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Role of season and interval of prescribed burning on ponderosa pine growth in relation to soil inorganic N and P and moisture

Jeff Hatten [a,*], Darlene Zabowski [b], Amanda Ogden [c], Walt Theis [d], Byoungkoo Choi [a]

[a] Department of Forestry, Mississippi State University, Mail Stop 9681, Mississippi State, MS 39762, USA
[b] College of Forest Resources, University of Washington, Mail Stop 352100, Seattle, WA 98195-2100, USA
[c] U.S. Army Corps of Engineers, Seattle District, P.O. Box 3755, Seattle, WA 98124-3755, USA
[d] USDA Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3200 Jefferson Way, Corvallis, OR 97331, USA

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ABSTRACT

Fire exclusion over the past 100 years has changed the vegetative community and led to an increase in the propensity for large catastrophic wildfires of ponderosa pine forests. Prescribed burning is used to reduce fuel loads and achieve desired stand conditions while the impact caused by this restoration process is primarily dependent on the severity of the fire, which is managed by burning in either fall or spring. The objectives of this study were to assess the effect of season and interval of burn on soil and tree productivity in a ponderosa pine forest in Malheur National Forest of the southern Blue Mountains of eastern Oregon. Prescribed burning was initiated in the spring of 1997 and fall of 1997 at 5- and 15-year intervals. This study was initiated in 2004 so that 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 since the last fire. Soils were sampled by major genetic horizon and A horizon samples were analyzed for soil available nitrogen (KCl extractable NH_4^+ and NO_3^-) and phosphorous (Bray 1 extract). Soil temperature (2 cm) and moisture (7.5, 25, 50, and 100 cm) were monitored for 24 months. Observations and previous studies indicated that fall burns were more severe than spring burns consuming more fuel and leading to higher rates of tree mortality. Extractable NH_4^+ and phosphate increased with multiple burns relative to the single burn treatments, but were statistically similar to the control. Soil temperatures were found to be highest in the more severe fall burn treatments, particularly the 5-year interval burns. Soil moisture was also slightly higher with the 5-year interval burns, possibly due to reduced transpiration from understory vegetation and/or reduced interception by the O horizon. These changes to the soil did not significantly affect ponderosa pine growth relative to the control and may have caused a slight increase in tree growth with the spring burns applied at a 5-year interval relative to the other burn treatments. We hypothesize that low severity spring burning improved the soil growing environment without injuring trees. Combined with results from previous studies spring burns appear to preserve stand productivity, soil carbon and nitrogen, and understory vegetative communities. However, more research is necessary to examine the long-term consequences of repeated burning in these forest types.

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1. Introduction

Fire exclusion 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 US Consequently, an increasing number of catastrophic wildfires have occurred, aided by recent climate trends (Neary et al., 1999; Tiedemann et al., 2000; Wright and Agee, 2004). To minimize the extent and severity of wildfires, land managers use prescribed burning to reduce fuel loads with the intention of obtaining desired stand conditions. However the ecological necessity for prescribed fires is being discussed (Tiedemann et al., 2000; Wright and Agee, 2004) and many of the effects of these prescribed burns on soils, ecosystem health, and site productivity are not well understood.

Ecosystem responses to prescribed burning are primarily dependent on fire severity; fire is typically managed by burning in either the fall or spring. Historically, fires burned through these forests during the summer or fall in the presence of a dry fuel load, but frequent burning limited fuels resulting in low-severity fires (Agee, 1993; Wright and Agee, 2004). Prescribed fires in ponderosa pine forests are frequently conducted during the spring when fuel conditions (higher moisture content) allow fuel consumption and fire behavior to be more controllable. Fall burning can be of moderate to high severity since fuels have dried during the summer

* Corresponding author. Tel.: +1 662 325 7481; fax: +1 662 325 8726.
E-mail address: jhatten@cfr.msstate.edu (J. Hatten).

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months, but may represent the natural fire-severity and timing better than the low-severity spring burn. Fall burning may have a larger impact on accumulated fuels, but the current high fuel load of many forests may result in a higher than natural fire severity, which could be detrimental to management goals. Despite recent increases in scientific understanding of the effects of fire on soil properties, very few studies have characterized how season (fall and spring) or interval of prescribed burning impact forest ecosystems and soils.

Fire directly affects soil through its ability to consume and transform soil organic matter and the O horizon. These transformations lead to outputs of volatilized and combusted C and nutrients. Fire also mineralizes organically bound elements such as N and P into more mobile mineralized forms that are available for uptake by plants or to be leached from the soil system (Giovannini and Lucchesi, 1997; DeBano et al., 1998). Immediate response of the N pool after burning is loss of N in the forest floor through volatilization, but remaining N is usually made more available directly after fire (Neary et al., 1999; Wan et al., 2001). Over time the available N is either leached or immobilized by microbes or plants so that N may be less available after several years (Monleon et al., 1997).

Phosphorus is another potential limiting nutrient for plant growth in some forest ecosystems. Phosphorous has a much higher volatilization temperature (774 °C) than N (200 °C) and very little is usually lost through burning (White et al., 1973; Raison et al., 1985; Certini, 2005). The major effects of fire on P availability come as a result of converting organic P into orthophosphate and by changes to soil pH. The peak in P availability occurs around pH 6.5 and a fire-induced change toward this value has a positive effect. A decline in post-fire P availability can occur as a result of orthophosphate chemically binding with polyvalent cations such as Fe, Al, Mn, and Ca.

In forests of eastern and central Oregon, water availability is a major limitation to growth and forest health. Losses of surface litter and vegetation can result in increased soil evaporation, higher soil temperatures and alter site microclimate affecting tree demand for water. However, fire may remove understory competition for water, thereby leaving more for tree uptake. Wayman and North (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. Similarly, Swift et al. (1993) found elevated soil moisture after felling and burning for site preparation in an eastern pine-hardwood stand. Iverson and Hutchinson (2002) found elevated soil temperatures and no differences in growing season soil moisture in eastern oak forests following prescribed burning. However, longer-term fire effects or repeated fire effects on soil moisture and temperature have not been documented in ponderosa pine forests.

The aforementioned changes to soil productivity appear to be positive (i.e. increased available nutrients and possible increases to soil moisture) which lead us to hypothesize that ponderosa pine stand productivity would also increase. However, research conducted on ponderosa pine stands has found a negative response to prescribed burning that appears to be dependent on fire severity. Landsberg (1992) found ponderosa pine growth was reduced in the burned sites and these reductions persisted for 12 years. Landsberg (1994) also reviewed the effects of prescribed fire and found that growth by *Pinus* species decreased due to root and crown injury. Busse et al. (2000) found minor reductions in ponderosa pine growth for 6 years after low severity prescribed burning that was correlated with crown length reduction, O horizon reduction, and site index. On the other hand no effect on ponderosa pine growth was detected 8 and 9 years after fall and spring prescribed fire (Sala et al., 2005). Tree productivity may be affected by changes in resource availability and injury which may be affected by season or interval of burn.

A season and interval of burn study was initiated 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 resources and tree growth. The objectives of this study were to (1) assess the effects of season of burn and burn interval on soil productivity in the form of available nutrients (extractable NH_4^+, NO_3^-, and orthophosphate), soil moisture, and soil temperature and (2) examine ponderosa pine growth using basal area and basal area increment in relation to soil nutrients and moisture with all burn treatments.

2. Materials and methods

2.1. 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 to 1815 m (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. Kerns et al. (2006) found that grasses and sedges that dominate the understory. 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* spp.). The 80–100 year old stands sites were thinned in either 1994 or 1995.

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 volcanoes in the Cascade Mountains to the west (Powers and Wilcox, 1964). The upper 30 cm of the soils on these study plots typically had an O horizon followed by an average of 15 cm of A and AB horizon and 15 cm of Bw horizon (Hatten et al., 2008). The A and AB horizons had an average bulk density of 1.17 g cm^{-3} while the Bw horizon had a bulk density of 1.32 g cm^{-3}. Soil textures were predominantly coarser textured loams in the surface horizons grading into finer texture loams at depth (Table 1). Coarse content increased from the A horizon (35%) to the B horizon (40%). The bulk density of the fine fraction was 0.87 and 0.95 g cm^{-3} for the A and B horizons respectively. There were no statistically significant differences between the treatments with regard to bulk density or coarse content (Hatten et al., 2008). The soils from the research site are generally dominated by Mollisols, but Inceptisols and Alfisols also are present.

At the Rock spring SNOTEL station (44°0′N/118°50 W), about 25 km WNW of the study site, annual precipitation averages 460 mm with 80% falling as snow between November and April (Natural Resource Conservation Service, 2007). Summers are dry and hot (17 °C mean air temperature in July–August) with cold winters (−3 °C mean air temperature in December–February).

2.2. Experimental design and treatment description

Six replicate study blocks were established and divided into three plots of similar stand type, aspect, slope, and parent materials (described further by Thies et al., 2006). Plot boundaries were established along roads and topographic features to control the prescribed burns. Each plot was randomly assigned as control, fall,

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

Block	Elevation (m)	Aspect	Slope (%)	Field determined soil texture				Soil classifications[a]
				7.5 cm	25 cm	50 cm	100 cm	
Driveway 14	1585–1645	S	13 ± 4	SaL, L, SiL	SaL, L, SaCL	SaL, SiL, SaCL	SaL, SaCL, SiCL	Lithic Argixerolls, Vertic Argixerolls
Driveway 17	1615–1700	S	6 ± 2	L, SiL	L, SaL, SiL SaCL	SaL, SaCL	LSa, Si, SaCL	Lithic Argixerolls, Vertic Argixerolls, Alfisols
Driveway 26	1660–1730	NE	8 ± 5	L, SiL	L, SiL, SaCL	L, SaCL, SiCL	SaCL, SiCL	Lithic Haploxerolls, Vertic Argixerolls, Lithic Argixerolls
Driveway 28	1700–1815	SE	6 ± 6	L, SiL	L, SiL	SiL, SaCL	SaCL	Lithic Haploxerolls, Vertic Argixerolls, Lithic Argixerolls, Alfisols
Kidd Flat	1675–1735	NE	6 ± 1	L	L, SaCL	SaL, L, SaCL	L, SaCL	Lithic Argixerolls, Inceptisols
Trout	1655–1675	W	3 ± 1	SaL, L	SaL, L, SiCL	L, SaCL, SiCL	SaCL, SiCL	Lithic Argixerolls, Inceptisols

[a] Carlson (1974).

or spring burn treatment. A burn interval of 5 or 15 years was assigned to a randomly designated half of each season's plot for five treatments (control, fall-5, fall-15, spring-5, and spring-15) replicated across six blocks. The plots were of similar size (ranging from 6 to13 ha) within each block and were within a range of 0.5–20 km from one another.

Fires were ignited by hand-carried drip torches using a multiple-strip head-fire pattern. Flame lengths were maintained at approximately 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, wind speed, and wind direction were similar during the application of all burns. Both 5- and 15-year-interval plots were burned at the same time during the initial burn. 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.

2.3. Sample collection

A transect of eight 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, residual organic matter, and presence of char at surface of soil. A low-severity fire would produce char heights less than 2 m on a tree bole, have a residual O horizon thickness near that of the controls (~2.5 cm), and have no tree mortality. Moderate-severity fires produce char heights higher than 2 m, residual O horizon would be composed of a thin layer of char on the surface of the soil, and mortality was moderate (<10% of trees within 10 m of soil sample point). High-severity fire was designated when char heights on trees were >2 m, mineral soils were exposed, and tree mortality was high (>10% of trees within 10 m of soil sample point).

2.4. Soil sampling and analysis

A full description and results of the effects of treatments on soil carbon and nitrogen pools can be found in Hatten et al. (2008). Representative soils were sampled from every major genetic horizon to a depth of 30 cm at each sampling point. The water repellency of the surface of each mineral soil horizon was measured in the field by dropping 0.5 ml water and measuring the amount of time needed for the droplet to completely infiltrate the soil (Krammes and DeBano, 1965).

Soil samples were air-dried, weighed, and mineral horizons were separated into coarse and fine fractions with a 2 mm sieve. Coarse fractions were weighed to determine rock content. Subsamples from each air-dried mineral and O horizon were analyzed for pH using the saturated-paste method (Van Miegroet et al., 1994). Each O horizon and the fine fraction of every mineral soil sample were ground using a mortar and pestle for analysis of C and N on a Perkin Elmer 2400 CHN analyzer.

Samples were combined by horizon to provide one composite O horizon and A horizon per plot. Composite samples were analyzed for available N and P. Subsamples of each composite were homogenized using a small grinder. Available N was extracted with 2 M KCl solution using a 10:1 ratio of solution to soil (Keeney and Nelson, 1982; Mulvaney et al., 1996). The extraction was filtered using VWR 494 quantitative filter paper (1 μm retention) and analyzed for NH_4^+ and NO_3^- using an autoanalyzer. Phosphorous was extracted using a Bray 1 solution (0.03 M NH_4F and 0.025 N HCl) at a ratio of 7:1 (solution to soil) and filtered using a VWR 494 quantitative filter paper (Olsen and Sommers, 1982). The filtrate was analyzed for total extractable P using an ICP.

2.5. 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 ECH20 and EC10 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 EM5 5-channel data logger that collected a reading from each sensor once per day (midnight).

Since water and temperature are the dominant factors that limit productivity on these sites we will determine the apparent growing season based upon soil temperature and moisture status. Growing season conditions begin near the time of snow melt in the spring and when freezing soil temperatures begin to rise. Lopushinsky and Max (1990) report that root growth of ponderosa pine and other conifer species began when soil temperatures reached 5 °C. The growing season ends sometime during the summer when soil moisture falls below the plant wilting point (PWP) of

−1500 kPa, for an extended period. We called this period the early growing season (GS_E). Late summer or early fall rains cause soil moisture to rise above the PWP and initiate a possible late growing season (GS_L) that lasts until soil temperatures fall below 5 °C. Growing seasons were calculated for late 2005, early 2006, late 2006, and early 2007 using two temperature and soil moisture indicators. The date when soil temperature was higher than 5 °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 for those locations where the data logger failed to record temperature through the winter (i.e. equipment malfunction). The date at which soil temperature dropped below 5 °C for at least 7 days was the end of the late growing season, which usually occurred in the late fall. During 2005 and 2006 all plots were within ±4 days (95% CI) of each other so any missing dates were replaced with the average date of all plots.

For each soil depth the PWP (−1500 kPa) was determined using the field determined soil texture, organic matter content (two times carbon concentration), and a system of equations developed by Saxton and Rawls (2006). The date at which the PWP was achieved for at least 10 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. Length of early growing season was calculated by the following formula:

$$GS_E = [T > 5\,^\circ C] - [M < -1500\ kpa] \quad (1)$$

where GS_E is the length of the early growing season, $T > 5$ °C is the number of days after January 1 at which the soil temperature is higher than 5 °C for at least 7 days, and $M < -1500$ kPa is the number of days after January 1 at which the soil moisture drops below the plant wilting point of −1500 kPa for at least 10 days. The length of the late growing season was calculated using a similar formula:

$$GS_L = [M > -1500\ kpa] - [T < 5\,^\circ C] \quad (2)$$

where GS_L is the length of the late growing season, $T < 5$ °C is the number of days after January 1 at which the soil temperature drops below 5 °C for at least 7 days, and $M < -1500$ kPa is the number of days after January 1 at which the soil moisture rises above the plant wilting point of −1500 kPa for at least 10 days.

2.6. Tree core sampling and analysis

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. We calculated averages by plot of individual tree parameters to remove the direct effect of mortality on basal area. To convert growth increment to basal growth increment, the DBH for the year of interest was calculated using the following formula:

$$DBH_Y = \left(DBH_{2004} - \sum (GI_{2004}, GI_{2003}, \ldots GI_Y)\right) \quad (3)$$

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:

$$BAI_Y = (\pi(DBH_Y/2)^2) - (\pi(DBH_Y - GI_Y)/2)^2 \quad (4)$$

Basal area accounts for the radial growth of each tree, however there still may be pre-existing differences among the plots. To correct for these differences and isolate 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 that year's basal area using the following formula:

$$PBAI_Y = BAI_Y/[\pi(DBH_Y/2)^2 - BA_Y] \quad (5)$$

where PBAIY is the basal area increment as a proportion of basal area for any given year and BAY is the calculated basal area of that tree 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:

$$PBAI_{1997-2004} = (BA_{2004} - BA_{1997})/BA_{2004} \quad (6)$$

where $PBAI_{1997-2004}$ 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.

2.7. Statistical analysis

To analyze the soil, average values for each horizon or depth were calculated for each treatment within each study block (six replicates), N = 30 for each horizon. Cover and $PBAI_{1997-2004}$ were analyzed by averaging the values for each by grid point and then each plot, N = 30 for each measurement. The experimental design was treated as a completely randomized block (two by two 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 two by two factorial of season and interval of burn. A significance level of $\alpha = 0.10$ was used for all statistical tests.

3. Results

Prescribed fires applied in either the fall of spring were of low severity (Table 2). However, the fall burns experienced slightly higher estimated severity than the spring burns. The fall-5, fall-15, and spring-5 treatments all had lower CWD coverage relative to the control suggesting that fuel loads have been reduced as a result of both fall and spring burning. Furthermore, these three treatments also exhibited higher bare ground coverage.

Fall-5 treatments had significantly lower O horizon thickness, which was 65% lower than the control (Fig. 1a). With one fall (fall-15) and two spring (spring-5) burns, O horizon thicknesses was reduced by approximately 30%, but this reduction was not significantly different from the control. Fall burning at 5-year intervals may keep O horizon thickness thin and patchy decreasing the infiltration rate and reducing the chance that throughfall and precipitation are intercepted and lost through evaporation from this horizon. An increase in water flux to the mineral soil surface may either increase runoff (and erosion) or increase the amount of water infiltrating the soil (elevating soil moisture).

O horizon thickness from plots treated to only one spring burn was not significantly different from the control. The lower severity

Table 2
Canopy, ground cover and soil pH characteristics after (1) (15-year-interval) or (2) (5-year-interval) prescribed fires applied during the fall or spring.

		Control	Fall		Spring		p	p	$p_{\#}$	$p_{s*\#}$
			5	15	5	15				
Burn severity		ND	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	0.600
Bare ground (%)		11 ± 7[a]	28 ± 9[b]	21 ± 9[ab]	22 ± 12[ab]	13 ± 10[a]	**0.012**	**0.043**	**0.031**	0.868
Grass (%)		11 ± 8[ab]	8 ± 2[ab]	14 ± 8[b]	5 ± 3[a]	11 ± 7[ab]	**0.099**	0.156	**0.019**	0.957
Canopy (%)		37 ± 9[bc]	24 ± 8[a]	25 ± 9[ab]	33 ± 6[abc]	41 ± 8[a]	**0.006**	**0.001**	0.142	0.342
Basal area ($m^2\ ha^{-1}$)		21 ± 6	17 ± 4	12 ± 3	17 ± 4	23 ± 1	0.359	0.204	0.892	0.163
	O horizon pH	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 horizon pH	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 horizon pH	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

Data are displayed as means ± standard deviation. Significant ($\alpha = 0.1$) 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.

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. Water repellency at the surface of the A horizon

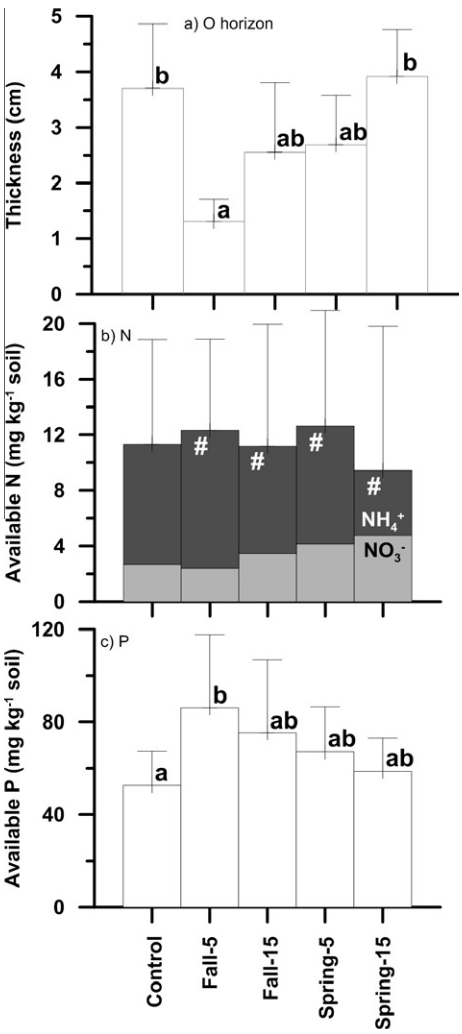

Fig. 1. (a) O horizon thickness, (b) total inorganic N, NH_4^+, and NO_3^- concentration of A horizons (mean ± standard deviation of total inorganic N concentration), and (c) total Bray extractable P in the A horizons after (1) (15-year-interval) or (2) (5-year-interval) fall and spring burns (mean ± standard deviation). Significant ($\alpha = 0.1$) differences between treatments were determined by a one-factor ANOVA. Letters indicate similar groups using Tukey's HSD after determining significant ($\alpha = 0.1$) differences using a one-factor ANOVA. A # indicates significant differences ($\alpha = 0.1$) among NH_4^+ concentrations between number of burns as tested by orthogonal contrasts.

was lowest on fall burn treatments and significantly negatively correlated with bare ground coverage ($R = -0.522$) (Table 2). Erosion occurring after the initial fall burn could have removed fire-produced hydrophobic materials from the surface of the A horizon. However, there was little evidence of erosion so it is more likely that by removing the O horizon by fire inputs of hydrophobic materials from the O horizon into the mineral soil were reduced (Doerr et al., 2000). Thus, the higher-severity fall burns reduced natural hydrophobicity and it remains low, but the lower-severity spring burn maintained mineral soil hydrophobicity. Hydrophobicity in combination with a thicker O horizon may impact the amount of water that is available for plant uptake in the mineral soil.

3.1. Soil pH and available nutrients

O and A horizon pH values were elevated by burning with the more recent higher-severity fall burns (Table 2). Fall burns increased A horizon pH while pH from spring-5 treatments may be influenced by a reduction in understory grass and grass-litter cover. Additionally, a recent influx of fresh litter containing organic acids from fire-induced litter fall could have lowered the pH.

There was more extractable NH_4^+ on the plots most recently burned (represented by # in Fig. 1b). 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 fall-5 treatments had a significantly higher proportion of total N as NH_4^+ relative to the plots with one spring burn. Nitrate concentration or total inorganic N was not significantly different among the treatments ($p > 0.10$) (Fig. 1b). However, total available N was significantly related to forb cover ($R = 0.357$) suggesting that these understory species responded to the increases in available N.

The fall-5 treatments had significantly increased the labile P concentration over the control (Fig. 1c). Since the fall-5 treatments had the greatest amount of O horizon consumed this likely resulted in 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 1 extraction) (Olsen and Sommers, 1982).

3.2. Soil moisture and temperature

Generally, average weekly soil temperature followed average weekly air temperature (Fig. 2a). 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

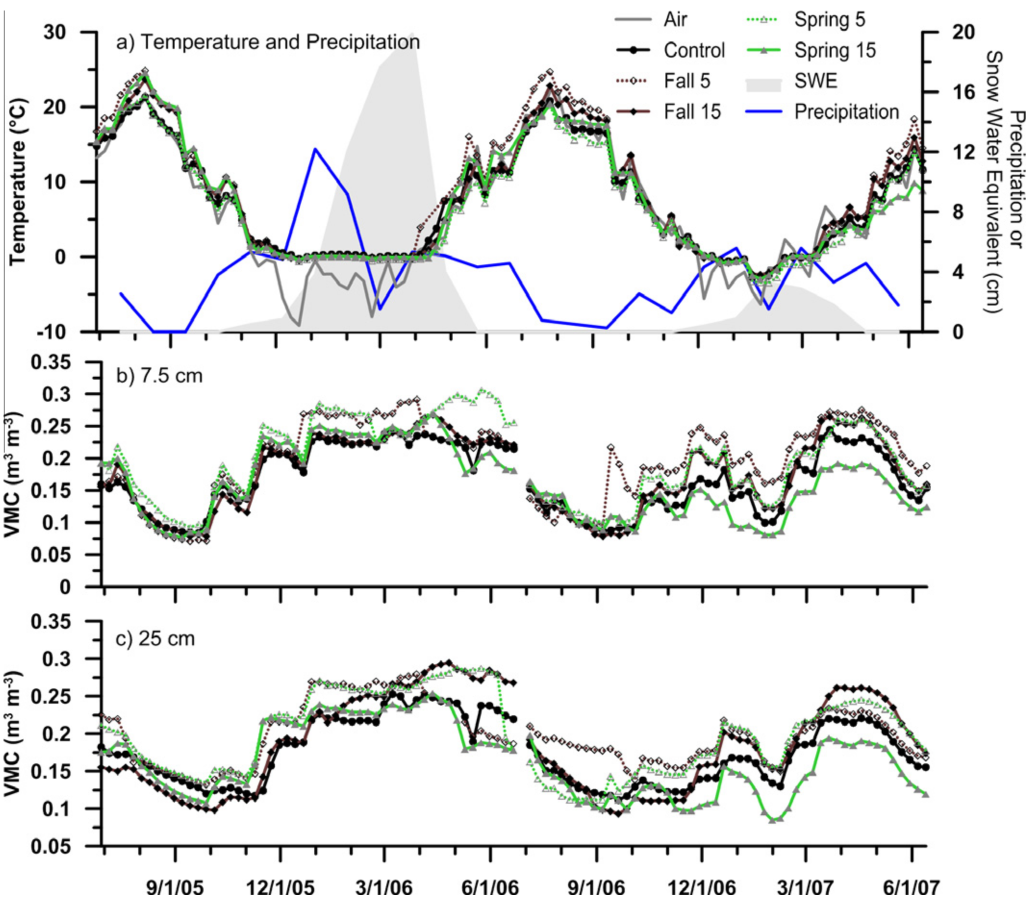

Fig. 2. (a) Weekly average air and soil temperature and monthly precipitation and snow water equivalent at the Rock spring SNOTEL station. Weekly average soil moisture at (b) 7.5 cm soil depth and (c) 25 cm soil depth for plots treated to (1) (15-year-interval) or (2) (5-year-interval) fall and spring burns.

winter of 2007 the lower than average snow pack and a possible February melt, was not able to insulate the soil so that temperatures fell below freezing.

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 (Fig. 2a). Furthermore, the average monthly temperature of fall burns are statistically higher than spring burns during the months of July 2006, August 2006, September 2006, April 2007, and May 2007, however they did not have higher temperatures than the control. The soil temperature during these months was significantly 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 reach the soil surface. Additionally, bare ground has a lower albedo than O horizon, which would be exacerbated by charcoal on the surface. Spring-15 treatments had higher monthly temperatures than the spring-5 treatments in October 2006 possibly as a result of plots treated to one spring burn having a higher average slope (16% versus 11% on the two spring burn plots).

Higher temperatures in the fall burn 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 in stands treated to spring burns at 5-year-intervals. If seed germination patterns are altered it is possible that the season of burn could be important for favoring some species over others.

Soil moisture across the treatments was highest in the winter and lowest during the summer (Fig. 2b and c). The snow pack and precipitation were higher than average for the 2005–2006 water year which may have led to higher soil moisture at all depths during the late fall and winter of that year. Lower transpiration and interception as a result of the reduction of understory vegetation and O horizon thickness may be resulting in higher soil moisture at the 7.5 cm depth with multiple burns (5-year burn interval). Bare ground coverage was significantly 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). During September and October of 2006 the 5-year-interval treatments had higher soil moisture than the 15-year-interval treatments, but were not significantly different from the control. The monthly moisture at the 7.5 cm depth of the fall-5 treatments were significantly higher than the fall-15 treatments during September 2006. 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 (Fig. 2b). The soil moisture at the 25 cm depth of the fall burn plots was found to be significantly higher than that of spring burning during August 2006, but not significantly different from the control or during any other month. There were no significant differences in average monthly soil moisture among treatments at the 50 and 100 cm depth so the data are not shown.

As would be expected, the length of the calculated growing season increases with depth. The average length of the early 2006

Table 3
Average growing season (number of days) for plots treated with (1) (15-year-interval) or (2) (5-year-interval) fall or spring burns ($n = 6$) at 7.5 cm depth.

	Control	Fall		Spring		p	p_s	$p_{\#}$	$p_{s*\#}$
		5	15	5	15				
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

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 tension is less than −1500 kPa. Length of the late growing season is the length of time after the early season that soil moisture tension is less than −1500 kPa for at least 7 days and greater than 5 °C. Significant ($\alpha = 0.1$) 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.

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 susceptible to alteration by treatments that affect surface environmental variables such as burning.

The early and late growing seasons appears to have been lengthened by multiple burns especially multiple fall burns (Table 3). Prescribed fires at 5-year intervals have 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 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 (data below 7.5 cm not reported). Nevertheless, the fall burns of the 5-year-interval plots often have the longest GS_E and total growing season as a result of there being plant available water later into the season.

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 particular importance to annuals that extract water from shallower depths than perennials or trees. Forb coverage was significantly 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).

The prescribed burning treatments appear to cause an increase in water availability and soil temperature in the surface horizons. These effects may be responsible for some of the changes witnessed in understory composition (Kerns et al., 2006). We would also expect that along with the trends in available nutrients these changes would lead to changes in tree productivity.

3.3. Tree growth

The results from this study indicate no significant difference among the treatments for basal area (Table 2). This is counter to the results that Thies et al. (2005) found, this discrepancy is likely due to high variability in the basal area measurements; the grand mean for basal area was 18.2 $m^2\,ha^{-1} \pm 3.67\,m^2\,ha^{-1}$ (95% CI). Thies et al. (2005) used permanent plots and examined mortality over time at each plot. Basal area estimated in this study appears

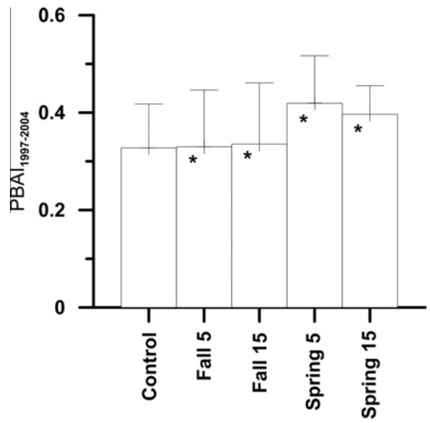

Fig. 3. Proportion of basal area (BA) growth between 1997 and 2004 to BA growth of 2004 for plots treated to (1) (15-year-interval) or (2) (5-year-interval) fall and spring burns. Orthogonal contrasts between the plots treated to prescribed fire found a significant interaction between season and number of burns which is denoted by an *.

to be higher than Thies et al. probably due to tree growth as shown below and a decrease in pine mortality since 1998 measurements performed by Thies et al.

There were no significant differences between individual years' basal area growth between the treatments (as PBAI) from 1994 to 2004. However the basal area production as a proportion of 2004 BA ($PBAI_{1997–2004}$) shows that the spring-5 and spring-15 treatments may be experiencing slightly increased growth over the other treatments although not significantly different from the control (Fig. 3). Total N was positively correlated with $PBAI_{1997–2004}$ ($R = 0.341$) suggesting that N is a limiting nutrient on these sites during part of the growing season. This limitation to growth may have been partially relieved through mineralization of N by the prescribed burns. 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 ($R = 0.365$, $p = 0.047$), which suggests that increased growth, occurring in the plots treated to multiple spring burns (5-year-intervals), may be caused by a reduction in competing vegetation allowing more water and nutrients to be available.

4. Discussion

Available N and P increased with multiple burns relative to the single burn treatments, but were statistically similar to the control. The fall-5 treatments were found to have the highest soil temperatures and soil moisture. These changes to the soil environment did not significantly affect ponderosa pine growth relative to the control, but may have caused a slight increase in tree growth on the spring burns applied at a 5-year interval relative to the other burn treatments.

4.1. Available nutrients

The response of ecosystems and soils to fire is dependent on fire severity. We found that the initial burns may have been higher severity since evidence of high severity fire was the same across all burn intervals. In a previous study on these sites the fall burns were quite severe, killing 29% of all trees (Thies et al., 2005), supporting our assertion that these initial burns were the most severe. These initial burns had the highest severity compared to the second burn likely due to high fuel loading. As a result of the second fire, fuels were reduced 23–25% with significant reductions in the O horizon, 10-h, and 100-h fuels (Kerns et al., 2011). Both fall and spring prescribed burning had an effect on fuels on these sites. Therefore, it is possible that spring burning could reduce the fuel loading and prepare the site for fall burning, if achieving a fall-burn prescribed-fire regime is a management objective.

Overall, we found that there was more extractable NH_4^+ on the plots most recently burned; however they were not significantly different from the control. Of these only the fall burns had a significantly higher proportion of total N as NH_4–N relative to the plots with one spring burn, again not significantly different from the control. However there was more P available after the second fall burn. This is a result of a mineralization of P by burning as well as higher orthophosphate activity due to significantly higher pH in the A horizon of fall burn plots. These effects have persisted for at least two years after the last prescribed burn. 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).

Elevated available N in the fall-5 and spring-5 treatments could come about as a result of mineralization by the most recent fires, lower uptake by plants, higher mineralization rates, or increased N inputs by N fixers. Soil samples were collected during the summer drought when most of the understory was senescing, so differences in available N between treatments may be less affected by temporal variability in soil available N. The ratio of C–N in O horizons has an inverse relationship with the ability of OM to be mineralized and release N into a plant available form. The C/N of the O horizon was not different from control O horizon with any treatment (no differences among the mineral soils), but among the burn treatments was significantly higher in the 5-year-interval treatments. This result is counter to what would be expected if higher mineralization rates were elevating available N in these soils. Nitrogen mineralization rates may also be affected by higher soil moisture and temperature, which occurred on the fall burn treatments but not the spring burn treatments. There are at least two N fixing species at this site: *L. caudatus* and *C. velutinus* (Kerns et al., 2011). *L. caudatus* is a perennial forb which as a class accounted for less than 7% of the cover across all treatments (no significant differences among control, fall-5, or spring-5 treatments). While *C. velutinus* cover doubled as a result of fall burns it accounted for less than 0.6% of the total cover on these sites. There were minor differences among the treatments with regard to N-fixers; however both fall-5 and spring-5 treatments had a similar response in total available N. This suggests that N fixers did not cause available N to be elevated on the 5-year-interval treatments. Elevated N could be caused by a decrease in uptake as a result of a lower cover of vegetation, which did occur on the fall-5 treatments, but not the spring-5 treatments. There may be a complicated interaction of these processes which produced elevated available N on the fall-5 and spring-5 treatments, but the simplest explanation appears to be mineralization caused by the most recent fire.

Available P was also elevated across the burn treatments; however it was not significantly greater than the control on treatments other than fall-5. This suggests that available P is responding to something other than mineralization by the most recent fire. pH is a strong controller of orthophosphate activity in soils (Brady and Weil, 2004). O and A horizon pH was significantly correlated with available P ($R = 0.410$ and $R = 0.311$, respectively), suggesting that elevated available P is a result of fire induced increases in pH. Fire induced pH changes may last for over 3 years after burning (Ulery et al., 1993), nearly long enough to begin accumulating available P in the 5-year-interval treatments. Schafer and Mack (2010) found that the effects of burning on available P were longer lasting than available N suggesting that the effects of burning on available P may accumulate when sites are reburned if the burning interval is short enough.

Extractable NH_4^+ and NO_3^- concentrations were very high compared with other studies in the region. Monleon et al. (1997) found total inorganic N concentrations of about 1.0–6.0 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. We hypothesize that this is a result of these soils being rich in organic matter. The A and B horizon of this site (current study) had C and N concentrations that were the highest among reported values for ponderosa pine stands in eastern Washington, eastern Oregon, and western Montana (Monleon et al., 1997; Baird et al., 1999; DeLuca and Zouhar, 2000; Hatten et al., 2005). Therefore, high available N is likely due to the very high average OM concentration of the A horizon, and total inorganic N concentration was correlated with total C content ($R = 0.549$, $p = 0.002$).

In ponderosa pine stands west of our study site in central Oregon, Monleon (1997) found that available N began to decline 1 year after prescribed burns. Available N eventually declined to the point that it was lower than control plots 5 years after burning. We did not observe any significant decline in available N among our treatments and relative to the control for the 1–7 years since prescribed burns had been applied. This again is likely indicative of the rich soils present on these sites and throughout the southern Blue Mountains. 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. All other factors being equal (e.g. tree mortality and injury, soil moisture availability) we expected that there would be some positive changes to site productivity as a result of prescribed fire treatments.

4.2. Ponderosa pine growth

We did not detect a reduction in ponderosa pine growth as a result of prescribed burning as other authors have shown (Grier, 1989; Landsberg, 1992; Busse et al., 2000). We may have found a slight increase in ponderosa pine growth as a result of multiple spring burns. Differences among the studies do not appear to be a result of fire severity since the severity of prescribed burning in the current study was higher (60 cm versus 26 cm flame lengths) than reported in Busse et al. (2000), similar to Landsberg (1992), and lower than Grier (1989). The high organic matter and nutrient content of these sites may be buffering it from reductions in productivity. Within the region the ponderosa pine forests examined in this study had the highest C and N contents, (as reported in Hatten et al., 2008) this includes sites similar to those studied by Landsberg (1992), Busse et al. (2000) and Grier (1989).

We found that multiple fall burns were associated with better post-fire growing conditions in the form of the longest growing seasons, highest soil temperatures, highest soil moisture, highest pH, and highest available nutrients (NH_4^+ and labile P). Fall burning at 5-year-intervals did have the highest mortality (Thies et al., 2005); however our measure of stand productivity (PBAI) was normalized by stand basal area reducing the direct effects of mortality by examining averages of individual trees. We hypothesize that the trees that survived the higher-severity fall burns may have been injured, thereby reducing their productivity despite the better growing environment. In support of this hypothesis was the result of Thies et al. (2005) who reported that there were differences in crown scorch between the fall and spring burns however they were not statistically significantly different. Tree roots in the surface soil may have been killed or injured at a higher rate under the fall burning relative to spring burning; however we did not observe any differences in root abundance during pit excavation and soil moisture and temperature probe installation. The result that tree productivity was not lower than the control on the plots treated to multiple fall burns at 5-year-intervals suggest that the better growing environment in this treatment may be canceling out the effects of tree injury.

4.3. Implications for understory

Kerns et al. (2006) hypothesized that changes to soil resources (e.g. nutrients and moisture) caused by the initial fall burns resulted in an increase in cover and richness of both exotic and native annuals/biennials. The greatest change in soil resources occurred in the surface soil horizon which is likely the soil volume being utilized by these shallow rooted plants. Indeed, we found that understory forb cover was correlated with available N and soil temperature, suggesting that soil resources are being affected by fire which then may subsequently effect understory composition and productivity. While there are few studies that adequately tie together changes to soils after prescribed burning and plant ecology 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. These results suggest that successive fall burns may lead to even more drastic changes to understory composition on plots burned in the fall potentially leading to greater cover of exotic species.

5. Conclusions

Reinitiating fire into a fire-suppressed forest achieves management goals of fuel reduction whether the burns are applied in the fall or spring. The effect of these treatments appears to lead to better growing environment as measured by available nutrients and soil moisture. However, only the spring burns responded to the better growing environments with slightly higher tree productivity probably as a result of a lower rate of tree injury in the spring burns relative to the fall burns. These results are contrary to other studies of post-prescribed fire productivity of ponderosa pine in the region possibly as a result of the high organic matter and nutrient content of these soils. Additionally, changes to available soil nutrients and moisture caused by fall burning at 5-year intervals may be contributing to observed changes in understory species composition on these plots. Combined with the results from previous studies on these sites (Kerns et al., 2006; Hatten et al., 2008) show that spring burns appear to preserve stand productivity, soil carbon and nitrogen, and understory vegetative communities. However, more research is necessary to examine the long-term consequences of repeated burning in these forest types.

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