Madrean Pine-Oak Forest in Arizona: Altered Fire Regimes, Altered Communities

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Abstract—*In Madrean pine-oak forests in the Chiricahua Mountains, surface fire favors pines, which exhibit high top-survival, but resprouting allows oaks to rebound during inter-fire periods. These patterns plus age structure and radial growth data suggest that frequent presettlement surface fire maintained open stands, promoted a high pine:oak ratio, and excluded less fire resistant species—patterns reversed by a century of reduced fire. Recent anomalous stand-replacing crown fires have further transformed some stands: most oaks resprouted but pine establishment was sparse, exacerbated by a protracted drought. This synthesis argues for the careful and flexible use of fire to restore more open pine-oak stands.*

Introduction

Prior to Euro-American settlement, lightning fires shaped much of the forest land of the Western United States and Northern Mexico, including the Madrean Archipelago (Fulé and Covington 1996; Marshall 1962; Swetnam and others 2001). Reduction in fire frequency, beginning in the mid-19th century in the United States and more recently in Mexico, has radically changed the structure, composition, and processes of many of these forests (Allen and others 2002; Covington and Moore 1994; Fulé and Covington 1996; Rodriguez-Trejo and Fulé 2003; Swetnam and others 1999, 2001). This context is essential for understanding most aspects of the evolution, ecology, and conservation of the Madrean Archipelago ecoregion.

The purpose of this paper is to synthesize past research on fire-driven dynamics of Madrean pine-oak forests in the Chiricahua Mountains in southeastern Arizona. As in most pine and oak dominated forests in this region, frequent surface fires characterized the presettlement fire regime (Swetnam and others 1989, 1992, 2001). I will, accordingly, first address the intrinsic differences in response to these fires between the pines and the oaks in the Chiricahuas. Understanding these contrasting responses is central to any general conceptual model of the fire-driven dynamics, anthropogenic changes, and restoration of Madrean pine-oak communities. Second, I will examine the impacts of a century of fire exclusion on stand structure, the ratio of pines to oaks, and the presence of fire sensitive species. One of the effects of fire exclusion in pine-oak communities in the Madrean Archipelago has been increased fuel loads, which has led to stand-replacing fires generally outside the range of natural variability for these systems (Fulé and others 2000; Swetnam and others 1999, 2001; see Moore and others 1999). My final goal, then, is to summarize my recent research on the transforming community effects of crown fires, as well as the exacerbating influence of coinciding drought.

Study Site and Fire History

The Chiricahua Mountains are located in southeastern Arizona in Cochise County, U.S.A. (31^{o} 52' N, 109^{o} 15' W), in the northern part of the Madrean Archipelago. The mountains extend southeast to northwest for about 80 km and rise from about 1,100 to 3,000 m altitude. The climate is semi-arid, with two wet seasons, one in July-September, when more than 50 percent of total precipitation falls, and the second December-March. A pronounced dry season usually occurs between the final winter storms in March or April and the onset of the rainy season in July (Sellers and others 1985).

The Chiricahuas support a wide diversity of desert, Petran, and Madrean communities (Barton 1994; Brown 1982). This study focused on Madrean pine-oak forest (Mexican oak-pine woodland subtype #3; Brown 1982), the most abundant community type between 1,650-2,050 m. The major tree species are *Pinus leiophylla* (Chihuahua pine), *P. engelmannii* (Apache pine), *P. arizonica* (Arizona pine; *P. ponderosa* var. *arizonica*), *Quercus hypoleucoides* (silverleaf oak), *Q. arizonica* (Arizona white oak), and *Q. emoryi* (Emory oak).

A three-century fire history of Rhyolite Canyon in the Chiricahua Mountains (Swetnam and others 1989, 1992; see also Barton and others 2001) revealed a fire regime characterized by frequent (every 5-15 years), low-severity surface fires, similar to results for other Madrean pine-oak forests (Fulé and Covington 1996; Swetnam and others 2001). Fires were often synchronous, suggesting extensive fires the length of the canyon. This inferred synchrony was interrupted, possibly as a result of flood events (Swetnam and others 1991), from 1801-1851, when fires ceased in most of middle Rhyolite but continued in lower Rhyolite. Fire frequency declined drastically beginning in the 1870s, probably as a result initially of intensive livestock grazing and then fire suppression (Bahre 1995; Swetnam and others 2001).

Methods

This paper synthesizes data from five different sources. Details for each of these can be found in the references provided.

1. Population age structures were constructed for pines and *Quercus hypoleucoides* in lower Rhyolite Canyon (Barton 1999; Barton and others 2001), and for pines and *Pseudotsuga menziesii* in Cave Creek Canyon (see Barton 1994 for site details). Increment cores were prepared and cross-dated using standard dendrochronology practices. Seedling growth was used to estimate age at coring height where appropriate.
2. To examine the relationship between tree radial growth and fire, ring widths were measured to the nearest 0.001 mm for 77 *P. arizonica* trees from Rhyolite Canyon that germinated before 1860 (Barton and others 2001).
3. I quantified the responses of two pines (*P. leiophylla* and *P. engelmannii*) and four oaks (*Q. hypoleucoides*, *Q. arizonica*, *Q. emoryi*, and *Q. rugosa*) to recent low-severity fires (Barton 1999). In each fire, which had occurred during the previous 10 years, data were collected along belt transects on top-kill, resprouting, and seedling establishment. Using this retrospective approach, I calculated stand data for each species for pre-fire, immediate post-fire, and actual sample period 3-10 years after fire.
4. I collected similar data for *P. leiophylla*, *P. engelmannii*, and *Q. hypoleucoides* for two stand-replacing crown fires. Sampling was carried out in 1999 in the 10,330-ha 1994 Rattlesnake Fire and in 1992 in the 23-ha 1983 Methodist Fire (Barton 2002). Data were collected along belt transects, in areas of complete top-kill, on resprouting, height of resprouts, and number and height of seedlings.
5. The Rattlesnake Fire was resampled in 2003 for resprouts and seedlings in 16 plots in each of three types of burned areas: "interior," >75 m inside the perimeter of the area in which all canopy trees were top-killed (crown fire perimeter); "edge," 5-30 m inside the crown fire perimeter; and "periphery," 5-100 m outside the crown fire perimeter. The expected relative soil moisture of these 48 sample plots was assessed using the Topographic Relief Moisture Index (TRMI; Parker 1982) to examine its potential role in pine establishment patterns.

Results and Discussion

Presettlement Madrean Pine and Oak Dynamics

Pines and oaks exhibited contrasting responses to low-severity fires characteristic of the presettlement fire regime. Pines were fire resistant, with high levels of top-survival, whereas oaks were fire resilient, with lower top-survival but prolific resprouting (table 1). *Pinus leiophylla* also resprouted after top-kill but at much lower levels than for oaks. As a result of these responses, low-severity fire favors pines in the short-term, but resprouting allows oaks to increase relative to pines during inter-fire periods (Barton 1999; see Fulé and others 1996, 1997).

Age structures reveal, similarly, that pine individuals persisted through many fires, whereas *Q. hypoleucoides* stems arose in a narrower window of time after the last series of frequent fires in 1850-1870 (figure 1). Although pines survived fire well, their establishment was closely tied to periods of relatively low fire frequency (figure 1). In fact, number of pine stems for a given decade is negatively correlated with number of subsequent fires but not correlated with number of past fires (Barton 1999; Barton and others 2001). These results suggest that regeneration of these pines requires, in addition to other factors, fire-free periods sufficient to allow growth to a height that provides resistance to subsequent fires.

These studies taken together (see also Fulé and others 1996, 1997; Rodriguez-Trejo and Fulé 2003), then, suggest a presetttlement Madrean pine-oak forest in which occasional pulses of pines arose, many of which persisted in open stands for centuries through frequent surface fires. Oaks also probably persisted for long periods of time, but many of them were forced to resprout repeatedly after top-kill from these fires, which maintained them at relatively low cover levels. Other important but less common tree species in these communities also appear to follow the resprouting strategy of oaks (e.g., *Arbutus arizonica*; Barton, in press).

Table 1—Oak and pine top-survival, resprouting, and seedling establishment after low-severity and high-severity fires[a].

Fire name	Fire severity	Top-survival		Resprouting		Seedlings	
		Oaks	Pines	Oaks	Pines[b]	Oaks	Pines
		pct. (n)	pct. (n)	pct. (n)	pct. (n)	$\#ha^{-1}$	$\#ha^{-1}$
Rhyolite III	Low	53.2 (124)	84.9 (33)	44.8 (58)	0.0 (5)	9680	5900
Rhyolite T	Low	39.6 (265)	61.1 (36)	56.2 (160)	0.0 (8)	1400	950
Methodist 1	Low	11.0 (154)	50.4 (141)	59.1 (137)	11.6 (43)	2140	640
Methodist 2	Low	18.8 (218)	63.7 (55)	43.5 (177)	12.5 (16)	980	480
Animas	Low	30.5 (128)	69.5 (95)	38.2 (89)	6.9 (29)	2690	30
Rattlesnake	High	0.0 (355)	0.0 (217)	90.1 (355)	23.2 (164)	150	77
Methodist	High	0.0 (63)	0.0 (55)	92.0 (63)	13.3 (15)	30	70

[a]Sampling carried out 3-10 years post-fire in belt transects; for details on methods and data for individual oak, pine, and other species, see Barton (1999, 2002).
[b]*Pinus leiophylla* included only; *P. engelmannii* does not resprout.

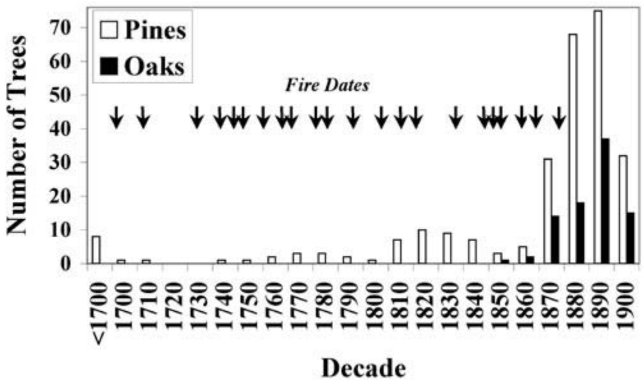

Figure 1—Age structure of pines (*Pinus engelmannii* and *P. leiophylla* combined) and oaks (*Quercus hypoleucoides*) in Rhyolite Canyon in relation to fire dates. Fire dates are from Swetnam and others (1989, 1992; see Barton and others 2001).

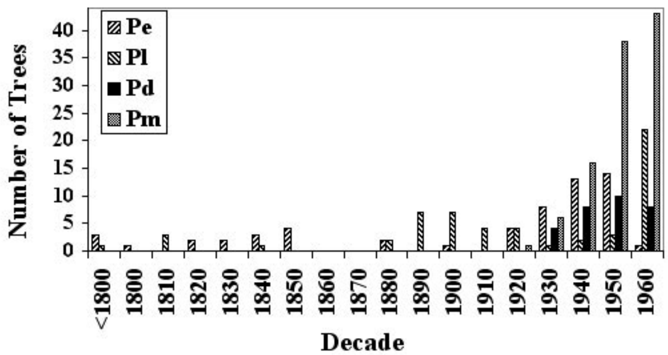

Figure 2—Age structure evidence of recent invasion of *Pseudotsuga menziesii* (Pm) and *Pinus discolor* (Pd) in a stand of *P. engelmannii* (Pe), *P. leiophylla* (Pl), and *Quercus hypoleucoides* (data not shown) in Cave Creek Canyon. All stems at least 2 m tall were cored in 1.75 ha (Pm), 0.5 ha (Pd), 0.3 ha (Pe), and 1 ha (Pl).

Community Response to Reduced Fire Frequency

Reduction in fire frequency has resulted in major changes in the structure and composition of Madrean pine-oak forests in the Chiricahuas. Age structures reveal large increases in the density of all species beginning in the late 1800s, coincident with the reduction in fire frequency (figure 1; see also Fulé and others 1996, 1997; Rodriguez-Trejo and Fulé 2003). This suggests again that frequent presettlement fires maintained stands with more widely spaced trees than today (see also Mills 2002).

P. arizonica radial growth declined in the 20th century in association with fire reduction and increased stand density (Barton and others 2001). Superposed epoch analysis demonstrated that presettlement fires did not generally lead to growth releases (Barton and others 2001). However, as in the 20th century, radial growth was significantly reduced during the 50-year fire hiatus in middle Rhyolite, an effect not recorded in lower Rhyolite where fires continued unabated (Barton and others 2001). Apparently, stands were generally so open during presettlement times that growth was stimulated through fire-caused thinning only after an unusually long inter-fire period.

Both age structures and responses to low-severity fires suggest that the ratio of pines to oaks was higher during presettlement times than today. Furthermore, frequent fire appeared to exclude *P. discolor* and *Pseudotsuga menziesii*, species with fire-sensitive juveniles, which have recently invaded some pine-oak sites (figure 2). Interestingly, *P. menziesii* is a relatively shade tolerant species invading from moister, generally higher elevation sites, whereas *P. discolor* is a large-seeded, relatively shade tolerant pinyon (Barton 1993), invading from drier, generally lower elevation sites (see also Mills 2002).

Community Response to Anomalous Crown Fires and the Exacerbating Influence of Drought

In areas subject to complete top-kill (table 1), most oaks resprouted. *P. leiophylla* exhibited low levels of resprouting, which nonetheless could be an important source of pine recruitment. Seedlings were rare for all three species, much lower than after low-severity fires (table 1). Oak seedlings and resprouts were significantly taller than those of pines (Barton 2002). Several years after high-severity fire, then, fast-growing oak resprouts had formed a dense, coalescing canopy over sparse pine seedlings and resprouts. These results suggest that anomalous crown fires can transform complex Madrean pine-oak forests into more homogenous oak woodlands, perhaps for decades if not centuries (see also Fulé and others 2000).

Resampling in Rattlesnake Fire nine years post-fire revealed continued very low seedling densities, no higher than for five years post-fire and an order of magnitude lower than for before the fire (1988; table 2). The especially low establishment levels for interior parts of the crown fire might suggest unfavorable conditions created by severe fire effects. However, three types of data suggest that curtailed establishment is at least exacerbated by an extended dry period. First, precipitation in the eight years before the 1988 was substantially higher than for the eight years after the fire (2003; figure 3). Second, values for the Topographic Relative Moisture Index differed significantly among fire areas in the same order as seedling abundance: periphery > edge > interior ($P = 0.01$; table 2). In fact, the number of pine seedlings in a plot was positively related to this index of soil moisture ($P = 0.0002$; figure 4). Finally, *P. engelmannii*, a species with abundant seedlings in 1988, had almost no seedlings as of 2003. This species is substantially less drought tolerant than *P. leiophylla* (Barton 1993), and its near absence in these sites, which are near its lower (drier) elevational boundary, is likely a result of drought.

Restoration of Madrean Pine-Oak Forest

This synthesis reveals major changes in Madrean pine-oak forests resulting from a reduction in surface fires. Increases in stand density, the ratio of pines:oaks, and the abundance of fire intolerant species are direct effects that are likely to continue.

Table 2—Number of pine sprouts and seedlings before (1988), five years after (1999), and nine years after (2003) the Rattlesnake Fire. Topographic Relief Moisture Index (TRMI) is also given for the three types of areas sampled in 2003.

	Periphery[a] (2003)	Edge[a] (2003)	Interior[a] (2003)	I & E[b] (1999)	Pre-Fire[c] (1988)
	mean/ha (SE)	mean/ha (SE)	mean/ha (SE)	mean/ha (SE)	mean/ha (SE)
P. leiophylla sprouts	50.0 (16.1)	67.5 (14.5)	17.5 (6.3)	93.3 (19.9)	NA[c]
P. leiophylla seedlings	187.5 (48.4)	110.0 (30.4)	17.5 (8.9)	60.0 (30.6)	1002.5 (278.5)
P. engelmannii seedlings	7.5 (4.0)	12.5 (6.0)	2.5 (2.5)	16.7 (6.0)	677.5 (129.5)
# of Plots	16	16	16	12	10
TRMI[d]	36.3 (1.5)	29.9 (1.4)	19.1 (1.1)		

[a] Interior: >75 m inside perimeter of the area in which all canopy trees were top-killed by the fire (crown fire perimeter); Edge: 5-30 m inside the crown fire perimeter; Periphery: 5-100 m outside the crown fire perimeter.
[b] I&E: Interior and Edge; Periphery were not sampled in 1999.
[c] Since no recent fire had occurred, juvenile plants of sprout and seedling origin were not distinguished. For details, see Barton (1993, 1994).
[d] Larger values indicate higher expected soil moisture availability. Means are significantly different: $F_{2,45} = 5.1$, P = 0.01.

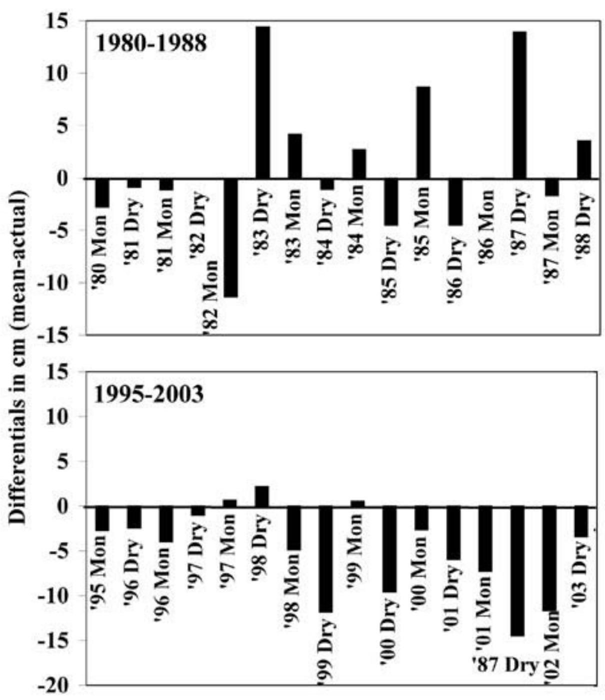

Figure 3—Precipitation records for 1980-1988 and 1995-2003 for the National Weather Station Portal 4 SW—within four km of the Rattlesnake Fire study area. Data are provided for two periods each year: July-October ("monsoon") and the rest of the year ("dry"). For each period, recorded precipitation is subtracted from the long-term mean (1965-1994) for that portion of the year.

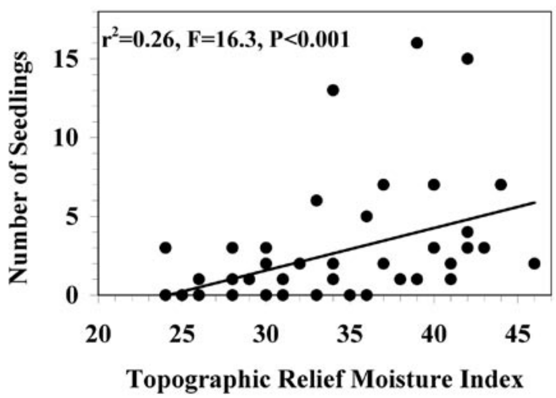

Figure 4—Regression of number of seedlings (in 250-m² plots) of *Pinus leiophylla* against Topographic Relative Moisture Index, which estimates expected moisture availability. Statistical results are for regression of log (x + 1) transformed data (to correct non-normality of residuals).

Anomalous crown fires, however, pose an increasing and equally serious threat by drastically reducing the abundance of pines. The results discussed here suggest that the impacts of such fires might depend strongly on their timing, especially relative to drought.

This synthesis argues for the use of fire to restore more open pine-oak stands, bearing in mind the following caveats. Madrean pine-oak forest varies tremendously in pine and oak composition over its range from the borderlands to far south in the Sierra Madre Occidental (Rodriguez-Trejo and Fulé 2003). Presettlement fire regimes also exhibited substantial variation over time and among mountain ranges (Swetnam and others 2001). Finally, burning areas with dense oak thickets without igniting crown fires might be a serious challenge for fire managers (C. Baisan, personal communication). These caveats suggest the need for a variety of careful and flexible restoration approaches (see Allen and others 2002; Rodriguez-Trejo and Fulé 2003).

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