Madrean Pine-Oak Forest in Arizona: Past Dynamics, Present Problems[1]

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Abstract

This paper synthesizes research on presettlement dynamics and modern disruption of Madrean pine-oak forests in Arizona. In response to surface fires characteristic of presettlement times, pines were fire resistant, exhibiting high top-survival, whereas oaks were fire resilient, exhibiting lower top-survival but pronounced resprouting. Thus, low-severity fire favors pines, but resprouting allows oaks to rebound during inter-fire periods. Age structures reveal large increases in stand density, especially for oaks, as a result of modern fire suppression, suggesting more open conditions and higher pine:oak ratio during presettlement times. Stands were, in fact, so open that fire-caused thinning rarely stimulated radial growth. Frequent fires also apparently excluded less fire tolerant species, which have invaded some pine-oak sites. In anomalous stand-replacing crown fires, seedling establishment was very low for pines and oaks, but most oaks resprouted. *Pinus leiophylla* also resprouted but at low levels, which might nonetheless be an important source of future pines. These results suggest anomalous high-severity fires can transform Madrean pine-oak forests into more homogenous oak woodlands. This synthesis argues for urgent restoration using a variety of flexible approaches.

Introduction

Prior to Euro-American settlement, lightning fires shaped the forests of the American Southwest (Covington and Moore 1994, Swetnam and Betancourt 1998). The dramatic anthropogenic reduction in fire frequency, beginning in the mid-19th century, has radically changed the structure, composition, and processes of many of these forests (Allen and others 2002, Covington and Moore 1994, Noss and others 1995, Swetnam and others 1999).

Initially, ecologists investigated the direct effects of reduction in fire frequency on species, communities, and ecosystems (e.g., Cooper 1960, Covington and Moore 1994, Marshall 1962). More recently, researchers recognized that exclusion was not only reducing fire frequency but also promoting stand-replacing crown fires (Covington and Moore 1994, Dahm and Geils 1997, Fulé and Covington 1996, Swetnam and others 1999, 2001). For many ecosystems characterized by presettlement surface fire regimes, these high-severity fires are outside the natural range of variation (Moore and others 1999, Swetnam and others 1999), and can cause long-term disruption, even transforming some forests into grasslands or shrublands (Allen and others 2002).

Effective restoration requires documentation of the presettlement and altered fire regimes and an understanding of the natural and altered dynamics of major forest tree species. Although vigorous debate continues on restoration strategies, these bases have been relatively well established for southwestern ponderosa pine ecosystems

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(Allen and others 2002). Knowledge of the fire ecology of Madrean pine-oak systems in the Southwest lags far behind. This is a widespread forest type that harbors tremendous biological diversity (DeBano and others 1995).

My goal is to contribute to an understanding of the fire-driven dynamics of Madrean pine-oak forests in order to promote effective fire management and restoration. I will synthesize my relevant past work (published and unpublished, solo and collaborative) from the Chiricahua Mountains, Arizona. The paper will focus on three themes: 1) presettlement dynamics of pine and oak species in response to frequent, low-severity surface fires, 2) changes in community and ecosystem attributes in response to reduced fire frequency, and 3) changes in community composition in response to anomalous, high-severity crown fires.

Study Site and Fire History

The work reported here was carried out in the Chiricahua Mountains, located in southeastern Arizona in Cochise County (31^{o} 52' N, 109^{o} 15' W), and considered part of the Sierra Madre "archipelago" (DeBano and others 1995). 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 and 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 to 15 yr), 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, Barton and others 2001). Most presettlement fires occurred in late spring to early summer (Swetnam and others 2001), and during unusually dry years (Barton and others 2001).

Methods

This paper synthesizes data from four 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 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.

4) I collected similar data for *P. leiophylla*, *P. engelmannii*, and *Q. hypoleucoides* for two high-severity 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 sprouts, and number and height of seedlings.

Results and Discussion

Presettlement Madrean pine and oak dynamics

Pines and oaks contrasted in their response to low-severity fires characteristic of the presettlement fire regime. Pines were fire resistant, exhibiting high levels of top-survival, whereas oaks were fire resilient, exhibiting 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 narrow window of time after the last series of frequent fires in 1850 to 1870 (*fig. 1*). Although pines survived fire well, their establishment was closely tied to periods of relatively low fire frequency (*fig. 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, in addition to appropriate rainfall and seed availability, regeneration of these pines requires fire-free periods sufficient to allow growth to a height that provides resistance to subsequent low-severity fires.

These studies taken together (see also Fulé and others 1996, 1997, Rodriguez-Trejo and Fulé 2003), then, suggest a presettlement 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 were forced to resprout repeatedly after top-kill from these fires, which maintained them at relatively small sizes and low cover levels.

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

Fire name	Fire severity	Top-survival Oaks	Top-survival Pines	Resprouting Oaks	Resprouting Pines[2]	Seedlings Oaks	Seedlings 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
Animals	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

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

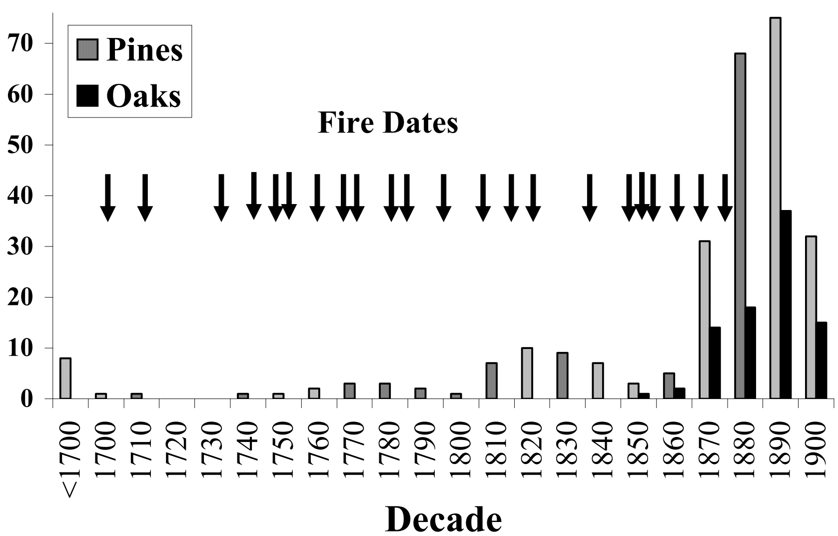

Figure 1—Age structure of pines (*Pinus engelmannii* and *P. leiophylla* combined) and oaks (*Quercus hypoleucoides*) in Rhyolite Canyon in relation to fire dates.

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 (*fig. 1;* 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 (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 lead to growth releases (Barton and others 2001). However, similar to the 20th century, radial growth was significantly reduced during the 50 yr fire hiatus in middle Rhyolite compared to before or after, whereas no such differences occurred 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 probably higher during presettlement times than today. Furthermore, frequent fire appeared to exclude *P. discolor* and *Pseudotsuga menziesii*, two relatively fire-sensitive species that have recently invaded some pine-oak sites (*fig. 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 (Mills 2002).

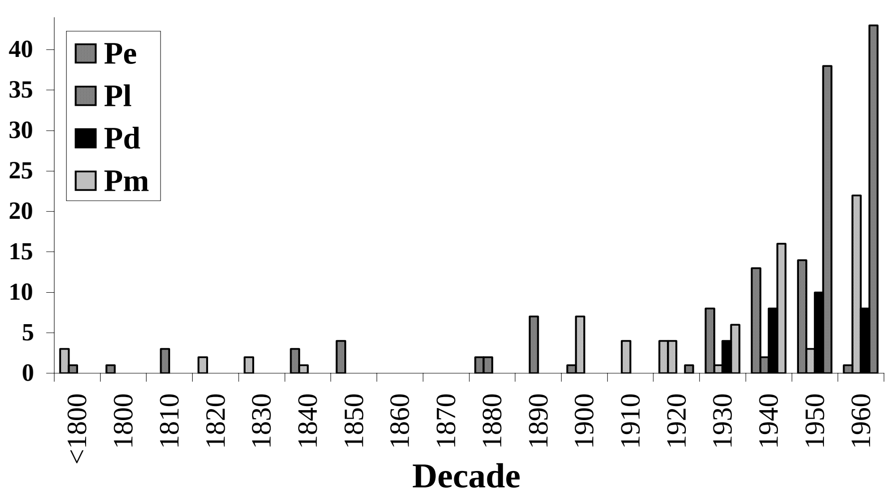

Figure 2—Age structure evidence of recent invasion of *Pseudotsuga menziesii* (Pm) and *Pinus discolor* (Pd) in a stand of *P. engelmannii* (Pe), *P. leiophylla* (Pl), and *Quercus hypoleucoides* in Cave Creek Canyon. All stems at least 2 m tall were cored in 1.75 ha, 0.5 ha, 0.3 ha, and 1 ha, respectively.

Community Response to Anomalous Crown Fires

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

Restoration of Madrean pine-oak forest

This synthesis reveals major changes in Madrean pine-oak forests resulting from a reduction in low-severity surface fires. Stands have become denser, especially for oaks, and an increase in high-severity crown fire poses long-term disruption. The consequences for species associated with these communities are likely to be serious. This synthesis argues strongly for restoration of Madrean pine-oak forests, especially the return of frequent surface fires. In designing restoration strategies, it is important to bear in mind that 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). This variability suggests the need for a variety of flexible restoration approaches (Allen and others 2002, Rodriguez-Trejo and Fulé 2003).

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