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Understory vegetation response after 30 years of interval prescribed burning in two ponderosa pine sites in northern Arizona, USA

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ABSTRACT

Southwestern USA ponderosa pine (*Pinus ponderosa* C. Lawson var. *scopulorum* Engelm.) forests evolved with frequent surface fires and have changed dramatically over the last century. Overstory tree density has sharply increased while abundance of understory vegetation has declined primarily due to the near cessation of fires. We examined effects of varying prescribed fire-return intervals (1, 2, 4, 6, 8, and 10 years, plus unburned) on the abundance and composition of understory vegetation in 2007 and 2008 after 30+ years of fall prescribed burning at two ponderosa pine sites. We found that after 30 years, overstory canopy cover remained high, while understory plant canopy cover was low, averaging <12% on all burn intervals. We attributed the weak understory response to a few factors – the most important of which was the high overstory cover at both sites. Graminoid cover and cover of the major grass species, *Elymus elymoides* (squirreltail), increased on shorter fire-return intervals compared to unburned plots, but only at one site. Community composition differed significantly between shorter fire-return intervals and unburned plots at one site, but not the other. For several response variables, precipitation levels appeared to have a stronger effect than treatments. Our findings suggest that low-severity burn treatments in southwestern ponderosa pine forests, especially those that do not decrease overstory cover, are minimally effective in increasing understory plant cover. Thinning of these dense forests along with prescribed burning is necessary to increase cover of understory vegetation.

1. Introduction

Much of our knowledge on the effects of fire on understory vegetation in forested systems comes from one-time prescribed burns or wildfires that are often studied only a few years post-fire. Fewer studies have examined long-term effects of repeated burns on understory vegetation. Compared to a single burn, repeated burning may differentially influence species recruitment and persistence, seed longevity within the seedbank, and thus species composition (Bond and van Wilgen, 1996). Ruderal species may increase with repeated fires while resprouting perennial species may recover within a few years following a single fire but not tolerate frequent repeated fires (Grime, 1977). In ecosystems that evolved with frequent fire regimes, such as southwestern ponderosa pine (*Pinus ponderosa* C. Lawson var. *scopulorum* Engelm.) forests, it is important to understand how the effects of repeated burning on the understory plant community differ from one-time burns.

Repeated-fire studies provide the opportunity to examine ecosystem responses to factors such as varying fire-return intervals, fire frequency, or time since a fire. In some studies, short fire-return intervals and high fire frequency tend to favor herbaceous species over woody plants, with woody vegetation increasing with time-since-fire (Waldrop et al., 1992; Glitzenstein et al., 2003; Peterson et al., 2007). Graminoids often increase in abundance following high frequency (annual or biennial) burning compared to unburned treatments (Tester, 1996; Brockway and Lewis, 1997; Glitzenstein et al., 2003; Uys et al., 2004; Peterson et al., 2007). Some annual and biennial forbs are favored by either single or repeated fires and then decrease with time-since-fire, but perennial forbs are usually less tolerant of frequent and repeated burning (Brockway and Lewis, 1997; Laughlin et al., 2005; Peterson et al., 2007; Peterson and Reich, 2008). Overall species richness is often enhanced by burning, especially at intermediate fire frequencies and intervals (Peterson and Reich, 2008), and plant community composition tends to

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diverge, especially between frequently burned and unburned areas (Mehlman, 1992).

In a number of repeated-fire studies, understory plant responses to varying fire-return intervals, fire frequency, and time-since-fire are subtle. In forested ecosystems, the combination of low-intensity fires and high overstory cover often constrain understory response. Low-intensity burning can contribute to continued high overstory dominance and limited understory response (Mehlman, 1992; Hutchinson et al., 2005; Peterson et al., 2007). In ponderosa pine forests, understory abundance is strongly related to tree density (Pase, 1958; Clary and Ffolliott, 1966; Uresk and Severson, 1989; Moore and Deiter, 1992), and in the southwest, understory plant response is highly dependent on precipitation patterns (Fulé et al., 2005; Moore et al., 2006; Laughlin et al., 2008; Laughlin and Moore, 2009). Thus, the effects of repeated burns can be highly variable and ecosystem-dependent.

Our study explores the effects of 30 years of repeated prescribed burning at varying fire-return intervals on two southwestern ponderosa pine sites. Southwestern ponderosa pine forests evolved with frequent fire and have changed dramatically over the last century. Across much of these forests tree density has increased sharply while understory vegetation abundance has declined, due in part to changes in the fire regime (Cooper, 1960; Covington and Moore, 1994). Before the late 1800s, frequent fires were common in southwestern ponderosa pine forests (Weaver, 1951; Biswell, 1972; Fulé et al., 1997). Estimates on mean fire-return intervals range from 2 to 17 years (Swetnam and Baisan, 1996). These frequent fires kept pine regeneration at low levels resulting in an open, park-like forest structure with an understory abundant in grasses and forbs (Weaver, 1951; Cooper, 1960; Biswell, 1972). In the late 1800s, Euro-Americans began to settle in the region bringing with them grazing, logging, and fire suppression practices (Cooper, 1960; Friederici, 2003). These practices led to a steep decline in the number of wildfires, allowing development of dense thickets of pines which reduced light and other resources and resulted in a sharp decline in understory vegetation (Cooper, 1960; Biswell, 1972; Covington and Moore, 1994). In recent decades prescribed fire has been increasingly used to restore the structure and function of ponderosa pine forests (Friederici, 2003). In 1976, Sackett (1980) began a long-term, interval prescribed fire study on two southwestern ponderosa pine sites that had not burned for at least 75 years. This is the only long-term study that explores the effects of varying fire-return intervals in southwestern forests. In the southeastern USA there have been some longer studies of fire frequency and interval effects including a study begun in 1946 in loblolly pine (*Pinus taeda* L.) and another begun in 1958 in longleaf pine (*Pinus palustris* Mill.; Mehlman, 1992; Waldrop et al., 1992; Glitzenstein et al., 2003).

The goal of this study was to determine the effects of varying fire-return intervals on forest characteristics including fuel loadings, overstory tree density, and understory plant cover. This paper focuses on the effects of varying fire-return intervals, fire frequency (number-of-fires over 30+ years; hereafter number-of-fires), and time-since-fire on abundance and composition of understory vegetation after 30 years of prescribed burning. We hypothesized that understory plant cover would increase with shorter fire-return intervals in response to reductions in overstory canopy cover and litter. We expected that graminoid cover would increase on shorter return interval treatments and decline with time-since-fire, and annual/biennial species richness would respond negatively to time-since-fire and fire-return interval and positively to number-of-fires. We expected that total species richness would be highest at moderate levels of burning. We hypothesized that after 30 years, plant community composition would differ among treatments, particularly between unburned and shorter fire-return intervals.

2. Methods

2.1. Study area

We conducted this study at two sites, Chimney Spring on Fort Valley Experimental Forest, and Limestone Flats on Long Valley Experimental Forest, in the Coconino National Forest in northern Arizona, USA. Both sites are characterized as dense ponderosa pine communities with an understory strongly dominated by the bunchgrasses *Elymus elymoides* (Raf.) Swezey (squirreltail) and *Festuca arizonica* Vasey (Arizona fescue). In recent surveys of the entire study site, approximately 40–48 ha, we found a total of 122 species at Chimney Spring and 138 at Limestone Flats (Scudieri et al., 2008). Prescribed burning treatments began at Chimney Spring in 1976 and at Limestone Flats in 1977 (Sackett, 1980), and have been continuously maintained since. The Chimney Spring study area is 11 km northwest of Flagstaff, at an elevation of 2250 m on basalt-derived soils; annual precipitation averages 51 cm (Western Regional Climate Center, 2009). Limestone Flats is 90 km southeast of Flagstaff, at an elevation of 2100 m; soils are derived from sandstone and limestone, and annual precipitation averages 67 cm. This region primarily receives precipitation as late summer rain and winter snow. Annual precipitation (October–September) was 42 cm in 2007 and 57 cm in 2008 at Chimney Spring, and 47 cm in 2007 and 66 cm in 2008 at Limestone Flats.

Livestock grazing was eliminated before the study began and no commercial logging occurred at either site (Sackett, 1980; Peterson et al., 1994). The historical fire-return interval at Chimney Spring averaged 2.6 years for all fires and 7.1 years for widespread fires; while at Limestone Flats the average fire-return interval was 2.5 years for all fires and 5.4 years for widespread fires (Swetnam and Baisan, 1996). Swetnam and Baisan (1996) based the fire-return interval for all fires on every fire scar date recorded between 1700 and 1900 from every sample collected (fire-scarred cross sections from several ponderosa pines at each site), and based the fire-return interval for widespread fires on fire scars dates recorded by at least 25% of the samples.

2.2. Study design

Each site has 21 plots with three plots randomly assigned to each of seven treatments. The treatments consist of burning 1 ha (100 m × 100 m) plots at six different intervals (every 1, 2, 4, 6, 8, and 10 years) and an unburned control. We burn plots each year with strip head fires in late fall after a killing frost. Temperatures during the burns generally range from 10 to 16 °C, relative humidity range from 20% to 50%, and wind speeds range from 3 to 16 kph. Fire intensity is low, with average flame lengths <20 cm. Our analyses cover 2007 and 2008, and therefore time-since-fire varies from 1 to 10 years and number-of-fires range from 3 to 31 on the burn treatments at the two sites (Table 1).

We measured overstory basal area and tree density in 2006 at Chimney Spring, and in 2007 at Limestone Flats. We measured the dbh of all trees >5 cm dbh in five permanently marked 0.04-ha circular subplots within each plot. In 2007 and 2008, we measured overstory canopy cover at 1-m intervals using a GRS densitometer (Ben Meadows Company, Janesville, WI, USA) along four permanent 25-m transects. We calculated overstory canopy cover as the percentage of canopy hits out of the total possible hits per plot.

We collected understory vegetation data in 2007 and 2008 in late July and August. We estimated percent canopy cover of understory species and litter, plus species richness, on each plot. The sampling design for understory canopy coverage consisted of four 25-m transects permanently marked within each plot. We placed a 20 cm × 50 cm quadrat at 1-m intervals along each transect, for a total of 100 quadrats per plot. Percent cover was estimated by

Table 1
Number of years since an interval was last burned (time-since-fire) and number of times an interval has been burned (number-of-fires) since the study began at both study sites. At Chimney Spring the 1-, 2-, 6-, 10-year intervals were burned in the late fall of 2006 and these same intervals were burned in 2007 at Limestone Flats.

Year	Interval	Chimney Spring		Limestone Flats	
		Time-since-fire (years)	Number-of-fires	Time-since-fire (years)	Number-of-fires
2007	1 year	1	31	1	30
	2 year	1	16	2	15
	4 year	3	8	2	8
	6 year	1	6	6	5
	8 year	7	4	6	4
	10 year	1	4	10	3
	Unburned	∼100	0	∼75	0
2008	1 year	1	32	1	31
	2 year	2	16	1	16
	4 year	4	8	3	8
	6 year	2	6	1	6
	8 year	8	4	7	4
	10 year	2	4	1	4
	Unburned	∼100	0	∼75	0

cover classes, for total vegetation, litter, graminoids, forbs, shrubs, and individual species. Cover classes were: trace (<1%), 1 (1–5%), 2 (5–25%), 3 (25–50%), 4 (50–75%), 5 (75–95%), and 6 (95–100%) (modified from Daubenmire, 1959). We quantified species richness by systematically searching a 25 m × 52 m area between transects and recording every species encountered. Nomenclature and nativity are based on USDA-NRCS (2009). Reference specimens are deposited at the U.S. Forest Service Rocky Mountain Research Station herbarium in Flagstaff, AZ.

We estimated ground char severity shortly after burning on the 1-, 2-, 6-, and 10-year interval plots that were burned in 2006 at Chimney Spring, and in 2007 at Limestone Flats. We estimated percent cover of unburned, light, moderate, and deep char (adapted from Ryan and Noste, 1985) in every 5th quadrat using the same layout and cover classes as plant canopy cover. To convert the cover of the four char classes into a single measure of ground char severity, we multiplied the midpoint of each cover class by a weighted char factor (0 = unburned, 1× = light char, 2× = moderate char, and 3× = deep char), and averaged them by transect (Fowler et al., 2008). This value has a possible range of 0–3 with higher values representing higher fire severity.

2.3. Statistical analysis

We used repeated measures analysis of variance (ANOVA) to test for differences in overstory canopy cover and litter cover (2007 and 2008), and one-way ANOVA to test for differences in tree basal area, tree density, and ground char severity among fire-return intervals using the PROC MIXED procedure in SAS 9.1 statistical software (SAS Institute Inc., 2004). We evaluated normality of the residuals using a Shapiro–Wilk test. When significant main effects were found, we used Tukey HSD pairwise comparisons to determine which specific burn treatments differed.

We developed and compared three different models for each response variable using either fire-return interval, time-since-fire, or number-of-fires as the categorical, fixed-effects treatment. Response variables we analyzed were cover of total vegetation, graminoids, forbs, shrubs, and major graminoid species (*E. elymoides*, *F. arizonica*, and *Muhlenbergia montana* (Nutt.) Hitchc. (mountain muhly) as well as total, annual/biennial, and perennial species richness. In each model, we used repeated measures analysis of covariance (ANCOVA) with overstory canopy cover and litter cover as potential covariates, and site and plot as random variables using the PROC MIXED procedure (SAS Institute Inc., 2004). If residuals were non-normal, we computed pairwise comparisons of the adjusted treatment means using the MULTTEST procedure (SAS Institute Inc., 2004). Litter cover was omitted from the models due to high correlation with overstory cover, but even with this omission, overstory cover was not identified as a significant covariate for any response variable. Due to lower Akaike Information Coefficients (AIC) and more interpretable results, we present results based on separate models for each of the two sites.

To examine differences in plant community composition, we ordinated plant cover data by species from each site using nonmetric multidimensional scaling (NMDS). In NMDS, distance among points is proportional to compositional dissimilarity; the greater the distance among the points, the less similar they are in composition. We ran the ordinations with 250 iterations using random starting conditions and 250 randomized runs with a stability criterion of 0.000001. We ran a multi-response permutation procedure (MRPP) to test for differences in community composition among fire-return intervals. We used the Sorensen distance measure for the MRPP and NMDS analyses and these analyses were performed using PC-ORD software (McCune and Mefford, 2006).

3. Results

3.1. Effect of fire-return interval on overstory, ground char severity, and litter cover

Even after 30+ years of burning, closed-canopy, dense stands of ponderosa pine dominated both sites. Overstory canopy cover ranged from 57% to 83% and basal area ranged from 32 to 47 m^2 ha^{-1}, and neither differed among burn intervals at Chimney Spring ($ps > 0.09$); but at Limestone Flats both were lower on 6-year compared to 10-year and unburned plots ($ps \leq 0.019$; Fig. 1). Tree density ranged from 652 to 2377 trees ha^{-1} and was higher on unburned plots compared to burned treatments ($p = 0.003$) at Chimney Spring, but did not differ among intervals at Limestone Flats ($p = 0.08$).

Ground char severity indices for the 2006 and 2007 fires ranged from 0.04 to 1.03 (Fig. 1). At both sites ground char was higher ($ps < 0.0001$) on longer fire-return intervals compared to shorter intervals. Litter cover ranged from 74% to 89%, and at Chimney Spring was higher ($p = 0.032$) on unburned plots compared to 1- and 4-year intervals and higher ($p = 0.046$) in 2007 than 2008; but at Limestone Flats, litter cover did not differ by treatment or year ($ps > 0.06$).

3.2. Effect of fire-return interval, time-since-fire, and number-of-fires on plant response variables

The models using time-since-fire and number-of-fires as the treatment did not differ substantially from the fire-return interval

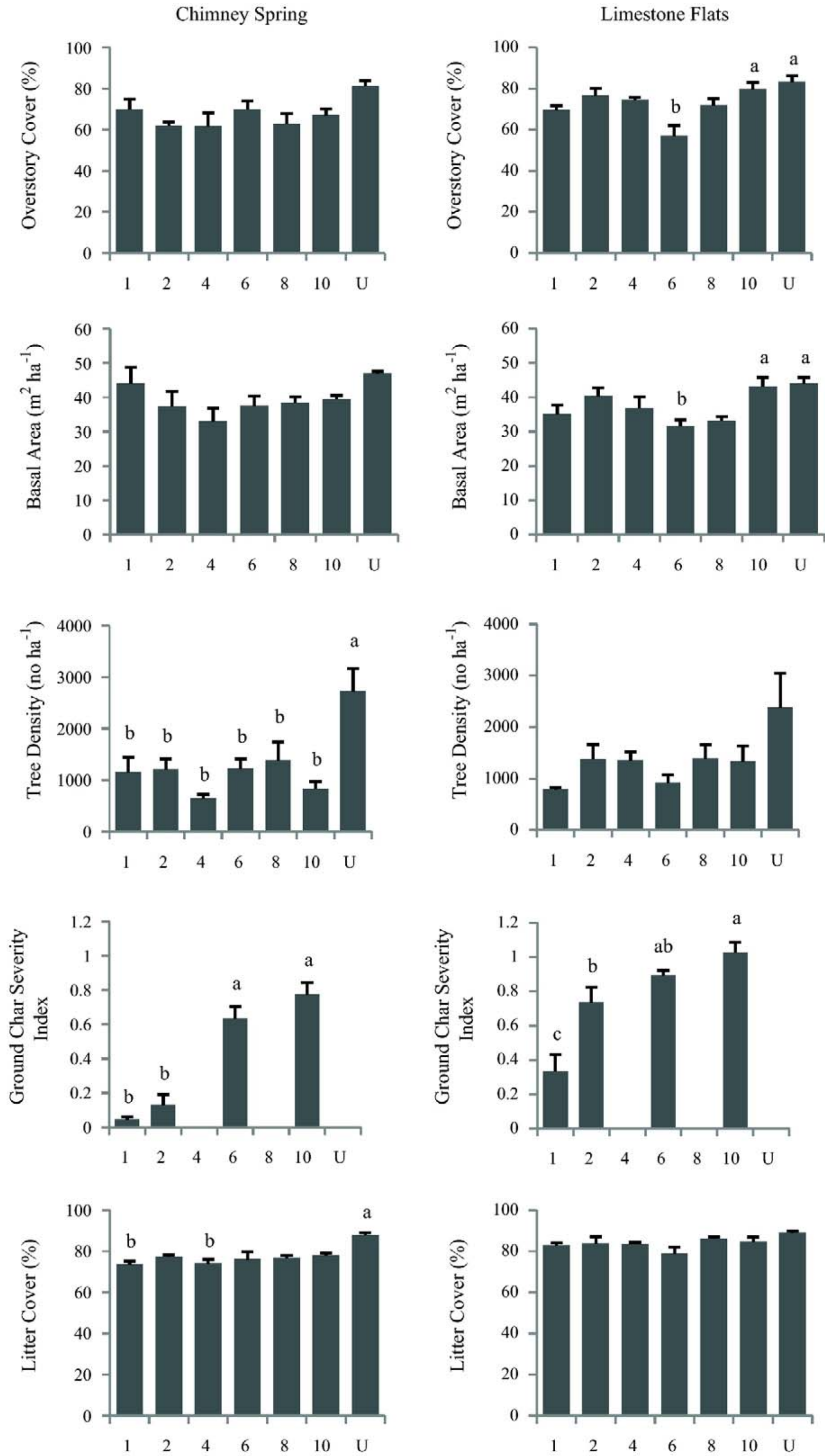

Fig. 1. Average (SE) overstory cover, tree basal area, tree density, ground char severity index (0–3 scale; 0 = unburned, 3 = severe char), and litter cover by fire-return interval for both study sites. Significant differences among treatments are indicated by letters.

model and did not improve interpretability of the results, therefore we only present the results for the fire-return interval model below.

Total plant canopy cover was very low on all burn intervals, averaging <12%, and the minor differences in cover among burn intervals were not significant ($p > 0.1$; Fig. 2). Total plant canopy cover did not differ by year at Chimney Spring ($p = 0.26$), but was higher ($p = 0.0002$) in 2008 compared to 2007 at Limestone Flats. The understory cover was strongly dominated by graminoids, followed by forbs and shrubs.

Graminoid cover averaged <8% and showed low variability among fire-return intervals. The only differences detected were

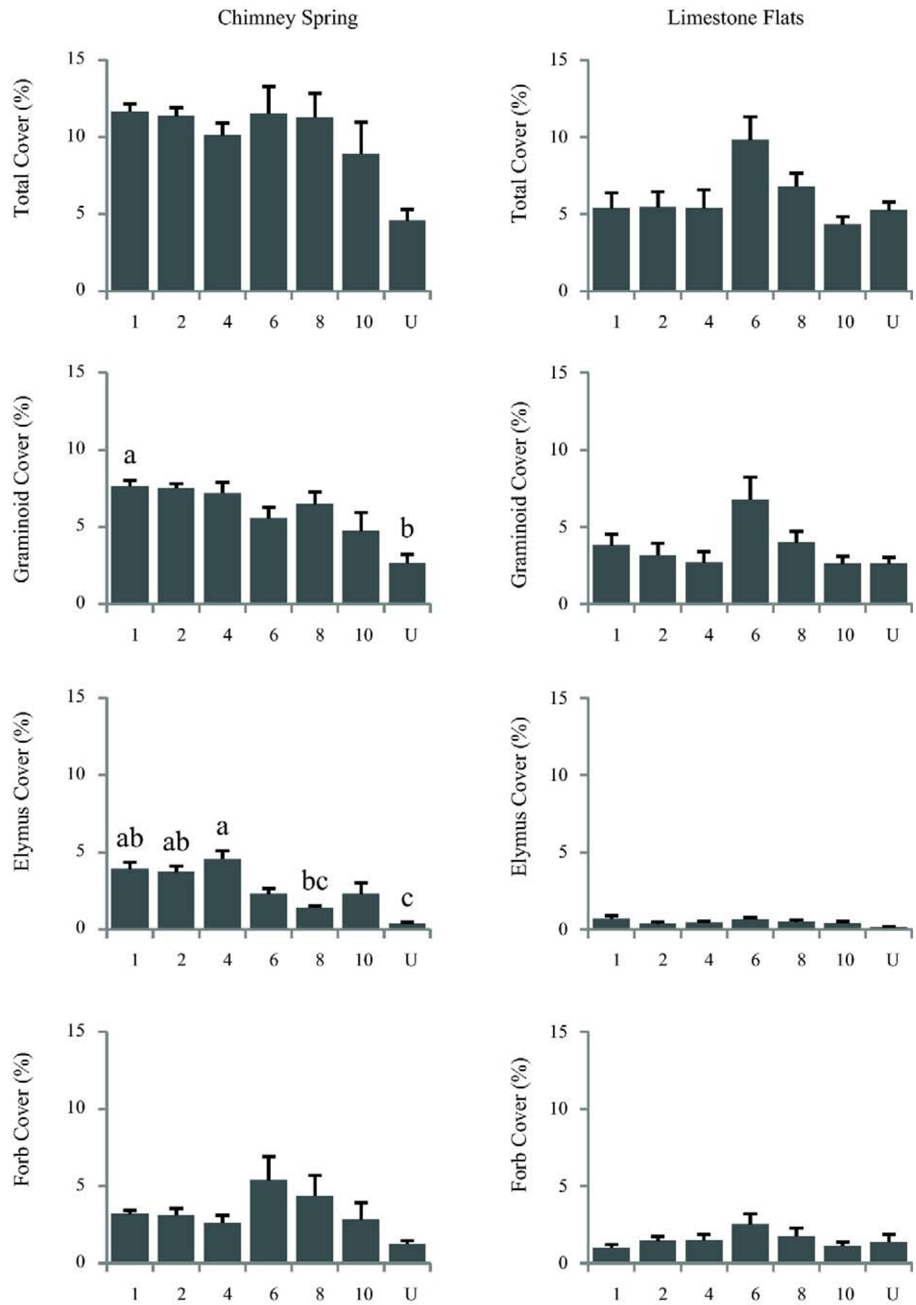

Fig. 2. Two-year average (SE) of understory plant cover variables by fire-return interval for both study sites. Significant differences among treatments are indicated by letters.

lower ($p = 0.035$) graminoid cover at Chimney Spring on unburned than on plots burned at 1-year intervals and higher cover ($p = 0.003$) in 2007 than in 2008 (Fig. 2). At Limestone Flats graminoid cover did not differ among burn intervals ($p = 0.12$) or between years ($p = 0.12$). *E. elymoides* cover differed significantly ($p = 0.004$) among intervals at Chimney Spring, and was lower on unburned plots (averaging <1% cover) and longer fire-return interval plots compared to shorter interval plots. *E. elymoides* cover did not differ among intervals at Limestone Flats ($p = 0.18$). *E. elymoides* cover was higher in 2007 than in 2008 at Chimney Spring ($p = 0.009$) but was higher in 2008 at Limestone Flats ($p = 0.008$). *F. arizonica* and *M. montana* cover did not differ among intervals ($ps > 0.1$) or between years ($ps > 0.16$) at either site.

At both sites, forb cover averaged <6% and shrub cover averaged <2%, and did not differ by burn interval ($ps > 0.1$; Fig. 2). Forb cover did not differ between years at Chimney Spring ($p = 0.08$) but was higher in 2008 at Limestone Flats ($p < 0.0001$). Shrub cover did not differ by year at either site ($ps > 0.4$). Common forb species included *Solidago velutina* DC (threenerve goldenrod), *Cirsium wheelerii* (A. Gray) Petr. (Wheeler's thistle), *Antennaria parvifolia* Nutt. (small-leaf pussytoes), and *Pseudocymopterus montanus* (A. Gray) J.M. Coult. & Rose (alpine false springparsley); shrubs included *Ceanothus fendleri* A.Gray (Fendler's ceanothus) at both sites and *Rosa woodsii* Lindl. (Woods' rose) at Chimney Spring.

Total species richness averaged between 287 and 369 species ha^{-1} and perennial species richness between 257 and 321 species ha^{-1}; neither response variable differed among intervals at either site ($ps > 0.06$; Fig. 3). Annual/biennial species richness averaged between 29 and 56 species ha^{-1} and did not differ ($p = 0.16$) among treatments at Chimney Spring. In contrast, annual/biennial species richness was higher on the 6-year interval and unburned than on most other treatments at Limestone Flats. At both sites

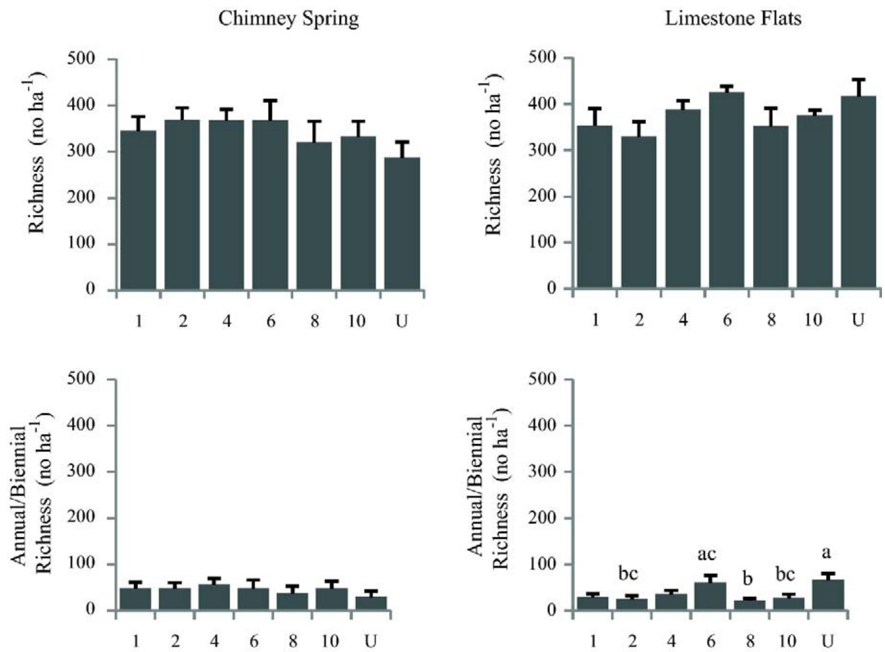

Fig. 3. Two-year average (SE) of understory plant richness variables by fire-return interval for both study sites. Significant differences among treatments are indicated by letters.

total, annual/biennial, and perennial species richness were higher in 2008 than in 2007 ($ps < 0.009$).

3.3. Plant community composition

At Chimney Spring, the ordination showed differentiation in species composition among fire-return intervals (Fig. 4). There was a clear distinction in community composition between unburned and burned plots as well as some distinction between shorter and longer fire-return intervals. The axes were rotated around *E. elymoides*, since it had the strongest correlation to the axes, in order to improve interpretability. The ordination axes captured >88% of the variance in the understory composition. Shorter fire-return intervals generally were the most strongly and positively correlated with *E. elymoides*. Longer return intervals were less strongly correlated with *E. elymoides* and unburned plots were negatively correlated with cover of *E. elymoides*. The MRPP analysis indicated that community composition differed ($p < 0.0001$, $A = 0.21$) among all intervals except that composition on 1-year intervals did not differ from that on 2- and 4-year intervals. At Limestone Flats the ordination and MRPP ($p > 0.29$) analyses did not detect differences in community composition among fire-return intervals (Fig. 4).

4. Discussion

In contrast to our hypothesis, prescribed fire treatments led to few significant changes in overstory attributes and only minor decreases in litter cover on some shorter fire-return intervals at Chimney Spring. We attributed the generally weak effect on the overstory and litter cover to low severity burning treatments, as evidenced by ground char ratings averaging between 0 (unburned) and 1 (light char). The higher ground char ratings on longer fire-return intervals were likely the result of greater fuel accumulation and thus slightly better burning compared to shorter-interval burning treatments, as has been found in other studies (Glitzenstein et al., 1995; Hutchinson et al., 2005). Yet, even on longer fire-return intervals, the treatments were not severe enough to substantially reduce the overstory cover or remove most of the litter cover.

Our results provided some support for our hypotheses regarding the role of varying fire-return intervals on understory vegetation. However, the results were not consistent between the two sites and were influenced by other factors such as overstory cover. We expected graminoid cover to increase with shorter return intervals. This was partially supported by our findings at Chimney Spring but not at Limestone Flats. The increased graminoid cover on frequently burned plots compared to unburned plots at Chimney Spring was attributed mostly to the C_3 species, *E. elymoides*, a successful colonizing species on burned areas in this region (Moore et al., 2006). *E. elymoides* responds positively to burning with increased growth of surviving plants, reproductive shoot density, and recruitment (Young and Miller, 1985; Vose and White, 1991).

Our hypotheses that annual/biennial species richness would respond negatively to fire-return interval and that total species richness would be highest at moderate levels of burning are not supported by our findings. Total species richness did not differ among intervals and at Limestone Flats, the higher annual/biennial richness on the 6-year interval plots is likely due in part to lower overstory cover on these plots.

Our hypothesis that plant community composition would differ among treatments, particularly between shorter fire-return intervals and unburned plots, was supported by our findings at Chimney Spring but not at Limestone Flats. The distinction in community composition between shorter and longer fire-return intervals and unburned treatments at Chimney Spring was largely driven by the response of *E. elymoides*, which had higher cover on the shorter-interval plots and was strongly correlated with the main axis in the ordination. These results are similar to a long-term fire study in northern Florida pine forests that documented a divergence in community composition between frequently burned, less frequently burned, and unburned plots (Mehlman, 1992). At Limestone Flats, there were no apparent differences in community composition among treatments, which mirrors the lack of differences in the cover of major plant species among treatments.

Variations in annual precipitation likely contributed to the differences in plant responses we observed. The fact that we detected more significant differences between years than among treatments is an indication of the importance of precipitation levels on plant

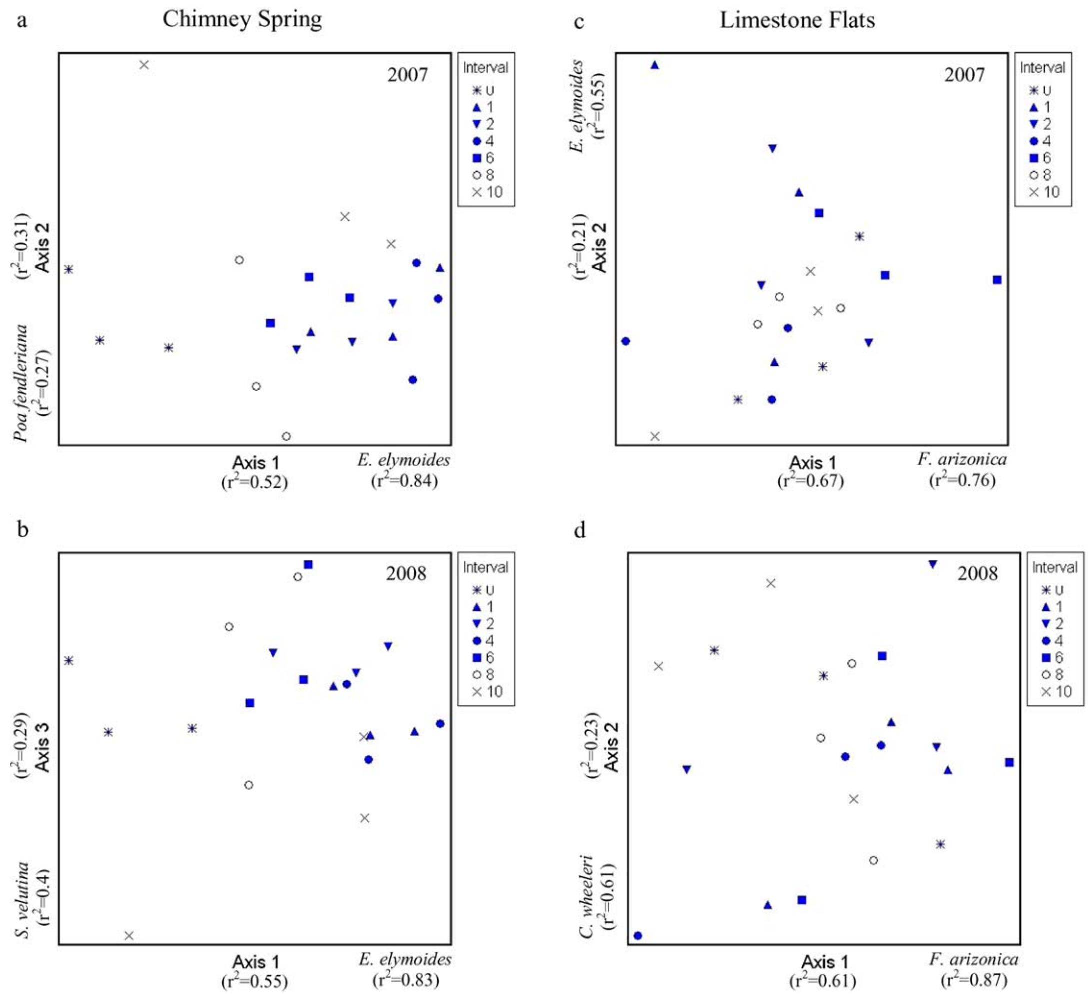

Fig. 4. Chimney Spring and Limestone Flats NMDS ordinations for 2007 (a, c) and 2008 (b, d). Distance among points is proportional to compositional dissimilarity. At Chimney Spring the ordinations show distinct compositional differences between burned and unburned plots but not at Limestone Flats. (a) A two-dimensional solution was recommended and required 88 iterations; stress = 16.2, instability <0.000001, $p = 0.008$. (b) Three-dimensional solution, 139 iterations, stress = 8.5, instability <0.000001, $p = 0.004$. (c) Two-dimensional solution, 56 iterations, stress = 11.2, instability <0.000001, $p = 0.02$. (d) Two-dimensional solution, 57 iterations, stress = 14.1, instability <0.000001, $p = 0.008$.

growth in this region. Moore et al. (2006) reported increased plant standing crop in response to thinning and burning treatments until a severe drought reduced standing crop to pre-treatment levels. Watson and Wardell-Johnson (2004) found that precipitation levels, in addition to time-since-fire and fire frequency, affected plant community composition in an Australian study.

Precipitation differences also likely contributed indirectly to the weaker treatment response at Limestone Flats. The lack of response of *E. elymoides* may have been simply due to *E. elymoides* being less abundant at Limestone Flats, but we suspect that differences in initial burn conditions set these two sites on different trajectories. The initial burns at Chimney Spring took place at night due to very dry conditions in early November 1976 (Sackett, 1980). The site received 1.3 cm of precipitation in the month before the burns, compared to 8 cm in the month before the initial burns at Limestone Flats in late October 1977. Sackett (1980) noted that the humus (H) layer was especially wet (28% moisture content) at Limestone Flats compared to Chimney Spring (14.5%), and the initial burns apparently resulted in more severe fire effects and greater fuels reduction at Chimney Spring compared to Limestone Flats. At Chimney Spring the initial fires consumed 65% of the surface, ground, and large woody fuels (from 50.1 to 17.5 Mg ha^{-1}), while at Limestone Flats the initial fires consumed 43% of the surface, ground, and large woody fuels (from 72.3 to 41.4 Mg ha^{-1}) (Sackett, 1980). We suspect that the higher reductions in litter and duff at Chimney Spring played a key role in the *E. elymoides* response. The initial burns resulted in a large reduction in surface and ground fuels and the shorter fire-return intervals have likely continued to burn off new accumulations, allowing *E. elymoides* to respond positively to the shorter intervals.

We attributed the relatively weak treatment response at both sites to the high overstory cover. Several studies have shown that in ponderosa pine forests an increase in understory abundance was unlikely until the overstory canopy was sharply reduced (Pase, 1958; Clary and Ffolliott, 1966; Uresk and Severson, 1989; Moore and Deiter, 1992; Sabo et al., 2009). Herbaceous production increased exponentially when overstory canopy cover was sufficiently reduced (Pase, 1958). Uresk and Severson (1989) found that understory production did not increase until overstory basal area was reduced to 14 m^2 ha^{-1} while Sabo et al. (2009) found the basal area needed to be below 10 m^2 ha^{-1} before understory production increased significantly. At our study sites, the overstory basal area was approximately 39 m^2 ha^{-1}, well above both these threshold values.

Several long-term, repeated fire studies in the southeastern USA found relatively subtle effects on understory abundance and richness as well. Mehlman (1992) found that species richness differed primarily between burned and unburned plots. Glitzenstein et al. (2003) found that understory vegetation shifted from woody- to herbaceous-dominated communities with increasing fire frequency but only at one of two sites and Waldrop et al. (1992) found a similar shift but only with annual burning. Without fire, these systems were invaded by woody species and frequent burning significantly reduced woody sprouts and shrubs allowing increased herbaceous species abundance. We would not expect to find a similar shift since our sites have very low woody species cover in the understory. Reduced herbaceous cover on our sites is due primarily to an increase in overstory cover.

5. Conclusion

This long-term repeated fire study initiated in 1976 is among few such studies in western USA forest types. In contrast to the vast majority of studies that track one or a few fire frequencies for one or a few years, this study has maintained seven treatments (burning every 1, 2, 4, 6, 8, and 10 years, plus unburned) at two ponderosa pine sites in northern Arizona for over 30 years. Overall, these low-severity burn treatments have had a minimal impact on the abundance and composition of the understory vegetation after 30 years of repeated burning. The primary effect was that the abundance of some early colonizing species, including *E. elymoides* and annuals, differed slightly among the burn treatments.

Our findings suggest that using low-severity burns alone, even for 30 years, will not reduce overstory density and return southwestern pine forests to the open, park-like structure found prior to Euro-American settlement. These findings are important to land managers who are looking to increase understory production or restore ecosystem attributes. Low-severity treatments in southwestern ponderosa pine forests, especially those that do not significantly decrease overstory cover, are unlikely to increase understory abundance. Thinning of these dense forests along with prescribed burning is necessary to increase understory vegetation.

Many southwestern ponderosa pine forests may require heavy thinning to meet a goal of significantly increased understory vegetation. Unfortunately, the increased level of disturbance due to thinning may increase the abundance of exotic species. Several studies have noted an increasing abundance of exotic as well as native colonizing species with increasing fire or treatment severity (Crawford et al., 2001; Griffis et al., 2001; Wienk et al., 2004; Keeley et al., 2005; Kerns et al., 2006; Sabo et al., 2009). Other studies have suggested delaying burning after thinning or scheduling longer intervals between burning in thinned ponderosa pine forests to reduce the invasion of exotic species, especially in forests that are well outside the historical range of variability (Laughlin et al., 2008; Sabo et al., 2009). Further study is needed on methods to significantly increase native understory vegetation without significantly increasing exotic species.

Finally, this study also suggested that precipitation patterns and initial burn conditions were important factors in the response of the understory vegetation and that the effects of burning in dry conditions were still evident 30 years later.

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