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Soil Response to Season and Interval of Prescribed Fire in a Ponderosa Pine Forest of the Blue Mountains, Oregon

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Proposal Title: Does season of burn and burn interval affect soil productivity and
processes in a ponderosa pine ecosystem?

Project Location: Malheur National Forest, Burns, Oregon

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Executive Summary

Soil properties were examined at a season of burn and burn interval study located in the Malheur National for responses to prescribed burns used to reduce fuel loads and wildfire hazard. Prescribed burn comparisons included spring vs. fall burning, with either one 15-year interval burn or two 5-year interval burns of each season. Results showed that major change to soil organic matter was a reduction in the amount of O horizon. The percent bare ground increased with both spring and fall burning and was highest with multiple burns, indicating a loss of O horizon cover. There was also a decrease in O horizon thickness, particularly with two fall burns. Overall ecosystem C decreased by 21-31 percent with the prescribed burns. Extractable ammonium and phosphorus increased with the multiple burns relative to the single burn, but was similar to the controls. The flush of nutrients available following the burns may not persist more than 5 years. No burn effects were seen on soil cation exchange capacity or percent base saturation, possibly due to the high CEC and base cations in these soils.   Soil temperatures were found to be highest with fall burns, particularly the 5-year interval burns. However, the soil moisture was also slightly higher with the 5-year interval burns, possibly due to decrease transpiration from reduced vegetation. Results to date suggest that the frequent fall burns may be harsher for soils than less frequent burns or spring burns, but could be used if needed, however they will reduce ecosystem C pools.

INTRODUCTION

Fire exclusion and timber harvesting practices over the last 100 years have caused fuel loads to increase and changed the vegetative community of Ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws) forests in the inland Western U.S. Consequently, an increasing number of catastrophic wildfires has occurred aided by recent climate trends (Tiedemann et al., 2000; Wright and Agee, 2004). To avoid such wildfires, managers use prescribed burning to reduce fuel loads and return ecosystem structure to that of the late 1800's. However, many of the effects of these prescribed burns on soils, ecosystem health, and site productivity are poorly understood. The impact to the ecosystem caused by this restoration process is primarily dependent on the severity of the prescribed fire, which is managed by burning in either the fall or spring.

Historically, fires burned through these forests during the summer when fuels were dry, but frequent burning limited fuels resulting in low-severity fires (Agee, 1993). Heyerdahl (2001) found fire-return-intervals as short as 5 years in drier areas of the Blue Mountains of Oregon. Prescribed fires in ponderosa pine forests are frequently ignited during the spring when fuel moisture is high and fire behavior is controllable. Fall burning can be of moderate to high intensity since the fuels have dried during the summer months and may represent the natural fire-severity better than the low-severity spring burn. The higher severity of fall burning would have a larger impact on accumulated fuels, but the current high fuel load may result in higher fire severity, which could be detrimental to management goals of preserving soil processes and restoring vegetation. Soils are a critical component of these ecosystems as they are the source of a forest's productivity and are readily affected by management decisions. Changes in soil processes can affect broader ecosystem processes such as productivity and biodiversity. Very few studies have characterized the difference between spring and fall burning or burn interval on ecosystem components, especially soils.

Fire effects on soils

Fire affects soil through its ability to transform soil organic matter (SOM) and change ecosystem components. These transformations lead to outputs of volatilized and combusted C and nutrients as well as the convection of ash material. Fire mineralizes organically bound elements such as N, P, and base cations into more mobile mineralized forms that are available for uptake by plants or leached from the soil system (DeBano et al. 1998). Fire also creates charcoal and alters SOM which may have significant effects on post-fire C cycling and nutrient availability. The consumption of canopy and ground cover may lead to changes in physical factors such as soil moisture and temperature that may affect post-fire C cycling and nutrient cycling. These alterations are dependent on fire severity.

When carbonaceous material in the O horizon is combusted total OM pools are reduced however the concentration of the elements remaining in the ash is principally dependent on temperature. Combustion of organic materials begins between 200 and 315°C; N containing substances are slightly more resistant, beginning to combust at temperatures between 200 and 400°C (Neary et al. 1999). Hatten (2007) found that N was concentrated relative to C during low severity fires while higher severity fires were characterized by an equal loss of C and N as a

proportion of combusted OM. High severity fires are required to volatilize organically bound P and K (777 ^{o}C) and even higher temperatures (>1484°C) are required to volatilize Ca (Raison et al. 1985). These temperatures are not often reached so that these nutrients are either left as ash, and enrich the mineral soil, or are caught up in the smoke plume and taken off site. After low severity fire, ash, unburned O horizon and plant material may be incorporated into the surface mineral horizon thereby increasing the pools of C and N (Johnson and Curtis, 2001; Certini, 2005). On the other hand high severity fires may consume the entire O horizon and significantly heat the mineral soil. In this situation mineral soil C and N pools may decrease due to the materials being directly volatilized or combusted and little residue from the O horizon remains for be incorporation into the mineral soil.

Multiple treatments of prescribed fire may be necessary to obtain the desired forest conditions especially if the burn applications are low severity. The frequency with which fires are applied will determine if fire-induced changes accumulate or if the forest is able to recover between burn applications. Soil carbon recovery largely depends on ecosystem productivity and litterfall, while recovery of N largely depends on atmospheric deposition and N-fixation. Some researchers believe that low-severity fires may increase soil C and N over successive burns due to the more favorable environment for N-fixers and incorporation of unburned-dead residues into the mineral soil (Johnson and Curtis, 2001). If the soil processes and pools that are affected by fire do not completely recover before a subsequent fire, then the effect of the fire becomes additive over time. The interaction of frequency and intensity may achieve some desired outcomes such as fuel reduction, but may cause cumulative impacts on soil nutrients and soil organic matter (SOM), potentially impacting forest productivity.

In general the chemical changes that occur in SOM after heating and combustion are increases in aromatic structures with disproportionate losses of H and O relative to C (Almendros, 1990; Baldock and Smernick, 2002; Almendros et al., 2003; Gonzalez-Vila and Almendros, 2003; Gonzalez- Perez et al., 2004; Knicker et al., 2005). Increasing heating severity on SOM has been shown to decrease the oxygen content, thereby reducing fulvic acid (FA) and humic acid (HA) fractions while increasing humin content and aromaticity (Almendros et al., 1990; Fernandez et al., 1997, 2001, and 2004).

The consumption and transformation of SOM by fire leads to competing results on N availability to plants. Nitrogen is consumed and released by fire so that directly after burning there is less N but the remaining N is usually made more available directly after fire (Neary et al. 1999). Over time the available N is either leached or immobilized in microbes or plants so after several years N is less available (Monleon and Cromack, 1997). Additionally, the creation of recalcitrant SOM may also reduce N availability after a fire (Guinto, 1999b). These transformations are likely dependent on fire severity however few studies have examined the effect of varying fire severity in a natural setting on N availability, especially in terms of season of prescribed burning or burn interval.

Organic matter can provide a significant portion of the soil's CEC (Stevenson, 1994). When organic matter is removed by fire the soil's CEC can be reduced (Giovannini et. al., 1990). Even if the fire does not completely remove the organic matter, the quality of the remaining material may initially have a lower number of exchange sites. However, charcoal added to soil

has been shown to increase CEC after the charcoal as had time to age (Liang et al. 2006). In the short-term, fire may decrease CEC of a soil due to decreasing SOM and SOM quality, but increase CEC over the long-term from the incorporation of charcoal.

Soil Water

In forests such as those of eastern central Oregon, water availability is a major limitation to growth and forest health. It is well known that pine beetles, for example, will attack drought stressed trees (Mattson and Hack 1988). While fire directly affects many soil properties during and immediately after a burn, it may also alter soil components such as humus which can have longer term affects on soil and ecosystem properties. Losses of surface litter can result in increased soil evaporation, higher soil temperatures and alter site microclimate affecting tree demand for water. Likewise, hydrophobicity may decrease soil water infiltration also reducing water availability. There will be an offset of reduced water availability to trees if there is reduced understory competition for soil water. Iverson and Hutchinson (2002) found elevated soil temperatures and seasonal changes in soil moisture in eastern oak forests following prescribed burning. Swift et al. (1993) found elevated soil moisture using fell and burn practices for site preparation in an eastern pine-hardwood stand. On the other hand, Wayman et al. (2007) found that burning did not have an effect on soil moisture of a mixed-conifer forest of the Sierra Nevada unless it was accompanied by thinning, no indication of burn severity was given. Longer-term fire effects on soil moisture and temperature have not been documented.

Tree growth

The effect of prescribed fire on tree growth appears to be dependent on fire severity. Landsberg (1994) reviewed the effects of prescribed fire and found that growth by *Pinus* species decreased due to root and crown injury. On the other hand no effect on ponderosa pine growth was detected after 8 and 9 years after fall and spring prescribed fire (Sala et al., 2005). On a site in Queensland Australia Guinto (1999a) found that fire frequency, site moisture, and tree species were important factors in determining growth response of trees, with some species increasing growth with fire and others decreasing. Tree productivity may be affected by changes in resource availability, such as water and nutrients, which may be affected by season or interval of burn.

A season of burn and burn interval study was begun in the southern Blue Mountains of eastern Oregon in 1997. This study provided an opportunity to examine prescribed burn severity (season) and repeated burn effects on soil. The objectives of this study were to
1. Assess effects of season of burn and burn interval on water availability.
2. Determine if available nutrients or CEC have been altered by either season of burn or burn repetition.
3. Quantify soil carbon with all burn treatments and determine if repeated prescribed burning or season of burn has altered total ecosystem carbon and nitrogen pools.

MATERIALS AND METHODS

Site characteristics

The study site is located within the Malheur National Forest of the southern Blue Mountains of eastern Oregon (43°52'41"N/ 118°46'19"W). Elevation ranged from 1585-1815 m (5200-5955 ft) (Table 1). Ponderosa pine is the dominant tree with some western juniper (*Juniperus occidentalis* Hook.) and mountain mahogany (*Cercocarpus ledifolius* Nutt.) in drier areas that have shallow soils. The ponderosa pine trees are predominantly between 80 and 100 years old; the sites were thinned in either 1994 or 1995. Kerns et al. (2006) found that grasses and sedges that dominate the understory include Idaho fescue (*Festuca idahoensis* Elmer), bluebunch wheatgrass (*Agropyron spicatum* (Pursh)), sedges (*Carex* spp.), bottlebrush squirreltail (*Sitanion hystrix* (Nutt.)), Great Basin wild rye (*Elymus cinereus* Scribn. & Merr.), California Brome (*Bromus carinatus* H. & A.), and western needlegrass (*Stipa occidentalis* Thurb.). Herbaceous cover consists of parsnipflower buckwheat (*Eriogonum heracleoides* Nuttall.), and large flowered collimia (*Collomia grandiflora* Douglas Ex Lindl.). Tailcup lupine (*Lupinus caudatus* Kellogg) and snowbrush (*Ceanothus velutinus* Dougl. ex Hook) are the N-fixers with the highest coverage on these sites(Becky Kerns personal communication). Shrub cover is dominated by sage brush (*Artemesia tridentate* Nutt.), Oregon grape (*Berberis repens* Lindl.), and rabbitbrush (*Chrysothamnus* Nutt. Spp.).

Table 1. Site characteristics and soil classifications (means±standard deviation) of season and interval of burn study. Soils classified by Carlson (1974) were confirmed and some Alfisols and Inceptisols occurrence determined on the sites.

Block	Elevation (m)			Aspect	Slope (%)			Soil Classifications
Driveway 14	1585	-	1645	S	13	±	4	Lithic Argixerolls, Vertic Argixerolls
Driveway 17	1615	-	1700	S	6	±	2	Lithic Argixerolls, Vertic Argixerolls, Alfisols
Driveway 26	1660	-	1730	NE	8	±	5	Lithic Haploxerolls, Vertic Argixerolls, Lithic Argixerolls
Driveway 28	1700	-	1815	SE	6	±	6	Lithic Haploxerolls, Vertic Argixerolls, Lithic Argixerolls, Alfisols
Kidd Flat	1675	-	1735	NE	6	±	1	Lithic Argixerolls, Inceptisols
Trout	1655	-	1675	W	3	±	1	Lithic Argixerolls, Inceptisols

Parent materials of the study sites consist of basalt, andesite, rhyolite, tuffaceous interflow, altered tuffs, and breccia (Carlson 1974). In addition, the soil has received ash from pre-historic eruptions of ancient Mount Mazama and other volcanos in the Cascade Mountains to the west (Powers and Wilcox 1964). The soils from the research site are generally dominated by Mollisols, but Inceptisols and Alfisols also are present (Table 1).

At the Rock Spring SNOTEL station (44°0'N/ 118°50W), about 25 km WNW of the study site, annual precipitation averages 46 cm with 80% falling as snow between November and April (NRCS 2007). Summers are dry and hot (17 ^{o}C mean air temperature in July-August) with cold winters (-3 ^{o}C mean air temperature in December-February).

Experimental design and treatment description

Six replicate study blocks were established and divided into 3 plots of similar stand type, aspect, slope, and parent materials (described by Thies *et al*. 2006a). Plot boundaries were established along roads and topographic features to control the prescribed burns. Each plot was randomly assigned as control, fall, or spring burn treatment. A burn interval of 5 or 15 years was assigned to a randomly designated half of each season's plot. The 5 treatment plots were of similar size (ranging from 6 to13 ha) within each block.

Fires were ignited by hand-carried drip torches using a multiple-strip head-fire pattern. Flame lengths were maintained at 60 cm during all burns. Fall burns were initiated in October 1997 and reburned in 2002. Spring burns were initiated in June 1998 and reburned in 2003. Temperature, humidity, and wind speed and direction were similar during the application of all burns. At the time of soil sampling (summer of 2004), the 5-year-interval plots had burned twice with 1-2 years of recovery while the 15-year interval plots had burned only once with 6-7 years of recovery.

Sample collection

A transect of 8 points with 50 or 100 m spacing (depending on size of the particular plot) was established in each plot. Starting points and bearing were randomly chosen. Aspect, slope, and geomorphic shape were recorded at each point. Canopy cover was measured by estimating the amount of sky reflected off of a convex mirror held at chest level. A 4 m^2 plot was used to characterize vegetative and bare ground coverage at each sample point. Ground cover estimates of coarse woody debris (CWD), bare ground, grass, forbs, shrubs, and eroded soil were made. Burn severity was classified as low, moderate, or high at each point by examining char height on trees, tree mortality, organic matter consumption, and presence of char. A low-severity fire would produce char heights less than 2 m on a tree bole and consumed little of the O horizon. Moderate-severity fires produce char heights higher than 2 m and left a thin layer of char on the surface of the soil. High-severity fire was designated when tree mortality was high and little O horizon remained.

A 10 m diameter circular plot centered on each grid point was used to characterize the overstory vegetation. Each tree's species was noted and diameter at breast height (DBH) recorded. Where possible, short cores were removed from three representative trees with an increment borer to determine recent growth. After mounting and sanding 312 cores were scanned using a high resolution scanner and the resulting images were analyzed using WinDendro software. Each growth ring was identified and measured to the nearest 1 µm. Pre-treatment growth was compared with post-treatment growth by calculating average growth increment for the 7 years since treatments began (1998-2004) and prior to treatment initiation (1991-1997. The ratio of pre-treatment to post-treatment growth was radial wood increment (RWI) and was calculated using the following formula:

$$RWI=GI_{1998\text{-}2004}/GI_{1991\text{-}1997} \tag{1}$$

Where $GI_{1998\text{-}2004}$ is the average yearly growth increment since treatments were initiated in 1997 and $GI_{1991\text{-}1997}$ is the average yearly growth increment prior to treatment initiation.

To convert growth increment to basal growth increment, the DBH for the year of interest was calculated using the following formula:

$$DBH_Y=(DBH_{2004}-\Sigma(GI_{2004},GI_{2003},\ldots GI_Y)) \tag{2}$$

where DBH_Y is the diameter at breast height for any given year, and GI_{2004}, GI_{2003}, and GI_Y is the growth increment for 2004, 2003 and to any given year. Then basal area increment (BAI) was calculated using the following formula:

$$BAI_Y=[(\pi((DBH_Y-B_Y)/2)^2))- (\pi(((DBH_Y-GI_Y)-B_Y)/2)^2 \tag{3}$$

where B_Y is the bark thickness for any given year. Bark thickness was estimated to be 2, 3, 4, 5, and 6 cm thick for DBH classes <30, 30-50, 50-70, 70-90, >90 cm, respectively (Jim Agee, personal communication). Basal area accounts for the radial growth of each tree, however there still may be pre-existing differences among the treatments. To correct for these differences and find treatment effects, the BAI as a proportion of total basal area was calculated. The BAI of each cored tree was calculated for each year and is expressed as a proportion of basal area using the following formula:

$$PBAI_Y = BAI_Y / [\pi((DBH_Y- B_Y)/2)^2] \tag{4}$$

where $PBAI_Y$ is the basal area increment as a proportion of basal are for any given year. To determine if there was any change in growth since treatment initiation, which may not be detected by examining individual years, the total basal area growth as a proportion of 2004 basal area was calculated using the following formula:

$$PBAI_{1997\text{-}2004}=(BA_{2004}-BA_{1997})/BA_{2004} \tag{5}$$

Where $PBAI_{1997\text{-}2004}$ is the proportion of 2004 basal area that was produced between 1997 and 2004, BA_{2004} is the measured basal area in 2004, and BA_{1997} is the calculated basal area in 1997.

(*e.g.,* lignin and cellulose) from the O horizons. The supernatant solution and one rinse containing fulvic acid (FA) and humic acid (HA) fractions were collected for further processing. Humin or NS fractions were dried in a convection oven at 50 $^{\circ}$C, weighed, prepared for loss on ignition (LOI; heated to 550 $^{\circ}$C for 6 hours in a muffle furnace), and C, H, and N analysis. The supernatant containing FA and HA was acidified to pH 1 using 6 N HCl and allowed to stand overnight to precipitate HA. Fulvic acid was separated from HA by centrifugation at a force of 6635g for 10 minutes. Humic acid was freeze dried in a benchtop lypholizer, weighed, and stored in a light-protected dessicator.

The samples containing FA were purified to remove base-extracted acid-soluble non-humic materials and salts using a method adapted from Swift (1996). The solution containing FA was passed through a column containing 60 mL of DAX-8 resin (Supelco Supelite^{TM} DAX-8; methyl methacrylate ester). The column was rinsed with 2 bed-volumes of deionized H_2O, and then eluted with 2 bed-volumes of 0.1 N NaOH. The eluate containing FA was collected and passed over a column containing Dowex H^+ exchange resin to remove Na^+. The solution containing FA was freeze dried, weighed, and stored in a light-protected dessicator. Prior to C, H, and N analysis, FA and HA samples were placed in pre-weighed tins and dried at 50 $^{\circ}$C for 48 hours. Fulvic acid and HA subsamples were analyzed for C, H, and N concentration.

Soil water

During the summer of 2005 one soil moisture monitoring station location was chosen within each plot (N=30). Soil pits were excavated to 1 m depth or lowest possible horizon using hand tools. Horizons were identified and recorded with thickness and field determined texture. Decagon ECH$_2$0 EC-10 soil moisture probes were installed at 7.5 and 25 cm depth in all monitoring locations and at 50 cm (N=28) and 100 cm (N=13) at locations that allowed soils to be excavated to that depth or coarse content did not interfere with installation. A temperature probe was installed at 2 cm depth. The moisture and temperature probes were connected to a Decagon EM-5 5-channel data logger that collected a reading from each sensor once per day (midnight).

Growing season conditions begin near the time of snow melt in the spring and when freezing soil temperatures that would effectively stop any biologic activity begin to rise. Lopushinsky and Max (1990) report that root growth of ponderosa pine and other conifer species began when soil temperatures reached 5 $^{\circ}$C. Low soil moisture availability ends the growing season sometime during the summer when it falls below the plant wilting point (PWP) of 1500 kPa, for an extended period (GS$_E$). Late summer, or early fall, rains cause the soil moisture to rise above the PWP and initiate a possible late growing season (GS$_L$) that lasts until soil temperatures fall below 5 $^{\circ}$C. Growing seasons were calculated for late 2005, early 2006, late 2006, and early 2007 using 2 temperature and soil moisture indicators. The date when soil temperature was higher than 5 $^{\circ}$C for at least 7 days was considered to be the initiation of the growing season. During 2006 and 2007 the average date of growing season initiation occurred 11 and 33 days after zero snow water equivalent (SWE) occurred at the nearby Rock Spring SNOTEL Station, and therefore reasonably estimates the beginning of the growing season. The date at which soil temperature dropped below 5 $^{\circ}$C for at least 7 days was the end of the late growing season, which usually occurring in the late fall. During 2005 and 2006 the all plots

were within ±4 days (95% CI) of each other so any missing dates were replaced with the average date that temperature was less than 5 ^{o}C for at least 7 days. For 2005 and 2006 the end of the growing season occurred 10 days before and 14 days after, respectively, there was measureable SWE at the Rock Springs SNOTEL station. The maximum length of each year's growing season was calculated using the following equation:

$$GS_{max} = T_{>5 ^oC} - T_{<5 ^oC} \qquad (6)$$

where GS_{max} is the maximum length of the growing season, $T_{>5 ^oC}$ is the number of days after January 1 at which the soil temperature is higher than 5 ^{o}C for at least 7 days, and $T_{<5 ^oC}$ is the number of days after January 1 at which the soil temperature drops below 5 ^{o}C for at least 7 days.

For each depth the PWP (1500 kPa) was determined by inputting texture and OM content of each depth into a system of equations developed by Saxton and Rawls (2006). The date at which the PWP was achieved for at least 7 days during the spring or summer was the end of the early growing season while the point when soil wetted and the plant wilting point was passed in the late summer/fall was the beginning of the late growing season. Growing seasons were calculated for the 7.5, 25, 50, and 100 cm depths. An average moisture content and PWP was calculated for each depth using a weighted average for all probes above, and including, the depth of interest.

Length of early growing season was calculated by the following formula:

$$GS_E = T_{>5 ^oC} - M_{<1500kPa} \qquad (7)$$

where GS_E is the length of the early growing season and $M_{<1500kPa}$ is the number of days after January 1 at which the soil moisture drops below the plant wilting point of 1500kPa for at least 10 days. The length of the late growing season was calculated using a similar formula:

$$GS_L = M_{>1500kPa} - T_{<5 ^oC} \qquad (8)$$

where GS_L is the length of the late growing season, and $M_{<1500kPa}$ is the number of days after January 1 at which the soil moisture rises above the plant wilting point of 1500kPa for at least 7 days.

Statistical analysis

To analyze the soil, average values for each horizon or depth were calculated for each treatment within each study block (6 replicates), N=30 for each horizon. Cover, RWI, and BAI were analyzed by averaging the values for each by grid point and then each plot for a N=30 for each measurement. The experimental design was treated as a completely randomized block (2 by 2 factorial with season and interval of burn) with an augmented control. Differences between the soil and site characteristics from the control, 2 fall burns, 1 fall burn, 2 spring burns, and 1 spring burn were tested using a one factor ANOVA. Tukey's HSD was used to delineate significant homogenous subsets among the 5 treatments. Orthogonal contrasts were conducted to determine if season, number of burns, or the interaction of the two created significant

differences within the 2 by 2 factorial of season and interval of burn. A significance level of α=0.10 was used for all statistical tests.

RESULTS AND DISCUSSION

Soil cover characteristics

Prescribed fire applied in the fall imparted a slightly higher estimated severity than spring burns (Table 2). Canopy cover was lowest on the fall burn plots partly as a result of higher tree mortality after the initial burn as reported by Thies et al. (2005 and 2006b). Coarse woody debris cover was also lowered by burning and Thies et al. (2006a) found that the second fall and spring burn reduced woody fuels 85 and 75%, respectively, relative to the control. The greatest reduction in woody fuel was caused by fall burning. Highest tree mortality occurred after the initial fall burn, suggesting that the initial fall burns were the most severe.

Table 2. Canopy and ground cover characteristics after 1 or 2 prescribed fires applied during the fall or spring. Data are displayed as means±standard deviation. Significant (α=0.1) differences are in bold as determined by a one-factor ANOVA (p) and orthogonal contrasts for season (p_s) and number of burns ($p_#$). Interaction between season and number of burns was not significant. Letters indicate similar subsets (rows) using Tukey's HSD. CWD indicates coarse woody debris surface cover.

	Control	Fall		Spring		p	p_s	$p_#$
		2	1	2	1			
Estimated Burn Intensity	--	Low-Mod.	Low-Mod.	Low	Low			
CWD (%)	13 ± 6^a	5 ± 3^b	7 ± 3^b	7 ± 2^b	10 ± 2^{ab}	*0.014*	*0.205*	*0.124*
Bare Ground (%)	11 ± 7^a	28 ± 9^b	21 ± 9^{ab}	22 ± 12^{ab}	13 ± 10^a	*0.012*	*0.043*	*0.031*
Grass (%)	11 ± 8^{ab}	8 ± 2^{ab}	14 ± 8^b	5 ± 3^a	11 ± 7^{ab}	*0.099*	*0.156*	*0.019*
Canopy (%)	37 ± 9^{bc}	24 ± 8^a	25 ± 9^{ab}	33 ± 6^{abc}	41 ± 8^a	*0.006*	*0.001*	*0.142*

It appears that burn severity is affecting the understory species composition. Plots burned twice have reduced grass coverage relative to both controls and plots burned once. Fall burns had a slightly elevated coverage of forb species relative to spring burning (*p=0.058*). Similarly,

Kerns et al. (2006) found reduced grass cover after the initial spring burn and increased forb coverage after the initial fall burn.

Repeated burning can decrease O horizon coverage and with reductions in grass cover can expose the mineral soil surface to erosion. Percent bare ground increased after burning in the fall and spring and was highest on plots burned twice. This suggests increased erosion risk and there was a small significant ($p=0.089$) increase in the percent of evident surface soil erosion on plots treated with 2 burns relative to plots with one burn (7% and 4% respectively). However, the increased incidence of erosion could be reflecting a higher coverage of bare ground, allowing the evidence of erosion to be more observable.

Soil characteristics and available nutrients

The two fall burns significantly decreased O horizon thickness to 65% of the control (Figure 1). With one fall and two spring burns, O horizon thicknesses was reduced by approximately 30%, but this reduction was not significantly different from the control. Similar to the current study, forest floor reduction caused by spring and fall prescribed burns was found to be 77 and 94%, respectively. Fall burning consumed more fuel due to lower fuel moisture (Knapp et al. 2005). Time since burning (1-7 years) allowed litter to accumulate increasing the observed O horizon thickness and reducing the proportion of difference with the control. Fall burning at 5-year intervals may keep O horizon thickness thin and patchy, exposing mineral soil to erosion and reducing organic matter inputs to the mineral soil.
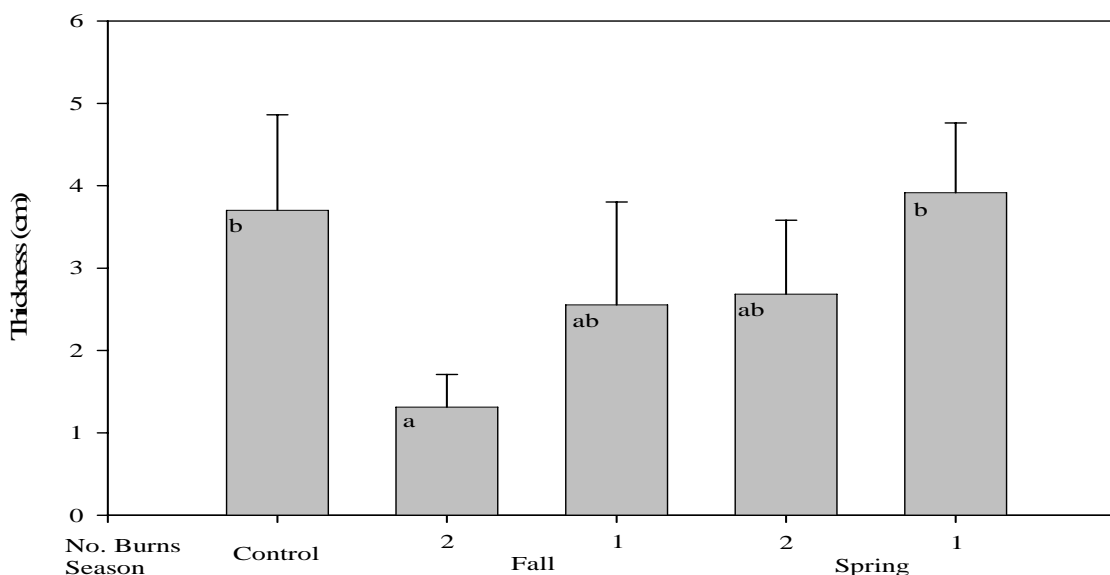
Figure 1. O horizon thickness (mean ± standard deviation) in plots treated with 1 or 2 fall or spring burns (n=6). Significant ($\alpha=0.1$) differences between treatments were determined by a one-factor ANOVA. Letters indicate similar subsets using Tukey's HSD.

O horizon thickness from plots treated to only one spring burn was not significantly different from the control. The lower severity of the spring burns removed a smaller portion of

O horizon and time since burning (6-7 years) has allowed O horizon depth to recover to control levels. Approximately 2.4 cm of O horizon has accumulated since the initial fall and spring burns, when O horizons were measured by Smith et al. (2004). O horizon thickness of the plots with one spring burn appear to have completely recovered sooner than plots with one fall burn, implying that it remained and has protected the mineral soil from erosion. Additionally, organic matter and nutrient inputs from the O horizon to the mineral soil are being maintained on the plots with one spring burn.

Water repellency at the surface of the A horizon was lowest on fall burn treatments and significantly negatively correlated with bare ground coverage (R=-0.522; *p=0.003*) (Table 3). Unobserved erosion occurring after the initial fall burn could have removed fire-produced hydrophobic materials from the surface of the A horizon. Hydrophobic O horizon materials were removed by fire, thereby reducing inputs of hydrophobic materials into the mineral soil. Further, mycelia of fungi have been shown to promote hydrophobicity along with litter of certain plants (Doerr et al. 2000). Smith et al. (2004) found that the initial fall burns of these sites had significantly reduced live ectomycorrhizal root biomass and ectomycorrhizal fungi species richness in the surface 10 cm. The higher severity initial fall burn may have caused a decrease in hydrophobic compounds in both the O and A horizons and reduced the populations of fungal species that produce hydrophobic materials. Thus, the higher severity fall burns reduced natural hydrophobicity and it remains low, but the lower severity spring burn maintained mineral soil hydrophobicity.

O and A horizon pH values were slightly elevated by burning with the more recent higher-severity fall burns (Table 3). Ash produced by burning contains hydroxides and carbonates which raised soil pH (Ulery et al. 1993). There was a significant interaction between season and number of burns on the A horizon pH. Soil pH from plots with two spring burns may be influenced by a reduction in understory grass and grass litter. Additionally, a recent influx of fresh litter containing organic acids from fire-induced litterfall could have lowered the pH. The mineral soil pH of the control burns may be lower than historical levels due to the lack of fire for the last 100 years. If fall burning replicates the severity of fires that historically burned these forests, then pH may have returned to pre-fire suppression levels on these plots.

Similar to pH, the labile P concentration may be elevated by ash left on site after burning (Figure 2). The most recent fall burning has significantly increased the labile P concentration over the control. Since 2 fall burns had the greatest amount of O horizon consumed there was also likely the largest amount ash produced providing increased P in an inorganic form such as Ca phosphates that would be extracted by dilute acid-fluoride solution (Bray extraction) (Olsen and Sommers 1982). The elevated available P levels may benefit the trees and understory plants, which may experience deficiencies otherwise due to a lower level of mycorrhizal fungi on the fall burned plots as shown by Smith et al. (2004).

Burning had no effect on the soil's ability to store and exchange nutrients as measured by cation exchange capacity (CEC) and % base saturation (%BS) (Table 3). The CEC and %BS of these soils is very high, likely as a result of high C content (the relationship between C concentration and CEC has an R=0.578 and *p=0.001*) and low levels of precipitation and leaching. Even though there has been little effect on CEC and %BS by burning, any further

reduction in mineral soil C by future burning could lead to a reduced ability of the soil to store and exchange nutrients.

Table 3. Soil characteristics (mean ± standard deviation) in plots treated with 1 or 2 fall or spring burns (n=6). Significant (α=0.1) p-values are in bold as determined by a one-factor ANOVA (p) and orthogonal contrasts for season (p_s), number of burns ($p_{\#}$), and interaction of season and number of burns ($p_{s*\#}$). Letters indicate similar subsets (rows) using Tukey's HSD. Abbreviations are: CEC=cation exchange capacity and BS=base saturation.

	Hor.	Control	Fall 2	Fall 1	Spring 2	Spring 1	p	p_s	$p_{\#}$	$p_{s*\#}$
pH	O	5.01±0.40[ab]	5.34±0.11[c]	5.26±0.07[bc]	4.93±0.13[a]	5.07±0.10[abc]	***0.004***	***0.001***	*0.655*	*0.150*
	A	6.04±0.22[ab]	6.29±0.07[b]	6.26±0.17[ab]	5.91±0.13[a]	6.14±0.05[ab]	***0.070***	***0.018***	*0.334*	*0.208*
	B	6.24±0.25	6.28±0.08	6.30±0.11	6.29±0.11	6.35±0.06	*0.896*	*0.627*	*0.568*	*0.716*
C (%)	O	40.9±5.1[abc]	39.1±1.8[ab]	38.0±1.8[a]	42.9±1.5[bc]	42.9±2.0[c]	***0.015***	***0.001***	*0.619*	*0.657*
	A	5.30±2.08	5.55±0.61	5.02±0.77	6.34±0.74	6.36±0.75	*0.379*	***0.081***	*0.664*	*0.642*
	B	2.64±1.15	2.75±0.56	2.00±0.22	2.28±0.18	2.75±0.23	*0.443*	*0.587*	*0.841*	*0.081*
N (%)	O	1.01±0.14[ab]	0.90±0.03[a]	0.98±0.03[ab]	1.05±0.04[ab]	1.09±0.06[b]	***0.046***	***0.006***	*0.155*	*0.606*
	A	0.30±0.14	0.30±0.02	0.28±0.03	0.33±0.04	0.33±0.05	*0.843*	*0.319*	*0.761*	*0.723*
	B	0.14±0.07	0.14±0.03	0.13±0.01	0.12±0.01	0.14±0.03	*0.964*	*0.798*	*0.905*	*0.529*
C:N	O	42.7±6.4[ab]	46.8±1.5b	39.7±1.3[a]	45.3±3.8[ab]	41.8±3.1[ab]	***0.073***	*0.869*	***0.007***	*0.313*
	A	20.2±5.1	19.2±1.3	19.7±1.8	20.9±3.2	20.7±1.4	*0.774*	*0.212*	*0.942*	*0.735*
	B	23.0±8.5	20.0±1.6	16.8±2.6	20.7±4.1	23.9±3.5	*0.274*	*0.108*	*0.948*	*0.179*
Water Rep. (sec. of infilt.)	A	39±17.2[a]	14±3.1[b]	17±3.6[b]	37±6.9[a]	30±6.7[ab]	***0.008***	***0.003***	*0.721*	*0.361*
	B	2±0.3	3±0.7	2±0.3	3±0.4	2±0.5	*0.259*	*0.770*	***0.058***	*0.802*
CEC (meq 100g^{-1} soil)	A	22.4±1.9	22.6±1.3	20.1±2.4	20.6±1.6	23.2±1.5	*0.274*	*0.633*	*0.964*	*0.038*
	B	19.0±1.8	17.4±1.1	17.9±1.6	18.6±1.9	17.1±1.1	*0.773*	*0.852*	*0.680*	*0.410*

Carbon and Nitrogen

The C and N concentration of the mineral soil was unaffected by burning possibly as a result of high values in comparison to other similar forest soils (Table 3). Average A horizon C and N concentration was 49 g C kg^{-1} soil and 2.7 g N kg^{-1} soil with B horizon concentrations averaging 25 g C kg^{-1} and 1.3 g N kg^{-1} soil. Ponderosa pine stands in eastern Washington, eastern Oregon, and western Montana averaged 8-56 g C kg^{-1} soil and 7-13 g C kg^{-1} soil for A
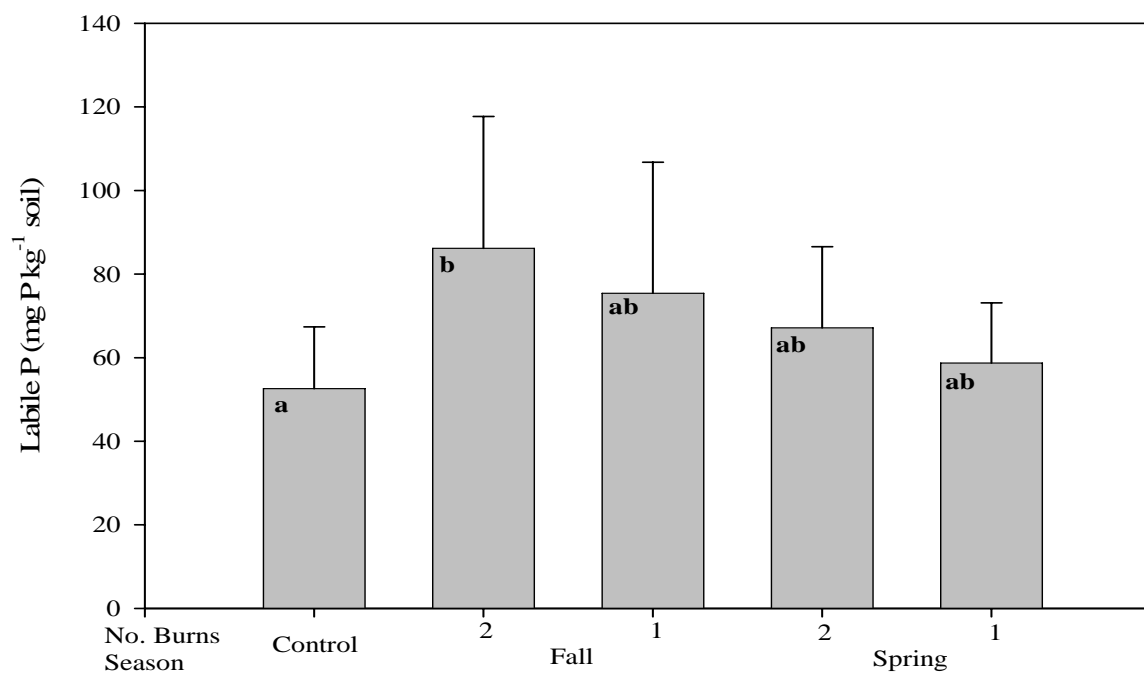
Figure 2. Total Bray extractable P in the A horizons after 1 or 2 fall and spring burns. Error bars are 1 standard deviation from the mean. Letters indicate similar groups using Tukey's HSD after determining significant (α=0.1) differences using a one-factor ANOVA (p).

and B horizons, respectively (Monleon et al. 1997, Baird et al. 1999, DeLuca and Zouhar 2000, Hatten et al. 2005). Nitrogen concentrations in these forests averaged 1.3-2.0 g N kg^{-1} soil and 0.7-1.8 g N kg^{-1} soil for A and B horizons, respectively. The highest values of C and N occurred under ponderosa pine stands in central Oregon (Monleon et al. 1997) and this study (eastern Oregon). Andic materials in both eastern and central Oregon sites may be promoting C and N accumulation in the soil through complexation of organic matter with allophanic mineral materials (Zunino et al. 1982a, 1982b). Additionally, understory vegetation of both of these forests is dominated by grasses which could have increased the amount C and N through the incorporation of fine roots into the upper soil horizons.

Fall burn treatments had a lower O horizon C concentration than the spring burns, likely as a result of SOM consumption and higher ash content (Table 3). Increasing fire frequency has been shown to decrease the concentration of C and N of the upper 5 cm of A horizon in an Arizona ponderosa pine forest (Neary et al. 2003). Neither the season nor interval of burn-treatments had a significant effect on A or B horizon total C or N concentrations, however the extractable NH_4^+, and total C and N content of the soil was affected.

There is more extractable NH_4^+ on the plots most recently burned (Figure 3). The 5-year interval burn plots had significantly higher NH_4^+ concentration relative to the 15 year interval plots, however they were not significantly different from the control. The plots with two fall burns had a significantly higher proportion of total N as NH_4-N relative to the plots with one

spring burn. Nitrate concentration or total inorganic N was not significantly different among the treatments (*p>0.10*) (Figure 3). The release of available N from recent ash is likely elevating the NH_4^+ concentration.
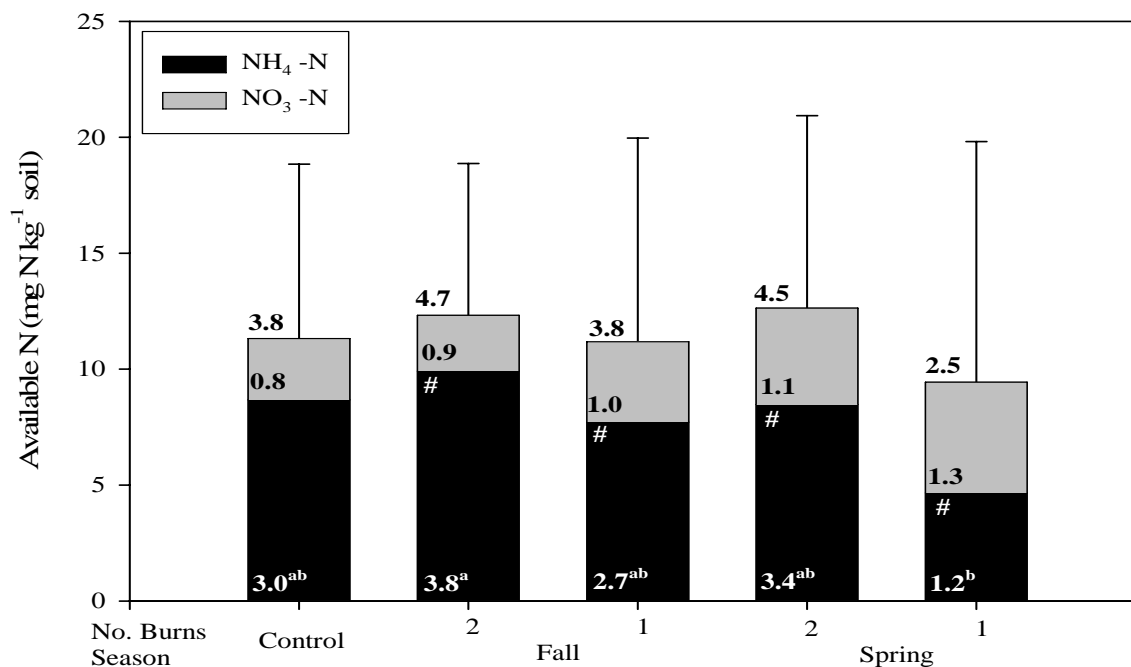

Figure 3. Total inorganic N, NH_4^+, and NO_3^- concentration (mean ± standard deviation of total inorganic N concentration) of A horizons from plots treated with 1 or 2 fall or spring burns (n=6). Numbers indicate proportion of total N as total inorganic N, NO_3-N, and NH_4-N (from upper to bottom number) for each treatment relative to mg g^{-1} total N. Letters indicate similar groups using Tukey's HSD after determining significant (α=0.1) differences using a one-factor ANOVA (p). A # indicates significant differences (α=0.1) among NH_4^+ concentrations between number of burns as tested by orthogonal contrasts.

Monleon and Cromack found that 4 months after prescribed burning inorganic N concentrations were higher than a control, but 5 years after prescribed burning inorganic N concentrations were depressed relative to the controls. The inorganic N concentration of the prescribed burn soils from the current study may be declining with time as evidenced by slightly lower NH_4^+ and total inorganic N concentration on the plots treated to one fall or spring burn.

Both NH_4^+ and NO_3^- concentrations were very high compared with other studies. Monleon et al. (1997) found total inorganic N concentrations of about 1-6 mg N kg^{-1} soil in unburned soils sampled from 0-5 cm and 5-15 cm depth on a site in central Oregon and Choromanska and DeLuca (2001) found 1.3-4.3 mg N kg^{-1} soil on unburned soils under ponderosa pine forest in Montana. The ratio of total N as NH_4^+ or NO_3^- is 0.7-3.3 and 1.1-3.6 mg available N g^{-1} per g of total N for the Oregon and Montana sites respectively, which is slightly lower than the range of values obtained during this study (Figure 3). The high available N is likely due to the very high average OM concentration of the A horizon, total inorganic N

concentration was correlated with total C content (R=0.549, *p=0.002*). This high concentration of OM may help this site resist future fire effects, but if C content is reduced by repeated burning, then a subsequent decrease in total inorganic N may follow. Even though inorganic N was high on these plots, and able to withstand some reduction, reduced available N may lead to lower productivity or a change in understory species composition.

The C and N content of woody fuels was assessed using the fuel masses reported by Thies et al. (2006a). The C and N concentration of woody fuel varies by the size of the wood. Laiho and Prescott (1999) found that 51.0 and 47.8% of the <7.5 cm and > 7.5 cm classes, respectively of pine wood are C and Page and Dumroese and Jurgensen (2006) report that 0.25 and 0.06% of the <7.5 cm and >7.5 cm classes, respectively, of pine wood are N. These values were used to calculate total C and N contents of CWD. Summing total C and N of woody debris, O horizon, and mineral soil total C to a 30 cm depth shows that fall burns reduced C by 23-33 Mg C ha^{-1} (21-31%) relative to the control treatments, while total N was reduced 744-1120 kg N ha^{-1} (15-23%) (Figure 4). Carbon loss with fall burning was driven by consumption of C from the O and A horizons, which accounted for 48-95% of the losses from fall burning, relative to the control. Additionally, there is a reduction in C and N of the B horizons of plots burned 6-7 years ago which may be the result of a change in vegetative community or due to the random placement of the treatment plots onto soil types with B horizons that have less SOM.
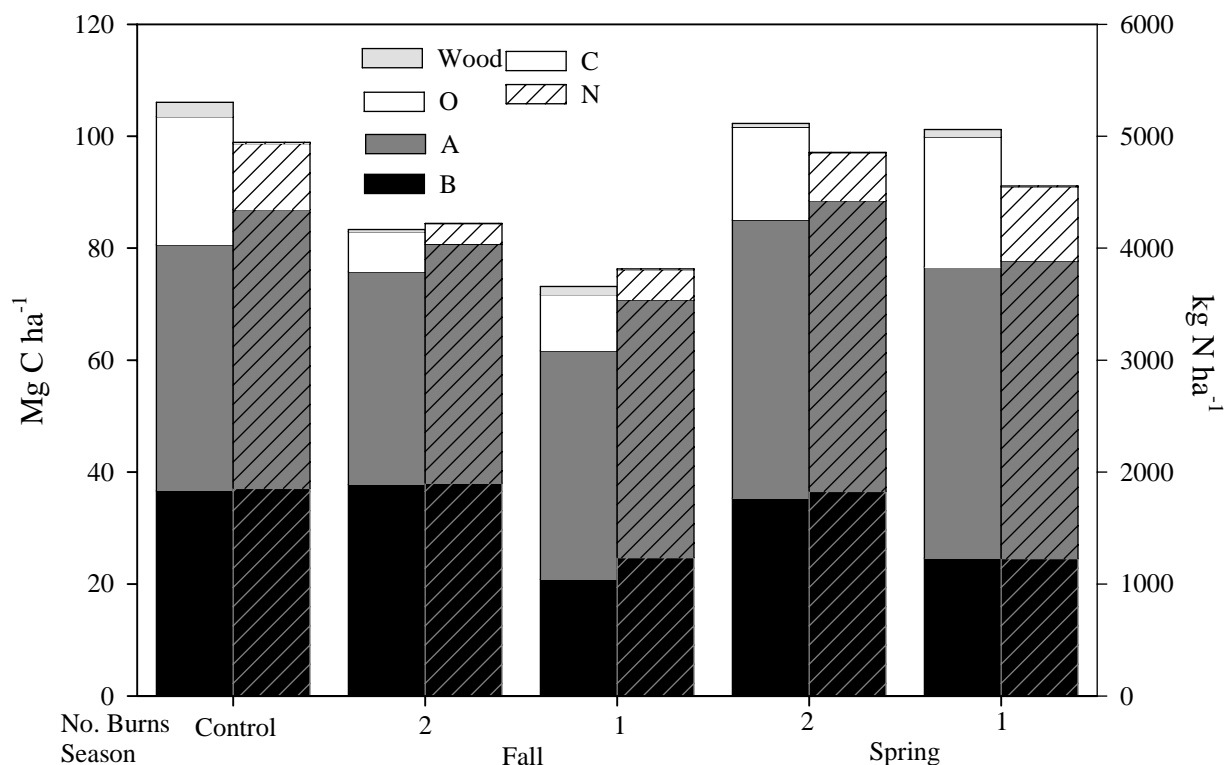

Figure 4. Total carbon and nitrogen content in the top 30 cm of soil, O horizon and woody fuels after 1 or 2 fall and spring burns. Woody fuel mass data from Thies et al. (2006a).

Baird et al. (1999) found a total C content of 48 Mg ha^{-1} in the upper 30 cm, including the O horizon, of an unburned ponderosa pine forest in eastern Washington. A high intensity wildfire reduced C content to 30 Mg ha^{-1} (a 37% reduction from control). Of the 18 Mg C ha^{-1} lost due to wildfire 61% of the loss was caused by consumption of C directly from the A horizon, while B horizons were unaffected by burning. In the current study only 17% of the 26 Mg ha^{-1} difference in total soil C between the control and fall burns was due to reduced A horizon C content, with most C reduction caused by consumption of O horizon. The lower severity of fall prescribed burning relative to wildfire is helping to preserve C in the A horizon. Further, the high C content of the A horizon (44 Mg C ha^{-1} in control A horizon) relative to Baird et al. (1999) (23 Mg ha^{-1} in control A horizon) reduces the magnitude of change. Relative to wildfire even the higher severity fall burning may protect soil C.

More favorable growing conditions of the fall burn treatments may also increase the rate and amount of C mineralized from the mineral soil of the fall burn plots leading to their lower C contents. If this were the case then N would be expected to be preserved and the mineral soil C:N ratio would be lower on the fall burn plots. The C:N ratio of A and B horizons is unaffected (Table 3) by the treatments and N content is significantly lower on these treatments (Figure 4), suggesting that the C and N losses have been caused by combustion of mineral soil SOM.

Nitrogen is likely the 2nd most limiting factor to plant growth on these sites after available water. The loss of N through volatilization may have impacts on future productivity if this stores N is not replaced. Assuming that there will be no gain or loss of N between fires, the annual losses of N amount to 81, 35, 8, and 0 kg N ha^{-1} yr^{-1} for the Fall 5, Fall 15, Spring 5, and Spring 15 treatments, respectively. There is one major N fixing species of lupine (*Lupinus caudatus*) that may help recover some of the N lost to burning. Sprent and Silvester (1973) suggest that lupine species may fix about 15 kg N ha^{-1} yr^{-1} under radiata pine canopy (*Pinus radiate* D. Don). Fenn et al. (2003) propose that the Interior Western United States may have an atmospheric deposition rate of 1-4 kg N ha^{-1} yr^{-1}. These deposition and fixation rates could compensate for losses experienced by spring burning at either 5 or 15 year intervals suggesting that these losses may be recovered between fire applications; however, the natural accretion rates of N are not enough to recover N store lost due to fall burning, which may result in more intense N limitations over successive prescribed burns. Since the fires that historically occurred in these forests occurred during the summer when severities had the potential to be high if not limited by fuels, the question arises as to how these forests adapted to this level of N loss.

The initial prescribed burns on these sites consumed an understory with an elevated amount of fuels that ashed a large portion of burnable N-rich material. Historically these sites had a lower fuel load so that less N would be exposed and therefore lost during each fire. A lower fuel load would also likely lead to lower fire severity thereby preserving mineral soil C and N. The majority of N lost appears to have occurred during the initial burn with 23-27% of the N lost by the second burn, assuming no N has accumulated between fires and the difference between the control and the plots with one fire is the N lost during the initial fire. Repeated application of prescribed fire on these sites may see a reduction in N losses until N loss per fire application is stable with the new fire regime. In addition, lower O horizon thickness and higher bare ground coverage may create a better environment for N-fixer growth since many of these fixers are early successional species.

Lower fuel level may also cause the fuels to be patchy causing any fire to burn sporadically exposing less soil to fire and causing an increase in soil heterogeneity, especially O horizon characteristics. The total variability of a characteristic may be represented by the standard deviation calculated for each plot. The average standard deviation of O horizon thickness and pH was not statistically affected by burning ($p>0.10$) suggesting that the burns were applied evenly and did not burn in a patchy manner across the plots. These prescribed burns were ignited in strips spaced so that the fire would burn evenly with a 60 cm flame length (Thies et al. 2005, Becky Kerns, personal communication).

Gundale et al. (2006) found that the heterogeneity of total inorganic N increased with prescribed burn treatments in a ponderosa pine forest of Montana. The prescribed burns used by Gundale et al. (2006) (as reported in Gundale (2005)) were ignited by drip torches along transects, suggesting that there were no adjustments to the ignition pattern to keep the fire behavior constant across the burn area. The heterogeneity caused by these fires may be due to the ignition pattern and not simply the application of fire. Gundale et al. (2006) showed that the heterogeneity of total inorganic N was associated with an increase in species richness which was elevated with burning treatments. If creating a heterogeneous soil environment causes higher understory biodiversity then managers may desire to use ignition patterns that promote greater soil heterogeneity.

The lower C and N losses during prescribed burning relative to wildfire highlight the importance of restoring these systems by reducing fuel loads so that fire burns at a lower severity. However, prescribed burning in the fall may have too high a severity that could reduce C and N pools below adequate levels in these ecosystems. Future prescribed burning on these sites will allow a determination of a stable level of C and N loss is for each burn season and burn interval.

Soil organic matter characteristics

The consumption of O horizon had the greatest effect on the FA and HA C and N content of the soils (Table 4). The intensity of the prescribed fires in the current study may not have been high enough to cause lasting changes to the composition of SOM. While low- and moderate- severity fires have been shown to affect SOM composition, these changes did not persist, suggesting that prescribed burning will not have long-lasting effect on SOM composition (Hatten 2007).

Both O and A horizon total C was dominated by NS (nonsoluble organics in the O horizon) or humin materials in the mineral soil (63 and 58%, respectively) (Table 4). There was significantly higher NS C in the O horizons treated to two burns, which is probably due to an increase in charcoal. Charring may be increasing the NS C:H ratio of the plots with the most recent burns having a C:H ratio above 2.0. Baldock and Smernik (2002) found that wood (C:H = 0.7) heated to temperatures above 250 $^{\circ}$C had C:H ratios greater than 2.0 and Almendros et al. (2003) observed a similar response to the C:H ratio of heated peat. Hatten (2007) showed that NS C concentration in the O horizon subjected to moderate- or high-intensity prescribed fire did not change after decomposition, suggesting that this charred material does not readily

Table 4. Total C and N by each soil organic matter fraction (mean ± standard deviation) of O and A horizons in plots treated with 1 or 2 fall or spring burns (n=6). Significant (α=0.1) differences are in bold as determined by a one-factor ANOVA (p) and orthogonal contrasts for season (p_s), and number of burns ($p_\#$). Letters indicate similar subsets (rows) using Tukey's HSD. Interaction between season and number of burns was not significant. Sum of HA and FA C and all fractions of N were not significantly different between the treatments. NS indicated nonsoluble extractable O horizon organic matter.

		Control	Fall 2	Fall 1	Spring 2	Spring 1	p	p_s	$p_\#$
				Mg Carbon ha^{-1}					
NS	O	13.8±6.5	4.3±1.0	7.1±3.0	9.4±3.1	14.3±6.4	*0.148*	***0.067***	*0.183*
Humin	A	25.0±9.4	22.9±4.2	25.9±11.2	28.7±11.0	26.3±5.1	*0.787*	*0.341*	*0.926*
	Sum	38.8±13.7^{ab}	27.3±4.0^{a}	33.0±10.8^{ab}	38.0±11.0^{ab}	40.6±9.5^{b}	***0.081***	***0.016***	*0.244*
Humic	O	2.6±1.4ab	0.7±0.2a	1.2±0.5a	1.7±0.7ab	3.1±1.2b	***0.023***	***0.014***	***0.061***
Acid	A	11.8±5.3	9.7±2.6	10.2±4.8	11.4±3.8	10.4±2.8	*0.805*	*0.496*	*0.859*
Fulvic	O	0.8±0.4^{bc}	0.2±0.1^{a}	0.3±0.1^{ab}	0.4±0.1^{abc}	0.7±0.2^{c}	***0.014***	***0.024***	*0.105*
Acid	A	1.1±0.4	1.1±0.4	1.1±0.4	1.1±0.5	1.2±0.6	*0.991*	*0.833*	*0.960*
				kg Nitrogen ha^{-1}					
NS	O	355±195^{ab}	99±32^{a}	171±93^{ab}	230±114^{ab}	358±152^{b}	***0.051***	***0.028***	*0.140*
Humin	A	1520±783	1271±434	1467±720	1527±599	1413±501	*0.830*	*0.568*	*0.816*
Humic	O	82±51	20±9	36±16	51±20	97±46	*0.760*	*0.424*	*0.503*
Acid	A	709±318	547±162	562±252	635±168	572±144	*0.546*	*0.525*	*0.757*
Fulvic	O	9±7^{a}	3±3^{b}	3±2^{b}	5±2^{ab}	7±6^{a}	***0.004***	***0.008***	*0.444*
Acid	A	38±18	34±18	30±26	32±12	34±19	*0.903*	*0.864*	*0.918*

decompose. If charred NS C is not consumed by wildfire or another prescribed fire, then it may accumulate in the soil due to slower decomposition.

Fulvic acid was concentrated equally across both O and A horizons (3% of total C). The C:N ratio of FA from O horizons was very high (Table 4) suggesting that there was a large quantity of N-free tannins or lignin decomposition products (e.g., vanillin) which may be included in the FA fraction (Qualls and Haines 1991). Humic acid content of the A horizon was higher than the O horizon (24 and 11%, respectively) likely as a result of a higher degree of SOM humification.

The non-soluble materials, NS and humin, appear to be accumulating in the O and A horizons of the treatment with one spring burn while being consumed by multiple fall burns (Table 4). Treatments with one spring burn are 6% higher than the control and 49% higher than plots with 2 fall burns. Repeated fall burning may be consuming material that contributes to humin and NS substances in both A and O horizons. The consumption of O horizon may be the most important factor regulating the quantity of long-term fire-affected SOM after repeated low-intensity prescribed fire.

Table 4. Total C and N by each soil organic matter fraction (mean ± standard deviation) of O and A horizons in plots treated with 1 or 2 fall or spring burns (n=6). Significant (α=0.1) differences are in bold as determined by a one-factor ANOVA (p) and orthogonal contrasts for season (p_s), and number of burns ($p_\#$). Letters indicate similar subsets (rows) using Tukey's HSD. Interaction between season and number of burns was not significant. Sum of HA and FA C and all fractions of N were not significantly different between the treatments. NS indicated nonsoluble extractable O horizon organic matter.

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Humic	O	2.6±1.4ab	0.7±0.2a	1.2±0.5a	1.7±0.7ab	3.1±1.2b	***0.023***	***0.014***	***0.061***
Acid	A	11.8±5.3	9.7±2.6	10.2±4.8	11.4±3.8	10.4±2.8	*0.805*	*0.496*	*0.859*
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Acid	A	1.1±0.4	1.1±0.4	1.1±0.4	1.1±0.5	1.2±0.6	*0.991*	*0.833*	*0.960*
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Acid	A	38±18	34±18	30±26	32±12	34±19	*0.903*	*0.864*	*0.918*

Non-soluble materials such as charcoal may be providing soils under fire-prone forests with materials which contribute to the total soil CEC. Liang et al. (2006) showed that charcoal incorporated into mineral soil can impart a higher CEC over time. The proportion of total soil C as humin C was positively correlated with CEC when total soil C concentration is controlled for

(partial R=0.389, *p=0.037*). Total soil C concentration has a greater positive correlation with CEC (R=0.685, *p=0.000*), and therefore is likely a principle factor in determining CEC; however, an increase in the proportion of total soil C as humin, possibly as charcoal, may lead to increases in CEC as long as total soil C is maintained. Charcoal may be combining with slightly higher pH in the A horizon of the plots with one spring burn to result in high CEC (Table 3).

The reduction of non-soluble materials caused by the fall burning at a 5-year interval may be further reduced with frequent repeated burning and could affect soil processes such as CEC in addition to available nutrients and understory species reestablishment. Charcoal has been shown to reduce the inhibitory effect of allelopathic compounds on seedling establishment and nitrification (Zackrisson et al. 1996, Wardle et al. 1998, DeLuca et al. 2002, 2006). If the understory species of ponderosa pine forests are adapted to the presence of charcoal at the time of understory reestablishment after low-intensity fire, then a fire regime that allows charcoal to accumulate may provide the most robust soil conditions for native plant restoration. The initial fall burn has caused a higher cover of non-native understory species (Kerns et al. 2006). If non-soluble materials in this study are dominated by charcoal then the higher-severity fall burning at 5-year intervals may reduce the success of understory native species reestablishment through the consumption of charcoal. The initial fall burn and 2nd fall burns at 5-year intervals may be consuming charcoal and other non-soluble materials that are important for soil processes and C sequestration.

Tree ring growth

As was reported by Ogden (2006) there was not a significant difference in radial wood increment (RWI) relative to the control with burn treatments. However, significant differences were found with the number of prescribed burns on RWI (Figure 5). It appears that two burns may be depressing wood production while one burn may be elevating it slightly. Ogden (2006) also separated the trees into DBH classes and found no significant difference in RWI among the treatments.

The minor differences detected in the RWI did not show significant differences in yearly basal area (BA) growth, however the total wood production may have been increased by multiple spring burns (Figures 6 and 7). Figure 6 shows basal area increment as a proportion of yearly basal area for each year 7 years pre- and post- treatment initiation. No significant differences were found between the treatments in any year. The BA production as a proportion of 2004 BA ($PBAI_{1997-2004}$) shows that the plots treated to 2 spring burns may be experiencing increased growth over the other treatments, but not the control (Figure 7). Total N was positively correlated with $PBAI_{1997-2004}$ (R=0.341, *p=0.065*) suggesting that N is a limiting nutrient on these sites during part of the growing season. Additionally, $PBAI_{1997-2004}$ was slightly correlated with shrub cover (R=-0.310, *p=0.095*), canopy cover (R=-0.301, *p=0.106*), and O horizon bulk density (R=.365, *p=0.047*), which suggests that increased growth, occurring in the Spring 5 plots, may be caused by a reduction in competing vegetation allowing more water and nutrients to be available; suitable O horizon characteristics may be preserving soil water during the growing season.
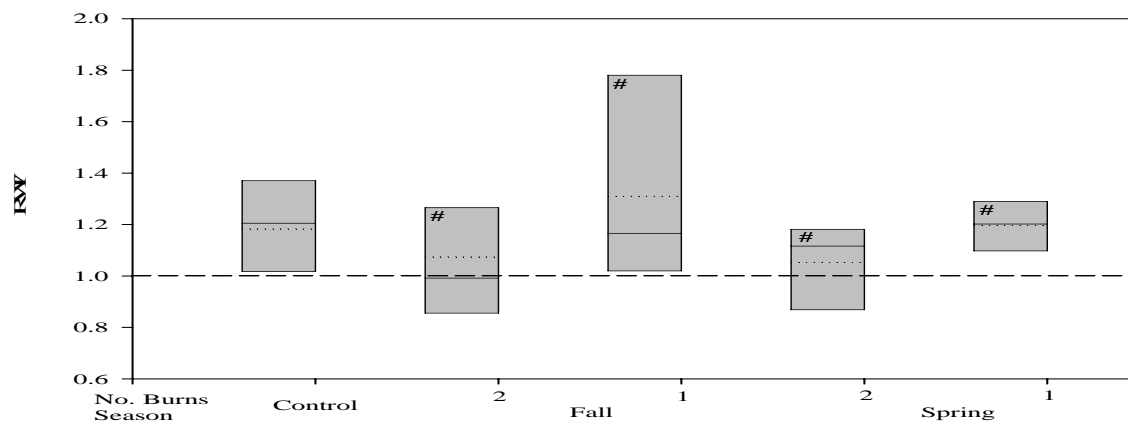
Figure 5. Average radial wood increment (RWI) ratio for the 7 years prior to treatment initiation (1991-1997) and 7 years after treatment initiation (1998-2004). A # indicates significant differences (α=0.1) between number of burns as tested by orthogonal contrasts. Burned plots were not significantly different from the control as tested by a one-factor ANOVA. Upper and lower limits of boxes are the 75th and 25th percentiles respectively. The olid line within each box is the median and the dotted line is the mean. Dashed line across the diagram denotes a RWI of 1 above which growth is increased.
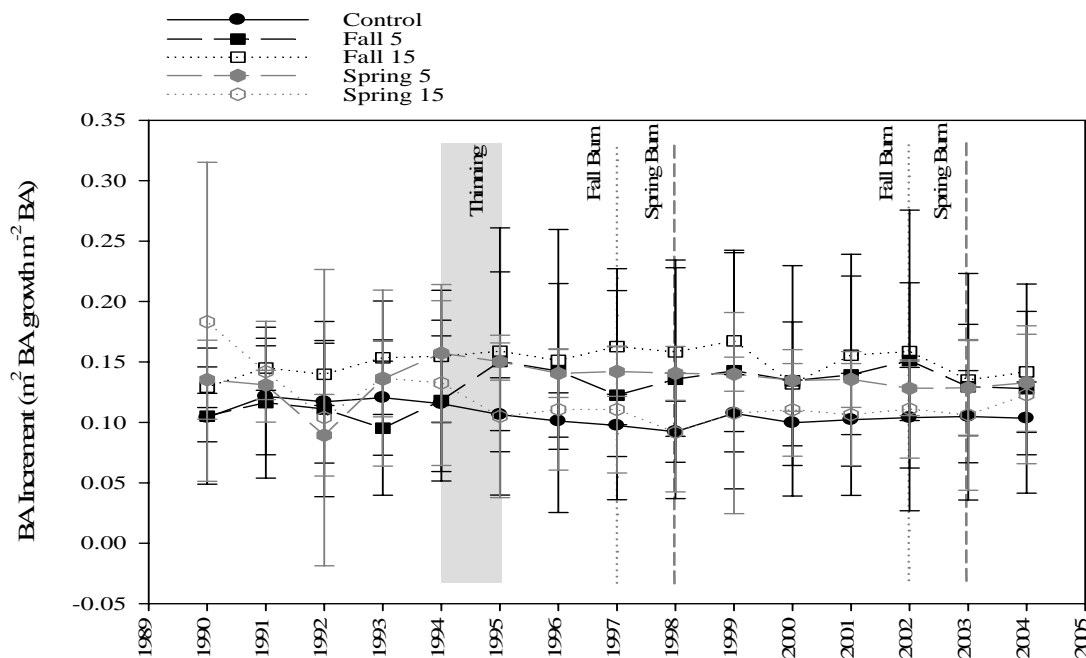
Figure 6. Yearly basal area (BA) increment as a proportion of yearly BA for plots treated to 1 or 2 prescribed burns applied in the fall or spring. Error bars are one standard deviation from the mean. Thinning occurred in either 1994 or 1995 and is denoted by vertical gray rectangle. No significant (α=0.10) statistical differences were found among the treatments for any year. Dotted and dashed vertical lines show years in which fall and spring, respectively, prescribed burns were applied.
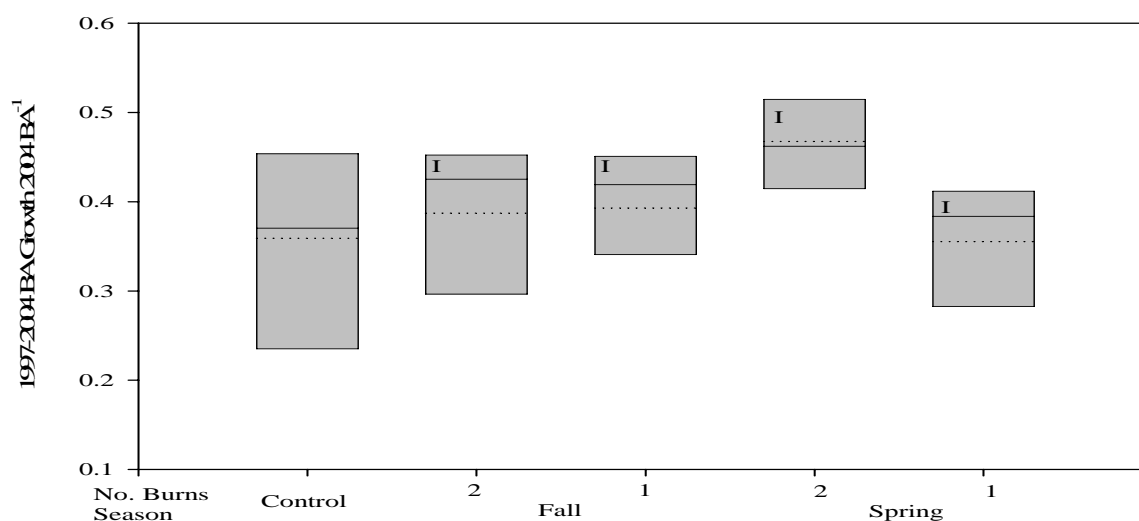
Figure 7. Proportion of basal area (BA) growth between 1997 and 2004 to BA growth of 2004 for plots treated to 1 or 2 prescribed burns applied in the fall or spring. Upper and lower limits of boxes are the 75th and 25th percentiles respectively. The solid line within each box is the median and the dotted line is the mean. Orthogonal contrasts between the plots treated to prescribed fire found a significant interaction between season and number of burns which is denoted by an I.

Soil moisture and temperature

Generally, average weekly soil temperature follows average weekly air temperature as seen in Figure 8. During the summer average weekly soil temperatures attain higher temperatures than the average weekly air temperature due to the ability of the soil to retain heat over night. The winter snow pack insulates the soil and keeps temperatures from deviating far below 0 °C. During the winter of 2007 the lower than average snowpack, and a possible February melt, was not able to insulate the soil so that temperatures did fall below freezing (Figures 8 and 9).

Soil temperature appears to have been highest on fall burn plots for the summer of 2005 and 2006 and during the early growing season of 2007 (Figure 8). The average monthly temperature of Fall burns are statistically higher (α=0.10) than spring burns in July 2006, August 2006, September 2006, April 2007, and May 2007 (all *p<0.035*), however they did not have higher temperatures than the control. The soil temperature during these months was significantly (*p<0.05*) correlated with bare ground coverage (R between 0.388 and 0.571), and negatively correlated with canopy coverage (R between -0.438 and -0.639) and O horizon thickness (R between -0.449 and -0.581). The decreased O horizon and tree canopy cover with the fall burning appears to allow more solar energy to strike the soil surface. Additionally, bare ground has a lower albedo than O horizon, which would be exacerbated by charcoal at the surface. The plots with one spring burn had higher monthly temperatures than the 2 spring burn plots in October 2006 possibly as a result of one spring burn plot having a higher average slope (16% versus 11% on the two spring burn plots). Higher temperatures in the fall plots could increase the length of the growing season as well increase evaporation from the soil surface. Many species of plants depend on soil temperature for seed germination which may start later on spring

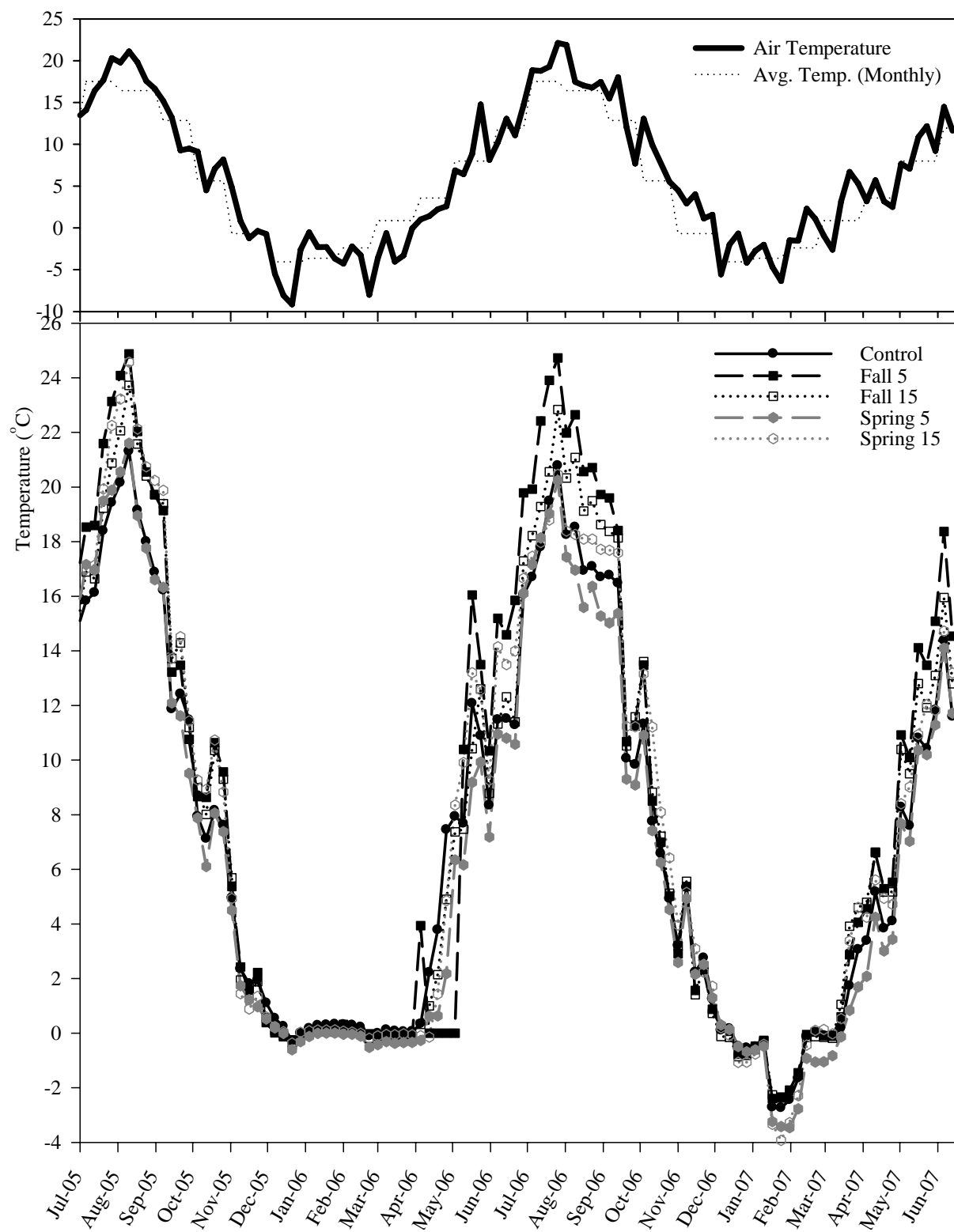**Figure 8.** Weekly average air and soil temperature for plots treated to 1 or 2 prescribed burns in the Fall or Spring.
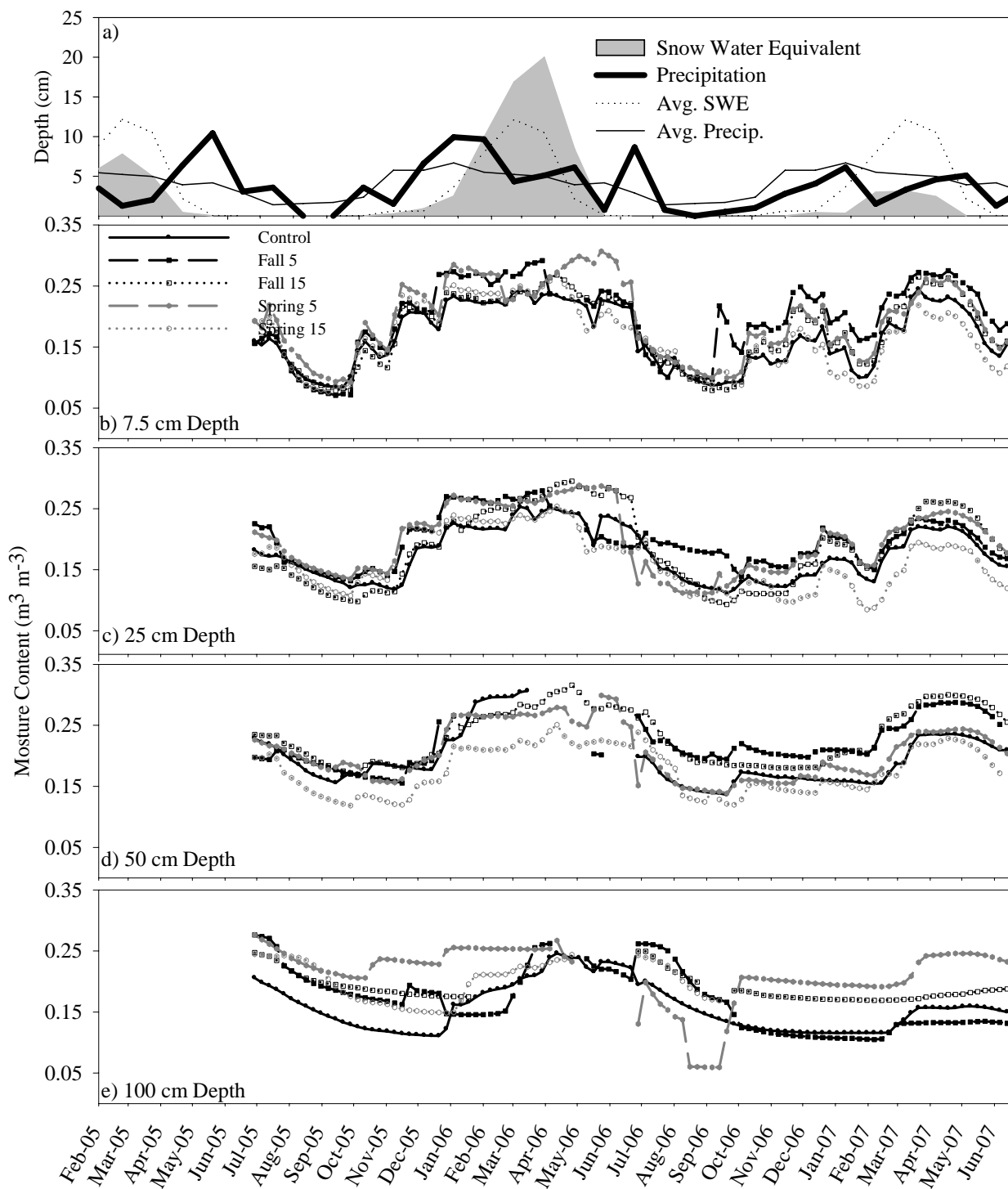
Figure 9. Total monthly precipitation and snow water equivalent (SWE) at the Rock Springs SNOTEL station (a) and weekly average soil moisture content for 7.5 cm (b), 25 cm (c), 50 cm (d), and 100 cm (e) depths for plots treated to 1 or 2 prescribed burns in the Fall or Spring.

5 plots. If seed germination patterns are altered it is possible that spring burning could favor some species over others.

Two spring burns appear to have caused a significantly later thaw and warming of the soil during the spring of 2007. This treatment was significantly different from the other burn treatments, but not different from the control. It is interesting to note that the spring 15 plots have such an early thaw relative to the Spring 5 treatments. Steeper slopes of the spring 15 burn plots may be causing the soils to warm faster than the spring 5 plots. The timing of soil cooling below 5 $^{\circ}$C does not appear to be affected by the season or number of prescribed burns. The spring 5 plots appear to have a lower temperature throughout the growing season and summer.

Soil moisture across the treatments was highest in the winter and lowest during the summer. The snow pack and precipitation was higher than average for the 2005-2006 water year which may have lead to higher soil moisture at all depths during the late fall and winter of that year.

The reduction of understory vegetation is may be resulting in a higher soil moisture at the 7.5 cm depth with the 5-year burn treatments (2 burns), likely as a result of lower transpiration (Figure 9). Bare ground coverage was significantly ($p<0.05$) positively correlated with the average monthly moisture content at 7.5 cm during April and May of 2007 when controlling for slope (partial R between 0.417 and 0.451). The later snow melt on the Spring 5 plots may cause soil moisture to be elevated later into the growing season; however there were no significant correlations with initiation of the 2006 growing season and soil moisture at any depth. During September and October of 2006 the 5-year-interval burn plots had a higher soil moisture than the 15-year-interval plots, but were not significantly different from the control ($p=0.049$ and 0.073, respectively). The monthly moisture at the 7.5 cm depth of the Fall 5 was significantly higher that the Fall 15 during September 2006 ($p=0.099$). During much of 2006 and 2007 the Fall 5 treatments consistently had the highest soil moisture at the 7.5 cm depth, but this did not result in a significant difference in average monthly moisture from the controls (Figure 9). The soil moisture at the 25 cm depth of the fall burn plots was found to be significantly higher than that of spring buring ($p=0.093$) during August 2006, but not significantly different from the control. There were no significant differences in average monthly soil moisture among treatments at the 50 and 100 cm depth.

As would be expected, the length of the calculated growing season increases with depth. The length of the early 2006 growing season was 104, 105, 113, and 133 days at 7.5, 25, 50, and 100 cm depths, respectively. The increased growing season at depth allows deeper rooted species, such as trees, shrubs and some grasses, to acquire water later into the summer. Shallow rooted species, such as some annuals, may be more at risk by treatments that affect surface environmental variables such as burning.

It appears that burning at 5 year-intervals may be causing the soil to be warmer and more moist, possibly increasing the length of the growing season followed by the Spring 5 treatments (Table 5). The growing season has been lenghtened by multiple burns especially multiple fall burns. Multiple prescribed fires at 5 year intervals has increased the GS_E 2006 and total 2006 growing season of the 7.5 cm depth over the other burn treatments, but not the control.   The

Table 5. Average growing season (number of days) for plots treated with 1 or 2 fall or spring burns (n=6) at 7.5 cm depth. Length of early soil activity season is the length of time that soil temperature is greater than 5°C for 7 days and soil moisture content is above 1500 kPa. Length of the late growing season is the length of time after the early season that soil moisture content is above 1500 kPa for at least 7 days and greater than 5°C. Significant (α=0.1) p-values are in bold as determined by a one-factor ANOVA (p) and orthogonal contrasts for season (p_s), number of burns ($p_\#$), and interaction of season and number of burns ($p_{s*\#}$). Letters indicate similar subsets (rows) using Tukey's HSD. There were no significant differences among treatments for growing season length as calculated for 25, 50, or 100 cm depths, therefore those data are not shown.

	Control	Fall		Spring		p	p_s	$p_\#$	$p_{s*\#}$
		2	1	2	1				
	----------------------------------			Days	----------------------------------				
GS_L 2005	32±4	30±4	17±16	25±12	27±20	0.518	0.698	0.409	0.281
GS_E 2006	91±38	143±52	87±42	99±29	101±47	0.134	0.362	**0.085**	**0.068**
GS_L 2006	16±19	55±74	13±15	14±11	53±67	0.313	0.962	0.871	**0.052**
Total 2006	107±55	165±43	106±55	113±35	122±45	0.173	0.381	0.166	**0.068**
GS_E 2007	55±26	56±24	44±17	44±19	36±40	0.483	0.255	0.154	0.627

magnitude of increase is large, 52 more GS_E days (57% increase) and 58 more total growing season days (54% increase) in the fall 5 treatments relative to the control. These differences become less pronounced with depth so that there are no significant differences below 7.5 cm. Nevertheless, the fall 5 plots often have the longest GS_E and total growing season as a result of there being plant available water later into the season, and not as a result of differences in GS_{max} caused by higher temperatures (Figure 10).
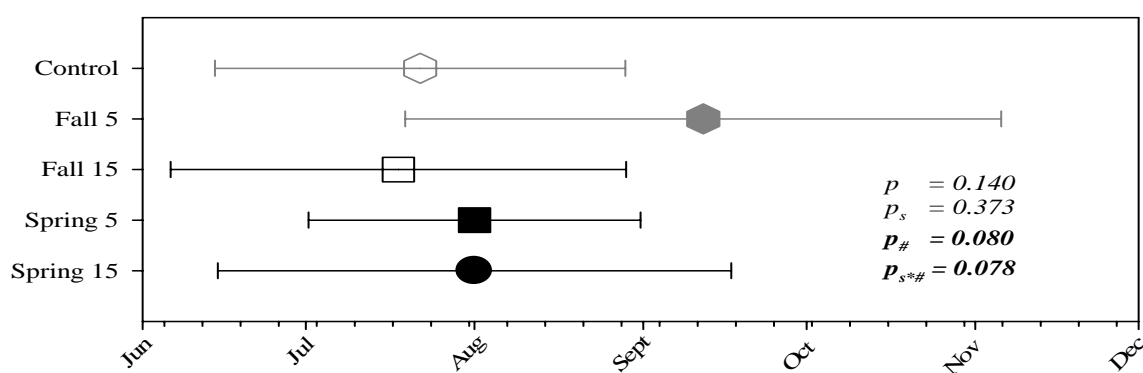
Figure 10. Average end to early growing season for the year 2006 (mean ±standard deviation) at the 7.5 cm depth. End of growing season was determined when the soil moisture content fell below the plant wilting point (1500 kPa). Significant (α=0.1) p-values are in bold as determined by a one-factor ANOVA (p) and orthogonal contrasts for season (p_s), number of burns ($p_\#$), and interaction of season and number of burns ($p_{s*\#}$).

The growing season conditions at shallower depths are impacted more by burning in the fall and at 5-year intervals which could have increased impacts on the understory species composition of these plots. This may be of special importance to annuals that extract water from shallower depths than perennials or trees. Forb coverage was significantly (*p<0.05*) positively correlated with average monthly soil temperature during September 2006, October 2006, April 2007, May 2007, and June 2007 (partial R between 0.417 and 0.630) when controlling for slope. It is possible that seed germination of annuals is being enhanced on plots with higher soil temperature during the early growing season, such as the fall burn plots, leading to their slightly higher coverage (4.5% on fall burn plots versus 3% on control and spring burn plots).

Wayman and North (2007) found that early season soil moisture from the upper 15 cm of soil was positively correlated with annual herb cover after fuel reduction treatments of burning and thinning. Higher temperatures during the longer growing season on the fall burn plots create a much more favorable environment for plant growth and establishment. Whether or not these are the causes of the increase in invasive species on fall burn plots as seen by Kerns et al. (2006) would need further study to conclusively determine.

Longer growing season and higher temperatures may increase primary productivity on the plots with 2 burns, thereby helping them recover lost C. Additionally, this environment could favor N-fixing species that will help recover lost soil N.

CONCLUSIONS

Reinitiating fire into a fire-suppressed forest achieves management goals of fuel reduction whether the burns are applied in the fall or spring. However, increased SOM consumption of the fall burns may lead to significant changes to soil processes in these stands in the future. It is possible that the high SOM content of these soils gives them the capacity to resist major changes caused by the initial fall burning compared to effects with a lower quality soil. Burning at 5-year intervals consumes the understory and O horizon causing higher temperatures and soil moisture leading to a longer growing season. The change in growing season length may be contributing to observed species changes on the plots, but do not appear to be affecting tree growth. Using fall burns initially to reduce fuel loads may need to be avoided to sequester C in fire-suppressed stands. Results to date suggest that the frequent fall burns may be harsher for soils than less frequent burns or spring burns, but could be used if needed, however they will reduce ecosystem C pools.

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Appendix 1.

DELIVERABLES

Proposed	Status
Annual progress reports	Completed
Publication to peer-reviewed journal on effects of prescribed burning on soil carbon and nutrients	One paper has been submitted to Forest Management and Ecology and is in revision: Hatten, J.A., D. Zabowski, A. Ogden, and W. Thies. Soil organic matter in a ponderosa pine forest with varying season and Interval of prescribed burn. Forest Ecology and Management.
Publication to peer-reviewed journal on soil moisture and temperature changes with prescribed burn	This manuscript is in progress with submission to SSSAJ planned In addition, a draft of a Gen. Tech. Rep. for submission to PNW that encompasses overall soil results has been completed and is now in review. Title: Soil Response to Season and Interval of Prescribed Fire in a Ponderosa Pine Forest of the Blue Mountains, Oregon, by Hatten, J.A., D. Zabowski, A. Ogden and W. Thies
Presentation to the Malheur National Forest	Completed: a field tour was given to the Malheur NF and others in 2006
Spatial Data Presentation to NF	Maps of the soils in the study area were prepared and given to the Emigrant Creek Ranger District of the Malheur NF in 2006
Additional Accomplishments	One dissertation was completed incorporating research from this project: Hatten, J.A. 2007. Prescribed fire and fire intensity effects on soil organic matter. Ph.D. Dissertation. University of Washington. 114pp. One MS thesis was completed from research at this site: Ogden, A. 2006. Ponderosa pine growth increment responses to prescribed burning in the Southern Blue Mountains of Oregon. M.S. Thesis, Univ. of Washington, 62p.