Fire history of pinyon–juniper woodlands at upper ecotones with ponderosa pine forests in Arizona and New Mexico

David W. Huffman, Peter Z. Fulé, Kristen M. Pearson, and Joseph E. Crouse

Abstract: We used maps of fire evidence, fire scar dendrochronology, forest age-structure analysis, and landscape analysis to investigate fire history at pinyon pine (*Pinus edulis* Engelm.) – juniper (*Juniperus osteosperma* (Torr.) Little, *Juniperus scopulorum* Sarg.) woodland – ponderosa pine (*Pinus ponderosa* P. & C. Lawson) forest ecotones in Arizona (Tusayan) and in New Mexico (Canjilon). Results showed that charred trees were not evenly distributed across vegetative communities but were significantly ($p < 0.001$) more abundant than expected in ponderosa pine communities. Composite fire scar analysis indicated that surface fires occurred in ponderosa pine stands at both sites and burned at intervals of 7.2–11.1 years (WMPI; Weibull median probability interval). At Tusayan, landscape structure was fine grained, and maximum pinyon age was >200 years across 80% of the site. At Canjilon, landscape pattern was relatively coarse, and most pinyon patches were 200–300 years old. Cumulative standing age distributions suggested pinyon–juniper fire rotations of 340 and 290 years at Tusayan and Canjilon, respectively. We concluded the following: (*i*) surface fires in ponderosa pine stands did not spread through pinyon–juniper communities at either site, (*ii*) fire evidence was prevalent across both sites, but old pinyon trees indicated that no widespread lethal fires had occurred in the last 300–400 years, and (*iii*) structurally heterogeneous landscapes suggested that historical pinyon–juniper fires were of limited extent but lethal in patches.

Résumé : Nous avons utilisé la cartographie des feux, la dendrochronologie des cicatrices de feu, l'analyse de la structure d'âge de la forêt et l'analyse du paysage pour étudier l'historique des feux, en Arizona (Tusayan) et au Nouveau-Mexique (Canjilon), dans l'écotone entre la forêt claire de pinyon (*Pinus edulis* Engelm.) – genévrier (*Juniperus osteosperma* (Torr.) Little, *Juniperus monosperma* (Engelm.) Sarg.) et la forêt de pin ponderosa (*Pinus ponderosa* P. & C. Lawson). Les résultats ont montré que les arbres calcinés n'étaient pas régulièrement distribués parmi les communautés végétales mais étaient significativement ($p < 0{,}001$) plus abondants que prévu dans les communautés de pin ponderosa. L'analyse composite des cicatrices de feu a montré que des feux de surface sont survenus dans les peuplements de pin ponderosa aux deux endroits à des intervalles de 7,2 à 22,5 ans (intervalle médian de probabilité de Weibull). À Tusayan, la structure du paysage était fine et l'âge maximum du pinyon était supérieur à 200 ans sur 80 % de la station. À Canjilon, la structure du paysage était relativement grossière et la plupart des bouquets de pinyon avaient 200 à 300 ans. Selon les distributions cumulatives de l'âge des arbres sur pied, la rotation des feux dans la forêt claire de pinyon–genévrier était respectivement de 340 et 290 ans à Tusayan et Canjilon. Nous tirons les conclusions suivantes : (*i*) les feux de surface dans les peuplements de pin ponderosa ne se sont pas propagés dans les communautés de pinyon–genévrier à ni l'un ni l'autre des endroits, (*ii*) les indices de feux étaient répandus aux deux endroits mais les vieilles tiges de pinyon indiquaient qu'aucun feu létal de grande envergure n'était survenu au cours des 300 à 400 dernières années et (*iii*) des paysages structurellement hétérogènes indiquaient que les feux dans la forêt claire de pinyon–genévrier ont été dans le passé limités en étendue mais létaux par bouquets.

[Traduit par la Rédaction]

Introduction

Pinyon–juniper woodlands cover approximately 22.5×10^6 ha in the western United States and are a dominant vegetation type on the semiarid landscapes of the American Southwest (Brown 1994; Powell et al. 1994). Pinyon–juniper woodlands typically occur at elevations of 1500–2500 m and are highly variable in species composition and stand structure. For example, at upper ecotones where woodlands grade into ponderosa pine (*Pinus ponderosa* P. & C. Lawson) forests, pinyon pine (*Pinus edulis* Engelm.) becomes more abundant in the overstory, whereas at lower, drier sites juniper species (e.g., Utah juniper (*Juniperus osteosperma* (Torr.) Little), oneseed juniper (*Juniperus monosperma* (Engelm.) Sarg.))

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D.W. Huffman,[1] K.M. Pearson, and J.E. Crouse. Ecological Restoration Institute, Northern Arizona University, Flagstaff, AZ 86011-5107, USA.
P.Z. Fulé. Ecological Restoration Institute, Northern Arizona University, Flagstaff, AZ 86011-5107, USA; School of Forestry, Northern Arizona University, Flagstaff, AZ 86011-5107, USA.

[1] Corresponding author (e-mail: David.Huffman@nau.edu).

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tend to dominate. Variability in vegetation is related to changes in site characteristics including climate and soils (West 1999). These differences, in turn, are likely reflected in fuel structure and potential fire regime changes. Thus, generalization of historical disturbance regimes for the pinyon–juniper type as a whole is challenging. In addition, few data are available that describe historical fire regimes or structural patterns of pinyon–juniper ecosystems (West 1999; Baker and Shinneman 2004). Romme et al. (2003) suggested that high-frequency, low-severity fires most likely maintain open stand conditions on juniper savannas or in pinyon–juniper communities at ecotones with other frequent fire types like ponderosa pine forests. In contrast, it is thought that fire occurs infrequently in persistent woodlands found on less productive, rocky sites with less abundant herbaceous plant cover, or sites where topographic influences break fuel continuity (Tausch and West 1988; Floyd et al. 2000). Under these conditions, infrequent severe fires would result in canopy openings of various sizes. Indeed, Floyd et al. (2004) reported extents of historical stand-replacing fires >1000 ha at Mesa Verde National Park in Colorado.

Methodological limitations of previous studies have contributed to the uncertainty surrounding historical pinyon–juniper fire regimes. For example, investigations based solely on fire-scarred trees can be misleading. Although more research is needed to identify conditions that lead to scarring of pinyon and juniper trees (Baker and Shinneman 2004), others have suggested that pinyon and some juniper species are typically killed by low-intensity fire and do not record surface fires well (West 1999). Using dendrochronological techniques to precisely determine fire years is difficult even if juniper scars are located, and without crossdating scars cannot be used in composite fire interval analysis. Further, decades to hundreds of years may be required for some pinyon–juniper systems to fully recover after severe disturbance (Arnold et al. 1964; Erdman 1970). For this reason, and because reburning can be difficult to determine, natural fire rotation estimates based on stand-structure analysis can be imprecise. To reduce these limitations and gain greater insight into historical patterns, studies employing multiple lines of evidence are recommended (Egan and Howell 2001; Baker and Shinneman 2004).

Historical reference condition information aides in the design of ecosystem management strategies meant to emulate natural ranges of ecological variability (Kaufmann et al. 1994). For pinyon–juniper ecosystems of the Southwest, variability in historical fire regimes can lead to widely divergent management actions. For example, on sites where high-frequency, low-severity surface fire prevailed, management goals may be to maintain or restore open structural conditions and low-intensity fire (Jacobs and Gatewood 1999). In contrast, management of ecosystems with stand-replacing fire regimes may require maintenance of dense, older stand conditions as well as creation of large open patches that mimic fire-created mosaics.

In this study, our goal was to use multiple lines of evidence and intensive sampling to increase basic understanding of historical fire regimes of pinyon–juniper ecosystems at ecotonal boundaries with ponderosa pine forests in the Southwest. We were interested in historical fire type (e.g., nonlethal surface fire versus stand-replacing fire) as well as spatial patterns of forest structure that may have resulted from past fire events. We were particularly interested in testing the hypothesis that although surface fires were uncommon in pinyon–juniper woodlands of the western United States (Baker and Shinneman 2004), such fires may have occurred in upper ecotonal environments where pinyon–juniper communities are found adjacent to frequent-fire types such as ponderosa pine forests (Romme et al. 2003). We expected that nonlethal surface fires would leave evidence such as fire scars on trees (older live and dead structures). In contrast, if historical fires were mainly infrequent stand-replacing fires (e.g., Floyd et al. 2004), we expected that this would be apparent in discrete patches of charred snags and logs as well as relatively large areas where the ages of the oldest trees are similar. We intensively sampled ecotonal sites in northern Arizona and New Mexico and used fire scar dendrochronology, forest age-structure analysis, and landscape analysis to determine which of the two models of historical fire more closely applied. By restricting our study to pinyon–juniper woodland – ponderosa pine forest ecotones, we intended to provide focused information concerning a portion of the natural range of variability for southwestern pinyon–juniper ecosystems.

Methods

Study sites

We selected two sites that represented typical transition habitat between pinyon – juniper woodlands and ponderosa pine forests of Arizona and New Mexico. One site was located on the Tusayan Ranger District of the Kaibab National Forest (hereafter, "Tusayan"), and a second site was on the Canjilon Ranger District on the Carson National Forest in New Mexico (hereafter "Canjilon"). The Tusayan site (lat. 36°01′24″N, long. 112°11′55″W) was located immediately south of Grand Canyon National Park and comprised approximately 770 ha. The Canjilon site (lat. 32°24′31″N, long. 106°31′31″W) was approximately 61 km northwest of Espanola, New Mexico on La Mesa de Las Viejas and was 409 ha in size. Although the two sites were not precisely similar in terms of climate, soils, and management history, we felt they were representative of upper ecotone sites with sedimentary soils and mostly low-shrub understory vegetation.

Tusayan

The Tusayan site ranges 2005–2073 m in elevation with topography of relatively flat uplands dissected by shallow canyon draws. Annual precipitation averages 430 mm and occurs bimodally, falling mainly as snow in winter (December–March) and rain in summer (July–September) (Western Regional Climate Center 2006). Annual maximum and minimum temperatures average 17 and 0 °C, respectively. Terrestrial Ecosystem Survey (TES) descriptions (USDA Forest Service 1991) indicate that soils at the site are mainly typic eutroboralfs, lithic haploborolls, and typic haplustalfs formed in residuum from limestone and sandstone parent material. Overstory tree species are primarily pinyon pine, Utah juniper, ponderosa pine, and Gambel oak (*Quercus gambelii* Nutt.).

Pinyon–juniper woodlands are present on the upland sites (approximately 80% of the total area), and ponderosa pine forests occupy the canyon draws as well as locations along the western and eastern edges of the study area (approximately 20% of the area). Florist variability is likely a result of microclimate and soil differences (USDA Forest Service 1991). Understory shrubs present included big sagebrush (*Artemisia tridentata* Nutt.), Mexican cliffrose (*Purshia mexicana* (D. Don) Henrickson), and Apache plume (*Fallugia paradoxa* (D. Don) Endl. ex Torr.).

Resource use and management activities over the last 130 years at the Tusayan site have varied. Intensive grazing by domestic livestock in the late 1800s and early 1900s is known to have occurred throughout the area (Miller 1921; Olberding et al. 2005). No livestock have grazed the site since 1996, although severe overstocking had been noted for several decades prior to this time (D. Brewer, US Forest Service, personal communication). Ponderosa pine stumps and a few old log decks observed at the site indicate there was a timber harvest that probably occurred around 1930, when logging railroads reached the area (Putt 1995). Fuelwood harvesting of dead and down pinyon and juniper trees has been an on-going yet minor use of the site over the last 10–20 years. Small wildfires have occurred on the site in the last 35 years (see Results), and a prescribed fire intended to reduce surface fuels 30%–70% was implemented in 1993 across approximately half the study area. Based on our observations, this burn mainly consumed dead and downed fuels but only minimally affected tree density.

Canjilon

Similar to the Tusayan site, vegetation at the Canjilon site is transitional between ponderosa pine forests and pinyon–juniper woodlands. Elevation ranges from 2347 m along the eastern study site boundary to 2438 m at the southwestern edge. The eastern boundary is the abrupt edge of La Mesa de Las Viejas. Annual precipitation averages about 388 mm with a pronounced peak of occurrence July–September (Western Regional Climate Center 2006). Annual maximum and minimum temperatures average 17 and –2.7 °C, respectively. TES descriptions (USDA Forest Service 1987) indicate that soils are mainly typic ustochrepts, typic eutroboralfs, and typic haplustalfs derived from various parent materials including shale. Overstory tree composition is dominated by pinyon pine and Rocky Mountain juniper (*Juniperus scopulorum* Sarg.), particularly along the eastern boundary. Ponderosa pine and Gambel oak communities dominate the lower northwestern edge as well as an area along the southern boundary. Understory shrub communities are made up of big sagebrush, mountain mahogany (*Cercocarpus montanus* Raf.), and rubber rabbitbrush (*Ericameria nauseosa* (Pallas ex Pursh) Nesom & Baird). Historical land use at the Canjilon site is not well known, although Native American and Hispanic activities are likely to have influenced woodland structure and dynamics to some extent before the late 19th century (Allen 2002). More recently (ca. 1951), efforts were made to rehabilitate overgrazed land on La Mesa de Las Viejas (Scurlock 1998).

Charred tree evidence and fire scar sampling

To identify areas of fire activity, we mapped charred tree structures (hereafter called "charred trees") at each site using 100 m wide belt transects. At the Tusayan site, the abundance of charred structures within the 1993 prescribed fire area forced us to limit our surveys to outside the boundary of the burn. We used transects to systematically survey 50% of the total area (i.e., transects were spaced 100 m apart) outside the burn, and spatial coordinates were recorded for each charred tree found within the belts. At the Canjilon site, we conducted a complete census (100% of the study area) of charred trees using these transects.

In addition to mapping charred trees, we made use of the transects to search for fire-scarred trees. Spatial coordinates, species, diameter, condition, and number of apparent fire scars were recorded for each scarred tree found within the belts. We used these data to help target scarred trees for fire scar collection. To gain as large a sample size as possible, we also searched areas not sampled by transects (i.e., within the 1993 prescribed burn and intertransect areas at Tusayan). Live and dead trees with multiple lesions and visible charring were targeted, and partial cross-sections were collected using chainsaws. For each sample collected, data regarding spatial location, slope and aspect of the microsite, species, condition, location of the sample, and number of visible scars were recorded. Samples were brought back to the laboratory for fire interval analysis (Arno and Sneck 1977). In the laboratory, samples were glued to plywood mounts and sanded with fine-grit sandpaper until ring structure was clearly visible under magnification. We collected 120 and 66 partial cross-sections at the Tusayan and Canjilon sites, respectively (Table 1).

Sampling woodland structure

To examine woodland structural characteristics, we systematically established sample plots on 200 m × 200 m grids at both sites. Sample plots were circular and 0.04 ha (11.28 m radius) in size. In total, we established 182 and 106 plots at Tusayan and Canjilon, respectively. On all plots, live and dead pinyon and juniper trees ($\geq$1.37 m in height) were measured for diameter at root collar (DRC, measured at ground level) and examined for charcoal and (or) fire scars. Diameter of each stem was measured for multiple-stemmed trees. Live ponderosa pine and Gambel oak trees were measured for diameter at breast height (DBH, measured at 1.37 m above ground), whereas dead trees of these species were measured at 40 cm above root collar (DSH, diameter at stump height). At both sites, increment cores were collected from pinyon trees at DSH to determine their ages. At Tusayan, cores were collected from all trees greater than 25 cm DRC and from a 20% random sample of smaller trees on 48 randomly selected plots. At Canjilon, cores were collected from a 20% random sample of all live trees on plots.

Modern fire records

Fire records were collected from US Forest Service archives to describe characteristics of modern fires and make comparisons with historical evidence. Records available were in both electronic (geographical information system) and paper form, and data collected included location, date, size class, cause, and fire name. For Tusayan, records from as early as circa 1940 were available. For Canjilon, the ear-

Table 1. Number of partial tree cross-sections collected for composite fire scar analysis at Tusayan and Canjilon (values in parentheses are the number of samples that were dendrochronologically crossdated).

			Dead			
Site	Species[a]	Living	Standing	Down	Stump	Total
Tusayan	JUOS	2 (0)	4 (0)	0 (0)	0 (0)	6 (0)
	PIED	7 (3)	2 (0)	8 (3)	1 (0)	18 (6)
	PIPO	21 (12)	7 (4)	16 (2)	52 (19)	96 (37)
	Total	30 (15)	13 (4)	24 (5)	53 (19)	120 (43)
Canjilon	JUSC	9 (0)	2 (0)	0 (0)	3 (1)	14 (1)
	PIED	13 (4)	4 (2)	1 (0)	5 (3)	23 (9)
	PIPO	10 (7)	5 (2)	0 (0)	8 (5)	23 (14)
	QUGA	0 (0)	1 (0)	0 (0)	0 (0)	1 (0)
	Total	32 (11)	12 (4)	1 (0)	16 (9)	61 (24)

[a] Species codes: JUOS, Utah juniper; PIED, pinyon pine; PIPO, ponderosa pine; JUSC, Rocky Mountain juniper; QUGA, Gambel oak.

liest fire records were from circa 1970. These data served as points of reference for interpreting other evidence such as charred trees and fire scars.

Analysis

Charred tree distribution

We analyzed spatial patterns of charred trees using χ^2 goodness-of-fit tests (Devore and Peck 1986). At each site, expected abundance for an even distribution of charred trees across TES units was tested against observed amounts. Statistically significant differences were indicated when χ^2 exceeded upper-tail critical values (significance level ≤0.05).

Fire intervals

To determine surface fire frequency, we conducted a composite fire interval analysis as described by Arno and Sneck (1977). Fire scars on partial cross-section samples were crossdated using local master chronologies (Stokes and Smiley 1996). Accuracy of crossdating was verified using the computer software COFECHA (Grissino-Mayer 2001). Composite fire return intervals were determined for the set of all scars as well as for only the fire years that occurred on 10% or more of the samples. The 10% filter corresponds with increasing size and (or) intensity of fires, removing the fire dates represented by only one or a few samples (Swetnam and Baisan 1996). Fire interval analysis started from the earliest fire date observed on our samples. We used FHX2 software (Grissino-Mayer 1995) to generate Weibull median probability intervals (WMPI), and mean fire interval (MFI) statistics for the presettlement periods (before 1887 and 1890 for Tusayan and Canjilon, respectively). The filtered analyses resulted in WMPI that were nearly identical to those of unfiltered analyses. We therefore only report fire return interval statistics from the set of all crossdated fire scars.

We also determined point fire intervals for samples showing two or more fire scars (Brown et al. 2001). Mean point fire intervals (MPFI) were calculated as the average of the number of tree rings present between scars on individual samples. MPFI values were determined for crossdated ponderosa pine and pinyon fire scars. Ring counts were used to determine MPFI values for pinyon and juniper fire scars that could not be reliably crossdated. MPFI were placed into broad interval classes (1–25, 26–100, 101–300, and >300 years) by species to account for errors related to false and missing rings. Trends were investigated using frequency histograms.

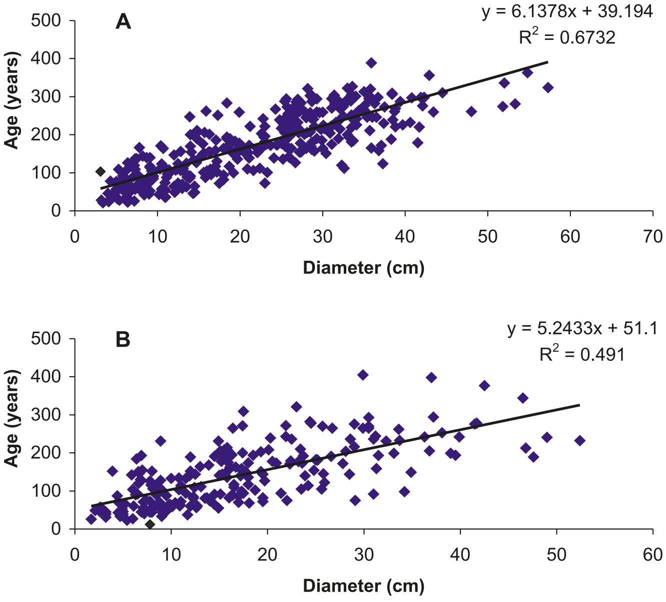
Structural conditions

Species importance values were determined for overstory trees on plots as described by Husch et al. (2003). Species importance was calculated as the relative proportion of density (TPH, trees per hectare) plus the relative proportion of basal area (BA) represented by each species. Thus, an importance value of 200 would indicate complete dominance by a given species on a plot (i.e., 100% of the total TPH + 100% of the total BA).

Similar to fire scar samples, increment cores from pinyon trees were crossdated using standard dendrochronology techniques (Stokes and Smiley 1996). We used crossdated cores (N = 363 and 215 for Tusayan and Carson, respectively) to develop diameter–age relationships and create stand age maps. We focused on pinyon pine for the following reasons: (*i*) its sample size was greater than juniper species; (*ii*) it was well distributed across the study sites; and (*iii*) its cores could be crossdated. In addition, pinyon is relatively intolerant of fire, so the oldest pinyon trees in an area are likely to represent the minimum time since the last lethal fire (West 1999). Tree age–diameter relationships were analyzed using simple linear regression (α = 0.05) (Fig. 1). Equations derived from these analyses were then used to estimate ages of trees for which no cores were collected. We considered pinyon ages predicted in this way to be underestimates of true tree age, since increment cores were collected at 40 cm above the ground. We used maximum pinyon age on plots to create stand maps (see GIS analysis) and assess landscape structural patterns that may have arisen from historical wildfires.

To evaluate stand-replacing fire cycles for pinyon–juniper communities at the sites, we selected plots where ponderosa pine importance was less than 50 (i.e., only plots where pinyon and juniper trees dominated). We tested the fit of maximum pinyon age data from these plots to negative exponential and Weibull models as described by Johnson and Gutsell (1994). When data did not significantly fit either

Fig. 1. Age–diameter relationships used to predict tree ages for pinyon pine at (A) Tusayan and (B) Canjilon.



model, we estimated fire rotation by examining cumulative plot age distributions. We followed the example of Floyd et al. (2004) and interpreted fire rotation as the number of years encompassed by the standing pinyon ages and thus the time over which the entire area may have burned (i.e., fire cycle). This approach assumes that fire is an episodic stand-initiating process, although other factors such as insects and drought also are likely to cause patch-scale mortality (Baker and Shinneman 2004). It should be noted that data resolution is likely to affect model fit. We used 10, 50-year age classes in these analyses for reasons described below (see GIS analysis).

GIS analysis

To examine spatial patterns of age structure and fire evidence, we used the Spatial Analyst extension for ArcView GIS to construct surface maps of maximum pinyon age on plots (McCoy and Johnston 2001). Cell values between plots were estimated using inverse distance weighted (IDW) interpolation. Because our sample plots were 0.04 ha in size and spaced on a regular 200 m grid across the study sites, we used a 20 m cell size and a 250 m fixed radius cell neighborhood as interpolation parameters. Cells of interpolated surfaces were reclassified into 50-year age classes to account for tree age errors and to identify broad cohorts that may have established after disturbance such as fire. We analyzed landscape characteristics of the maps using the FRAGSTATS extension of ArcView designed for raster GIS coverages (McGarigal and Marks 1995). We summarized the following landscape metrics: total class area, number of patches per class, and mean patch size. Additionally, we overlaid locations of fire-charred tree structures and partial cross-section samples on these maps to provide greater insight into historical fire patterns.

Results

Charred trees and fire scar evidence

Charred tree structures were found across the Tusayan site near older as well as younger stands (Fig. 2). χ^2 tests indicated significantly ($P < 0.001$) different abundances of charred trees than expected for an even distribution among TES mapping units (Table 2). Pinyon–juniper units had 36% fewer charred trees than expected, whereas two of three ponderosa pine units showed almost twice as many as expected. Charred trees were primarily found as isolated individuals; we did not find extensive cohorts of standing dead (or downed) trees that indicated large lethal fire events.

At Tusayan, we were able to crossdate 36% ($N = 43$) of the collected fire scar samples. Of the crossdated samples, 86% were from ponderosa pine and 14% were from pinyon pine. All crossdated fire scars were collected within TES units dominated by ponderosa pine, thus composite fire intervals represented approximately 235 ha, or 30% of the total study site area (Table 2). On these microsites, the highest number of recorded presettlement (i.e., before 1887) fires occurred in the 1600s. Although scars indicated numerous fires throughout the 1600s and 1800s, a gap in the fire record between 1680 and 1805 was observed. Twelve post-settlement fires (i.e., 1887–2004) were noted. Based on all crossdated scars, presettlement MFI was 10.9 years, and WMPI was 7.2 years (range = 1–64 years) (Fig. 3).

We were not able to crossdate juniper (*J. osteosperma*) wood, although we did collect six scarred samples. Four juniper trees that showed scars from repeated nonlethal fire were located along the edges of ponderosa pine stands; no such samples were found on upland microsites within the pinyon–juniper woodlands. Presettlement mean point fire intervals (MPFI) on all ponderosa and pinyon pine trees were ≤100 years; 36% of ponderosa MPFI and 50% of pinyon MPFI values were ≤25 years. MPFI values for juniper were all ≥26 years, but half of these were ≥100 years (Fig. 4).

Similar to Tusayan, charred trees at Canjilon were found throughout the site, although significantly ($P < 0.001$) more charred trees than expected were found within ponderosa pine dominated TES units (Table 2). A group of charred trees was found on the eastern edge of the study site near the rim of Mesa de Las Viejas (Fig. 2).

At Canjilon, we were able to crossdate 39% ($N = 24$) of the collected fire scar samples (Table 1). Of the crossdated samples, 58% were from ponderosa pine, 37% were pinyon pine, and one juniper (*J. scopulorum*) sample was crossdated (Table 1). Although less distinct than at Tusayan, fire scars at Canjilon were found mainly on microsites dominated by ponderosa pine. Composite fire intervals at Canjilon represented approximately 99 ha, or 24% of the total study site area (Table 2). No fire-scarred trees were found within the pinyon–juniper woodlands occupying the eastern portion of the study site (Fig. 2). The greatest number of presettlement (i.e., before 1890) surface fires occurred in the 1600s (6 fire years). Similar to Tusayan, data showed two noticeable gaps in the fire record; one was from 1665 to 1755, and the other was from 1805 to 1875. Eight fire years were found for the postsettlement period (i.e., 1890–2005). For all crossdated scars, presettlement MFI at Canjilon was 22.5 years, and WMPI was 11.1 years (range 1–94 years) (Fig. 3).

Fig. 2. Maps of maximum pinyon pine age across (A) Tusayan and (B) Canjilon study sites. Locations of charred trees, fire scar samples, and point interval samples are shown. Contours are 10 m intervals. At Tusayan, charred trees were only mapped outside the 1993 prescribed fire area.

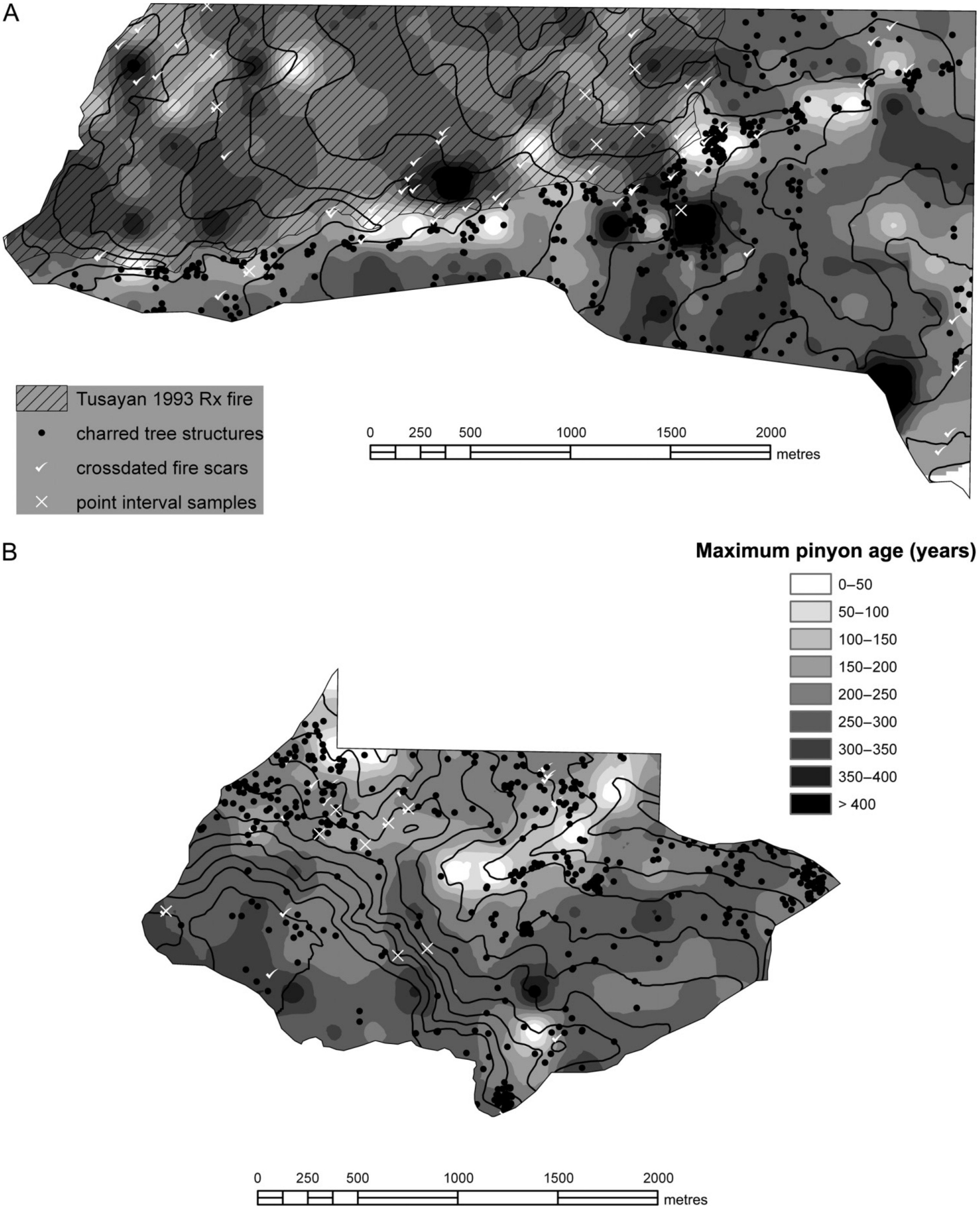


Table 2. χ^2 tests of charred tree abundance by Terrestrial Ecosystem Survey map units.

					Charred trees (no.)			
Site	Map unit	Overstory[a]	Hectares	Area (%)	Expected	Observed	χ^2	*P*
Tusayan[b]	0272	PIED-JUOS-QUGA	168	42	222	142	28.7	
	0275	PIPO-PIED-QUGA	90	22	119	216	79.5	
	0276	PIPO-PIED-QUGA	8	2	11	20	8.4	
	0283	PIPO-PIED-QUGA	137	34	181	154	4.0	
	Sum		403	100	532	532	120.6	<0.001
Carson								
	119	PIED-JUMO-QUGA	250	61	428	250	74.3	
	157	PIED-JUMO-QUGA	61	15	105	22	65.2	
	162	PIPO-PIED-QUGA	99	24	170	433	408.8	
	Sum		412	100	706	706	548.3	<0.001

Note: Data from USDA Forest Service 1987, 1991. We found no *J. monosperma* during our surveys; the overwhelming majority of juniper observed was *J. scopulorum.*

[a] Species codes: PIED, *Pinus edulis*; JUOS, *Juniperus osteosperma*; QUGA, *Quercus gambelii*; PIPO, *Pinus ponderosa*; JUMO, *Juniperus monosperma* (see note above).

[b] Charred tree comparisons at Tusayan were done for areas outside of the 1993 prescribed fire.

A limited number (N = 5) of junipers were found with multiple fire scars. The vast majority (86%) of ponderosa pine samples showed MPFI values ≤100 years. All pinyon pine MPFI values were ≥26 years, but 33% of these were ≥101 years. In contrast, 60% of juniper MPFI values were ≥100 years (Fig. 4).

Stand ages and fire rotation

Approximately 80% of the Tusayan landscape was made up of patches (i.e., cells with similar interpolated values) where the oldest pinyon trees were ≥200 years old (Fig. 2; Table 3). The 250- to 300-year class made up the largest proportion (36%) of the study area and had the largest mean patch size (30 ha) (Table 3). Mean patch sizes of all other age classes were <5 ha except for the 200- to 250-year class (13 ha). Pinyon stands with maximum age ≤150 years were generally found on mixed ponderosa pine – pinyon–juniper microsites (i.e., ponderosa pine importance values were ≥50).

Standing age class distribution for pinyon- and juniper-dominated plots (i.e., ponderosa importance <50) at Tusayan did not significantly fit a negative exponential or Weibull model. Analysis of the cumulative plot age distribution suggested that fire rotation was 340 years during the period 480–140 years before our sampling date (1524–1864) (Fig. 5). On pinyon- and juniper-dominated plots, maximum pinyon age was >140 years, although it was not clear whether this indicated a recent shift in fire frequency.

Canjilon showed a narrower range of patch ages and generally greater mean patch size than Tusayan (Table 3). The oldest patches (>250 years) were located at the upper elevations, while young patches were near a prominent big sagebrush meadow in the center of the study area (Fig. 2). Similar to Tusayan data, age distribution for pinyon- and juniper-dominated (i.e., ponderosa importance <50) plots at Canjilon did not significantly fit a negative exponential or Weibull model. Analysis of the cumulative plot age distribution indicated a fire rotation of 290 years during the period 420–130 years before our sampling date (1585–1875) (Fig. 5).

Modern fires

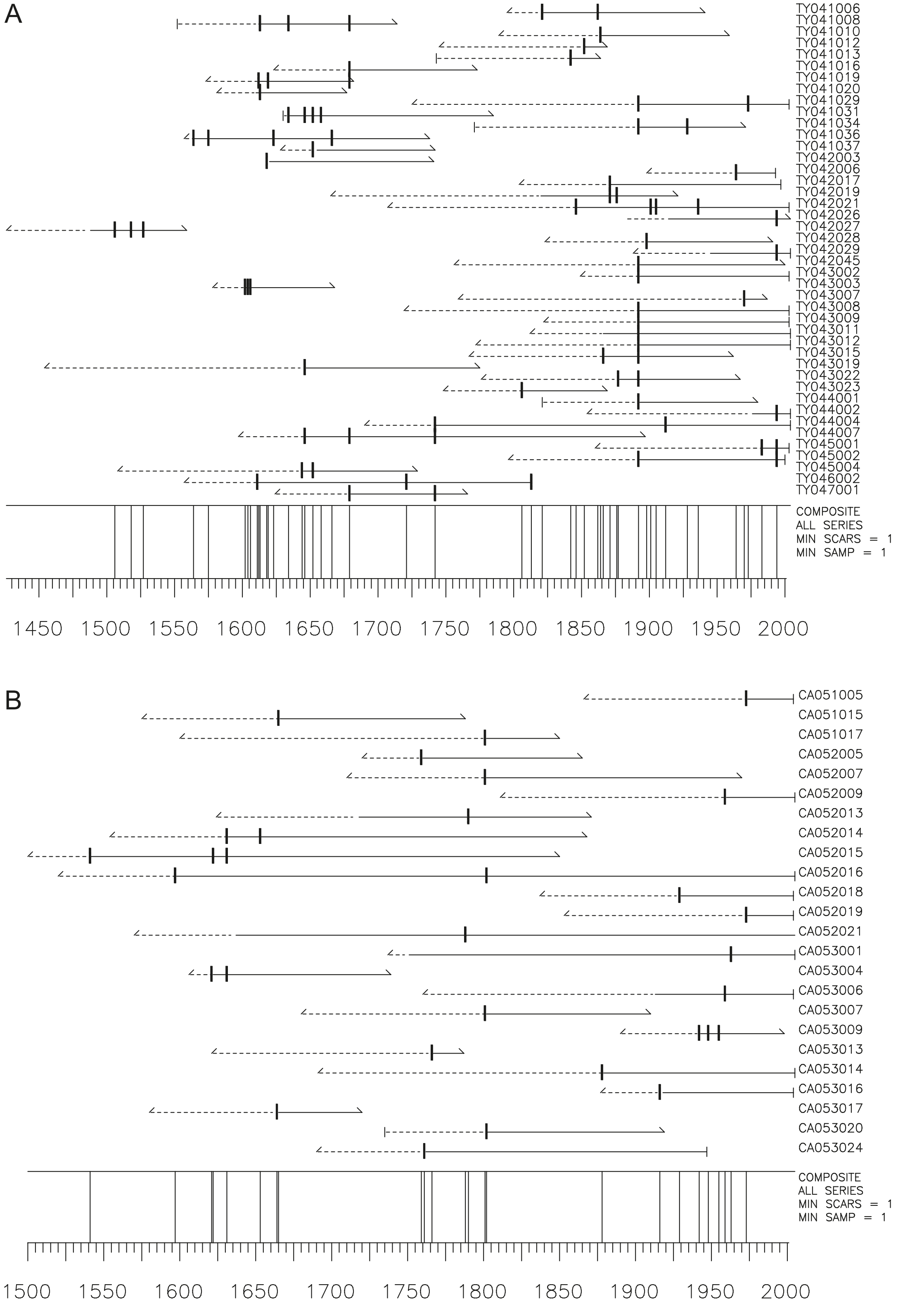
US Forest Service records indicated 16 fires at Tusayan from 1970 to 2004. Twelve of the fires were caused by lightning, and the rest were caused by human activity. Nine fires had occurred early to mid summer, and the rest were in late season. No fires were greater than 4 ha in size, and most (94%) were less than 0.25 acre (1 acre = 0.4047 ha). Canjilon records indicated four fires occurring from 1975 until 2005. All fires at Canjilon were caused by lightning, and three occurred in early summer. None of the fires were greater than 0.25 acre in size.

Discussion

Historical surface fires in ponderosa pine stands

Fire scars indicated that surface fires recurred at intervals of 7.2–7.4 years (WMPI) (MFI, 10.9–11.6 years) and 11.1 (WMPI) (MFI, 22.5 years) in the ponderosa pine forest communities at Tusayan and Canjilon, respectively. These frequencies are somewhat longer than those reported for surface fire regimes in ponderosa pine forests at other sites in northern Arizona (Swetnam and Baisan 1996; Fulé et al. 2003). In our study, relatively long fire-free gaps were encountered at both sites, which certainly increased fire return interval estimates. Shorter gaps, especially associated with the transition from the late 18th to early 19th centuries have been reported elsewhere in southwestern North America (e.g., Stephens et al. 2003), and there is some evidence of inter-hemispheric links between altered fire frequencies in North and South American forests (Kitzberger et al. 2001, 2007). However, the gaps we observed in the fire record are not linked in time to periods identified by other researchers. Instead, we suspect that they represent the relatively limited availability of fire-scarred ponderosa pines at the ecotone. Similar WMPI values between the set of all scars and analysis of only the fire years that occurred on 10% or more of the samples provided further support for this conclusion. Several postsettlement fires were noted in fire scars from both sites. These were likely the result of human activities including prescribed burning (H. McRae, US Forest Service, personal communication). Because of gaps in the fire scar

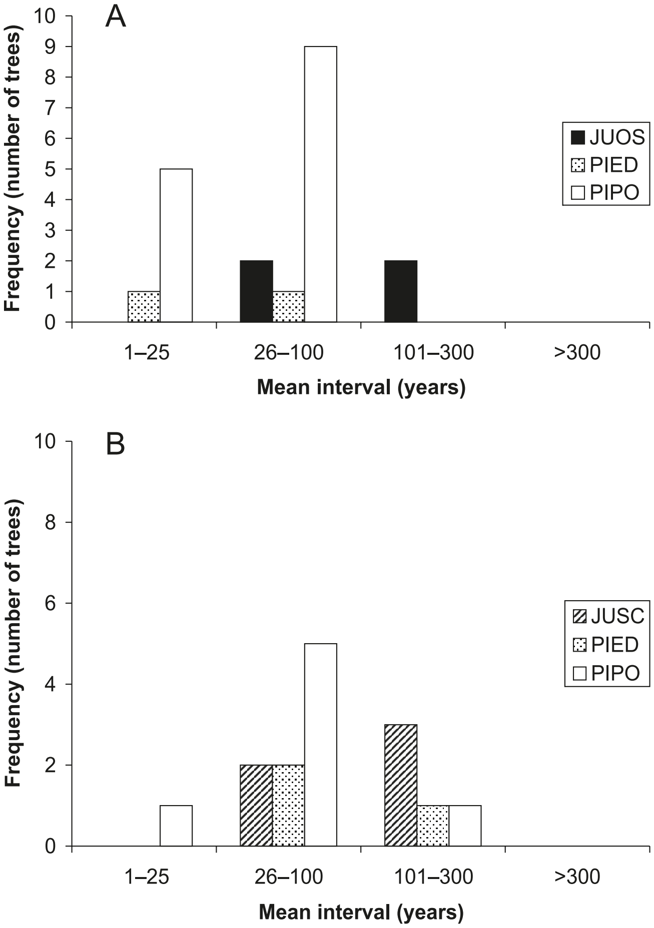
Fig. 3. Composite fire histories for (A) Tusayan and (B) Canjilon showing years for which fire scars (vertical lines) were found on all partial cross-sections (horizontal lines).



records and the occurrence and postsettlement fires at both sites, we could not clearly determine whether fire regimes had substantially changed between pre- and post-settlement periods.

At Tusayan, fire scars were encountered in lowland arroyos and canyons occupied by ponderosa pine stands. At Canjilon, fire scars were found primarily within the ponderosa pine stands along the western portion of the study

Fig. 4. Distribution of point fire interval means by species for tree cross-sections collected at (A) Tusayan and (B) Canjilon. Species are Utah juniper (JUOS), pinyon pine (PIED), ponderosa pine (PIPO), and Rocky Mountain juniper (JUSC).



site. No scars were found at the lower elevations or within the pinyon- and juniper-dominated areas of the eastern portion of the Canjilon site. Spatial location and species composition of fire scar samples suggested that historical fires did not spread far from ponderosa pine stands into pinyon–juniper woodlands at either site. Thus, composite intervals probably did not reflect pinyon–juniper fire frequencies. This conclusion was also supported by lower than expected numbers of charred trees in pinyon–juniper communities as well as a limited number of juniper scars; these were found only at the edges of ponderosa pine communities at Tusayan. Mean point fire intervals (MPFI) of scarred juniper, although determined from ring counts, appeared longer than those of pinyon and ponderosa. Broad MPFI classes were used to make up for errors due to false and (or) missing rings, and these samples were of limited value for reconstructing precise fire intervals. They did, however, demonstrate that multiple nonlethal surface fires may be recorded by these species (*J. osteosperma* and *J. scopulorum*) and are one line of evidence often discounted in studies of historical fire patterns in these ecosystems (but see Young and Evans 1981). Brown et al. (2001) reported MPFI ranging 10–49 years for 19 fire years recorded on seven fire-scarred pinyon trees in the Sacramento Mountains of New Mexico. The possibility of fire scar occurrence on pinyon and juniper trees suggests that fire frequency estimates based on samples from fire-resistant species should be viewed cautiously. For example, previous studies have interpreted fire intervals of 7–20 years for pinyon–juniper woodlands based on analysis of scars collected from ponderosa pine trees (Miller and Rose 1999; Perryman and Laycock 2000). Perhaps in many cases, scarcity of fire scars in pinyon–juniper communities indicates infrequent, lethal fire regimes (Floyd et al. 2004). At our sites, we found a lack of support for the hypothesis that surface fires were common in pinyon–juniper woodlands adjacent to ponderosa pine forests (Romme et al. 2003). We were not able to investigate factors related to the apparent abrupt differences in fire regimes between the ponderosa pine and pinyon–juniper communities. Microclimate and soil differences, and their effects on vegetation cover and fuel characteristics, were undoubtedly important in determining the patterns we observed (Romme et al. 2003).

Heterogeneity of stand ages

Stand age maps, patch analysis, and plot age class distributions indicated that widespread lethal fires were not an aspect of the pinyon–juniper fire regime at either site for at least 400 years. Rather, we found converging lines of evidence to suggest that relatively small patch-scale events were historically important. Patches with similar maximum pinyon ages were generally small, and a broad range of stand age classes were found. At Canjilon, small lethal fires may have occurred near the eastern boundary, where we found concentrated numbers of charred trees, and pinyon stands were relatively young (Fig. 2). Pinyon trees at both sites were up to ~450 years old. Floyd et al. (2008) reported similar fine-grained landscape patterns in pinyon–juniper woodlands of southern Utah, with trees up to 600 years old interspersed with younger stands <10 ha in size. These patterns were attributed to combined factors of soil texture, topography, and fire occurrence (Floyd et al. 2008). At our sites, scattered charred trees indicated that fire ignitions were not historically limiting but did not lead to widespread tree mortality. In contrast, Brown et al. (2001) concluded that severe fire within the last century produced numerous dead and downed trees, stands of mainly young trees, and an absence of old trees. Similarly, Arnold et al. (1964) described a large area with numerous charred juniper snags near Supai, Arizona (west of our Tusayan study site). It should be noted that charred structures do not necessarily indicate tree mortality per se. Charred trees could result from snags that have burned (i.e., trees that are dead before the fire occurs). In fact, widespread mortality events related to drought and insect outbreaks have occurred at various southwestern sites the past century (Betancourt et al. 1993; Breshears 2005).

Large infrequent crownfires are thought to represent natural fire regimes of pinyon–juniper woodlands in some parts of the Southwest (Arnold et al. 1964; Baker and Shinneman 2004). For example, Floyd et al. (2000) estimated pinyon–juniper and shrubland fire rotations were ∼400 years at Mesa Verde National Park in Colorado. In another study at Mesa Verde, Floyd et al. (2004) described stand-replacing

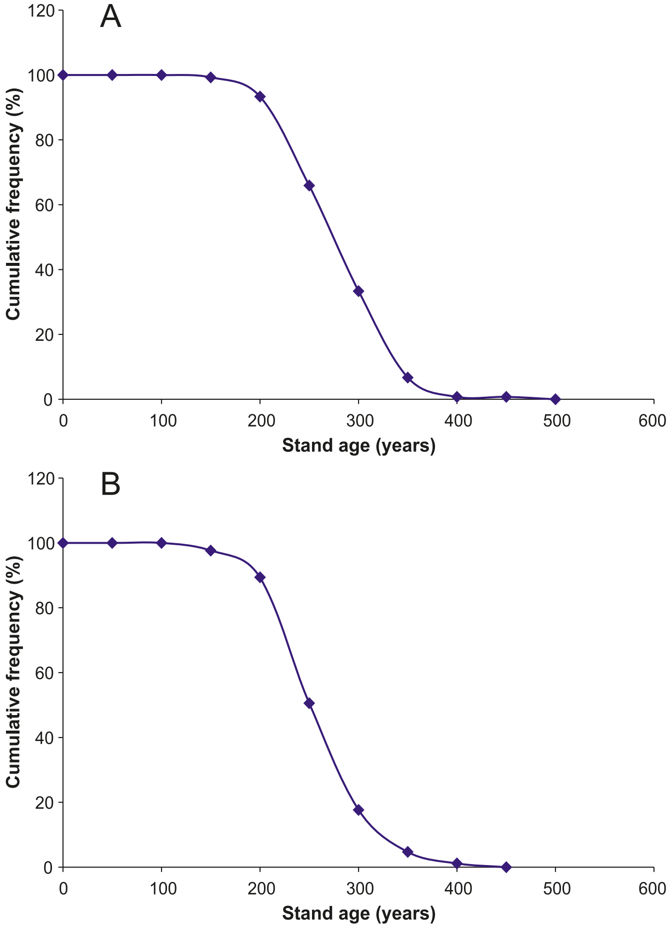
Table 3. Landscape structure of Tusayan and Canjilon sites based on interpolation of maximum pinyon pine age.

		Land area (ha)		Patches	
Site	Age (years)	Extent (ha)	Percentage[a]	Number	Size[b] (ha)
Tusayan	0–50	6.84	0.93	9.00	0.76 (0.15)
	50–100	14.64	1.98	12.00	1.22 (1.04)
	100–150	32.80	4.44	16.00	2.05 (1.77)
	150–200	86.64	11.73	23.00	3.77 (3.95)
	200–250	194.68	26.35	14.00	13.91 (19.81)
	250–300	267.28	36.18	9.00	29.70 (46.73)
	300–350	108.20	14.65	33.00	3.28 (4.33)
	350–400	15.84	2.14	15.00	1.06 (0.65)
	>400	11.88	1.61	5.00	2.38 (1.40)
Canjilon	0–50	0.00	0.00	0.00	—
	50–100	0.00	0.00	0.00	—
	100–150	5.04	1.23	3.00	1.68 (1.05)
	150–200	42.08	10.28	7.00	6.01 (6.60)
	200–250	166.48	40.68	7.00	23.78 (45.40)
	250–300	159.16	38.89	2.00	79.58 (74.86)
	300–350	32.48	7.94	11.00	2.95 (4.81)
	350–400	3.44	0.84	5.00	0.69 (0.75)
	>400	0.60	0.15	1.00	0.60 (0.00)

[a] Percentage of total landscape area.

[b] Mean patch size (SD).

Fig. 5. Cumulative standing age distributions for (A) Tusayan and (B) Canjilon as determined by maximum pinyon pine age.



fires that burned areas of up to 3461 ha in the early 1800s. In these studies, Floyd et al. (2000, 2004) used multiple lines of evidence, including delineation of historic fire perimeters, stand age analysis, and Gambel oak sprout dendrochronology, to interpret fire history. In our study, we used cumulative pinyon age class distributions to estimated fire rotations. Similar to the methods of Floyd et al. (2004), we calculated fire rotation as the time required to burn our sites, as indicated by the number of years encompassed by standing cohorts. Our estimates of fire rotation at Tusayan and Canjilon were 340 and 290 years, respectively. From this, and evidence described above, we concluded that infrequent fire cycles were made up of fires of limited extent. Our fire rotation estimates were considerably lower than those reported by Floyd et al. (2000, 2004). Further, we were not able to identify areas that may have reburned, which would have resulted in even lower fire rotation estimates.

Although this study increased our understanding of historical fire patterns in ecotonal pinyon–juniper woodlands, we identified a number of limitations. For example, we were not able to clearly determine whether historical fire regime characteristics had changed since Euro-American settlement, although fire suppression is thought to have had minimal effects on infrequent fire types (Romme et al. 2003). In addition, it was clear that stand age estimated minimum time since lethal fire; however, pinyon establishment after severe fires in these systems can require decades (Arnold et al. 1964; Erdman 1970). Further, we could not be sure that other mortality factors such as drought and insects were not responsible for initiating stands. Finally, we were not able to determine several other important fire regime characteristics (e.g., fire severity, fire intensity), and links between fire occurrence and climate were not investigated.

Implications

Fire undoubtedly influenced historical structure and function of the pinyon–juniper ecosystems at our study sites. However, there is still great uncertainty surrounding historical processes across the range of this type, and fire regimes appear to be highly variable (West 1999; Baker and Shinneman 2004). In this study, we used multiple lines of evidence and intensive sampling to elucidate fire and landscape patterns at two sites representing pinyon–juniper communities at upper ecotones with ponderosa pine forests. Such ecotones are common on landscapes of the Southwest and thus account for a meaningful fraction of the variability in this region's pinyon–juniper ecosystems. More work is needed at similar sites to fully describe fire regimes of these complex environments. Such information can help land managers to develop sound, science-based management strategies for conservation and ecosystem management.

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