Available online at www.sciencedirect.com
SCIENCE DIRECT®

Forest Ecology and Management 220 (2005) 227–241

Forest Ecology and Management

www.elsevier.com/locate/foreco

A comparison of soil properties after contemporary wildfire and fire suppression

Jeff Hatten [*], Darlene Zabowski, George Scherer, Elizabeth Dolan

University of Washington, College of Forest Resources, Box 352100, Seattle, WA 98195-2100, USA

Abstract

Forests that were subject to frequent wildfires, such as ponderosa pine/Douglas-fir forests, had fire-return intervals of approximately 6–24 years. However, fire suppression over the last century has increased the fire-return interval by a factor of 5 in these forests, possibly resulting in changes to the soil. The objective of this study was to determine if soils of recently burned areas (representative of the natural fire-return interval) have different properties relative to soils in areas without recent fire. To assess this, recent low-intensity, lightning-caused, spot wildfire areas were located within fire-suppressed stands of ponderosa pine/Douglas-fir of the central, eastern Cascade Mountains of Washington State. Soil horizon depths were measured, and samples collected by major genetic horizons. Samples were analyzed for pH, C, N, C/N ratio, cation exchange capacity (CEC), base saturation (%BS), hydrophobicity and extractable P. Results show very little difference in soil properties between sites burned by low-severity fires and those areas left unburned. Such minimal changes, from these low-severity fires, in soil properties from fire suppression suggest there has also been little change in soil processes.

Keywords: Carbon; Cation exchange capacity; Forest soil; *Pseudotsuga menziesii*; Low-severity wildfire; Nitrogen; *Pinus ponderosa*

1. Introduction

Fire is integral to ponderosa pine (*Pinus ponderosa*)/Douglas-fir (*Psuedotsuga menzesii*) ecosystems of eastern Washington and is a major determinant of community composition. The direct interaction of fire with vegetation and soil would seem to be a factor influencing soil variability. During any day, 44,000 thunderstorms occur on the earth. Although the northwestern United States does not have a high number of thunderstorms, those that do occur in the interior have a significant chance of igniting a fire due to low precipitation levels during summer months (Agee, 1993). These lightning-strike forest fires may play a significant role in the variability of soil characteristics. Over the last 100 years fires ignited by lightning and other sources have been quickly extinguished. This practice of fire suppression in the forests of the United States led to changes in many ecosystem properties and could be affecting soil properties as well.

Community and fuel structure in many forests is changing or has changed from the pre-fire suppression era to the present date due to the lack of fire. Fire may

---

[*] Corresponding author. Tel.: +1 206 616 1879; fax: +1 206 685 0790.
E-mail address: jhatten@u.washington.edu (J. Hatten).

0378-1127/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2005.08.014

affect ponderosa pine/Douglas-fir ecosystem structure and community composition largely by removing fire intolerant organisms, e.g. young Douglas-fir, and reducing the amount of fuel. Douglas-fir in this ecosystem is a somewhat shade-tolerant species that can grow in the understory of ponderosa pine. Usually smaller Douglas-fir seedlings are killed by low-intensity fires (Agee, 1993). Previously these forests were open and park-like with frequent low-intensity fires; with fire suppression they are now more likely to burn intensely when ignited due to these changes in the vegetation structure and fuel load.

Changes in vegetation and fuels, due to fire suppression, may be affecting soils because vegetation is one of the five soil forming factors. Jenny (1980) stated that in the prairie-forest ecotone fire essentially acts as a soil forming factor. While the ponderosa pine/Douglas-fir forest is not a typical prairie-forest ecotone it does share some of the same characteristics, implying that fire may play a role in determining soil variability in this landscape.

Fire affects soil through its ability to transform soil and ecosystem components. These transformations include outputs in the form of volatilized and combusted material as well as the convection of ash material. Fire can also mineralize organically bound elements such as N, P, and base cations which are then available for uptake by plants or leaching from the soil (DeBano et al., 1998).

Fire combusts the organic material lying on the forest floor thereby leaving the mineral soil less protected from water and wind erosion. The increased likelihood of erosion to occur after a fire means nutrient-rich material from the surface horizons can be lost from burn areas. In areas of erosion, such as ridges, shoulder slopes, and back slopes, these surface mineral horizons may have reduced depth; while areas down slope may have material from upslope redeposited at the surface and will be thicker. Erosion exposes younger mineral material which could affect chemical characteristics resulting in higher pH, lower C and N concentrations, CEC, base saturation, and extractable P of surface mineral horizons. Organic material may also be transported and mixed with mineral materials, which when redeposited will lower pH, increase C and N concentrations, CEC, base saturation, and extractable P. The long-term effects of fire on soils are dependent on the particular soil characteristic being observed and its rate of change after a fire. The rate of change can depend on site characteristics such as precipitation (Woodmansee and Wallach, 1981).

Very few studies have considered long-term effects of low-severity fires on soils of ponderosa pine/Douglas-fir forests. Monleon et al. (1997) studied effects of low-intensity prescribed fires on soils 4 months, 5 years, and 12 years after burning in an eastern Oregon ponderosa pine forest. They found that 4 months after fire total C and inorganic N had increased in the mineral soil surface (0–5 cm). After 5 years total C, total N, and inorganic N had decreased from the control. By 12 years these variables had returned to unburned levels.

Baird (1998) studied the effects of a large wildfire that burned a ponderosa pine/Douglas-fir forest in the Cascade Mountains of Washington State. She designated three levels of fire severity (low, moderate, and high). In soils within the low-severity burn areas she found a decrease in total N 1 year after burning, while C/N was not significantly affected.

This study was done on a Joint Fire Science Program (JFSP) Fire and Fire Surrogates (FFS) study area located near Mission Creek on the east side of the Cascade Mountain Range in Washington State on USFS land. The study was designed to determine the effects of wildfire surrogates (prescribed fire and thinning) on ecosystem properties. During the baseline sampling phase of the study it was noticed that parts of the study plot had burned recently. These burned areas provided an opportunity to examine the effects of low-severity fires caused by lightning-strikes in this ecosystem.

Dolan (2002) examined the spatial variability of soils on the total Mission Creek FFS study area and found them to be highly variable. O horizon depth was significantly correlated with aspect, amount of erosion, canopy cover, and grass cover. Depth of A horizon was correlated with herbaceous cover, grass cover, and amount of erosion, while B horizon thickness was only correlated with amount of erosion. The three correlations had R^2 values ranging from .412 for the O horizon to .274 for the A horizon. These low R^2 values suggest other variables are controlling soil horizon depth. She surmised that the disturbance history and age of the soil may also affect soil horizon depth. Fire, as one of the disturbance agents mentioned, but not tested, may be partly responsible for this variability.

The purpose of this study was to (1) determine how these soils are affected by low-intensity lightning-caused wildfires; and (2) establish the role of fire in affecting the magnitude of soil spatial variability.

2. Materials and methods

2.1. Site characteristics

The study area is located in the eastern Cascade Mountains in central Washington State, USA (47°25′N, 120°50′W) at elevations 640–1160 m. The dry forests of the area consist of ponderosa pine and Douglas-fir on steep mountainous to foothill landscapes. Climatic data from Blewett Pass (elevation 1301 m), located approximately 5.5 km west of the study site, show an average annual precipitation of 88 cm, of which 75 cm falls between October and April, mostly as snow, and an average annual air temperature of 5 °C (NRCS, 2001a,b).

The bedrock consists of non-glaciated sandstone intermixed with limited amounts of shale and conglomerate from the Chumstick formations (Tabor et al., 1982). Loess and ash deposits from numerous volcanic eruptions and fire are present in some areas. Ash deposits have likely been removed by the process of erosion from areas without field detectable accumulations because of its high erosivity. Typical soil types found on the site include Haploxerepts, primarily found on the 1- and 3-year-old burn plots, Haploxerolls, Argixerolls and Haploxeralfs found throughout the remaining plots (Soil Survey Staff, 1995).

The FFS plots used for this study are located within the Douglas-fir association (Franklin and Dyrness, 1988). The ponderosa pine/Douglas-fir forest is widespread throughout the Pacific Northwest, extending as far south as northeastern California and east into western Montana. The forest type consists of a ponderosa pine/Douglas-fir canopy with various shrub and herbaceous species mixed with pinegrass (*Calamagrostis rubescens* Buckl.) in the understory. The shrub species are dominated by bitterbrush (*Purshia tridentata* (Pursh) DC.), spirea (*Spirea* sp.), rose (*Rosa* sp.), huckleberry (*Vaccinium* sp.), snowberry (*Symphoricarpos* sp.), and creambush oceanspray (*Holodiscus discolor* (Pursh) Maxim.). Some of the herbaceous species present are arrowleaf balsamroot (*Balsamorhiza sagittata* (Pursh) Nutt.), lupine (*Lupinus* sp.), western yarrow (*Achillea millefolium* L.), and Oregon grape (*Berberis* sp.). Ponderosa pine/bitterbrush associations are found on the drier south slopes with an increase in Douglas-fir canopy on northern aspects. Because of past disturbance and aspect differences on the site, tree ages and densities vary from old growth (~350 years old) pine stands to <10-year-old regenerating Douglas-fir.

The study area has been under a regime of fire suppression since the early 1900s. A fire history study conducted in a ponderosa pine/Douglas-fir forest on the east slope of the Cascade Mountains in Washington State (Everett et al., 2000) found a pre-settlement mean fire-free interval of 6.6–7 years on sites 60 km southwest and 40 km northeast of this study area. During fire suppression the mean fire-free interval increased to 38–43 years. Fire history studies conducted in other areas of the Mission Creek drainage found a mean fire-free interval of 8.2 years for the pre-settlement period (D. Schellhaas, personal communication). Schellhaas also found that the area was subject to large fires around 1929 and 1890. These were likely stand replacing fires that burned the plots in this study (D. Schellhaas, personal communication). Finch (1984) reported a fire-return interval of 10–24 years for individual trees from a Douglas-fir association forest north of the FFS plots in the Okanogan National Forest in Washington State.

2.2. Burn plot history

Lightning-strike data from the USFS was consulted to determine when the last wildfires burned on the study sites. Lightning strikes designated within an FFS plot were examined to determine the extent of the fire. Fire was determined by the presence or absence of charred bark on trees, fire scars, and charred woody debris. After a fire area had been determined, samples of fire scars were taken where available using the increment-borer method of Barrett and Arno (1988). If no fire scars were available the lightning-caused fire was verified by a observing a timely tree-ring response, such as a spurt or decline in growth, signifying a possible fire related environmental change.

Recently burned areas were discovered on 4 of the 12 Mission Creek FFS plots. All four recently burned areas fell within the range of reported fire-return intervals. Three of the plots were found to have burned within the fire-free interval found by Everett et al. (2000) of 6.6–7 years and Schellhaas (unpublished data) at 8.2 years. The oldest plot had been burned at about the fire-return interval, 10–24 years, as reported by Finch (1984). All fires appeared to be low-intensity with no observed occurrence of crowning. The Forest Service responded to each of the fires with ground crews. No evidence of fire retardant was found at any of the burn sites, and no documentation of the use of fire retardant was found in the Forest Service records.

The oldest burn (27+ years old) was determined to be between 27 and 34 years old. Forest Service records denote a lightning strike and response in 1975 (27 years prior to fire scar sampling), while fire scar samples taken in 2002 indicate a fire age of up to 34 years. The disparity in ages is likely due to the prevalence of double and false rings in the fire scar samples. This plot represented the longest documented fire-return interval for this type of forest. This fire was found to have burned a wide variety of topographic positions and probably started down valley and burned up slope to the ridge of the study plot (Table 1). The forest on the 27+ years old site was characterized by large old-growth trees with clumps of ‘‘dog-hair’’ trees (smaller Douglas-fir trees about the age of the last burn growing very densely) separated by patches of bitter brush, and grasses. Similar unburned controls were only found on back slopes; however, other environmental variables were consistent between the control and burned areas (Table 1).

The next oldest burn site was 8+ years old. No fire scar was located on the site; however, tree-rings were sampled during the summer of 2002. The tree-rings record a ‘‘release’’ that occurred about 8 years prior to sampling. This release corroborates the lightning-strike data. The lightning-strike records indicated a lightning-caused fire occurred in 1993, to which the USFS responded with ground crews. The fire burned over a steep back slope characterized by very few trees, dominated by grasses and bare talus. Control

Table 1
Site characteristics and soil horizons for burned and control sample locations

Plot	Fire	Last burned (years)	Aspect	Slope (%)	Topographic positions[a]	Canopy cover (%)	*n*	Horizon	Horizon thickness (cm)[b]
1 and 3 years	Control	70	SW	31	R, BS	47	9	O	5.7 ± 1.1
								A	8.4*i* ± 1.6
								Bw, Bt	19.6+ ± 2.5
1 year	Burned	1	SW	25	R	13	2	O	4.0 ± 3.3
								A	15.5*i* ± 14.0
								Bt	25.5+ ± 2.5
3 years	Burned	3	W	12	R, SS	38	4	O	3.6 ± 1.2
								A	6.3*i* ± 2.2
								Bw, Bt	11.8+ ± 3.8
8+ years	Control	70	SW	59	BS	42	4	O	6.5 ± 4.3
								A	4.3*i* ± 2.2
								Bw, BC	29.0+ ± 2.8
8+ years	Burned	8+	SW	56	BS	73	3	O	4.3 ± 0.5
								A	3.0*i*
								Bw	17.7+ ± 8.8
27+ years	Control	109	NW	44	BS	66	4	O	4.5 ± 1.1
								A	10.3*i* ± 1.3
								Bw	24.0 ± 5.7
27+ years	Burned	27+	W	30	R, BS, TS, V	56	5	O	4.6 ± 1.0
								A	10.3*i* ± 1.3
								Bw, Bt	24.0+ ± 5.7

[a] Topographic position designated as R—ridge, SS—shoulder slope, BS—backslope, TS—toeslope, and V—valley.

[b] Data displayed as average ± 90% confidence interval. *i* = significant interaction between plot and presence/absence of burn at $\alpha = 0.05$ using a two-way ANOVA.

sites were only found in steeper areas with higher canopy cover.

According to USFS records, the same fire burned two of the FFS plots (1-year and 3-year-old sites). The plots were sampled 1 year and 3 years after the fire occurred. Lighting-strike records show a strike and a Forest Service ground crew response to the area in 1999. Two fire scar samples from the burn area corroborate the lightning strike record and show ages of 0 and 8 years. The tree with the younger scar may not have completely recovered to produce a ring after the fire. The older tree-ring may have had some of the outer cambium removed by the fire, thereby lengthening the estimated time since fire. The fire largely burned along a ridge connecting the two plots. Vegetation within the burned area is consistent over the entire area. Trees are mostly 70 years old (about the age of the last major stand replacing fire in the Mission Creek Drainage) and consist of Douglas-fir and ponderosa pine with an understory of bitter brush and grasses. Controls were quite similar to both the 1- and 3-year-old burn plots, however the 1-year-old burn plot had a much lower canopy cover than either the controls or 3-year-old burn plot.

2.3. Soil sampling

Two to five sample sites were located within each burn area, with four to nine sample locations within the control areas (Table 1). At every sampling site, slope, aspect, slope position (ridge, shoulder slope, back slope, toe slope, and valley), and canopy cover was recorded. Controls were chosen by their similarity to the burned area based on the preceding environmental factors. The 27+-, 8+-, 1-year-old burn areas and 27+-, 8+-, 3-, and 1-year-old control areas were sampled in 2000. The 3-year-old burn was sampled in 2002. The 1- and 3-year-old burn plots were sampled from the same fire area at two different times. The controls for these plots were the same for each of the burns. Controls were assumed to have remained unchanged from 1 year to 3 years after fire.

Soil samples were collected from O, A, and B horizons to a depth of 30 cm. Major genetic horizons were identified and measured for depth. Hydrophobicity of each O, A, and B horizon was measured in the field by dropping 1 ml of water and measuring the amount of time needed for the droplet to completely infiltrate the soil. Bulk samples were removed from each horizon to be analyzed in the lab for chemical properties.

2.4. Soil analysis

Soil samples were air-dried and mineral horizons separated into coarse and fine fractions with a 2 mm sieve; coarse fractions were discarded. Some charcoal larger than 2 mm was discarded with the coarse fraction, smaller than 2 mm was left in the fine fraction. Subsamples from each mineral horizon were analyzed for pH, C, N, extractable P, cation exchange capacity, and base cations. O horizons were only analyzed for pH, and N. Ratios of C:N were calculated for each sample. The saturated paste method was used to determine pH.

Phosphorous extracts were created by shaking 10 g of soil with a 0.01 M solution of $CaCl_2$ for 30 min. Soil was separated from the solution with a Whatman no. 42 filter paper. Solutions were analyzed using the molybdenum blue method of Olsen and Sommers (1982). Subsamples were ground and analyzed for percent C and N using a Perkin-Elmer 2400 CHN analyzer.

Base cation extracts on a 5 g subsample were made using 50 ml of 2N NH_4Cl and extracted using a syringe extractor for 12 h (Skinner et al., 2001). Base cation extracts were analyzed using an ICP. Excess NH_4Cl was removed with an ethanol rinse. To determine CEC, samples were subsequently extracted for 12 h with 50 ml of a 2N KCl solution and the extract analyzed for ammonium (Skinner et al., 2001).

2.5. Statistical analysis

Results from all measurements were tested for significance using a two-factor analysis of variance, factors in the significance test being presence or absence of fire and time since fire (which is the same as plot since each burn plot was different except for the 1- and 3-year-old burn plots). The variable ‘‘plot’’ (i.e. time since fire) would include any site differences among plots. The 2-factor ANOVA was conducted using SPSS© (Version 10.1.3 for Windows) (SPSS, 2000).

3. Results and discussion

3.1. Soil horizonation

The top 20 cm of the soil found in the Mission Creek area typically has horizons of O, A, and either a Bw or Bt-horizon. O horizons were Oi with very little Oe, sometimes a very thin layer of charcoal separated the O horizon from the surface mineral horizon. The Bw or Bt horizons usually extended deeper than 20 cm and BC or C horizons were found at depth (22–51 cm). In high erosion areas, prevalent on the 8+-year-old burn plot, the A horizon was absent. All sample sites had an O horizon and either a Bw or Bt horizon.

O-horizon depths were shallowest in the 3-year-old burn areas and thickest in the 8+-year-old control plot (Table 1). In this study O-horizon depth was not significantly different between burned and control plots, including the 1- and 3-year-old plots. Choromanska and DeLuca (2001) saw a 42% reduction in O-horizon depth 5 months after a spring prescribed fire in a ponderosa pine forest of western Montana. Covington and Sackett (1984) found a 51% reduction in the mass of the forest floor 7 months after a low/moderate intensity prescribed fire. The fire that burned through the 1- and 3-year-old plots was likely of low severity and may not have consumed a substantial amount of the O horizon. The site also had a year or more to recover from the burn, during which time aboveground litterfall could have replaced material that was consumed.

A horizons were thickest on the 1-year-old burn plot largely due to a sample location that had an A and AB horizon totaling 27 cm. On the 8+-year-old burn, average A-horizon depth was highly affected by erosion; two of the sample locations had no A horizon present. A-horizon depth was significantly affected by an interaction between the two factors, plot (time since burn) and presence/absence of fire, as tested with two-factor ANOVA ($\alpha = 0.05$). This interaction between fire and plot (as time since burn) was most likely due to fire interacting with site variables, e.g., slope, to bring about secondary effects such as erosion and redeposition, which were not measured. Dolan (2002) found when examining all the grid-points of the Mission Creek FFS study area that site factors, along with various vegetation variables, were significant in modeling O- and A-horizon thickness, although presence or absence of fire was not taken into account.

3.2. Soil hydrophobicity

O horizons at all of the plots had the highest hydrophobicity (Table 1). This is expected, due to the low surface area fresh organic material, as well as the presence of hydrophobic compounds such as waxes (DeBano, 2000). The hydrophobicity data was highly variable, with confidence intervals ($\alpha = 0.10$) ranging from 23 to 161% of the mean value; no significant difference was found between burned and control areas or plot for any horizon. The high variability is likely driven by environmental factors such as fire, time since fire, or soil factors such as organic matter content. However, high variability could have been caused by other factors not measured in this study, such as litterfall, air temperature, time since last rain, or human error.

Low-intensity burns have been found to create little if any detectable hydrophobic layers due to the low amount of heat produced resulting in the generation of few vaporized hydrophobic compounds (DeBano, 2000; Huffman et al., 2001). The low-severity fires that burned over these sites were probably not hot enough to create a significant hydrophobic layer.

3.3. Soil chemical properties

Of all chemical variables measured, no significant difference was found between the soils with recent fire (burned plots) and those without (control plots). All the controls were similar enough to the burn plots that it could not be determined if they were different from each other due to the background variability. Interaction between presence of fire and plot (including time since burn) was the only way in which fire exhibited any significant effect on chemical variables; interaction was significant for A-horizon pH and C/N ratio. There are a few instances where time since burn, i.e. plot (including any site differences), is a significant factor in explaining the variability for O-horizon pH, and B-horizon C, N, extractable P concentration, and C/N ratio.

It is generally expected that pH will increase in conifer forests after fire and decrease with time, the rate at which it does so being dependent on precipitation (Woodmansee and Wallach, 1981). Precipitation in this semi-arid forest is low so the rate at which pH returns to baseline levels would be

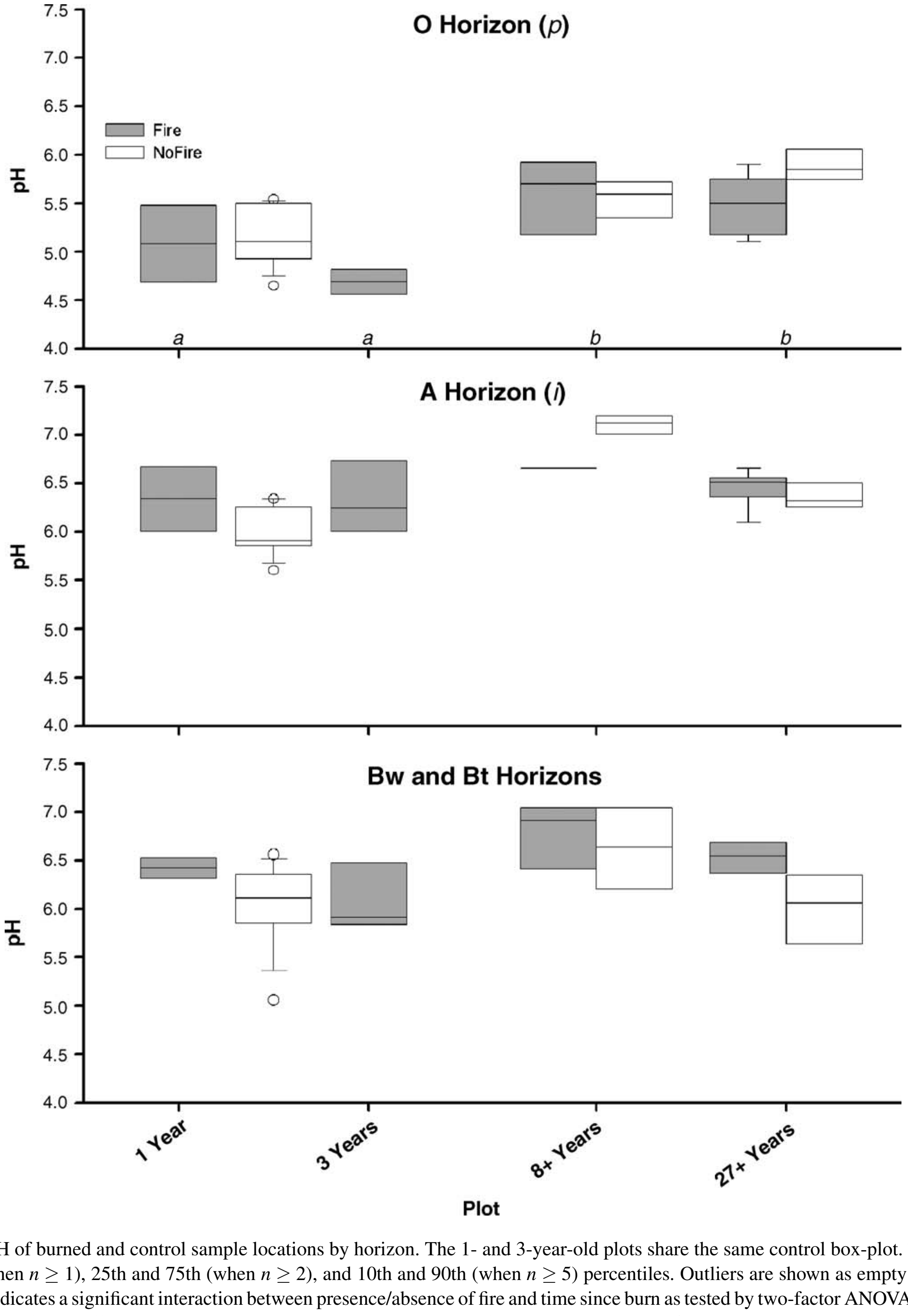

Fig. 1. Soil pH of burned and control sample locations by horizon. The 1- and 3-year-old plots share the same control box-plot. The box-plots show 50th (when $n \geq 1$), 25th and 75th (when $n \geq 2$), and 10th and 90th (when $n \geq 5$) percentiles. Outliers are shown as empty circles (when $n \geq 6$). An *i* indicates a significant interaction between presence/absence of fire and time since burn as tested by two-factor ANOVA ($\alpha = 0.05$). A *p* indicates a significant difference between time since burn as tested by two-factor ANOVA ($\alpha = 0.05$). *a* and *b* indicate significant differences as tested by two-factor ANOVA and Tukey's HSD ($\alpha = 0.05$).

relatively slow. Average pHs of the control soils of this study averaged 5.5 in the O horizon, 6.5 in the A horizon, and 6.2 in the B horizon (Fig. 1). Baird et al. (1999) found pHs of 6.7 and 6.6, A and B horizons, respectively, in an unburned ponderosa pine/Douglas-fir forest near the FFS study area.

A- and B-horizon pH was lowest in the 1-, 3-, and 27+-year-old burn areas, while the 8+-year-old burn had the highest pH. This pattern runs contrary to our expectations due to fire's ability to raise pH of the soil shortly after fire (DeBano et al., 1998). A-horizon data at the 8+-year-old burn was limited as it only had one site with an A horizon. This suggests that the low number of samples, as well as the steep slopes of the burn area with observed signs of erosion, affected the results. This may have resulted in lower pH material from the surface horizons being removed by erosion exposing material from less weathered B horizons with a higher pH at the 8+-year-old burn area. The two-factor ANOVA showed a significant interaction with plot (including time since burn) and presence/absence of fire for pH in the A horizon.

O-horizon pH was found to be significantly different among the plots ($\alpha = 0.05$). The pH is lowest on the 1- and 3-year-old burn plots in the O horizon, which is contrary to our expectations (Fig. 1). Using Tukey's HSD test it was found that 1- and 3-year-old plots comprised a similar group in terms of pH, and 8+ and 27+-year-old plots comprised a second group. The 1- and 3-year-old plots were the most similar in site

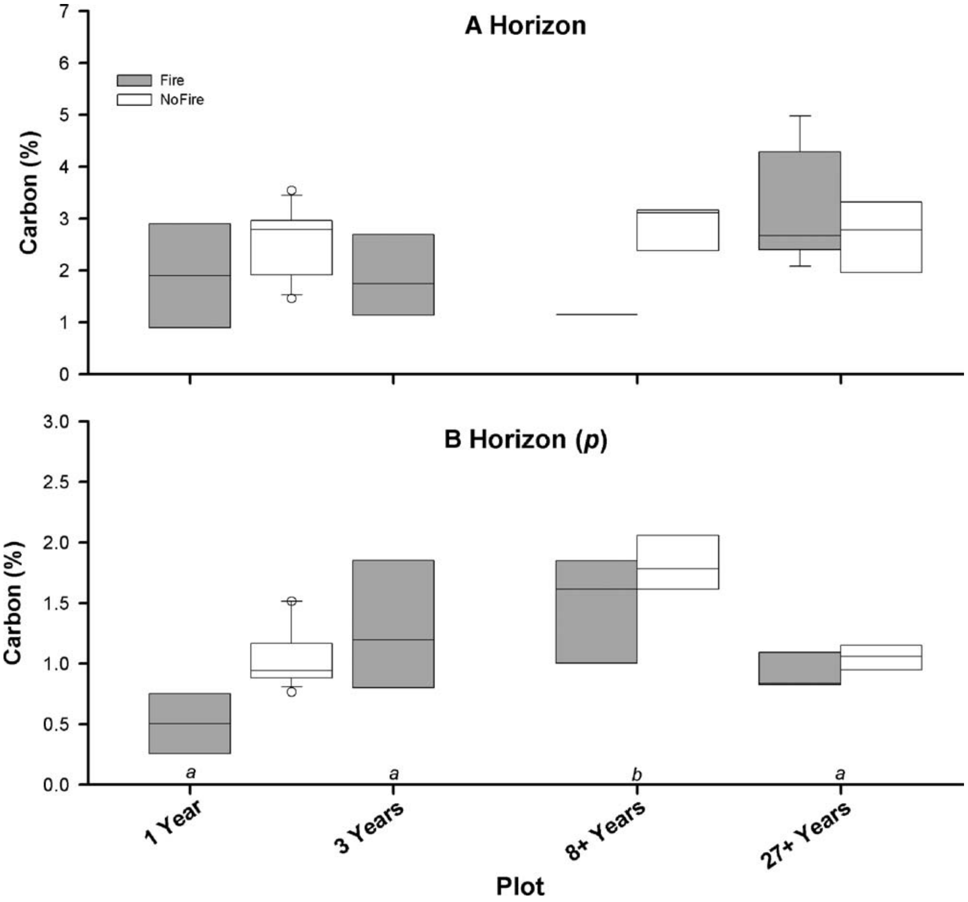

Fig. 2. Soil carbon concentration of burned and control sample locations by horizon. The 1- and 3-year-old plots share the same control box-plot. The box-plots show 50th (when $n \geq 1$), 25th and 75th (when $n \geq 2$), and 10th and 90th (when $n \geq 5$) percentiles. Outliers are shown as empty circles (when $n \geq 6$). A *p* indicates a significant difference between time since burn as tested by two-factor ANOVA ($\alpha = 0.05$). *a* and *b* indicate significant differences as tested by two-factor ANOVA and Tukey's HSD ($\alpha = 0.05$).

properties (i.e. canopy, aspect, age of trees) and are similarly located geographically.

Carbon concentration averaged 2.7 and 1.3% in the A and B horizons, respectively (Fig. 2). Baird et al. (1999) found similar C concentrations of 2.1 and 0.8% in unburned A and B horizons.

Carbon concentrations were expected to be lower in the burn areas compared to the control, but no significant difference was found for time since burn (i.e. plot) in the A horizon. Carbon concentrations ranged between 2 and 3% on the 1-, 3-, and 27+-year-old burn plots. The A horizon of the 8+-year-old burn area had the lowest C concentration of all the groups, likely due to erosion removing organic material from the surface of the soil.

Time since burn (i.e. plot) was a significant factor, as tested by a two-factor ANOVA, in C concentrations the B horizon. Site factors such as slope and vegetation cover could increase and decrease C content through erosion and redeposition. The 1-, 3- and 27+-year-old burns had similar characteristics while the 8+-year-old burn was in a group by itself, as tested by Tukey's HSD test. Erosion on the 8+-year-old control sites likely controlled the C concentration. On these control sites where fire did not burn away organic material, erosion and redeposition likely caused the mixing of organic material with horizons of low organic matter content. One of the control sites had no A horizon likely due to erosion, while two sites had depths shallower than the average. These sites probably had A horizons quickly form after deposition of mineral and organic material that originated upslope.

Nitrogen concentrations averaged 1.3, 0.2, and 0.1% in the O, A, and Bw horizons, respectively (Fig. 3), similar to values of Baird et al. (1999) of 1.0, 0.12 and 0.08%, respectively. The pattern of N concentration in the soil horizons was similar to that of C concentrations, highest in the O and A horizons and lowest in the B horizons. O- and A-horizon N concentrations appeared to be similar across all plots. Similar to the processes affecting C concentration, N concentration was not significantly affected by the presence or absence of fire in any of the horizons but was affected by plot (time since burn) in the B horizon. N concentration groups were 1-, 3-, and 27+-year-old sites and 1-, 3-, and 8-+year-old sites as tested by Tukey's HSD test. Nitrogen concentration was highest in the B horizons of the 8+-year-old control plots. Similar to the C concentration results, the N concentration may be affected by the mixing of organic material into the mineral soil through erosion and subsequent redeposition events.

In this study C/N ratios averaged 38, 29, and 29 in O, A, and B horizons, respectively (Fig. 4). Carbon/nitrogen ratios found in the mineral soil by Baird et al. (1999) were lower than those found on the FFS plots (44, 18, and 11 for O, A, and Bw horizons, respectively).

Time since burn appears to be affecting the C/N ratio of O and B horizons and interacting with presence/absence of fire in the A horizons (Fig. 4). Differences in productivity, vegetation, and average tree age among plots could be causing the differences in O horizon C/N ratio. The interaction between plot and presence or absence of fire in the A horizons, is likely due to site specific variables, such as erosion and redeposition as well as the aforementioned productivity, vegetation, and forest age that may be affecting the O horizon. C/N ratios appear to increase with time since burn. The C concentrations in the A horizons are similar between areas with fire and those areas without fire, while in the B horizon it tends to increase with time since fire, except in the case of the 27+-year-old burn plot. Nitrogen concentrations seem to be following the same pattern. This suggests N concentration is increasing at a slower rate than C is increasing, but both are increasing at such a low level as to be difficult to separate, resulting in no statistically significant differences.

In the top 25 cm of the soil profile Baird (1998) found 41.2 and 4.6% decreases in total C content 3 months and 1 year, respectively, after low-intensity wildfire. She found 47.3 and 32.8% decreases in total N content 3 months and 1 year after fire. The large decreases in N concentrations in the soil lead to a 17 and 87% increase in total C/N ratio 3 months and 1 year after fire.

Monleon et al. (1997) observed an increase in C and N concentrations and C/N ratios immediately following prescribed fire in the surface 0–5 cm of mineral soil. While the same study found a decrease in C and N concentrations 5 years after fire, and no effect 12 years after fire. C/N ratios were not affected by fire 5 or 12 years after burn. The fires in this study were low-intensity, as in this study. The high variability at the FFS sites precludes detection of differences from the controls. Monleon et al. (1997) also found no

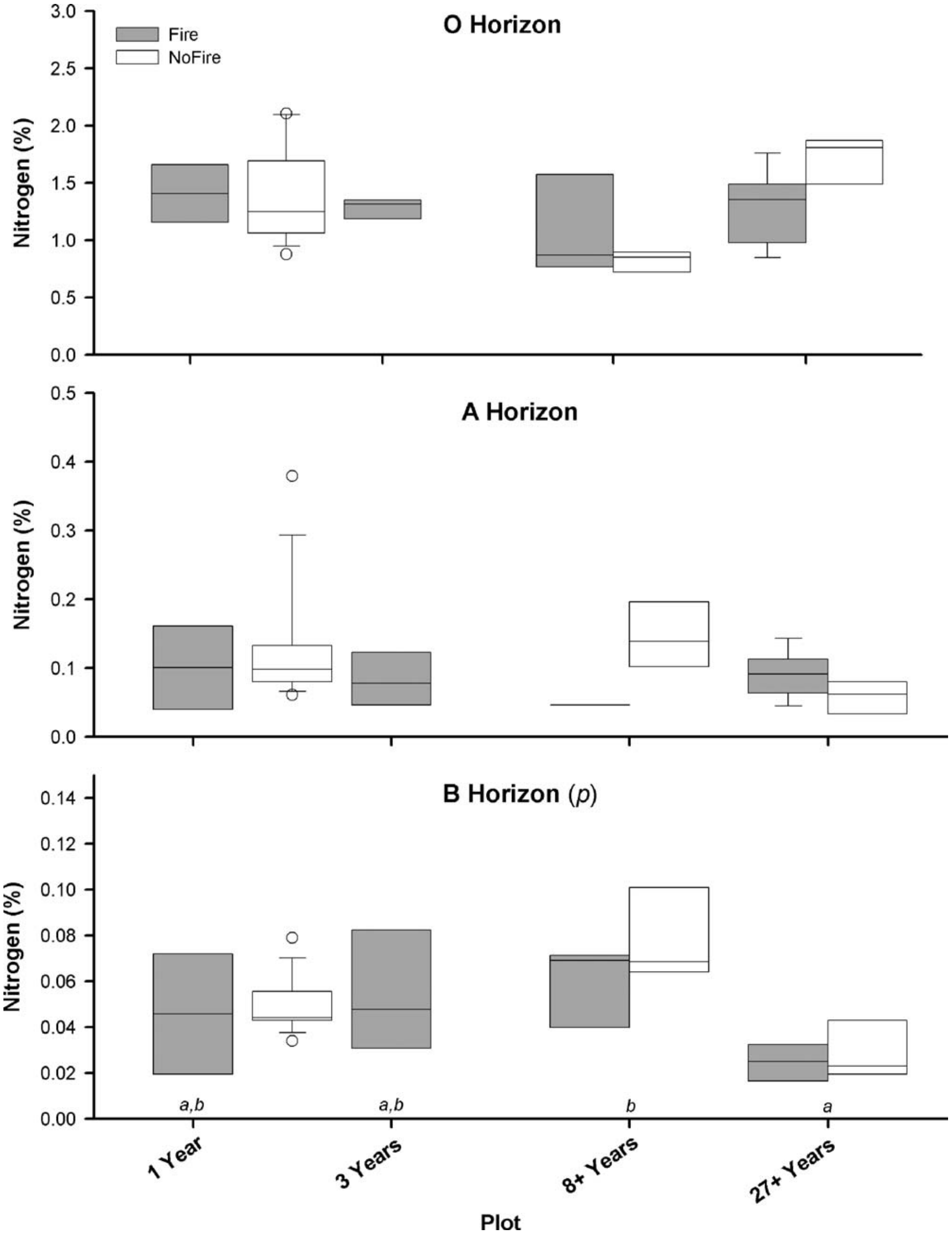

Fig. 3. Soil nitrogen concentration of burned and control sample locations by horizon. The 1- and 3-year-old plots share the same control box-plot. The box-plots show 50th (when $n \geq 1$), 25th and 75th (when $n \geq 2$), and 10th and 90th (when $n \geq 5$) percentiles. Outliers are shown as empty circles (when $n \geq 6$). A *p* indicates significant difference between time since burn as tested by two-factor ANOVA ($\alpha = 0.05$). *a* and *b* indicate significant differences as tested by two-factor ANOVA and Tukey's HSD ($\alpha = 0.05$).

difference in C and N concentrations and C/N ratios at any age burn (0, 5, and 12 years) at soil depths slightly shallower than those of the B horizons found at the FFS plots (0–15 cm).

Extractable P in the A horizon was significantly different among all of the plots, most likely due to site factors such as ash deposition and erosion (Fig. 5). Although the B horizon exhibits similar trends in

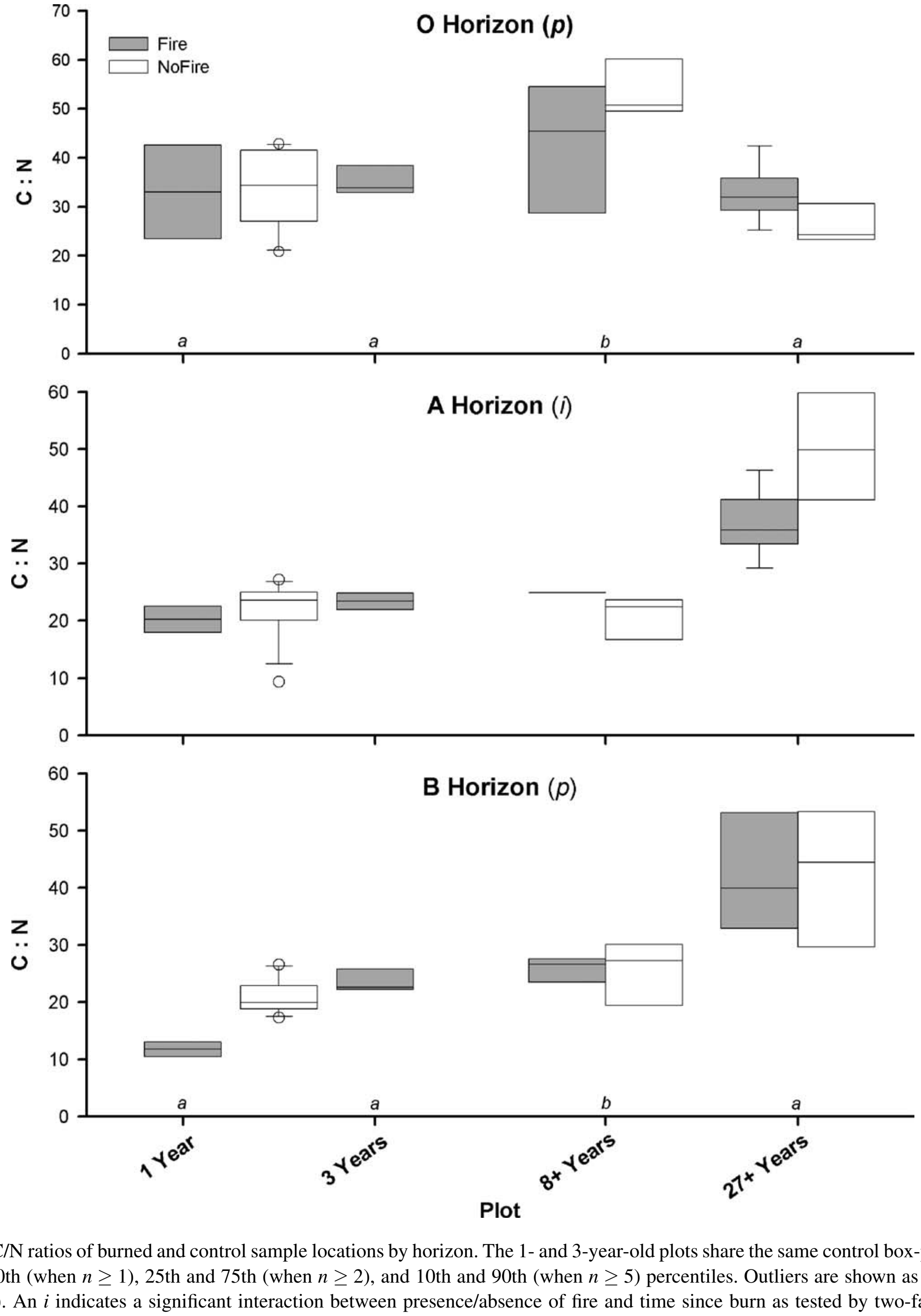

Fig. 4. Soil C/N ratios of burned and control sample locations by horizon. The 1- and 3-year-old plots share the same control box-plot. The box-plots show 50th (when $n \geq 1$), 25th and 75th (when $n \geq 2$), and 10th and 90th (when $n \geq 5$) percentiles. Outliers are shown as empty circles (when $n \geq 6$). An *i* indicates a significant interaction between presence/absence of fire and time since burn as tested by two-factor ANOVA ($\alpha = 0.05$). A *p* indicates a significant difference between time since burn as tested by two-factor ANOVA ($\alpha = 0.05$). *a* and *b* indicate significant differences as tested by two-factor ANOVA and Tukey's HSD ($\alpha = 0.05$).

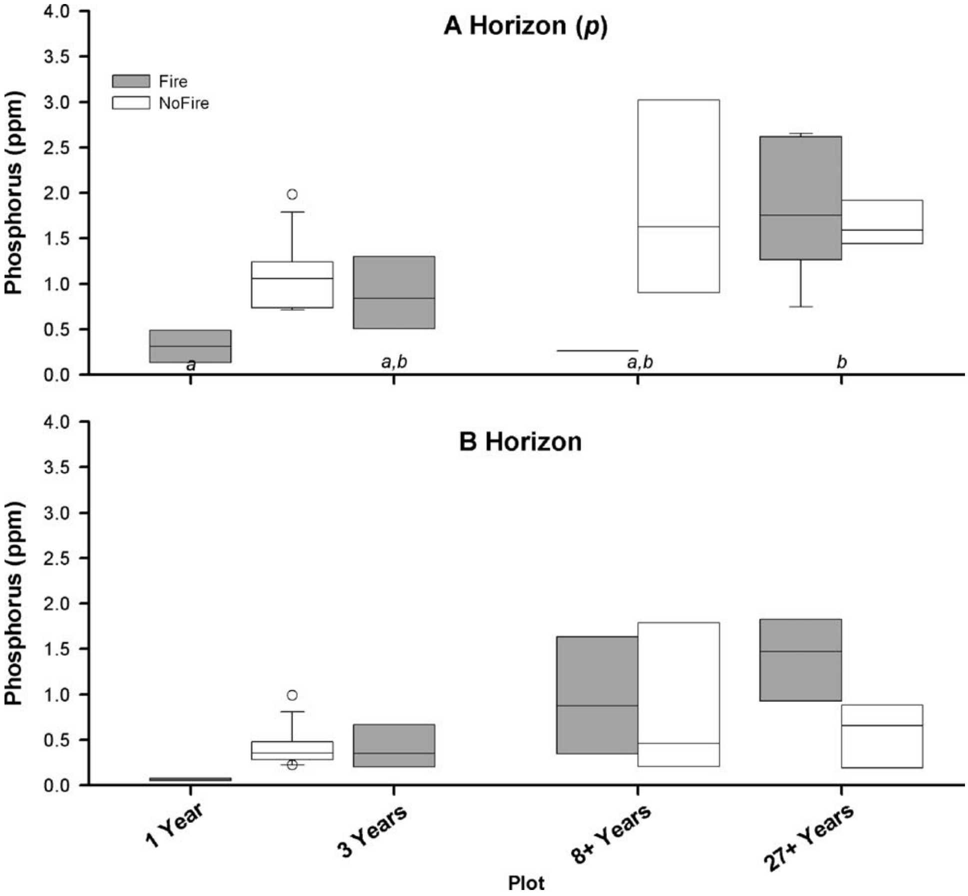

Fig. 5. Soil P concentration of burned and control sample locations by horizon. The 1- and 3-year-old plots share the same control box-plot. The box-plots show 50th (when $n \geq 1$), 25th and 75th (when $n \geq 2$), and 10th and 90th (when $n \geq 5$) percentiles. Outliers are shown as empty circles (when $n \geq 6$). A *p* indicates significant difference between time since burn as tested by two-factor ANOVA ($\alpha = 0.05$). *a* and *b* indicate significant differences as tested by two-factor ANOVA and Tukey's HSD ($\alpha = 0.05$).

extractable P concentration as the A horizon, the high variability precluded detection of any significant difference among plots. A-horizon-extractable P was lowest in the 1- and 8-+year-old burn areas. Fire may be mineralizing organically bound P thus decreasing residual extractable P. The A horizon of the 8+-year-old burn is likely low in extractable P due to the young age of the relatively unweathered newly exposed material of the horizon and the low P content of the parent material. One possibility for low extractable P is that PO_4^{3-} can be bound by volcanic ash (DeBano, 1998). Extractable P may have been affected by the presence of volcanic ash deposits that are spatially non-uniform in distribution across the FFS plots. Kraemer and Hermann (1979) saw no difference in P among burned and unburned controls 25 years after clear cut and broadcast burning on the west side of the Cascade Mountains. Wagle and Kitchen (1972) found no difference in extractable P among a 3-year-old burn, 14-year-old burn, and control in ponderosa pine forest in northern Arizona.

Cation exchange capacity averaged 16 and 15 meq/100 g in the A and B horizons of the control sample areas, respectively (Table 2). Base saturation was quite high on these control plots, 82 and 80% for A and B horizons, respectively. The low amount of precipitation likely results in low leaching rates of base cations. The interaction between plot (as time since burn) and

Table 2
Soil chemical properties for burned and control sample locations

Plot	Fire	Horizon	*n*	Hydrophobicity (s)	CEC (meq/100 g)	Base saturation (%)
1 and 3 years	Control	O	9	75 ± 47		
		A		4 ± 2	15*i* ± 2	71 ± 4
		Bw, Bt		5.9 ± 3	12*i* ± 1	76 ± 8
1 year	Burned	O	2	183 ± 232		
		A		66 ± 106	9*i* ± 1	77 ± 19
		Bt		8 ± 3	10*i* ± 3	102 ± 53
3 years	Burned	O	4	93 ± 106		
		A		42 ± 56	21*i* ± 1	77 ± 8
		Bw, Bt		7 ± 5	22*i* ± 3	85 ± 4
8+ years	Control	O	4	28 ± 17		
		A		7 ± 8	21*i* ± 9	91 ± 14
		Bw, BC		2 ± 1	20*i* ± 10	70 ± 10
8+ years	Burned	O	3	36 ± 52		
		A		2	10*i*	77
		Bw		3 ± 2	14*i* ± 3	72 ± 12
27+ years	Control	O	4	58 ± 50		
		A		2 ± 1	15*i* ± 2	77 ± 11
		Bw		2 ± 1	12*i* ± 3	81 ± 9
27+ years	Burned	O	5	32 ± 30		
		A		2 ± 1	16*i* ± 2	69 ± 23
		Bw, Bt		2 ± 1	11*i* ± 1	61 ± 29

Data displayed as average ± 90% confidence interval. *i* = significant interaction between plot and presence/absence of burn at $\alpha = 0.05$ using a two-way ANOVA.

presence/absence of fire was significant for A- and B-horizon CEC. Presence of fire and site characteristics (i.e. plot factor) such as slope and vegetative cover can combine to cause secondary effects, i.e. erosion, which affects cation exchange capacity in both the A and B horizons. The exposure of younger mineral materials would tend to lower CEC while the deposition of organic rich substrates that originated upslope would tend to increase CEC.

Base saturation was expected to increase after fire and return to control levels with time. No significant differences were found with either time since burn and presence or absence of fire. Both A and B horizons had a similar, high, base saturation. Kraemer and Hermann (1979) found an increase in base cations 25 years after a broadcast burn. In Kraemer and Hermann's study, burning may have concentrated exchangeable bases by consuming the organic material that bound the cations. Grier (1975) found a decrease in all base cations immediately after an intense wildfire; this was attributed to volatization and ash convection. The intensity of the lightning-strike fires at the FFS plots was likely too low to cause a loss of cations by either convection or volatization.

4. Summary and conclusions

Site factors, such as erosion of mineral and organic material, redeposition of this material, vegetation type and cover, and site productivity, appear to be controlling the variability of soil properties and not low-severity lightning-strike fires. Low-severity fire may be playing a smaller role than may be typically attributed to these ecosystesms (Jenny, 1980). This study shows that in these eastern Cascade Mountain ponderosa pine/Douglas-fir forests there is little difference in terms of soil properties between areas burned by low-severity lightning-caused fires and similar areas that remained unburned. These soils appear to be unchanged in the face of low-severity forest fires. It follows that the restoration of this ecosystem to pre-settlement conditions may only require managing vegetation and fuel. Further, the heterogeneity of these soil systems may result in these low-intensity fires having little significant effect at the stand level. The difficulty in detecting any difference between soils exposed to low-intensity fire and those left unburned may be due to the interplay of fire with these site characteristics giving rise to secondary effects. This large variability allows this system to have resilience, in other words it may take a severe disturbance to affect the properties of the soil great enough to be detected by our methods. The low-intensity fires do not provide the force needed to change the course of pedogenesis for this system. A fire with a higher intensity, and likely higher severity, may be required to change the development course of this soil. Secondary fire effects, such as erosion and redeposition, on steeply sloped sites such as these, may have greater effect on soils than the direct effects from fire.

Have these soils been changed by fire suppression? The answer is not clear from these study results, either due to variables or factors we did not measure or because these fires were of low severity and may not have caused a measurable change. These fires were suppressed by the Forest Service which could have contributed to their low impact on soil physical and chemical properties. Fires, within the range of reported fire-return intervals, did occur, but with little physical and chemical effects on the soil.

Does the long period of suppression lead to effects on soils? If we assume that there were no other fires since the early 1900s it may be that there is little detectable effect of fire suppression on soil properties. Soil processes appear to proceed with little effect from low-intensity fire-disturbance events. The variability of the soils on these sites may be the result of past disturbance and secondary effects from those disturbances. Pedogenic inertia could allow the spatial characteristics of historic disturbances to persist in the soil a long time, thus increasing variability. To detect any change in the soil, impacts would have to overcome the existing variability by either being large in size, to overwhelm the spatial extent, or high severity, to overwhelm the immediate effects of the previous disturbances. We suggest that secondary effects, such as erosion and redeposition of surface materials, may be a stronger factor in creating the high variability rather than direct effects from fires. The variability present on the sites may have been influenced by other historical fires of varying severity. Wildfires are not homogenous; within each fire there is a range of severity from high to low. The greater the range of fire severity present on a site, the greater the range of direct effects, and presumably a greater range of secondary effects would follow.

Due to fire suppression, these eastern Cascade Mountain ponderosa pine/Douglas-fir forests have large amounts of fuel that may support high-severity wildfires under appropriate conditions. Restoration efforts through thinning and/or prescribed fire could reduce fuel loads. This study indicates that a low-severity prescribed fire, if similar to a lightning-strike fire, is likely to have little direct effect on the soils' physical and chemical properties, suggesting that little effort will be needed for belowground restoration as long as efforts are made to minimize indirect effects on the soil.

Acknowledgement

This is Contribution Number 76 of the National Fire and Fire Surrogate Project (FFS), funded by the U.S. Joint Fire Science Program.

References

Agee, J.K., 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Covelo, CA.

Baird, M., 1998. Wildfire Effects on Nutrient Capitals in Inland Coniferous Forests. College of Forest Resources University of Washington, Seattle, WA.

Baird, M., Zabowski, D., Everett, R.L., 1999. Wildfire effects on carbon and nitrogen in inland coniferous forests. Plant Soil 209, 233–243.

Barrett, S.W., Arno, S.F., 1988. Increment-borer methods for determining fire history in coniferous forests. USDA For. Serv. Gen. Tech. Re INT-GTR-244, pp. 1–15.

Choromanska, U., DeLuca, T.H., 2001. Prescribed fire alters the impact of wildfire on soil biochemical properties in a ponderosa pine forest. Soil Sci. Soc. Am. J. 65, 232–238.

Covington, W.W., Sackett, S.S., 1984. The effects of a prescribed burn in southwestern ponderosa pine on organic matter and nutrients in woody debris and forest floor. For. Sci. 30, 183–192.

DeBano, L.F., 2000. The role of fire and soil heating on water repellency in wildland environments: a review. J. Hydrol. 231–232, 195–206.

DeBano, L.F., Neary, D.G., Ffolliott, P.F., 1998. Fire's Effects on Ecosystems. Wiley, New York.

Dolan, E., 2002. Soil and Site Variability in the Northeast Wenatchee Mountains, Washington. College of Forest Resources University of Washington, Seattle, WA.

Everett, R.L., Schellhaas, R., Keenum, D., Spurbeck, D., Ohlson, P., 2000. Fire history in the ponderosa pine/Douglas-fir forests on the east slope of the Washington Cascades. For. Ecol. Manage. 129, 207–225.

Finch, R.B., 1984. Fire history of selected sites on the Okanogan National Forest. Undocumented Report. USDA For. Serv., Pacific Northwest Region, Okanogan National Forest, Okanogan, WA.

Franklin, J.C., Dyrness, C.T., 1988. Natural Vegetation of Oregon and Washington. Oregon State University Press, Corvalis, OR.

Grier, C.C., 1975. Wildfire effects on nutrient distribution and leaching in a coniferous ecosystem. Can. J. For. Res. 5, 599–607.

Huffman, E.L., MacDonald, L.H., Stednick, J.D., 2001. Strength and persistence of fire-induced soil hydrophobicity under ponderosa pine and lodgepole pine. Colorado Front Range Hydrol. Process. 15, 2877–2892.

Jenny, Hans, 1980. The Soil Resource. Springer-Verlag, New York.

Kraemer, J.F., Hermann, R.K., 1979. Broadcast burning: 25-year effects on forest soils in the western flanks of the Cascade Mountains. For. Sci. 25, 427–439.

Monleon, V.J., Cromack Jr., K., Landsberg, J.D., 1997. Short- and long-term effects of prescribed underburning on nitrogen availability in ponderosa pine stands in central Oregon. Can. J. For. Res. 27, 369–378.

Natural Resource Conservation Service (NRCS), 2001a. National water and climate center: average air temperature. USDA. Available at ftp://ftp.wcc.nrcs.usda.gov/data/climate/table/temperature/history/washington/20b02s_tavg.txt (accessed 8 April 2003; verified 13 June 2005).

Natural Resource Conservation Service (NRCS), 2001b. National water and climate center: Washington monthly precipitation averages: 1961–1990. USDA. Available at ftp://ftp.wcc.nrcs.usda.gov/data/snow/ads/wa/wa6190pr.html (accessed 8 April 2003; verified 13 June 2005).

Olsen, S., Sommers, L., 1982. Phosphorus. In: Page, A.L. (Ed.), Methods of Soils Analysis. Part II. Agron, Monograph 9. 2nd ed. ASA/SSA, Madison, WI.

Skinner, M.F., Zabowski, D., Harrison, R., Lowe, A., Xue, D., 2001. Measuring the cation exchange capacity of forest soils. Commun. Soil. Sci. Plant Anal. 32, 1751–1764.

Soil Survey Staff, 1995. Cashmere Mountain soil survey: Leavenworth Ranger District soil handbook: non-wilderness. Preliminary report.

SPSS, 2000. SPSS Version 10.1 SPSS, Chicago, IL.

Tabor, R.W., Waitt Jr., R.B., Frizzell Jr., V.A., Swanson, D.A., Byerly, G.R., Bentley, R.D., 1982. Geologic map of the Wenatchee Quadrangle, Central Washington. United States Geological Survey Investigation Map I-1311. Scale 1:100,000. Washington, USA.

Wagle, R.F., Kitchen, J.H., 1972. Influence of fire on soil nutrients in a ponderosa pine type. Ecology 53, 118–125.

Woodmansee, R.G., Wallach, L.S., 1981. Effects of fire regimes on biogeochemical cycles. In: Clark, F.E., Rosswall, T. (Eds.), Terrestrial Nitrogen Cycles. Ecological Bulletin (Stockholm), vol. 33. pp. 649–669.