

layer. The same was done for the 5-10 cm mineral soil layer. The horizon types and colours that characterized the majority of each layer were noted.

## LABORATORY ANALYSIS

The preparation and analysis of the soil samples was based on the procedures outlined by Kalra and Maynard (1991).

When the soil samples arrived at the laboratory from the field they were set out on paper plates to air dry. The purpose of air drying was to prevent microbial changes and to condition the soil to ambient temperature and humidity. The samples were left to dry for three weeks.

After the mineral soil samples had dried they were rolled to break up any clumps, and coarse pieces of stone and organic matter were removed. The samples were then further broken up using a mortar and pestle and subsequently passed through a two millimetre sieve. Approximately 300 grams of mineral soil were retained for chemical and physical analyses.

The organic matter samples were ground using a Wiley mill with a two millimetre screen. The mill was cleaned after each sample was ground. The ground samples were mixed and stored in labeled containers.

Particle size analysis of the June 0-5 cm and 5-10 cm mineral soil layer samples was completed using the Bouyoucos Hydrometer method. Due to the low amount of organic matter in the samples no pretreatment was done; however, the percent organic matter found from the loss on ignition test was used to adjust the percent clay values. Each sample was pretreated with 10 ml Calgon solution which contained phosphate. After the samples were stirred with a milkshake machine for fifteen minutes, transferred to the sedimentation cylinder and brought up to volume (1 litre), they were allowed to stand for a minimum of one hour.

The tubes were covered and turned upside down vigorously to put the soil particles into suspension. Amyl alcohol was used to remove the foam from the surface of the suspension. The hydrometer was placed in the tube and after 40 seconds the reading was taken. The hydrometer was then removed and the temperature at a depth of five centimetres was recorded. The procedure was repeated after 2 hours. The hydrometer readings were corrected for temperature and calgon effects, and then the percent sand, silt and clay were calculated for the sample according to the method outlined in Kalra and Maynard (1991).

The pH of all the soil samples was measured using a pH meter which was standardized using buffer solutions of known pH. The soil samples were air dried so the pH reading was of the reserve acidity. The method used was the soil-to-solution ratio of 1:2 and 1:4 for mineral and organic samples, respectively; the solution being 0.01 M CaCl<sub>2</sub>. For the mineral soil, 10 g of sample was used with 20 ml of solution. The soil was allowed to absorb the solution and then was thoroughly stirred. The suspension was further stirred 4 or 5 times in the next half hour. The suspension was allowed to settle for 30 minutes and then the pH reading was taken by immersing the electrode in the supernatant solution. The pH was recorded when the reading stabilized. For the organic soil samples 5 grams and 20 millilitres of solution was used for the test.

The rest of the soil chemistry analysis tests were completed on pooled samples. At each plot there were four samples for each layer. Samples were randomly paired and pooled together. *This was done by thoroughly mixing the paired samples together and retaining a sufficient subsample for analysis.* With this method the 480 samples were reduced to 240 samples. The samples were pooled to keep laboratory analysis costs within budget.

Organic matter was estimated using the Loss-on-Ignition (LOI) method. Organic matter oxidizes at 375° C and was estimated by the loss of dry weight after the soil sample was heated in a muffle furnace . Values were reported as percentages of the total oven dried sample.

Total nitrogen was determined by digestion of the samples with  $\text{H}_2\text{SO}_4$  and a catalyst, followed by distillation in an alkaline medium and titration with dilute standardized  $\text{HCl}$ ; according to the method of Bremner and Mulvaney (1982). The data were reported as concentrations (milligrams of total nitrogen per kilogram of soil).

Available P was determined using the Bray 1 (Dilute Acid-Fluoride) procedure (Bray and Kurtz, 1945). The soil filtrate was acquired by extraction with  $\text{NH}_4\text{F}/\text{HCl}$  extraction solution. The concentration of available P was determined colorimetrically using a Cary 5E spectrometer.

Cation Exchange Capacity and Ca, Mg, and K ( $\text{cmol}(+) \text{kg}^{-1}$ ) for the soil samples were also determined. The soil filtrate containing the exchangeable cations was obtained from 10 g of soil extracted with ammonium acetate ( $\text{pH}=7$ ). The concentration of each cation was determined by inductively coupled plasma-atomic emission spectroscopy using an ICAP 9000 Jarrel Ash.

The CEC analysis was completed on the filtered residue from the exchangeable cation extraction. The residue was treated with  $\text{CaCl}_2$  and ammonium acetate with the resulting extract being used for ICP analysis to find the CEC value for the sample. The units for the data were  $\text{cmol}(+) \text{kg}^{-1}$  of soil.

The micronutrients Cu, Fe, Mn and Zn ( $\text{cmol}(+) \text{kg}^{-1}$ ) were also determined. Extraction for these nutrients was done with 0.1 M  $\text{HCl}$ . The filtrate was analyzed using the ICP.

## DATA ANALYSIS

The results of the soil chemistry analysis were averaged for each plot. The mean of the four hydrogen ion concentrations for each layer was calculated along with the stand error of the mean. There were also four texture values at each plot which were averaged. The mean of other soil chemistry properties measured was obtained by averaging two values. The statistical analysis was completed on the data set containing the mean values for each plot.

The statistical analysis involved the use of two techniques: (1) discriminant analysis to investigate the data from a multivariate, hypothesis generating perspective; (2) one-way analysis of variance, with a multiple comparison test (Student Newman-Keuls) to test the significance of individual soil chemistry variables. These variables were those that the discriminant analysis highlighted as being important in separating the five treatments. The analysis focused on differences in soil chemistry among treatments and between measurement dates. The soil chemistry data set of the treatment plot means for each date and layer that was used for the statistical analysis is included in Appendix V.

Discriminant analysis, also known as canonical variates analysis, is a linear multivariate ordination technique. It was used because the data are grouped by treatments, and the question was how the variables differed and interact among the groups. The method determines the weighted sum of the variables that maximizes the ratio of the between treatment sum of squares and the within treatment sum of squares along the first and subsequent ordination axes (Podani, 1994).

Since the chemical properties measured had different units, a transformation of the data set was required before the discriminant analysis was done so variables would be comparable. The Z-transformation was used because it standardizes the data to zero mean and unit variance (Jongman,

*et al.*, 1995). Each value was converted by subtracting it from the mean of all the samples for that variable and then dividing by the standard deviation. The transformed value indicates whether it deviates positively or negatively from the mean.

A discriminant analysis was completed for each layer at both collection periods as well as for each layer with both periods combined.

Analysis of variance with a multiple comparison test was done on those variables which the ordination suggested may be significant among treatments. The Student Newman-Keuls multiple comparison test was reported. Other tests (LSD and Tukey) were tried but Student Newman-Keuls test consistently fell in the middle ground when determining significance. In some instances the data were transformed so that the ANOVA assumptions of normality would be met. The natural log transformation was used. Differences were considered significant at a probability value of less than 0.05. Differences with a probability value of less than 0.10 were also identified because although the differences might not be statistically significant, they might be of biological importance.



## RESULTS

The results of the discriminant and ANOVA analyses are presented as three major sections which correspond to the soil layers investigated (Organic, 0 - 5 cm mineral and 5 - 10 cm mineral). Within each section there are separate subsections for each sampling period (June and August), both individually and together.

### ORGANIC LAYER

The organic layer showed the greatest differences in soil chemistry among treatments at both sampling periods and between periods in the same treatment.

#### June

Figure 3 presents the discriminant ordination diagram for the organic layer sampled in June. Following the diagram are three tables which assist in the interpretation of the ordination plot. Table 3 presents the eigenvalues and canonical correlations for each canonical variate in the discriminant analysis. The first two axes together accounted for 96 % of the variance in the data and both axes were highly correlated ( $r^2 > 0.9$ ) with the grouping variable (treatments).

Table 4 presents the CHI-Square tests with successive variates removed from the discriminant analysis. When all the variates were included the test was significant, but when the

first variate was removed, it was not. This indicates that the first axis was responsible for the significance.

Table 5 presents the correlations of soil chemistry variables with the canonical variates from the discriminant analysis. Since the first axis was responsible for explaining the greatest amount of variance in the data, those variables highly correlated with it indicate the causes of the differences between treatments.

Hydrogen ion concentration was positively correlated with the first axis, while Ca, Mg, K, Zn and available P were negatively correlated with it. The first axis in Figure 3 represented a pH and available P gradient. At the positive end, pH and available P were low which was associated with unburned sites, *i.e.* the Control and Harvest plots. Higher pH and available P at the negative end were the result of the addition of cations and P to the soil from the mineralization of organic material by fire.

The first axis separated the three fire treatments from the Harvest and Control treatments (Figure. 3). The second axis separated the three fire treatments: Wildfire was at the positive end of the axis, PB was in the middle and the RB treatment was at the negative end. There were no variables highly correlated with this axis but three variables were moderately correlated: total nitrogen (0.445), Loss-on-Ignition (0.429) and Fe (-0.463). These three variables suggest the potential sources of differences among the fire treatments.

Those soil chemistry variables highly correlated with the first axis were tested for significance among the treatments using one-way analysis of variance and the Student Newman-Keuls multiple comparison test. All six variables were statistically significant ( $p \leq 0.05$ ) and the results of the multiple comparisons test are presented in Table 6.

The Harvest treatment had significantly lower values than the three fire treatments for the variables pH, available P, Zn, Ca, and K. For Mg the Harvest treatment amount was significantly less than the PB and RB treatments.

The Control treatment contained significantly less available P than the three fire treatments as well it contained significantly less Zn than the WF and Mg than the PB and RB treatments. Differences which were not significant, but had a probability value of less than ten percent included: (1) Control from Harvest and WF for pH; (2) Control from PB and RB for Zn and K; (3) Control from WF for Ca and Mg.

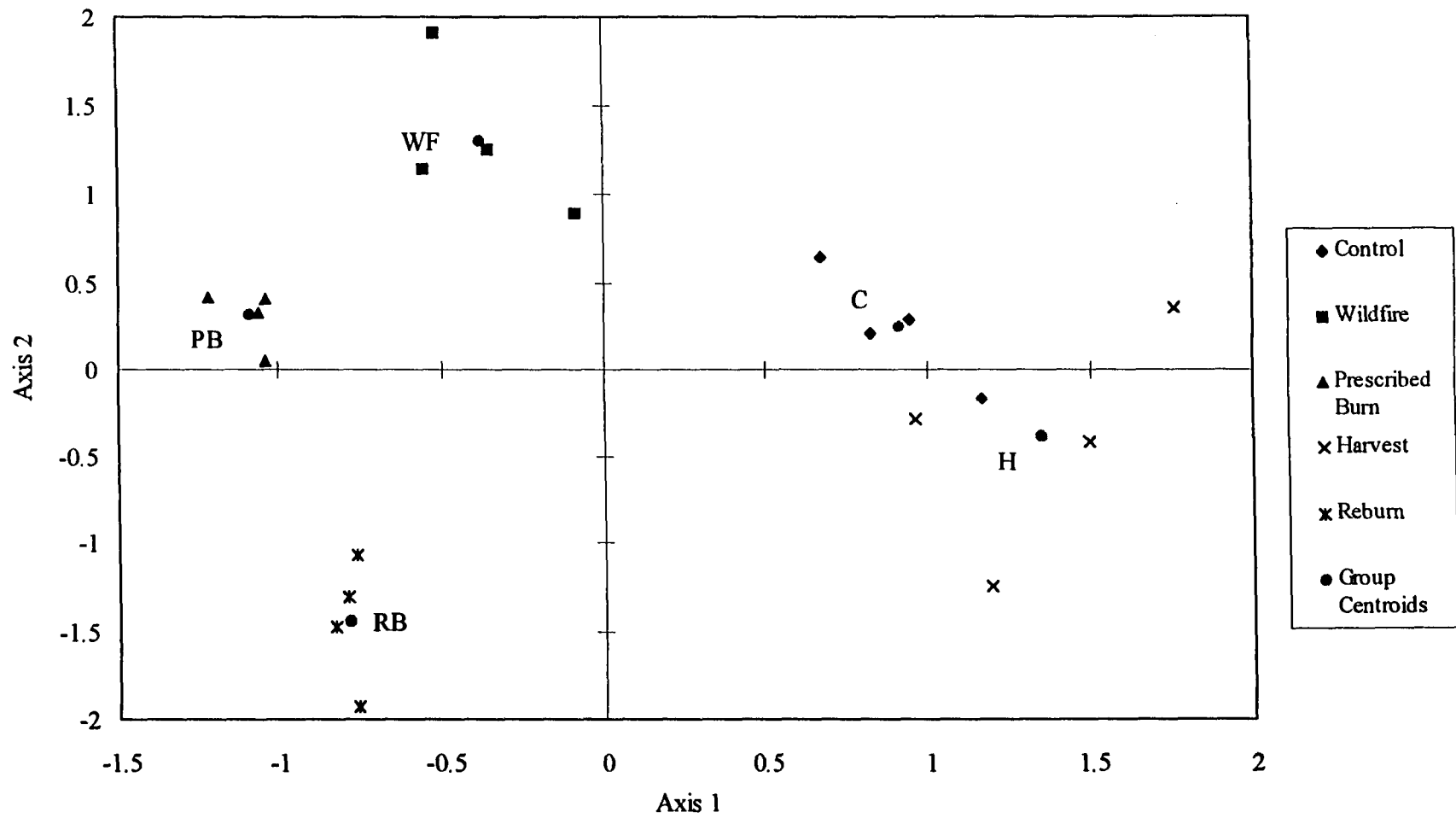


Figure 3. Discriminant analysis ordination of the organic layer soil chemistry data for June showing the relationships between the plots on the five treatments. Treatment abbreviations: C, Control; WF, Wildfire; PB, Prescribed Burn; H, Harvest; RB, Reburn.

Table 3. Eigenvalues and canonical correlations for the canonical variates of the discriminant analysis of the organic soil layer sampled in June.

Canonical Variate	Eigenvalue	Eigenvalue as % of Variance	Canonical Correlation
1	27.80	79.18	0.982
2	6.04	17.21	0.926
3	0.91	2.58	0.689
4	0.36	1.03	0.515

Table 4. CHI-SQUARE tests with successive variates removed for the discriminant analysis of the organic soil layer sampled in June.

Canonical Variates Removed	CHISQ	Degrees of Freedom	Significance Level
UP TO 0	65.79	48	**
UP TO 1	30.51	33	n.s.
UP TO 2	10.01	20	n.s.
UP TO 3	3.24	9	n.s.

\* =  $p \leq 0.10$

\*\* =  $p \leq 0.05$

n.s. = not significant

Table 5. Correlations of soil chemistry variables with canonical variates for the discriminant analysis of the organic soil layer sampled in June.

Soil Chemistry Variables	Canonical Variates			
	1	2	3	4
Hydrogen	0.766	-0.074	0.279	0.259
Loss on Ignition	0.198	0.429	-0.153	0.389
Cation Exchange Capacity	0.137	0.119	-0.487	0.210
Available Phosphorus	-0.703	-0.053	0.126	-0.353
Total Nitrogen	-0.266	0.445	-0.125	0.147
Iron	0.066	-0.463	-0.135	0.065
Manganese	-0.474	-0.043	-0.042	-0.395
Zinc	-0.659	-0.131	-0.092	-0.199
Copper	0.488	-0.161	-0.096	-0.182
Calcium	-0.702	0.075	-0.141	-0.115
Magnesium	-0.674	-0.182	0.020	-0.067
Potassium	-0.641	0.155	0.018	0.067

Table 6. Comparison of soil chemistry characteristics in the organic layer sampled in June among the five treatments. Values reported are the treatment means and the ones in parentheses are one standard error. Values within each column followed by a different letter are significantly different, others non-significant (ANOVA and Student Newman-Keuls multiple comparison test,  $p \leq 0.05$ ).

Treatments	pH	Available Phosphorus (mg/kg)	Zinc (cmol/kg)	Calcium (cmol/kg)	Magnesium (cmol/kg)	Potassium (cmol/kg)
Control	3.47c (0.23)	27.13a (3.23)	0.092ab (0.036)	16.90c (5.46)	3.03a (0.71)	1.19c (0.24)
Harvest	3.22ac (0.24)	27.94a (5.14)	0.066a (0.006)	9.76ac (2.17)	2.77a (0.42)	0.97ac (0.07)
Wildfire	4.10bc (0.39)	151.50b (20.49)	0.141bc (0.011)	26.67bc (2.87)	4.39 (0.44)	1.88bc (0.09)
Prescribed Burn	4.28bc (0.30)	156.14b (69.66)	0.162b (0.026)	29.54bc (5.22)	5.42b (0.98)	2.01bc (0.52)
Reburn	4.50bc (0.43)	180.06b (39.40)	0.182b (0.042)	27.90bc (5.41)	5.76b (0.97)	1.76bc (0.22)

## August

The ordination diagram for the organic layer sampled in August appears in Figure 4 and the information associated with the discriminant analysis follows in Tables 7 to 9.

The CHI-Square test was significant when all axes were included but not when the first one was removed. Therefore, the first axis was responsible for explaining significant differences among the treatments.

In the June ordination diagram, the first axis separated the fire treatments from the Control and Harvest treatments but in the August ordination diagram these treatments were separated along the second axis. In both diagrams, the separation was due to a gradient of pH and cations. When tested using ANOVA, pH was found to be significantly different between treatments and the multiple comparison test showed the differences to be between the Harvest and Control treatments and the three fire treatments (Table 10). In June, the Control treatment was not significantly different from the fire treatments, therefore the difference in pH among the treatments became greater with time. The only cation found to be significantly different between treatments in August was Zn (Table 10).

Along with pH, the second axis was also a function of organic matter content. Loss on Ignition had a correlation coefficient of -0.546 with the second axis. Organic matter content was found to be significantly different between the Control and RB treatments (Table 10) while the difference between Harvest and RB was nearly significant ( $p = 0.081$ ).

What stands out in this ordination diagram is the separation of the Harvest, PB and RB treatments from the WF and Control treatments along the first axis. Cation exchange capacity, a variable which was not significant in the June analysis, is most responsible for the separation of these treatments. Analysis of variance confirmed that the WF and Control treatments were indeed statistically different from the Harvest, PB and RB treatments (Table 10).



Cation exchange capacity was the only variable to vary statistically among fire treatments. The two surface fire treatments (PB and RB) had significantly lower CEC than the crown fire treatment (WF). Although not statistically significant, total nitrogen was positively correlated with the first axis and like the June data, continued to indicate another source of separation between fire treatments. The WF treatment had a higher mean total nitrogen value in comparison to the RB and PB treatments.

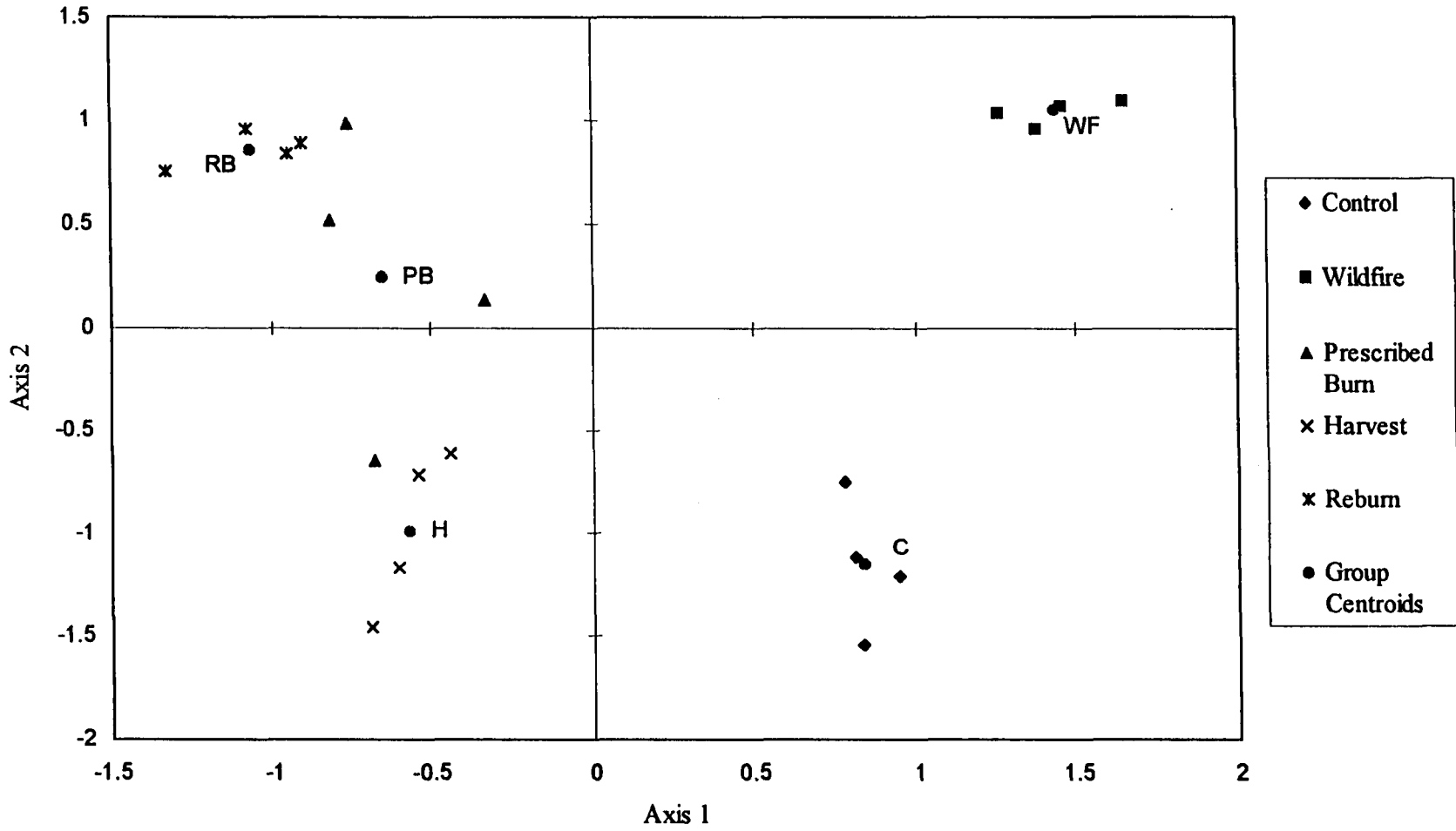


Figure 4. Discriminant analysis ordination of the organic layer soil chemistry data for August showing the relationships between the plots on the five treatments. Treatment abbreviations: C, Control; WF, Wildfire; PB, Prescribed Burn; H, Harvest; RB, Reburn.

Table 7. Eigenvalues and canonical correlations for the canonical variates of the discriminant analysis of the organic soil layer sampled in August.

Canonical Variate	Eigenvalue	Eigenvalue as % of Variance	Canonical Correlation
1	49.70	81.99	0.990
2	7.44	12.27	0.939
3	2.42	4.00	0.841
4	1.06	1.75	0.717

Table 8. CHI-SQUARE tests with successive variates removed for the discriminant analysis of the organic soil layer sampled in August.

Canonical Variates Removed	CHISQ	Degrees of Freedom	Significance Level
UP TO 0	84.12	48	**
UP TO 1	42.90	33	n.s.
UP TO 2	20.51	20	n.s.
UP TO 3	7.59	9	n.s.

\* =  $p \leq 0.10$

\*\* =  $p \leq 0.05$ .

n.s. = not significant

Table 9. Correlations of soil chemistry variables with canonical variates for the discriminant analysis of the organic soil layer sampled in August.

Soil Chemistry Variables	Canonical Variates			
	1	2	3	4
Hydrogen	0.047	-0.791	0.048	0.255
Loss on Ignition	0.419	-0.546	-0.127	0.144
Cation Exchange Capacity	0.767	0.127	0.130	-0.018
Available Phosphorus	-0.327	0.129	0.407	-0.512
Total Nitrogen	0.519	0.059	0.177	0.032
Iron	-0.167	-0.444	0.287	0.415
Manganese	0.012	0.676	0.070	-0.158
Zinc	-0.331	0.699	0.197	-0.287
Copper	0.113	-0.599	0.101	0.244
Calcium	-0.346	0.250	-0.143	0.206
Magnesium	-0.438	0.282	-0.086	0.150
Potassium	0.089	0.176	0.112	0.171

Table 10. Comparison of soil chemistry characteristics in the organic layer sampled in August among the five treatments. Values reported are the treatment means and the ones in parentheses are one standard error. Values within each column followed by a different letter are significantly different, others non-significant (ANOVA and Student Newman Keuls multiple comparison test,  $p \leq 0.05$ ).

Treatments	Loss on Ignition (%)	pH	Cation Exchange Capacity (cmol/kg)	Zinc (cmol/kg)
Control	78.92 <sup>ac</sup> (2.07)	3.34 <sup>a</sup> (0.20)	63.63 <sup>a</sup> (1.42)	0.099 <sup>ac</sup> (0.010)
Harvest	76.66 <sup>c</sup> (2.99)	3.32 <sup>a</sup> (0.16)	46.27 <sup>b</sup> (1.62)	0.090 <sup>ac</sup> (0.010)
Wildfire	73.51 <sup>c</sup> (3.87)	4.62 <sup>b</sup> (0.22)	70.98 <sup>a</sup> (8.20)	0.157 <sup>c</sup> (0.019)
Prescribed Burn	68.66 <sup>c</sup> (3.50)	4.21 <sup>b</sup> (0.46)	47.82 <sup>b</sup> (3.52)	0.190 <sup>bc</sup> (0.023)
Reburn	64.15 <sup>bc</sup> (4.06)	4.34 <sup>b</sup> (0.44)	47.62 <sup>b</sup> (5.29)	0.228 <sup>bc</sup> (0.044)

### June/August

The data sets for the June and August organic layer soil chemistry measurements were combined and analyzed. The purpose of doing this was to investigate how the treatments changed between the two sampling periods, with regards to soil chemistry. The ordination diagram from the discriminant analysis is presented in Figure 5 and the statistical output is presented in Tables 11, 12 and 13.

The first two axes of the ordination diagram accounted for 75 % of the variance in the data and the CHI-Square test showed that both axes were significant. As in the analysis of the June data, the first axis was a function of cation levels and pH. In addition, Cu was strongly negatively correlated (-0.771) with the first axis.

Cation exchange capacity, LOI and total-N were highly correlated with the second axis of the ordination and were also highly correlated with the first axis of the ordination of the August data. In addition, available P was highly correlated with the second axis.

The arrows in the ordination diagram join the treatment centroids for one date to the centroids of the corresponding treatment for the other. The shift in all treatments was in a similar direction from the June data to the August data, oriented from the upper left to lower right. The shift is associated with both axes. Depending on the treatment the shift was influenced more by the first or the second axis. The lines joining the treatment centroids only cross in the case of the Harvest and WF treatments and this cross over was caused by the difference in CEC between these two treatments in August.

The length of the arrows indicated how dissimilar the treatments were between dates, with Harvest and RB changing the most between June and August. Analysis of variance showed this change to be the result of significantly lower levels of Cu and higher levels of total nitrogen in the

August sample for the Harvest treatment and lower levels of available P and Cu in the Reburn treatment.

The results of the analysis of variance between collection periods for all treatments are summarized in Table 14. The level of Cu in all the treatments, except Control, decreased significantly from June to August. Available P significantly increased from June to August for the Control. The WF experienced the most significant changes from one period to the next, with CEC and total nitrogen increasing and available P and Cu declining.

Another important aspect of the ordination diagram was the way the five treatments at both dates separated from one another. The orientation of this shift was perpendicular to the one previously described, extending from lower left to upper right. This shift corresponded to degree of soil treatment. The Control treatments were in the lower left corner, the harvest and wildfire treatments were in the middle and the PB and RB treatments were in the upper right corner.

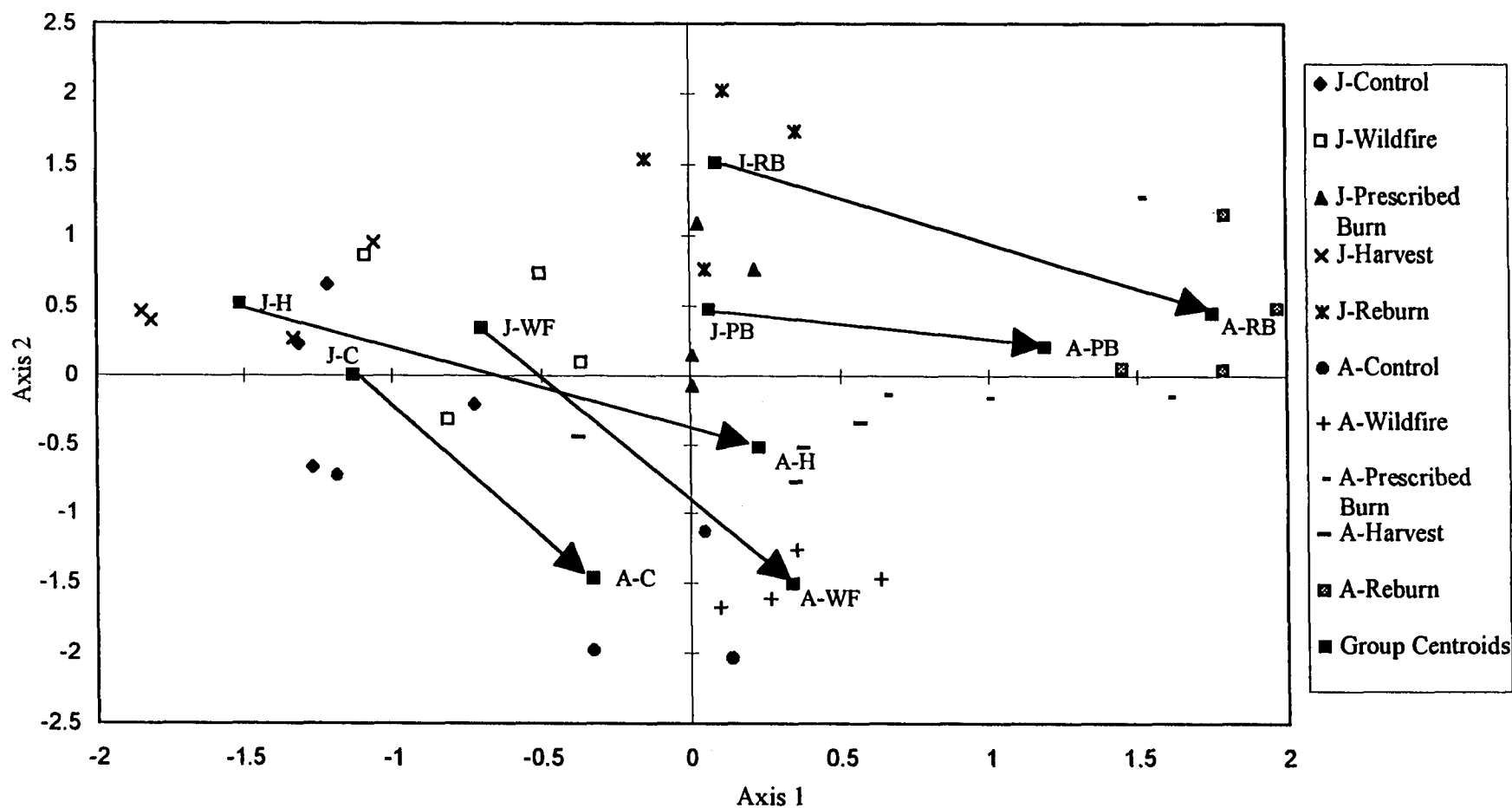


Figure 5. Discriminant analysis ordination of the organic layer soil chemistry data for June and August showing the relationships between the plots in the five treatments and the two dates. Treatment abbreviations: C, Control; WF, Wildfire; PB, Prescribed Burn; H, Harvest; RB, Reburn. Date Abbreviations: J, June; A, August.



Table 11. Eigenvalues and canonical correlations for the canonical variates of the discriminant analysis of the organic soil layer sampled in June and August.

Canonical Variate	Eigenvalue	Eigenvalue as % of Variance	Canonical Correlation
1	9.63	53.05	0.952
2	4.08	22.49	0.896
3	2.46	13.54	0.843
4	0.85	4.71	0.679

Table 12. CHI-SQUARE tests with successive variates removed for the discriminant analysis of the organic soil layer sampled in June and August.

Canonical Variates Removed	CHISQ	Degrees of Freedom	Significance Level
UP TO 0	190.64	108	**
UP TO 1	124.45	88	**
UP TO 2	78.93	70	n.s.
UP TO 3	44.20	54	n.s.
UP TO 4	26.90	40	n.s.

\* =  $p \leq 0.10$

\*\* =  $p \leq 0.05$

n.s. = not significant

Table 13. Correlations of soil chemistry variables with canonical variates for the discriminant analysis of the organic soil layer sampled in June and August.

Soil Chemistry Variables	Canonical Variates				
	1	2	3	4	5
Hydrogen	-0.498	-0.231	0.534	0.509	0.215
Loss on Ignition	-0.081	-0.640	0.063	0.227	-0.136
Cation Exchange Capacity	0.062	-0.626	-0.055	-0.369	0.236
Available Phosphorus	0.040	0.535	-0.702	0.157	-0.018
Total Nitrogen	0.290	-0.650	-0.225	-0.050	-0.021
Iron	-0.172	0.194	0.099	0.381	0.639
Manganese	0.340	0.187	-0.379	-0.344	-0.066
Zinc	0.651	0.272	-0.252	-0.314	-0.008
Copper	-0.771	0.453	-0.054	0.003	0.196
Calcium	0.570	0.057	-0.152	0.094	-0.188
Magnesium	0.631	0.148	-0.088	.147	-0.064
Potassium	0.343	-0.084	-0.448	0.066	-0.045

Table 14. Summary of soil chemistry variables with significant p-values from the oneway analysis of variance completed between dates (June and August) for each treatment. Significant level: \*,  $p \leq 0.05$ .

Treatment	CEC	Available Phosphorus	Total Nitrogen	Copper
Control	0.71	0.0326*	0.082	0.070
Harvest	0.092	0.74	0.011*	0.003*
Wild Fire	0.017*	0.002*	0.030*	0.001*
Prescribed Burn	0.48	0.21	0.77	0.026*
Reburn	0.23	0.026*	0.27	0.001*

## 0 - 5 cm MINERAL SOIL LAYER

The 0 - 5 cm mineral soil layer among the five treatments had a loamy fine sand texture. This layer corresponded generally to the Ae horizon, characterized by a loss of Fe, Al, organic matter and/or clay (Anon., 1978). Since the arbitrary depth of 0 - 5 cm was chosen the horizon designation does not fit all the samples. Some samples included an Ah horizon (dark coloured surface mineral horizon enriched with organic matter) and others included portions of the Bm horizon (brownish subsurface horizon with only a slight addition of Fe, aluminum and/or clay).

### June

The ordination for the June 0 - 5 cm mineral soil layer, shown in Figure 6, was not as easily interpreted as the ordination diagrams for the organic layer. The Control and Harvest treatments were not associated with each other in the ordination diagram.

Table 15 shows that the first two axes presented in the diagram account for 89 % of the variation in the data and the grouping variable Treatments was highly correlated with the axes. Table 16 presents the results of the CHI-Squared tests which show that both the first and second axes were significant. Table 17 lists the soil variables and their correlations with the canonical variates.

Potassium was highly correlated with the first axis (-0.728) and decreased from left to right in the ordination diagram. The PB and RB treatments have almost the same level, followed by Harvest, WF and Control treatments. Analysis of variance for K among the treatments indicated that the Control treatment had significantly less than the other four treatments (Table 18). The difference in K between the PB and the WF treatment was approaching significance ( $p = 0.099$ ).

The three fire treatments are separated to some degree in a diagonal direction from the lower left corner to the upper right, in the order PB, RB and WF. The major source of the difference was the level of K between the WF and the PB treatments.

Significantly higher levels of K in the Harvest treatment than in the Control treatment may be due to the differences in organic matter content. The higher CEC associated with increased organic matter allowed the Harvest treatment to retain more cations.

The second axis was correlated with the soil variables Fe and Ca, with correlation coefficients of 0.626 and 0.533, respectively. The relationship was not as strong as that of K with the first axis. No significant differences were found among the treatments for Ca and Fe but at a probability value of less than ten percent, the level of Fe was higher for the Harvest treatment than the Control ( $p = 0.089$ ) and PB ( $p = 0.093$ ) treatments. Again the differences between the Harvest and Control treatments may be related to CEC or possibly due to the mixing of soil from lower layers where Fe and Ca had accumulated.

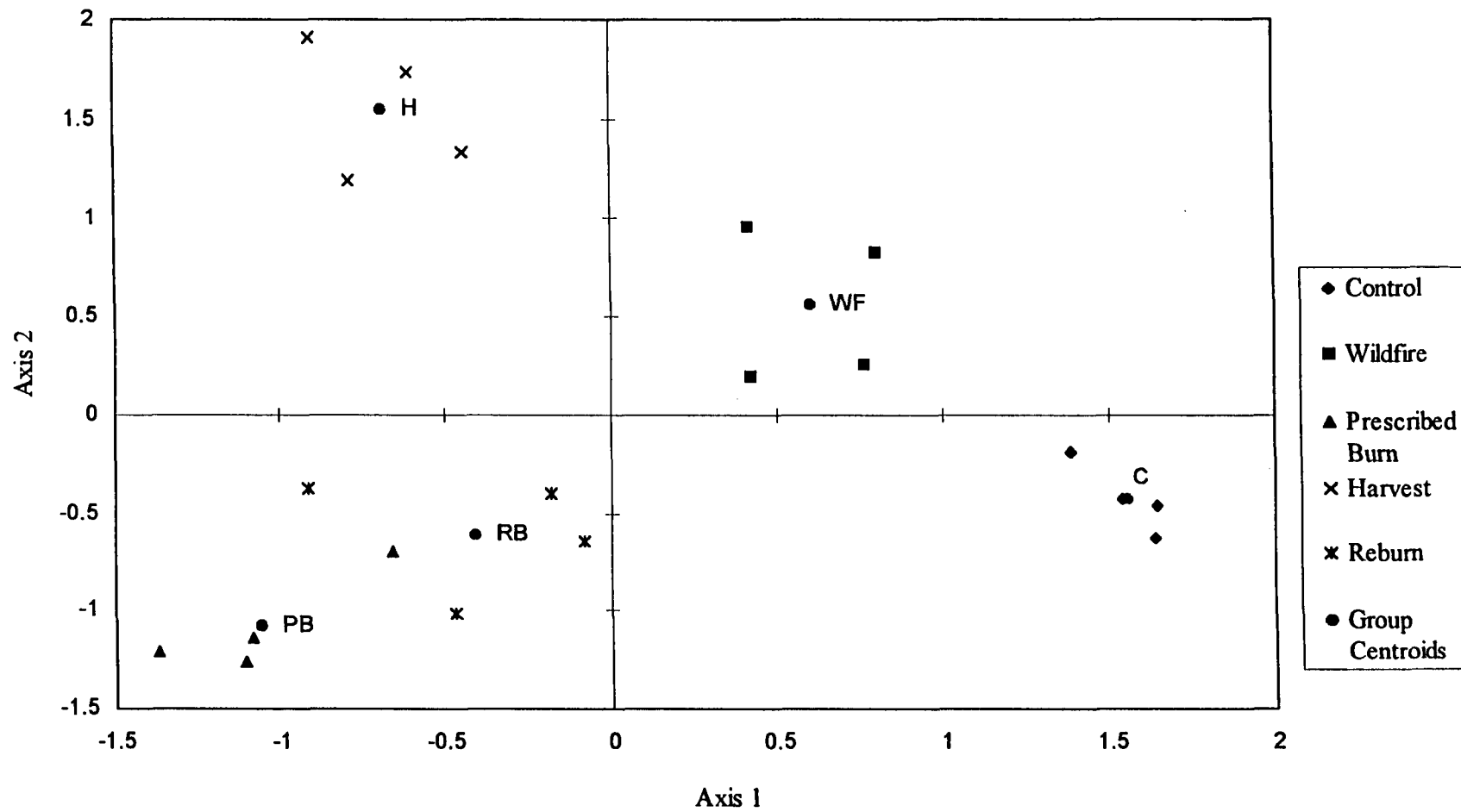


Figure 6. Discriminant analysis ordination of the 0 - 5 cm mineral layer soil chemistry data for June showing the relationships between the plots on the five treatments. Treatment abbreviations: C, Control; WF, Wildfire; PB, Prescribed Burn; H, Harvest; RB, Reburn.

Table 15. Eigenvalues and canonical correlations for the canonical variates of the discriminant analysis of the 0 - 5 cm mineral soil layer sampled in June.

Canonical Variate	Eigenvalue	Eigenvalue as % of Variance	Canonical Correlation
1	18.47	52.27	0.974
2	12.98	36.74	0.964
3	2.18	6.17	0.828
4	1.70	4.82	0.794

Table 16. CHI-SQUARE tests with successive variates removed for the discriminant analysis of the 0 - 5 cm mineral soil layer sampled in June.

Canonical Variates Removed	CHISQ	Degrees of Freedom	Significance Level
UP TO 0	81.47	48	**
UP TO 1	50.29	33	**
UP TO 2	22.60	20	n.s.
UP TO 3	10.45	9	n.s.

\* =  $p \leq 0.10$

\*\* =  $p \leq 0.05$

n.s. = not significant

Table 17. Correlations of soil chemistry variables with canonical variates for the discriminant analysis of the 0 - 5 cm mineral soil layer sampled in June.

Soil Chemistry Variables	Canonical Variates			
	1	2	3	4
Hydrogen	0.286	0.037	0.185	0.148
Loss on Ignition	-0.323	0.330	0.495	-0.234
Cation Exchange Capacity	-0.329	-0.234	-0.109	0.227
Available Phosphorus	0.032	-0.337	0.104	-0.404
Total Nitrogen	-0.098	-0.010	0.115	-0.223
Iron	-0.159	0.626	0.440	0.077
Manganese	-0.322	-0.361	-0.099	-0.061
Zinc	-0.078	-0.238	0.111	-0.380
Copper	0.125	0.063	0.664	-0.063
Calcium	-0.236	0.533	0.087	0.424
Magnesium	0.363	-0.126	0.130	0.269
Potassium	-0.728	-0.255	0.079	-0.312



Table 18. Comparison of potassium levels in the 0 - 5 cm mineral soil layer sampled in June among the five treatments. Values reported are the treatment means and the ones in parentheses are one standard error. Values within the column followed by a different letter are significantly different, others non-significant (ANOVA and Student Newman Keuls multiple comparison test,  $p \leq 0.05$ ).

Treatment	Potassium (cmol/kg)
Control	0.130a (0.022)
Harvest	0.253b (0.044)
Wildfire	0.218b (0.014)
Prescribed Burn	0.341b (0.039)
Reburn	0.344b (0.047)

### August

Iron increased from June to August, with the most dramatic change in the Harvest treatment. As a result of this increase, Fe was the variable most highly correlated with the first axis and was responsible for explaining the most variation in the data.

The ordination diagram depicting the August data appears in Figure 7. Tables 19 to 21 provide the numerical information connected with the discriminant analysis. The first two axes of the discriminant analysis accounted for 92 % of the variation in the data, but only the first axis was significant in explaining the variation.

Copper was also positively correlated with the first axis, with a correlation coefficient of 0.625. Analysis of variance for Cu among the treatments indicated that the Harvest treatment had a significantly higher level than the Control, PB and WF treatments while the RB treatment was approaching significance ( $p = 0.052$ ). The analysis of variance for Fe showed significant differences between the Harvest treatment and the Control, WF and RB treatments (Table 22). However, none was found between the Harvest and PB treatments.

There were no variables highly correlated with the second axis but the second axis does separate the three fire treatments, although not significantly. Magnesium and K were the variables that had the highest correlation with the second axis. As in the ordination of the June data, the order with respect to treatments remains consistent: PB, Reburn and WF. The WF treatment had a greater amount of Mg but a lower amount of K in relation to the other treatments. The PB treatment had a lower amount of Mg but a higher level of K compared to the other fire treatments while the RB treatment was in the middle.

Not evident in the ordination of the first two axes was that the level of Zn and Ca between treatments was also significantly different. This was due to the high correlation of Fe and Cu with

the first axis. These differences were pronounced on the fourth axis as indicated by the high correlation coefficients for these two variables with the axis.

In the case of Zn, the source of the significant difference was the high level in the Reburn treatment. It was found to be significantly higher than the Control and higher than the Harvest ( $p = 0.053$ ), WF ( $p = 0.086$ ) and PB ( $p = 0.082$ ) treatments (Table 22).

The low level of Ca in the Control treatment was the source of significant differences. The Ca level in the Control treatment was found to be significantly different from the Harvest and RB treatments while the difference with the PB treatment was approaching significance ( $p = 0.073$ ). WF and Control were not significantly different.

In the August ordination the dissimilarity of the Harvest and Control treatments continues. The cause of the difference between Harvest and Control in the ordination of the June data was K, but in August Fe, Cu and Ca were different.

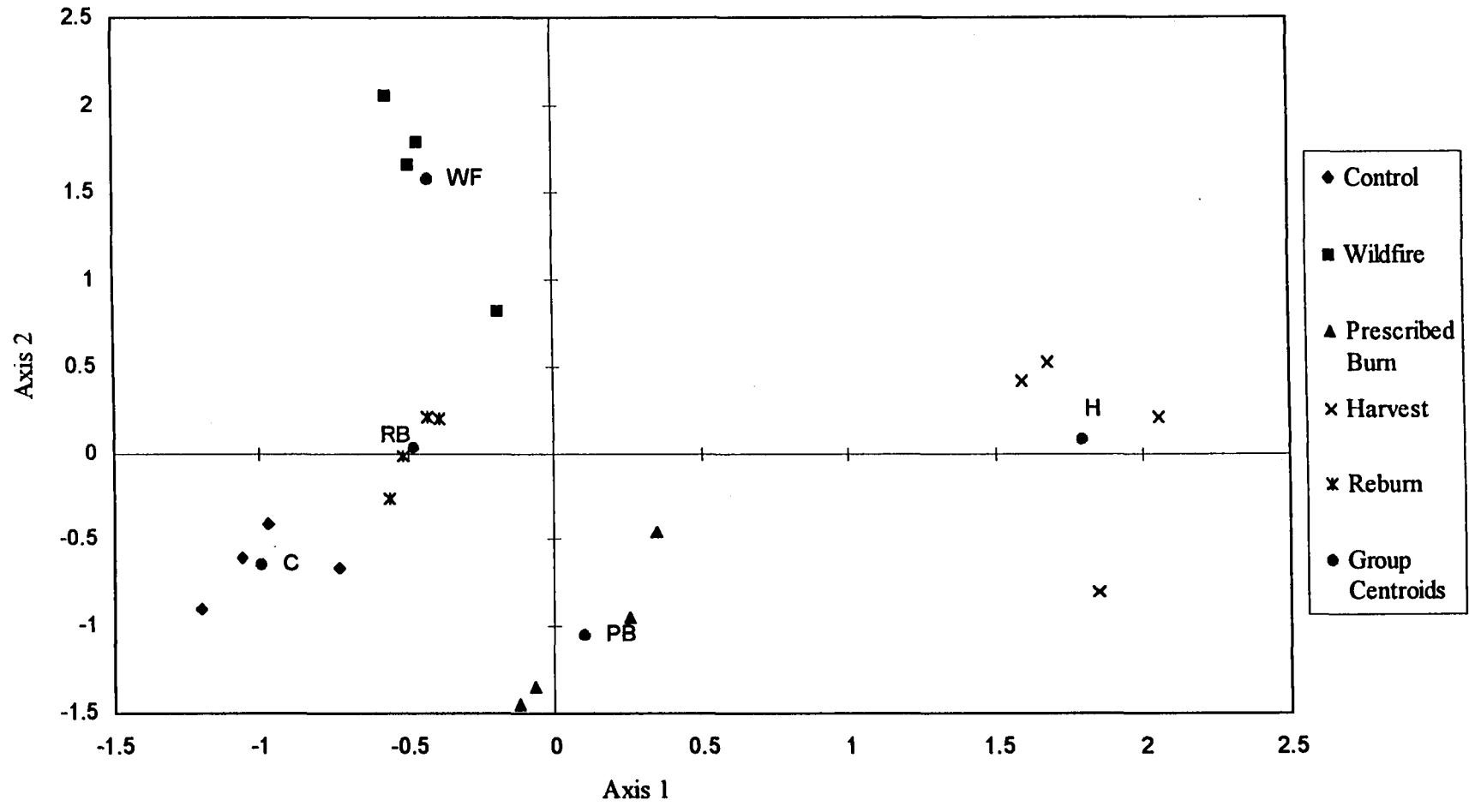


Figure 7. Discriminant analysis ordination of the 0 - 5 cm mineral layer soil chemistry data for August showing the relationships between the plots on the five treatments. Treatment abbreviations: C, Control; WF, Wildfire; PB, Prescribed Burn; H, Harvest; RB, Reburn.

Table 19. Eigenvalues and canonical correlations for the canonical variates of the discriminant analysis of the 0 - 5 cm mineral soil layer sampled in August.

Canonical Variate	Eigenvalue	Eigenvalue as % of Variance	Canonical Correlation
1	36.74	79.72	0.987
2	5.65	12.26	0.922
3	1.95	4.24	0.813
4	1.74	3.78	0.797

Table 20. CHI-SQUARE tests with successive variates removed for the discriminant analysis of the 0 - 5 cm mineral soil layer sampled in August.

Canonical Variates Removed	CHISQ	Degrees of Freedom	Significance Level
UP TO 0	79.98	48	**
UP TO 1	41.86	33	n.s.
UP TO 2	21.97	20	n.s.
UP TO 3	10.59	9	n.s.

\* =  $p \leq 0.10$

\*\* =  $p \leq 0.05$

n.s. = not significant

Table 21. Correlations of soil chemistry variables with canonical variates for the discriminant analysis of the 0 - 5 cm mineral soil layer sampled in August.

Soil Chemistry Variables	Canonical Variates			
	1	2	3	4
Hydrogen	-0.009	0.132	-0.655	0.070
Loss on Ignition	0.194	0.060	0.562	-0.088
Cation Exchange Capacity	-0.168	-0.096	0.336	0.019
Available Phosphorus	-0.307	-0.184	0.202	0.476
Total Nitrogen	0.245	0.141	0.244	-0.146
Iron	0.688	0.020	0.591	-0.088
Manganese	-0.194	0.312	-0.007	0.534
Zinc	-0.049	0.039	0.361	0.767
Copper	0.625	0.101	0.486	-0.026
Calcium	0.201	0.024	0.276	0.676
Magnesium	-0.136	0.502	0.149	0.426
Potassium	-0.266	-0.467	0.162	-0.376

Table 22. Comparison of soil characteristics in the 0 - 5 cm mineral soil layer sampled in August among the five treatments. Values reported are the treatment means and the ones in parentheses are one standard error. Values within each column followed by a different letter are significantly different, others non-significant (ANOVA and Student Newman Keuls multiple comparison test,  $p \leq 0.05$ ).

Treatment	Iron (cmol/kg)	Zinc (cmol/kg)	Copper (cmol/kg)	Calcium (cmol/kg)
Control	6.15bc (1.72)	0.003ac (0.001)	0.003bc (0.0007)	0.85ac (0.20)
Harvest	14.61ac (1.19)	0.006c (0.001)	0.006ac (0.0009)	2.78bc (0.73)
Wildfire	4.54bc (0.54)	0.005c (0.001)	0.003bc (0.0003)	1.63c (0.50)
Prescribed Burn	4.12c (0.93)	0.005c (0.001)	0.003bc (0.0003)	2.11c (0.33)
Reburn	7.72bc (2.23)	0.014bc (0.005)	0.004c (0.0004)	4.10cb (1.53)

### June/August

The data sets for the June and August collection periods were combined and analyzed using discriminant analysis (Figure 8). The first two discriminant axes accounted for 67 % of the variation in the data (Table. 23). Both axes were significant according to the CHI-Square test (Table 24).

The correlation of the soil variables with the canonical variates are presented in Table 25. The variables highly correlated with the first two axes were the same ones that correlated with the first axes of the June and August ordination diagrams: Fe and Cu with the first axis and K with the second.

In this ordination diagram, arrows join the group centroids of each treatment at each date. The arrow begins at the June treatment and extends to the same treatment at the August date. The Control treatment was the most dissimilar between dates, followed by the Harvest treatment.

The short arrows between dates of the fire treatments and the way in which they were clustered together shows that for the 0 - 5 cm mineral soil layer there were not many differences.

Results of the one-way analysis of variance ( $p$ -value  $\leq 0.05$ ) between the soil chemistry variables measured in the 0 - 5 cm mineral soil layer in June and August include: (1) WF and RB treatments experienced no significant changes in soil chemistry between the sampling periods; (2) Ca significantly decreased while K increased between June and August for the Control treatment; (3) Harvest treatment Fe and Cu significantly increased from June to August; available P increased as well, nearing significance ( $p= 0.052$ ); (4) the amount of Mg present in the PB treatment declined significantly between June and August.



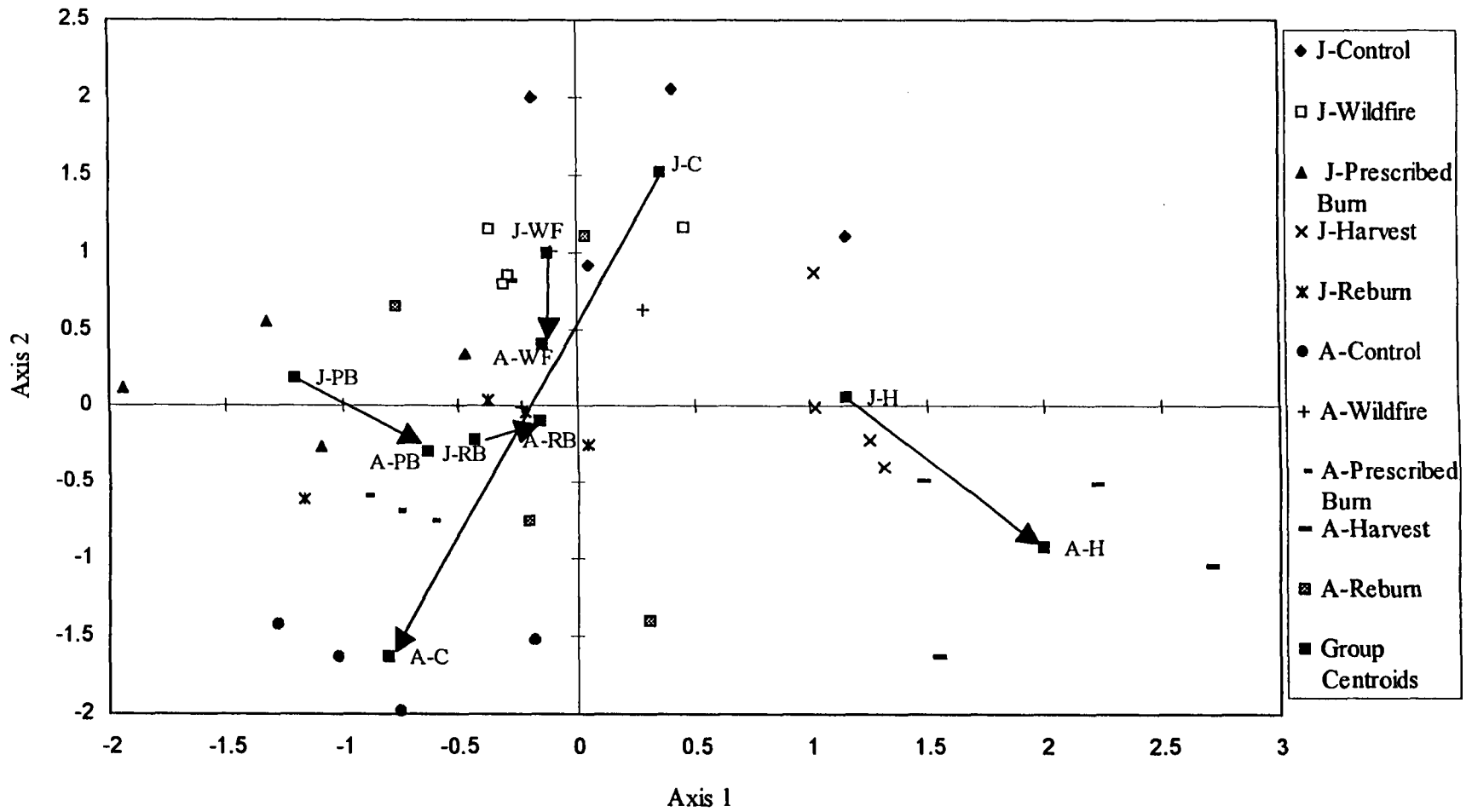


Figure 8. Discriminant analysis ordination of the 0 -5 cm mineral layer soil chemistry data for June and August showing the relationships between the plots in the five treatments and the two dates. Treatment abbreviations: C, Control; WF, Wildfire; PB, Prescribed Burn; H, Harvest; RB, Reburn. Date abbreviations: J, June; A, August.

Table 23. Eigenvalues and canonical correlations for the canonical variates of the discriminant analysis of the 0 - 5 cm mineral soil layer sampled in June and August.

Canonical Variate	Eigenvalue	Eigenvalue as % of Variance	Canonical Correlation
1	5.15	42.89	0.915
2	2.77	23.10	0.857
3	1.59	13.25	0.784
4	1.04	8.70	0.715

Table 24. CHI-SQUARE tests with successive variates removed for the discriminant analysis of the 0 - 5 cm mineral soil layer sampled in June and August.

Canonical Variates Removed	CHISQ	Degrees of Freedom	Significance Level
UP TO 0	166.29	108	**
UP TO 1	115.45	88	**
UP TO 2	78.28	70	n.s.
UP TO 3	51.64	54	n.s.
UP TO 4	31.63	40	n.s.

\* =  $p \leq 0.10$

\*\* =  $p \leq 0.05$ .

n.s. = not significant

Table 25. Correlations of soil chemistry variables with canonical variates for the discriminant analysis of the 0 - 5 cm mineral soil layer sampled in June and August.

Soil Chemistry Variables	Canonical Variates				
	1	2	3	4	5
Hydrogen	0.165	-0.035	-0.051	0.492	0.231
Loss on Ignition	0.328	-0.240	-0.250	0.057	-0.340
Cation Exchange Capacity	-0.200	-0.173	-0.017	-0.249	0.189
Available Phosphorus	-0.321	-0.020	0.285	-0.030	-0.461
Total Nitrogen	0.176	-0.048	-0.062	0.137	-0.073
Iron	0.770	-0.433	0.062	-0.124	-0.123
Manganese	-0.306	0.052	0.108	-0.320	-0.016
Zinc	-0.066	0.059	0.369	0.429	-0.583
Copper	0.596	-0.335	0.416	0.085	-0.106
Calcium	0.358	0.094	-0.166	-0.644	-0.202
Magnesium	0.056	0.331	0.220	0.242	0.162
Potassium	-0.334	-0.810	0.019	-0.091	-0.022

## 5 -10 cm MINERAL SOIL LAYER

The 5 - 10 cm mineral soil layer corresponded approximately to the Bm or Bf horizons but overlapped with the Ae horizon. The texture was loamy fine sand, similar to that of the 0 - 5 cm layer.

### June

The discriminant analysis identified the soil variables which were different between the treatments. The ordination diagram (Figure 9) shows the two axes accounting for 85 % of the variation in the data (Table 26). According to the CHI-Square test, only the first axis was significant, but at a p-value of ten percent (Table 27). The correlation of the soil variables with the canonical variates are presented in Table 28.

Cation exchange capacity was the variable with the highest correlation with the first axis (0.533). Zinc and Cu also had correlation coefficients above 0.4 while that of Mg was -0.4. These variables also influenced the placement of plots along the first axis. The Control and RB treatments were the most dissimilar and is shown by their separation along the first axis.

Potassium was highly correlated with the second axis, with a correlation coefficient of 0.642. The greatest dissimilarity along the second axis was between the Control and WF treatments.

Analysis of variance with multiple comparisons test for the 5 - 10 cm mineral soil layer chemistry data for June found no significant differences ( $p\text{-value} \leq 0.05$ ) among the treatments. However, differences in CEC and K among treatments was indicated at a  $p\text{-value} \leq 0.10$ . In the case of CEC the difference was between the Control and PB treatments ( $p = 0.096$ ) and for K the difference was between the Control and Harvest treatments ( $p = 0.089$ ) and Control and WF ( $p = 0.056$ ).

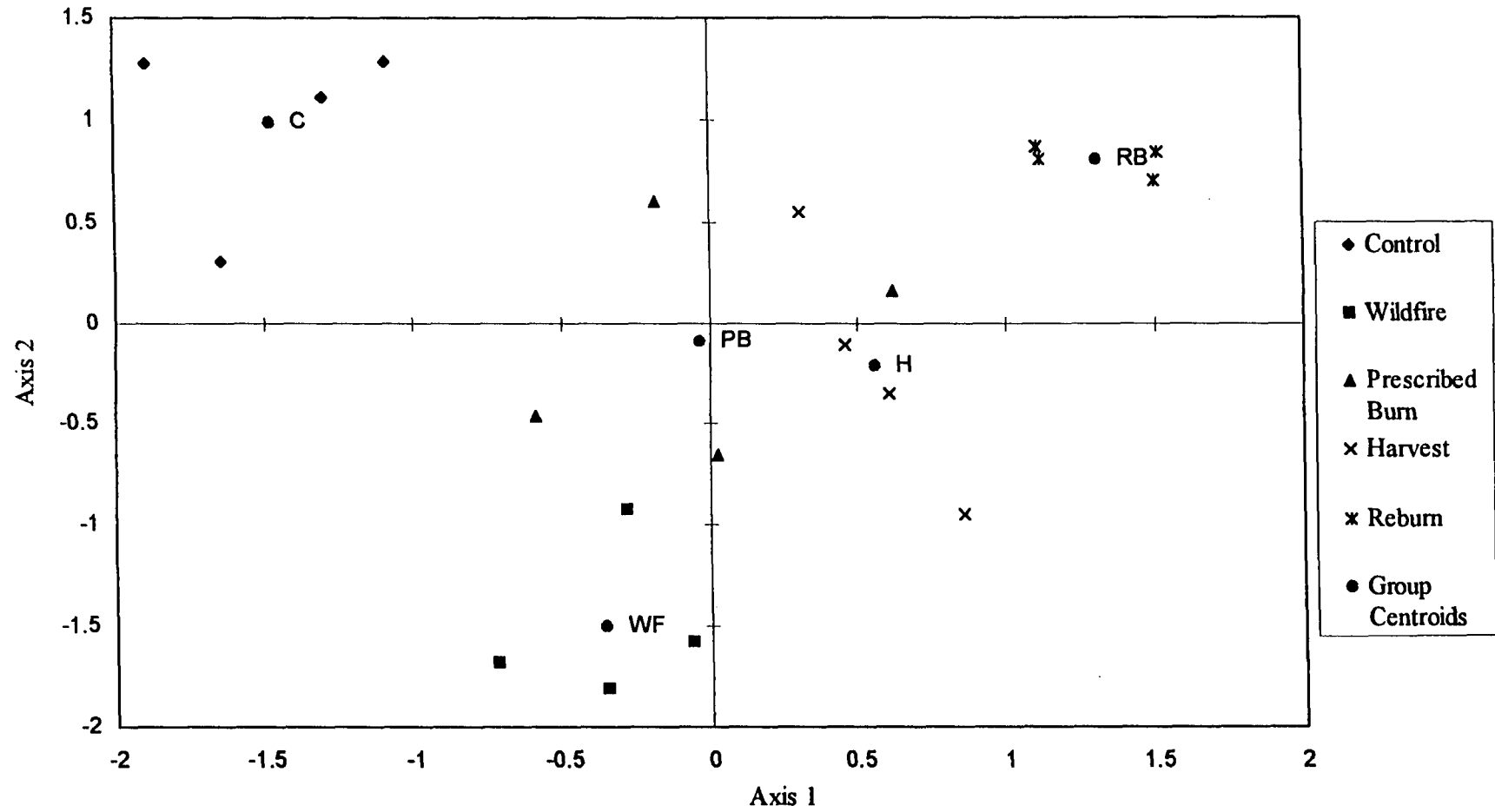


Figure 9. Discriminant analysis ordination of the 5 - 10 cm mineral layer soil chemistry data for June showing the relationships between the plots on the five treatments. Treatment abbreviations: C, Control; WF, Wildfire; PB, Prescribed Burn; H, Harvest; RB, Reburn.

Table 26. Eigenvalues and canonical correlations for the canonical variates of the discriminant analysis of the 5 -10 cm mineral soil layer sampled in June.

Canonical Variate	Eigenvalue	Eigenvalue as % of Variance	Canonical Correlation
1	10.27	57.99	0.955
2	4.78	26.99	0.909
3	1.82	10.28	0.804
4	0.84	4.74	0.676

Table 27. CHI-SQUARE tests with successive variates removed for the discriminant analysis of the 5 -10 cm mineral soil layer sampled in June.

Canonical Variates Removed	CHISQ	Degrees of Freedom	Significance Level
UP TO 0	61.16	48	*
UP TO 1	35.72	33	n.s.
UP TO 2	17.30	20	n.s.
UP TO 3	6.40	9	n.s.

\* =  $p \leq 0.10$

\*\* =  $p \leq 0.05$

n.s. = not significant

### August

The pattern of separation evident among treatments in the June organic layer ordination was also found in the 5-10 cm mineral soil layer (Figure 10). The Harvest and Control treatments were separated from the fire treatments along the first axis and the fire treatments along the second.

The first two axes of the discriminant analysis accounted for 79 % of the variation in the data (Table 29) but only the first axis was significant (Table 30). The soil chemistry variables and their correlation with the canonical variates are presented in Table 31.

The pattern of treatment separation was similar to that of the June organic layer but the variables responsible were different. Iron and Cu, with coefficients of -0.618 and -0.486 respectively, were highly correlated with the first axis and the sources of significant differences between treatments. Analysis of variance indicated significantly higher Fe present in the Harvest treatment as compared to the PB and WF treatments (Table 32). The level of Cu was significantly higher in the Harvest treatment than in the PB and WF treatments (Table 32). Other variables explaining the partition of the treatments in the first dimension include Mn (0.559) and available P (0.504). Available P was also significantly different between the burned and unburned treatments for the June organic layer.

The three fire treatments were separated along the second axis in the ordination diagram (Figure 10) This axis was correlated positively with K (0.496) and negatively with Zn (-0.512). The WF plots were located at the positive end of the axis, the PB plots were at and just below the origin and the RB plots were at the negative end. However, the PB treatment was more dissimilar to the WF than the RB treatment. This pattern of separation among the fire treatments was similar to the one seen in the ordination of the organic layer sampled in August.

The third canonical variate was not presented in the ordination but was important because of its high correlation with K (0.752). The level of K in both the Control and WF treatments was significantly higher than in the Harvest, PB and RB treatments (Table 32).

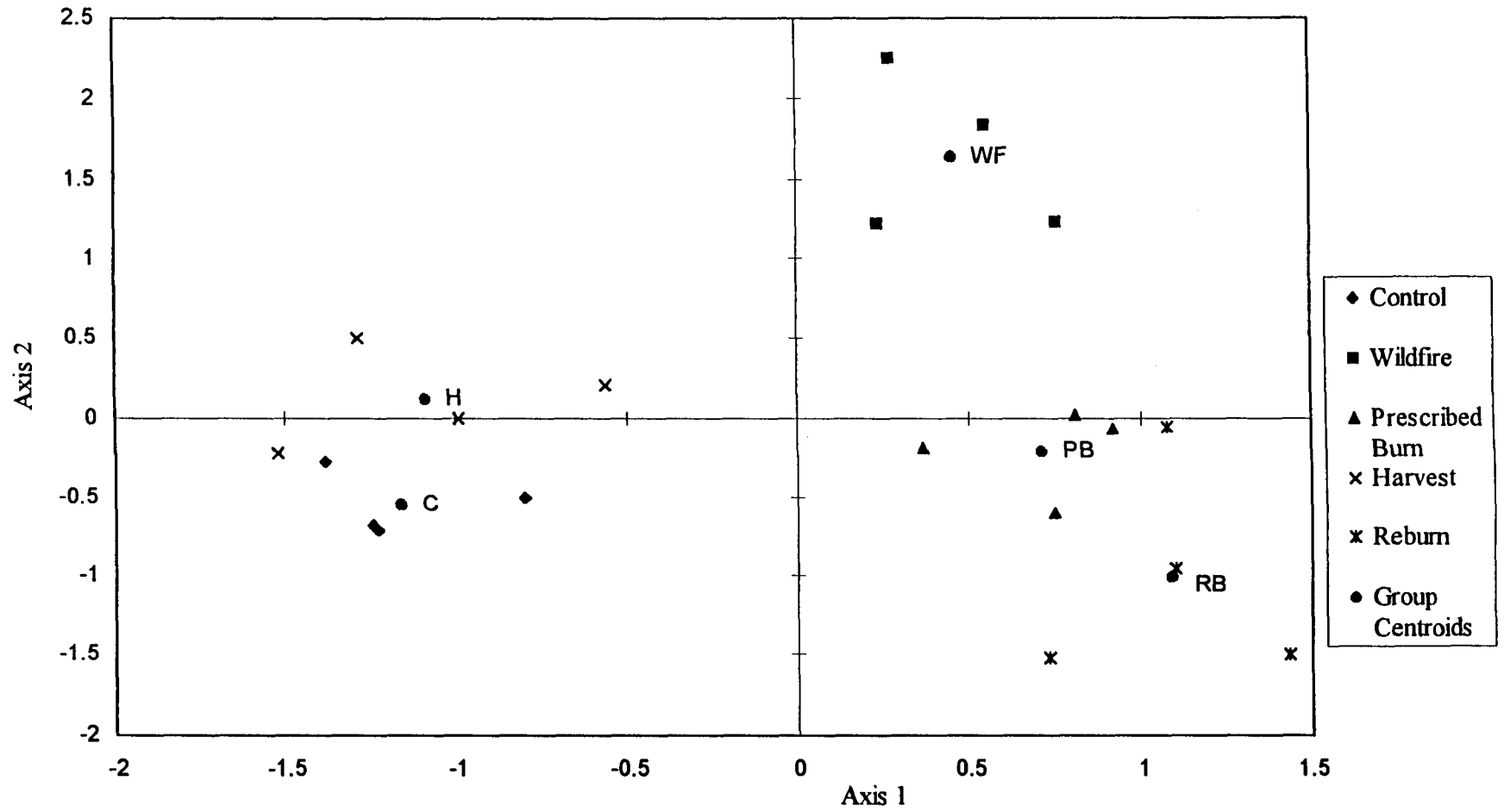


Figure 10. Discriminant analysis ordination of the 5 - 10 cm mineral layer soil chemistry data for August showing the relationships between the plots on the five treatments. Treatment abbreviations: C, Control; WF, Wildfire; PB, Prescribed Burn; H, Harvest; RB, Reburn.



Table 29. Eigenvalues and canonical correlations for the canonical variates of the discriminant analysis of the 5 - 10 cm mineral soil layer sampled in August.

Canonical Variate	Eigenvalue	Eigenvalue as % of Variance	Canonical Correlation
1	13.58	55.88	0.965
2	5.78	23.77	0.923
3	4.22	17.36	0.899
4	0.73	2.99	0.649

Table 30. CHI-SQUARE tests with successive variates removed for the discriminant analysis of the 5 - 10 cm mineral soil layer sampled in August.

Canonical Variates Removed	CHISQ	Degrees of Freedom	Significance Level
UP TO 0	71.31	48	**
UP TO 1	43.18	33	n.s.
UP TO 2	23.08	20	n.s.
UP TO 3	5.73	9	n.s.

\* =  $p \leq 0.10$

\*\* =  $p \leq 0.05$

n.s. = not significant

Table 31. Correlations of soil chemistry variables with canonical variates for the discriminant analysis of the 5 - 10 cm mineral soil layer sampled in August.

Soil Chemistry Variables	Canonical Variates			
	1	2	3	4
Hydrogen	-0.256	-0.074	0.226	-0.062
Loss on Ignition	-0.337	0.016	-0.037	0.685
Cation Exchange Capacity	-0.232	0.116	0.090	0.276
Available Phosphorus	0.504	0.097	0.053	-0.338
Total Nitrogen	-0.460	-0.018	0.135	0.329
Iron	-0.618	0.218	-0.274	0.299
Manganese	0.559	0.053	0.084	0.155
Zinc	0.372	-0.512	-0.123	0.392
Copper	-0.486	-0.239	-0.319	0.486
Calcium	-0.128	-0.275	-0.152	0.014
Magnesium	0.031	0.387	-0.022	0.289
Potassium	-0.207	0.496	0.752	-0.191

Table 32. Comparison of soil characteristics in the 5 - 10 cm mineral soil layer sampled in August among the five treatments. Values reported are the treatment means and the ones in parentheses are one standard error. Values within each column followed by a different letter are significantly different, others non-significant (ANOVA and Student Newman Keuls multiple comparison test,  $p \leq 0.05$ ).

Treatment	Iron (cmol/kg)	Copper (cmol/kg)	Potassium (cmol/kg)
Control	7.349c (1.601)	0.004c (0.0006)	0.259a (0.034)
Harvest	9.891ac (0.753)	0.005ac (0.0007)	0.043b (0.031)
Wildfire	6.857c (0.690)	0.003c (0.0003)	0.278a (0.067)
Prescribed Burn	5.312bc (1.184)	0.003bc (0.0005)	0.073b (0.019)
Reburn	5.063bc (0.330)	0.004c (0.0004)	0.050b (0.010)

### June/August

The ordination of the combined June and August data sets for the 5 -10 cm mineral soil layer is presented in Figure 11. The first two canonical variates account for 67 % of the variance in the data and both axes were significant (Tables 33 and 34).

The variation in K levels was so great among the treatments at both dates that it is the soil variable most highly correlated with both axes, 0.651 and 0.523, respectively (Table 35). The arrow joining the dates of the WF treatment in the ordination diagram had the longest length and the cause of the dissimilarity was due to K.

The Control and RB treatments also exhibited dissimilarity between dates. For the Control treatment the dissimilarity was the result of changes in CEC and Mg and for the RB treatment it was due to changes in Cu. The Harvest and PB treatments did not appear to change much between dates as indicated by short arrows joining them in the ordination diagram.

The results of the one-way analysis of variance completed to determine significant differences ( $p\text{-value} \leq 0.05$ ) in soil chemical properties between the two sampling periods for each treatment were as follows: (1) The PB and RB treatments showed no significant differences in soil chemical properties between June and August. The difference in Cu between periods was nearly significant for the RB treatment ( $p = 0.068$ ) (2) The Control treatment decreased significantly in its level of CEC and Mg between June and August. (3) pH decreased significantly between June and August for the Harvest treatment. (4) K levels increased significantly from June to August for the WF treatment while the decrease in Ca between dates for this treatment was nearly significant ( $p = 0.07$ ).

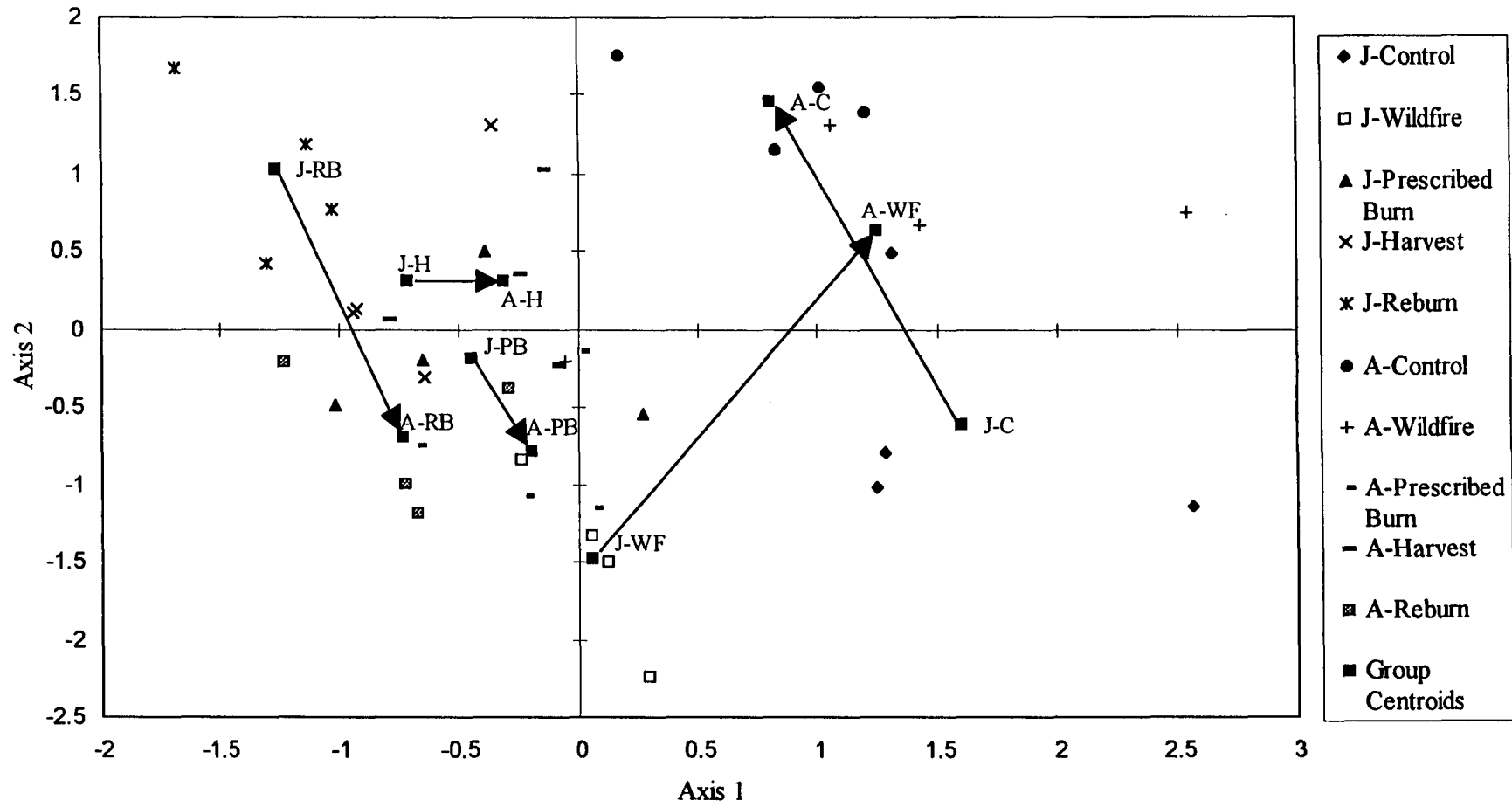


Figure 11. Discriminant analysis ordination of the 5 - 10 cm mineral layer soil chemistry data for June and August showing the relationships between the plots in the five treatments and the two dates. Treatment abbreviations: C, Control; WF, Wildfire; PB, Prescribed Burn; H, Harvest; RB, Reburn. Date abbreviations: J, June; A, August.

Table 33. Eigenvalues and canonical correlations for the canonical variates of the discriminant analysis of the 5 -10 cm mineral soil layer sampled in June and August.

Canonical Variate	Eigenvalue	Eigenvalue as % of Variance	Canonical Correlation
1	3.96	36.93	0.894
2	3.22	29.99	0.873
3	1.60	14.95	0.785
4	0.77	7.19	0.660

Table 34. CHI-SQUARE tests with successive variates removed for the discriminant analysis of the 5 -10 cm mineral soil layer sampled in June and August.

Canonical Variates Removed	CHISQ	Degrees of Freedom	Significance Level
UP TO 0	156.07	108	**
UP TO 1	111.22	88	**
UP TO 2	70.93	70	n.s.
UP TO 3	44.14	54	n.s.
UP TO 4	28.14	40	n.s.

\* =  $p \leq 0.10$

\*\* =  $p \leq 0.05$

Table 35. Correlations of soil chemistry variables with canonical variates for the discriminant analysis of the 5 - 10 cm mineral soil layer sampled in June and August.

Soil Chemistry Variables	Canonical Variates				
	1	2	3	4	5
Hydrogen	0.176	0.201	0.102	0.283	-0.233
Loss on Ignition	-0.143	-0.073	-0.389	-0.300	-0.486
Cation Exchange Capacity	0.407	-0.225	-0.277	0.342	-0.574
Available Phosphorus	-0.085	-0.156	0.579	-0.196	0.226
Total Nitrogen	-0.025	0.296	-0.094	-0.263	-0.254
Iron	-0.155	0.244	-0.625	-0.020	-0.221
Manganese	-0.235	-0.152	0.505	-0.262	-0.310
Zinc	-0.547	-0.083	0.172	0.328	-0.381
Copper	-0.404	0.336	-0.395	0.336	-0.383
Calcium	-0.070	-0.129	-0.310	0.034	0.061
Magnesium	0.354	-0.169	0.179	0.052	-0.288
Potassium	0.651	0.523	0.307	0.033	-0.135

## DISCUSSION

The Radio Lake research site provided a unique opportunity to characterize a range of disturbances and quantify and compare their immediate effects on soil chemistry. No studies were found in the literature that directly compared post disturbance soil chemistry following full-tree harvesting and fires of varying severity.

This section compares the treatments and Control in three ways: (1) Harvest versus Control; (2) Control and Harvest versus Fire treatments; (3) comparison among Fire treatments. In this way, the differences and similarities given in the results among treatments will be highlighted and explained. Following this, changes in soil chemical properties between sampling dates within each treatment are discussed. The section concludes by commenting on the implications of this study for forest management.

### HARVEST VERSUS CONTROL

The full-tree harvest treatment represented the effect of complete canopy removal and the addition of slash to the forest floor. From the review of previous research, increases in K, pH as well as decreases in organic matter in the forest floor were anticipated immediately following full-tree harvesting (Covington, 1981; Nykvist and Posen, 1985; Pare and Van Cleve, 1992). These changes were not observed in the organic layer of this study. The discriminant analysis and analysis of variance of the soil data collected in June and August showed that soil chemical properties associated with the Harvest treatment were generally similar to those in the Control.



At the first sample collection in June, the Harvest treatment differed from Control in pH and K concentration. The organic layer pH on the Harvest plots was 3.2 while that of the Control plots was 3.5; the difference approached significance ( $p < 0.10$ ). Causes of the lower pH in the Harvest plots may be dilution of the organic layer with mineral soil or increased nitrification as suggested by Johnson *et al.* (1991). The decrease was unexpected as greater decomposition rates are usually associated with increased pH. In August the organic layer pH of the Control and Harvest plots were nearly identical so the difference in June was more likely the result of dilution of the sample with mineral soil.

The concentration of K in the 0-5 cm mineral soil layer was significantly higher in the Harvest than in the Control plots. The concentrations, however, were very low with values of  $0.13 \text{ cmol kg}^{-1}$  for Control and  $0.25 \text{ cmol kg}^{-1}$  for the Harvest treatment. Such small values mean the difference is probably of little consequence to biological growth and is sensitive to error and sample variability. Potassium is the most soluble cation measured however, and would be the first to show increases in the mineral soil after release by organic matter decomposition. In August, K concentration was significantly higher in the Control than Harvest plots for the 5-10 cm mineral soil layer. If the difference in K observed in the 0-5 cm layer in June was due to increased decomposition, the same trend would be expected in the 5-10 cm layer in August because of the downward movement of ions; however the reverse occurred. Possible reasons why the same trend was not evident could be the uptake of K by vegetation and microbes, or the peak in K concentration in the 5-10 cm layer had already happened or the difference may have been the result of inherent soil variability.

The CEC of the organic layer sampled in August was significantly higher in the Control than Harvest plots. The variability in the Control data for June precluded this same difference from being significant. Cation exchange capacity in the organic layer is related to the amount of stable organic acids or humus present (Brady, 1990). The lower CEC in the Harvest treatment

probably stems from the site preparation activities. Other possible explanations for the lower CEC include conversion of some organic matter to CO<sub>2</sub>, downward percolation of humus material into the mineral profile or removal of it from the site by surface erosion (Bormann *et al.*, 1978; Johnson *et al.*, 1991). The physical disturbance of the soil profile by the scalping action of the site preparation implement altered the arrangement of the LFH layer, removed the ground vegetation cover and possibly diluted the organic layer with mineral soil. The exposure of the humus layer made it susceptible to the erosion forces of wind and rain. Cation exchange capacity did not differ among the mineral soil layers so relocation of humus in the profile following site preparation probably did not occur.

The Harvest treatment contained higher concentrations of Ca and Fe in comparison to the Control in the 0-5 cm layer sampled in August. The cause of the high Fe concentration in the Harvest plots was probably the natural occurrence of a Bf horizon at the 0-5 cm depth in some samples and the mixing of the upper mineral soil by the site preparation equipment. The ordination of the June data for this layer also showed the separation of Harvest and Control plots due to Fe (axis 2). The Harvest plots and one of the Control plots occurred on an esker complex, so soil profile development was different from that on the aeolian deposit. The Ae horizon on the esker parent material was not as prominent and the Bf horizon was dominant as compared to the Bm on the aeolian deposit.

Calcium concentration decreased by 60 % between collection periods in the Control plots. The Ca concentration in the Harvest treatment also decreased but not to the same extent. The decline may have been the result of the replacement of Ca by other cations released from the seasonal increase in decomposition or possibly from uptake by actively growing vegetation (Kimmins, 1987). Such a dramatic decrease in Ca concentration for the Control plots may also be related to soil variability.

The differences in pH and concentrations of K, Ca and Fe between Harvest and Control plots were due more to the effects of site preparation than to increased decomposition. The differences in mineral soil chemistry that were identified were not of biological significance because the majority of readily available nutrient capital in these sandy soils was located in the organic layer. The only difference, which may possibly be attributed to increased decomposition following harvesting, was the higher level of K in the 0-5 cm layer sampled in June.

The similarity in soil chemistry, especially in the organic layer, between Harvest and Control plots may be due to the relatively short time between harvesting and sample collection. The rate of decomposition and nutrient input was reduced by the slash composition (> 70 % coniferous) which is lower in nutrient content and decomposes slower because of the lignin content (Alban *et al.*, 1978; Kimmins, 1987). The vegetation present on the cutovers was dominated by herbaceous species so the microclimatic conditions still favoured increased decomposition rates (Rintoul, 1996). The unknown factor was the amount and fate of nutrients released during the first summer. If decomposition had increased significantly during the first summer after harvesting differences in the organic layer nutrient content would still be expected. Another possible explanation for the similarity may be the fact that the canopy on the Control plots was opening due to the death of trees from spruce budworm. The opening of the canopy allowed more direct solar radiation and precipitation to reach the forest floor, creating somewhat comparable microclimatic conditions to those found on the Harvest plots. Overall the evidence suggested that the Harvest treatment was similar to the Control and had not yet diverged in any soil related chemically significant manner.

## FIRE TREATMENTS VERSUS HARVEST AND CONTROL

The similarity in soil chemistry between the Harvest treatment and Control has been established; in this section they are grouped and compared to the soil chemistry resulting from the fire treatments.

The fire treatments differed in the amount of rainfall which fell between the time of the fire events and sampling. This affected how much and to what depth nutrients entered the soil profile. In addition, wind speed affected the surface movement of ash produced by the fires.

The three fire treatments or disturbances (WF, PB and RB) had an immediate impact on organic layer soil chemistry by mineralizing forest floor organic matter and woody fuels to varying degrees. The RB treatment had the highest forest floor consumption, followed by PB and WF. The instantaneous mineralization of organic matter during the fires tends to release nutrients in an available and mobile form (MacLean *et al.*, 1983).

The organic layer soil chemistry in the fire treatments was more similar to the Control than to the Harvest treatment. The ordination of the organic layer soil chemistry data for June grouped Harvest and Control plots and separated them from the fire treatments along the first axis, while for the August data they were separated along the second axis. Reasons why the fire treatments were not as different from the Control as from the Harvest treatment include: the amount of time between fire treatments and sample collection; small sample size; disturbance of the forest floor in the Harvest plots by site preparation; variability of effects within a treatment; and variability in soil chemical properties present before the treatments.

The amount of time between the three fire events and sample collection was relatively short and the amount of precipitation low. These factors affected how much and to what depth the nutrients had leached through the profile. Organic layer samples were representative of the ground layer as a whole and thus the fire treatment samples may not have fully reflected the increased

nutrient levels. The organic layer samples of the Control and fire treatments for the most part were intact divots. The Harvest treatment was not; because of the mechanical disturbance of the layer from site preparation. These factors were probably why the Control was more similar to the fire treatments than the Harvest treatment.

Available P increased five-fold in the WF and PB treatments and six-fold in the RB in comparison to the amounts in Harvest and Control plots in the organic layer sampled in June. Other studies also found increased levels of available P following fire. Viereck *et al.* (1979) reported available P increases of four to 10-fold depending on the percent reduction in organic matter depth. Smith (1970) found available P increased by five-fold immediately following burning in Ontario, while Dyrness *et al.* (1989) reported a 27-fold increase in available P in the heavily burned forest floor under a black spruce stand in Alaska.

The increase in available P was important because of its normally low supply and availability in boreal forest soils (Viro, 1974). The rapid vegetation growth following fire is thought to be partly a function of this pulse in available P (Viereck *et al.*, 1979). The change in available P was one of the most apparent differences between fire and full-tree harvesting identified in this study. Phosphorus was a prime example of the difference in the magnitude of effect that these disturbance agents have immediately on soil chemistry.

Elevated cation concentrations were observed following the fire treatments which agreed with studies by Smith (1970), Grier (1975) and Dyrness *et al.* (1989). The mineralizing action of fire concentrated cations in the ash layer in varying amounts depending on the fire treatment. Calcium, Mg and K concentrations were all greater in the organic layer of the fire treatments sampled in June as compared to the Harvest and Control plots.

The differences for Ca and K were only significant between all fire treatments and the Harvest treatment. One possible reason why Ca and K were significantly lower in the Harvest plots

might have been the dilution of the organic samples with mineral soil. Sample variability, however, was probably the biggest contributing factor to the lack of difference in Ca and K between the fire treatment plots and the Control plots. A larger sample size would most likely have resulted in significant differences.

In the case of Mg, the difference was significant for PB and RB from both Harvest and Control. The fact that significant differences were detected in Mg concentration between RB and PB, and Harvest and Control but not for Ca and K may indicate inherent soil chemistry variability within the soils and variability in fire severity within fire treatments. Possibly under the circumstances found in these fire treatments Mg was sensitive to burn severity. The level of Mg present in the fire treatments did follow the severity gradient with the two most severe treatments, RB and PB, having higher concentrations than WF.

The increased concentrations of cations in the organic layer of the fire treatments is reflected in higher pH values. The mean pH of the organic layer of all three fire treatments was greater than 4.0 while Harvest and Control had mean pH values of 3.5 or less. Variability among replicates of the same treatment was high, with the pH ranging from 3.6 - 5.5 for WF; 4.0 - 5.3 for PB; and 4.0 - 5.9 for the RB. The high range of pH values for individual fire treatments was due to the variability in fire severity and in soil conditions. Values at the low end were probably from sample locations that did not experience the full treatment effect. The pH of ash samples which were collected under trees and around stumps ranged from 8.2 to 8.7. The buffering capacity of the organic layer prevented the pH from being as high as that in the ash.

The buffering capacity of the soil was quite high because of the low base saturation (36 %) of the organic layer before the fire treatments. The addition of soluble cations greatly increased the base saturation of the organic layers of the fire treatments (Appendix VI). The principle of mass action would have been controlling the replacement of cations on exchange sites because of

the high concentrations of soluble cations entered the soil profile; resulting in the increased base saturation.

The increase in pH following fire has been documented and is usually attributed to the addition of soluble cations to the soil solution from the ash after rainfall (Smith, 1970; Dyrness et al., 1989). The degree to which soil pH increases is therefore dependent in part upon the amount of soluble cations released which is a function of the amount and type of fuel mineralized. The results of this study partly agree with this conclusion, with the RB treatment having the highest pH followed by the PB and WF.

Data of the amount of forest floor and slash mineralized were available for the RB and PB treatments so the pH increase could be related to the amount of mineralization. Double the amount of organic matter was consumed on the RB but the pH increase (1 unit) was similar to that on the PB. Other factors therefore must also control the increase in pH such as the type of organic matter being consumed, the amount of ash left on the site and in this case the amount of precipitation between the fire event and sampling.

All three fire treatments had elevated organic layer pH in comparison to the Harvest and Control treatments. The differences in pH were only significant between the fire treatments and Harvest for the organic layer sampled in June however, increasing the sampling intensity may have resulted in less variance making the Control significantly different as well.

Soil reaction of the organic layer continued to be a factor in discriminating between the fire treatments and Harvest and Control at the second collection period in August, even though, available cation levels were no longer significantly different. The Control and Harvest pH were both significantly lower than that of the three fire treatments. The reasons the Control was significantly different from the fire treatments was a decrease in pH and less variance in the August Control data.

A comparison of pH between collection periods for each treatment, however, did not show any significant changes. Mean hydrogen concentration, however, increased for all treatments except WF and Harvest. The WF pH increase may be the result of a delay in the subsequent addition of ash leachate to the soil profile because of the extra time it took for ash to fall to the surface from mineralization which occurred in the tree crowns (Dymess *et al.*, 1989). Elevated forest floor pH following fire has been reported to persist up to fifty years (Viro, 1974).

Except for Zn, cation levels were not significantly different in the organic layer between the fire treatments and Harvest and Control in August. The concentrations of cations in the fire treatments did increase between sample collections but the variance in the data as well as an increase in the Harvest treatment's cation levels were the reasons differences between treatments were not significant. The cause of the increased cation levels in the fire treatments was probably the on going translocation of cations deeper into the forest floor with precipitation. The continued difference in pH between fire treatments and Harvest and Control was indirect evidence of this difference in cation concentrations.

Although organic matter content, as estimated by LOI, was not significantly different among treatments at the first sampling period because of large variance, the general trend showed organic matter in the Control to be highest; Harvest, WF and PB had nearly equal amounts of organic matter, and RB had the least amount of organic matter. The data from the August collection period exhibited the same trend but with the difference between RB and Control significant and RB and Harvest nearly significant. The most severe treatment, RB, resulted in a substantial reduction in forest floor organic matter in comparison to Control and Harvest. The RB was a surface fire with the greatest degree of mineralization and the most heat generated, therefore probably the greatest amount of volatilization of carbon, hydrogen and oxygen and the most ash incorporated in the organic sample (Raison *et al.*, 1985 and Feller, 1988). The combination of



carbon loss to the atmosphere and the presence of inorganic ash particles in the samples contributed to the reduction in the amount of carbon in the organic layer samples in the RB.

The separation of the fire treatments from Harvest and Control was greatest and most clearly evident in the organic layer at both collection periods. This is because the fire treatments directly affected the organic layer and this layer receives rainfall first. The organic layer also contains the vast majority of the nutrient capital on this sandy site because of its high CEC relative to the mineral soil. Severity of fire did influence the extent to which the fire treatments were different from the Harvest and Control treatments.

The organic layer CEC was reduced by the surface fires in the RB and PB treatments. Variance in the Control data for June prevented the reduction observed in the PB and RB treatments from being significant. However, in August CEC was found to be significantly lower in the RB and PB treatments than in the Control. The mineralization of the forest floor in the surface fires of the PB and RB was great enough to lower the humus fraction which regulates CEC (Brady, 1990). Humus is found at the bottom of the organic layer. Evidence of this reduction in forest floor was indicated by the depth of burn and weight loss for the organic layers of these two treatments (Table 2). A possible lesser contributing factor for the lower CEC maybe the redistribution of humus colloids into the mineral soil or removal of them from the site while in solution following the fire treatments (Wells, 1971). The WF treatment exhibited a CEC similar to PB and RB in June but in August it was more similar to the Control.

The only nutrient which was significantly higher in the fire treatments than Control for the 0-5 cm mineral soil layer sampled in June was K. Potassium is highly soluble because of its low ionic potential so it is not retained on exchange sites very strongly (Brady, 1990). Increases may occur, however, when the K concentration is high enough to replace other cations through mass action. These were probably the reasons why it was the first cation to show an increase in the mineral soil. The level of K in the Harvest treatment was not significantly lower than that of the

fire treatments, probably because of organic matter decomposition. The Harvest treatment had an extra growing season before sampling was done so K released from decomposition may have leached to the upper layer of the mineral soil.

No differences in soil chemistry were evident in the 5-10 cm mineral soil layer sampled in June. However, the ordination showed that Control was most dissimilar to RB and that it was due to higher CEC and higher Mg concentration in the Control. The relationship was not very strong, but a possible explanation may be the destructive distillation of organic compounds by the heat produced by the fire which resulted in the volatilization of carbon. This theory would have more weight if the same difference was seen in the 0-5 cm layer, but it was not. The length of time between fire treatments and sample collection was probably too short for the expected translocation of nutrients and organic matter to reach this layer and change the levels present (Wells, 1971).

In August the concentration of Ca in the 0-5 cm mineral soil layer was greater in the fire treatments than Control. The Ca concentration in the Harvest treatment was higher than that of WF and PB which may have been due to organic matter contamination in the Harvest samples. The increase in Ca in the 0-5 cm mineral layer of the fire treatments suggests that the less mobile cations had begun to leach into the mineral soil. The RB treatment had the greatest amount of mineralization of the organic layer and showed a two-fold increase in the 0-5 cm mineral soil layer Ca concentration between sampling periods. Smith (1970) reported a 240 % increase in water soluble Ca in the 0-2 cm mineral soil layer following fire.

It was expected that the higher level of K observed in the 0-5 cm layer in June for RB and PB would be evident in the 5-10 cm layer at the second sampling period. This did not occur and instead the amount of K was higher in the Control than the RB and PB treatments. The rapid drainage of the porous sandy soil, the high solubility of K and the length of time between sample collection were potential reasons that the increase in K for this layer was not detected.

The fire treatments had an immediate and lasting effect on soil chemistry which resulted in major differences from the Control and Harvest. Clearly, the mineralizing action of fire dramatically altered the soil chemical properties in way that full-tree harvesting did not. Nutrient availability within the organic layer of the fire disturbed sites, was markedly increased by the addition of phosphorus, cations and the rise in pH. Fire severity and type influenced the degree to which soil chemistry was changed by affecting the level of mineralization and volatilization as well as the amount and timing of the addition of ash to the ground surface. Dyrness *et al.* (1989) reported similar changes in soil chemistry which were also affected by the fuel type and level of burn severity.

#### COMPARISONS AMONG FIRE TREATMENTS

Differences in the severity of individual fire treatments, as expressed by duff and fuel consumption, were affected by weather and fuel characteristics. The accumulation of woody fuels on the surface in conjunction with a reduction in forest floor moisture content in the PB and RB treatments affected the amount of forest floor mineralization and heat produced in comparison to the WF. The canopy of the standing timber in which the WF burned reduced the drying rate of the forest floor and surface fuels by intercepting both solar radiation and precipitation. The majority of fuel consumption in the WF was in the tree crowns and was affected by the vertical fuel arrangement, fuel loading and moisture content of the standing timber.

Ash produced during fire in the canopy was not concentrated on the surface immediately following the WF as it was in the RB and PB. The ash was more susceptible to loss in convection and wind movement during and after the disturbance because of the height at which combustion occurred. There was also a time delay in the fall of foliage killed by the fire as well as charred organic material as wind and gravity had their affect. The heat produced during combustion in the

crown was not concentrated at the surface which would affect the amount and type of nutrients volatilized.

Differences among fire treatments were a result of burn severity and timing of nutrient and organic matter input into the soil profile. Cation exchange capacity in the organic layer and the concentration of K in the 5-10 cm mineral soil layer sampled in August were the only soil chemical properties significantly different among fire treatments. In both cases WF contained higher levels than PB and RB.

Between sampling periods WF organic layer CEC increased significantly which resulted in the higher level in comparison to RB and PB in August. The causes of such a dramatic increase in the CEC of the WF organic layer are not clear. One hypothesis is that fine charred particulate organic matter fell from the burned tree crowns which subsequently percolated into the profile over time and acted as a source of negative charge. Another explanation may be that increased decomposition occurred because of the addition of needles and leaves to the forest floor from trees killed in the fire which resulted in the production of organic acids. The exact cause is not clearly understood but the key factors include reduced fire severity and the occurrence of combustion and mineralization within the tree crowns. The vertical fuel arrangement within the WF was responsible for these factors and differentiates this treatment from PB and RB.

The higher concentration of K in the WF 5-10 cm mineral soil layer sampled in August compared to PB and RB reflected the differential timing of nutrient input and movement through the soil profile resulting from disturbances with different characteristics and severity. The level of K was lower in the WF 0-5 cm layer sampled in June in comparison to RB and PB which suggested that the input of K was either not as great or not at the same rate. The fact that K was the only cation to show differences in the 5-10 cm layer sampled in August suggested that the peak of K input for PB and RB had already passed and that other less soluble cations had not yet peaked in the soil solution moving through this layer. It is hypothesized that the amount of time required

for nutrients to move through the profile increases with decreasing fire severity because of the increasing weight and thickness of the remaining organic layer and associated higher CEC.

Another example of how soil chemistry was affected to different degrees by the fire treatments was that only the severe disturbances were significantly different from Control and Harvest. An example was that the organic layer of the RB and PB had a significantly higher concentration of Mg than Control and Harvest when WF did not. Another example was that the RB had significantly lower organic carbon than the Control in the organic layer and higher Ca in the 0-5 cm layer sampled in August while the other fire treatments did not. The first example is related to the fact that the WF had the least depth of burn. The ash layer was not immediately concentrated at the surface reducing the amount and timing of nutrient movement into the profile. The WF organic layer was the thickest and therefore had the greatest depth for nutrients to move through. Samples collected from the deeper layer were less likely to indicate the influx of nutrients in comparison to the shallow remaining organic layers of the PB and RB.

The lower organic C measured in the organic layer of the RB treatment was partly due to more ash material being included in samples but mostly due to higher volatilization of C during the disturbance. The RB had the highest amount of combustion which implies greater residence time of the fire and therefore the time that temperatures were above the threshold necessary for volatilization of C to occur.

The higher Ca concentration in the 0-5 cm mineral soil layer of the RB in August was probably a function of higher mineralization and differential precipitation. The Ca concentration peak for the PB had most likely passed because it received more precipitation in comparison to the RB and WF. The WF received the same amount of precipitation but the severity of the disturbance was less in comparison to the RB, so less Ca was released. Fire severity affected the degree to which the soil chemical properties were differentiated from Control and Harvest.

The ordination diagrams of the organic layer sampled in June and August also showed that the separation of the fire treatments was due in part to differences in total N. In both instances high total N was associated with the WF and low levels with RB. Volatilization of N during the surface fires was seemingly responsible for this difference at the June sampling and was further enhanced by the subsequent addition of needle material to the forest floor of the WF. It is important to note that this measure did not indicate the degree of nitrogen availability, which has been found to increase even though total N was lowered (Raison *et al.*, 1990). The overall N capital, however, was decreased with increasing fuel consumption which agrees with Dymess *et al.* (1989).

Another relevant point is that the fire treatments did not differ significantly in cation concentrations and amount of available P in the organic layer in June. The data suggests differences that were related to the increase precipitation experienced by the PB and the severity of disturbance. If the sampling intensity had been greater, the variability within data sets could have been reduced and significant differences may have been evident.

The separation of the fire treatments was partly between “natural” and “managed” fires. Forest management activities both removed and rearranged fuel, creating a different set of fuel characteristics than that seen in the WF. The effects of these changes were expressed in the severity of the disturbance.

## CHANGES BETWEEN SAMPLE COLLECTIONS

The soil chemistry, measured in June and August for each treatment, changed over time and highlighted the dynamic nature of these properties. Changes were a result of the movement of nutrients and organic matter through the profile in the soil solution following the disturbance treatments and additions from decomposition and weathering.

The most notable change in the organic layer was that the high levels of available P measured in June did not persist for the fire treatments. The reduction in available P was significant in the case of the RB and WF but not PB due to the high degree of variability in the data. The P released during the mineralization of organic matter by fire was negatively charged and highly reactive (Brady, 1990). Possible causes of the reduction were the low anion exchange capacity of the organic layer, conversion to an insoluble form or uptake by vegetation. The return of available P to levels similar to the Control highlights the narrow window of opportunity for competing pioneer vegetation to sequester this valuable resource. The decrease in available P following the initial peak after a fire disturbance was consistent with what was reported by Smith (1970).

While the fire treatments showed a decrease over time in available P, the Control increased significantly, nearly doubling. Reasons for the increase may be the seasonal changes in decomposition rates resulting from increased soil temperatures. The amount of available P, however, remained about the same in the Harvest treatment at both dates. The disturbance of the organic layer by site preparation may have disrupted the release of available P; alternatively, uptake by herbaceous vegetation on the cutovers may have kept it at the same level.

The level of total N measured in the organic layer in August was significantly higher in the Harvest and WF treatments than that measured in June. In the case of the WF treatment, the cause was the fallout of needle and leaf material from the trees killed by the crown fire. The increase in

the Harvest treatment probably was due to sample variation and maybe less contamination of the organic sample with mineral soil.

The increase in organic layer CEC for the WF has already been discussed in the context of the difference between WF and PB and RB. Such an unexpected increase raises questions concerning the differences between surface fires and fires which include both a crown and surface component.

Part of the idea behind comparing treatments over time was to see if the individual treatments would become more or less similar with regards to soil chemistry. The discriminant analysis of the combined organic layer data for June and August produced an ordination diagram (Figure 5) that visually illustrated the hypothesis of soil chemistry response to disturbance severity. The diagram showed a clear gradient of fire severity with Control at one end and Reburn at the other. For each treatment, both dates were separated from the others, except in the case of WF. The trajectory of the line joining the plot centroids for the two dates of the WF intercepted the line joining the Harvest plot centroids (Figure 5) and was due to the increase in CEC. The severity gradient was a function of increasing available P and cations. With greater mineralization, more nutrients are released and concentrated in the remaining organic matter.

In the ordination (Figure 5), the time gradient was perpendicular to the severity gradient and was related to changes in CEC, organic matter, total N, Ca, Mg and Zn. The change in PB and RB treatments between collection periods was related to cation levels while for WF and Control the change was due to CEC, total N and organic matter content. The Harvest plots for August were located between these two groups. The Harvest and RB treatments showed the most dissimilarity between dates in the ordination. In the case of the RB the magnitude of the disturbance caused such an immediate modification in soil chemistry that with time any change would be dramatic which would make them dissimilar. The Harvest treatment had a high degree of



variability related to the rearrangement of the organic layer by site preparation which may partly explain the differences between dates.

All treatments showed differences in soil chemistry between June and August. This is because the time period covered the maximum period of biological activity within the soil due to the seasonal increase in temperatures (Kimmins, 1987.) The fire treatments were also reacting to the addition of nutrients and the reduction and relocation of organic matter. The direction of the arrows joining the dates of each treatment show that soil chemical properties were converging or becoming more similar with time for Control and WF and for Harvest, PB and RB. These two groups, however were diverging or becoming more dissimilar with time in regards to their soil chemical properties. Two sampling dates are not enough to establish a reliable trend; but the ordination diagram raises the question of whether disturbances related to forest management activities are taking soil chemical properties in a different direction than that which happens following WF. The consequence of this may be an increase in the amount of time that it will take soil chemistry to return to that observed in the Control.

The 0-5 cm mineral soil layer in the Control exhibited a significant increase in K between collection periods as well as a significant decrease in Ca. This combination of changes can be explained by the fact that K is the most soluble cation and Ca the most abundant. Seasonal increases in decomposition would release K and other nutrients but as the most mobile cation it would move through the layer at the fastest rate and by the principle of mass action replace Ca from exchange sites. Another explanation for the decrease in Ca maybe that other cations were also replacing it on exchange sites or that it was being taken up by vegetation.

The concentration of Mg decreased significantly between sample collections in the PB. The PB was the first fire treatment to occur and had the longest amount of time and most precipitation before sample collection was completed. The Mg concentration measured in June for

the PB was probably near the peak because it was similar to the RB which experienced greater mineralization but less precipitation and remained at that level in August while PB had declined.

Potassium concentration in the WF was the only variable to increase significantly between collections for the fire treatments in the 5-10 cm mineral soil layer. The increase reflects the mobility of K and is in agreement with the literature (Smith, 1970.). The peak for K concentration for RB and PB was not captured by the sampling completed. For WF, the delay of nutrient input and the greater organic layer depth probably slowed the movement of nutrients into the mineral soil.

## IMPLICATIONS OF STUDY

The results of this study provide one example of the impacts of full-tree harvesting and fires of varying severity and type on the soil chemistry of a sandy site with a moderate organic layer depth. The collection of fuels and weather data increases the usefulness of the results because they can be related to the characteristics of the disturbance and informed comparisons to other disturbances can be made.

The majority of the readily available nutrient capital on these sites was contained in the organic layer. The underlying mineral soil was a fine sand with low CEC so nutrient retention was low and leaching was rapid. Therefore, effects of disturbance on the organic layer were of the greatest ecological importance. The observed treatments affected the organic layer in different ways and to varying degrees. The reason treatments were different and the ways in which natural disturbances can be emulated on this site are dictated by what happened within the organic layer.

Important differences among treatments included removal and rearrangement of biomass on the site and whether or not this was followed by a fire. The harvesting operation affected fuel arrangement, fuel loading and also fuel drying rates. The overall quantity of fuel was reduced by

harvesting but what remained was concentrated at the surface. The WF, unlike the PB and RB, had a vertical as well as a horizontal fuel component. In addition, the overall fuel loading was higher but it was not concentrated at the soil surface. Another important difference was the composition of the fuel, which in the case of WF contained more foliage. Fuel drying rates were also different for the WF. The standing live timber dried much slower because of moisture in the tree. The surface fuel and organic layer dried slower because of less direct solar radiation.

It was assumed that all treatments investigated originally had soil chemistry similar to that of the Control. The WF was considered to be the natural disturbance because it occurred in standing timber and was that which would have happened with no intervention by man. The differences in soil chemistry between the Control and WF can be considered representative of nature and therefore one of the objectives of emulation by forest management activities. Based on this idea, full-tree harvesting does not affect soil chemistry the way WF does. The immediate mineralization of organic matter by fire was not replicated by the increased microbial decomposition that follows harvesting. Full-tree harvesting left soil chemistry similar to that of the Control. Emulation of WF cannot be done on the same time scale by full-tree harvesting alone.

The inclusion of prescribed fire as part of the silvicultural prescription after full-tree harvesting brings the mineralizing action of fire into the management of forest operations. The PB and RB were two examples of surface fires in cutovers. Differences between these fires and the WF result from the amounts of nutrients released, loss of organic matter, CEC, volatilization of carbon and other nutrients, timing of nutrient input and the rate of movement through the profile. Burn severity was greater in the PB and RB because the fuel was drier and concentrated at the surface. These differences affected nutrient retention and must be taken into account when planning the harvest and prescribed burn prescription before prescribed fire can emulate natural fire.

The degree to which resolution is possible is limited because full-tree harvesting removes biomass from the site and eliminates the vertical fuel arrangement. However the surface fire component of the WF can potentially be emulated. Fuel moisture is the critical fuel characteristic and is reflected by the Duff Moisture Code and Drought Code within the Canadian Forest Fire Danger Rating System (Stocks *et al.*, 1989). The fire danger indices for prescribed burn plans should reflect the moisture levels similar to those present in the organic layer when wildfires occur. Allowable depth of burn and fuel consumption should also reflect levels observed in natural wildfires. By doing so, excessive volatilization and organic matter removal will be controlled and nutrient input will be slowed giving vegetation more time to react. If emulation of natural disturbance was the most important management objective, leaving enough residual standing timber to give a vertical fuel component would be necessary.

Revegetation of this site type immediately following the three fire treatments would be essential if the higher concentration of cations and available P were to be used to increase the vigor of growth. Available P was the most sensitive to time and exhibited the greatest decrease. The longer the time period before germination, suckering or tree planting occurs, the greater the risk that nutrients will be lost from the rooting zone because of rapid drainage.

The degree of emulation possible is dependent upon what is known about the natural fire regimes for the vegetation and site type and how much harvesting modifies the site. Since the mineralization of organic matter is necessary for the emulation of natural disturbances, fire must be included as part of the management prescription. It could be suggested that any fire is better than no fire because there is no other way to produce similar results in terms of soil chemistry. The only reservation would be that fire severity does not detrimentally affect soil productivity.

Presently the lengthy prescribed burn planning process and the narrow window of acceptable weather makes a prescribed burn time-consuming and difficult. Recognizing the necessity for fire on the landscape will have to change the approach. Increasing the acceptable

range of burning indices and having larger escape allowances would assist in completing more prescribed burns. The range of acceptable indices could be widened or narrowed based on the importance of the organic layer in the overall fertility of the site, the depth of organic layer and the type of organic layer . If these options are not reasonable then changes in our approach to controlling natural fires should be considered to allow more wildfires to burn. Either way fire must be part of the management regime to retain the integrity of the ecosystem as reflected in soil chemical properties.

## CONCLUSIONS

(1) The organic layer contained the highest nutrient concentrations of the three soil layers sampled and was most affected by the disturbances because of its direct contact with them.

(2) As the observed changes in soil chemical properties associated with full-tree harvesting were always less than those resulting from fire, the hypothesis stands, that is the magnitude of changes in soil chemical properties resulting from fire are greater than those resulting from full-tree harvesting.

(3) The severity of fire affected the degree of change in soil chemical properties. Increasing fire severity reduced total nitrogen, organic matter, CEC and increased the concentration of cations and available P. Therefore the hypothesis stands that the degree of change in soil chemical properties increases with increasing fire severity.

(4) In addition to severity, the type of fire affected the amount and timing of nutrient input because of its effect on the location of mineralization. The crown fire resulted in an increase in organic layer CEC and total nitrogen over time, which did not occur in the surface fires.

(5) Emulation of wildfire requires fire, as part of the management prescription but surface fires alone cannot fully emulate a natural disturbance in which a crown fire occurs.

## LITERATURE CITED

- Ahlgren, I. F. and C. E. Ahlgren. 1960. Ecological effects of forest fires. *Bot. Rev.* 26:483-533.
- Alban, D. H., D. A. Perala and B.E. Schlaegel. 1978. Biomass and nutrient distribution in aspen, pine, and spruce stands on the same soil type in Minnesota. *Can. J. For. Res.* 8: 290-299.
- Alemdag, I. S. 1982. Aboveground dry matter of jack pine, black spruce, white spruce and balsam fir trees at two localities in Ontario. *For. Chron.* 58: 26-30.
- Alexander, M. E. 1980. Calculating and interpreting forest fire intensities. *Can. J. Botany.* 60: 349-357.
- Anderson, M. 1985. The impact of whole-tree harvesting on British forests. *Quarterly J. For.* 79: 33-36.
- Anonymous. 1978. The Canadian system of soil classification. *Can. Dep. of Agric. Publ.* 1646. Supply and Services Canada, Ottawa, Ont. 164 pp.
- Armson, K. A. 1979. *Forest soils: properties and processes.* University of Toronto Press. Toronto. 390 pp.
- Blake, T. 1994. *Personnal Correspondence.*
- Bohn, H. L., B. L. McNeal and G. A. O'Connor. 1989. *Soil Chemistry.* 2nd. Ed. Wiley-Interscience, New York. 341 pp.
- Bormann, F. H., G. E. Likens, T. G. Siccama, R. S. Pierce and J. S. Eaton. 1974. The export of nutrients and recovery of stable conditions following deforestation at Hubbard Brook. *Ecol. Monogr.* 44: 255-277
- Brady, N. C. 1990. *The nature and properties of soils.* Macmillan Publishing Company. New York. 621 pp.
- Brais, S., C. Camire and D. Pare. 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.
- Bray, R.H. and L. T. Kurtz. 1945. Determination of total , organic and available phosphorus in soils. *Soil Sci.* 59: 39-45.

- Bremner J. M. and C. S. Mulvaney 1982. Nitrogen-total. Pages 595-624. In *Methods of soil analysis. Part 2.* A. L. Page, R. H. Miller and D. R. Keeney (eds.). Agron. 9. Am. Soc. Agron., Madison Wisconsin.
- Brown, G. W. 1973. The impact of timber harvest on soil and water resources. Extension Bulletin 827. Oregon State University. 17 pp.
- Byram, G. M. 1959. Combustion of forest fuels. In: *Forest Fire Control and Use*, Davis, K. P. (ed). McGraw-Hill Book Co., New York. Pp. 61-89.
- Chandler, C., P. Cheney, P. Thomas, L. Trabaud, and D. Williams. 1983. *Fire in forestry*, vol. 1. Wiley Press, New York. 450 pp.
- Chorover, J., P. M. Vitousek, D. A. Everson, A. M. Esperanza and D. Turner. 1994. Solution chemistry profiles of mixed-conifer forests before and after fire. *J. Biogeochemistry*. 26:115-144.
- Christensen, N. L. 1987. The biogeochemical consequences of fire and their effects on the vegetation of the coastal plain of the southeastern United States. In: *The Role of Fire in Ecological Systems*. eds: L. Trabaud. Hague, Netherlands. Pp. 1-19.
- Covington, W. W. 1981. Changes in forest floor organic matter following clear cutting in northern hardwoods. *Ecology*. 62: 41-48.
- CFSA (Crown Forest Sustainability Act). 1994. Bill 171, Ontario Government, Queens Park, Toronto, Ontario. 37 pp.
- Dymess, C. T. and C. T. Youngberg. 1957. The effect of logging and slash burning on soil structure. Pages 444 - 447 in *Soil Science Society Proceedings*.
- Dymess, C. T. and R. A. Norum. 1983. The effects of fire of experimental fires on black spruce forest floors in interior Alaska. *Can. J. For. Res.* 13: 879-893.
- Dymess, C. T., K. Van Cleve and J. D. Levison. 1989. The effect of wildfire on soil chemistry in four forest types in interior Alaska. *Can. J. For. Res.* 19: 1389-1396.
- Etiegni, L. and A. G. Campbell. 1991. Physical and chemical characteristics of wood ash. *Bioresource Technology*. 37: 173-178.
- Feller, M. C. 1988. Relationships between fuel properties and slashburning-induced nutrients losses. *Forest Science*. 34:998-1015.
- Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. Forestry Canada Information Report ST-X-3, Ottawa, Ontario. 63 pp.
- Grier, C. C. 1975. Wildfire effects on nutrient distribution and leaching in a coniferous forest ecosystem. *Can. J. For. Res.* 5: 599-607.



## APPENDICES

APPENDIX I

PRE- AND POST FIRE FUEL DATA FOR THE  
FUEL TRIANGLES MEASURED IN PRESCRIBED  
BURN AND REBURN TREATMENTS

Pre-and post- fire fuel data for triangle # 4 (Prescribed Burn treatment) by size class and type as well as the level of fuel consumption. The species composition of the slash was 40 % white pine, 30 % balsam fir, 30 % white birch and the duff type was feathermoss.

Time	Amount of Slash by Diameter Size Class (kg/m <sup>2</sup> )						Total Slash (kg m <sup>-2</sup> )	Total Foliage (kg m <sup>-2</sup> )	Total Duff (kg m <sup>-2</sup> )	Total Loading (kg m <sup>-2</sup> )	Duff Depth (cm)
	0-0.49 (cm)	0.5-0.99 (cm)	1.0-2.99 (cm)	3.0-4.99 (cm)	5.0-6.99 (cm)	7.0 + (cm)					
Preburn	0.135	0.103	0.596	0.326	0.659	6.248	8.066	0.05	8.46	16.576	8
Post Burn	0.007	0.022	0.156	0.212	0.539	4.403	5.338	0	7.77	13.108	6.4
Difference	0.128	0.081	0.440	0.114	0.120	1.845	2.728	0.05	0.69	3.468	1.6
Percentage Consumed	95%	79%	74%	35%	18%	30%	34%	100%	8%	21%	20%

Pre- and Post- fire fuel data for triangle # 10 (Prescribed Burn treatment) by size class and type as well as the level of fuel consumption.  
 The species composition of the slash was 70 % balsam fir, 20 % spruce, 10 % white birch and the duff type was sphagnum.

Time	Amount of Slash by Diameter Size Class (kg/m <sup>2</sup> )						Total Slash (kg m <sup>-2</sup> )	Total Foliage (kg m <sup>-2</sup> )	Total Duff (kg m <sup>-2</sup> )	Total Loading (kg m <sup>-2</sup> )	Duff Depth (cm)
	0-0.49 (cm)	0.5-0.99 (cm)	1.0-2.99 (cm)	3.0-4.99 (cm)	5.0-6.99 (cm)	7.0 + (cm)					
Preburn	0.178	0.118	0.369	0.214	0.303	3.458	4.639	0.19	18.88	23.709	13.4
Post Burn	0.114	0.085	0.312	0.200	0.278	2.922	3.910	0.12	15.66	19.690	9.1
Difference	0.064	0.033	0.057	0.014	0.025	0.536	0.729	0.07	3.22	4.019	4.3
Percentage Consumed	36%	28%	15%	7%	8%	16%	16%	37%	17%	17%	32%

Pre- and post- fire fuel data for triangle # 14 (Prescribed Burn treatment) by size class and type as well as the level of fuel consumption.  
 The species composition of the slash was 50 % spruce, 30 % balsam fir, 20 % white birch and the duff type was sphagnum.

Time	Amount of Slash by Diameter Size Class (kg/m <sup>2</sup> )						Total Slash (kg m <sup>-2</sup> )	Total Foliage (kg m <sup>-2</sup> )	Total Duff (kg m <sup>-2</sup> )	Total Loading (kg m <sup>-2</sup> )	Duff Depth (cm)
	0-0.49 (cm)	0.5-0.99 (cm)	1.0-2.99 (cm)	3.0-4.99 (cm)	5.0-6.99 (cm)	7.0 + (cm)					
Preburn	0.121	0.096	0.485	0.314	0.357	2.712	4.084	0.06	24.88	29.024	16
Post Burn	0.101	0.096	0.440	0.364	0.505	1.158	2.664	0.05	23.75	26.464	13.8
Difference	0.020	0.000	0.045	-0.050	-0.149	1.554	1.420	0.01	1.13	2.560	2.2
Percentage Consumed	16%	0%	9%	-16%	-42%	57%	35%	17%	5%	9%	14%

Pre- and post- fire fuel data for triangle # 5 (Reburn treatment) by size class and type as well as the level of fuel consumption. The species composition of the slash was 40 % balsam fir, 30 % spruce, 20 % white birch, 10 % jack pine and the duff type was sphagnum.

Time	Amount of Slash by Diameter Size Class (kg/m <sup>2</sup> )						Total Slash (kg m <sup>-2</sup> )	Total Foliage (kg m <sup>-2</sup> )	Total Duff (kg m <sup>-2</sup> )	Total Loading (kg m <sup>-2</sup> )	Duff Depth (cm)
	0-0.49 (cm)	0.5-0.99 (cm)	1.0-2.99 (cm)	3.0-4.99 (cm)	5.0-6.99 (cm)	7.0 + (cm)					
Preburn	0.177	0.140	0.609	0.703	1.526	8.753	11.909	0.14	6.27	18.319	6.6
Post Burn	0.019	0.028	0.121	0.336	0.691	5.310	6.504	0.01	4.8	11.314	4
Difference	0.159	0.113	0.489	0.367	0.835	3.443	5.405	0.13	1.47	7.005	2.6
Percentage Consumed	90%	80%	80%	52%	55%	39%	45%	93%	23%	38%	39%

Pre- and post- fire fuel data for triangle # 9 (Reburn treatment) by size class and type as well as the level of fuel consumption. The species composition of the slash was 70 % balsam fir, 20 % spruce, 10 % white birch and the duff type was sphagnum.

Time	Amount of Slash by Diameter Size Class (kg/m <sup>2</sup> )						Total Slash (kg m <sup>-2</sup> )	Total Foliage (kg m <sup>-2</sup> )	Total Duff (kg m <sup>-2</sup> )	Total Loading (kg m <sup>-2</sup> )	Duff Depth (cm)
	0-0.49 (cm)	0.5-0.99 (cm)	1.0-2.99 (cm)	3.0-4.99 (cm)	5.0-6.99 (cm)	7.0 + (cm)					
Preburn	0.218	0.144	0.721	0.327	0.629	3.126	5.166	0.23	7.81	13.206	7.6
Post Burn	0.010	0.033	0.190	0.228	0.403	2.393	3.256	0.01	5.58	8.846	4.2
Difference	0.209	0.111	0.531	0.100	0.227	0.733	1.910	0.22	2.23	4.360	3.4
Percentage Consumed	96%	77%	74%	30%	36%	23%	37%	96%	29%	33%	45%

Pre- and post- fire fuel data for triangle # 12 (Reburn treatment) by size class and type as well as the level of fuel consumption. The species composition of the slash was 60 % spruce, 20 % balsam fir, 10 % white birch and the duff type was sphagnum.

Time	Amount of Slash by Diameter Size Class (kg/m <sup>2</sup> )						Total Slash (kg m <sup>-2</sup> )	Total Foliage (kg m <sup>-2</sup> )	Total Duff (kg m <sup>-2</sup> )	Total Loading (kg m <sup>-2</sup> )	Duff Depth (cm)
	0-0.49 (cm)	0.5-0.99 (cm)	1.0-2.99 (cm)	3.0-4.99 (cm)	5.0-6.99 (cm)	7.0 + (cm)					
Preburn	0.147	0.132	0.687	0.154	0.217	2.952	4.289	0.05	22.51	26.849	15
Post Burn	0.014	0.017	0.107	0.085	0.124	1.781	2.128	0	15.17	17.298	7.7
Difference	0.133	0.115	0.580	0.068	0.093	1.172	2.162	0.05	7.34	9.552	7.3
Percentage Consumed	91%	87%	84%	44%	43%	40%	50%	100%	33%	36%	49%



Pre- and post- fire fuel data for triangle # 13 (Reburn treatment) by size class and type as well as the level of fuel consumption. The species composition of the slash was 70 % balsam fir, 10 % spruce, 10 % white pine, 10 % white birch and the duff type was sphagnum.

Time	Amount of Slash by Diameter Size Class (kg/m <sup>2</sup> )						Total Slash (kg m <sup>-2</sup> )	Total Foliage (kg m <sup>-2</sup> )	Total Duff (kg m <sup>-2</sup> )	Total Loading (kg m <sup>-2</sup> )	Duff Depth (cm)
	0-0.49 (cm)	0.5-0.99 (cm)	1.0-2.99 (cm)	3.0-4.99 (cm)	5.0-6.99 (cm)	7.0 + (cm)					
Preburn	0.208	0.149	0.513	0.377	0.579	3.907	5.733	0.21	10.16	16.103	9
Post Burn	0.061	0.042	0.124	0.136	0.237	2.157	2.756	0.06	5.71	8.526	3.7
Difference	0.147	0.107	0.389	0.241	0.342	1.750	2.976	0.15	4.45	7.576	5.3
Percentage Consumed	71%	72%	76%	64%	59%	45%	52%	71%	44%	47%	59%

## APPENDIX II

WEATHER DATA AND FIRE WEATHER INDICES  
FOR THE FIRES AT RADIO LAKE

Date	Weather Data					Fire Indices					
	Air Temp. (° C)	RH (%)	Wind Dir.	Wind Speed (km hr <sup>-1</sup> )	Rain (mm)	FFMC	DMC	DC	ISI	BUI	FWI
<b>Prescribed Burn</b>											
6-May	14	31	270	4	0	80.8	12	41	1.5	14	1.4
7-May	14	35	112	7	0	86.5	15	46	3.7	17	5.4
8-May	18	37	270	13	0	88.8	18	52	6.9	19	10.2
<b>Reburn &amp; Wildfire</b>											
31-May	25	45	270	7	0	90.5	20	75	6.6	24	11.1
1-June	27	49	315	4	0	90.3	24	83	5.5	28	10.4

Source: Weather data from Wawang weather station. Codes and Indices from Canadian Forest Fire Danger Rating System (Forestry Canada Fire Danger Group, 1992).

Abbreviations: FFMC, Fine Fuel Moisture Code; DMC, Duff Moisture Code; DC, Drought Code; ISI, Initial Spread Index; BUI, Build Up Index; FWI, Forest Weather Index.

## APPENDIX III

## FIRE BEHAVIOR DATA FOR THE THREE FIRE TREATMENTS.

Treatment	Location	Forward Rate of Spread (m min. <sup>-1</sup> )		Frontal Fire Intensity (kW m <sup>-1</sup> )	
		7-May	8-May	7-May	8-May
PB	triangle # 4	0.2	0.5	170	550
PB	triangle # 10	0.2	0.7	256	827
PB	triangle # 14	0.1	0.3	69	223
		31-May	1-Jun	31-May	1-Jun
RB	triangle # 5	1.8	1.4	3753	2861
RB	triangle # 9	0.9	0.7	1094	834
RB	triangle # 12	2.4	1.8	6908	5267
RB	triangle # 13	1.9	1.5	4316	3290
WF		10.5	8.6	3132	3132

Source: FBP93 Prediction Program (REMSOFT, 1993)

## APPENDIX IV

RECORD OF RAINFALL FROM DATE OF THE INITIAL PRESCRIBED BURN  
UNTIL THE FINAL SOIL SAMPLE COLLECTION.

Date	Event	Rainfall (mm)
6-May	PB	0
7-May	PB	0
8-May	PB	0
May 9 – 30		66.3
31-May	RB & WF	0
1-Jun	RB & WF	0
June 2 – 19		25.0
20-Jun	Collection	1.2*
21-Jun	Collection	0
22-Jun	Collection	0
23-Jun	Collection	0
June 24 - August 13		100.4
14-Aug	Collection	12.4*
15-Aug	Collection	0
16-Aug	Collection	0
17-Aug	Collection	0
18-Aug	Collection	0

\* Rainfall occurred before sample collection began.

**APPENDIX V**

**SOIL CHEMISTRY DATA SETS USED FOR STATISTICAL ANALYSIS  
FOR ALL TREATMENTS AND LAYERS SAMPLED**

June organic layer soil chemistry data. Means and standard errors for each replicate.

Treat.	Plot Location	LOI %	pH	P (Available) (mg/Kg)	N (Total) (mg/Kg)	CEC (cmol/kg)	Fe <sup>3+</sup> (cmol/kg)
C	CO	68.50 ± 9.77	4.30 ± 0.19	36.75 ± 9.25	23443.33 ± 3676.67	110.61 ± 54.04	0.85 ± 0.28
C	T5	70.24 ± 2.51	3.39 ± 0.30	24.50 ± 2.50	12202.83 ± 2970.50	35.90 ± 5.33	1.45 ± 0.07
C	T9	81.81 ± 0.02	3.30 ± 0.16	22.75 ± 2.25	16064.33 ± 1041.33	40.21 ± 1.02	1.52 ± 0.00
C	T14	64.89 ± 3.13	3.42 ± 0.07	24.50 ± 0.00	15739.17 ± 348.83	39.62 ± 2.48	3.65 ± 1.74
WF	T5	58.98 ± 0.91	5.47 ± 0.13	199.75 ± 2.25	21510.33 ± 668.33	37.55 ± 3.57	0.82 ± 0.09
WF	T9	76.46 ± 1.39	3.59 ± 0.37	125.50 ± 10.50	21217.33 ± 335.33	51.19 ± 4.34	1.36 ± 0.04
WF	T13	60.87 ± 0.75	4.71 ± 0.31	110.50 ± 4.00	14894.33 ± 1223.67	42.70 ± 0.42	1.27 ± 0.13
WF	T14	75.03 ± 0.45	4.43 ± 0.25	170.25 ± 32.25	17253.67 ± 857.00	33.81 ± 13.38	1.35 ± 0.25
PB	T4	62.52 ± 6.85	5.26 ± 0.19	160.75 ± 3.75	18445.33 ± 4042.67	43.45 ± 4.51	0.70 ± 0.10
PB	T9B	67.08 ± 11.41	4.75 ± 0.47	351.00 ± 115.00	16802.67 ± 1426.67	48.68 ± 3.20	1.45 ± 0.80
PB	T10	63.73 ± 19.84	3.99 ± 0.19	43.20 ± 14.00	20903.67 ± 3015.00	25.71 ± 21.71	2.92 ± 0.34
PB	T14	77.64 ± 1.61	4.07 ± 0.35	69.60 ± 22.00	18113.33 ± 5400.67	52.62 ± 6.10	1.39 ± 0.71
H	1	83.30 ± 1.61	3.03 ± 0.19	35.75 ± 4.25	17754.33 ± 2436.33	43.93 ± 1.54	1.51 ± 0.30
H	2	66.35 ± 7.53	3.22 ± 0.05	29.50 ± 0.50	12527.33 ± 45.33	33.27 ± 2.65	1.47 ± 0.87
H	3	48.28 ± 7.95	4.06 ± 0.20	33.50 ± 7.00	13911.67 ± 257.67	33.04 ± 7.09	2.73 ± 0.44
H	4	64.95 ± 5.92	3.09 ± 0.04	13.00 ± 1.60	13541.33 ± 2223.33	45.25 ± 6.07	1.89 ± 0.37
RB	T5	56.27 ± 2.25	5.89 ± 0.21	242.00 ± 8.50	21081.33 ± 986.67	46.81 ± 1.62	1.29 ± 0.35
RB	T9	62.42 ± 15.97	4.56 ± 0.28	238.25 ± 53.75	10130.67 ± 6700.67	37.78 ± 4.08	2.11 ± 0.56
RB	T12	66.68 ± 11.15	4.03 ± 0.43	74.20 ± 16.20	15284.33 ± 341.67	41.64 ± 2.24	3.16 ± 0.64
RB	T13	39.19 ± 10.19	5.56 ± 0.18	165.80 ± 25.20	13647.00 ± 986.33	29.92 ± 6.42	2.53 ± 0.68

June organic layer soil chemistry data continued.

Treat.	Plot	Zn <sup>2+</sup>	Cu <sup>2+</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	K <sup>-</sup>	Mn <sup>2+</sup>
	Location	(cmol/kg)	(cmol/kg)	(cmol/kg)	(cmol/kg)	(cmol/kg)	(cmol/kg)
C	CO	0.1967 ± 0.0181	0.0066 ± 0.0023	32.98 ± 9.77	5.14 ± 1.08	1.90 ± 0.26	4.06 ± 0.23
C	T5	0.0489 ± 0.0187	0.0057 ± 0.0000	9.14 ± 2.91	2.39 ± 0.36	0.98 ± 0.23	0.56 ± 0.25
C	T9	0.0761 ± 0.0014	0.0052 ± 0.0004	14.06 ± 2.60	2.22 ± 0.13	1.06 ± 0.14	0.25 ± 0.00
C	T14	0.0462 ± 0.0062	0.0078 ± 0.0031	11.40 ± 1.85	2.36 ± 0.19	0.83 ± 0.12	0.27 ± 0.05
WF	T5	0.1719 ± 0.0503	0.0060 ± 0.0008	34.97 ± 3.71	5.64 ± 0.67	1.77 ± 0.13	8.10 ± 0.01
WF	T9	0.1200 ± 0.0265	0.0056 ± 0.0008	21.73 ± 1.98	3.58 ± 0.27	1.73 ± 0.04	2.07 ± 0.69
WF	T13	0.1367 ± 0.0307	0.0046 ± 0.0002	24.88 ± 4.52	4.13 ± 0.68	2.14 ± 0.05	1.44 ± 0.54
WF	T14	0.1358 ± 0.0161	0.0061 ± 0.0019	25.09 ± 5.63	4.23 ± 0.62	1.87 ± 0.07	2.12 ± 0.80
PB	T4	0.1545 ± 0.0564	0.0034 ± 0.0003	37.30 ± 9.31	4.59 ± 1.06	1.50 ± 0.21	4.70 ± 0.08
PB	T9B	0.2361 ± 0.1287	0.0055 ± 0.0007	39.58 ± 19.83	8.31 ± 4.45	3.53 ± 1.80	3.69 ± 1.54
PB	T10	0.1240 ± 0.0211	0.0064 ± 0.0008	18.65 ± 4.29	3.91 ± 0.74	1.23 ± 0.20	1.95 ± 0.17
PB	T14	0.1328 ± 0.0298	0.0052 ± 0.0000	22.62 ± 2.97	4.88 ± 0.53	1.79 ± 0.16	1.41 ± 0.41
H	1	0.0652 ± 0.0143	0.0074 ± 0.0013	9.31 ± 1.47	3.67 ± 0.85	0.98 ± 0.02	0.47 ± 0.28
H	2	0.0531 ± 0.0146	0.0061 ± 0.0000	6.05 ± 0.16	1.63 ± 0.20	0.95 ± 0.17	0.34 ± 0.03
H	3	0.0842 ± 0.0323	0.0068 ± 0.0004	15.97 ± 3.22	2.87 ± 0.06	1.15 ± 0.11	1.56 ± 0.08
H	4	0.0631 ± 0.0130	0.0055 ± 0.0004	7.71 ± 1.16	2.91 ± 0.75	0.80 ± 0.10	0.36 ± 0.04
RB	T5	0.2952 ± 0.0995	0.0055 ± 0.0015	44.04 ± 6.38	8.60 ± 1.70	2.41 ± 0.08	9.73 ± 2.06
RB	T9	0.1879 ± 0.0023	0.0058 ± 0.0010	23.34 ± 1.00	5.04 ± 0.44	1.70 ± 0.19	2.98 ± 0.83
RB	T12	0.1012 ± 0.0348	0.0065 ± 0.0012	20.93 ± 5.70	5.16 ± 0.92	1.49 ± 0.22	1.18 ± 0.52
RB	T13	0.1445 ± 0.0115	0.0054 ± 0.0002	23.30 ± 1.95	4.23 ± 0.39	1.45 ± 0.18	2.20 ± 0.11

June 0 - 5 cm mineral soil layer chemistry data.

Treat.	Plot Location	LOI %	pH	P (Available) (mg/Kg)	N (Total) (mg/Kg)	CEC (cmol/kg)	Fe <sup>3+</sup> (cmol/kg)
C	CO	6.15 ± 0.55	3.69 ± 0.13	34.80 ± 11.00	2528.25 ± 750.75	7.35 ± 0.31	3.40 ± 0.18
C	T5	5.22 ± 0.33	3.48 ± 0.05	5.13 ± 0.21	2436.75 ± 115.75	13.21 ± 4.26	10.17 ± 2.04
C	T9	2.16 ± 0.01	3.34 ± 0.04	1.46 ± 0.19	1222.50 ± 282.00	4.45 ± 0.72	0.55 ± 0.20
C	T14	4.82 ± 0.88	3.31 ± 0.09	6.16 ± 2.24	2774.50 ± 189.50	9.45 ± 0.79	3.08 ± 0.11
WF	T5	5.65 ± 0.23	4.01 ± 0.13	30.63 ± 15.65	3003.00 ± 302.00	7.73 ± 0.70	6.63 ± 2.29
WF	T9	4.00 ± 0.31	3.39 ± 0.16	7.25 ± 2.43	1899.50 ± 78.50	5.50 ± 0.70	1.78 ± 0.32
WF	T13	4.08 ± 0.35	3.78 ± 0.32	10.11 ± 6.90	2406.58 ± 481.92	6.81 ± 0.43	2.82 ± 1.43
WF	T14	6.82 ± 1.10	3.45 ± 0.22	8.46 ± 4.22	2702.25 ± 144.25	10.88 ± 0.72	6.02 ± 1.21
PB	T4	7.42 ± 3.78	4.18 ± 0.22	5.82 ± 2.79	4237.75 ± 1085.75	18.47 ± 9.36	1.94 ± 0.97
PB	T9B	4.42 ± 0.05	3.62 ± 0.13	17.72 ± 4.48	1307.75 ± 159.25	4.81 ± 0.21	2.81 ± 1.13
PB	T10	2.76 ± 0.23	3.51 ± 0.13	20.92 ± 11.77	1391.75 ± 463.25	6.09 ± 0.22	2.22 ± 0.90
PB	T14	4.52 ± 0.39	3.58 ± 0.12	7.85 ± 2.89	2637.75 ± 484.75	32.09 ± 24.75	3.44 ± 2.62
H	1	7.39 ± 0.62	3.54 ± 0.11	3.17 ± 0.17	2530.75 ± 198.25	8.45 ± 0.25	10.93 ± 0.05
H	2	7.14 ± 0.80	3.53 ± 0.08	3.00 ± 0.00	1423.75 ± 1281.25	8.74 ± 0.34	8.47 ± 1.43
H	3	7.46 ± 1.29	3.75 ± 0.06	3.00 ± 0.00	3173.50 ± 506.00	11.27 ± 2.17	8.36 ± 3.63
H	4	6.49 ± 0.11	3.43 ± 0.09	3.00 ± 0.00	2706.50 ± 154.50	11.65 ± 0.05	10.92 ± 0.93
RB	T5	8.62 ± 2.52	4.48 ± 0.02	53.55 ± 5.41	4217.50 ± 1216.50	9.62 ± 3.47	3.91 ± 1.97
RB	T9	7.77 ± 1.76	3.49 ± 0.08	5.73 ± 0.58	1517.50 ± 1485.00	10.50 ± 1.14	7.87 ± 0.90
RB	T12	4.50 ± 1.94	3.21 ± 0.06	8.25 ± 4.55	1911.75 ± 361.75	5.81 ± 0.67	2.21 ± 1.00
RB	T13	6.94 ± 0.73	3.98 ± 0.17	21.19 ± 6.70	3688.00 ± 619.00	13.93 ± 2.71	8.51 ± 3.94



June 0 - 5 cm mineral soil layer chemistry data continued.

Treat.	Plot Location	Zn <sup>2+</sup> (cmol/kg)	Cu <sup>2+</sup> (cmol/kg)	Ca <sup>2+</sup> (cmol/kg)	Mg <sup>2+</sup> (cmol/kg)	K <sup>+</sup> (cmol/kg)	Mn <sup>2+</sup> (cmol/kg)
C	CO	0.0037 ± 0.0016	0.0025 ± 0.0002	3.21 ± 0.46	15.45 ± 6.19	0.12 ± 0.00	0.03 ± 0.00
C	T5	0.0093 ± 0.0027	0.0058 ± 0.0007	1.98 ± 0.29	0.48 ± 0.05	0.11 ± 0.05	0.01 ± 0.00
C	T9	0.0034 ± 0.0007	0.0017 ± 0.0005	1.60 ± 0.06	0.36 ± 0.04	0.10 ± 0.01	0.00 ± 0.00
C	T14	0.0040 ± 0.0015	0.0038 ± 0.0006	1.65 ± 0.00	0.13 ± 0.03	0.20 ± 0.11	0.00 ± 0.00
WF	T5	0.0038 ± 0.0004	0.0033 ± 0.0007	3.38 ± 0.09	0.29 ± 0.03	0.18 ± 0.01	0.11 ± 0.03
WF	T9	0.0040 ± 0.0013	0.0018 ± 0.0003	2.57 ± 0.54	0.45 ± 0.10	0.24 ± 0.05	0.01 ± 0.00
WF	T13	0.0048 ± 0.0008	0.0020 ± 0.0001	1.14 ± 0.34	0.25 ± 0.04	0.23 ± 0.02	0.02 ± 0.00
WF	T14	0.0119 ± 0.0008	0.0027 ± 0.0001	0.71 ± 0.04	0.55 ± 0.05	0.23 ± 0.05	0.04 ± 0.02
PB	T4	0.0106 ± 0.0039	0.0026 ± 0.0007	0.76 ± 0.00	0.54 ± 0.08	0.44 ± 0.05	0.82 ± 0.75
PB	T9B	0.0042 ± 0.0027	0.0020 ± 0.0001	3.41 ± 0.41	0.56 ± 0.06	0.29 ± 0.28	0.04 ± 0.02
PB	T10	0.0033 ± 0.0000	0.0016 ± 0.0003	1.48 ± 0.58	0.59 ± 0.10	0.36 ± 0.03	0.06 ± 0.04
PB	T14	0.0063 ± 0.0008	0.0027 ± 0.0000	3.48 ± 1.13	0.56 ± 0.18	0.27 ± 0.09	0.03 ± 0.02
H	1	0.0028 ± 0.0005	0.0040 ± 0.0006	2.58 ± 0.13	0.24 ± 0.07	0.27 ± 0.03	0.01 ± 0.00
H	2	0.0049 ± 0.0002	0.0027 ± 0.0001	5.71 ± 1.02	0.32 ± 0.07	0.14 ± 0.01	0.01 ± 0.00
H	3	0.0040 ± 0.0000	0.0034 ± 0.0000	8.13 ± 2.02	0.31 ± 0.10	0.35 ± 0.02	0.03 ± 0.01
H	4	0.0058 ± 0.0004	0.0032 ± 0.0000	2.81 ± 0.41	0.72 ± 0.12	0.25 ± 0.11	0.01 ± 0.00
RB	T5	0.0132 ± 0.0032	0.0044 ± 0.0002	2.74 ± 0.09	0.82 ± 0.14	0.48 ± 0.12	0.35 ± 0.21
RB	T9	0.0094 ± 0.0043	0.0031 ± 0.0003	1.20 ± 0.21	0.83 ± 0.22	0.27 ± 0.01	0.08 ± 0.01
RB	T12	0.0024 ± 0.0002	0.0028 ± 0.0006	1.34 ± 0.14	0.32 ± 0.02	0.28 ± 0.02	0.01 ± 0.01
RB	T13	0.0074 ± 0.0009	0.0050 ± 0.0009	1.05 ± 0.45	0.36 ± 0.16	0.35 ± 0.15	0.14 ± 0.06

June 5 -10 cm mineral soil layer chemistry data.

Treat.	Plot Location	LOI %	pH	P (Available) (mg/Kg)	N (Total) (mg/Kg)	CEC (cmol/kg)	Fe <sup>3+</sup> (cmol/kg)
C	CO	6.89 ± 0.27	3.96 ± 0.09	31.80 ± 2.94	1760.25 ± 11.75	14.08 ± 6.08	8.71 ± 2.39
C	T5	4.60 ± 1.01	4.27 ± 0.09	8.21 ± 0.93	1153.58 ± 217.75	22.02 ± 5.27	8.00 ± 2.52
C	T9	3.27 ± 0.56	3.74 ± 0.12	3.17 ± 1.02	917.77 ± 99.06	19.27 ± 5.55	3.42 ± 0.58
C	T14	6.18 ± 0.44	3.57 ± 0.06	8.10 ± 0.46	2256.38 ± 289.95	18.67 ± 0.50	6.96 ± 1.50
WF	T5	9.33 ± 0.40	4.22 ± 0.10	42.07 ± 8.58	3305.14 ± 89.43	26.95 ± 3.23	8.39 ± 1.08
WF	T9	3.51 ± 0.75	4.15 ± 0.13	21.68 ± 16.98	1117.06 ± 41.77	5.65 ± 0.90	6.10 ± 1.09
WF	T13	6.01 ± 0.60	4.10 ± 0.23	16.30 ± 6.37	1777.25 ± 140.75	12.94 ± 1.68	6.32 ± 0.22
WF	T14	15.97 ± 9.70	3.82 ± 0.17	9.79 ± 0.22	1807.83 ± 99.17	12.43 ± 3.32	9.99 ± 0.82
PB	T4	4.14 ± 0.98	4.16 ± 0.09	5.78 ± 2.17	1404.33 ± 160.17	8.67 ± 0.18	6.44 ± 3.23
PB	T9B	4.86 ± 0.86	4.06 ± 0.10	36.75 ± 17.57	1312.33 ± 304.50	9.37 ± 1.53	6.75 ± 0.28
PB	T10	4.83 ± 0.19	3.97 ± 0.10	46.00 ± 2.17	1380.05 ± 42.55	9.17 ± 1.05	6.82 ± 0.56
PB	T14	9.07 ± 4.91	3.93 ± 0.17	26.58 ± 14.83	2217.28 ± 560.12	10.95 ± 0.92	7.49 ± 0.16
H	1	6.67 ± 0.15	4.26 ± 0.11	9.08 ± 0.81	1878.50 ± 337.50	8.19 ± 0.84	9.26 ± 0.48
H	2	8.20 ± 0.46	4.21 ± 0.16	10.37 ± 2.43	2105.83 ± 192.17	12.46 ± 0.13	8.59 ± 2.06
H	3	10.71 ± 0.97	4.20 ± 0.06	7.25 ± 0.40	< 0.02 ± 0.00	15.75 ± 1.82	14.78 ± 1.11
H	4	5.62 ± 2.32	4.07 ± 0.11	7.03 ± 0.26	2397.75 ± 345.08	12.06 ± 1.13	12.30 ± 2.87
RB	T5	8.32 ± 0.62	4.23 ± 0.04	63.30 ± 8.22	2473.20 ± 1095.40	13.08 ± 2.08	5.18 ± 1.05
RB	T9	8.61 ± 1.42	3.94 ± 0.10	9.61 ± 2.48	3107.20 ± 236.60	12.44 ± 1.14	16.53 ± 3.59
RB	T12	3.84 ± 0.02	3.52 ± 0.10	9.85 ± 2.57	1071.00 ± 20.83	7.79 ± 0.46	5.22 ± 0.54
RB	T13	3.81 ± 3.53	4.01 ± 0.23	19.95 ± 7.86	2052.10 ± 210.76	9.23 ± 1.91	4.77 ± 0.21

June 5 -10 cm mineral soil layer chemistry data continued.

Treat.	Plot Location	Zn <sup>2+</sup> (cmol/kg)	Cu <sup>2+</sup> (cmol/kg)	Ca <sup>2+</sup> (cmol/kg)	Mg <sup>2+</sup> (cmol/kg)	K <sup>+</sup> (cmol/kg)	Mn <sup>2+</sup> (cmol/kg)
C	CO	0.0040 ± 0.0001	0.0033 ± 0.0007	1.14 ± 0.32	0.52 ± 0.16	0.09 ± 0.09	0.01 ± 0.00
C	T5	0.0043 ± 0.0009	0.0042 ± 0.0003	1.09 ± 0.04	0.42 ± 0.03	0.20 ± 0.11	0.01 ± 0.01
C	T9	0.0015 ± 0.0000	0.0026 ± 0.0001	0.90 ± 0.46	0.40 ± 0.02	0.29 ± 0.05	0.00 ± 0.00
C	T14	0.0036 ± 0.0001	0.0047 ± 0.0005	2.41 ± 0.72	0.42 ± 0.08	0.25 ± 0.01	0.01 ± 0.01
WF	T5	0.0044 ± 0.0008	0.0045 ± 0.0001	2.37 ± 1.23	0.54 ± 0.04	0.05 ± 0.05	0.11 ± 0.05
WF	T9	0.0020 ± 0.0000	0.0021 ± 0.0007	1.24 ± 0.14	0.45 ± 0.08	0.02 ± 0.02	0.04 ± 0.03
WF	T13	0.0034 ± 0.0007	0.0028 ± 0.0002	1.50 ± 0.13	0.21 ± 0.03	0.08 ± 0.01	0.02 ± 0.00
WF	T14	0.0060 ± 0.0015	0.0039 ± 0.0000	1.05 ± 0.19	0.39 ± 0.00	0.00 ± 0.00	0.01 ± 0.00
PB	T4	0.0064 ± 0.0028	0.0027 ± 0.0007	1.25 ± 0.16	0.43 ± 0.04	0.10 ± 0.10	0.04 ± 0.01
PB	T9B	0.0026 ± 0.0009	0.0022 ± 0.0004	1.88 ± 0.28	0.32 ± 0.04	0.12 ± 0.12	0.03 ± 0.00
PB	T10	0.0055 ± 0.0010	0.0033 ± 0.0005	0.68 ± 0.18	0.33 ± 0.05	0.07 ± 0.07	0.05 ± 0.03
PB	T14	0.0057 ± 0.0025	0.0057 ± 0.0004	1.48 ± 0.05	0.44 ± 0.14	0.07 ± 0.03	0.01 ± 0.00
H	1	0.0022 ± 0.0004	0.0046 ± 0.0005	1.55 ± 0.60	0.26 ± 0.02	0.00 ± 0.00	0.00 ± 0.00
H	2	0.0041 ± 0.0004	0.0060 ± 0.0021	1.55 ± 0.11	0.32 ± 0.06	0.00 ± 0.00	0.00 ± 0.00
H	3	0.0064 ± 0.0005	0.0041 ± 0.0003	2.49 ± 0.37	0.24 ± 0.04	0.12 ± 0.02	0.01 ± 0.00
H	4	0.0048 ± 0.0004	0.0047 ± 0.0008	0.90 ± 0.30	0.36 ± 0.03	0.13 ± 0.03	0.01 ± 0.00
RB	T5	0.0065 ± 0.0007	0.0048 ± 0.0003	2.58 ± 1.02	0.38 ± 0.01	0.31 ± 0.23	0.15 ± 0.11
RB	T9	0.0046 ± 0.0000	0.0068 ± 0.0005	0.49 ± 0.05	0.48 ± 0.03	0.00 ± 0.00	0.03 ± 0.02
RB	T12	0.0078 ± 0.0000	0.0038 ± 0.0005	0.77 ± 0.06	0.24 ± 0.01	0.13 ± 0.10	0.01 ± 0.00
RB	T13	0.0033 ± 0.0000	0.0056 ± 0.0004	0.67 ± 0.26	0.30 ± 0.02	0.09 ± 0.09	0.02 ± 0.01

August organic layer chemistry data.

Treat.	Plot Location	LOI %	pH	P (Available) (mg/Kg)	N (Total) (mg/Kg)	CEC (cmol/kg)	Fe <sup>3+</sup> (cmol/kg)
C	CO	78.85 ± 6.06	4.01 ± 0.16	43.45 ± 3.67	28391.00 ± 835.00	63.24 ± 6.48	0.81 ± 0.10
C	T5	74.44 ± 8.64	3.02 ± 0.22	62.38 ± 11.42	21336.00 ± 1486.00	66.49 ± 5.02	3.35 ± 0.55
C	T9	77.96 ± 2.78	3.47 ± 0.05	31.99 ± 19.39	19820.00 ± 379.33	59.86 ± 7.07	2.04 ± 0.50
C	T14	84.44 ± 4.13	3.36 ± 0.17	63.81 ± 1.31	23034.67 ± 1585.33	64.94 ± 3.44	1.34 ± 0.27
WF	T5	81.35 ± 17.49	5.36 ± 0.24	37.56 ± 13.36	25591.33 ± 3023.33	95.06 ± 20.50	0.36 ± 0.10
WF	T9	74.26 ± 2.16	4.52 ± 0.32	11.78 ± 1.18	23778.67 ± 1717.33	65.59 ± 3.94	0.93 ± 0.06
WF	T13	62.86 ± 2.26	4.33 ± 0.09	35.90 ± 21.30	21307.67 ± 1971.00	58.31 ± 1.50	1.60 ± 0.17
WF	T14	75.57 ± 1.14	4.82 ± 0.22	43.60 ± 14.40	25657.50 ± 1269.17	64.95 ± 0.55	0.74 ± 0.18
PB	T4	64.08 ± 10.17	5.20 ± 0.26	87.75 ± 2.65	21365.83 ± 3049.17	55.19 ± 5.52	0.44 ± 0.04
PB	T9B	61.40 ± 2.51	5.72 ± 0.27	65.85 ± 7.95	14836.67 ± 778.33	51.95 ± 10.02	0.62 ± 0.22
PB	T10	73.35 ± 2.94	3.94 ± 0.45	22.57 ± 2.73	19920.00 ± 2300.00	44.44 ± 1.18	1.14 ± 0.14
PB	T14	75.81 ± 2.42	3.90 ± 0.49	49.20 ± 22.08	20170.83 ± 564.17	39.71 ± 11.34	1.33 ± 0.80
H	1	85.42 ± 0.99	3.19 ± 0.16	57.36 ± 5.76	19912.50 ± 29.17	50.61 ± 5.47	2.62 ± 1.22
H	2	75.11 ± 6.70	3.35 ± 0.08	17.30 ± 4.70	19111.67 ± 955.00	46.84 ± 2.56	2.41 ± 0.38
H	3	72.08 ± 1.28	3.86 ± 0.10	18.64 ± 6.68	20688.33 ± 915.00	43.37 ± 2.41	1.45 ± 0.44
H	4	74.01 ± 2.32	3.18 ± 0.18	33.44 ± 15.56	17409.17 ± 2637.50	44.28 ± 1.74	2.01 ± 0.43
RB	T5	67.62 ± 0.69	5.49 ± 0.17	77.80 ± 26.60	29343.33 ± 266.67	63.09 ± 6.18	0.36 ± 0.02
RB	T9	56.84 ± 4.85	4.77 ± 0.22	48.74 ± 15.66	18654.17 ± 339.17	40.58 ± 2.30	1.33 ± 0.07
RB	T12	73.98 ± 1.13	3.80 ± 0.04	49.08 ± 2.00	14148.33 ± 1486.67	40.97 ± 0.88	3.12 ± 0.28
RB	T13	58.16 ± 6.28	5.74 ± 0.08	74.20 ± 16.20	17392.50 ± 4809.17	45.82 ± 6.69	2.00 ± 0.14

August organic layer chemistry data continued.

Treat.	Plot Location	Zn <sup>2+</sup> (cmol/kg)	Cu <sup>2+</sup> (cmol/kg)	Ca <sup>2+</sup> (cmol/kg)	Mg <sup>2+</sup> (cmol/kg)	K <sup>+</sup> (cmol/kg)	Mn <sup>2+</sup> (cmol/kg)
C	CO	0.1269 ± 0.0006	0.0034 ± 0.0006	26.42 ± 0.62	4.92 ± 0.58	2.12 ± 0.32	3.03 ± 0.00
C	T5	0.0881 ± 0.0206	0.0036 ± 0.0005	11.22 ± 3.65	3.38 ± 0.10	2.01 ± 0.26	0.60 ± 0.15
C	T9	0.0821 ± 0.0183	0.0064 ± 0.0024	16.95 ± 3.48	3.09 ± 0.16	1.67 ± 0.13	0.68 ± 0.21
C	T14	0.0983 ± 0.0157	0.0038 ± 0.0009	17.96 ± 2.30	3.46 ± 0.32	1.02 ± 0.08	0.94 ± 0.21
WF	T5	0.1791 ± 0.0622	0.0029 ± 0.0006	50.36 ± 12.76	7.96 ± 1.03	1.73 ± 0.11	6.48 ± 1.02
WF	T9	0.1475 ± 0.0147	0.0036 ± 0.0002	22.09 ± 15.81	4.32 ± 3.03	2.17 ± 1.37	2.93 ± 0.03
WF	T13	0.1077 ± 0.0045	0.0030 ± 0.0001	17.97 ± 13.02	3.30 ± 2.36	1.38 ± 0.97	1.74 ± 0.29
WF	T14	0.1952 ± 0.0044	0.0036 ± 0.0004	24.56 ± 0.17	4.54 ± 0.11	2.61 ± 0.03	3.68 ± 0.40
PB	T4	0.2109 ± 0.0099	0.0027 ± 0.0000	36.73 ± 1.15	6.47 ± 0.05	1.93 ± 0.08	4.16 ± 0.58
PB	T9B	0.2390 ± 0.0489	0.0030 ± 0.0006	31.26 ± 1.16	5.92 ± 0.44	1.05 ± 0.03	3.88 ± 0.80
PB	T10	0.1330 ± 0.0223	0.0038 ± 0.0001	14.43 ± 2.68	3.57 ± 0.35	0.91 ± 0.06	1.83 ± 0.53
PB	T14	0.1761 ± 0.0851	0.0030 ± 0.0001	50.27 ± 3.41	8.71 ± 1.08	2.48 ± 0.00	2.22 ± 1.18
H	1	0.0995 ± 0.0033	0.0049 ± 0.0012	69.01 ± 29.55	11.03 ± 4.02	3.08 ± 1.66	0.82 ± 0.10
H	2	0.0978 ± 0.0158	0.0040 ± 0.0005	18.87 ± 3.10	4.00 ± 0.80	0.96 ± 0.12	0.65 ± 0.12
H	3	0.1004 ± 0.0265	0.0037 ± 0.0008	15.54 ± 0.08	3.77 ± 0.16	1.32 ± 0.10	1.53 ± 0.50
H	4	0.0612 ± 0.0001	0.0042 ± 0.0002	32.84 ± 6.31	5.03 ± 0.04	1.35 ± 0.03	0.48 ± 0.07
RB	T5	0.3060 ± 0.0888	0.0025 ± 0.0002	45.94 ± 1.34	5.59 ± 0.25	1.37 ± 0.07	6.90 ± 1.10
RB	T9	0.2590 ± 0.0432	0.0038 ± 0.0011	45.43 ± 0.92	8.65 ± 0.81	2.40 ± 0.00	2.73 ± 0.91
RB	T12	0.1033 ± 0.0000	0.0037 ± 0.0005	33.04 ± 6.29	6.72 ± 1.34	1.65 ± 0.27	1.01 ± 0.05
RB	T13	0.2422 ± 0.0417	0.0030 ± 0.0002	26.98 ± 0.94	7.22 ± 0.46	2.21 ± 0.10	3.91 ± 0.75

August 0 - 5 cm mineral soil layer chemistry data.

Treat. Location	LOI %	pH	P (Available) (mg/Kg)	N (Total) (mg/Kg)	CEC (cmol/kg)	Fe <sup>3+</sup> (cmol/kg)
C CO	8.46 ± 0.09	3.55 ± 0.10	44.11 ± 0.63	1985.75 ± 1464.25	6.89 ± 4.70	8.10 ± 0.77
C T5	5.37 ± 0.17	3.50 ± 0.05	4.59 ± 1.36	2601.00 ± 395.40	17.29 ± 6.88	8.95 ± 4.71
C T9	2.09 ± 0.52	3.69 ± 0.11	1.84 ± 0.59	1038.75 ± 196.08	5.04 ± 0.39	1.29 ± 0.15
C T14	6.77 ± 0.26	3.20 ± 0.08	6.06 ± 1.85	3409.10 ± 273.50	18.33 ± 8.40	6.27 ± 2.15
WF T5	6.21 ± 0.05	4.03 ± 0.27	18.04 ± 12.42	3735.87 ± 241.53	13.67 ± 1.73	5.32 ± 2.62
WF T9	3.18 ± 0.56	3.70 ± 0.17	2.52 ± 0.92	1706.25 ± 56.92	6.08 ± 1.36	3.88 ± 1.48
WF T13	5.06 ± 0.19	3.29 ± 0.06	2.44 ± 0.21	2378.27 ± 130.93	9.00 ± 1.59	3.37 ± 0.33
WF T14	4.17 ± 0.03	3.60 ± 0.08	12.96 ± 9.96	1358.10 ± 1340.70	7.76 ± 4.82	5.60 ± 0.06
PB T4	2.78 ± 0.17	3.96 ± 0.10	1.64 ± 0.47	1825.08 ± 158.42	6.36 ± 0.74	1.82 ± 0.58
PB T9B	3.81 ± 0.52	3.82 ± 0.10	29.65 ± 14.34	1919.50 ± 69.10	11.22 ± 1.12	6.32 ± 0.12
PB T10	3.30 ± 0.01	3.57 ± 0.08	12.77 ± 0.79	1396.58 ± 145.58	6.68 ± 0.13	3.92 ± 0.72
PB T14	5.16 ± 1.22	3.50 ± 0.07	15.52 ± 0.82	2167.15 ± 441.65	11.85 ± 0.53	4.44 ± 2.36
H 1	5.52 ± 0.83	3.50 ± 0.10	6.21 ± 0.04	2247.00 ± 465.00	11.56 ± 0.69	11.72 ± 2.14
H 2	8.45 ± 1.91	3.46 ± 0.09	9 ± 2.61	3298.45 ± 313.05	6.82 ± 5.73	15.39 ± 7.08
H 3	5.46 ± 0.18	3.52 ± 0.16	3.34 ± 1.33	3035.75 ± 302.75	9.83 ± 0.82	13.97 ± 8.00
H 4	7.01 ± 0.73	3.52 ± 0.09	5.11 ± 0.91	3058.20 ± 669.80	10.46 ± 0.78	17.34 ± 5.25
RB T5	4.44 ± 2.78	3.92 ± 0.17	23.32 ± 11.87	4060.20 ± 445.60	14.10 ± 2.48	5.57 ± 0.66
RB T9	5.28 ± 0.27	3.64 ± 0.13	12.24 ± 1.15	3068.30 ± 273.50	12.42 ± 2.24	10.23 ± 3.55
RB T12	9.85 ± 1.72	3.65 ± 0.17	36.38 ± 9.32	14.38 ± 14.38	15.31 ± 0.72	12.48 ± 0.07
RB T13	3.92 ± 1.25	4.15 ± 0.11	28.96 ± 20.52	1701.35 ± 342.85	5.57 ± 0.61	2.59 ± 1.00

August 0 - 5 cm mineral soil layer chemistry data continued.

Treat.	Plot Location	Zn <sup>2+</sup> (cmol/kg)	Cu <sup>2+</sup> (cmol/kg)	Ca <sup>2+</sup> (cmol/kg)	Mg <sup>2+</sup> (cmol/kg)	K <sup>+</sup> (cmol/kg)	Mn <sup>2+</sup> (cmol/kg)
C	CO	0.0034 ± 0.0006	0.0026 ± 0.0000	0.70 ± 0.25	0.31 ± 0.01	0.42 ± 0.07	0.02 ± 0.00
C	T5	0.0033 ± 0.0002	0.0050 ± 0.0004	0.59 ± 0.10	0.53 ± 0.29	0.42 ± 0.05	0.01 ± 0.00
C	T9	0.0015 ± 0.0005	0.0017 ± 0.0002	0.67 ± 0.07	0.39 ± 0.06	0.54 ± 0.04	0.00 ± 0.00
C	T14	0.0051 ± 0.0007	0.0039 ± 0.0003	1.46 ± 0.67	0.36 ± 0.11	0.49 ± 0.01	0.01 ± 0.00
WF	T5	0.0086 ± 0.0023	0.0039 ± 0.0000	1.13 ± 0.09	0.71 ± 0.29	0.40 ± 0.03	0.43 ± 0.18
WF	T9	0.0024 ± 0.0004	0.0027 ± 0.0003	3.13 ± 2.26	0.86 ± 0.61	0.27 ± 0.05	0.05 ± 0.04
WF	T13	0.0041 ± 0.0001	0.0026 ± 0.0002	1.15 ± 0.02	0.33 ± 0.05	0.18 ± 0.11	0.03 ± 0.00
WF	T14	0.0046 ± 0.0014	0.0038 ± 0.0000	1.10 ± 0.48	0.44 ± 0.02	0.28 ± 0.05	0.03 ± 0.00
PB	T4	0.0042 ± 0.0007	0.0025 ± 0.0000	2.93 ± 2.00	0.44 ± 0.01	0.49 ± 0.05	0.08 ± 0.05
PB	T9B	0.0096 ± 0.0008	0.0032 ± 0.0002	1.90 ± 0.00	0.47 ± 0.11	0.39 ± 0.16	0.08 ± 0.03
PB	T10	0.0030 ± 0.0002	0.0022 ± 0.0000	1.35 ± 0.04	0.34 ± 0.04	0.40 ± 0.09	0.06 ± 0.05
PB	T14	0.0049 ± 0.0005	0.0037 ± 0.0004	2.27 ± 1.02	0.33 ± 0.09	0.19 ± 0.10	0.03 ± 0.00
H	1	0.0071 ± 0.0002	0.0082 ± 0.0022	1.91 ± 0.24	0.38 ± 0.00	0.26 ± 0.26	0.01 ± 0.00
H	2	0.0059 ± 0.0026	0.0069 ± 0.0027	4.88 ± 2.85	0.50 ± 0.13	0.32 ± 0.01	0.01 ± 0.01
H	3	0.0051 ± 0.0016	0.0045 ± 0.0006	2.61 ± 0.76	0.43 ± 0.05	0.45 ± 0.26	0.04 ± 0.03
H	4	0.0045 ± 0.0004	0.0046 ± 0.0006	1.70 ± 0.02	0.45 ± 0.08	0.25 ± 0.09	0.02 ± 0.01
RB	T5	0.0245 ± 0.0097	0.0037 ± 0.0003	6.08 ± 5.49	0.78 ± 0.37	0.34 ± 0.05	0.33 ± 0.06
RB	T9	0.0084 ± 0.0008	0.0049 ± 0.0005	1.31 ± 0.08	0.60 ± 0.07	0.46 ± 0.00	0.07 ± 0.00
RB	T12	0.0182 ± 0.0031	0.0047 ± 0.0001	7.32 ± 5.96	0.44 ± 0.17	0.26 ± 0.17	0.25 ± 0.05
RB	T13	0.0041 ± 0.0001	0.0030 ± 0.0003	1.66 ± 0.01	0.57 ± 0.23	0.26 ± 0.11	0.03 ± 0.01

August 5 - 10 cm mineral soil layer chemistry data.

Treat.	Plot Location	LOI %	pH	P (Available) (mg/Kg)	N (Total) (mg/Kg)	CEC (cmol/kg)	Fe <sup>3+</sup> (cmol/kg)
C	CO	7.22 ± 1.68	4.23 ± 0.05	27.62 ± 0.86	4136.61 ± 1172.75	11.40 ± 1.36	6.00 ± 1.25
C	T5	5.07 ± 0.60	4.11 ± 0.08	9.41 ± 2.99	1854.14 ± 20.43	9.17 ± 1.04	8.90 ± 1.00
C	T9	3.62 ± 0.46	4.24 ± 0.10	15.03 ± 8.94	1128.29 ± 11.29	6.83 ± 0.42	3.61 ± 0.24
C	T14	7.32 ± 1.44	3.38 ± 0.12	7.63 ± 1.22	2574.14 ± 481.29	17.27 ± 4.54	10.89 ± 6.44
WF	T5	7.47 ± 1.00	4.20 ± 0.19	56.21 ± 31.19	2590.71 ± 98.00	14.09 ± 0.69	7.62 ± 2.26
WF	T9	3.73 ± 0.18	4.22 ± 0.07	39.46 ± 2.24	1233.86 ± 37.43	12.56 ± 5.51	4.79 ± 1.14
WF	T13	4.76 ± 0.60	3.96 ± 0.08	9.22 ± 1.22	1613.50 ± 263.50	8.18 ± 0.97	7.42 ± 0.55
WF	T14	6.25 ± 0.41	3.87 ± 0.22	14.08 ± 0.46	1991.57 ± 59.00	9.34 ± 0.46	7.60 ± 0.06
PB	T4	3.69 ± 0.95	4.23 ± 0.05	8.82 ± 4.10	1265.00 ± 95.57	7.46 ± 0.07	3.13 ± 0.96
PB	T9B	4.60 ± 0.06	4.10 ± 0.10	55.63 ± 1.23	1465.36 ± 89.79	8.05 ± 0.49	5.44 ± 1.42
PB	T10	2.67 ± 0.19	4.22 ± 0.09	63.36 ± 3.94	1040.57 ± 102.43	9.10 ± 0.83	4.10 ± 0.32
PB	T14	4.96 ± 0.89	3.88 ± 0.10	13.36 ± 1.27	1583.86 ± 26.14	12.03 ± 2.43	8.57 ± 0.19
H	1	6.21 ± 0.72	4.00 ± 0.08	9.49 ± 3.81	1708.57 ± 205.14	11.15 ± 1.27	9.08 ± 0.74
H	2	8.78 ± 0.78	4.13 ± 0.02	12.36 ± 2.93	2625.36 ± 108.64	14.19 ± 0.18	8.83 ± 1.78
H	3	5.74 ± 2.12	4.03 ± 0.11	8.39 ± 4.20	2663.07 ± 403.50	10.55 ± 1.44	9.55 ± 2.75
H	4	6.47 ± 0.84	3.90 ± 0.13	9.27 ± 1.79	2258.71 ± 251.71	9.21 ± 0.30	12.11 ± 1.93
RB	T5	7.20 ± 0.16	4.37 ± 0.02	36.79 ± 7.88	2691.93 ± 130.93	12.28 ± 1.95	4.12 ± 0.65
RB	T9	5.89 ± 0.08	3.84 ± 0.24	16.38 ± 5.33	2294.00 ± 78.29	9.76 ± 0.53	5.21 ± 1.17
RB	T12	2.99 ± 0.02	3.95 ± 0.19	28.32 ± 10.03	1134.21 ± 53.21	8.77 ± 1.20	5.27 ± 1.61
RB	T13	7.05 ± 1.19	4.38 ± 0.06	27.16 ± 2.31	974.92 ± 974.92	9.91 ± 1.40	5.65 ± 0.05



August 5 - 10 cm mineral soil layer chemistry data continued.

Treat.	Plot Location	Zn <sup>2+</sup> (cmol/kg)	Cu <sup>2+</sup> (cmol/kg)	Ca <sup>2+</sup> (cmol/kg)	Mg <sup>2+</sup> (cmol/kg)	K <sup>+</sup> (cmol/kg)	Mn <sup>2+</sup> (cmol/kg)
C	CO	0.0028 ± 0.0006	0.0034 ± 0.0004	0.73 ± 0.02	0.36 ± 0.09	0.18 ± 0.03	0.02 ± 0.00
C	T5	0.0026 ± 0.0011	0.0043 ± 0.0008	1.51 ± 0.79	0.31 ± 0.01	0.22 ± 0.12	0.00 ± 0.00
C	T9	0.0020 ± 0.0007	0.0024 ± 0.0002	2.42 ± 1.07	0.29 ± 0.02	0.33 ± 0.03	0.01 ± 0.00
C	T14	0.0034 ± 0.0010	0.0052 ± 0.0004	0.93 ± 0.33	0.38 ± 0.08	0.30 ± 0.06	0.01 ± 0.00
WF	T5	0.0032 ± 0.0002	0.0030 ± 0.0004	1.10 ± 0.19	0.57 ± 0.16	0.33 ± 0.01	0.09 ± 0.01
WF	T9	0.0016 ± 0.0001	0.0022 ± 0.0003	0.94 ± 0.14	0.43 ± 0.14	0.39 ± 0.06	0.01 ± 0.00
WF	T13	0.0020 ± 0.0003	0.0023 ± 0.0001	0.94 ± 0.11	0.30 ± 0.02	0.31 ± 0.16	0.01 ± 0.00
WF	T14	0.0031 ± 0.0007	0.0035 ± 0.0002	0.97 ± 0.27	0.37 ± 0.04	0.08 ± 0.08	0.03 ± 0.01
PB	T4	0.0026 ± 0.0004	0.0023 ± 0.0003	2.81 ± 2.03	0.40 ± 0.04	0.03 ± 0.03	0.02 ± 0.00
PB	T9B	0.0047 ± 0.0018	0.0028 ± 0.0001	1.04 ± 0.27	0.34 ± 0.04	0.06 ± 0.05	0.04 ± 0.00
PB	T10	0.0013 ± 0.0004	0.0021 ± 0.0001	0.90 ± 0.12	0.20 ± 0.03	0.11 ± 0.01	0.04 ± 0.03
PB	T14	0.0042 ± 0.0014	0.0042 ± 0.0003	0.70 ± 0.12	0.40 ± 0.05	0.10 ± 0.09	0.01 ± 0.00
H	1	0.0032 ± 0.0002	0.0060 ± 0.0001	1.58 ± 0.37	0.39 ± 0.10	0.00 ± 0.00	0.01 ± 0.00
H	2	0.0030 ± 0.0007	0.0064 ± 0.0024	1.96 ± 0.39	0.41 ± 0.02	0.04 ± 0.03	0.01 ± 0.00
H	3	0.0034 ± 0.0005	0.0038 ± 0.0004	1.58 ± 0.87	0.44 ± 0.18	0.00 ± 0.00	0.01 ± 0.01
H	4	0.0025 ± 0.0003	0.0037 ± 0.0003	0.94 ± 0.02	0.27 ± 0.03	0.13 ± 0.03	0.01 ± 0.00
RB	T5	0.0052 ± 0.0000	0.0030 ± 0.0004	1.62 ± 0.95	0.43 ± 0.01	0.07 ± 0.02	0.09 ± 0.01
RB	T9	0.0036 ± 0.0020	0.0037 ± 0.0003	0.92 ± 0.02	0.35 ± 0.10	0.06 ± 0.06	0.03 ± 0.01
RB	T12	0.0037 ± 0.0000	0.0046 ± 0.0000	1.06 ± 0.24	0.27 ± 0.01	0.05 ± 0.04	0.02 ± 0.01
RB	T13	0.0054 ± 0.0028	0.0032 ± 0.0000	2.02 ± 1.39	0.35 ± 0.02	0.02 ± 0.02	0.03 ± 0.00

## Ash chemistry data.

Treat. Plot Location	LOI %	pH	P (Available) (mg/Kg)	N (Total) (mg/Kg)	CEC (cmol/kg)	Fe <sup>3+</sup> (cmol/kg)
RB T5/9	24.00 ± 7.21	8.38 ± 0.11	58.30 ± 9.98	10360.83 ± 7582.50	62.0486 ± 2.5347	0.0304 ± 0.0070

Treat. Plot Location	Zn <sup>2+</sup> (cmol/kg)	Cu <sup>2+</sup> (cmol/kg)	Ca <sup>2+</sup> (cmol/kg)	Mg <sup>2+</sup> (cmol/kg)	K <sup>+</sup> (cmol/kg)	Mn <sup>2+</sup> (cmol/kg)
RB T5/9	0.0012 ± 0.0002	0.0025 ± 0.0004	117.00 ± 13.23	61.08 ± 10.22	27.55 ± 13.32	0.75 ± 0.02

APPENDIX VI

BASE SATURATION DATA FOR ALL  
TREATMENTS AND LAYERS SAMPLED

Treatment	Base Saturation (%)	Base Saturation (%)	Base Saturation (%)
	June organic layer	June 0 - 5 cm mineral soil layer	June 5 -10 cm mineral soil layer
C	37.7 ± 1.8	46.7 ± 18.8	11.2 ± 2.0
WF	79.5 ± 10.6	36.6 ± 10.7	16.7 ± 4.6
PB	87.0 ± 10.6	37.8 ± 18.2	18.8 ± 2.7
H	35.9 ± 8.3	54.4 ± 11.6	16.7 ± 2.3
RB	85.7 ± 7.9	27.4 ± 6.4	14.8 ± 3.7
	August organic layer	August 0 - 5 cm mineral soil layer	August 5 - 10 cm mineral soil layer
C	37.2 ± 5.8	18.4 ± 5.0	21.8 ± 8.1
WF	48.6 ± 5.3	32.1 ± 12.7	15.6 ± 1.1
PB	74.5 ± 12.0	35.0 ± 8.7	21.1 ± 7.6
H	71.8 ± 13.2	41.0 ± 14.5	17.1 ± 1.0
RB	90.8 ± 5.4	41.8 ± 7.7	17.7 ± 2.3

## APPENDIX VII

TEXTURE ANALYSIS RESULTS FOR  
MINERAL SOIL LAYERS SAMPLED  
MEANS AND STANDARD ERRORS

0-5 cm mineral soil layer

Treatment	Plot Location	% Clay	% Silt	% Sand
C	CO	2.36 ± 0.68	33.71 ± 2.75	63.93 ± 3.37
C	T5	3.15 ± 0.51	33.98 ± 2.65	62.87 ± 3.14
C	T9	0.83 ± 0.49	12.39 ± 0.91	86.78 ± 1.30
C	T14	3.12 ± 0.49	21.75 ± 1.48	75.12 ± 1.57
WF	T5	0.75 ± 0.75	33.80 ± 2.47	65.44 ± 3.05
WF	T9	1.15 ± 0.26	14.84 ± 1.09	84.00 ± 1.14
WF	T13	1.34 ± 0.43	25.67 ± 2.75	73.00 ± 2.75
WF	T14	2.22 ± 0.70	22.24 ± 0.56	75.55 ± 0.85
PB	T4	1.03 ± 0.29	17.52 ± 0.53	81.45 ± 0.82
PB	T9B	0.21 ± 0.38	15.23 ± 2.97	84.56 ± 3.29
PB	T10	0.80 ± 0.30	12.99 ± 1.11	86.20 ± 1.36
PB	T14	1.86 ± 0.68	21.60 ± 0.72	76.53 ± 1.36
H	1	1.82 ± 0.34	32.41 ± 5.00	65.78 ± 5.28
H	2	2.16 ± 0.45	34.99 ± 2.62	62.86 ± 2.99
H	3	3.55 ± 0.61	43.30 ± 0.31	53.14 ± 0.51
H	4	2.50 ± 0.61	32.34 ± 2.98	65.16 ± 2.55
RB	T5	1.25 ± 0.95	38.29 ± 2.34	60.46 ± 2.86
RB	T9	2.86 ± 0.70	28.92 ± 2.17	68.22 ± 2.19
RB	T12	0.92 ± 0.55	14.73 ± 1.87	84.35 ± 2.24
RB	T13	1.11 ± 0.81	32.41 ± 3.32	66.48 ± 3.66

## 5-10 cm mineral soil layer

Treatment	Plot Location	% Clay	% Silt	% Sand
C	CO	3.35 ± 0.70	36.72 ± 2.08	59.93 ± 1.70
C	T5	2.76 ± 0.42	25.95 ± 6.45	71.29 ± 6.50
C	T9	3.07 ± 0.35	10.59 ± 0.29	86.34 ± 0.32
C	T14	3.52 ± 0.31	20.60 ± 2.35	75.88 ± 2.66
WF	T5	1.31 ± 0.65	37.97 ± 2.11	60.72 ± 2.69
WF	T9	1.30 ± 0.31	12.05 ± 2.81	86.65 ± 3.08
WF	T13	2.48 ± 0.92	22.00 ± 5.25	75.52 ± 5.87
WF	T14	3.42 ± 0.65	22.48 ± 1.88	74.10 ± 2.46
PB	T4	2.67 ± 0.42	21.03 ± 4.87	76.30 ± 4.58
PB	T9B	1.67 ± 0.44	12.33 ± 2.98	86.00 ± 3.40
PB	T10	1.45 ± 0.71	11.56 ± 1.44	86.99 ± 2.12
PB	T14	2.36 ± 0.33	18.74 ± 0.74	78.90 ± 0.69
H	1	1.60 ± 0.58	30.74 ± 5.75	67.66 ± 6.16
H	2	1.63 ± 0.39	36.01 ± 2.98	62.37 ± 3.34
H	3	1.49 ± 0.29	41.09 ± 1.34	57.42 ± 1.08
H	4	2.49 ± 0.26	28.06 ± 3.11	69.44 ± 3.16
RB	T5	1.97 ± 0.27	39.38 ± 1.22	58.65 ± 1.27
RB	T9	2.60 ± 0.30	26.93 ± 1.51	70.47 ± 1.33
RB	T12	2.94 ± 0.51	14.50 ± 1.93	82.55 ± 2.15
RB	T13	3.49 ± 0.84	35.82 ± 1.85	60.69 ± 1.57