

Fire regimes of the piñon–juniper woodlands of Big Bend National Park and the Davis Mountains, west Texas, USA

H.M. Poulos, R.G. Gatewood, and A.E. Camp

Abstract: While piñon woodlands cover much of arid North America, surprisingly little is known about the role of fire in maintaining piñon forest structure and species composition. The lack of region-specific fire regime data for piñon–juniper woodlands presents a roadblock to managers striving to implement process-based management. This study characterized piñon–juniper fire regimes and forest stand dynamics in Big Bend National Park (BIBE) and the Davis Mountains Preserve of the Nature Conservancy (DMTNC) in west Texas. Mean fire return intervals were 36.5 and 11.2 years for BIBE and DMTNC, respectively. Point fire return intervals were 150 years at BIBE and 75 years at DMTNC. Tree regeneration in west Texas piñon–juniper woodlands occurred historically during favorable climatic conditions following fire years. The presence of multiple fire scars on our fire-scar samples and the multicohort stands of piñon suggested that low intensity fires were common. This study represents one of the few fire-scar-based fire regime studies for piñon–juniper woodlands. Our results differ from other studies in less topographically dissected landscapes that have identified stand-replacing fire as the dominant fire regime for piñon–juniper woodlands. This suggests that mixed-severity fire regimes are typical across southwestern piñon forests, and that topography is an important influence on fire frequency and intensity.

Résumé : Bien que des boisés de pin faux-arolle couvrent la plupart des zones arides de l'Amérique du Nord, il est surprenant qu'on connaisse très peu le rôle du feu dans le maintien de la composition en espèces et de la structure de la forêt de pin faux-arolle. L'absence de données sur les régimes de feux spécifiques à chaque région dans le cas des boisés de pin faux-arolle et de genévrier constitue un obstacle pour les aménagistes qui s'efforcent d'implanter un aménagement basé sur les processus. Cette étude caractérise les régimes de feux et la dynamique des peuplements de pin faux-arolle et de genévrier dans le parc national de Big Bend (BIBE) et les monts Davis (DMTNC) dans l'ouest du Texas. L'intervalle entre les feux était de 36,5 ans dans le cas de BIBE et de 11,2 ans dans le cas de DMTNC. L'intervalle entre les feux à un endroit donné était de 150 ans dans le cas de BIBE et de 75 ans dans le cas de DMTNC. Dans le passé, les boisés de genévrier et de pin faux-arolle de l'ouest du Texas se régénéraient lorsque survenaient des conditions climatiques favorables à la suite de feux. La présence de cicatrices de feu multiples sur nos échantillons de cicatrices de feu et les peuplements formés de plusieurs cohortes de pin faux-arolle indiquent que les feux de faible intensité étaient communs. Cette étude est une des rares études des régimes de feux basées sur les cicatrices de feu dans les boisés de pin faux-arolle et de genévrier. Nos résultats diffèrent de ceux d'autres études réalisées dans des paysages moins topographiquement découpés qui ont identifié les feux qui entraînent le remplacement des peuplements comme le régime de feux dominant dans les boisés de pin faux-arolle et de genévrier. Cela indique que les régimes de feux de sévérité mixte sont typiques dans les forêts de pin faux-arolle du sud-ouest et que la topographie a une influence déterminante sur l'intensité et la fréquence des feux.

[Traduit par la Rédaction]

Introduction

Piñon–juniper woodlands dominate over 325 000 km² of North America (West et al. 1975; Mitchell and Roberts 1999). Yet the role of fire in maintaining piñon–juniper forest structure and species composition remains poorly understood and widely debated (Floyd et al. 2000, 2004; Baker

and Shinneman 2004). Limited evidence indicates that fires in this forest type occur infrequently as stand-replacing events (Baker and Shinneman 2004; Romme et al. 2007; Huffman et al. 2008); however, the wide distribution of piñon–juniper woodlands across a range of topographic settings makes it difficult to generalize about the influence of fire on forest stand dynamics.

The lack of information about fire regimes and vegetation responses in piñon–juniper woodlands presents a dilemma for managers who wish to maintain sustainable vegetation patterns and ecosystem processes. Recent climatic shifts and the exclusion of frequent, low intensity fire are potential reasons why piñon–juniper woodlands have shifted from open savannas towards dense stands that are encroaching into grasslands and shrublands (Cottam and Stewart 1940; Tausch and West 1988; Miller et al. 2008). While frequent fires were common historically in other forest types of the western United States, limited tree age data suggest that in-

Received 5 November 2008. Accepted 5 April 2009. Published on the NRC Research Press Web site at cjfr.nrc.ca on 20 June 2009.

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frequent, high-severity fire regimes are typical in piñon–juniper woodlands (Floyd et al. 2000, 2004; Baker and Shinneman 2004). Stand age is a useful proxy for time since fire; however, fire-scar data provide annual fire history information that can be used in suite with age data for understanding fire–vegetation relationships.

While it appears that piñons and junipers can develop fire scars under certain conditions (Young and Evans 1981; Tausch and West 1988; Gruell 1997), cross-dated fire events in piñon–juniper woodlands are presently limited to studies that rely on fire scars obtained from other species in adjacent ponderosa pine forests (Miller and Rose 1999; Brown et al. 2001) or use a mixture of juniper, piñon, and ponderosa pine fire-scar samples (e.g., Huffman et al. 2008). Although juniper tree rings cannot be readily cross-dated (Fritts et al. 1965), piñon produces annual growth rings (Floyd et al. 2000, 2004, 2008), suggesting a potential for using that species to reconstruct fire histories. The one drawback is that few researchers have amassed a large enough sample size to accomplish this task.

Land managers need region-specific information about how fire frequency and intensity generates and maintains piñon–juniper woodlands (USDA and USDI 2000). While piñon fire regimes in mesa systems are characterized by infrequent, stand-replacing fire (Floyd et al. 2000, 2004, 2008), this paper increases management decision space by investigating how fire shapes piñon forest structure across topographically dissected landscapes. In doing so, we use age and fire-scar data from piñon (*Pinus cembroides* Bailey and Hawksworth) as well as size data from other dominant tree species to elucidate how past fires and their current exclusion have influenced piñon–juniper woodland dynamics.

Study area

Big Bend National Park (BIBE) and the Davis Mountains Preserve of The Nature Conservancy (DMTNC) are dominated by persistent piñon–juniper woodlands and savannas. Piñon–juniper woodlands cover approximately 90% of the 18 500 ha of forest that span the two sites (~12 500 ha in DMTNC and ~6000 ha in BIBE). They are located in Brewster and Jeff Davis counties in western Texas (Fig. 1). Big Bend National Park was founded in 1944, while the Davis Mountains Preserve was acquired by The Nature Conservancy over 50 years later in 1997. Both sites had similar histories of Native American occupation and ranching prior to becoming protected areas. Mescalero Apaches were the predominant Native American group prior to the arrival of Euro-American settlers in the late nineteenth and early twentieth centuries (Maxwell 2001). Cattle, sheep, and goat ranching were the major land uses from then until the two protected areas were formed. A policy of active fire suppression has been in place in BIBE and DMTNC since their protection. However, managers at both sites are currently using prescribed fire and fire surrogates such as thinning to reduce fuel loads and fire risk.

These mountains are rugged, with average slopes of 18° (range 0°–47°). Forested elevations in BIBE range from 1411 to 2352 m a.s.l. and they span from 1747 to 2469 m in DMTNC. The terrain is extremely complex, consisting of rocky uplands separated by steep-walled canyons. The two ranges form part of the northernmost extension of the Sierra

Madre Oriental, which continues over 1500 km southward to the states of Puebla and Querétaro in Mexico. The mountains are volcanic and consist mainly of extrusive igneous rock. They originated 35–39 million years ago in the same Oligocene orogeny that formed most of the Front Range of the Rocky Mountains (Maxwell 1968). Soils of the two study areas are a mixture of mollisols and entisols. They are composed of moderately deep gravelly loam, which is well drained and noncalcareous (USDA Soil Conservation Service 1977). Runoff is medium to rapid. Available water capacity is low.

The woody vegetation in BIBE and DMTNC is composed of piñon, juniper, oak, and mixed conifer tree species. Dominant trees include *Juniperus deppeana* Steud., *Quercus grisea* Liebm., *Q. gravesii* Sarg., and *Q. emoryi* Liebm. *Juniperus flaccida* Schltdl. is another dominant juniper species in BIBE, but is absent from DMTNC. Chihuahuan desert grasslands bound the sites at lower elevations, while relict montane conifer forests form the upper elevational boundary.

The climate is arid, with cool winters and warm summers. Precipitation is distributed bimodally in late summer and winter with the majority of precipitation falling during summer storms as part of the North American Monsoon System (NAMS). Mean annual precipitation is 40 cm (range 25–140 cm) in Fort Davis, Texas, just outside DMTNC. Mean January precipitation is 1.2 cm (range 0–8.1 cm), and in July during the NAMS it is 7.1 cm (range 0.4–23 cm). The January mean minimum temperature in Fort Davis is 0.0 °C, and the July minimum temperature is 17.7 °C. The mean January maximum temperature is 15.5 °C, and the mean July maximum temperature is 32.6 °C. Mean annual precipitation for the Chisos Basin in BIBE is 70 cm (range 32–135 cm). Mean precipitation is 1.5 cm (range 0.0–2.5 cm) in January and is 8.0 cm (range 0.2–20.5 cm) in July. Mean monthly minimum temperatures are 1.8 °C in January and 17.0 °C in July. Maximum temperatures are 14.1 °C in January and 29.1 °C in July. The reported values represent 10 year averages from the period of 1995–2005 for both sites.

Methods

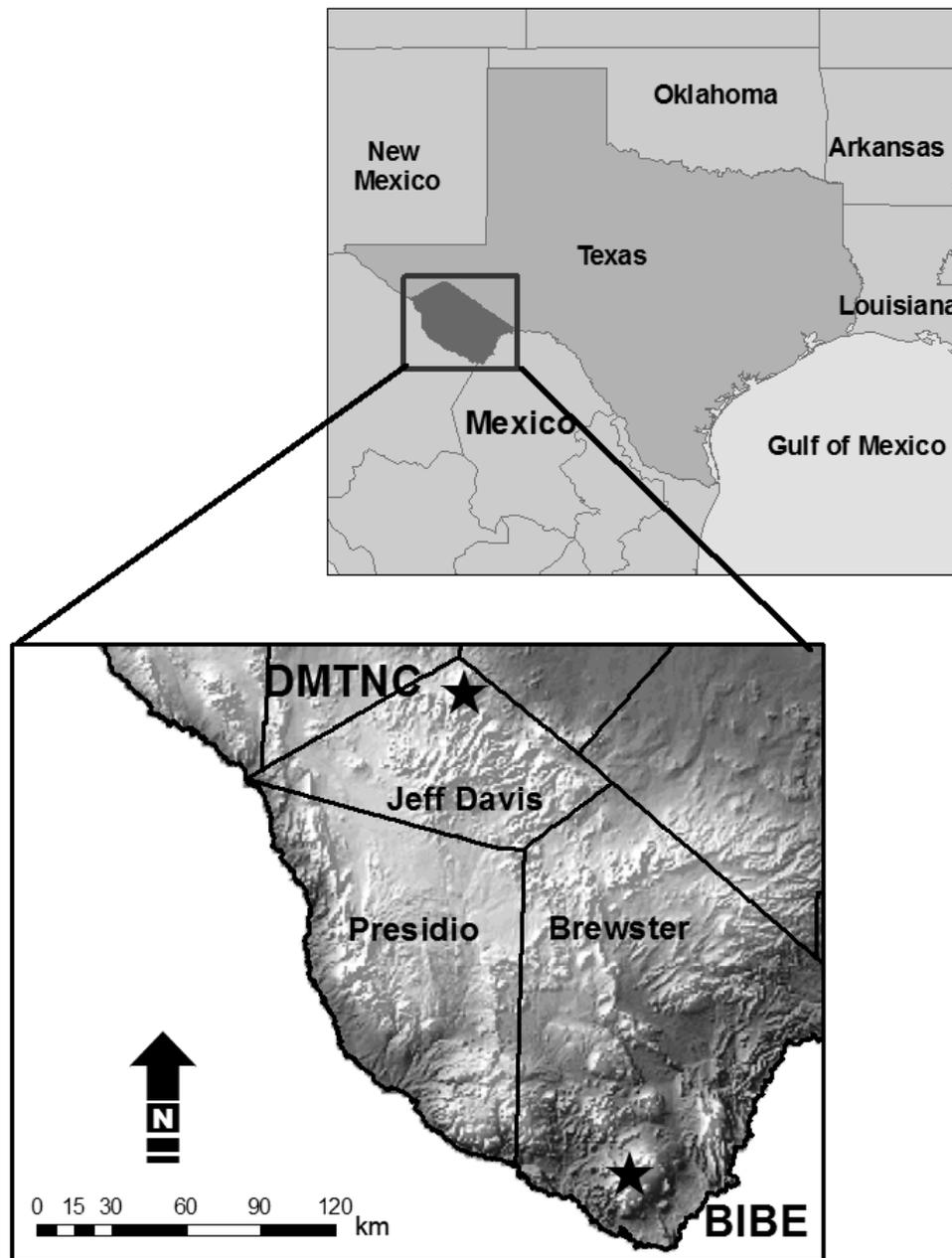
Field methods

Three hundred field plots (150 at each site) were established across the forested portions of BIBE and DMTNC during the summers of 2003 and 2004, respectively (Figs. 2 and 3). We used a sampling grid to systematically locate plots at 250 m intervals at BIBE and at 600 m intervals across DMTNC at the intersection of grid lines. These sampling intervals were chosen to ensure complete coverage of the forested areas for each of the two mountain ranges. Plot locations were located in the field using a global positioning system.

We sampled vegetation using nested, circular, fixed area plots that were 10 m in radius for trees >5 cm diameter at breast height (DBH) and 5 m radius plots for seedlings (i.e., individuals <5 cm DBH). We recorded the species of all trees and seedlings and measured the DBH of all trees. Plot areas were corrected for slope upon return from the field.

We quantified the piñon age structure by randomly coring

Fig. 1. Locations of the two study areas in Big Bend National Park (BIBE) and the Davis Mountains Preserve of The Nature Conservancy (DMTNC).



six *P. cembroides* trees in each plot that spanned the size distribution of stems (i.e., two small, two medium, and two large trees). A total of 900 cores were sampled (450 at each site). One core was taken for each tree at 30 cm height on tree stems. Three piñon seedlings (<5 cm dbh) were destructively sampled immediately outside the perimeter of the 5 m plots. We focused on *P. cembroides* in our age structure analysis, as it was the only species that produced reliable annual growth rings that could be cross-dated. Cross-sections were taken of each seedling at the base and at 30 cm height to determine their ages and to correct for the number of years lost by coring at 30 cm.

Fire-scarred piñons were sampled by searching in a 75 m radius around the center of each vegetation plot ($N = 65$).

We obtained a low number of fire-scarred samples relative to other fire history reconstructions because piñons are not as readily scarred as some other species often used for fire history reconstructions (i.e., *Pinus ponderosa* C. Lawson and *Pinus strobiformis* Engelm.). While several prior studies have incorporated fire-scarred samples from adjacent forest types to characterize piñon–juniper fire regimes (i.e., Baisan and Swetnam 1997; Brown et al. 2001; Huffman et al. 2008), we decided against it, because the adjacent forest types in BIBE and DMTNC that included readily cross-datable species including *P. ponderosa* and *P. strobiformis* differed dramatically in structure, species composition, and fuel bed characteristics. Our intent was to characterize the fire regimes of the piñon–juniper woodlands themselves,

Fig. 2. (A) Fire-scar and vegetation plots in Big Bend National Park and (B) the Davis Mountains Preserve of the Nature Conservancy.

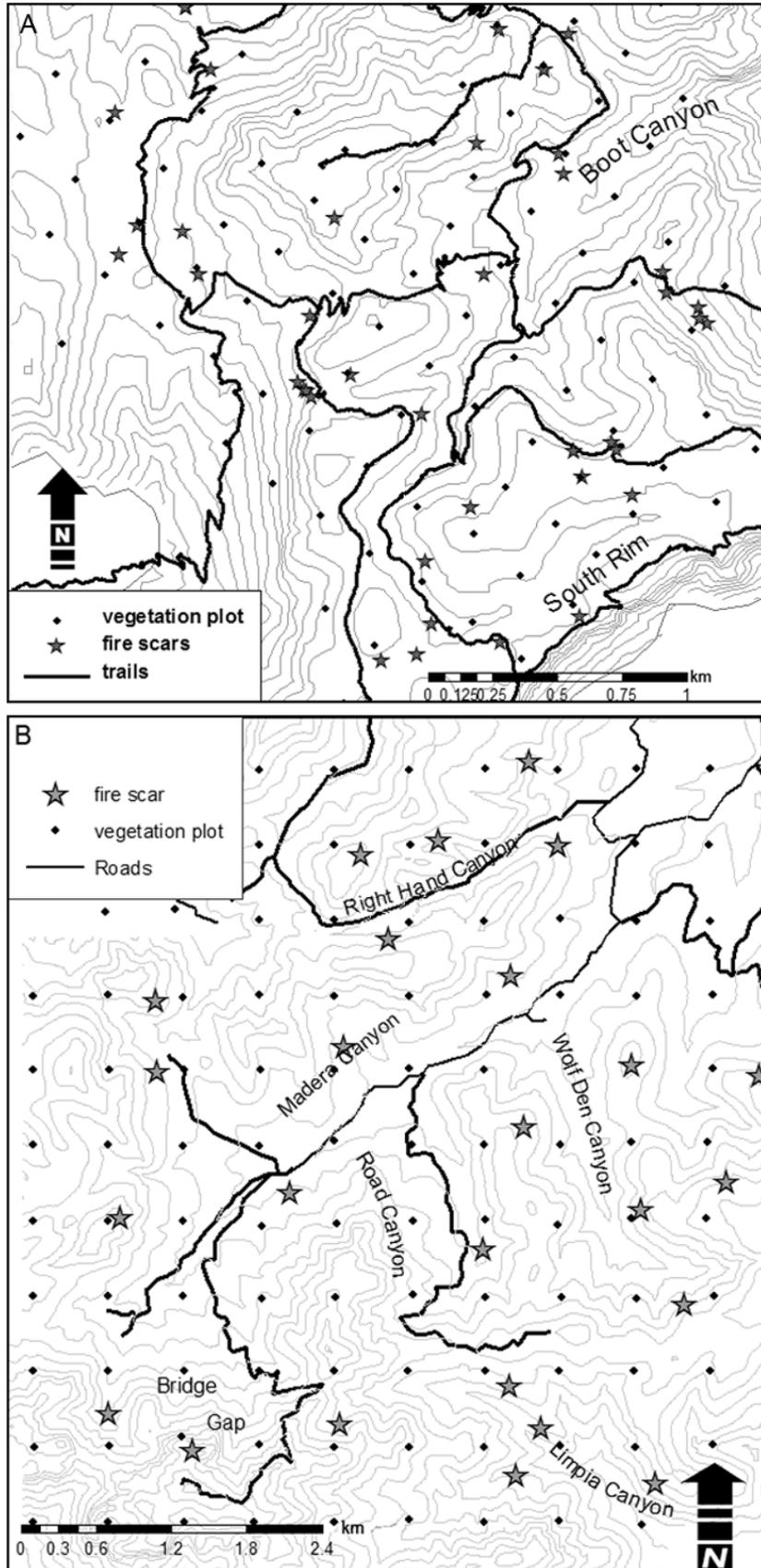
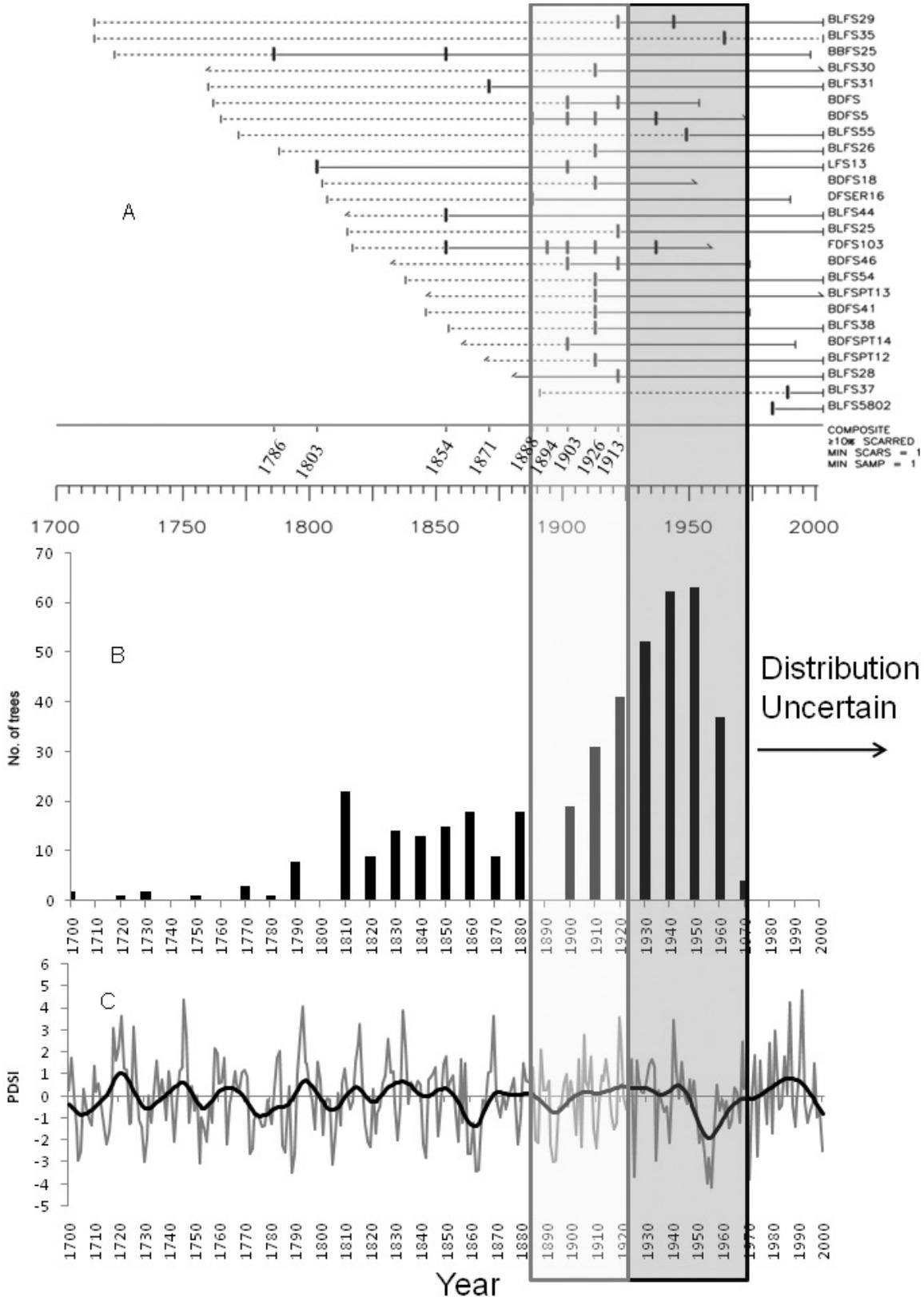


Fig. 3. (A) Master chronology of fire events for 10% or more of fire-scarred samples for Big Bend National Park (BIBE). Each horizontal line is an individual tree scar record, and each vertical tick is a dated fire scar. (B) Innermost ring dates of mature *Pinus cembroides* in BIBE ($N = 450$). (C) Palmer Drought Severity Index reconstruction. The open box shows the relationships among frequent fire, climate, and tree regeneration, while the grey box illustrates the relationships between fire cessation, tree regeneration, and climate.



rather than to extrapolate fire history records from adjacent forests to piñon.

Although we encountered several junipers with multiple fire scars, we did not collect them because of their lack of reliable annual growth rings. For the scarred piñon, full or partial cross-sections were cut from “catfaces” on trees, snags, logs, and stumps. Samples from living trees were collected as partial cross-sections, a method that does not require felling the tree. Sample locations were geo-referenced and were well distributed throughout the two study sites (Figs. 2 and 3).

Analyses

Fire history reconstruction

We dated the fire-scar samples by sanding them to a high polish and visually cross-dating them under a binocular microscope using standard dendrochronological techniques that included making skeleton plots for each sample (Stokes and Smiley 1968) and analyzing complacent ring patterns in some samples ($N = 15$) using statistical dating with the program COFECHA (Grissino-Mayer 2001a). Of the 65 fire-scar samples we collected, 44 were cross-dated and used for analysis. The remainder of the samples could not be cross-dated, and we therefore eliminated them from the study. Master chronologies for each site were used to aid in cross-dating. We developed a master tree-ring chronology DMTNC for use in cross-dating the tree cores and fire-scar samples since no chronology existed for that site (J. Villanueva-Díaz, J. Cerano, and H. Poulos, unpublished data). A master chronology for BIBE was obtained from the international tree-ring database (Cook and Montagu 1992). Of the samples collected, 27% were sampled from dead trees (mostly downed logs). We dated a total of 60 fire scars and estimated the season of fire occurrence on 85% of the scars. We estimated the season of fire occurrence (Baisan and Swetnam 1990) based on the relative position of each fire lesion within the annual ring according to the following categories: early earlywood, earlywood, middle earlywood, late earlywood, latewood, and dormant. Dormant season scars were assigned to the year following the earlywood (i.e., spring fires), a convention that appears valid for the spring drought – summer monsoonal climate pattern of northern Mexico (Fulé and Covington 1996, 1997; Heyerdahl and Alvarado 2003; Fulé et al. 2005). The season was listed as “not determined” when it could not be distinguished clearly.

We analyzed the fire history data using FHX2 software (Grissino-Mayer 2001b). “Recorder” trees were those with open fire scars or other injuries (i.e., lightning scars), leaving them susceptible to repeated scarring by fire (Swetnam and Baisan 1996). While we assumed that the fire scars on our samples represented fire events, we acknowledged that many trees may have experienced fire at their bases without recording a fire scar, which precluded precise assessments of spatial patterns of burning from fire-scar evidence.

We statistically analyzed the fire return intervals in different subcategories or filters. First, we determined the statistical distribution of fire intervals using all fire years, even those represented by only a single scar. Then, we included only those fire years for which 10% or more of the recording samples included a scar. We chose a 10% filter rather

than a larger 25% filter based on the limited sample size of fires that scarred 25% of the samples. In contrast with the all-scarred category, these filters captured fires that were relatively large in size or more intense than those fires that scarred only one or a few trees (Swetnam and Baisan 1996). The statistical analysis of fire return intervals included the minimum, maximum, and mean fire return intervals (MFI) and the Weibull median probability interval (WMPI), which were used to model asymmetric fire interval distributions and to express fire return intervals in probabilistic terms (Grissino-Mayer 1995).

Piñon age structure

We aged the tree cores and seedling cross-sections by sanding them to a high polish and visually cross-dating them under a binocular microscope using standard dendrochronological techniques (Stokes and Smiley 1968). Of the 900 tree cores sampled, 846 were successfully cross-dated and used in the analysis ($N = 450$ for BIBE; $N = 396$ for DMTNC). Additional years to the center were estimated using a pith locator (concentric circles matched to the curvature and density for the inner rings) for cores that missed the pith (Applequist 1958). We adjusted the tree ages for years lost at coring height using the tree seedling age data by subtracting the number of rings on each destructively sampled seedling at 30 cm from the number of rings at each seedling’s base. The mean number of years lost by the destructively sampled seedlings in each plot was then added to the tree ages for each plot to account for the years of growth missed by coring at DBH.

Woodland size structure

We quantified forest structure using size data for each tree species. Tree density (ha^{-1}) was calculated in 5 cm size-classes for each species in each plot. While it is well understood that size–age relationships can be poor in the arid Southwest, a regression of size versus age revealed a statistically significant relationship for piñon ($P < 0.0001$, $R^2 = 0.478$). Our lack of age data from tree species other than piñon precluded our ability to extrapolate size–age relationships across all trees. Instead, we inferred recent forest development trends by interpreting the shapes of the size-class distribution data (e.g., Whipple and Dix 1979).

Results

Fire regime characteristics

Fires recurred in piñon forests at intervals of 5–74 years in BIBE and 4–27 years in DMTNC (Fig. 4, Table 1). Mean fire intervals for the filtered data using the 10% criterion were 36.5 years in BIBE and 11.2 years in DMTNC. The WMPI values for the filtered data were 28.6 years in BIBE and 10.3 years in DMTNC. The average per-sample fire intervals (point fire return intervals) were 150.8 years in BIBE and 74.2 years in DMTNC. Major fire years in BIBE were 1880, 1903, 1916, and 1926. Fires in 1883, 1903, 1916, and 1988 scarred multiple samples in DMTNC, and several isolated fires occurred on individual samples at this site in the latter part of the twentieth century.

Dormant season scarring (i.e., spring burning) was the most common (76.5%), followed by early earlywood scar-

Fig. 4. (A) Master chronology of fire events for 10% or more of fire-scarred samples for the Davis Mountains Preserve of The Nature Conservancy (DMTNC). Each horizontal line is an individual tree scar record, and each vertical tick is a dated fire scar. (B) Innermost ring dates of mature *Pinus cembroides* in DMTNC ($N = 396$). (C) Palmer Drought Severity Index reconstruction. The open box shows the relationships among frequent fire, climate, and tree regeneration, while the grey box illustrates the relationships between fire cessation, tree regeneration, and climate.

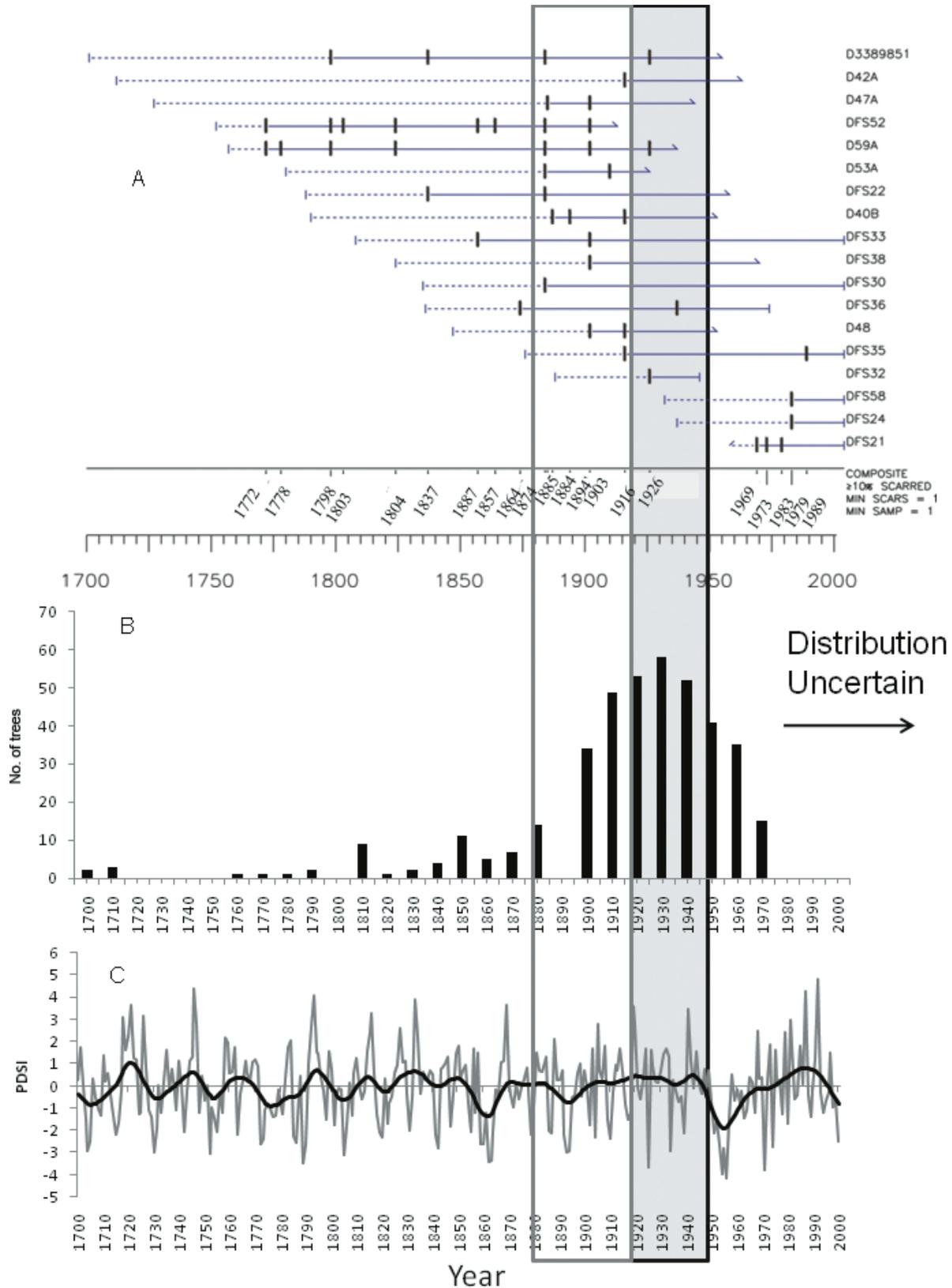
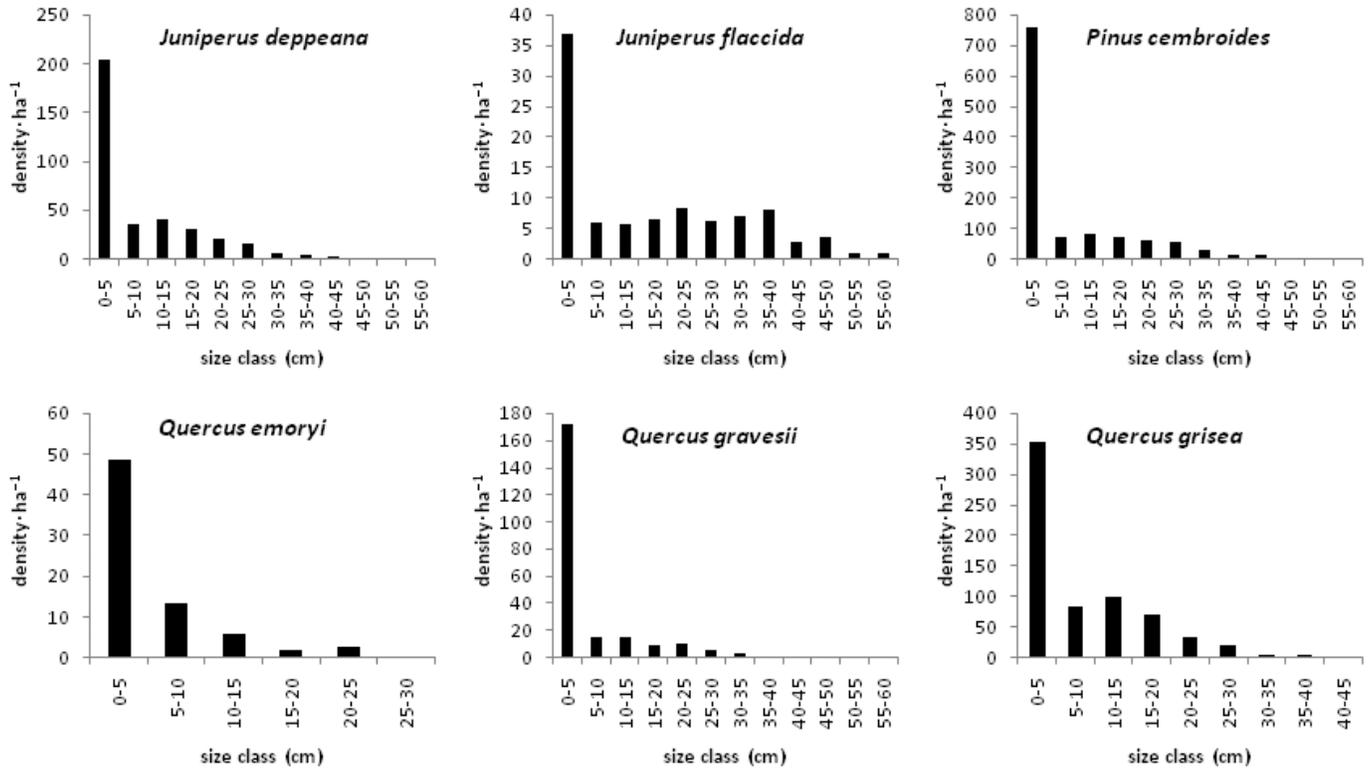


Table 1. Fire intervals (in years) for *Pinus cembroides* at the Davis Mountains Preserve of The Nature Conservancy (DMTNC) and Big Bend National Park (BIBE).

Site	Category of analysis	No. of intervals	MFI	Min.	Max.	Average per-sample interval	WMPI	Interval since last fire
BIBE	All scars	11	19.4	5.0	74.0	150.8	16.0	16
	10% scarred	4	36.5	9.0	74.0		28.6	
DMTNC	All scars	13	11.2	4.0	27.0	74.2	10.3	16
	10% scarred	13	11.2	4.0	27.0		10.3	

Note: MFI, mean fire interval; and WMPI, Weibull median probability interval.

Fig. 5. Mean size-class distributions in 5 cm classes of major tree species in Big Bend National Park. Note that the scales of the y-axes differ among graphs.



ring (22%). Less than 1% of the burns were middle earlywood or late earlywood. No scars occurred in the early latewood or latewood.

Piñon age structure

Piñons in BIBE and DMTNC showed three regeneration pulses around 1810, in the late 1800s, and during the early to mid-1900s (Fig. 5). Tree establishment occurred during fire-free intervals under positive phases of PDSI (Cook et al. 2004). The gaps in tree regeneration at both sites in the late 1800s corresponded with periods of high fire frequency and low PDSI. The peaks in tree regeneration in the mid-1900s corresponded with a drop in fire return intervals during favorable climatic conditions, while the decline in tree establishment in the latter half of the twentieth century corresponded with the timing of the 1950s drought that extended across the majority of the southwestern US.

Woodland size structure

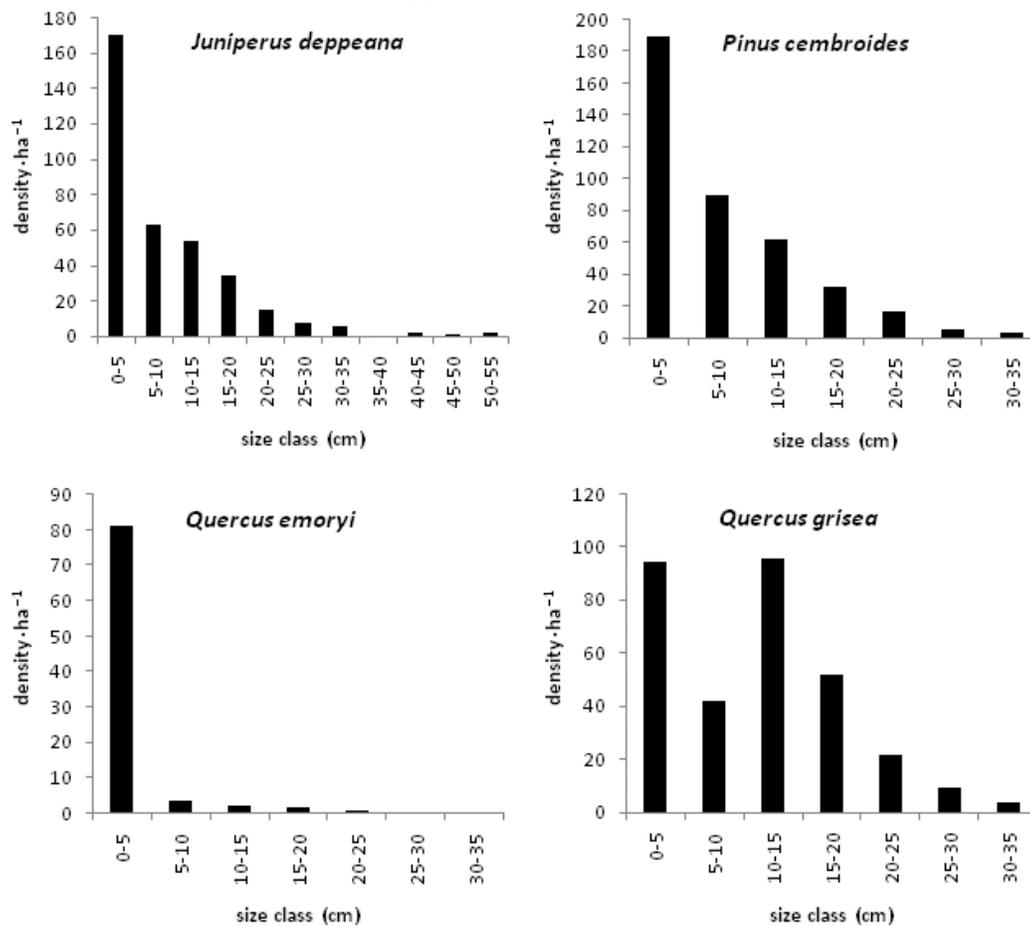
The size-class distributions of the dominant tree species in

BIBE and DMTNC indicated high densities of small (0–5 cm DBH), potentially young seedlings (Fig. 6) that most likely regenerated during wet intervals following the decreases in fire frequency in the early 1900s in BIBE and DMTNC. *Quercus grisea* and *Juniperus deppeana* also appeared to have large numbers of intermediate-sized individuals (10–15 cm), which may have occurred in response to postfire sprouting after the last major fire event in 1916 in DMTNC and in 1926 in BIBE.

Discussion

Fires occurred relatively frequently prior to 1930 in the two study sites, and a number of fires continued into the twentieth century in DMTNC. The tree age, fire record, and PDSI data for BIBE and DMTNC suggested frequent fires limited tree regeneration, while fire-free periods during wet years stimulated piñon recruitment. Although tree sizes are only a rough estimate of recent tree establishment trends, the high densities of small trees complemented the piñon

Fig. 6. Mean size-class distributions in 5 cm classes of major tree species in the Davis Mountains Preserve of The Nature Conservancy (DMTNC). Note that the scales of the y-axes differ among graphs.



age data, suggesting that most trees in BIBE and DMTNC probably established relatively recently. This pattern is consistent with other research findings for the Southwest that document similar tree recruitment pulses in the late nineteenth and early twentieth centuries in relation to fire exclusion and favorable climatic conditions (Savage and Swetnam 1990; Fulé and Covington 1996; Swetnam and Betancourt 1998).

Our research corroborated the 1880 and 1903 fires reported by Moir (1982) in BIBE, and we also identified major fires in 1916 and 1926. Eighteen eighty was a major fire year across the Southwest, which suggests that although our sites lie in the periphery of the American Southwest, they experienced the same major fire years as the rest of this larger biogeographical region. Our identification of the 1903 fire is consistent with historical accounts of a landscape-scale fire across the Chisos Mountains in the early 1900s (B. Miller, personal communication, 2000). That we found fires missed by Moir (1982) was probably a result of our increased fire-scar sample size, the wider distribution of samples across the Chisos Mountains, our use of cross-dating and focus on tree species that produce reliable annual growth rings, and the incorporation of tree age data into this study. The late twentieth century fires and the one larger fire in 1989 we identified in our fire history reconstruction at DMTNC were confirmed by wildlife biologist

John Karges, and local residents of the Eppenauer property adjacent to the preserve. Moreover, our inclusion of piñon fire-scar data from DMTNC provided a larger, regional-scale characterization of piñon-juniper fire regimes for west Texas, because these two ranges encompass the majority of piñon-juniper forests in this region.

It was surprising to see fires during the latter half of the twentieth century in DMTNC but not in BIBE, although DMTNC was exposed to indirect fire exclusion through grazing until its preservation in 1997. This suggests that while grazing was absent from BIBE since the 1940s, the direct fire suppression policies of BIBE may have been more effective at removing fire than grazing on a private ranch.

Higher fine fuel continuity in DMTNC relative to BIBE may explain why MFIs were longer in BIBE. The Davis Mountains are characterized by a grassy fuel bed that covers the majority of the forested area of the mountain range. In contrast, grassy fuel beds exist across a relatively small portion of BIBE along the South Rim and Laguna Meadows. Most of the mountain range is made up of rugged, skeletal soils that support little grass cover. While the complex topography in BIBE probably facilitates faster fire spread rates, it also promotes shallow, dry soils with sparse grasses.

Fire intensity

In contrast with the infrequent, stand-replacing fires iden-

tified by Floyd et al. (2000, 2004, 2008) in mesa systems of Colorado and Utah, the presence of several piñon cohorts and multiple fire scars on individual fire-scar samples in our study suggests that fires across BIBE and DMTNC occurred as lower intensity surface fires. Surface fires are typical of open piñon–juniper woodlands (Romme et al. 2007), and the grassy fuel beds that dominate large expanses of the two study sites most likely burned historically as low intensity events that moved quickly across the landscape.

A low intensity fire regime may also explain why we found few fire-scarred piñons in this study. Trees within a predominantly grassy fuel matrix may not have had fires heat their bases sufficiently to injure their vascular cambium. Closed canopy sites where we did find fire-scar samples may have had higher litter accumulation, and may have burned slowly enough in some portions of the landscape to scar trees.

Comparisons with other piñon–juniper woodland fire regimes

The mean fire interval statistics of 11 (DMTNC) and 36 (BIBE) years suggest that our sites experienced fires much more frequently at the landscape scale than found by Floyd et al. (2000, 2004, 2008) and Huffman et al. (2008). The shorter mean fire return intervals we identified in BIBE and DMTNC relative to the 200 to 600 year intervals found by Floyd et al. (2000, 2004, 2008) may have been related to their use of age, rather than fire-scar data for reconstructing the disturbance history of Mesa Verde in Colorado (Floyd et al. 2000, 2004) and the Kaiparowits Plateau in Utah (Floyd et al. 2008). While the point fire return intervals of 150 (BIBE) and 75 (DMTNC) years and the piñon age data correspond more closely with Mesa Verde fire return intervals, the shorter mean and point fire return intervals in our study suggest that west Texas piñon–juniper woodlands burned more frequently than other piñon–juniper sites. That Floyd et al. (2000, 2004, 2008) were working with a different piñon species (*Pinus edulis* Engelm.) from another biogeographic province and in mesa, rather than topographically dissected landscapes, are other potential explanations for differences in the fire intervals among the sites.

The point fire return intervals in our study more closely matched the 26 to 100 year intervals of Huffman et al. (2008) from Arizona and New Mexico. However, the abundance of young trees in BIBE and DMTNC contrasted their age data, which indicated that frequent, low intensity fires were uncommon, because the majority of the trees in their sites were over 200 years old. However, an analysis of the distribution of young versus old piñon like that of Jacobs et al. (2008) relative to fire history could help elucidate where tree regeneration has occurred since the removal of fire from BIBE and DMTNC. Like Floyd et al. (2000, 2004, 2008), Huffman et al. (2008) were also working in relatively flat areas. The steeper slopes of BIBE and DMTNC may have facilitated the movement of fires across the landscape from lowland grasslands to forest uplands, and the rapid movement of fire over steep slopes may explain why several older cohorts of trees survived multiple fire events. While we did not perform an analysis of the topographic influences on fire regime characteristics in BIBE and DMTNC because of our small sample size, topographic complexity may be an

important influence on piñon–juniper fire regimes and stand structures. The differences in fire regime characteristics between our sites and other piñon–juniper woodlands suggest that this forest type may experience mixed-severity fire regimes across the Southwest, and that fire frequency, intensity, and severity can be influenced by topographic complexity.

This study presented new information for west Texas regarding the role of fire in piñon–juniper forests. It showed a close association among fire, climatic conditions, and tree regeneration. Fire return intervals were shorter in our study sites than in other, less topographically dissected landscapes of the West where fire-return intervals of greater than 200 years are typical. Differences between the fire regime characteristics of our piñon–juniper sites relative to other parts of the Southwest demonstrate the need for site-specific fire history information for informing fire and forest management.

Acknowledgements

We thank The Davis Mountains Preserve of The Nature Conservancy of Texas and Big Bend National Park for logistical support for this project. John Zubia and John Morlock from the Big Bend National Park Fire Management Office contributed greatly to the project through their assistance in collecting fire-scar samples. We also thank three anonymous reviewers assisting us in improving the manuscript. Fire history and tree age data are available through the International Multiproxy Paleofire Database (available online at www.ncdc.noaa.gov/paleo/impd/paleofire.html). Funding for this research was graciously provided by the Joint Fire Sciences Program (03-3-3-13).

References

- Allen, C.D. 1989. Changes in the landscape of the Jemez Mountains, New Mexico. Ph.D. dissertation, University of California, Berkeley, Calif.
- Applequist, M.B. 1958. A simple pith locator for use with off-centered increment cores. *J. For.* **56**: 141.
- Baisan, C.D., and Swetnam, T.W. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, USA. *Can. J. For. Res.* **20**(10): 1559–1569. doi:10.1139/x90-208.
- Baisan, C.H., and Swetnam, T.W. 1997. Interactions of fire regimes and land use in the central Rio Grande Valley. USDA For. Serv. Res. Pap. RM-RP-330.
- Baker, W.L., and Shinneman, D.J. 2004. Fire and restoration of piñon–juniper woodlands in the western United States: a review. *For. Ecol. Manage.* **189**(1–3): 1–21. doi:10.1016/j.foreco.2003.09.006.
- Brown, P.M., Kaye, M.W., Huckaby, L.S., and Baisan, C.H. 2001. Fire history along environmental gradients in the Sacramento Mountains, New Mexico: influences of local patterns and regional processes. *Ecoscience*, **8**: 115–126.
- Cook, E.R., and Montagu, N. 1992. Tree ring data, Big Bend National Park, Texas., International Tree Ring Data Bank, IGBP PAGES/World Data Center for Paleoclimatology Program, NOAA/NGDC Paleoclimatology Program, Boulder, Colo., USA.
- Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., and Stahle, D.W. 2004. Long-term aridity changes in the Western United States. *Science*, **306**(5698): 1015–1018.
- Cottam, W.P., and Stewart, G. 1940. Plant succession as a result of

- grazing and of meadow desiccation by erosion since settlement in 1862. *J. For.* **38**: 613–626.
- Floyd, M.L., Romme, W.H., and Hanna, D.D. 2000. Fire history and vegetation pattern in Mesa Verde National Park, Colorado, USA. *Ecol. Appl.* **10**(6): 1666–1680. doi:10.1890/1051-0761(2000)010[1666:FHAVPI]2.0.CO;2.
- Floyd, M.L., Hanna, D.D., and Romme, W.H. 2004. Historical and recent fire regimes in piñon–juniper woodlands on Mesa Verde, Colorado, USA. *For. Ecol. Manage.* **198**(1–3): 269–289. doi:10.1016/j.foreco.2004.04.006.
- Floyd, M.L., Romme, W.H., Hanna, D.D., Winterowd, M., Hanna, D., and Spence, J. 2008. Fire history of piñon–juniper woodlands on Navajo Point, Glen Canyon National Recreation Area. *Nat. Areas J.* **28**(1): 26–36. doi:10.3375/0885-8608(2008)28[26:FHOPWO]2.0.CO;2.
- Fritts, H.C., Smith, D.G., Cardis, J.W., and Budelsky, C.A. 1965. Tree-ring characteristics along a vegetation gradient in northern Arizona. *Ecology*, **46**(4): 393–401. doi:10.2307/1934872.
- Fulé, P.Z., and Covington, W.W. 1996. Changing fire regimes in Mexican pine forests: ecological and management implications. *J. For.* **94**: 33–38.
- Fulé, P.Z., and Covington, W.W. 1997. Spatial patterns of Mexican pine-oak forests under different recent fire regimes. *Plant Ecol.* **134**(2): 197–209. doi:10.1023/A:1009789018557.
- Fulé, P.Z., Villanueva-Díaz, J., and Ramos-Gómez, M. 2005. Fire in a conservation reserve in Chihuahua, Mexico. *Can. J. For. Res.* **35**: 320–330. doi:10.1139/x04-173.
- Grissino-Mayer, H.D. 1995. The climate and fire history of El Malpais National Monument, New Mexico. Ph.D. dissertation, The University of Arizona, Tucson, Ariz.
- Grissino-Mayer, H.D. 2001a. Evaluating cross-dating accuracy: a manual and tutorial for the computer program COFECHA. *Tree-Ring Res.* **57**: 205–221.
- Grissino-Mayer, H.D. 2001b. FHX2-software for analyzing temporal and spatial patterns in fire regimes from tree rings. *Tree-Ring Res.* **57**: 115–124.
- Gruell, G.E. 1997. Historical role of fire in piñon–juniper woodlands, Walker River watershed project, Bridgeport Ranger District. Unpublished Report to USDA. Humboldt-Toiyabe National Forest, Bridgeport Ranger District, Bridgeport, Calif.
- Heyerdahl, E.K., and Alvarado, E. 2003. Influence of climate and land use on historical surface fires in pine–oak forests, Sierra Madre Occidental, Mexico. *In* Fire and climatic change in temperate ecosystems of the Western Americas. *Edited by* T.T. Veblen, W.L. Baker, G. Montenegro, and T.W. Swetnam. Springer-Verlag, New York. pp. 196–217.
- Huffman, D.W., Fulé, P.Z., Pearson, K.M., and Crouse, J.E. 2008. Fire history of piñon–juniper woodlands at upper ecotones with ponderosa pine forests in Arizona and New Mexico. *Can. J. For. Res.* **38**(8): 2097–2108. doi:10.1139/X08-053.
- Jacobs, B.F., Romme, W.H., and Allen, C.D. 2008. Mapping “old” versus “young” piñon–juniper stands with a predictive topoclimatic model. *Ecolog. Apps.* **18**(7): 1627–1641.
- Maxwell, R.A. 2001. The Big Bend of the Rio Grande. Bureau of Economic Geology, University of Texas at Austin, Austin, Tex.
- Miller, R.F., and Rose, J.A. 1999. Fire history and western juniper encroachment in sagebrush steppe. *J. Range Manage.* **52**(6): 550–559. doi:10.2307/4003623.
- Miller, R.F., Tausch, R.J., Durant McArthur, E., and Sanderson, S.C. 2008. Age structure and expansion of piñon–juniper woodlands: a regional scale perspective in the intermountain west. USDA For. Serv. Res. Pap. RMRS-RP-69.
- Mitchell, J.E., and Roberts, T.C., Jr. 1999. Distribution of piñon–juniper in the western United States. *In* Proceedings of the Ecology and Management of Piñon–juniper Communities within the Interior West. *Edited by* S.B. Monsen and R. Stevens. USDA For. Serv. Proc. RMRS-P-9. pp. 146–154.
- Moir, W.H. 1982. A fire history of the high Chisos, Big Bend National Park, Texas. *Southwest. Nat.* **27**(1): 87–98. doi:10.2307/3671411.
- Romme, W., Allen, C., Bailey, J., Baker, W., Bestelmeyer, B., Brown, P., Eisenhart, K., Floyd-Hanna, L., Huffman, D., Jacobs, B., Miller, R., Muldavin, E., Swetnam, T., Tausch, R., and Weisberg, P. 2007. Historical and modern disturbance regimes of piñon–juniper vegetation in the Western U.S. Colorado Forest Reforestation Institute, Fort Collins, Colo.
- Savage, M., and Swetnam, T.W. 1990. Early 19th-century fire decline following sheep pasturing in a Navajo ponderosa pine forest. *Ecology*, **71**(6): 2374–2378. doi:10.2307/1938649.
- Stokes, M.A., and Smiley, T.A. 1968. An introduction to tree ring dating. University of Chicago Press, Chicago, Ill.
- Swetnam, T.W., and Baisan, C.H. 1996. Historical fire regime patterns in the southwestern United States since AD 1700. *In* Proceedings of the 2nd La Mesa Fire Symposium. *Edited by* C.D. Allen. USDA For. Serv. Gen. Tech. Rep. RM-GTR-286. pp. 11–32.
- Swetnam, T.W., and Betancourt, J.L. 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. *J. Clim.* **11**(12): 3128–3147. doi:10.1175/1520-0442(1998)011<3128:MDAERT>2.0.CO;2.
- Tausch, R.J., and West, N.E. 1988. Differential establishment of piñon and juniper following fire. *Am. Midl. Nat.* **119**(1): 174–184. doi:10.2307/2426066.
- USDA Soil Conservation Service. 1977. Soil survey of Jeff Davis County, Texas. USDA Soil Conservation Service, Texas Agricultural and Experimental Station, Marfa, Texas.
- USDA and USDI (USDA Forest Service, and US Department of the Interior). 2000. National fire plan: managing the impacts of wildfires on communities and the environment. A report to the president in response to the wildfires of 2000 [online]. Available from www.forestsandrangelands.gov/NFP/index.shtml [accessed June 2007].
- West, N.E., Rea, K.H., and Tausch, R.J. 1975. Basic synecological relationships in piñon–juniper woodlands. *In* The piñon–juniper ecosystem: a symposium. *Edited by* G.F. Gifford and F.E. Busby. Utah State University, Logan, Utah.
- Whipple, S.A., and Dix, R.L. 1979. Age structure and successional dynamics of a Colorado subalpine forest. *Am. Midl. Nat.* **101**(1): 142–158. doi:10.2307/2424909.
- Young, J.A., and Evans, R.A. 1981. Demography and fire history of a western juniper stand. *J. Range Manage.* **34**(6): 501–506. doi:10.2307/3898108.