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The Effects of Repeated Prescribed Burning on *Pinus ponderosa* Growth

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Abstract. The effect of repeated prescribed burning on long term growth of *Pinus ponderosa* in northern Arizona was examined. Fire treatments for hazard reduction were initiated in 1976, and growth was evaluated in 1988 for fire rotations of 1, 2, 4, 6, 8, and 10 years. Dendroecological analysis shows that there were only small changes in tree growth (compared to controls) in the first few years after the initial fire treatment despite large fuel reductions and thinning, and that annual precipitation was positively correlated with growth. Moderate changes in growth relative to that of control trees were apparent after 1984. The 1-, 2-, 8-, and 10-year treatments had lower growth than controls after this date, while 4- and 6-year treatments had slightly higher growth. Although additional data are needed to determine long term growth effects in the longer fire rotations, a fire treatment interval of 4 to 6 years appears to provide adequate fuel reduction without reducing long term growth in Southwestern *P. ponderosa* forests.

Keywords: Dendroecology; *Pinus ponderosa*; Prescribed fire; Tree growth.

Introduction

Fire is being increasingly used as a management tool in both commercial and protected forest areas (Martin and Dell 1978, Sackett 1980, Sandberg 1980, Hunt and Simpson 1985). Prescribed fires can reduce fuel loading, thereby reducing the probability of subsequent high intensity fires (Wagle and Eakle 1979, Covington and Sackett 1990, Ffolliott and Guertin 1990, Agee 1993). The damaging effects of fire on trees through crown, stem, and fine root damage (Wyant et al 1983, Ryan and Reinhardt 1988, Peterson and Arbaugh 1989, Ryan and Steele 1989, Ryan and Frandsen 1991, Peterson et al 1991, Swezy and Agee 1991) must be balanced against the potential benefits of thinning and nutrient release on growth (Covington and Sackett 1986, 1992; Harris and Covington 1983, Reinhardt and Ryan 1988, Sutherland and Covington 1987, Oliver and Larson 1990, Sutherland et al 1991).

Most previous research on the effects of fire on conifers has focused on the relationship between physical injury and tree survival (Lynch 1959, Methven 1971, Dieterich 1979, Peterson and Arbaugh 1986, Wyant et al 1986, Ryan and Reinhardt 1988, Ryan et al 1988, Peterson and Arbaugh 1989). Several studies have examined the effect of prescribed burning on conifer growth, although the results vary widely. Investigators have found increases (Morris and Mowat 1958, Van Sickle and Hickman 1959, Cooper 1960, Weaver 1967, Wyant et al 1983, Reinhardt and Ryan 1988), decreases (Wooldridge and Weaver 1965, McCormick 1976, Landsberg et al. 1984, Johansen and Wade 1987, Sutherland 1989, Cochran and Hopkins 1991), or no change (McCormick 1976, Waldrop and van Lear 1984, Hunt and Simpson 1985) in growth after wildfire or prescribed burning treatments in different forest types.

Most of the studies cited above address short term changes in fuel reduction (Sackett 1980, Sandberg 1980), tree survival, and other site conditions after fire. There is little information on the *long term* effects of prescribed burning (Reinhardt and Ryan 1988) or wildfire (Peterson and Ryan 1986, Peterson et al 1991) on growth and productivity. If prescribed burning is to be used as a management tool in forests, then information on long term growth of the residual stand is needed. Data on stand growth as well as fuel reduction must be evaluated in order to determine the effectiveness of prescribed burning programs. In this study, we evaluate the impact of prescribed burning on *Pinus ponderosa* growth in northern Arizona over an 11-year period. Specifically we quantify the effect of burns repeated at different intervals over time. This will assist in identifying an optimal schedule for future prescribed burn treatments in this forest type.

Methods

Study Sites

The study was conducted in the Chimney Spring unit of the Fort Valley Experimental Forest, in the Coconino National Forest. This 36-ha unit is located 11 km northwest of Flagstaff, Arizona, USA, at 35°16' north, 111°45' west. The study site is on a southwest-facing slope (< 10% throughout), 9 km south of the San Francisco Mountains, at a mean elevation of 2260 m. Soils are primarily Brolliar stony clay loam, derived from volcanic cinders and basalt parent material (Meurisse 1971). Climate is cool and dry with mean annual precipitation of 55 cm.

The Chimney Spring unit is virtually undisturbed by timber cutting. The last known fire at the site occurred in 1876, although the area burned every few years prior to European-American settlement (Dieterich 1980, Dieterich and Swenam 1984). Intensive cattle grazing after 1876 prevented tree establishment in the area (Harrington and Sackett 1992) until forest reserves were created and grazing was reduced about 1910. Most of the mature trees that occupy the Chimney Spring site today regenerated from the heavy seed crops of 1914 and 1919. This unit is the site of a long term study designed to determine burning techniques adequate to provide continuous fire hazard abatement (Sackett 1980).

The study is comprised of 21 1.1-ha plots, which are contiguous with one another. Treatment plots were randomly assigned among the 21 plots in 1976 prior to the first prescribed fire, which was applied to all plots except controls. There are 3 "replications" for plots burned at 1-, 2-, 4-. 6-, 8-, and 10-year intervals, including 3 unburned plots as "controls" (Table 1). These treatment plot designations are to be maintained indefinitely.

Stand structure prior to the start of the study in 1976 consisted of only one tree species, *P. ponderosa*, with primarily even-aged groups of trees of varying size. Mean basal area was 39.7 m^2/ha, and mean stem density was 4620 stems/ha (Table 2). The high stem density was comprised primarily of small trees, with densities of 970 stems/ha for trees <1.4 m tall and 2730 stems/ha for trees 1.5-10 cm dbh (Sackett 1980). There was considerable variation in basal area and stem density among treatment plots prior to prescribed burning, although there were no significant differences among plots.

Fuel Loading and Prescribed Fire Treatments

Burn treatments were conducted on the plots in autumn at the appropriate time intervals. Lightning-caused fires normally occur in this area between May through July when there is substantial atmospheric convective activity with lightning, and fuels are dry enough to burn. Prescribed fires in autumn generally have lower rates of spread and flame lengths than in the summer and are less likely to become uncontrolled, which is an important management consideration for this site. Potential for crown kill in trees is considerably less in autumn than in late spring and summer because buds of *P. ponderosa* are set and more resistant to heating.

The unit had 33.8 tonnes/ha of dead surface and ground fuel ≤2.5 cm in diameter, and 16.0 tonnes/ha of woody fuel >2.5 cm in diameter. The first prescribed burn treatments were conducted in November 1976 on 18 of the plots (with 3 unburned control plots). Rates of spread averaged 1.5-2.0 m/min, and flame lengths in litter fuels rarely exceeded 50 cm. Fuel ≤2.5 cm in diameter was reduced to 12.6 tonnes/ha (63%), with greatest reduction in needles and duff. Mineral soil was exposed on 16% of the area. Large woody fuel (2.5-7.5 cm diameter) was reduced to 4.9 tonnes/ha (54%). Sixty-four percent of all dead organic material on the site was consumed by the fire. Many small trees (<5 cm dbh) in thickets were killed, resulting in a

Table 1. Prescribed fire applications over time are indicated (X) for each treatment.

	Year of fire											
Treatment	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
1-year	X	X	X	X	X	X	X	X	X	X	X	X
2-year	X		X		X		X		X		X	
4-year	X				X				X			
6-year	X						X					
8-year	X								X			
10-year	X										X	
Control												

reduction in stem density (Table 2). Very few larger trees were killed. Further details of fuel loading and burn treatments are found in Sackett (1980).

Rates-of-spread and fuel consumption varied for the subsequent burn treatments, although rate-of-spread was usually less than 2 m/min and flame length rarely exceeded 50 cm (details of individual fire characteristics are on file with S. Sackett, USDA Forest Service, Riverside, California). The fires removed primarily needles and small woody fuel on the surface, and mineral soil was not normally exposed. The fires rarely killed trees >10 cm dbh. Fire behavior was most extreme and fuel reductions greatest (normally all fuels accumulated since the last fire) in the 4-year rotations; some of the trees in the 4-year rotations were scorched in the lower crown. The number of burns that had been conducted at the time of sampling (July 1988) is as follows for the various treatments (Table 1): control (none), 1-year (12), 2-year (6), 4-year (3), 6-year (2), 8-year (2), 10-year (2).

Sampling and Measurements

We used dendroecological methods to evaluate the effect of periodic burning on long term tree growth. Trees were sampled in each of the 21 plots (7 treatments, 3 "replicates" per treatment) previously described. Transects (10 m wide) were established through the center of each plot, and trees were sampled starting at one end of the transect. The first 20 trees located along the transect that fit the sampling criteria were selected to represent growth on each plot. In order to be included in the sample, trees were required to be codominant or dominant *Pinus ponderosa* >10 cm dbh with no major crown or stem defects (unrelated to fire).

Dbh was measured in the field for all sample trees. Two cores were extracted with an increment borer from the cross-slope sides of each sample tree at breast height (1.4 m). Cores were stored in paper straws for transport to the laboratory. Current stand structure (basal area, stem density) was determined by measuring dbh for stems >1.4 m tall within five 0.02-ha quadrats in each plot.

Tree cores were mounted in wooden blocks and sanded until individual tracheids were visible under the microscope. Cores were crossdated (by accurately associating each ring with a specific calendar year) visually (Stokes and Smiley 1968, Fritts 1976, Swetnam et al. 1985) and with the program COFECHA (Holmes 1983). Ring width was measured to the nearest 0.01 mm with an incremental measuring machine interfaced with a digital encoder and microcomputer to record measurements (Robinson and Evans 1980).

Analysis

Current stem density and basal area were assessed by combining data for all plots within a treatment (data for each treatment are based on fifteen 0.02-ha quadrats [5 quadrats in each of 3 plots]). Stem density and basal area data are also available from 1976, just prior to the initiation of prescribed fire treatments. Differences among treatments in basal area and total stem density were determined with analysis of variance and the Student-Newman-Keuls (SNK) multiple comparison test. Significant differences were identified at the =.05 level.

Ring width measurements were used to calculate annual basal area increments (BAI) for all tree cores. The time series of BAI for individual trees were used for all subsequent analyses. Growth trends for the

Table 2. Summary of treatment plot characteristics (± 1 SD). Data for each treatment are based on 15 0.02-ha quadrats (5 quadrats in each of 3 plots). Treatments with significant differences (determined by SNK test, α=.05) in basal area and total stem density are indicated by different letters within columns.

Treatment	Basal area (m^2/ha)		Stem density in each dbh size class (stems/ha)						
	Measured in 1976	Measured in 1988[1]	Dbh size class (cm) of trees measured in 1988					Total in 1988[2]	Total in 1976
			< 10	11-20	21-30	31-40	> 40		
1-year	37.8 (7.4)^{a}	51.0 (11.5)^{a}	460 (430)	740 (610)	330 (190)	170 (90)	50 (60)	1740 (870)^{ab}	5030 (1610)^{a}
2-year	43.1 (7.2)^{a}	41.5 (13.5)^{a}	620 (810)	370 (310)	240 (120)	180 (90)	30 (30)	1450 (910)^{b}	3440 (1770)^{a}
4-year	35.4 (5.8)^{a}	41.0 (8.2)^{a}	220 (240)	390 (400)	270 (110)	160 (70)	35 (40)	1080 (480)^{b}	3630 (670)^{a}
6-year	36.7 (2.0)^{a}	47.0 (14.1)^{a}	1180 (1040)	680 (330)	320 (150)	140 (90)	20 (40)	2350 (1160)^{a}	5830 (770)^{a}
8-year	36.7 (4.6)^{a}	49.5 (10.6)^{a}	550 (470)	540 (310)	300 (130)	190 (90)	50 (30)	1630 (480)^{ab}	4060 (2180)^{a}
10-year	40.7 (3.8)^{a}	40.5 (4.5)^{a}	750 (300)	380 (130)	380 (80)	90 (40)	30 (40)	1630 (200)^{ab}	5150 (1480)^{a}
Control	37.8 (2.2)^{a}	50.0 (13.0)^{a}	1040 (780)	760 (260)	380 (190)	120 (70)	30 (40)	2350 (720)^{a}	5020 (1980)^{a}

[1] SNK test indicates that differences in basal area are not significant at α=.05, although ANOVA indicates a significant difference among treatments (F=2.21, prob.>F=.05).

[2] ANOVA indicates a significant difference among treatments (F=4.86, prob.>F=.01).

different treatments were initially compared visually. BAI was plotted over time (1949 to 1987) for all trees within each treatment (number of observations ranges from 58 to 60 per treatment). BAI was expressed as an index for each tree for each year in order to have a relative measure of growth that was comparable among trees of different sizes and ages:

$$\text{BAI index} = \frac{\text{BAI}_{ix}}{\overline{\text{BAI}}_{nx}} \qquad (1)$$

where BAI_{ix} is BAI in year i for tree x, and $\overline{\text{BAI}}_{nx}$ is mean BAI for tree x for the period 1949-1987. Mean BAI index was calculated and plotted for each treatment. Differences in growth between fire treatment trees and control trees were calculated as:

$$\text{Difference from control} = \frac{\text{BAI}_{ixt}}{\overline{\text{BAI}}_{nxt}} - \frac{\text{BAI}_{ic}}{\overline{\text{BAI}}_{nc}} \qquad (2)$$

where $\text{BAI}_{ixt}/\overline{\text{BAI}}_{nxt}$ is mean BAI index for all trees in treatment t, and $\text{BAI}_{ic}/\overline{\text{BAI}}_{nc}$ is mean BAI index for all control trees in a given year. Time series of differences between treatment and control tree growth were plotted and compared to determine the effects of fire treatments on long term growth. Differences in growth between different time periods were compared with ANOVA and the SNK test.

Results and Discussion

Stand and Sample Characteristics

Current stand basal area is lower than controls for all fire treatments except the 1-year treatment (Table 2); the SNK test indicates these differences are not significant at α=.05, although ANOVA indicates a significant difference among treatments (F=2.21, prob.>F=.05) Current total stem density is higher (although not always significantly) in control plots than in all treatments except the 4-year treatment. Most of the differences in stem density among treatments are accounted for by differences in the number of stems <10 cm dbh; there are few differences among treatments for stems >20 cm dbh. Only 3 trees >60 cm dbh were sampled in any of the stand structure quadrats at the study site.

Current stem densities are approximately 40% of stem density in 1976 prior to the initiation of fire treatments (Table 2); this proportion is remarkably consistent among treatments and controls, although absolute numbers vary. Most of the reduction in stem density on treatment plots occurred in stems <5 cm dbh after the first fire (Sackett 1980, Sackett unpublished data), although the large decrease in stem density on control plots indicates there may have been additional mortality due to competition and other non-pyrogenic causes. Basal area has remained relatively constant or increased over time in both treatment and control trees.

Table 3. Summary of sample tree characteristics (± 1 SD).

Treatment	n	Dbh (cm)	Age at dbh (yr)
1-year	60	32.2 (8.8)	71 (4)
2-year	58	34.4 (8.0)	71 (7)
4-year	60	32.0 (7.1)	69 (5)
6-year	58	29.5 (5.7)	68 (5)
8-year	59	32.0 (7.0)	69 (6)
10-year	60	28.8 (6.0)	67 (4)
Control	59	29.0 (4.8)	70 (4)

Characteristics of sample trees are relatively homogeneous across all treatments (Table 3). Mean dbh has a narrow range of only 28.8 to 34.4 cm, and tree age at dbh is also uniform across all treatments. The uniformity of size and age minimizes the possibility that between-treatment variation in tree growth is caused by differences in sample tree characteristics.

Effects of Prescribed Fire Treatments on Tree Growth

There was a substantial decrease in growth in all treatments (including controls) in 1977, the year after the first prescribed burn treatment. Precipitation was extremely low in this year (Figure 1, U.S. Department of Agriculture weather data for Fort Valley Experimental Forest). *Pinus ponderosa* growth is positively correlated with soil moisture at most locations in western North America (Fritts 1974, Peterson and Arbaugh 1988, Peterson et al. 1991), so it is logical that growth tracks precipitation patterns to some extent.

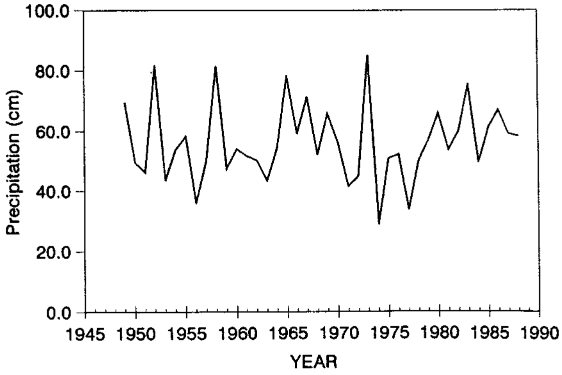

Figure 1. Mean annual precipitation at the Chimney Springs site for 1949-1988. Summarized from U.S. Department of Agriculture weather data for Fort Valley Experimental Forest.

Unfortunately the occurrence of low precipitation the year after the first fire treatment makes it difficult to differentiate the initial effect of fire from that of climate. The occurrence of a large growth decrease in both treatment and control trees in 1977 (Figures 2-4) suggests that climate was the dominant factor affecting growth immediately after the fire. In fact, growth patterns of treatment and control trees (Figures 2-4) are clearly correlated with precipitation patterns (Figure 1) until about 1984.

Crown scorch and cambial injury to trees >10 cm dbh were minimal (Sackett 1980), so reduced photosynthesis or translocation are unlikely causes of the growth decrease. Previous studies have shown that prescribed burning can damage the fine roots of *pinus ponderosa*, causing decreased postfire survival (Swezy and Agee 1991) and growth (Grier 1989). However, mineral soil exposure was minimal on all fires (maximum of 16% after the first fire treatment), so root damage is unlikely. Standard deviations of BAI growth are higher in the fire treatments than in the controls during 1977-1978, which indicates variation in individual tree growth response to the fire (Biondi et al. 1992). Standard deviations are similar to those of controls thereafter, which suggests that subsequent fires had little influence on the variation in growth response within treatments.

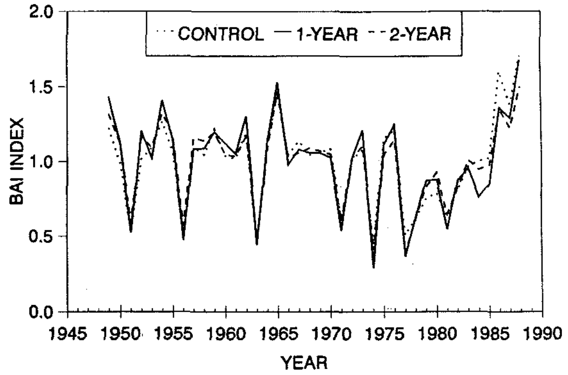

Figure 2. Time series of BAI index for 1-year and 2-year fire rotation treatment trees and control trees.

Growth expressed as time series of BAI index values (see Equation 1) is displayed in Figures 2-4 for fire treatment and control trees. It can be seen that interannual growth patterns of treatment and control trees are similar over time, with only small differences between treatment and control trees after the initiation of fire treatments in 1976. Only data for 1949-1987 are shown in the figures because growth prior to this time was predominantly juvenile growth characterized by a steady increase in BAI.

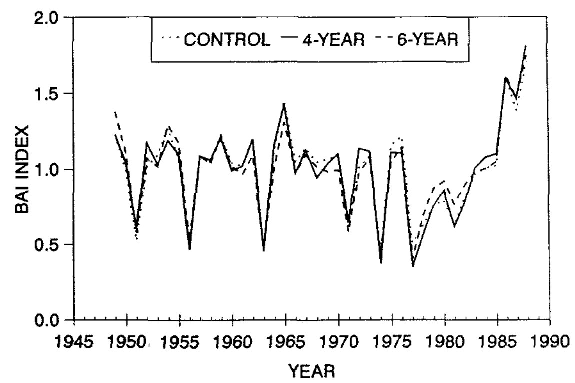

Figure 3. Time series of BAI index for 4-year and 6-year fire rotation treatment trees and control trees.

Plots of BAI index values (Figures 2-4) make it difficult to discern fire treatment impacts after 1976 because of variation throughout the time series. An alternative approach of assessing growth patterns is to more closely examine "difference from control" (see Equation 2) for each of the fire treatments (Figure 5). This analysis shows that all fire treatment groups have negative values (that is, growth was less than in control trees) in 1977 and 1978, which suggests a possible effect of the initial fire beyond the growth decrease caused by low precipitation (Figure 1). Difference from control was mostly positive (that is, growth was greater than in control trees) for all treatments from 1980 through 1983. After 1984, difference from control remained mostly positive for 4-year and 6-year fire treatments but was negative for 1-year, 2-year, 8-year, and 10-year treatments.

It is unclear why there was a similar decrease in growth for several of the treatments. The effect of fire in 1984 could be related to some of the decreases if there were damage to fine roots (Grier 1989, Swezy

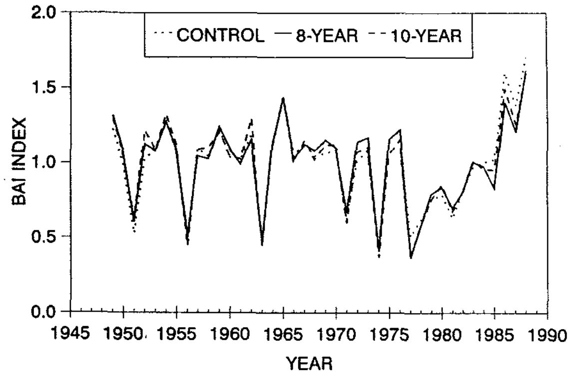

Figure 4. Time series of BAI index for 8-year and 10-year fire rotation treatment trees and control trees.

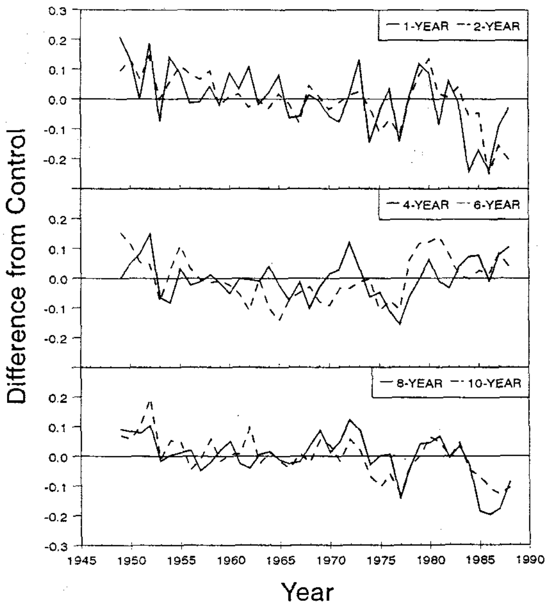

Figure 5. Difference in growth between fire rotation treatment trees and control trees calculated as the difference in their respective BAI index values. Positive values indicate growth greater than that of control trees; negative values indicate growth less than that of control trees.

and Agee 1991) or changes in site fertility (Landsberg et al. 1984, Cochran and Hopkins 1991). However, the 4-year treatment was burned in 1984 as well, but did not have a decrease in growth.

Statistical analysis shows that differences in BAI growth among fire treatments are marginally significant for the entire 11-year period (1977-1987) after the first prescribed fire (Table 4). Graphical presentation of the data appears to indicate that postfire growth was greater in the 4- and 6-year burns than in unburned control stands and other fire treatments (Figure 5), although this contrast in growth was not manifested until 8 years after the initial prescribed fire. ANOVA results confirm differences among treatments in growth after 1984 (Table 4), although the SNK test suggests that only the 4-year fire treatment differs significantly (α=.05) from other treatments. A combination of graphical and statistical results indicate that growth after 1984 was clearly greater for the 4-year treatment than other treatments; growth was also greater for the 6-year treatment, but differences cannot be stated as confidently.

A postfire growth increase might be expected as a result of thinning (Reinhardt and Ryan 1988, Oliver and Larson 1990, Peterson et al. 1991, Sutherland et al. 1991). Stem density in 4-year and 6-year treatments in 1988 was 40% of pre-fire density in 1976 (Table 2). Other fire treatments had similar percentage (but different absolute) decreases in stem density, but appeared to have growth decreases after 1984 (Figure 5). Analysis of thinning impacts is confounded somewhat by differences in absolute stem densities between treatment and control plots. Although thinning may be partly related to the different growth patterns, the relationship between stem density and long term growth is not consistent.

Previous studies of the effects of fire in *Pinus ponderosa* forests of Arizona have documented a transfer of nutrients from the forest floor to the mineral soil (Covington and Sackett 1984, 1990, 1992). Transfers of nitrogen are especially large, and increased nitrogen in the mineral soil can be measured several years after fire (Harris and Covington 1983, Covington and Sackett 1986). Increased concentrations of inorganic nitrogen, primarily NH_4-N, greatly enhance short-term soil fertility at the study site (Covington and Sackett 1990, 1992). However, the relative impact of postfire nutrient availability on tree growth is difficult to determine. Perhaps burning at 4- and 6-year intervals produces a combination of soil fertility, soil moisture (Covington and Sackett 1990), and reduced understory competition that is more favorable (or less detrimental) for tree growth conditions associated with other burning intervals.

It is unclear why different growth patterns among treatments were not manifested until after 1984 (Figure 5). Four of the treatments were burned in this year, including 3 treatments with growth decreases (1-, 2-, and 8-year) and 1 without decreases (4-year). One of the treatments not burned in 1984 (10-year) also had growth decreases. The response of *Pinus ponderosa* growth to fire is apparently complex, despite the fact that the sample appears to be relatively homogeneous and the study site contains little variation in slope, aspect, and soils. A better understanding of the possible interactive effects of fire and climate may be

Table 4. Summary of ANOVA comparing BAI index among fire treatments for different time periods.

Time period	F value	Probability > F
1977-1987	3.76	<.01
1984-1987	2.64[1]	.02
Ratio of:		
1977-1987 : 1949-1976	1.18	.31
1949-1983 : 1984-1987	0.48	.82
1977-1983 : 1984-1987	4.93[2]	<.01

[1] SNK test indicates that there are no significant differences (α =.05) among individual fire treatments.

[2] SNK test indicates that the 4-year treatment is significantly different (α =.05) from all other treatments, with no other significant differences among treatments.

critical for interpreting long term tree growth trends. Studies of the effects of prescribed fire on *P. ponderosa* growth in Oregon have suggested that repeated fire can reduce long term site productivity and tree growth (Landsberg et al. 1984, Cochran and Hopkins 1991), although the studies were conducted on low fertility ash and pumice soils. There may be some factors related to soil properties or other environmental features not considered in this study, such as fine root damage (Grier 1989, Swezy and Agee 1991, Agee 1993), that account for a substantial portion of the variation in growth over time (Biondi et al. 1992).

Despite the lack of direct causation between fire and tree growth response, there are some general inferences that can be made. The use of prescribed fire at intervals of 4 to 6 years in *Pinus ponderosa* forests in Arizona appears to effectively reduce fuels without detrimental impacts on tree growth. More frequent or less frequent fires could result in reduced long term growth. In addition, fires that were conducted at 4- and 6-year intervals at the Chimney Spring study site provided better fuel consumption than fires at other intervals—perhaps because of a more continuous fuelbed—without producing fireline intensities or flame lengths that would injure trees (Harrington and Sackett 1990, Sackett unpublished data).

Previous studies in this region have demonstrated that periodic use of prescribed fire can effectively reduce fuel accumulation and wildfire hazard (Ffolliott and Guertin 1990, Harrington and Sackett 1990). If prescribed fire is used in Southwestern *Pinus ponderosa* forests at intervals of 4 to 6 years, then it should be possible to attain the multiple management objectives of reducing fuels, eliminating understory vegetation, and maintaining adequate growth rates in the forest overstory. Longer term analysis of data from our study site and other locations is needed to provide a stronger basis for recommending appropriate intervals for prescribed burning in *P. ponderosa* forests.

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