THINNING AND PRESCRIBED FIRE FOR ECOSYSTEM RESTORATION IN ROCKY MOUNTAIN FORESTS OF BRITISH COLUMBIA: CHANGES IN PHYSICAL, CHEMICAL AND BIOLOGICAL PROPERTIES OF FOREST FLOORS AND SOIL

by

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B.Sc., University of Idaho, 2008

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

The Faculty of Graduate Studies

(Forestry)

THE UNIVERSITY OF BRITISH COLUMBIA
(Vancouver)

May 2011

Abstract

Prevention of uncontrolled wildfire and restoration of Rocky Mountain forests can be accomplished through ecosystem restoration practices such as thinning followed by prescribed fire. The objective of this study is to determine how much thinned fuel can be left on the ground without causing fire temperatures high enough to impair soil physical, chemical and biological properties. I assess the effects of different fuel loadings on soil properties (forest floor depth, soil pH, carbon and nutrient levels, and soil bacteria and fungal communities) during the first year after fire and explore relationships among fuel loadings, fire temperatures and indicators of soil health.

Five fuel management treatments were assessed: large piles, small piles, areas of cut-and-leave, deep litter and an unburned control. In all burned treatments, fuel loadings were greatly reduced and maximum temperatures at the forest floor surface ranged from 60 to 850°C. Temperatures were over 300°C for over 3 hours in the large-pile treatment but were lower and of shorter duration in the small-pile and cut-and-leave treatments. The deep-litter treatment had temperatures above 200°C for over 2 hours and complete combustion of the forest floor occurred.

The low moisture content and resulting consumption of the forest floor in the deep-litter treatment resulted in the largest negative impacts on soil chemical and microbiological properties, while few significant differences were evident among the other treatments. Higher nitrate availability and significant increases in pH were found in the forest floors of burned plots and in the mineral soil of the deep-litter treatment. Microbial abundance did not recover to pre-fire levels in any burned treatments after one year, which may be attributed to the persistence of significant increases in pH.

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C	carbon
°C	degrees Celsius
Ca^{2+}	calcium
CL	cut-and-leave
cm	centimetre
dbh	diameter at breast height
DL	deep litter
$H_2PO_4^-$	phosphate
IDF	interior Douglas-fir
K^+	potassium
LP	large pile
m	metre
Mg^{2+}	magnesium
MRPP	multi-response permutation procedure
N	nitrogen
NH_4^+	ammonium
NO_3^-	nitrate
PCA	principal component analysis
PC-ORD	Principal Components Ordination
PLFA	phospholipid fatty acid
PRS™	Plant Root Simulator™-probes
SO_4^{2-}	sulphate
SAS	Statistical Analysis Systems
SP	small pile
UC	unburned Control

Acknowledgements

This project would not have been possible if it wasn't for the guidance of my supervisory committee, which included Dr. Cindy Prescott, Dr. Sue Grayston and Dr. Graeme Hope. Our Belowground Ecosystem Group, especially Kate Del Bel, Denise Brooks and Carolyn Churchland, was instrumental in keeping our labs up-to-date with the current knowledge and practices in our field.

I would also like to thank Greg Anderson and the Ecosystem Restoration branch of the British Columbia Ministry of Forests for funding the first year of this study. Randy Harris and Mike Daigle of the British Columbia Ministry of Forests and Range assisted this project by creating the management treatments and conducting the prescribed fire. Thanks are also due to Mr. Ian MacDonald for his field assistance during one of my sampling trips to the East Kootenay mountains.

Dr. Gary Bradfield and Dr. Tony Kozak were also extremely helpful when asked about statistical methods and analysis. I would also like to thank all of our support staff in the Forest Sciences Department and the wonderful people who keep the Forest Sciences Centre looking great.

To this day, I still feel privileged to have had the opportunity to study in Canada and to work with such a professional group of students and researchers.

To Dr. Penelope Morgan for her inspiration

1.0 Introduction

1.1 Rationale

Management of fuel loadings is critical for reducing the risk of large, uncontrolled wildfires in Rocky Mountain forest ecosystems (USDA Forest Service 2000, Schmidt *et al*. 2002). Fire suppression has caused encroachment of small-diameter saplings into forest meadows, leading to more intense wildfires, higher rates of disease and transformations of wildlife habitat (Keane *et al*. 2002). In developed areas where wildland fire-use programs cannot be initiated, ecosystem restoration programs are being implemented to address these issues by improving stand and habitat conditions.

Reducing stand density and fuel loadings are two ways of restoring these ecosystems and lowering the potential of extreme wildfire behaviour (Fulé *et al*. 2001). Commercial logging decreases stand density but results in increased surface fuel loading (Alexander & Yancik 1977). Likewise, mechanical thinning treatments reduce stand density, but only lower the height of the fuel and do not reduce overall fuel amounts. Surface fuel can act as a ladder fuel during wildfire, initiating canopy consumption and running crown-fires. Prescribed fire can be used to reduce the amount of surface fuels that are left after mechanical treatments, but fuel loadings need to be manipulated to ensure that flame lengths do not reach into mature-tree canopies (Graham *et al*. 2004).

A variety of fuel management options can be utilized to increase the effectiveness of fuel reduction projects. They include pile-building of leftover slash, broadcast-burning with slash in place, or both. All of these treatments result in the burning of a compacted fuel loading near the soil surface, which increases fire temperatures in forest floors and soil. This temperature increase further alters the magnitude of changes in the soil's physical, chemical and biological properties, which could be detrimental to forest structure and function.

Fire severity and intensity determine ecosystem response after prescribed fire (Keeley 2008). Fire severity is determined by the amount of fuel combusted, while fire intensity is the subsequent heat produced from combustion. Aboveground consumption radiates 10-15% of its heat to the soil (DeBano 1974). Although moist soils do not rise above 95°C until all water has been driven off, soil temperatures can rapidly rise to 200-300°C once that threshold is reached (Certini 2005, Franklin *et al*. 1997). Many biological mortality thresholds are reached at those temperatures, including seed (50°C), plant tissue (60°C), fungi (100°C) and bacteria (110°C) (Neary 2005, Hare 1961, Dunn 1979, Busse *et al*. 2005). Temperature increases to 200°C can begin to volatilize nitrogen (N), while half of nitrogen in organic matter can be lost at 500°C (Neary *et al*. 1999). Temperatures greater than 760°C are needed to volatilize other potentially limiting forest nutrients. While combustion of vegetation and organic matter releases carbon (C), an analysis of studies on soil C also showed that prescribed fire lowered C levels (Johnson & Curtis 2001).

The aim of this study is to determine which fuels management treatment best minimizes prescribed-fire temperatures and negative impacts to soil, while consuming a majority of surface fuels. To assess the effects of fire temperatures on forest floors and soil, I measured fire temperatures, forest-floor depth and several indicators of soil health (moisture content, C and N concentrations, pH, nutrient availability and microbial community composition) which were the most vulnerable soil properties in this ecosystem that could be disproportionately affected by a range of fire temperatures (Neary *et al*. 1999, Page-Dumroese *et al*. 2000). This study provides insight into the effects of a prescribed fire over a 15-month period. We measured pre-fire conditions and conditions 10 days, 3 months and one year after fire and compare them to unburned controls. Relationships among fuel loadings, fire temperatures and these indicators of soil health were explored using the statistical package PC-ORD. Multi-response permutation procedure was used to determine if the fuel management treatments that experienced fire were significantly different than the unburned control one year after prescribed fire. Principal component analysis was utilized to determine the relationships among several abiotic factors and microbial community composition.

1.2 Literature review

1.2.1 Fuel loading and fire temperature

Woody debris (hereby regarded as fuel) consumption is caused by oxidation of organic matter. Fire temperatures are a direct result of the amount of fuel consumed and duration. Consumption of forest fuel loadings leads to increased surface and belowground temperatures. Fire consumption has resulted in aboveground fuel amounts decreasing 63% (Covington & Sackett 1984). Forest floor losses have been recorded between 2 and 37% (Covington & Sackett 1984, Gundale *et al*. 2005). Aboveground fire temperatures at 10 cm above mineral soil have reached between 157-240°C during low intensity prescribed fires in Ohio (Boerner *et al*. 2000, 2005). Likewise, Giai & Boerner (2007) found that temperatures at the same height reached a maximum temperature between 356 and 415°C during a prescribed fire with 2 m tall flame lengths, with similar average temperatures recorded throughout most of the fire.

Soil heating during fire is also an effect of amount of fuel consumed and duration (Wells *et al*. 1978). Fire temperatures decrease in the mineral soil with increasing depth due to the soil's thermal conductivity (Campbell & Norman 1998). Temperatures of 500-700°C have been recorded under highly-compacted fuel loadings at the soil surface, while most surface fires are much less (Massman *et al*. 2008, Raison *et al*. 1986). At depths of 2-5 cm, temperatures have reached 400°C (Massman *et al*. 2008). During the same study, temperatures at 10 cm depth reached 225°C. Another study found burning of masticated fuels over dry and wet soils resulted in high temperatures of 105 and 61°C, respectively, at 10 cm depth (Busse *et al*. 2005). From a depth of 15-50 cm, temperatures can rise from 50-80°C under highly compacted burn piles, although most soils at that depth do not experience a temperature increase (Massman *et al*. 2008).

1.2.2 Chemical properties

Wildfire suppression in forest ecosystems results in the accumulation of C at a rate between 0.14 and 0.18 kg m^{-1} yr^{-1} (Birdsey 1992, Tilman *et al*. 2000). Organic matter (OM) is the largest terrestrial carbon sink and fire alters accumulation and decomposition rates of OM (Schlesinger 1993, Abril *et al*. 2005). Fire intensity dictates the amount of OM and soil organic C that is lost during fire, as well as the overall amount of C emissions during combustion (Johnson & Curtis 2001). Fire effects on C levels are highly variable and range from no effect to higher levels in unburned forests than burned and vice versa.

Soil organic C was found to be lower in a burned *Pinus pinaster* (Maritime pine) ecosystem than an unburned control in Spain (Prieto-Fernández *et al*. 1998). Both mechanical thinning/prescribed fire and prescribed fire treatments reduced C levels in vegetation and soil throughout twelve fire and fire surrogate (FFS) study sites in the United States (Boerner *et al*. 2008).

Many studies have also shown that previously burned ecosystems have higher soil C concentrations than unburned soils. Soil organic C was found to be slightly higher in burned soils than unburned soils in the Dry Chaco forests of Argentina (Abril *et al*. 2005), but litter organic C was significantly lower in the burned treatments. Likewise, Chromanska & DeLuca (2002) found higher total C concentrations in burned soils in *Pinus ponderosa* (ponderosa pine) forests of western Montana. Higher C levels were also found in burned plots compared to unburned controls, both in mounds and furrows, nine months after a prescribed fire in a *Eucalyptus marginata* (Jarrah) forest in Western Australia (Banning & Murphy 2008).

Soil organic C levels in burned soils were found to be unchanged with time since fire in a mixed *Quercus* (oak) forest (Boerner *et al*. 2005). While unburned soil C levels increased four months after fire (to ~35 g C kg soil^{-1}), burned soils remained at the same level that both previous treatments were at immediately after fire (23.5 g C kg soil^{-1}). In another study, higher C levels were found in unburned plots than burned plots one month after fire, with no changes in either treatment after one year in a *Pinus pinaster* forest (Vásquez *et al*. 1993). Boyle *et al*. (2005) found no significant differences in total C after different treatments (control, thinning and thin/burn) or canopy types (pre-settlement, post-settlement retained and grass) in a western Montana *Pinus ponderosa* ecosystem. Also, a meta-analysis showed that prescribed fire had no significant effects on soil C until 10 years after fire, when levels increased (Johnson & Curtis 2001).

Nitrogen is a critical nutrient for the productivity of forest ecosystems and soil N concentration is affected by silvicultural treatments, including prescribed fire (Vitousek & Howarth 1991). Fire can cause N transformation and volatilization in the forest floors and soil, and alter rates of mineralization and nitrification (Raison 1979). Changes in N availability can alter plant community populations and influence post-fire succession.

Soil total N concentration was significantly lower in a complete restoration treatment that included thinning and prescribed fire than in the control and thin-only treatments (Kaye & Hart 1998). Nitrogen concentrations in the mineral soil were highest in the thin-only stand, while the control and thin/prescribed fire treatment had slightly lower levels. In a similar study, mineral soil N concentration was again highest in a thinned stand, while the composite restoration and the control treatment had slightly lower amounts (Boyle *et al*. 2005). Banning & Murphy (2008) found that total N was slightly higher in burned soils than unburned soils. Vásquez *et al*. (1993) found that total N concentrations were similar in burned and unburned plots one month and one year after fire. Contradictorily, N was 50% lower in soils that had not experienced fire for the last 80 years compared to soils that were recently burned (<6 yrs.) (Chromanska & DeLuca 2002).

Other studies have shown no effect of treatment on N concentrations. Total N in a control plot was not significantly different from plots that had been clear-cut or clear-cut/burned in Finland (Pietikäinen & Fritze 1995). Another study in Spain found no significant differences in total N concentrations between unburned soils and measurements that were taken 3, 6 and 14 months after fire (Andreu *et al*. 1996).

Nitrate (NO_3^-) and ammonium (NH_4^+) levels can also change as a result of fire. From one week to 15 months after a pile-burning treatment in a *Pinus ponderosa* and *Pseudotsuga menziesii* (Douglas-fir) forest, NO_3^- and NH_4^+ concentrations increased significantly beneath the pile edge (Jiménez Esqilín *et al*. 2007). The concentrations beneath the pile center were not significantly different from 1 week to 15 months after fire, but did increase 29% over that time. In the savannas of central Brazil, Nardoto & da Cunha Bustamante (2003) found that NH_4^+ levels in the mineral soil increased significantly four days following a prescribed fire, but decreased to pre-fire levels after one month. Inorganic N was much higher in burned than unburned soil both 1 month and 1 year after fire (Vázquez *et al*. 1993). However, Boyle *et al*. (2005) found no significant differences in NO_3^- between thinned, thinned/burned and unburned control treatments, but NH_4^+ was significantly higher in the thinning treatment than the unburned control.

Nitrogen mineralization rates change because of fire and time-since-fire influences the amount of mineralization that occurs (MacKenzie *et al*. 2006). Potentially mineralized N was higher in recently burned soils than in soils not previously exposed to fire (Chromanska & DeLuca 2002). Fourteen years after the stand-replacing Yellowstone fires in Wyoming, Metzger *et al*. (2008) did not find significant differences in mineralization rates under a range of regeneration conditions in a *Pinus contora* (lodgepole pine) stand.

Significant differences in soil phosphorus (P) concentrations have been found after forest management treatments, including both increases and decreases. Kaye & Hart (1998) reported that forest floor total P in the control and partial restoration treatments was significantly higher than in the complete restoration treatment. Mineral soil (0-5 cm depth) differences were not significantly different among treatments. Andreu *et al*. (2005) found that available P was not significantly different between sampling periods or treatments. Vásquez *et al*. (1993) found higher total P in burned plots compared to unburned one month after fire. Organic P was also higher in burned furrow soils than in unburned (Banning & Murphy 2008).

Calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na) levels have also been found to differ among forest management treatments. Calcium and Mg^{2+} were significantly higher in a clear-cut/burned site than the unburned control or a clear-cut site (Pietikäinen & Fritze 1995), whereas K^+ was found to be 50% lower in the clear-cut and the clear-cut/burned than the unburned control. Other studies have reported no significant differences in Ca^{2+}, Mg^{2+}, K^{+} and Na between treatments or over sampling periods after fire (Gundale *et al*. 2005, Andreu *et al*. 2005).

Soil pH increases after soil heating when organic acids denature and the oxidation of organic matter occurs, which releases base cations into the soil (Certini 2005, Jiménez Esqilín *et al*. 2007). Soil pH can also increase when ash, which has high concentrations of Ca^{2+}, Mg^{2+} and K^{+}, infiltrates soil (Bååth *et al*. 1995). This occurs when hydrogen (H) and aluminum (Al^{3+}) ions are displaced by Ca^{2+}, Mg^{2+}, and K from soil colloids (Arocena & Opio 2003). Soil pH influences nutrient availability and can influence post-fire succession (Eivazi & Bayan 1996).

Soil pH beneath a recently burned *Pinus ponderosa* and *Psuedotsuga menziesii* stand in western Montana had a pH of 6.0, while soils that had not been burned in 80 years had a pH of 5.5 (Chromanska & DeLuca 2002). Soil pH from the edge of a burn pile rose from 6.35 one week after fire to 6.52 after 15 months in a *Pinus ponderosa* stand in Colorado (Jiménez Esqilín *et al*. 2007). Soil pH at the pile center increased from 6.38 to 6.74 over the same time period, while the pH of soil in the unburned control plots decreased slightly from 5.76 to 5.53 during the study. In another study, burned soils had a pH of 4.9, while unburned soils had a pH of 4.5 one month after fire (Vásquez *et al*. 1993). Both sites had a soil pH of 4.9 one year after fire.

Soil pH was higher in clear-cuts (4.9) and clear-cut/fire treatments (5.85) than unburned controls (3.93) in *Picea abies* (Norway spruce) stands of northern Finland (Pietikäinen & Fritze 1995). Similarly, in a 100-year-old *Pinus sylvestris* L. (Scots pine) stand in central Finland, Fritze *et al*. (1994) found higher soil pH in burned stands (4.41) than the unburned control (3.85). In southern Finland, a site dominated by *Picea abies* was clear-cut and burned in consecutive years. Soil pH increased from 4 to 6 and remained for two growing seasons at that level, with a decrease to 5.2 at the end of the third growing season (Pietikäinen & Fritze 1993). In the same study on a site in eastern Finland, a simulated forest fire in a *Pinus sylvestris* stand increased soil pH from 3.8 to 4.2

Small decreases in soil pH have also been encountered after forest treatments. Soil pH decreased from 5.3 to 5.0 in control, thin, burn, and thin/burn restoration treatments from year 1 to 3 after in a *Pinus ponderosa/Pseudotsuga menziesii* ecosystem (Gundale *et al*. 2005). Abril *et al*. (2005) found soils with no grazing or fire influence had pH of 6.9, while fire and no grazing treatments had a pH of 6.6.

1.2.3 Biological properties

Forest management treatments have also been found to alter biological properties of forest soils. The phospholipid fatty acid (PLFA) analysis measures the abundance of bacteria and fungi in organic matter and soil and can be used to determine the amount of change in microbial communities after a treatment. Phospholipid fatty acids are found in the cell membranes of soil microorganisms and degrade rapidly upon cell death (White *et al.* 1979). It is possible to distinguish differences between microbial communities using their phospholipid biomarkers, which are found in the living cells of bacteria and fungi. Gram-positive, Gram-negative bacteria, and actinomycete communities can be separately distinguished, and along with other bacterial biomarkers, can provide an indication of total bacterial abundance. Arbuscular mycorrhizae fungi can also be identified through PLFA, as well as a general fungal biomarker. Total PLFA can also be estimated by adding all identified biomarkers in the forest floor and soil. This method also allows for determining bacteria-to-fungi ratios, as well as Gram-positive-to-Gram-negative bacteria ratios.

Campbell *et al*. (2008) found significantly lower PLFA abundance on sites that experienced fire every two years than sites that had 4-year fire intervals in a native, wet sclerophyll forest with a shrub understory in Queensland, Australia. The unburned control plots were not significantly different than the 4-year fire interval plots, indicating that total PLFA levels recovered to similar levels as the unburned plots when fire was applied every four years. Gram-positive bacteria, Gram-negative bacteria and actinomycete abundance were ~50% lower in the soil that experienced fire every two years compared to every four years. The unburned control was not significantly different that the 4-year fire intervals. Total bacterial abundance, which included Gram-positive and Gram-negative bacteria, was lower in sites that were burned every 2 and 4 years, when compared to an unburned control. Fungal abundances were lower in stands that were burned every 2 and 4 years compared to the unburned control.

Gundale *et al*. (2005) found no significant differences in total PLFA between treatments from week 1 to week 5 comparing different forest treatments (control, thin, prescribed fire, thin/prescribed fire) in *Pinus ponderosa/Pseudotsuga menziesii* forest of western Montana. A significant difference was found between the earlier sampling and sampling after 16-18 weeks, which was related to an increase in actinomycetes in the thin+burn treatment. Three-year post-fire results indicated no significant differences between time or treatments, indicating that restoration treatments under those conditions had no long-lasting effects on microbial communities.

In *Pinus sylvestris* stands of central Finland, total PLFA abundance, as well as total bacteria and fungi, were significantly lower in the organic matter of a burned site 2 years after fire than in an unburned control site (Bååth *et al*. 1995). Addition of wood-ash also resulted in decreases in total PLFA. In a similar study, they found that total bacteria and total PLFA was significantly lower in a *Picea abies* stand that underwent a clear-cut and prescribed fire 2 years prior than in an unburned control soil. Fungal abundance was significantly lower in the clear-cut site and the clear-cut and burned site than in the unburned control.

Díaz-Raviña *et al*. (2006) found that granitic and acid schist soils heated to 350°C for 10 minutes under laboratory conditions had 24 and 40% less total PLFA abundance than two unheated soils, respectively. Fungal abundance was also significantly lower in the heated granitic soil than in the unheated soil.

1.3 Hypotheses

Based on this review of the literature regarding the effects of various fire and fuel-management treatments on soil properties, I developed the following hypotheses to be tested in my study.

1. Changes in soil chemical and microbiological properties will be greatest in treatments with the largest fuel loadings.
2. Soil nitrogen and microbial biomass will be reduced in treatments with the highest fire temperatures.
3. Inorganic N concentrations and pH will increase and microbial biomass will decrease in burned plots, especially in those with the highest fire temperatures.
4. Microbial community structure and abundance will return to pre-fire levels within one year.

2.0 Methods

2.1 Site description and history

The study site is located in the Rocky Mountain Trench of southeast British Columbia (BC) (49º 43′ 10 N and 115º 38′ 35 W, elev. 1000 m, 7-12% slope), approximately 20 km northeast of Cranbrook, BC. It is positioned on a geographic bench above the valley bottom with surrounding mountains that rise to 2500 m. The site is classified as Interior Douglas-fir Dry Mild (IDFdm2/04) under the BC Biogeoclimatic Ecosystem Classification (BEC), with IDF forests encompassing 5.5% of BC's land area. The adjacent valley bottom has a mean annual precipitation of 32 cm, with 30% in the form of snow (National Climate Data and Information Archive). Annual monthly mean high and low temperatures average 11.4ºC and -0.37ºC, respectively. *Pseudotsuga menziesii* var. *glauca* and *Larix occidentalis* (western larch) are the dominant tree species, while shrub species include *Spiraea betulifolia* (birch-leaved spirea), *Arctostaphylos uva-ursi* (kinnikinnick), *Rosa acicularis* (prickly rose). Herbs present after thinning include *Calamagrostis rubescens* (pinegrass), *Cirsium vulgare* (bull thistle), *Cirsium arvense* (Canada thistle), *Arnica cordifolia* (heart-leaved arnica), and *Medicago lupulina* (black medick). The soil is classified as Orthic Eutric Brunisol and is less than 1 m in depth above the parent material, morainal veneer (Soil Classification Working Group 1998). It is a well-drained, sandy loam that consists of between 30-50% coarse fragments and is non-effervescent until immediately above a calcareous bedrock. Forest floor depth before fire averaged 4.6 cm over all plots.

A variety of silvicultural treatments were implemented by the BC Ministry of Forests and Range in this area over the last 5 years to obtain a range of management goals. The largest treatment unit (TU), TU 2, was commercially thinned of trees smaller than 30 cm diameter at breast height (dbh) in 2004 and slash-piled in 2008. Before the 2009 Big Hill Prescribed Fire, TU 2 consisted of large (~4 m^3) and small (~1 m^3) slash piles. An adjacent unit, TU 5, consisted of a cut-and-leave thinning treatment in 2008, where trees less than 30 cm dbh were cut and all were felled in the same direction. The mature trees that remained in this TU were not mechanically thinned and had relatively deep forest-floor depths (>6 cm deep). Areas outside these TUs and the prescribed fire perimeter have low surface-fuel loadings and abundant saplings.

The Big Hill prescribed fire was ignited on April 21, 2009, with an air temperature of 20°C, a relative humidity of 29%, and a west-southwest wind between 10-20 km h^{-1}. Firing was conducted with drip torches around the perimeter and with a heli-torch within the 400 ha fire perimeter. Treatment unit 2 and TU 5 were near the center of the prescribed fire perimeter.

2.2 Experimental design

Fifteen plots (1.25-m radius) were non-randomly placed within five different fuel management treatments. Three plots were under large slash piles (~2 m in height, ~2 m in diameter); three were under small slash piles (~1 m in height, ~1 m in diameter); three were under thinned trees that had been cut <2 years previously and retained red needles; three were directly beneath standing mature trees and had deep accumulation of litter; and three plots that served as unburned controls were outside of the fire perimeter. Sampling took place 10 days before the Big Hill Prescribed Fire, which occurred on April 21, 2009, and approximately 10 days, 3 months and 1 year after the fire. Both the forest floor and mineral soil (<10 cm) were sampled three times from within each plot, with each sample taken in a 120° angle from the first sample (Figure 2.2.1). Forest-floor sample sizes were 15 cm x 15 cm x depth; soil samples were taken with a soil auger to a depth of 10 cm immediately below where the forest floor was removed. Following the fire, forest floor samples from the deep-litter treatment were collected from low spots in the soil as no forest floor remained in other areas.

Portions of these samples were used for analyses of the physical, chemical and biological properties of the forest floor and mineral soil.

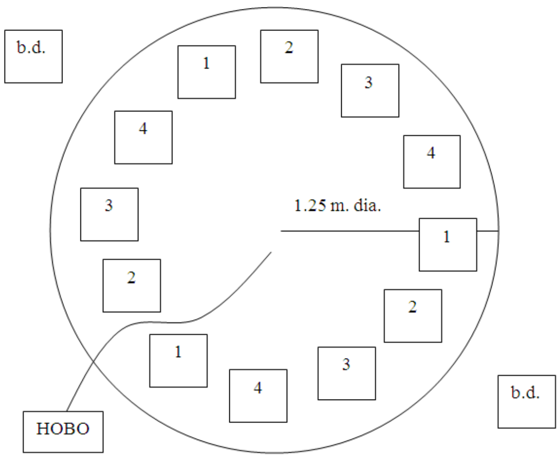

Figure 2.1. Layout of sampling. 1 indicates before-fire sampling points, 2,3 and 4 indicate sampling points 10 days, 3 months and 1 year after fire, respectively. ‘b.d.’ indicates where the bulk density was taken and ‘HOBO’ indicates the location of the HOBO data logger.

2.3 Measuring fuel loadings and fire temperatures

Large and small pile volumes were estimated using their height, length and shape (Wright *et al*. 2010). Approximate fuel loadings were calculated for the small piles and cut-and-leave treatment area using the Photo Sampling Guide (Keane & Dickinson 2007). Fire temperatures immediately above the forest floor were recorded during the prescribed fire using HOBO data loggers (Onset Computer Corporation, Bourne, MA, USA). The HOBO data loggers were set to record fire temperatures every 2 seconds beginning 3 hours before ignition time until 9 a.m., the morning following the prescribed fire.

2.4 Analysis of physical properties

Forest floor and mineral soil moisture contents were determined by oven-drying 40 g samples at 72°C for 72 hours and 105°C for 24 hours, respectively. Moisture content (%) was calculated with the equation: θ_{dw} = (weight of wet soil - weight of dry soil)/weight of dry soil, where (θ_{dw}) is the water content on dry-weight basis. Two bulk-density measurements were taken in soil adjacent to each plot in order to minimize plot disturbance. To determine bulk density, soil was removed from an approximate volume of 10 cm x 10 cm x 10 cm. A bag was then placed into the hole and filled with water. The amount of water used to reach the soil surface was then used to determine the volume of the hole. Removed soil was then oven-dried and weighed and bulk density was calculated from the volume of the hole and the weight of the removed sample.

2.5 Analysis of chemical properties

Forest floor and soil samples were air-dried and sent to BC Ministry of Forests Analytical Laboratory in Victoria, BC, Canada, where C and N concentrations were measured using a Carlo Erba NA-1500 Nitrogen/Carbon Analyzer (Fisons Instruments, Dearborn, MI, USA). This instrument uses a dynamic flash combustion process to burn samples in pure oxygen at ~1000°C and quantifies the amount of gases combusted with an integrated gas chromatographer. Samples were pre-ground to 100-mesh particle size using a Rocklabs ring grinder.

Nutrient availability was determined *in situ* by inserting Plant Root Simulator (PRS)™-probes (Western Ag. Innovations Inc., Saskatoon, Saskatchewan, Canada) into both forest floor and mineral soil. The ion-exchange resin membrane within each probe absorbs available nutrients and stores them until the probes are removed (Bengtson *et al*. 2007). Six probes were inserted vertically into mineral soil to a depth of 10 cm throughout each plot, with three probes measuring cations and three measuring anions. Likewise, six probes (three cation & three anion) were inserted horizontally into forest floors throughout the plot. The PRS™-probes were incubated over three time periods: the first two summers after fire (May-August 2009 and 2010) and the overwinter period (August 2009-May 2010).

Forest floor and mineral soil pH were determined by adding 0.01*M* $CaCl_2$ to 2 g of forest floor or 10 g of mineral soil and measuring with a Oakton 510 Series pH bench meter (Oakton Instruments, Vernon Hills, IL, USA) (Hendershot *et al*. 2008).

2.6 Analysis of biological properites

Biomass of Gram-positive bacteria, Gram-negative bacteria, actinomycetes, total bacteria, arbuscular mycorrhizae and total fungi were measured using the Phospholipid Fatty Acid analysis (PLFA), as described by Frostegård *et al*. (1993). Fresh samples were sieved free of roots and wood matter using a 2 mm screen and freeze-dried. Fatty acids were extracted from samples (1 g of forest floor, 1.5 g of mineral soil) following the procedure of Dewi (2009). Fatty acids are designated by the ratio of the total number of carbon atoms:number of double bonds, followed by the position (ω) of the double bond from the methyl end of the molecule. Cis and trans configurations are indicated by *c* and *t*, respectively. The prefixes *a* and *i* indicate anteiso- and iso-branched fatty acids, respectively. Cyclopropane fatty acids have the prefix 'cy' (Bååth *et al*. 1995, Steer & Harris 2000). Fatty acids identifying Gram-positive bacteria include *i*15, *a*15:0, *i*16:0, *i*17:0 and *a*17:0. Gram-negative bacteria's fatty acids include *i*16:1ω7*c*, 16:1ω9*c*, 16:1ω7*c*, i17:1ω8*c*, cy17:0, 18:1ω7*c*, 18:1ω5*c*, cy19:0. Total bacteria is the sum of Gram-positive and Gram-negative bacteria's fatty acids, plus 15:0, 17:0 18:0. Actinomycetes are identified by a methyl group on the tenth carbon atom from the carboxyl end of the molecule and include 10Me16:0, 10Me17:0, 10Me18:0, 10Me19:0. The fatty acid identifying arbuscular mycorrhizae is 16:1ω5*c*, while total fungi was identified using 18:2ω6,9. Biomarkers were identified using a gas chromatograph (Agilent 6890N, Agilent Inc., USA) equipped with a mass selective detector (Agilent 5973N, Agilent Inc., USA).

2.7 Methods of statistical analysis

Significant differences between treatments were analyzed at each sampling date, as well as the amount of change in each treatment prior to and after the prescribed fire. Significant differences were determined using a 95% confidence interval with two-way ANOVA (SAS Institute Inc., Version 9.2, Cary, NC, USA). *Post-hoc* pair-wise comparisons were determined using a Bonferroni correction. Data were analyzed to determine time period influences, treatment effects and time and treatment interactions. Significant treatment interactions were interpreted as effects of fuel treatments, while fire temperatures created by the fuel loadings served as time influence. Tests of normality and uniformity of variance were applied.

The relationship between the pre-fire forest floor moisture and the amount of forest floor consumed during the fire was explored to determine if moisture content influenced the heating and consumption of the forest floor. Relationships among microbial community abundances and abiotic factors, such as maximum fire temperatures, fire temperature durations, soil moisture, the reduction in forest floor depth, carbon and nitrogen concentrations, carbon-to-nitrogen ratios and pH to the different microbial communities.

Multi-response permutation procedure (MRPP) was utilized using PC-ORD Version 5.19 (MjM Software, Gleneden Beach, Oregon, U.S.A). MRPP is a non-parametric method used to est the hypothesis of no difference between two or more groups and has been used to compare the effects of prescribed fire with unburned areas (McCune & Grace 2002, Zimmerman and Goetz 1985). MRPP calculates a delta-value, which is a measure of the within-group distance, and an A-value, which is the chance-corrected within-group agreement. These values provide a means for determining if groups are more homogeneous than expected by chance, where an A-value of 1 indicates that all samples within groups are identical (i.e. maximum homogeneity), and an A-value of 0 indicates that groups are no more homogeneous than expected by chance. The p-value determines the significance level associated with differences among groups such that $p<0.05$ was chosen to indicate that differences among groups are statistically significant (McCune & Grace 2002).

Principal component analysis (PCA) was utilized using PC-ORD to explore which abiotic variables may have influenced microbial community composition. PCA can be used to transform data sets with many variables to determine which abiotic variables are correlated the greatest amount of variation in the biotic data, i.e. the strongest correlation with the microbial communities. The strongest linear correlation is then represented by the 1^{st} PCA axis, which provides a summary of most of the variation present. The variation explained in all PCA axes (expressed as the eigenvalues) will add up to 100%; usually, most variation is explained within the first 3 or 4 axes. If the data's variance is randomly divided among the components, it should have a broken-stick distribution. When the broken-stick eigenvalue is greater than the actual eigenvalue, the axis' variance can be ignored because it contains no more information than expected by chance (McCune & Grace 2002). Abiotic variables compared to the microbial communities include carbon and nitrogen concentrations, the carbon-to-nitrogen ratio, moisture, forest floor depth and pH. The abiotic variables were then overlayed on the microbial community's response in ordination space, with the length and angle of the radiating lines indicating strength of relationship.

3.0 Results

3.1 Fuel loadings and fire temperatures

Fuel loadings were greatly reduced in all burned treatments during the 2009 Big Hill Prescribed Fire. In the large pile treatment area, all piles were consumed, except for a few small-diameter branches on the pile edge. Maximum fire temperatures at the forest floor surface for plots 1, 2 and 3 reached 427, 668 and 715°C, respectively (Figure 3.1). Plot 1, which was beneath a pile that had a parabolic shape and an approximate volume of 4.9 m^3, experienced fire temperatures above 100°C for over 12 hours and over 300°C for 6 hours. Plot 2 experienced two distinct heat pulses, with the first one above 450°C for over 30 minutes, while the second pulse was above 150°C for 30 minutes. This pile had a half-cylinder shape and was approximately 9.4 m^3 in volume. Plot 3 was beneath was a half-ellipsoid pile of 5.2 m^3 in volume and had temperatures above 400°C for 1 hour and above 100°C for more than 2 hours.

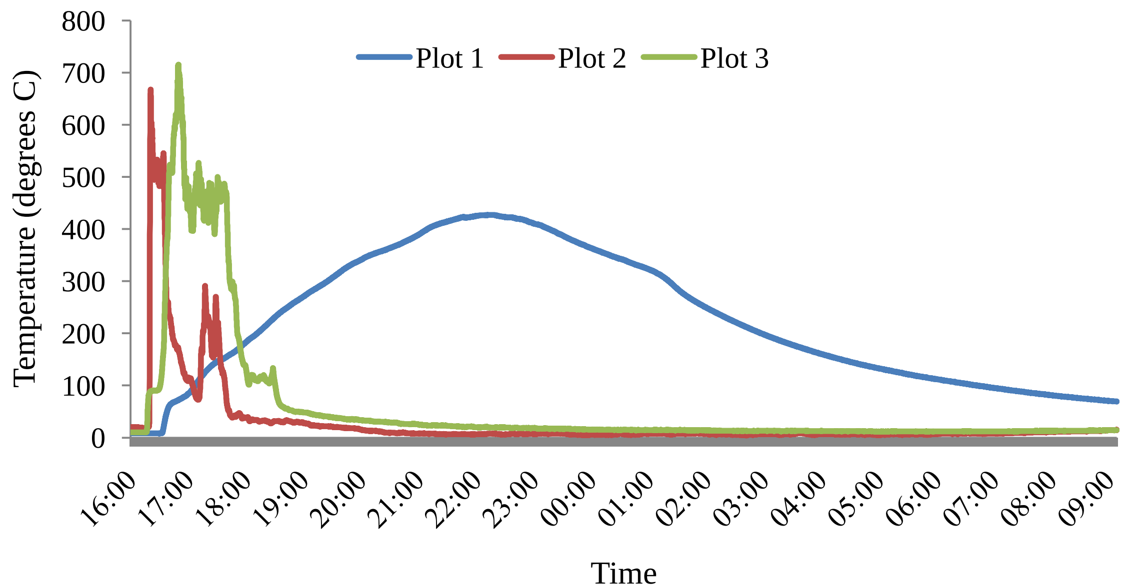

Figure 3.1. Fire temperature profiles for the three plots in the large-pile treatment area from 16:00, 21/4/2009 to 9:00, 22/4/2009.

In the small-pile treatment, small diameter fuels (< 10 cm) were completely consumed, while larger fuels (>10 cm) remained intact. Maximum fire temperatures in plots 4, 5 and 6 were 203, 60 and 69°C, respectively (Figure 3.2). Plot 4 experienced the highest maximum temperature of 203°C, with temperatures above 40°C for 2 hours. Temperatures greater than 80°C were only sustained for 20 minutes. While the maximum temperature of plot 5 was 60°C, it remained above 40°C for 2 hours and above 20°C for 6 hours. During the maximum temperature of 69°C in plot 6, temperatures remained above 30°C for 4 hours before decreasing.

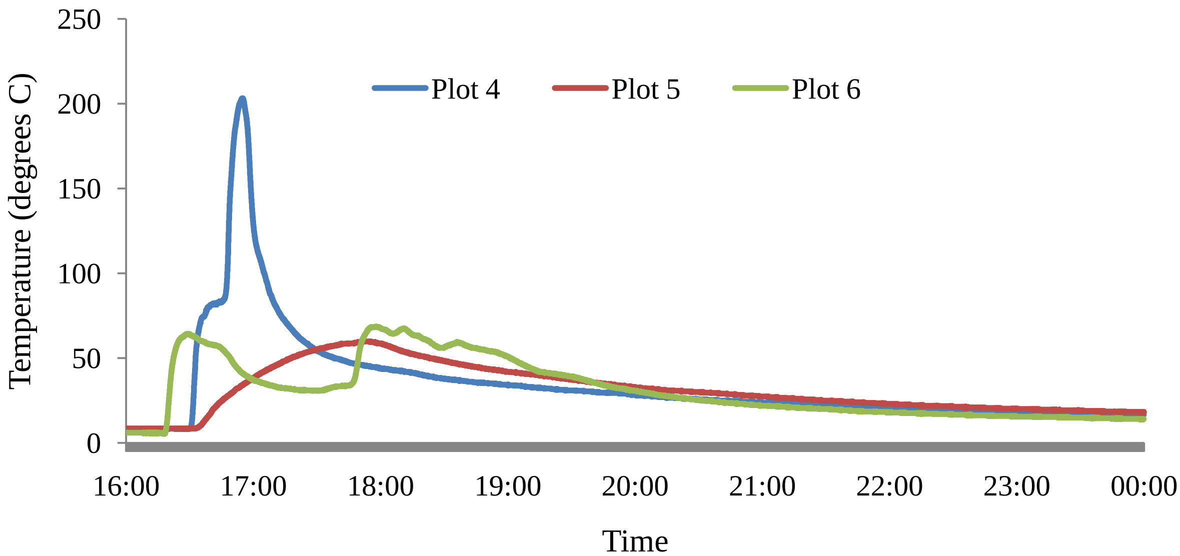

Figure 3.2. Fire temperature profiles for the three plots in the small-pile treatment area from 16:00, 21/4/2009 to 0:00, 22/4/2009.

In the cut-and-leave thinning treatment area, all needles and branches were consumed, with only the boles remaining. Maximum fire temperatures in plots 7, 8 and 9 were 853, 254 and 202°C, respectively (Figure 3.3). Temperatures did not remain above 50°C for more than 40 minutes in any of these three plots.

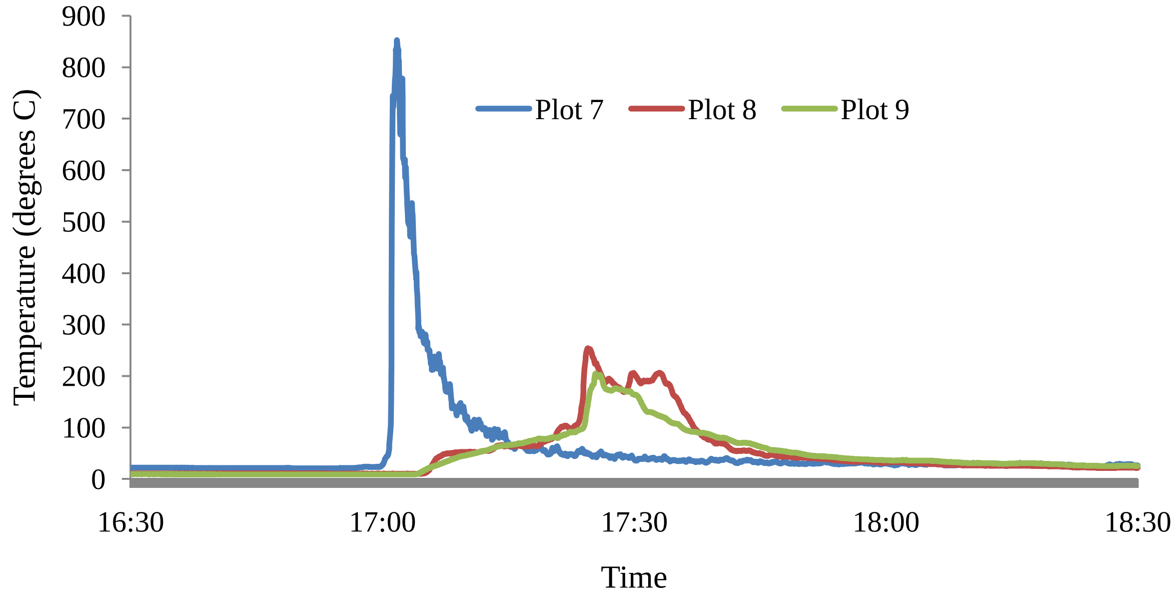

Figure 3.3. Fire temperature profiles for the three plots in the cut-and-leave treatment area from 16:30 to 18:30 on 21/4/2009.

In the deep-litter treatment where the mature trees were the plot center, all litter within 1.25 m of the tree was consumed, leaving accumulations of ash less than 0.5 cm deep. Maximum temperatures reached 411, 568, and 389°C in plots 10, 11 and 12, respectively (Figure 3.4). Two of the plots had temperatures above 200° for 4 hours, while the third had temperatures above 200° for 2 hours. All three plots remained near their maximum temperature for nearly 30 minutes before and after the maximum temperature were reached. Unfortunately, the mature trees (d.b.h. >30 cm) in this treatment area experienced crown consumption and mortality, even though most trees in this size class survive periodic fire events.

In each of the four burned treatments, two of the three plots had similar rates of temperature increase and decrease, while one plot in each treatment had a much different temperature profile. This may have resulted from different placement of sensor relative to fuel loadings or movement of fuel during combustion (i.e. piles burning from the bottom and fuel falling on top of the temperature sensor).

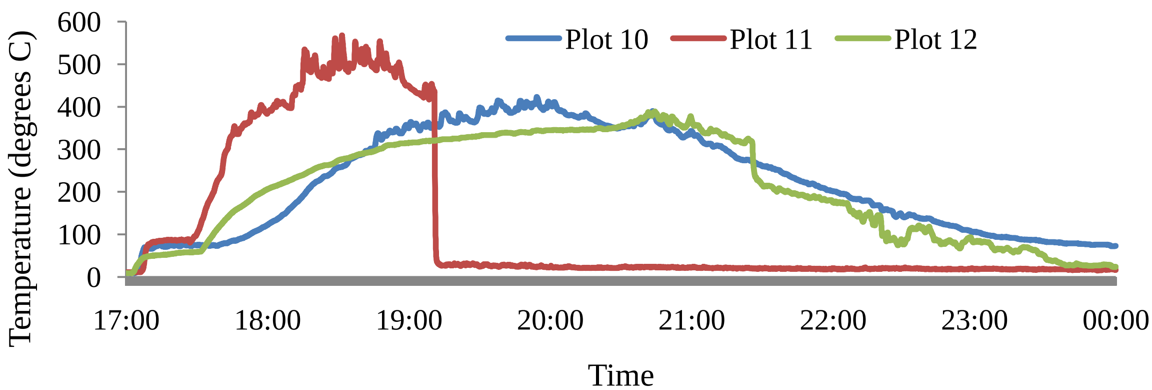

Figure 3.4. Fire temperature profiles for the three plots in the deep-litter treatment area from 17:00 on 21/4/2009 to 0:00, 22/4/2009.

3.2 Physical properties

3.2.1 Forest floor depth

The forest-floor in the deep-litter treatment, which averaged a depth of 6.6 cm before fire, was completely consumed during the prescribed fire (Figure 3.5). The large-pile, small-pile and cut-and-leave treatment areas experienced smaller decreases in forest-floor depth. For all burned treatments combined, forest-floor depth decreased on average from 4.6 to 2.5 cm during the prescribed fire.

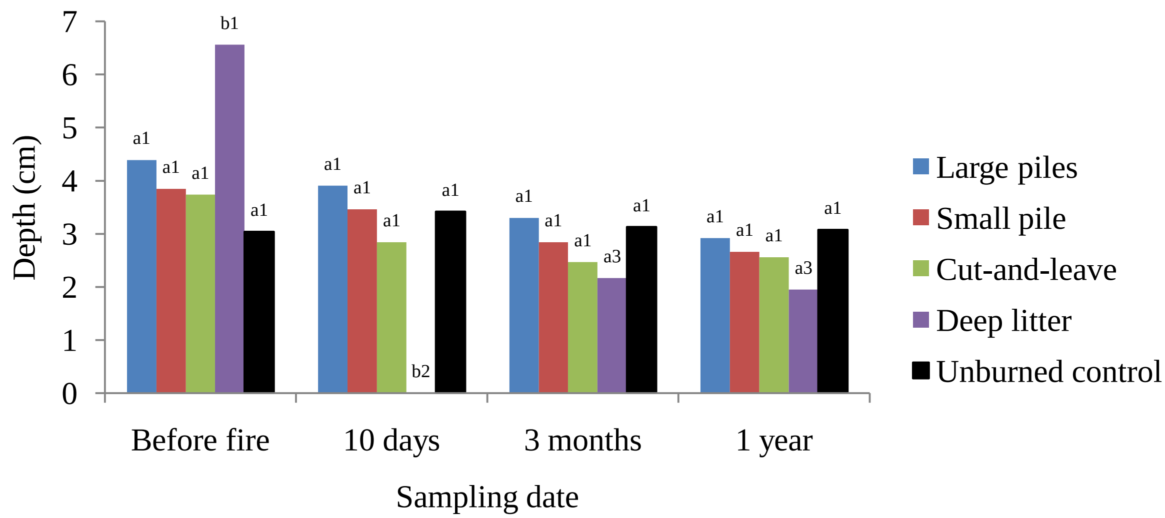

Figure 3.5. Forest floor depth in the five fuel treatments prior to and during the first year following prescribed fire. Different letters on top of bars indicate significant differences ($p<0.05$) between treatments (within a sampling date). Different numbers on top of bars indicate significant differences ($p<0.05$) between sampling dates (within a treatment).

3.2.2 Moisture

Before the fire, the forest floor layer beneath the large and small piles had significantly higher moisture levels than deep litter and unburned control treatments (Figure 3.6). Ten days after the prescribed fire, moisture levels were significantly lower in the forest floor of large and small pile treatments than compared to the start of the experiment. After 3 months, moisture levels in beneath the cut-and-leave treatment were significantly higher than in the large and small pile areas. After one year, the small piles had significantly more moisture than the deep litter and unburned control.

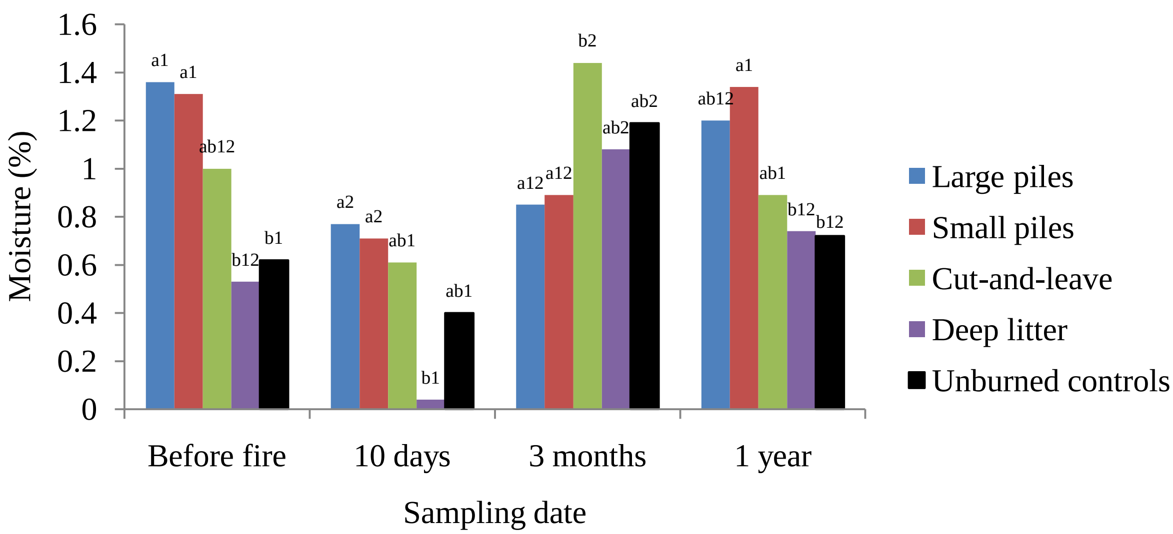

Figure 3.6. Forest-floor moisture concentrations in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments (within a sampling date). Different numbers above bars indicate significant differences ($p<0.05$) between sampling date (within a treatment).

In the mineral soil, moisture levels increased significantly beneath the large pile, small pile and cut-and-leave treatment area after fire (Figure 3.7). Up to 10 cm of snow fell over the prescribed fire site immediately after the prescribed fire, which explains the increase 10 days after fire. At 3 months and one year after fire, there were no treatment effects.

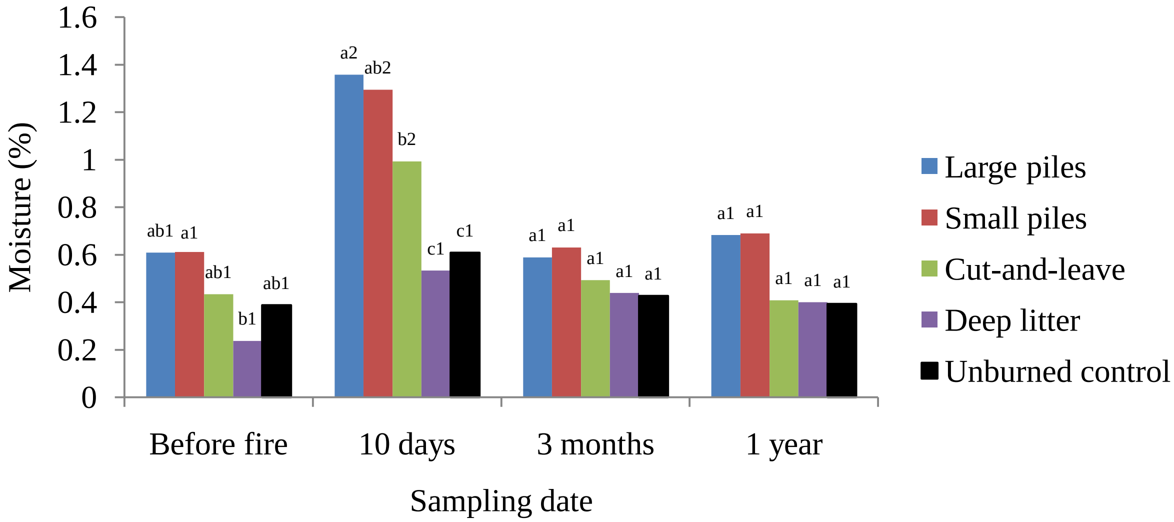

Figure 3.7. Mineral soil moisture content in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments (within a sampling date). Different numbers above bars indicate significant differences ($p<0.05$) between sampling dates (within a treatment).

3.3 Chemical properties

3.3.1 Carbon

Carbon concentrations in the forest floor layer were significantly higher in the deep-litter plots than beneath the small piles before fire (Figure 3.8). During the fire, the deep litter was consumed, leaving only a thin layer of ash. After 10 days, significant decreases in C concentrations were found in the deep-litter plots, but there were no significant changes in the other treatments. The forest floors in the unburned control plots remained between 33.9 and 38.3% C throughout the study.

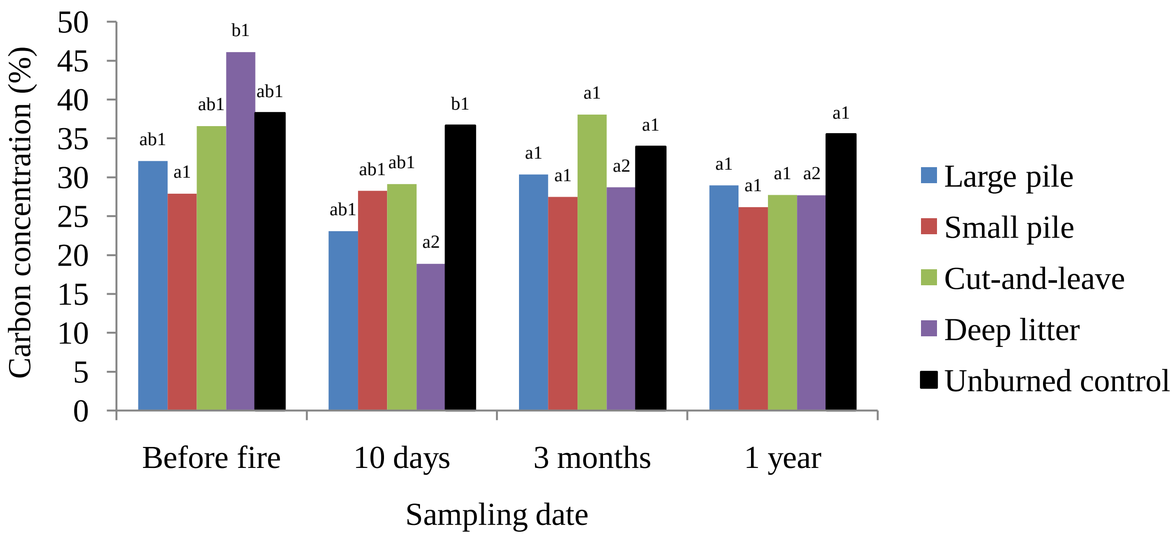

Figure 3.8. Forest floor carbon concentrations in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments (within a sampling date). Different numbers above bars indicate significant differences ($p<0.05$) between sampling dates (within a treatment).

Total carbon was significantly higher in the large-pile treatment compared to the other treatments before fire. After the fire, there was a significant decrease of total carbon in the large-pile and deep-litter treatments due to combustion of the forest floor (Figure 3.9). The unburned control did not change significantly over one year.

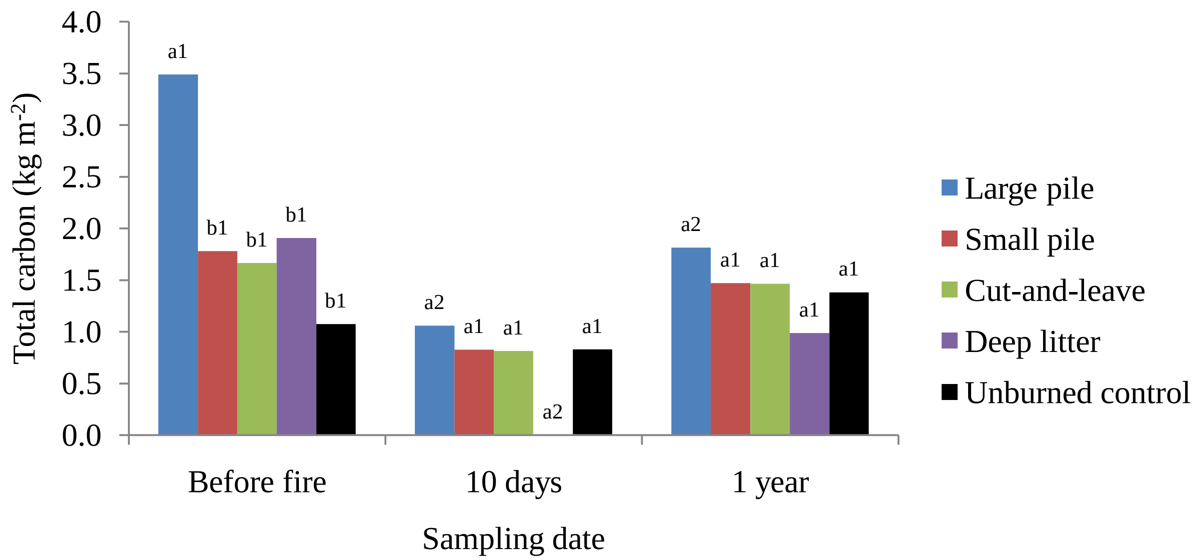

Figure 3.9. Total forest floor carbon in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments (within a sampling date). Different numbers above bars indicate significant differences ($p<0.05$) between sampling dates (within a treatment). Data unavailable for 3-month-after-fire sampling.

Mineral soil C concentrations did not decrease significantly after the prescribed fire in any treatment and pre-fire differences persisted throughout the study (Figure 3.10). When averaged over all four sampling dates, soils beneath large piles had significantly higher concentrations of C than the unburned control. This difference in concentration may be the result of the thinning that took place in different years prior to the prescribed fire, since these two treatments were in different management treatment units (TU 2 and TU 5).

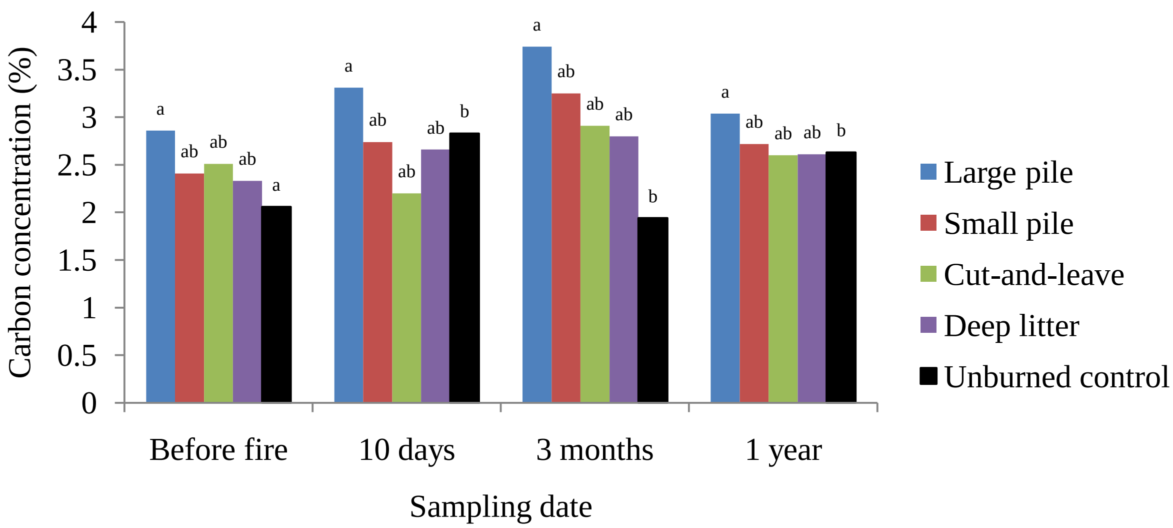

Figure 3.10. Mineral soil carbon concentrations in the five fuel treatments prior to and during the first year following prescribed fire. Different letters on top of bars indicate significant differences ($p<0.05$) between treatments when averaged over all time periods.

3.3.2 Nitrogen

Differences in forest-floor N concentrations within treatments were not significant after the prescribed fire (Figure 3.11). Concentrations of N were significantly higher in the cut-and-leave treatment than the other four treatments before the fire and remained higher throughout the study.

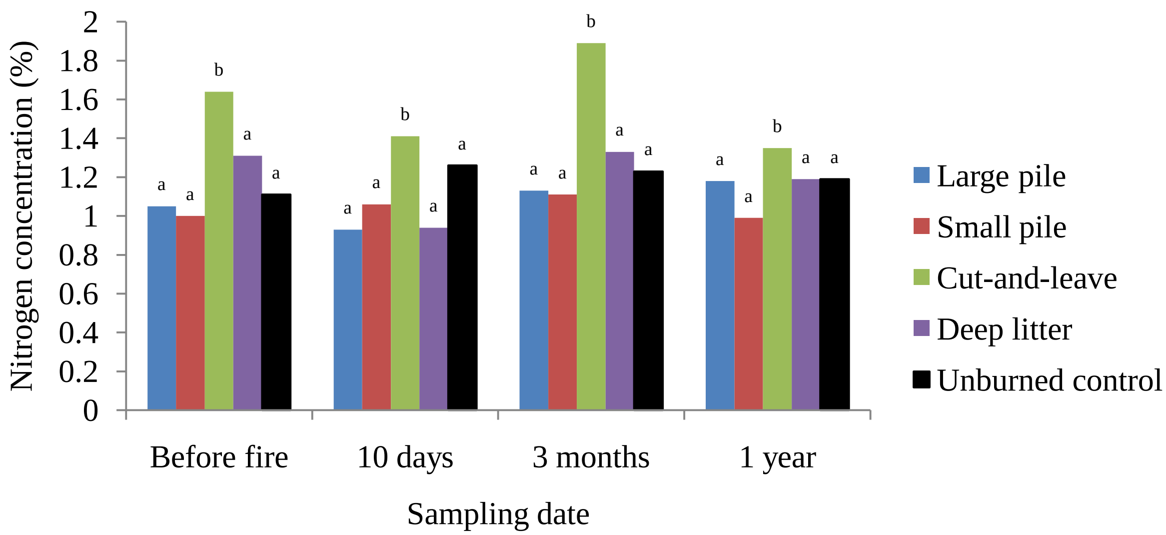

Figure 3.11. Forest floor nitrogen concentrations in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments when averaged over all sampling dates.

Total N was significantly higher in the large-pile treatment before fire compared to the other treatments (Figure 3.12). There was a significant decrease in total N after the prescribed fire in the large-pile and deep-litter treatment after fire.

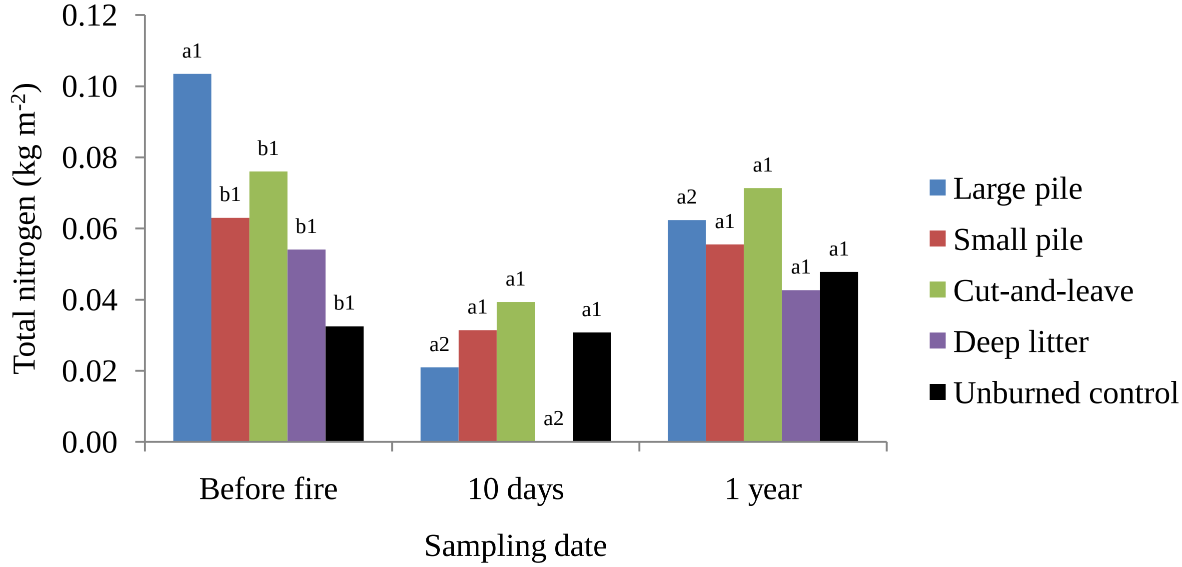

Figure 3.12. Total forest floor nitrogen in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments (within a sampling date). Different numbers above bars indicate significant differences ($p<0.05$) between sampling dates (within a treatment). Data unavailable for 3-month-after-fire sampling.

Mineral-soil nitrogen concentrations were significantly different among treatments and times, but the interaction between the two was not significant, indicating no effect of the fire treatments. When averaged over the four time periods, values in the unburned control were significantly lower than in the large-pile, small-pile and the deep-litter treatments (Figure 3.13). Also, nitrogen concentrations were significantly higher during the 3-month post-fire sampling than the pre-fire sampling.

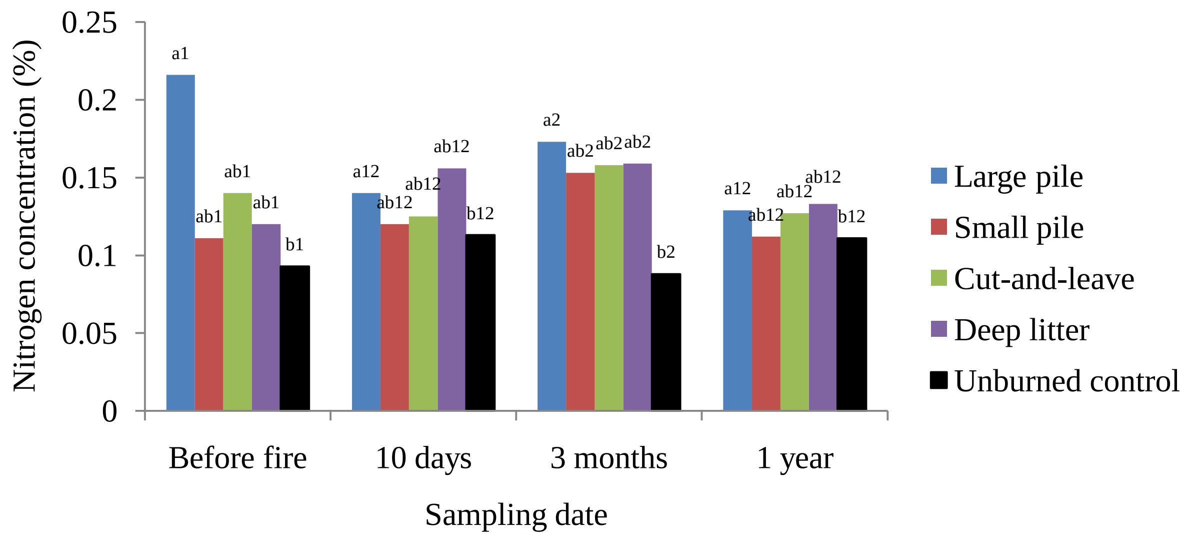

Figure 3.13. Mineral soil nitrogen concentrations in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments when averaged over all sampling dates. Different numbers above bars indicate significant difference ($p<0.05$) between sampling dates when averaged over all treatments.

3.3.3 Carbon-to-nitrogen ratios

Carbon-to-nitrogen ratios in the forest floor were significantly broader in the deep litter and unburned control plots than in the cut-and-leave plots before fire (Figure 3.14). After fire, the C:N ratio was significantly narrower in the deep-litter plots and remained so for the rest of the study. Forest floor C:N ratios in the large-pile, small-pile, cut-and-leave and unburned control plots did not change significantly during the study.

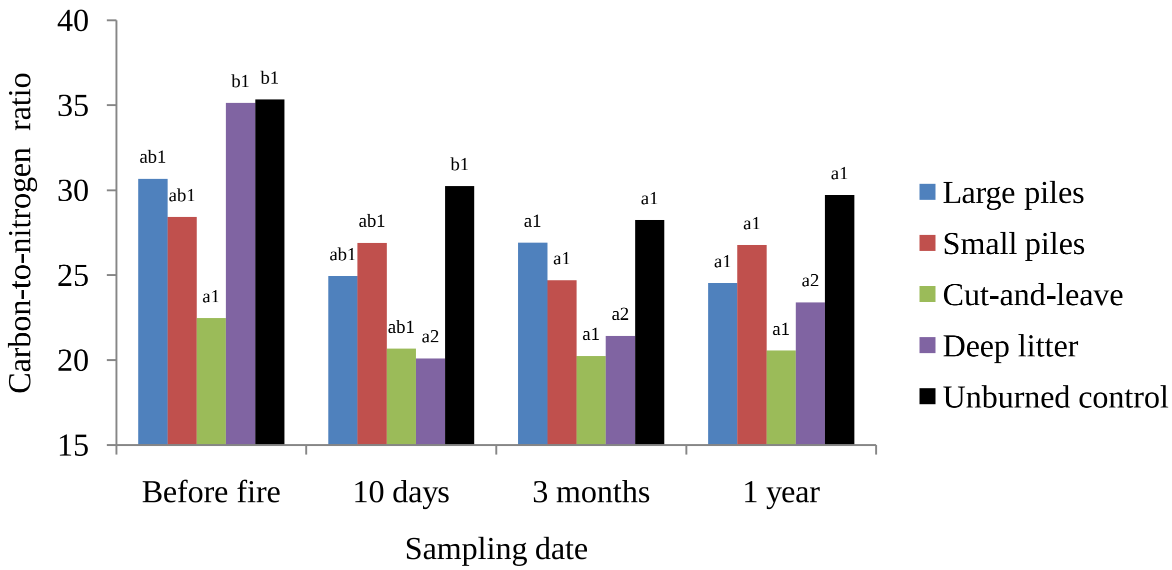

Figure 3.14. Forest floor carbon-to-nitrogen ratio in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments (within a sampling date). Different numbers above bars indicate significant differences ($p<0.05$) between sampling dates (within a treatment).

In the mineral soil, the C:N ratio was significantly broader one year after fire than 3 months after fire (Figure 3.15). The C:N ratios in the large-pile, small-pile and unburned control plots were significantly broader than the cut-and-leave and deep-litter plots when averaged over all sampling dates.

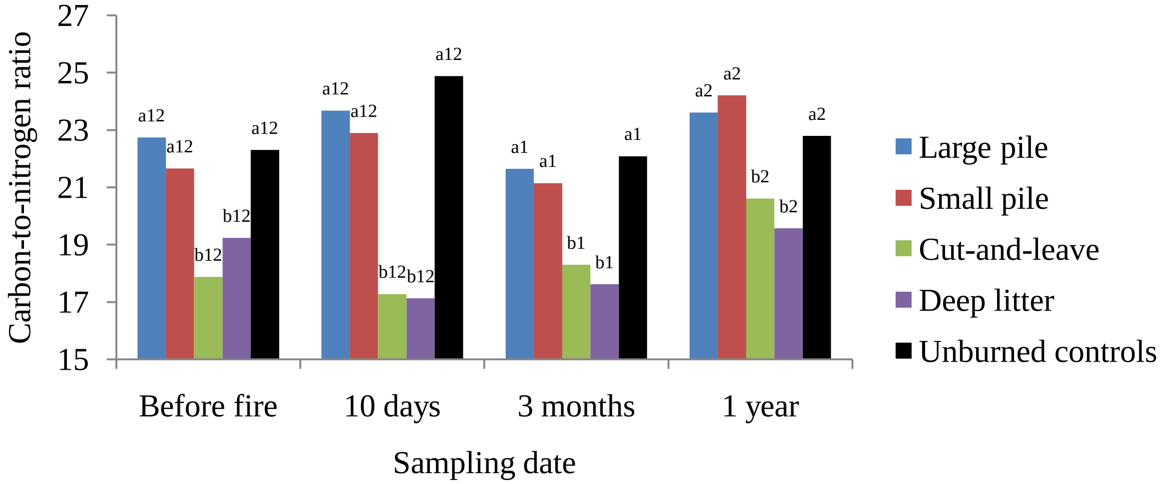

Figure 3.15. Mineral soil carbon-to-nitrogen ratio in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments when averaged over all sampling dates. Different numbers above bars indicate significant difference ($p<0.05$) between sampling dates when averaged over all treatments.

3.3.4 pH

Forest floor pH in burned plots increased significantly immediately after the fire; in the deep-litter (treatment in which the residual forest floor was mostly ash), pH increased from 5.7 to 8.2 (Figure 3.16). After one year, the pH was still significantly elevated in each of the fire treatments. The unburned control remained between pH 4.75 and 5.0 throughout the study.

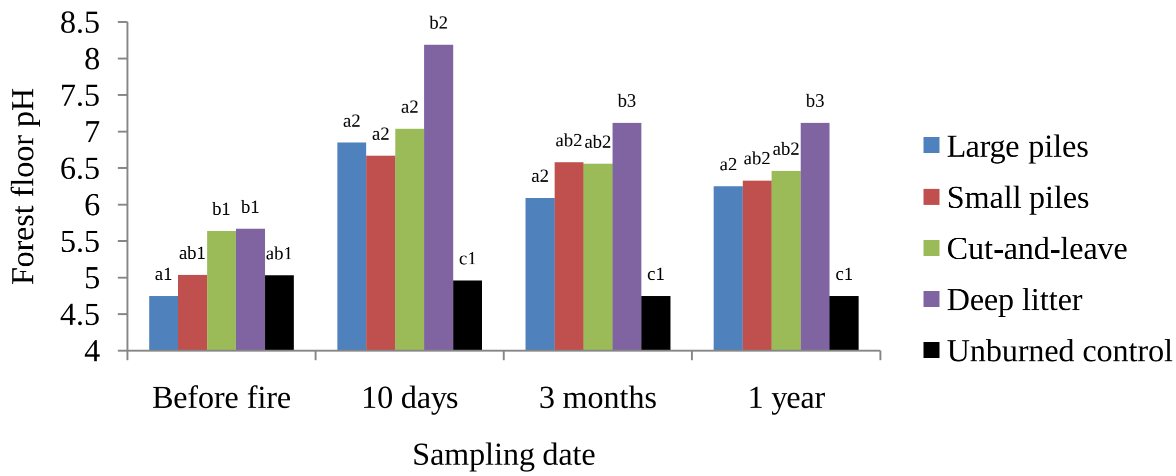

Figure 3.16. Forest floor pH in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments (within a sampling date). Different numbers above bars indicate significant differences ($p<0.05$) between sampling dates (within a treatment).

The only significant change in mineral soil pH after fire was an increase in the deep-litter treatment (Figure 3.17). This treatment had the highest pH throughout the study period.

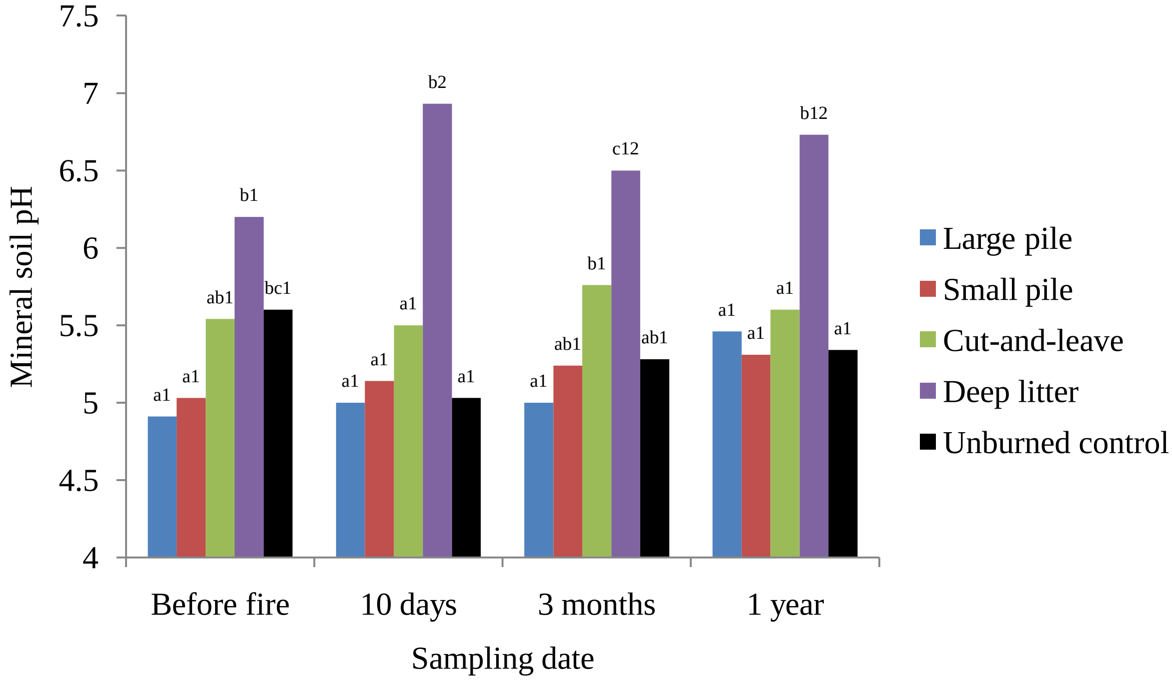

Figure 3.17. Mineral soil pH in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments (within a sampling date). Different numbers above bars indicate significant differences ($p<0.05$) between sampling dates (within a treatment).

3.3.5 Nutrient availability

PRS™-probes were only inserted into the forest floor and mineral soil after the prescribed fire, therefore, no comparisons can be made of pre-fire nutrient availability. Furthermore, only the two summer sampling periods can be directly compared, as the probes collect ions at an uneven rate (µg/10 cm^2/burial length), and so can only be compared among incubations of similar length.

3.3.5a Nitrogen availability

Ammonium (NH_4^+) availability in the forest floor and mineral soil did not differ significantly among any of the treatments or between the two summer sampling times (Figures 3.18 and 3.19).

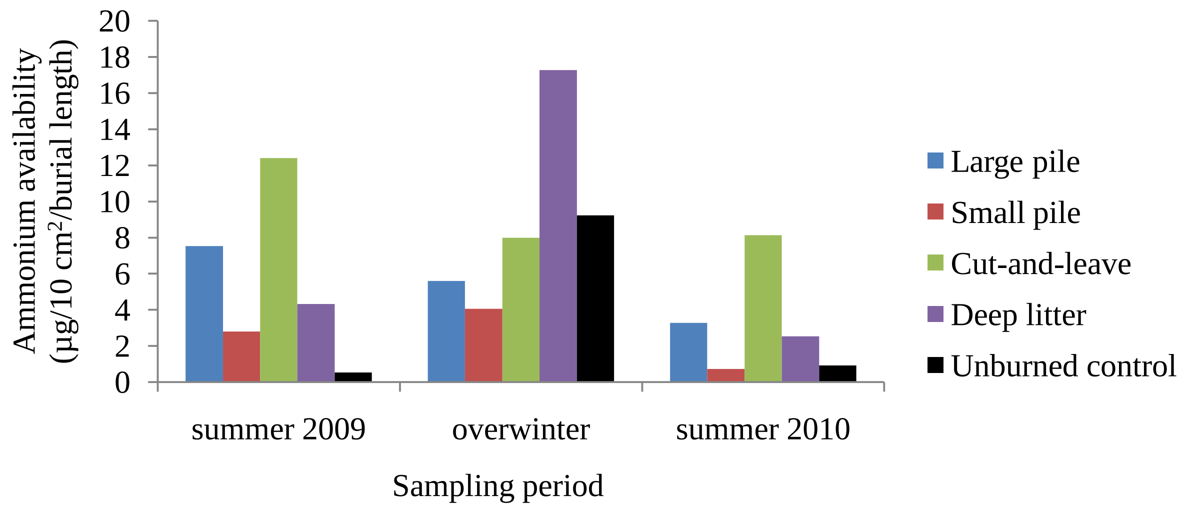

Figure 3.18. Forest floor ammonium availability in the five fuel treatments during three post-fire sampling periods.

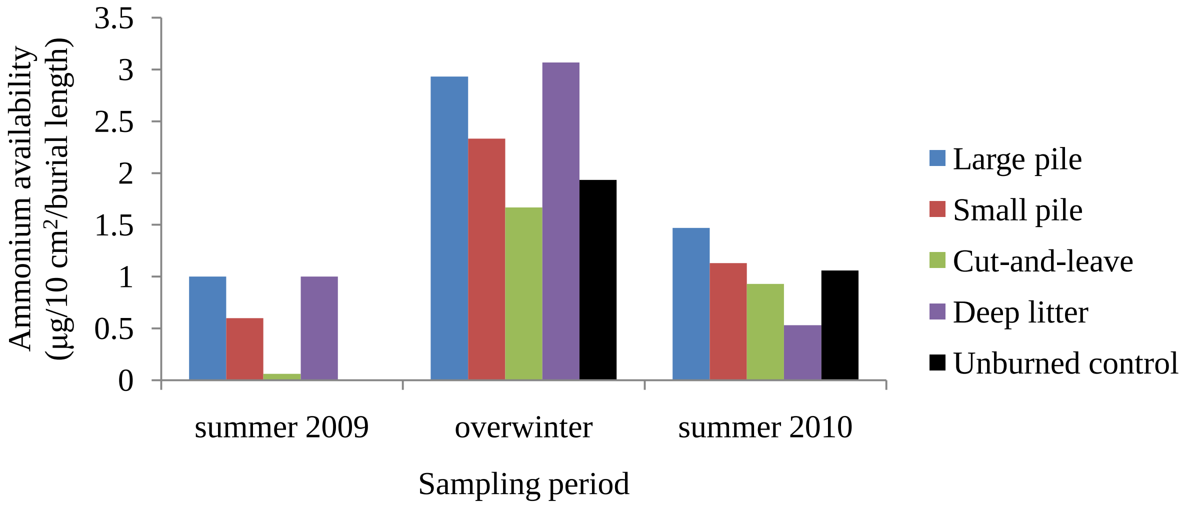

Figure 3.19. Mineral soil ammonium availability in the five fuel treatments during three post-fire sampling periods.

In contrast to NH_4^+, NO_3^- availability was influenced by treatment. Forest floor NO_3^- availability was significantly higher in the deep-litter than the unburned-control and large-pile treatments (Figure 3.20). Nitrate availability in the mineral soil was significantly higher in the deep-litter treatment than in the other four treatments (Figure 3.21).

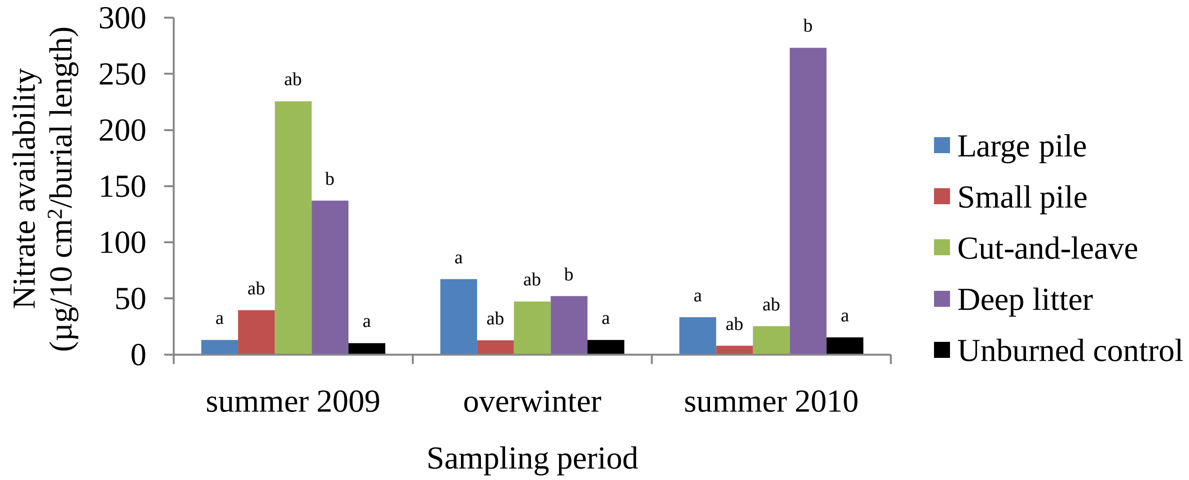

Figure 3.20. Forest floor nitrate availability in the five fuel treatments during three post-fire sampling periods. Different letters above bars indicate significant differences ($p<0.05$) between treatments when averaged over all sampling periods.

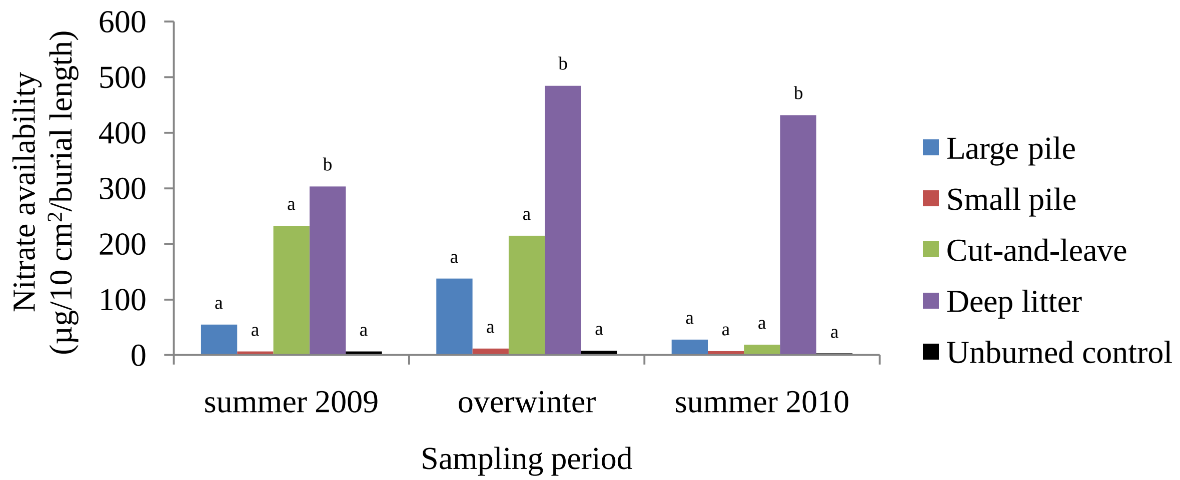

Figure 3.21. Mineral soil nitrate availability in the five fuel treatments during three post-fire sampling periods. Different letters above bars indicate significant differences ($p<0.05$) between treatments when averaged over all sampling periods.

3.3.5b Phosphate availability

Forest floor phosphate (H_2PO_4) availability was significantly higher in all burned treatments than the unburned control during the overwinter period (Figure 3.22). This trend was apparent (but not significant) during the two summer periods, with the exception of the deep-litter in the summer of 2009. Mineral soil H_2PO_4 was significantly higher in the large-pile treatment than the deep-litter and unburned control when averaged over all sampling periods (Figure 3.23)

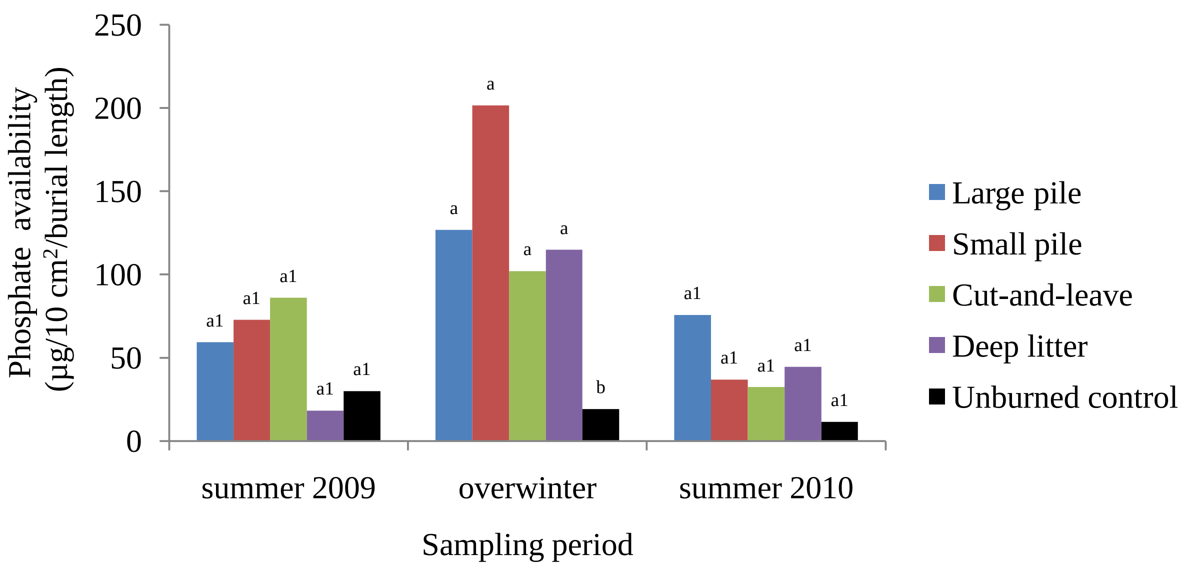

Figure 3.22. Forest floor phosphate availability in the five fuel treatments during three post-fire sampling periods. Different letters above bars indicate significant differences ($p<0.05$) between treatments (within a sampling period). Different numbers above bars indicate significant differences ($p<0.05$) between sampling periods (within a treatment).

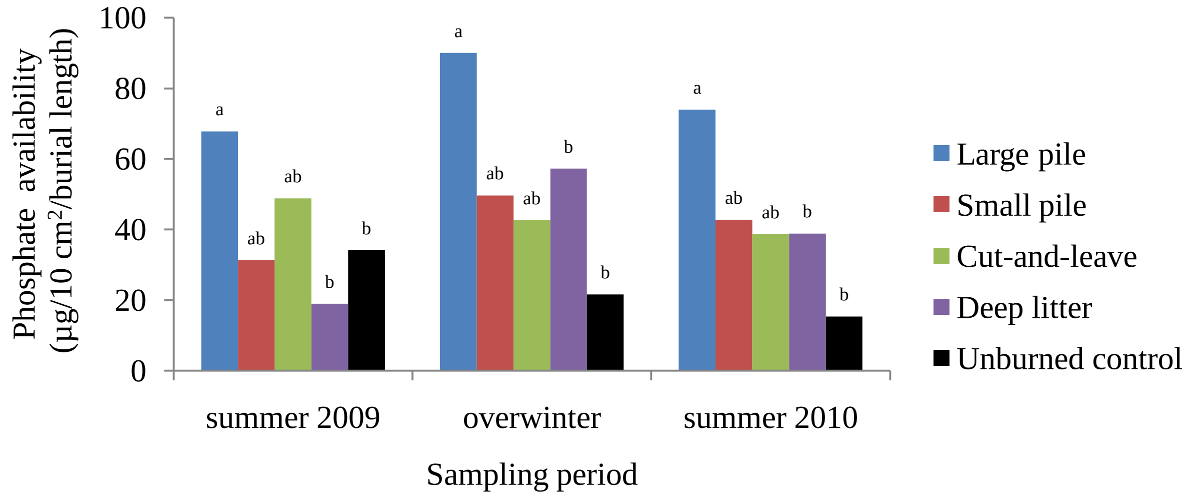

Figure 3.23. Mineral soil phosphate availability in the five fuel treatments during three post-fire sampling periods. Different letters above bars indicate significant differences ($p<0.05$) between treatments when averaged over all sampling periods.

3.3.5c Potassium availability

There was no effect of treatment or sampling time on K^+ in the forest floor (Figure 3.24). In the mineral soil, K^+ availability was significantly higher in the large pile treatment than in the cut-and-leave treatment (Figure 3.25).

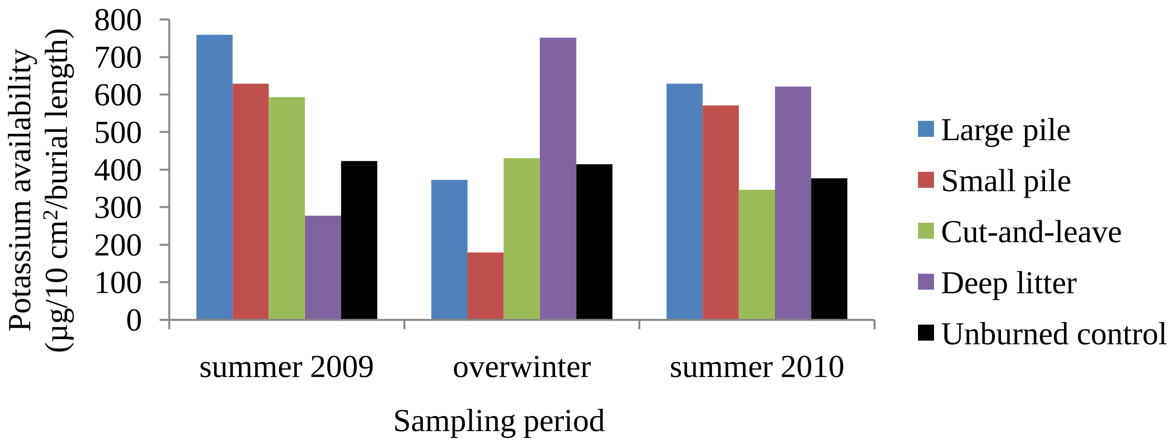

Figure 3.24. Forest floor potassium availability in the five fuel treatments during three post-fire sampling periods.

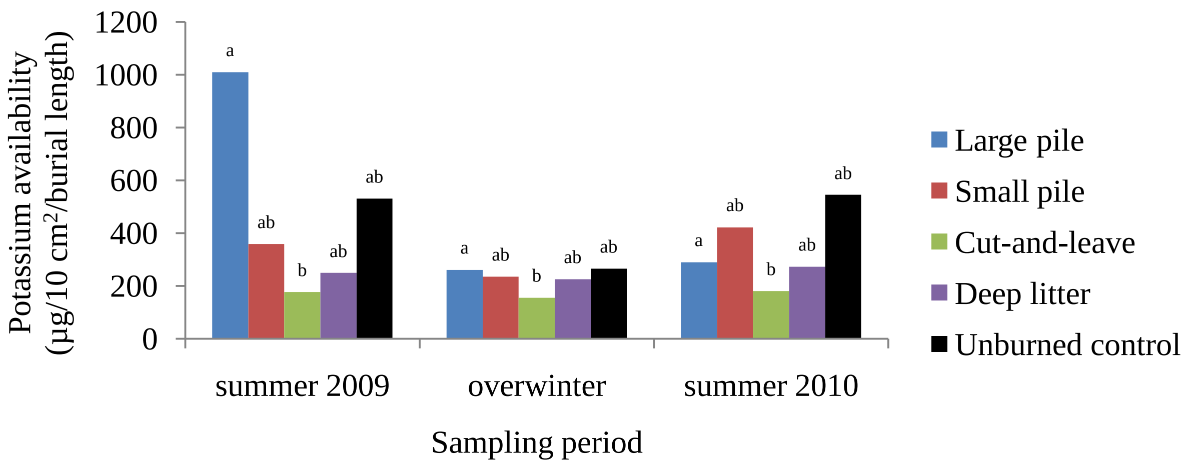

Figure 3.25. Mineral soil potassium availability in the five fuel treatments during three post-fire sampling periods. Different letters above bars indicate significant differences ($p<0.05$) between treatments when averaged over all sampling periods.

3.3.5d Calcium availability

Forest floor Ca^{2+} availability was significantly higher in burned plots than unburned plots during the first two time periods after the prescribed fire (Figure 3.26). During the third sampling period, Ca^{2+} levels in the burned plots declined in the small pile and cut-and-leave treatment area

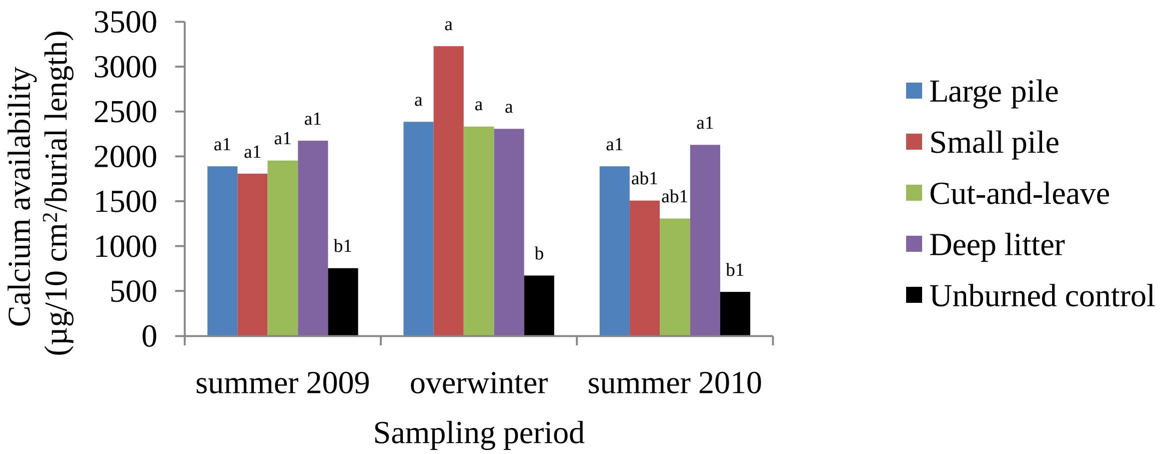

Figure 3.26. Forest floor calcium availability in the five fuel treatments during three post-fire sampling periods. Different letters above bars indicate significant differences (p<0.05) between treatments (within a time period). Different numbers above bars indicate significant differences (p<0.05) between time periods (within a treatment).

In the mineral soil, Ca^{2+} availability in the large-pile, cut-and-leave and the deep- litter treatments were significantly higher than in the unburned control plots (Figure 3.27).

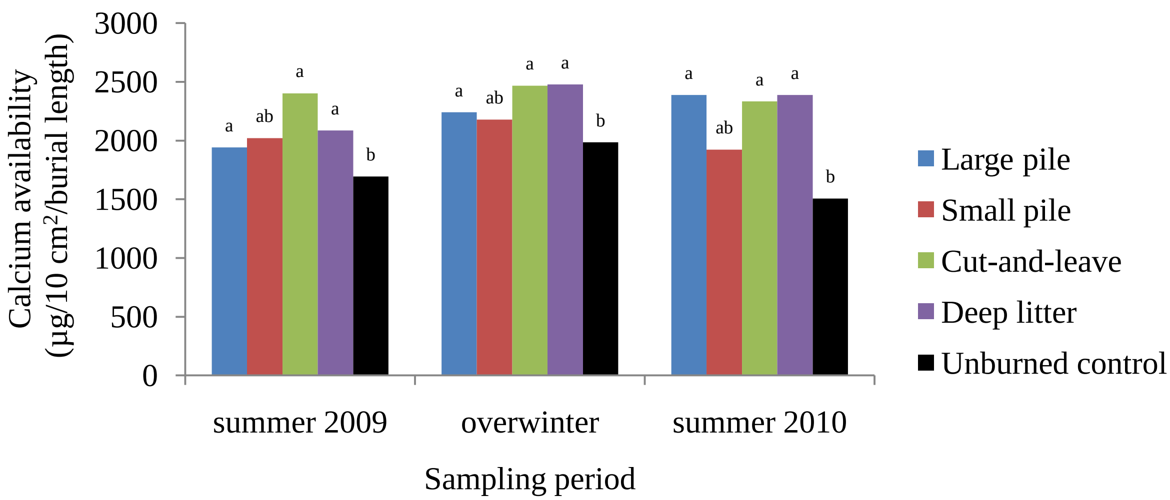

Figure 3.27. Mineral soil calcium availability in the five fuel treatments during three post-fire sampling periods. Different letters above bars indicate significant differences ($p<0.05$) between treatments when averaged over all sampling periods.

3.3.5e Magnesium availability

Forest floor magnesium (Mg^{2+}) availability was significantly higher in burned treatment than in unburned controls during all three post-fire periods (Figure 3.28).

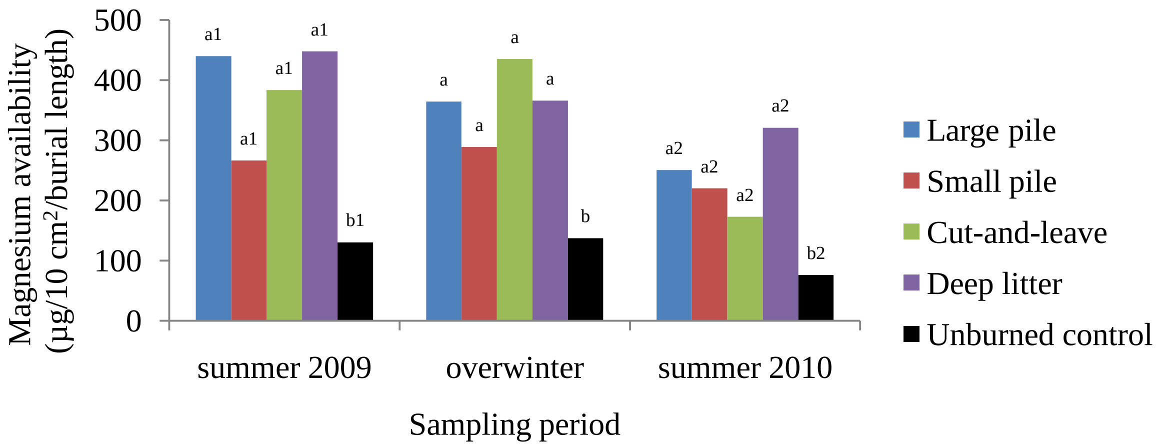

Figure 3.28. Forest floor magnesium availability in the five fuel treatments during three post-fire sampling periods. Different letters above bars indicate significant differences ($p<0.05$) between treatments when averaged over all sampling periods. Different numbers above bars indicate significant difference ($p<0.05$) between sampling periods when averaged over all treatments.

Magnesium in the mineral soil was significantly higher in the deep-litter treatment than the large-pile and small-pile treatments (Figure 3.29). Availability in the unburned control was not significantly different from any of the burned treatments.

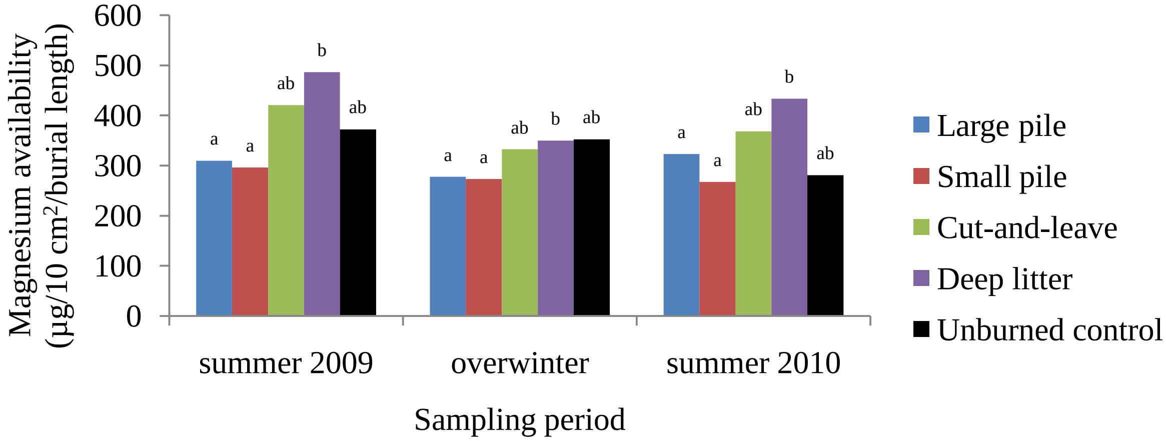

Figure 3.29. Mineral soil magnesium availability in the five fuel treatments during three post-fire sampling periods. Different letters above bars indicate significant differences ($p<0.05$) between treatments when averaged over all sampling periods.

3.3.5f Sulphate availability

Forest floor sulphate (SO_4^{2-}) availability was significantly higher in the deep-litter treatment than the other treatments throughout sampling periods (Figure 3.30). There were also significantly higher amounts of SO_4^{2-} available immediately after the fire, compared to the following summer.

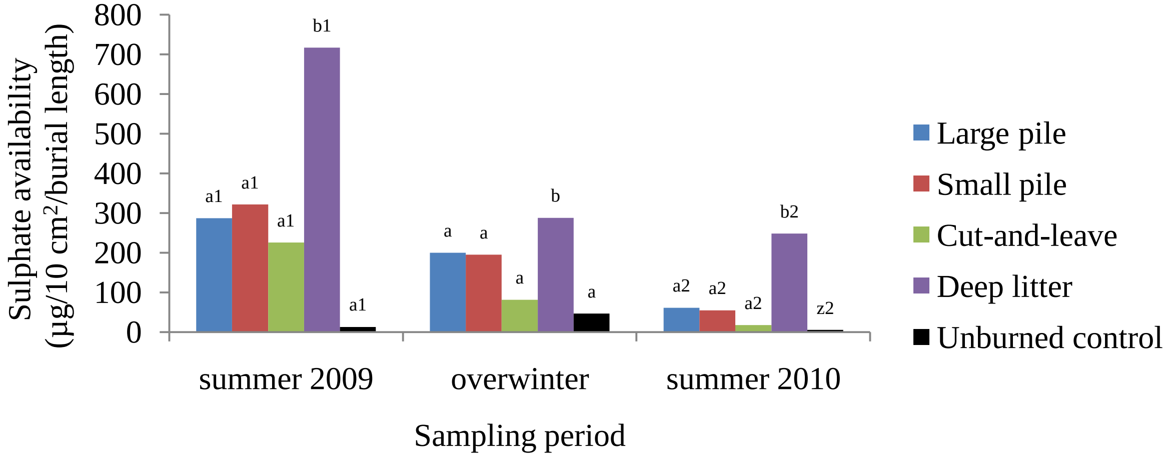

Figure 3.30. Forest floor sulphate availability in the five fuel treatments during three post-fire sampling periods. Different letters above bars indicate significant differences (p<0.05) between treatments when averaged over all sampling periods. Different numbers above bars indicate significant difference (p<0.05) between sampling periods when averaged over all treatments.

In the mineral soil, SO_4^{2-} availability in the deep-litter treatment was significantly higher than in the small-pile, cut-and-leave and the unburned control (Figure 3.31). Sulphate availability was significantly higher during the first summer than during the second summer.

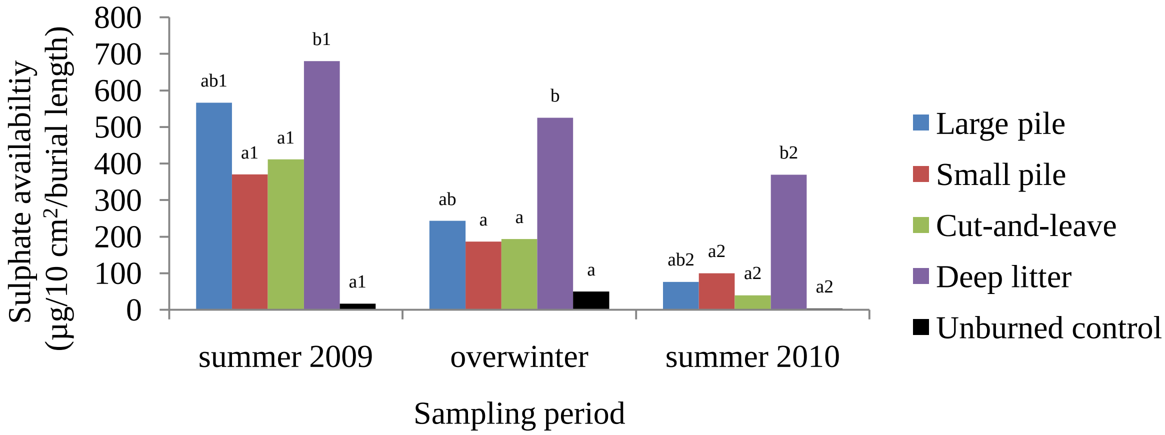

Figure 3.31. Mineral soil sulphate availability in the five fuel treatments during three post-fire sampling periods. Different letters above bars indicate significant differences (p<0.05) between treatments when averaged over all sampling periods. Different numbers above bars indicate significant difference (p<0.05) between sampling periods when averaged over all treatments.

3.4 Biological properties

3.4.1 Gram-positive bacteria abundance

Gram-positive bacterial abundances in the forest floor decreased significantly in all treatments after the prescribed fire, with little to no recovery after 3 months and 1 year (Figure 3.32). Before fire, abundance of Gram-positive bacteria in the cut-and-leave treatment was significantly higher than the large pile and deep litter treatment, but it decreased to similar levels as the other treatments after the fire. Gram-positive bacterial abundance in the deep-litter treatment was negligible 10 days after fire. Gram-positive bacteria in the unburned control plots remained at similar levels throughout the study.

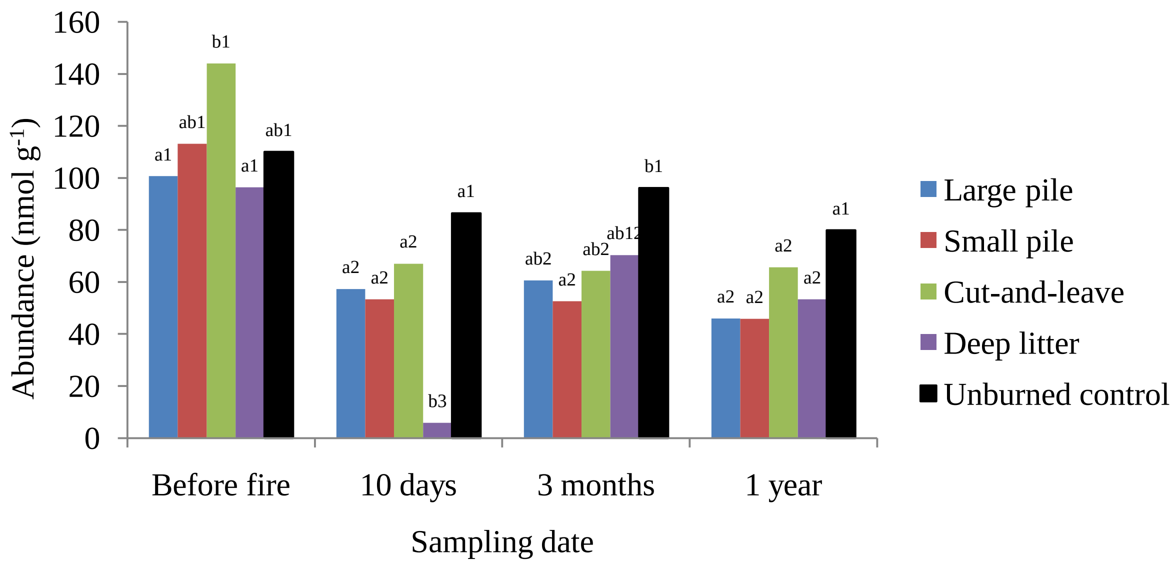

Figure 3.32. Forest floor Gram-positive bacteria abundance in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments (within a sampling date). Different numbers above bars indicate significant differences ($p<0.05$) between sampling dates (within a treatment).

In the mineral soil, there were no significant differences in Gram-positive bacteria abundance between treatments before fire (Figure 3.33). Abundance decreased significantly in the cut-and-leave treatment 10 days after fire. The Gram-positive bacteria in the large-pile and deep-litter treatments declined significantly from pre-fire levels to one year after fire. Gram-positive bacteria in the unburned control remained at similar levels throughout the study.

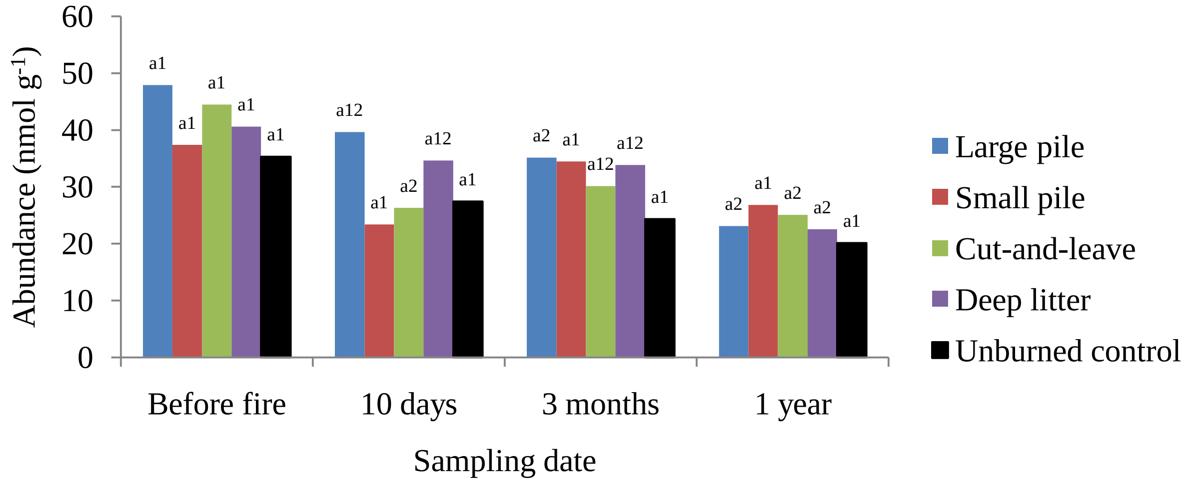

Figure 3.33. Mineral soil Gram-positive bacteria abundance in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments (within a sampling date). Different numbers above bars indicate significant differences ($p<0.05$) between sampling dates (within a treatment).

3.4.2 Gram-negative bacteria abundance

Gram-negative bacteria abundance in the forest floor decreased after the prescribed fire, with significant losses in all four burned treatments (Figure 3.34). Abundance had not recovered in subsequent sampling. No significant changes occurred in the unburned control.

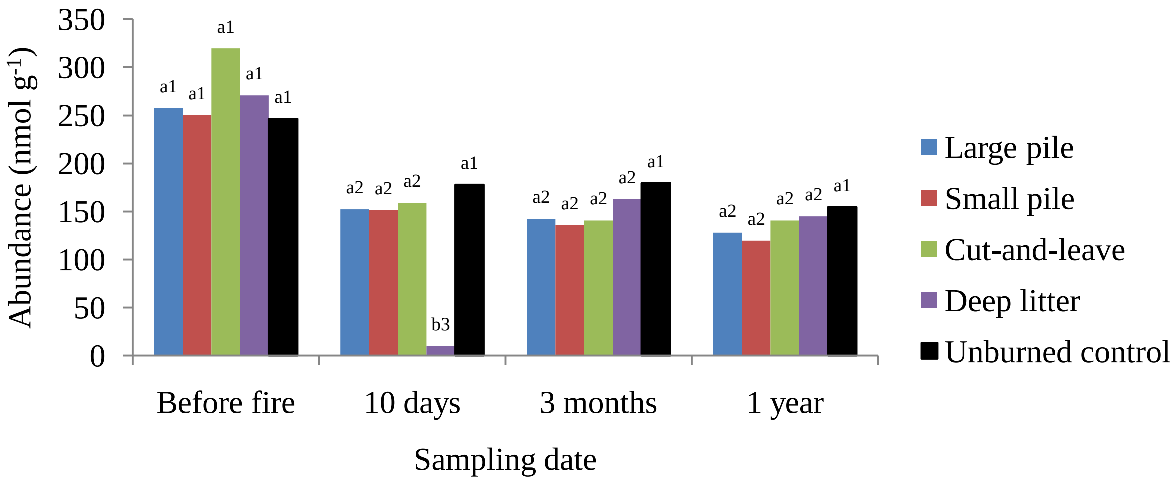

Figure 3.34. Forest floor Gram-negative bacteria abundance in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments (within a time period). Different numbers above bars indicate significant differences ($p<0.05$) between time periods (within a treatment).

In the mineral soil, Gram-negative bacteria abundance in soil in the large-pile treatments was significantly higher than in the unburned control throughout the study (Figure 3.35). Abundance during the before-fire sampling was significantly higher than during each of the post-fire samplings. Gram-negative bacteria were significantly more abundant during the 3-month sampling compared to the one-year post-fire sampling.

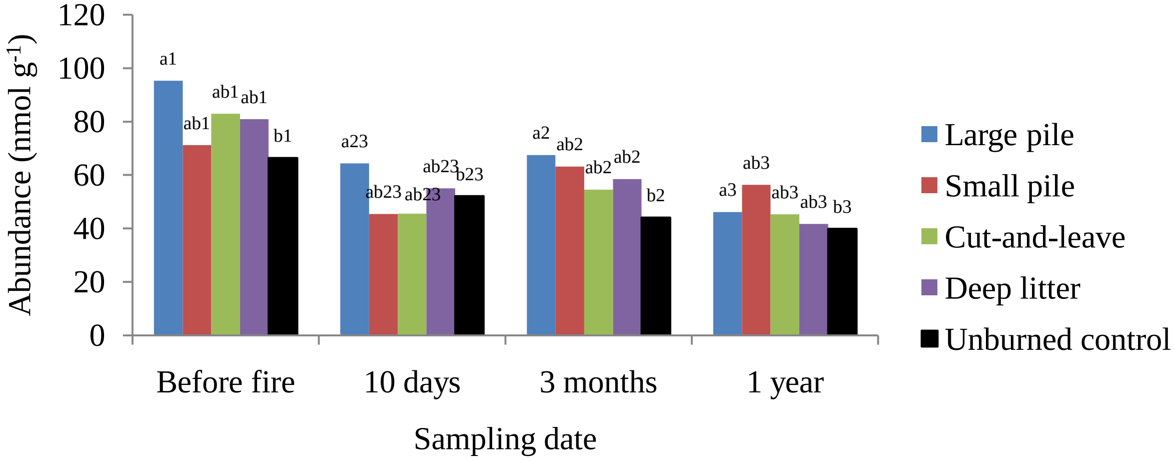

Figure 3.35. Mineral soil Gram-negative bacteria abundance in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences (p<0.05) between treatments when averaged over all sampling dates. Different numbers above bars indicate significant difference (p<0.05) between sampling dates when averaged over all treatments.

3.4.3 Actinomycete abundance

Actinomycete abundance in the forest floor decreased significantly after the prescribed fire in the burned treatments, with the greatest losses in the cut-and-leave and deep litter treatments (Figure 3.36). There was no recovery in the burned treatments during the last 2 sampling dates. Actinomycete abundance in the unburned control also declined during the sampling period, but much less so than in the burned plots.

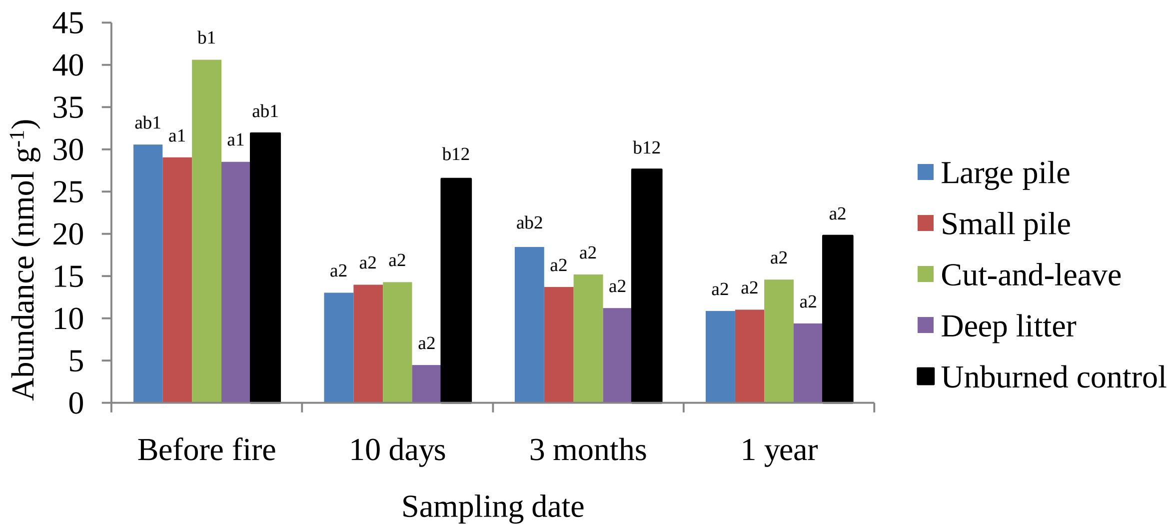

Figure 3.36. Forest floor actinomycete abundance in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments (within a sampling date). Different numbers above bars indicate significant differences ($p<0.05$) between time periods (within a sampling date).

In the mineral soil, actinomycete abundance was significantly higher in the large-pile plots than the unburned control plots throughout the study (Figure 3.37). Actinomycete abundance decreased with time after prescribed fire, with significantly higher abundance before fire than after fire. There was also a significantly higher abundance of actinomycetes in the 3-month sampling than the 1-year sampling.

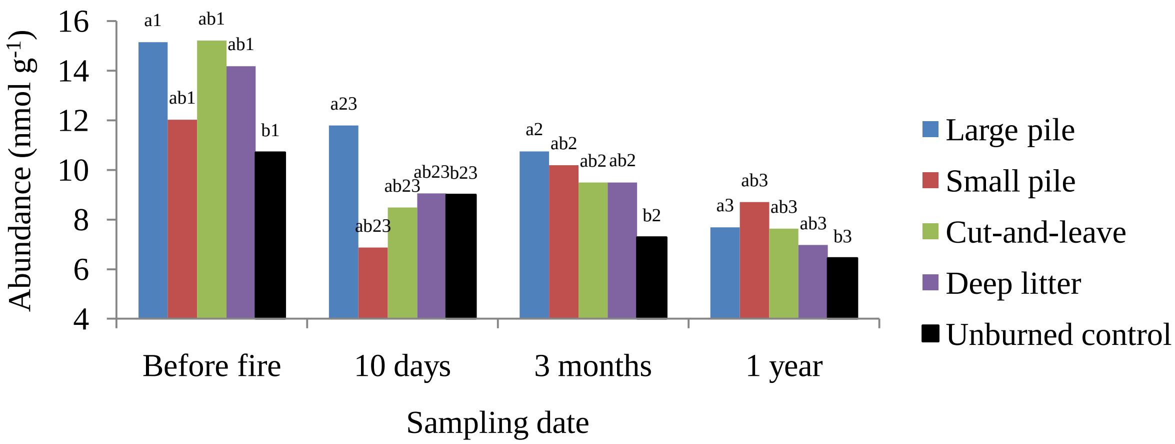

Figure 3.37. Mineral soil actinomycete abundance in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments when averaged over all sampling dates. Different numbers above bars indicate significant difference ($p<0.05$) between sampling dates when averaged over all treatments.

3.4. 4 Total bacteria abundance

The total bacteria abundance in the forest floor decreased significantly in all treatments immediately after the prescribed fire (Figure 3.38). The largest decreases were in the deep-litter treatment, where abundance dropped from over 400 to less than 20 nmol g^{-1}. Total bacteria abundances remained below 50% of their pre-fire levels after one year. Bacterial abundance in the unburned controls plots was significantly lower one year after fire than in the pre-fire sampling.

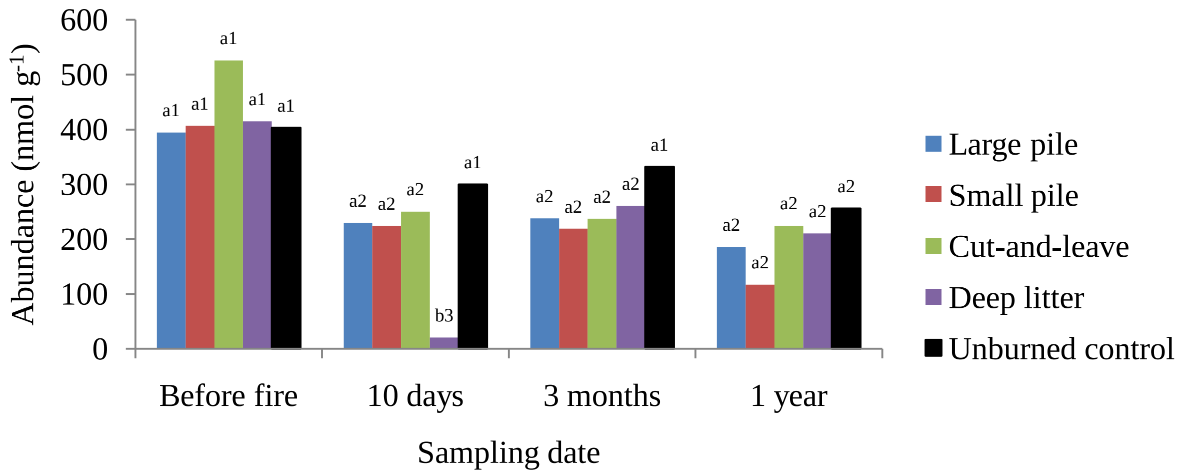

Figure 3.38. Forest floor total bacteria abundance in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments (within a sampling date). Different numbers above bars indicate significant differences ($p<0.05$) between sampling dates (within a treatment).

In the mineral soil, total bacteria decreased significantly in all treatments after fire, including the unburned control (Figure 3.39). Throughout the study, bacterial abundance in the large-pile treatment was significantly higher than in the unburned control.

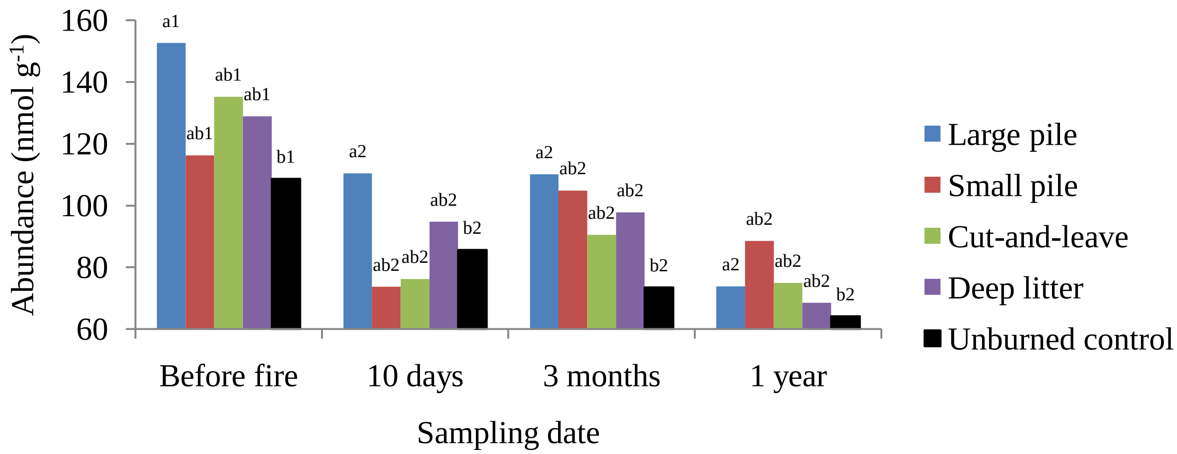

Figure 3.39. Mineral soil total bacteria abundance in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments when averaged over all sampling dates. Different numbers above bars indicate significant difference ($p<0.05$) between sampling dates when averaged over all treatments.

3.4.5 Arbuscular mycorrhizae abundance

Abundances of arbuscular mycorrhizae (AM) in the forest floor layer decreased significantly after fire in all burned treatments (Fig. 3.40). The largest AM decreases occurred in the deep-litter treatment, where no PLFAs were detected in samples collected 10 days after fire. While AM abundance in the unburned control plots did not change significantly throughout the study, abundances in the burned treatments did not recover to pre-fire levels after one year.

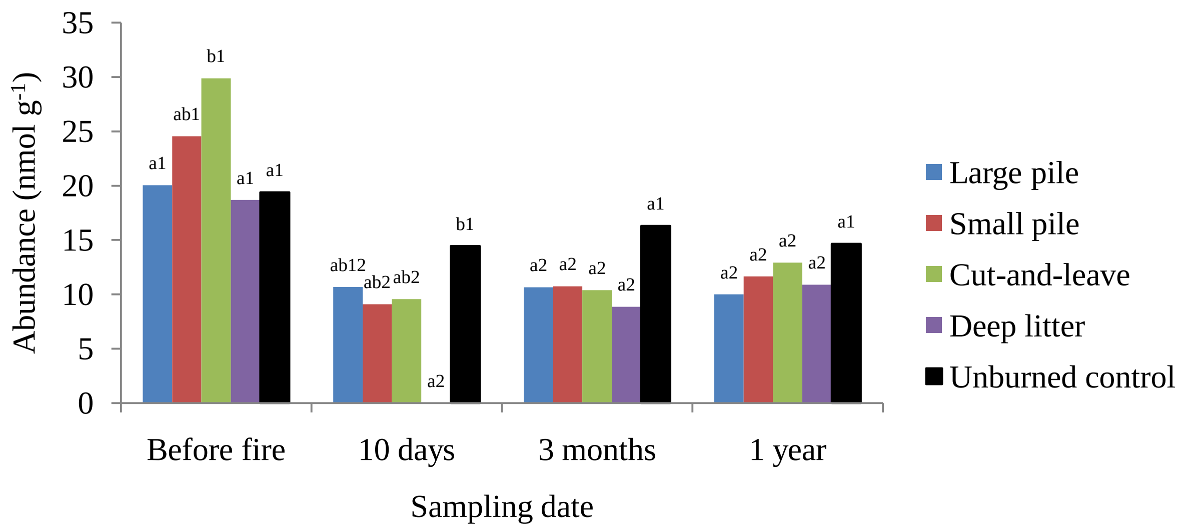

Figure 3.41. Forest floor arbuscular mycorrhizae abundance in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments (within sampling date). Different numbers above bars indicate significant differences ($p<0.05$) between sampling dates (within a treatment).

Arbuscular mycorrhizae abundance in the mineral soil was significantly higher in the large-pile treatment than in the deep litter and unburned control throughout the study (Fig. 3.41). Pre-fire AM abundance was significantly higher than the post-fire abundances. Although some recovery was apparent after 3 months, a significant reduction was still present after one year.

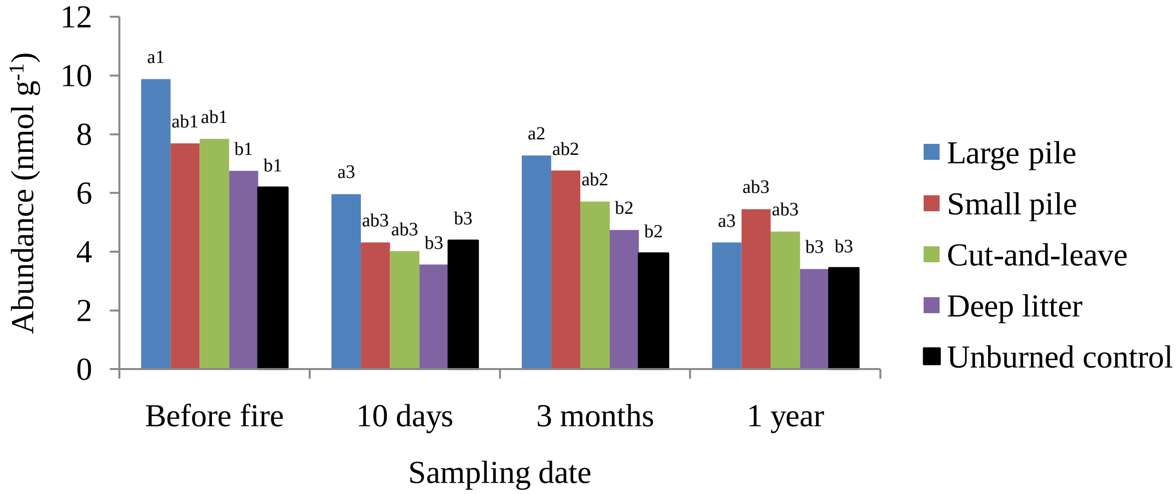

Figure 3.41. Mineral soil arbuscular mycorrhizae abundance in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments when averaged over all sampling dates. Different numbers above bars indicate significant difference ($p<0.05$) between sampling dates when averaged over all treatments.

3.4.6 Total fungi abundance

The abundance of total fungi in the forest floor layer decreased significantly after the prescribed fire and remained low for the first year (Fig. 3.42). A progressive decline occurred in the unburned control over the four time periods.

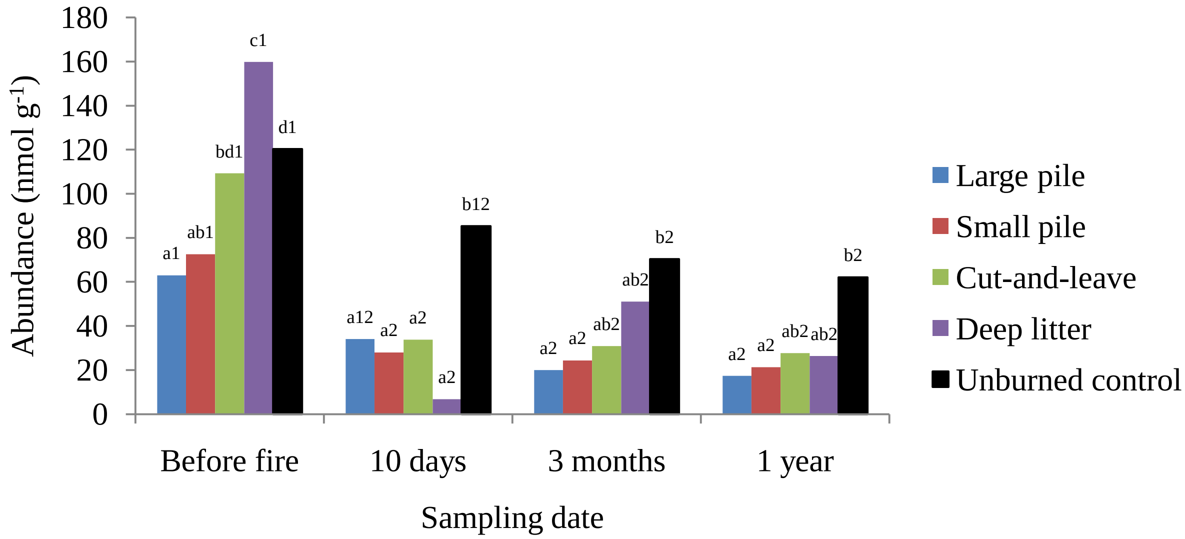

Figure 3.42. Forest floor total fungi abundance in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments (within sampling date). Different numbers above bars indicate significant differences ($p<0.05$) between sampling dates (within a treatment).

In the mineral soil, there were no significant differences in fungal abundance over time periods or treatments (Fig. 3.43). Fungal abundance in all burned treatments declined from the first sampling date to the second, with the cut-and-leave and deep litter treatment areas decreasing throughout the four sampling periods.

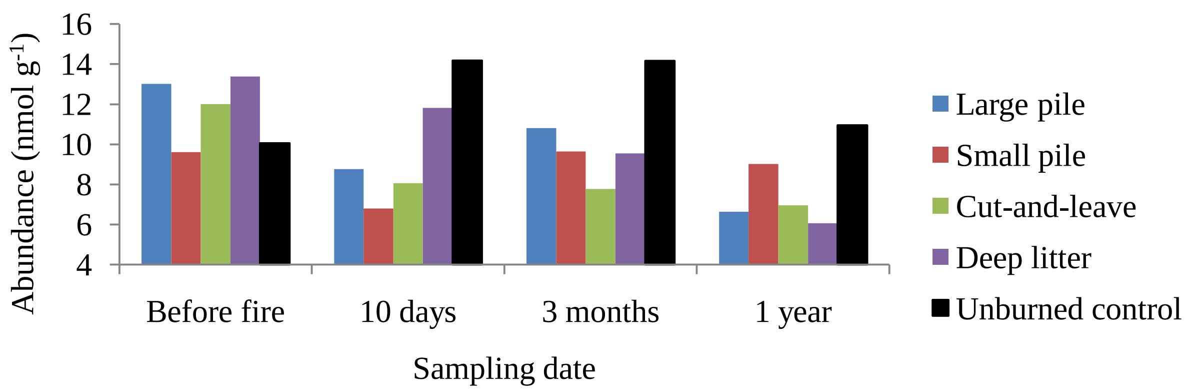

Figure 3.43. Mineral soil total fungi abundance in the five fuel treatments prior to and during the first year following prescribed fire.

3.4.7 Bacteria-to-fungi ratio

The forest floor bacteria-to-fungi (B:F) ratio was not influenced by treatment before fire or after 10 days (Fig. 3.44). The B:F ratio was significantly broader in the large-pile than in the cut-and-leave, deep-litter and unburned control plots 3 months after fire. After one year, forest floor B:F ratios in the large-pile and small-pile treatments were significantly broader than in the unburned control. The B:F ratio became broader over time in the large-pile and deep-litter treatments.

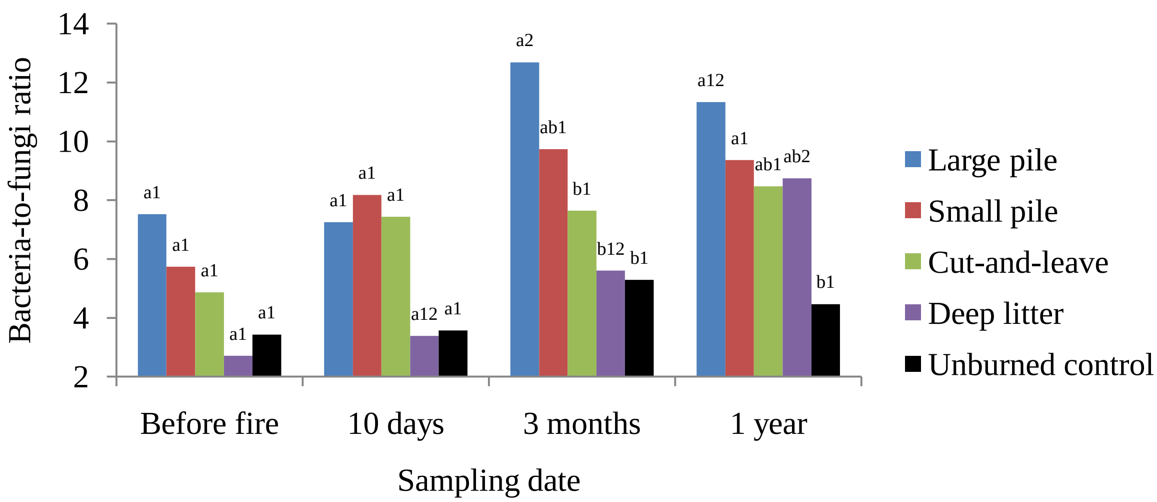

Figure 3.44. Forest floor bacteria-to-fungi ratio in the five fuel treatments prior to and during the first year following prescribed fire. Different letters above bars indicate significant differences ($p<0.05$) between treatments (within sampling date). Different numbers above bars indicate significant differences ($p<0.05$) between sampling dates (within a treatment).

In the mineral soil, there was no significant effect of treatment or sampling date on the B:F ratio (Fig. 3.45).

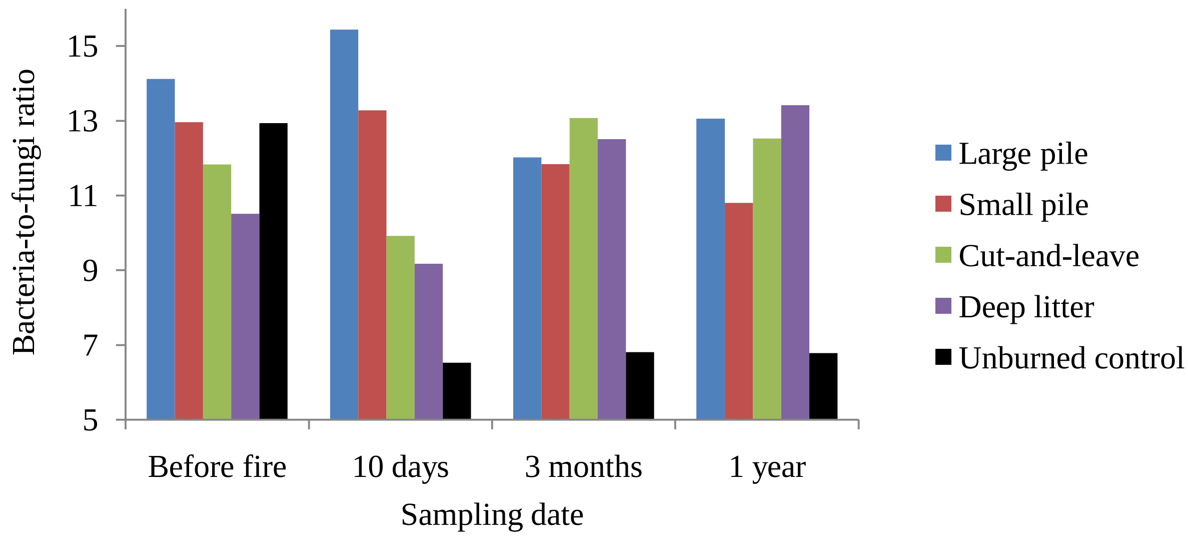

Figure 3.45. Mineral soil bacteria-to-fungi ratio in the five fuel treatments prior to and during the first year following prescribed fire.

3.5 Multi-variate analysis of response variables

3.5.1 Forest floor results

MRPP analysis of all measured forest floor variables indicated that the soils in the four burned treatment areas were similar to those in the control plots prior to the prescribed fire. There was less agreement within groups before fire than expected by chance between the unburned control plots and the four treatments that were to be burned, with all within-group agreement (A) being below zero (Table 3.1). One year after fire, soils in each of the burned treatments were significantly different than the unburned control. Chance-corrected within-group agreement ranged from 0.28 to 0.52, with all p-values below 0.02. Comparing unburned control plots before fire and after one year, MRPP results showed an agreement (A) of 0.52 (p=0.02), indicating significant differences between time periods.

Table 3.1. Multi-response permutation procedure results comparing the measured forest floor variables in burned treatments with those in the unburned controls.

	Treatments compared	A value (*= p< 0.05)
Before fire	Unburned control vs. Large pile	-0.06
	Unburned control vs. Small pile	-0.03
	Unburned control vs. Cut-and-leave	-0.27
	Unburned control vs. Deep Litter	-0.19
1 year after fire	Unburned control vs. Large pile	0.50*
	Unburned control vs. Small pile	0.52*
	Unburned control vs. Cut-and-leave	0.29*
	Unburned control vs. Deep Litter	0.35*

Principal component analysis (PCA) indicated that soil C:N ratio was strongly positively correlated with microbial abundance before fire, with nitrogen also having a high negative correlation (Figure 3.46). During the three post-fire sampling periods, forest floor pH had the highest correlation with the microbial community abundance with an average *r* of 0.75 (Table 3.2). A strong negative correlation also existed between microbial communities and forest floor depth and C concentration 10 days after fire. After 1 year, moisture content was strongly correlated with microbial abundance. The variance extracted within the first axis for the before-fire sampling, 10-day, 3-month and 1-year sampling was 75%, 88%, 79% and 82%, respectively, so most of the variation will be explained in Axis 1.

Table 3.2. Principal component analysis results for correlations between microbial community abundance and abiotic variables in the two soil layers prior to and after fire.

Layer	Variable	Before fire	10 days	3 months	1 year
Forest floor	floor depth	0.174	-0.752	-0.28	-0.219
	moisture	-0.049	-0.537	-0.318	0.607
	pH	0.206	0.852	0.732	0.72
	%C	-0.039	-0.759	-0.077	-0.49
	%N	0.457	-0.435	0.155	-0.155
	C:N	-0.574	-0.525	-0.374	-0.438
Mineral soil	floor depth	-0.508	-0.095	-0.217	-0.374
	moisture	-0.282	-0.166	-0.74	-0.409
	pH	0.215	0.04	0.13	0.455
	%C	0.785	0.54	0.68	0.682
	%N	0.764	0.574	0.656	0.49
	C:N	0.054	-0.13	0.008	-0.572

One year after the fire, the PCA ordination grouped the unburned control, with significant distance along the first axis, from the burned treatments, indicating that the measured variables had not yet returned to pre-fire levels (Figure 3.47).

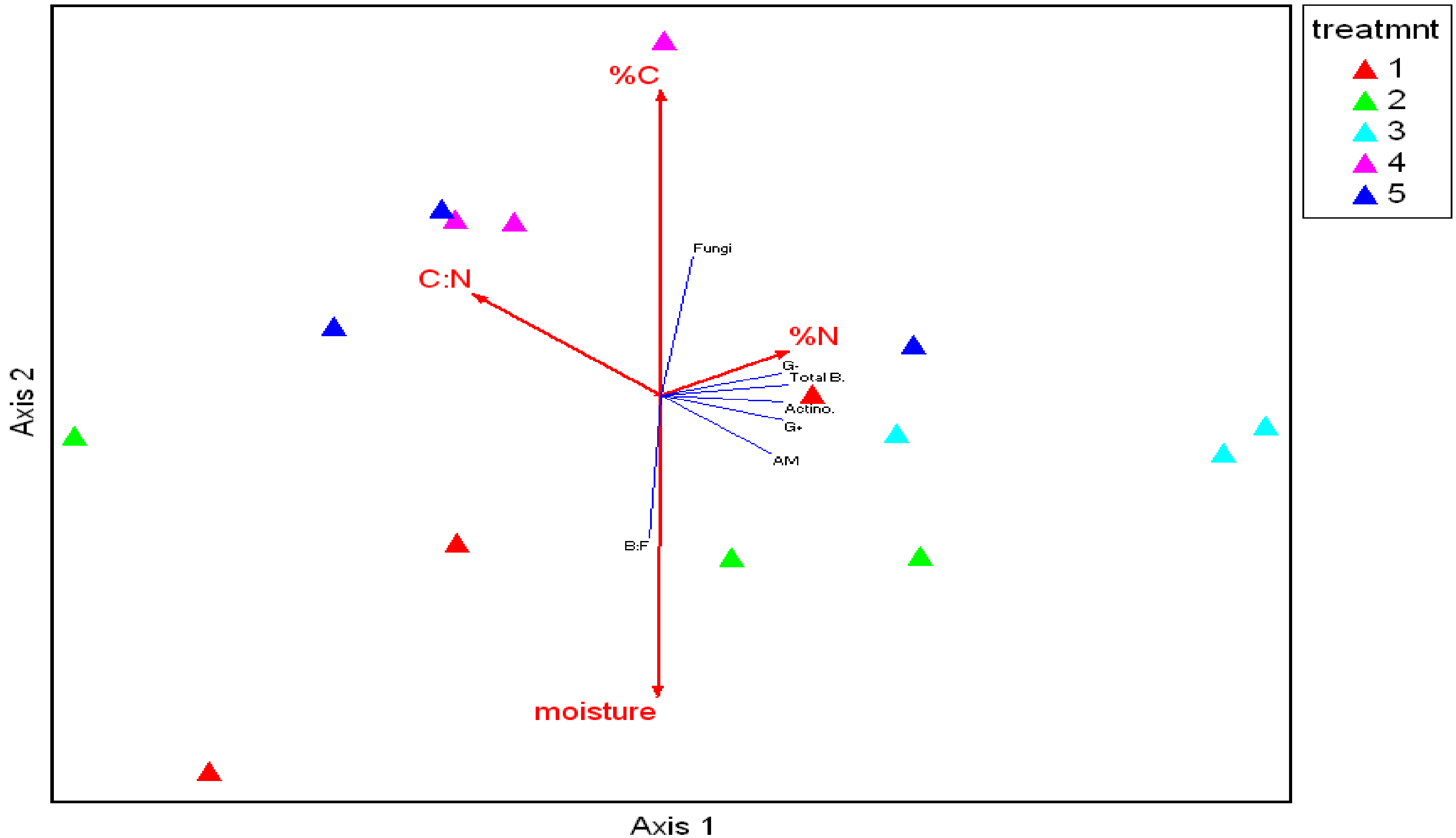

Figure 3.46. Forest floor PCA ordination before fire. Treatment 1represents the large-pile treatment, while 2,3,4 and 5 represents the small-pile, cut-and-leave, deep-litter and unburned control treatments, respectively. Axis 1 contained 65% of variation, while axis 2 contained 30%. '%N' indicates nitrogen concentration, '%C' indicates carbon concentration, 'C:N' indicates carbon-to-nitrogen ratio. 'Fungi' indicates total fungi, 'G-' indicates gram-negative bacteria, 'Total B.' Indicates total bacteria, 'Actino.' indicates actinomycetes, 'G+' indicates gram-positive bacteria, 'AM' indicates arbuscular mycorrhizae, and 'B:F' indicates bacteria-to-fungi ratio.

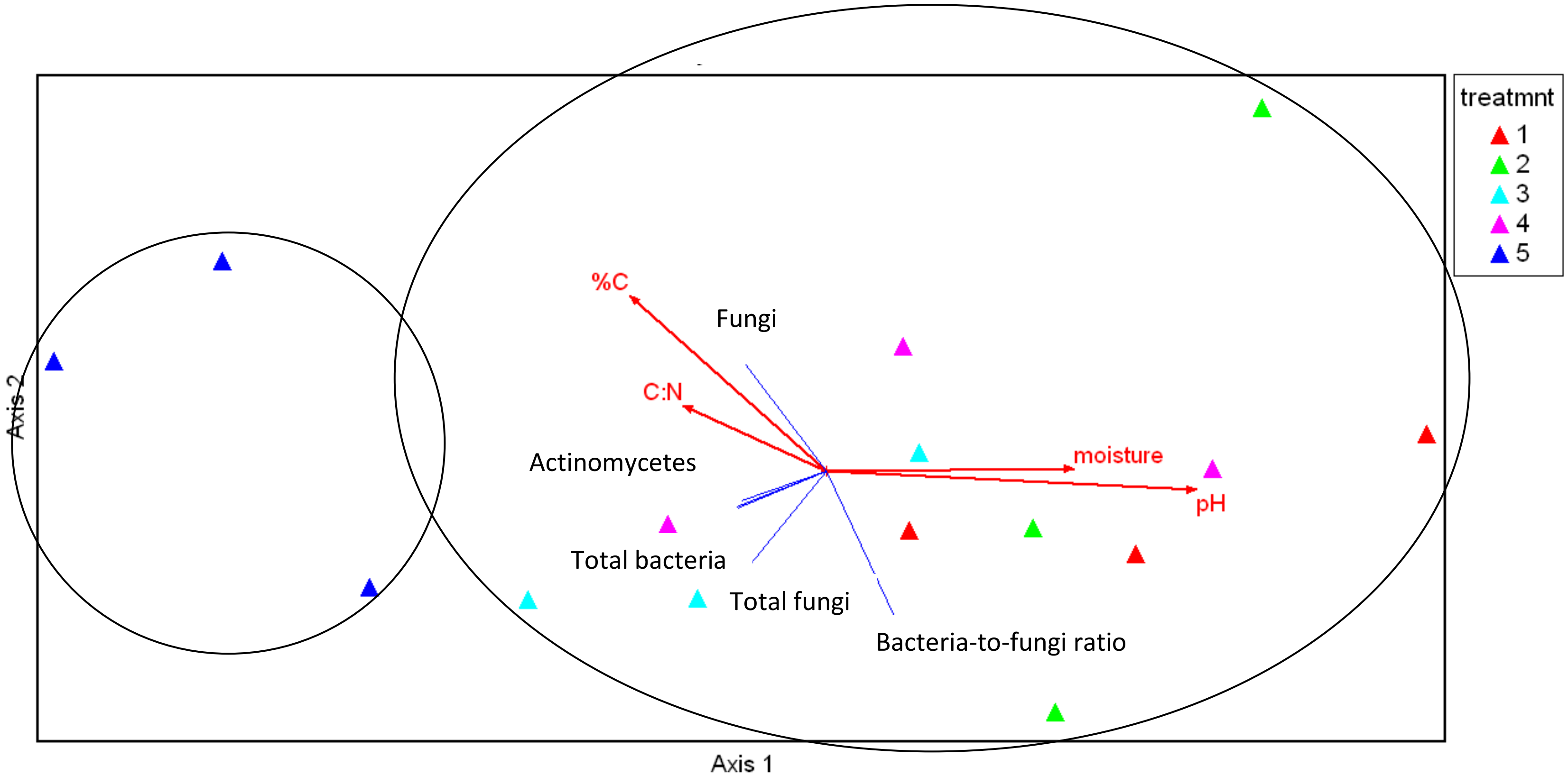

Figure 3.47. Forest floor PCA ordination one year after fire. Axis 1 contained 77% of the variation, while axis 2 contained 13% of the variation. Treatment 1 represents the large-pile treatment, while 2,3,4,5 are small-pile, cut-and-leave and deep-litter and unburned control treatments, respectively. '%C' represents % carbon, '%N' represents % nitrogen. The black circles represent the MRPP results of significant differences between the unburned controls and the burned treatments. The circle on the left encompasses the unburned control plots, while the circle on the right encompasses the burned plots

3.5.2 Mineral soil results

MRPP results show that the unburned control values were similar to the four treatments that were to be burned immediately before the prescribed fire, with the exception of the large piles (Table 3.3). After one year, the only significant difference evident was between the unburned control and the small pile treatment. Comparing the unburned control at different time periods, before-fire variance and that of 3 months after and 1 year after were significantly different (A=0.23, p=0.04), indicating that the burned plots had similar changes as the unburned controls.

Table 3.3. MRPP results comparing treatments prior to and after the prescribed fire in the mineral soil.

	Treatments compared	A value (*=p value<0.05)
Before fire	Large pile vs. unburned control	0.27*
	Small pile vs. unburned control	-0.14
	Cut-and-leave vs. unburned control	0.09
	Deep litter vs. unburned control	-0.07
1 year after	Large pile vs. unburned control	-0.06
	Small pile vs. unburned control	0.18*
	Cut-and-leave vs. unburned control	-0.01
	Deep litter vs. unburned control	-0.11

PCA results indicated that mineral soil C and N concentrations had the strongest positive correlation with microbial communities throughout the study (Table 3.2). Moisture had a strong negative correlation during the 3 months post-fire sampling, likewise with the C:N ratio at one-year after fire. The amount of variation explained in the first axis was 76%, 74%, 73% and 77% for the before-fire, 10-day, 3-months and 1-year sampling dates, respectively.

3.6 Relationships among response variables

3.6.1 Forest floor results

Forest floor consumption was negatively correlated with pre-fire moisture content of the forest floor (Figure 3.48). Higher moisture contents of the forest floor resulted in less forest floor consumption (r^2=0.69). The deep-litter treatment was significantly drier than the other treatments and experienced the highest consumption.

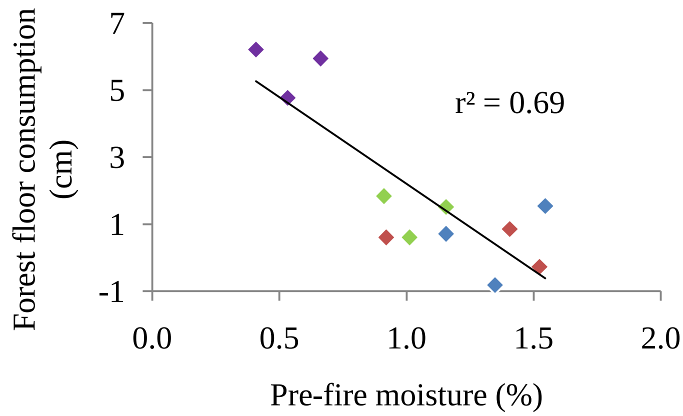

Figure 3.48. Relationship between pre-fire moisture content and forest floor consumption during the prescribed fire. Blue diamonds represent large-pile, red=small-pile, green=cut-and-leave, purple=deep-litter treatments.

Forest floor pH had the strongest correlations with microbial community abundance among the abiotic variables measured. Fire-induced increases in pH immediately after the fire were associated with declines in all microbial groups (Gram-positive bacteria, Gram-negative bacteria, actinomycetes, total bacteria, arbuscular mycorrhizae and total fungi), with r^2 values ranging between 0.53 and 0.78 (Figure 3.49 and 3.50). After 3 months and one year, correlations between pH and actinomycete abundance were still high (r^2= 0.88 and 0.72, respectively). Total fungi and Gram-positive bacteria was also highly correlated with pH after one year (r^2=0.61 and 0.48, respectively).

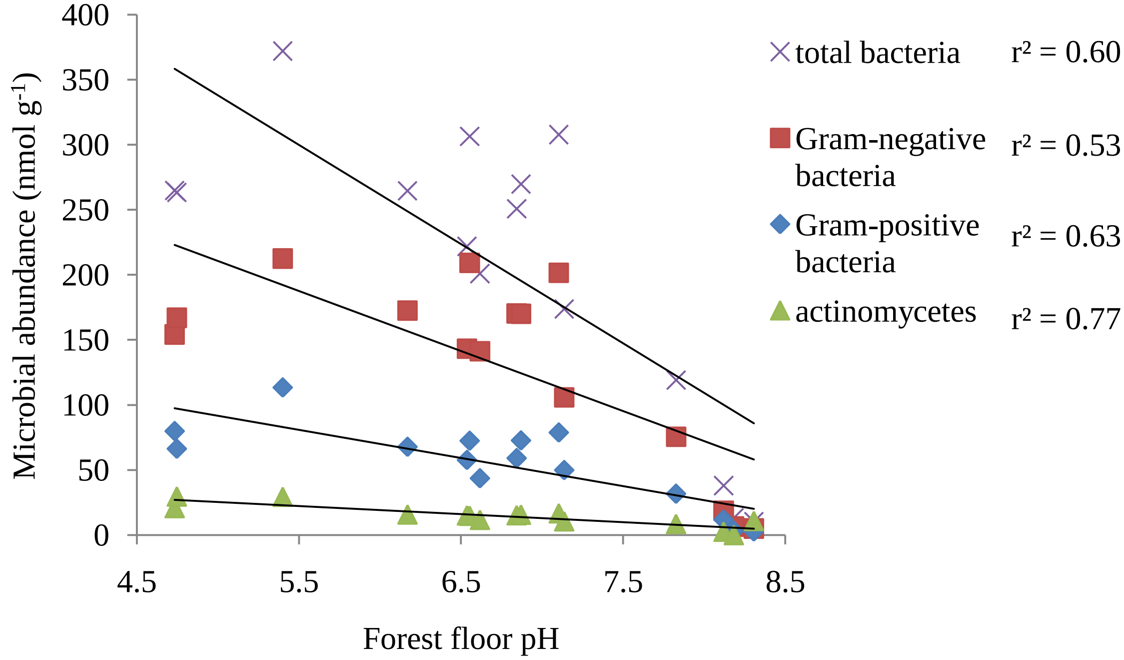

Figure 3.49. Relationship between bacterial community abundance and pH in the forest floor 10 days after fire.

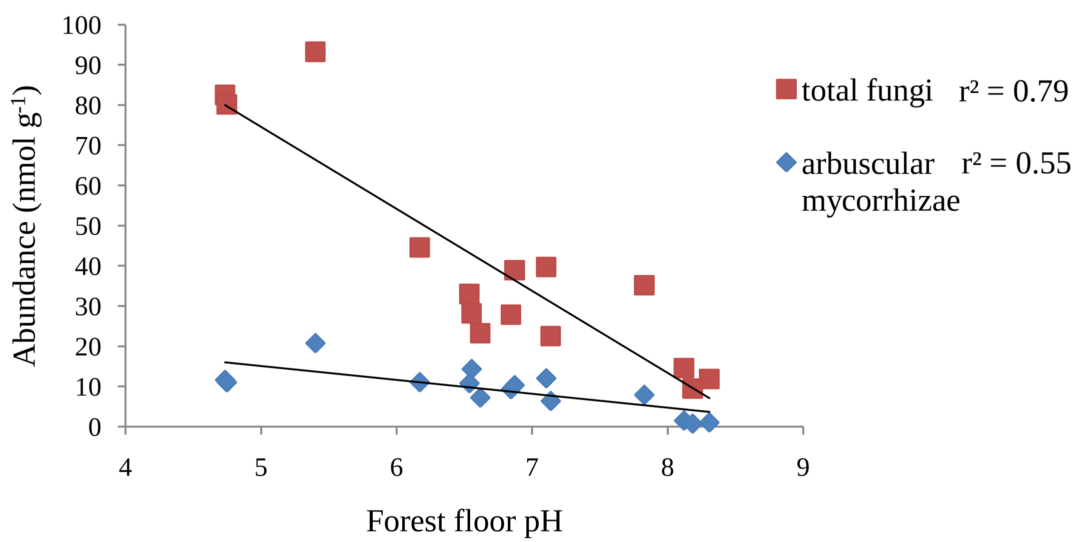

Figure 3.50. Relationship between pH and fungal community abundance in the forest floor 10 days after fire.

Microbial abundances were also negatively correlated with forest floor consumption, with lower abundances as more forest floor depth was consumed (Figure 3.51 and 3.52).

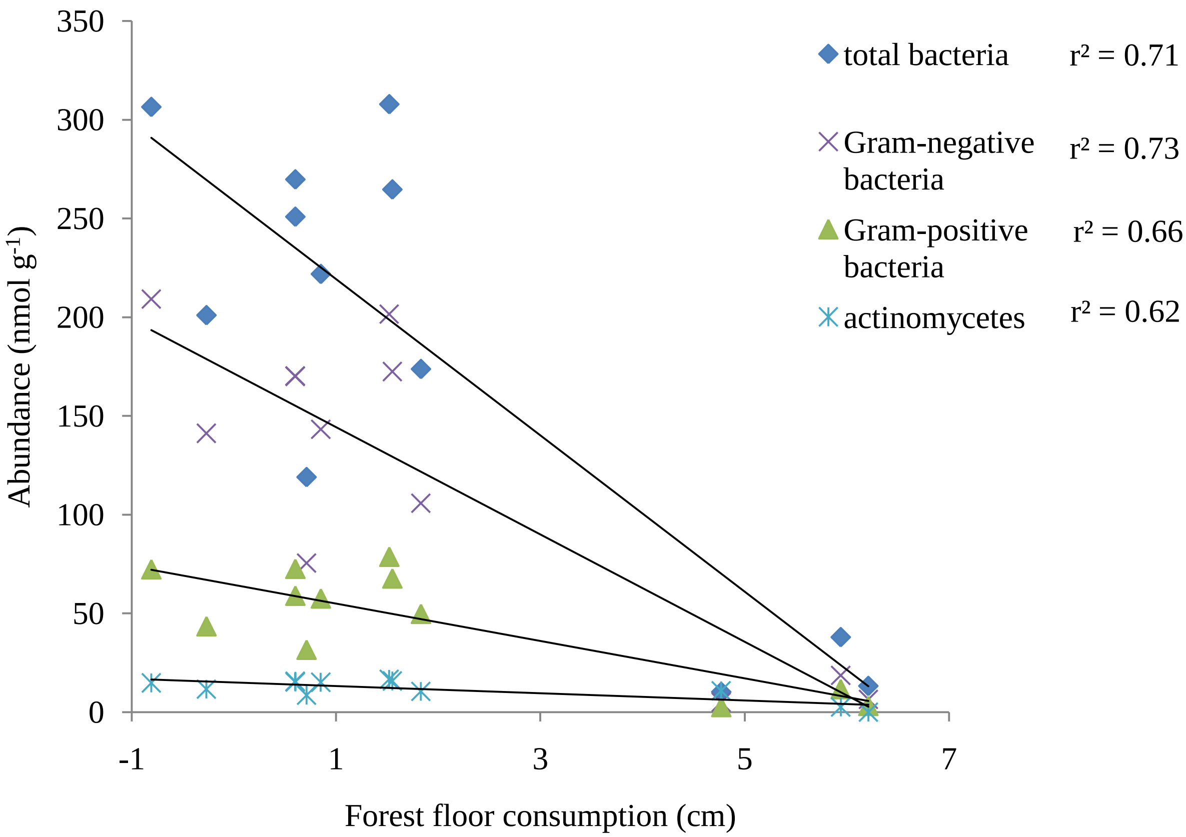

Figure 3.51. Relationship in the forest floor between bacterial community abundance and forest floor consumption 10 days after fire.

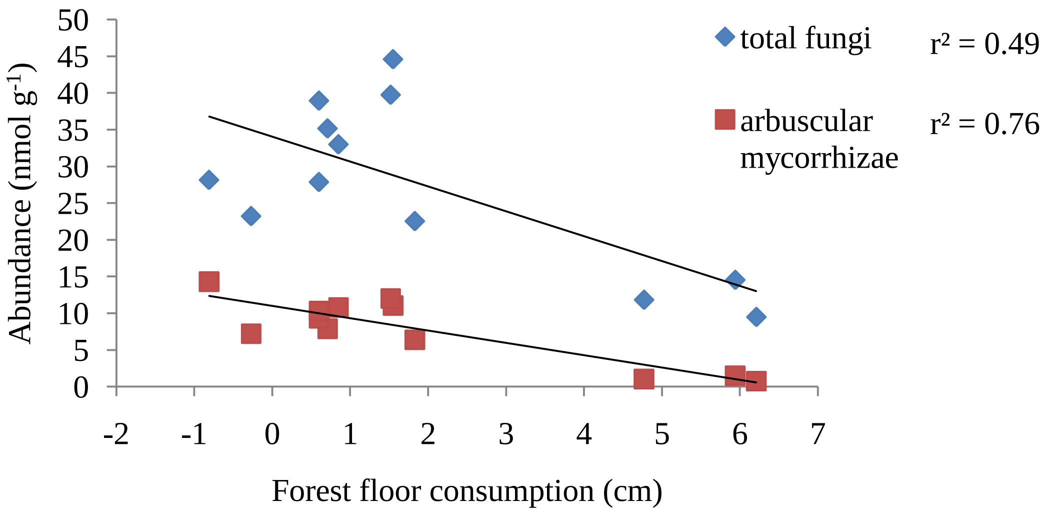

Figure 3.52. Relationship in the forest floor between fungal community abundance and forest floor consumption 10 days after fire.

Similar r^2 values were present when comparing microbial community abundance and both pH and the reduction in forest floor. In turn, there was a positive correlation between the loss in forest floor and an increase in pH 10 days after fire (r^2=0.65) (Figure 3.53).

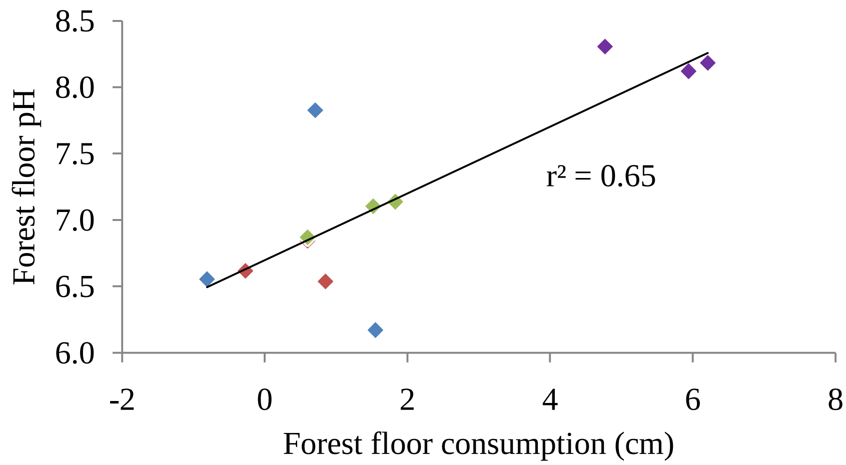

Figure 3.53. Relationship between forest floor pH and the forest floor consumption 10 days after fire. Blue diamonds represent large-pile, red=small-pile, green=cut-and-leave, purple=deep-litter treatments.

3.6.2 Mineral soil results

Microbial abundances in the mineral soil were most strongly correlated with soil C concentrations. This correlation was positive and was strongest during the pre-fire sampling (Figure 3.54 and 3.55). Gram-negative bacteria, total bacteria, and actinomycete abundance had the highest correlations, with r^2 values of 0.66, 0.59 and 0.54, respectively. Arbuscular mycorrhizae abundance was also correlated with soil C concentrations before fire (r^2=0.49)

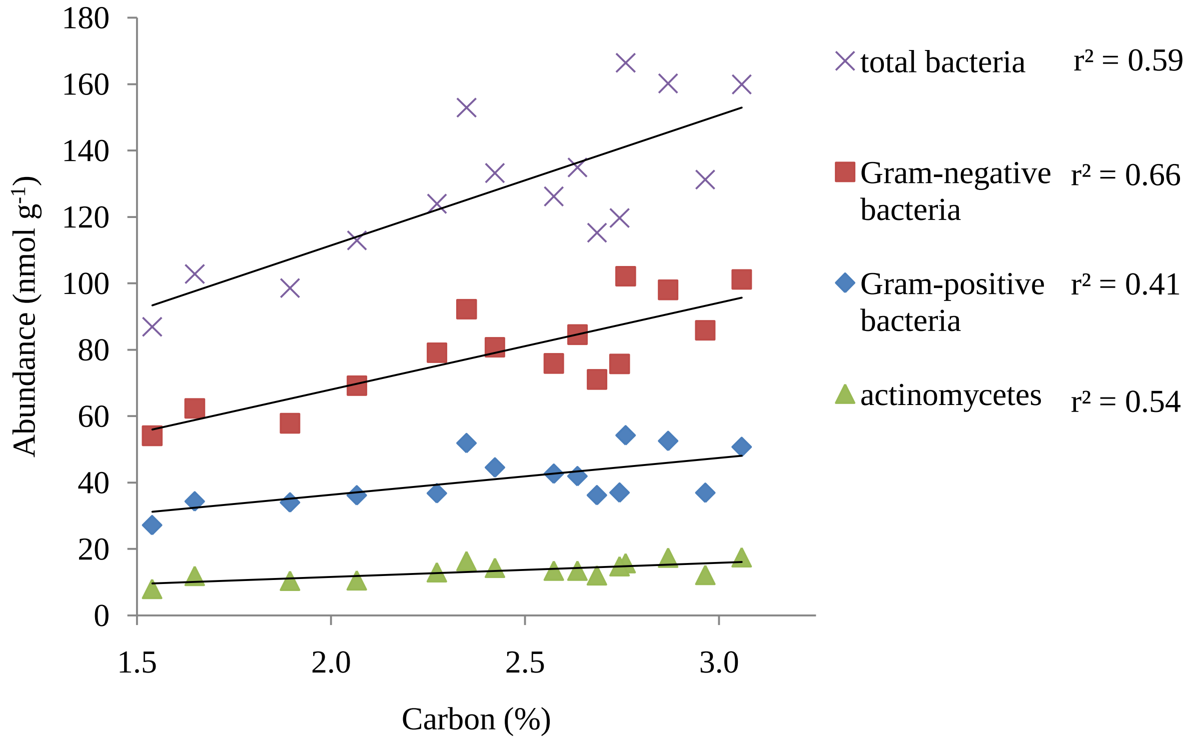

Figure 3.54. Relationship between bacterial community abundance and carbon concentrations in the mineral soil before fire.

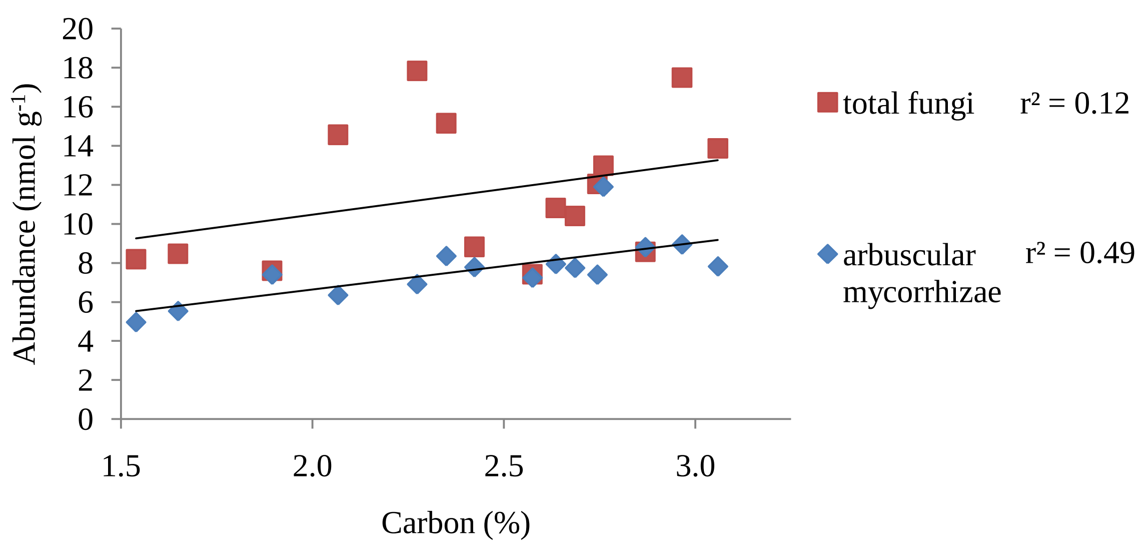

Figure 3.55. Relationship between fungal community abundance and carbon concentrations in the mineral soil before fire.

4.0 Discussion

The findings of this study indicate that all the prescribed fire treatments altered chemical and biological properties of the forest floor and soil for at least one year following the fire, based on the MRPP analysis of all measured variables combined. The effects of fire differed greatly among the measured response variables and among the fuel management treatments, and were not entirely consistent with my hypotheses.

My first hypothesis was that changes in soil chemical and microbiological properties will be greatest in treatments with the largest fuel loadings. This would have been supported if changes were greatest in the large-pile treatment and least in the cut-and-leave treatment. However, there was no evidence of large differences among response variables between the large-pile, small-pile and cut-and-leave treatment areas. Significant differences were observed 10 days after the fire but similar differences were observed among treatment plots prior to the prescribed fire, and so cannot be ascribed to the fuel treatments. Instead, the greatest treatment effects occurred in the deep-litter treatment. This may be attributable to the lower moisture levels in these plots. Forest floor moisture content was significantly lower in the deep litter and unburned control before fire and this difference occurred over two of the next three sampling periods. Mineral soil moisture was also significantly lower in these treatments prior to fire and 10 days after. This indicates that fuel moisture rather than fuel loading was the factor most influencing fire effects on soil properties in this experiment. Therefore manipulations that influence fuel moisture levels may be as critical as fuel loadings in determining fire impacts on soil.

My second hypothesis was that significant reductions in soil nitrogen and microbial communities would occur in treatments where the highest fire temperatures were reached. The longest durations of high temperatures (>300°C) occurred in the large piles, but there were no significant declines in nitrogen concentrations in the forest floor or mineral soil in this treatment. Microbial communities responded similarly in all fire treatments despite the large range of maximum temperatures and durations among plots and treatments, and there was no evidence of different microbial response in the large-pile treatment compared to the small-pile treatment, in which temperatures did not exceed 200°C.

My third hypothesis was that pH and inorganic N concentrations will increase and microbial biomass will decrease in burned plots, especially in those with the highest fire temperatures. There was a significant increase in forest floor pH throughout all burned treatments, consistent with previous studies (Bååth *et al*. 1995, Jimémez-Esquilín *et al*. 2007, Pietikäinen & Fritze 1993), but no change in mineral soil pH. This may occur in the future, as ash and base cations from the surface are leached into the soil. Ammonium availability was not significantly higher in burned plots but nitrate was significantly higher in the deep-litter treatment compared to the other treatments. Total bacteria decreased significantly in all treatments, with the greatest decreases in the deep-litter and cut-and-leave treatments. In the small-pile treatment, where the range of fire temperatures was between 60 and 200°C, total bacteria declined as much as in the large-pile treatment, which had much higher fire temperatures. Arbuscular mycorrhizal abundance was significantly higher in the cut-and-leave treatment than the large-pile and small-pile treatments prior to fire. Immediately after the fire, significant decreases in abundance occurred, with no significant differences in abundance levels among treatments. Likewise, total fungal abundance was significantly different among treatments before the fire. Total fungal abundance decreased significantly in all burned treatments after the fire, with no treatment effects present. These observations indicate that bacterial and fungal communities may respond more to changes in environmental conditions after fire than to temperatures during fire.

Consistent with the meta-analysis findings of Johnson & Curtis (2001), I found no significant effect of prescribed fire on total C and N concentrations in soil. Mineral soil C concentration was significantly higher under the large piles before fire, and the difference remained throughout the study. Similarly, forest floor N concentration in the cut-and-leave treatment remained significantly higher than the other treatments throughout the study. There were losses of C and N associated with combustion of the forest floor; significant decreases of total C in the large-pile and deep-litter treatments amounted to losses of 24,327 and 19,075 kg ha^{-2}, respectively. Nitrogen losses were also greatest in these two treatments, with 827 and 540 kg ha^{-2} lost, respectively.

I detected higher $H_2PO_4^-$ availability in both the forest floor and mineral soil in most burned plots compared to the unburned control over all three sampling periods. Higher available phosphorus in burned treatments relative to unburned treatments was also found by Giovaninni & Lucchesi (1997). Volatilized phosphorus has been reported to translocate from the forest floor into the mineral soil after fire (Overby & Perry 1996), but I did not detect an increase in the mineral soil $H_2PO_4^-$ availability or decrease in forest floor $H_2PO_4^-$ availability over time. Sulphur availability was elevated in the forest floor and the mineral soil beneath the deep litter treatment. It was also significantly higher immediately after fire compared to the next two sampling periods. Although sulphur is lost through volatilization during fire, availability of sulphur may be elevated immediately after fire (Wohlgemuth *et al*. 2006, Feller 1988, Tiedemann & Anderson 1980).

My fourth hypothesis was that microbial community structure and abundance would recover to pre-fire levels one year after fire. Microbial communities in some treatments increased after 3 months, but none had returned to pre-fire levels after one year. This may be related to the substantial increases in pH after fire, which remained after one year. pH was the factor most closely related to microbial abundance in the forest floor, so it could be that the microbial community will not return to its pre-fire state until the pH also returns to pre-fire level. Campbell *et al*. (2008) found that sites that were burned every four years did not have significantly different PLFA totals than unburned control sites, indicating that microbial communities may recover to pre-fire levels within four years of prescribed fire.

The strong relationship between the fire-induced declines in abundance of all microbial groups and the pH of the forest floor indicates that pH was the major determinant of the abundance and structure of forest floor communities in post-fire forest floors. This is consistent with many studies in which pH has been found to be a major factor influence soil microbial communities (Bååth *et al*. 1995, Frostegård *et al*. 1993, Högberg et al. 2007, Lauber *et al*. 2009). Negative correlation between pH and bacterial abundance was unexpected as bacteria abundance and the B:F ratio tend to increase with increasing pH (Alexander 1977). In this experiment, the increase in pH was greatest in the forest floor of the deep-litter plot which was nearly completely consumed in the fire, which drove the strong correlations between forest floor reduction and post-fire pH and abundances of bacteria and fungi. This may indicate that combustion of the forest floor actually drove the changes in microbial abundance and community composition, but was not the most highly correlated due to the difficulty in precise measurement this parameter. This suggests that great declines in forest floor microbial communities can be avoided by minimizing forest floor consumption during fire.

Prior to the fire, microbial community abundance in the forest floor was most closely (positively) related to forest floor N concentration, while that in the mineral soil was positively associated with concentrations of C and N (hence presumably with organic matter content). Högberg *et al.* (2006) also reported a strong correlation between microbial PLFA and C:N ratio of the humus layer in Swedish forests, associated with higher fungal:bacterial ratios at high C:N. A strong positive relationship between soil organic carbon and microbial biomass C and N has also been reported in larch and pine forests in China (Yang *et al.* 2010); declines in C content with depth are correlated with changes in soil microbial profiles between soil layers in forests of coastal British Columbia (Leckie *et al*. 2004, Grayston and Prescott 2005).

This study also tested the hypothesis that PLFAs degrade rapidly upon cell death, as reported by White *et al*. (1979). It was anticipated that bacterial and fungal mortality would occur in burned plots, but the presence of their yet-degraded fatty acids would possibly not represent the amount of active bacteria and fungi. Significantly lower PLFA levels were detected in all burned treatments 10 days after fire. This finding indicates that not only was there bacterial and fungal mortality associated with the fire treatment, but that their phospholipid fatty acids degraded enough after 10 days to be undetected with the PLFA analysis. This finding allows for more precise measurements of microbial abundance after forest management treatments.

5.0 Conclusions

- Low moisture content and consumption of the forest floor in the deep-litter treatment resulted in the largest negative impacts, while few significant differences were evident between the large-pile, small-pile and cut-and-leave treatments on soil chemical and microbiological properties after fire.

- Losses of N and reductions of microbial communities were not as great as anticipated when fire temperature duration increased above previously reported thresholds for many hours.

- Higher nitrate availability and significant increases in pH were found in the forest floor of burned plots and in the mineral soil in the deep-litter treatment.

- Microbial abundance had not recovered to pre-fire levels after one year, which may be attributed to the significant increases in pH which persisted for at least one year.

- The PLFA analysis was able to distinguish changes to microbial community following prescribed fire and can be used to monitor biological effects of forest management treatments 10 days after treatment.

6.0 Management implications

The greatest negative effects of the prescribed fire were detected in the deep-litter treatment, in which fire temperatures were above 300°C for over 3 hours and the forest floor was almost completely combusted. This was probably the consequence of the forest floor in this treatment having significantly lower moisture content than that in the other burned treatments. The low forest-floor moisture content in this treatment can be attributed to the architecture of the mature-tree canopy, which restricted precipitation penetration and snow accumulation. Pruning of mature-tree branches to allow more precipitation to collect before fires would reduce the likelihood of sustained high fire temperatures and complete forest-floor consumption around mature trees. In addition, raking the forest floor material away from the bole or building a fireline around mature trees would reduce cambium heating and the potential for flaming combustion beneath the canopy, which contributed of the mortality of leave-trees in this treatment.

Fire effects were smaller in the large-pile, small-pile and cut-and-leave treatments. Forest floor depth was not significantly reduced in these three treatments, indicating that high fire temperatures were not sustained long enough to cause complete combustion of the forest floor. Forest-floor moisture levels in all of these treatments were higher than in the deep-litter treatment, and soils were still frozen before the fire under some of the piles. Therefore piles may reduce fire impact to soils during spring-time prescribed fires, and should be constructed such that they allow moisture to penetrate to the forest floor while blocking solar radiation and evaporation.

During wildfire suppression, fire personnel move ignited fuels away from the fire perimeter and build piles to consume these fuels. High fire temperatures during consumption drive off any remaining moisture, resulting in forest floor consumption and an increase in soil temperatures. When pile building during fire suppression is needed, the forest floor should be manually moved to the side so it can be used as ground cover after pile burning is completed (Jiménez-Esquilín *et al*. 2007). To reduce soil heating, piles should be built as vertical as possible so radiant heat moves upwards. Other potential ways to reduce negative impacts would include choosing sites that have little or no forest floor and to build fewer, larger piles instead of many.

Literature cited

Abril, A., P. Barttfeld, E.H. Bucher. 2005. The effect of fire and overgrazing disturbances on soil carbon balance in the Dry Chaco forest. *Forest Ecology and Management*, 206, 399-405.

Alexander, M. 1977. Introduction to soil microbiology, 2nd edition. Wiley, New York, USA. 467 pp.

Alexander, M.E., R.F. Yancik. 1977. The effect of pre-commercial thinning on fire potential in a lodgepole pine stand. *Fire Management Notes*, 383, 7-9.

Andreu, V., J.L. Rubio, J. Forteza, R. Cerni. 1996. Post-fire effects on soil properties and nutrient losses. *International Journal of Wildland Fire*, 6(2), 53-58.

Arocena, J.M., C. Opio. 2003. Prescribed fire-induced changes in properties of sub-boreal forest soils. *Geoderma*, 113, 1-6.

Bååth, E., Å. Frostegård, T. Pennanen, H. Fritze. 1995. Microbial community structure and pH response in relation to soil organic matter quality in wood-ash fertilized, clear-cut or burned coniferous forest soils. *Soil Biology and Biochemistry*, 21(2), 229-240.

Banning, N.C., D.V. Murphy. 2008. Effect of heat-induced disturbance on microbial biomass and activity in forest soil and the relationship between disturbance effects and microbial community structure. *Applied Soil Ecology*, 40, 109-119.

Bengtson, P., N. Basiliko, C.E. Prescott, S.J. Grayston. 2007. Spatial dependency of soil nutrient availability and microbial properties in a mixed forest of *Tsuga heterophylla* and *Pseudotsuga menziesii*, in coastal British Columbia, Canada. *Soil Biology and Biochemistry*, 2429-2435.

Birdsey, R.A. 1992. Carbon storage and accumulation in United States forest ecosystems. USDA Forest Service. GTR-WO-59.

Boerner, R.E.J. 2000. Effects of fire on the ecology of the forest floor and soil of central hardwood forests. Conference Proceedings: Workshop on Fire, People, and the Central Hardwoods Landscape. USDA Forest Service General Technical Report. GTR-NE-274.

Boerner, R.E.J., J.A. Brinkman, A. Smith. 2005. Seasonal variations in enzyme activity and organic carbon in soil of a burned and unburned hardwood forest. *Soil Biology and Biochemistry*, 37, 1419-1425.

Boerner, R.E.J., J. Huang, S.C. Hart. 2008. Fire, thinning, and the carbon economy: Effects of fire and fire surrogate treatments on estimated carbon storage and sequestration rate. *Forest Ecology and Management*, 255, 3081-3097.

Boyle, S.I., S.C. Hart, J.P. Kaye, M.P. Waldrop. 2005. Restoration and canopy type influence soil microflora in a ponderosa pine forest. *Soil Science Society of America Journal*, 69, 1627-1638.

Busse, M.D., K.R. Hubbert, G.O. Fiddler, C.J. Shestak, R.F. Powers. 2005. Lethal soil temperatures during burning of masticated forest residues. *International Journal of Wildland Fire*, 14, 267-276.

Campbell, C.D., C.M. Cameron, B.A. Bastias, C. Chen, J.W.G. Cairney. 2008. Long term repeated burning in a wet sclerophyll forest reduces fungal and bacterial biomass and responses to carbon substrates. *Soil Biology and Biochemistry*, 40, 2246-2252.

Campbell, G.S., J.M. Norman. 1998. Thermal properties of soil: Thermal conductivity. In: An introduction to environmental biophysics. Springer Sciences, NY, USA. 113-128 pp.

Certini, G. 2005. Effects of fire on properties of forest soils: A review. *Oecologia*, 143, 1-10.

Choromanska, U., T.H. DeLuca. 2002. Microbial activity and nitrogen mineralization in forest mineral soils following heating: Evaluation of post-fire effects. *Soil Biology and Biochemistry*, 34, 263-271.

Covington, W.W., S.S. Sackett. 1984. The effect of a prescribed burn in southwestern ponderosa pine on organic matter and nutrients in woody debris and forest floor. *Forest Science*, 30(1), 183-192.

DeBano, L.F. 1974. Chaparral soils. P. 16-19 in M. Rosenthal (ed.), Proceedings of a symposium on living with the chaparral, March 30-31, 1973, Riverside CA. Sierra Club, San Fransico, USA.

Dewi, M. 2009. Soil microbial community responses to green-tree retention harvesting in coastal British Columbia. Master's thesis. University of British Columbia.

Díaz-Raviña, M., E. Bååth, A. Martín, T. Carballas. 2006. Microbial community structure in forest soils treated with fire retardant. *Biololgy and Fertility of Soils*, 42, 465-471.

Dunn, P.H., L.F. DeBano, G.E. Eberlein. 1979. Effects of burning on chaparral soils:II. Soil microbes and nitrogen mineralization. *Soil Science Society of America Journal*, 45, 504-514.

Eivazi, F., M.R. Bayan. 1996. Effects of long-term prescribed burning on the activity of select soil enzymes in an oak-hickory forest. *Canadian Journal of Forest Research*, 26, 1799-1804.

Feller, M.C. 1988. Relationships between fuel properties and slashburning-induced nutrient losses. *Forest Science*, 34(4), 998-1015.

Franklin, J.E., D.R. Berg, D.A. Thornburgh, J.C. Tappeiner. 1997. Alternative silvicultural approaches to timber harvesting: variable retention harvesting systems. P. 111-139 in K.A. Kohm and J.E. Franklin (eds.) Creating a forestry for 21st Century. Island Press, Washington, D.C., USA.

Frostegård, A., E. Bååth, A. Tunlid. 1993. Shifts in the structure of soil microbial communities in limed forests as revealed by phospholipid fatty acid analysis. *Soil Biology and Biochemistry*, 25(6), 723-730.

Fulé, P.Z., A.E.M. Waltz, W.W. Covington, T.A. Heinlein. 2001. Measuring forest restoration effectiveness in reducing hazardous fuels. *Journal of Forestry*, 99(11), 24-29.

Giai, C., R.E.J. Boerner. 2007. Effects of ecological restoration on microbial activity, microbial functional diversity, and soil organic matter in mixed-oak forests of southern Ohio, USA. *Applied Soil Ecology*, 35, 281-290.

Giovaninni, G., S. Lucchesi. 1997. Modifications induced in soil physic-chemical parameters by experimental fires at different intensities. *Soil Science*, 162, 479-486.

Graham, R.T., S. McCaffrey, T.B. Jain. 2004. Science basis for changing forest structure to modify wildfire behavior and severity. USDA Forest Service, Rocky Mountain Research Station General Technical Report, RMRS-GTR-120, Fort Collins, CO, USA.

Grayston, S.J., C.E. Prescott. 2005. Microbial communities in forest floors under four tree species in coastal British Columbia. *Soil Biology and Biochemistry*, 37, 1157-1167.

Gundale, M.J., T.H. DeLuca, C.E. Fiedler, P.W. Ramsey, M.G. Harrington, J.E. Gannon. 2005. Restoration treatments in a Montana ponderosa pine forest: Effects on soil physical, chemical and biological properties. *Forest Ecology and Management*, 213, 25-38.

Hare, R.C. 1961. Heat effects on living plants. USDA Forest Service Occasional Paper. S-183. 32 p.

Högberg, M.N., H. Fan, M. Quist, D. Brinkley, C.O. Tamm. 2006. Tree growth and soil acidification in response to 30 years of experimental nitrogen loading on boreal forest. *Global Change Biology*, 12, 489-499.

Högberg, M.N., P. Högberg, D.D. Myrold. 2007. Is microbial community composition in boreal forest soils determined by pH, C-to-N ratio, the trees, or all three? *Oecologia*, 150, 590-601.

Jiménez Esquilín, A.E., M.E. Stromberger, W.J. Massman, J.M. Frank, W.D. Shepperd. 2007. Microbial community structure and activity in a Colorado Rocky Mountain forest soil scarred by slash pile burning. *Soil Biology & Biochemistry*, 39, 1111-1120.

Johnson, D.W., P.S. Curtis. 2001. Effects of forest management on soil C and N storage: Meta analysis. *Forest Ecology and Management*, 140, 227-238.

Kaye, J.P., S.C. Hart. 1998. Ecological restoration alters nitrogen transformations in a ponderosa pine-bunchgrass ecosystem. *Ecological Applications*, 8(4), 1052-1060.

Keane, R.E., K.C. Ryan, T.T. Veblen, C.D. Allen, J. Logan, B. Hawkes. 2002. Cascading effects of fire exclusion in Rocky Mountain ecosystems: A literature review. USDA Forest Service General Technical Report, RMRS-GTR-91.

Keane, R.E., L.J. Dickinson. 2007. The photoload sampling technique: estimating surface fuel loadings from downward-looking photographs of synthetic fuelbeds. USDA Forest Service General Technical Report, RMRS-GTR-190.

Lauber, C.L., M. Hamady, R. Knight, N. Fierer. 2009. Pyrosequencing-based assessment of soil pH as a predictor of soil bacterial community structure at the continental scale. *Applied and environmental microbiology*, 75(15), 5111-5120.

Leckie, S.E. 2005. Methods of microbial community profiling and their application to forest soils. *Forest Ecology and Management*, 220, 88-106.

MacKenzie, M., T. DeLuca, A. Sala. 2006. Fire exclusion and nitrogen mineralization in low elevation forests of western Montana. *Forest Ecology and Management*, 203, 331-343.

Massman, W.J., J.M. Frank, N.B. Reisch. 2008. Long-term impacts of prescribed burns on soil thermal conductivity and soil heating at a Colorado Rocky Mountain site: A data/model fusion study. *International Journal of Wildland Fire*, 17, 131-146.

McCune, B., J.B. Grace. 2002. Analysis of Ecological Communities. MjM Software Design. Gleneden Beach, OR, U.S.A.

Nardoto, G.B., M.M. da Cunha Bustamante. 2003. Effects of fire on soil nitrogen dynamics and microbial biomass in savannas of Central Brazil. *Pesq. agropec. bras., Brasília*, 38(8), 955-962.

National Climate Data and Information Archive. Retrieved 13/5/2011 at http://climate.weatheroffice.gc.ca/climate_normals/results_e.html?stnID=1210&lang=e&dCode=0&province=BC&provBut=&month1=0&month2=12

Neary, D.G., C.C. Klopatek, L.F. DeBano, P.F. Ffolliott. 1999. Fire effects on belowground sustainability: a review and synthesis. *Forest Ecology and Management*, 122, 51-71.

Neary, D.G., K.C. Ryan, L.F. DeBano. 2005. Wildland fire in ecosystems: Effects of fire on soils and water. USDA Forest Service, Rocky Mountain Research Station General Technical Report. RMRS-GTR-42-4. 250p. Ogden, UT, USA.

Overby, S.T., H.M. Perry. 1996. Direct effects of prescribed fire on available nitrogen and phosphorus in an Arizona chaparral watershed. *Arid Soil Resources and Rehabilitation*, 10, 347-357.

Page-Dumroese, D., M. Jurgensen, W. Elliot, T. Rice, J. Nesser, T. Collins, R. Meurisse. 2000. Soil quality standards and guidelines for forest sustainability in northwestern North America. *Forest Ecology and Management*, 138, 445-462.

Pietikäinen, J., H. Fritze. 1993. Microbial biomass and activity in the humus layer following burning: Short-term effects of two different fires. *Canadian Journal of Forest Research*, 23, 1275-1285.

Pietikäinen, J., H. Fritze. 1995. Clear-cutting and prescribed burning in coniferous forest: Comparison of effects on soil fungal and total microbial biomass, respiration activity and nitrification. *Soil Biology and Biochemistry*, 27, 101-109.

Powers, R.F. 2002. Effects of soil disturbance on the fundamental, sustainable productivity of managed forests. USDA Forest Service, General Technical Report, PSW-GTR-183.

Prieto-Fernández, A., M.J. Acea, T. Carballas. 1998. Soil microbial and extractable C and N after wildfire. *Biology and Fertility of Soils*, 27, 132-142.

Raison, R.J. 1979. Modification of the soil environment by vegetation fires, with particular reference to nitrogen transformations: A review. *Plant and Soil*, 51, 73-108.

Raison, R.J., P.V. Woods, B.F. Jakobsen, G.A.V. Bary. 1986. Soil temperatures during and following low-intensity prescribed burning in a *Eucalyptus pauciflora* forest. *Australian Journal of Soil Research*, 24, 33-47.

SAS Institute. 2004. SAS 9.1 user's guide. Copyright 2004. Cary,NC: SAS Institute Inc.

Schlesinger, W.H. 1993. Response of the terrestrian biosphere to global climate change and human perturbation. *Vegetatio*, 104, 295-305.

Schmidt, K.M., J.P. Menakis, C.C. Hardy, W.J. Hann, D.L. Bunnell. 2002. Development of coarse-scale spatial data for wildland fire and fuel management. USDA Forest Service, Rocky Mountain Research Station General Technical Report. RMRS-GTR-87. Fort Collins, CO, USA.

Soil Classification Working Group. 1998. The Canadian System of Soil Classification. Agriculture and Agri-Food Canada. Publication 1646 (Revised). National Research Press, Ottawa, Ontario.

Steer, J., J.A. Harris. 2000. Shifts in the microbial community in rhizosphere and non-rhizosphere soils during the growth of Agrostis stolonifera. *Soil Biology & Biochemistry*, 32, 869-878.

Tiedemann, A.R., T.D. Anderson. 1980. Combustion losses of sulphur from native plant materials and forest litter. Fire and Forest Meteorology Conference Proceedings, 6, 220-227.

Tilman, D., P. Reich, H. Phillips, M. Menton, A. Patel, E. Vos, D. Peterson, J. Knops. 2000. Fire suppression and ecosystem carbon storage. *Ecology*, 81(10), 2680-2685.

USDA-USDI. 2000. A report to the President in response to the wildfires of 2000. USDA and USDI . Retrieved 17/5/2011 at www.fireplan.gov/president.cfm.

Vázquez, F.J., M.J. Acea, T. Carballas. 1993. Soil microbial populations after wildfire. *FEMS Microbiology Ecology*, 13, 93-104.

Vitousek, P.M., R.W. Howarth. 1991. Nitrogen limitation on land and in the sea: How can it occur? *Biogiochemistry,* 13, 87-115.

Wells, C.G., R.E. Campbell, L.F. DeBano, C.E. Fredricksen, E.C. Franklin, R.C. Froelich, P.H. Dunn. 1979. Effects of fire on soil: a state-of-the-knowledge review. USDA Forest Service General Technical Report. GTR-WO-7. Washington, D.C., USA.

White, D.C., W.M. Davis, J.S. Nickels, J.D. King, R.J. Bobbie. 1979. Determination of the sedimentary microbial biomass by extractible lipid phosphate. *Oecologia*, 40, 51-62.

Wohlgemuth, P.M., K. Hubbert, M.J. Arbaugh. 2006. Fire and physical environment interactions. In N.G. Sugihara, J.W. Van Wagtendonk, K.E. Schaffer, J. Fites-Kaufman, A.E. Thode (eds.). Fire in California's ecosystems. University of California Press, Berkely, CA, USA.

Wright, C.S., C.S. Balog, J.W. Kelly. 2010. Estimating volume, biomass and potential emissions of hand-piled fuels. USDA Forest Service, Pacific Northwest Research Station, General Technical Report. PNRS-GTR-805.

Yang, K., J. Zhu, M. Zhang, Q. Yan, O.J. Sun. 2010. Soil microbial biomass carbon and nitrogen in forest ecosystems of Northeast China: a comparison between natural secondary forest and larch plantation. *Plant Ecology*, 3(3), 175-182.

Zimmerman, G.M., H. Goetz. 1985. Use of an improved statistical method for group comparisons to study fire effects of prairie fire. *Ecology*, 66(2), 606-611.