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Fire Frequency Effects on Fuel Loadings in Pine-Oak Forests of the Madrean Province

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Abstract—Loadings of downed woody fuels in pine-oak forests of the Madrean Province are heavier on sites in southeastern Arizona with low fire frequencies and lower on sites in northeastern Sonora, Mexico, with high fire frequencies. Low fire frequencies in southeastern Arizona are attributed largely to past land uses and the fire suppression policies of land management agencies in the United States. Ecologists and land managers interested in reintroducing fire into these forests to reduce fuel loadings and meet other land management objectives could use information about fuel buildups in their planning efforts. Quantifying these fuel loadings could also be useful in improving fire behavior models for the forests.

Keywords: Madrean Province, pine-oak forests, fire frequency, fuel loadings, downed woody fuels, coarse woody debris

Introduction

Ecologists and land managers are reintroducing fire into ecosystems of the Madrean Province in the Southwestern United States to reduce excessive buildups of fuels that have a high probability of igniting and becoming unnaturally severe wildfires. Prescribed fire can also meet other land management objectives such as improving ecosystem functioning, watershed conditions, wildlife habitats, and stocking of natural regeneration (Ffolliott and others 1996; Gottfried and others 1999). Incomplete knowledge of wild-land fuel conditions, however, often constrains successful reintroductions of fire. Quantifying fuel buildups under different fire frequencies and severities could provide useful information on fire regimes that might be prescribed in the reintroduction efforts. We discuss the effects of contrasting fire frequencies on fuel loadings in the pine-oak forests of the Madrean Province in the Southwestern United States and Northwestern Mexico (Brown 1994).

"Fire frequency" is defined (in this paper) as the number of fires occurring on the sites studied since 1900, when fire suppression polices of land management agencies in the Southwestern United States dictated that, in general, fires should be suppressed as quickly as possible after their ignition (Pyne and others 1996; Williams 2000). "Fuel loadings" are the total oven-dry weights of fuels per unit of surface area (DeBano and others 1998; Pyne and others 1996; Whelan 1995). Fuel loadings, therefore, are measures of the potential energy that might be released by a fire. The "downed woody fraction" of wild-land fuel loadings are the focus of this paper. Accumulations of duff and humus on soil surfaces and herbaceous fuels were not measured in this study.

Study Area

Madrean Province

The Madrean Province is situated at the convergence of the Sonoran, Chihuahuan, Madrean, and Rocky Mountain biogeographic regions (Brown 1994; DeBano and others 1995) and the Sierra Madre Occidentalis and Rocky Mountain ranges. Parts of southeastern Arizona and southwestern New Mexico, and northwestern Chihuahua and northeastern Sonora in Mexico are included in the Province. Elevations range from 2,300 to more than 8,500 feet. The isolated mountains are characterized by oak and pinyon-juniper woodlands

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on the lower elevations and pine-oak and other montane forests on the higher elevations (Brown 1994; Gottfried and others 1995; McLaughlin 1995). The mountain ranges are separated by broad plains and valley floors covered with a variety of desert-shrub and desert-grassland plant communities.

Study Sites

Fuel loadings were measured on five study sites in the pine-oak forests of the Madrean Province. Two sites, the McClure and Upper Sawmill, were in the Huachuca Mountains of southeastern Arizona, and one site, the El Tigre, was in the Chiricahua Mountains of southeastern Arizona. Two sites, the Plantio and Pinos Grandos sites, were in the Sierra de Los Ajos of northeastern Sonora, Mexico. The climate, vegetation, and physiography of the five study sites have been described elsewhere (Kaib and others 1999; Swetnam and Baisan 1996a,b). All of the sites have the same general climatic, vegetative, and physiographic characteristics (Escobedo Montoya 1998); therefore, it might be assumed that fuel loadings on the sites would be similar. However, their land-use histories differ.

Livestock ranches, timber harvesting enterprises, and mining operations spread across southeastern Arizona in the late 1880s, causing profound changes in forest landscapes (Bahre 1991, 1995; Bahre and Shelton 1996; Sayre 1999). There was also a significant reduction of widespread recurring fires with this settlement period (Swetnam and Baisan 1996a,b). The scarcity of tree fire scars after the 1880s is attributed largely to the influence of heavy livestock grazing and other intensive land uses that fragmented the forest landscapes and, as a result, reduced the spread of surface fires over large areas (Baisan and Swetnam 1990). The fire suppression policies of land management agencies after the 1900s also contributed to this reduction in fires.

The existing forests in northeastern Sonora evolved under a different land-use history. Some fire-regime changes coincided with land tenure and agricultural reforms in the 1940s and 1950s (Fulé and Covington 1994; Kaib 1998). In more recent decades, commercial logging ventures also entered the last remaining stands of uncut pine-oak forests to modify forest structures (Gingrich 1993). Because lightning ignitions have been and continue to be infrequently suppressed, fire continues to be a forest-structuring process (Kaib and others 1999). Fire regimes in northeastern Sonora have continued unchanged for more than a century.

All of the sites studied are classified as a *Pinus engelmanii/Muhlenbergia longiligula* habitat type association (Muldavin and others 1996). Trees, the primary contributors to the downed woody fraction of fuel loadings on the sites, included (in varying intermixtures) Apache pine (*Pinus engelmanii*), ponderosa pine (*P. ponderosa*), southwestern white pine (*P. strobiformis*), alligator juniper (*Juniperus deppeana*), border pinyon (*P. discolor*), Gambel oak (*Quercus gambelii*), Arizona white oak (*Q. arizonica*), silverleaf oak (*Q. hypoleucoides*), and netleaf oak (*Q. rugosa*). The occasional shrubs were New Mexican locust (*Robinia neomexicana*), Chihuahua ash (*Fraxinus papillose*), and mountain-mahogany (*Cercocarpus montanus*). While not all of the tree and shrub species were present on all of the sites, there was no pattern in the composition of woody species and fire frequencies. No attempt was made to separate the fuels measured on a site by species or species groups in the analysis of this study.

The densities of all tree species 5 inches d.b.h. and larger on the Upper Sawmill and McClure sites in southeastern Arizona and the Plantio site in northeastern Sonora were statistically similar and averaged about 85 square feet of basal area per acre. Densities of these trees on the El Tigre site in southeastern Arizona and the Pinos Grandos site in northeastern Sonora were also similar and averaged 70 square feet of basal area per acre. There was no relationship between overstory densities and fire frequencies of these sites.

Fire frequencies on the sites differed. The three sites in southeastern Arizona were characterized by changed fire regimes in which the (historical) frequent and low severity regimes ceased in the early 1900s, largely because of the occurring forest fragmentation and fire suppression policies in the region. These sites have had relatively fewer fires of generally higher severity since 1900. In contrast, the two sites in northeastern Sonora have had more continuous and higher frequencies of fire since 1900. Local people's interest and involvement in fire suppression activities had been insignificant throughout Mexico until the middle 1980s, when the federal government initiated active programs to suppress uncontrolled forest fires (Bojorquez-Tapia 1990). The fire regimes on the northeastern Sonora sites mostly reflect the earlier lack of the public's concern about fire. Fire frequencies since 1900 for all study sites (table 1) had been established earlier from fire chronologies of fire-scarred trees on or near the sites (Kaib and others 1999; Swetnam and Baisan 1996a,b).

Methods

Fuel loadings on each site were measured on a 2.5-acre grid of systematically located plots established at equally spaced intervals on the site. Similar grids have been used in other studies to measure fuel loadings in pine and other pine-oak ecosystems (Arno and others 1997; Fulé and Covington 1994, 1995; Harrington 1985). The grids consisted of 30 plots on the Chiricahua and Huachuca Mountain sites and 25 plots on the Sierra de Los Ajos sites. Errors of 20 percent or less, adequate levels of precision for most fuel inventories (Brown 1974), were obtained with these plot numbers. Plot

Table 1—Means and standard errors of loadings of downed woody fuels and the fire frequencies for study sites.

Site	Smaller fuels: Sound wood 0.1–0.25 inch	Smaller fuels: Sound wood >0.25–1 inch	Larger fuels: Sound wood >1–3 inches	Larger fuels: Sound wood >3 inches	Larger fuels: Decaying wood >3 inches)	Coarse woody debris (all fuels >3 inches)	Total fuel loadings (all downed woody fuels)	Fire frequency (fires since 1900)
	tons per acre							*number*
McClure	0.25 ± 0.0091	0.40 ± 0.018	1.0 ± 0.091	1.8 ± 0.38	6.5 ± 0.22	8.3 ± 0.44	9.9 ± 0.46	5
Upper Sawmill	0.16 ± 0.0073	0.56 ± 0.019	3.0 ± 0.093	8.7 ± 0.40	0.9 ± 0.19	9.6 ± 0.43	13.3 ± 0.47	2
El Tigre	0.73 ± 0.0092	0.98 ± 0.036	4.1 ± 0.090	12.6 ± 0.39	3.2 ± 0.20	15.8 ± 0.46	21.6 ± 0.48	0
Plantio	0.15 ± 0.012	0.16 ± 0.021	0.9 ± 0.12	3.3 ± 0.48	0.6 ± 0.27	3.9 ± 0.52	5.1 ± 0.48	9
Pinos Grandos	0.14 ± 0.011	0.22 ± 0.020	1.3 ± 0.26	3.1 ± 0.46	0.3 ± 0.26	3.4 ± 0.54	5.0 ± 0.42	13

centers were the starting point for a randomly oriented planar-intersect transect that was established to measure fuels. The planar-intersect technique has the same theoretical basis as the line-intersect technique (Van Wagner 1968). It involves counting intersections of fuels with vertical sampling planes that resemble guillotines dropped through the accumulated fuels.

Diameter classes of fuels that were intersected by the planar transects were tallied by the classification of Brown (1974), that is, sound woody fuels 0.1 to 0.25 inch, >0.25 to 1 inch, >1 to 3 inches, >3 inches, and decaying (rotten) woody debris >3 inches. These diameter classes correspond to the 1-hour, 10-hour, 100-hour, and 1,000-hour time-lag classes of the National Fire Danger Rating System (Martin and others 1979; Pyne and others 1996), respectively. Fuels >3 inches in diameter, both sound and decaying, are also called "coarse woody debris." Coarse woody debris includes limbs, stems, and roots of trees and shrubs in various stages of decay (DeBano and others 1998; Graham and others 1994; Pyne and others 1996). Tallies of the respective diameter classes with their standard specific gravity values were used in determining fuel loadings in tons per acre.

The null hypothesis that fire frequencies since 1900 did not affect the loadings of downed woody fuels on the study sites was tested by comparative statistics at the 0.05 level of significance. Analyses of variances (ANOVAs) were tested for homoscedacity by Levene's test for unequal variances (Ramsey and Shafer 1997). Normality assumptions were assessed by residual and normal probability plots. Data sets obtained in the study were skewed, which is typical of fuel loading studies (Harmon and others 1986). The data were transformed to natural logs to meet the ANOVA assumptions (Zar 1974). One-way classification ANOVAs were used to determine the effects of fire frequencies on fuel loading. The Tukey-Kramer multiple range test was used to determine differences in fire frequencies to account for unequal sample sizes between the sites in the southeastern Arizona and the sites in northeastern Sonora (Ramsey and Shafer 1997). Only the transformed data were used in the statistical tests.

Results and Discussion

Fuel loadings and fire frequencies since 1900 for the five study sites are summarized in table 1. In general, there were heavier fuel loadings on the sites in southeastern Arizona than on the sites in northeastern Sonora. These differences are attributed largely to fewer fires since 1900 on the southeastern Arizona sites than on the sites in northeastern Sonora. Consequently, fuels tend to accumulate for longer periods of time on the southeastern Arizona sites than on the northeastern Sonoran sites. Loadings of downed woody fuels have been arbitrarily separated into those of "smaller fuels" up to 1 inch in diameter, "larger fuels" greater than 1 inch in diameter, and "coarse woody debris" for discussion purposes.

Smaller Fuels

El Tigre, the study site with no fires since 1900, had the heaviest loading of downed woody fuels in the 0.1- to 0.25-inch diameter class (table 1). This site had about five times the amount of fuels in this diameter class than the Plantio and Pinos Grandes sites, the sites with the highest fire frequencies. El Tigre also had heavier loadings of fuels in this diameter class than the Upper Sawmill and McClure sites. There were no statistical differences in the loadings of fuels in this diameter class among the Upper Sawmill (two fires since 1900), McClure (five fires), Plantio (nine fires), and Pinos Grandes (13 fires) sites. Loadings of fuels in the >0.25- to 1-inch diameter class were similar to the pattern observed for the 0.1- to 0.25-inch diameter class. That is, the loading of downed woody fuels in this diameter class was significantly heavier on the El Tigre site than the other sites, and there were no statistical differences in loadings of fuels in this diameter class among the other sites.

Downed woody fuels up to 1 inch in diameter are more readily ignited and consumed by fire than are larger fuels and, consequently, are less likely to accumulate and persist in large amounts on sites with repeated or recent fire (Anderson 1982; DeBano and others 1998; Pyne and others 1996). This trend in fuel loadings is borne out by the results of this study. While the fire chronology for the Upper Sawmill site indicated that only two fires had occurred since 1900, the most recent fire burned in 1983, and therefore, a relatively low loading of smaller fuels was measured.

Larger Fuels

Loadings of downed woody fuels >1 to 3 inches in diameter were heavier on the two sites with lowest fire frequencies, El Tigre (0) and Upper Sawmill (2), than on the other study sites (table 1). There were no statistical differences in the lower loadings in this diameter class among the McClure, Plantio, and Pinos Grandes sites. The El Tigre and Upper Sawmill sites also had three to four times heavier loadings of sound woody fuels >3 inches in diameter than the sites with higher fire frequencies. Loadings of fuels in this diameter class on the McClure, Plantio, and Pinos Grandos sites were not statistically different. Loadings of decaying woody debris >3 inches in diameter were heaviest on the McClure and El Tigre sites. One explanation for the heavier loading of decaying fuel on the McClure site is that soil on this site had the deepest A horizon of all the study sites (Escobedo Montoya 1998), suggesting that this site also had the greatest surface stability which, in turn, could contribute to a higher rate of decomposition than the other sites (Edmonds 1991). There were no statistical differences in the lower loadings of this fuel class among the Upper Sawmill, Plantio, and Pinos Grandes sites, likely because all of the sites have experienced some fire occurrence since the late 1970s.

Larger fuels tend to ignite and burn more slowly than smaller fuels with fire of low to medium severity and, therefore, might not be totally consumed in such a fire (DeBano and others 1998; Pyne and others 1996). Some larger fuels, therefore, can remain following burning of the site. With fire of high severity, however, larger fuels can burn vigorously, and the rate of fuel reduction is greater than in the case with smaller fuels. The general pattern of loadings illustrated for both smaller and larger fuels in this study is that lesser loadings occurred on the sites with a more frequent occurrence of fire.

Coarse Woody Debris

El Tigre has the heaviest loading of coarse woody debris, followed by the loadings on the Upper Sawmill and McClure sites, which were statistically similar, and the Plantio and Pinos Grandos sites, which were also statistically similar (table1). The range of loadings of coarse woody debris observed in this study is comparable to the loadings reported in other pine-oak forests of the Madrean Province. Sackett (1979) found an average loading of coarse woody debris of 7.8 tons per acre in ponderosa pine-Gambel oak stands on the San Carlos Reservation in east-central Arizona. Harrington (1981) indicated that the range of loadings of coarse woody debris was 4 to 10 tons per acre in pine-oak stands that had not been burned for 70 years on the Santa Catalina Mountains in southeastern Arizona. Alanis-Morales (1996) reported a range of 5 to 20 tons per acre *Pinus durangesis* stands near Madera, Chihuahua, Mexico.

Total Loadings of Downed Woody Fuels

The heaviest total loadings of downed woody fuels occurred on the El Tigre site, followed by the Upper Sawmill and McClure sites, which were statistically similar (table 1). The lower total loadings found on the Plantio and Pinos Grandes sites were statistically similar. All of the sites had experienced some timber harvesting in the past and, therefore, unknown amounts of logging slash likely contributed to the total fuel loadings of downed woody fuels measured in this study. The total loadings of downed woody debris found in this study were similar to values reported for ponderosa pine forests in the Southwestern United States in previous studies. Sackett (1979) found an average loading of downed woody material fuels greater than 1 inch of 9.2 tons per acre. Harrington (1982) reported loadings of 5 to 11 tons per acre. Graham and others (1994) reported total fuel of 5 to 13 tons per acre.

Management Implications

Information on the effects of fire frequencies on wildland fuel conditions could be helpful to ecologists and land managers considering the reintroduction of fire as a natural disturbance process in the pine-oak forests of the Madrean Province. While the information presented in this paper is both *site-specific* and *specific to the type of fuels* measured, the trends illustrated show that sites with higher fire frequencies accumulate less downed woody fuels than sites with lower fire frequencies. Depending on the fuel loading that might be acceptable on a site, an initial schedule of introduced fire occurrences could be prescribed, tested, and evaluated in reference to maintaining fuel loadings at the acceptable level while attaining other land management objectives. This initial schedule might then be modified through time and, as necessary, to sustain the desired fuel loading conditions and land management objectives.

The fuel loading values presented in table 1 could also be incorporated into *fuel models* to describe the fuel component in fire behavior models. *Fire behavior models* simulate how a fire reacts to the available fuels, local weather conditions, and topography (DeBano and others 1998; Pyne and others 1996). Differences in fire behavior are largely related to fuel loadings and the diameter-class distributions and moisture contents of the fuels. However, further investigations of the applicability of available fuel models and fire behavior models, such as BEHAVE (Burgan 1987; Burgan and Rothermel 1984), to the pine-oak forests of the Madrean Province are necessary before their widespread usage in these ecosystems.

Reintroducing fire to reduce fuel loadings and meet other land management objectives must be balanced against the importance of sustaining the cycling of nutrients in the ecosystem to be burned. Excessive removal of coarse woody debris by repeated fires could disrupt the mycorrhizal activity that is associated with this debris and, in doing so, affect the functioning of soil that is necessary to maintain a "high level" of plant productivity (Graham and others 1994; Harmon and others 1986; Jurgensen and others 1997). Depending on the habitat type association, Graham and others (1994) concluded that loadings of coarse woody debris from 5 to almost 25 tons per acre were "optimal" to maintain properly functioning soils in the forest types of the Rocky Mountains. Loadings of coarse woody debris necessary to sustain the "health" of forest soils in the pine-oak forests of the Madrean Province have not been determined.

Conclusions

Fire is important to the functioning of ecosystems because of its impacts on nutrient cycling, vegetative structure and composition, and the spatial distributions of plants and animals. Natural fire regimes have been altered in the Southwestern United States by past land-use practices and by the fire suppression policies of land management agencies. One consequence of this alteration has been the changes in loadings of downed woody fuels compared to those in similar forest stands in northwestern Mexico where more natural fire regimes continue.

Study sites in southeastern Arizona where fires have occurred less frequently since 1900 have heavier fuel loadings than sites in northeastern Sonora where fires are more frequent. The combination of heavier fuel loadings on the former sites provides the potential for high-intensity, stand-replacing fires. Information presented in this paper on relationships between fire frequencies and loadings of downed woody fuels in pine-oak forests should be helpful to ecologists and land managers in reintroducing periodic fire into this ecosystem of the region. Although these results are site specific, the information should be applicable to the larger region covered by the pine-oak forests of the Madrean Province.

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