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Research article

Mixed-severity fire regime in a high-elevation forest of Grand Canyon, Arizona, USA

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Abstract

Fire regime characteristics of high-elevation forests on the North Rim of the Grand Canyon, Arizona, were reconstructed from fire scar analysis, remote sensing, tree age, and forest structure measurements, a first attempt at detailed reconstruction of the transition from surface to stand-replacing fire patterns in the Southwest. Tree densities and fire-/non-fire-initiated groups were highly mixed over the landscape, so distinct fire-created stands could not be delineated from satellite imagery or the oldest available aerial photos. Surface fires were common from 1700 to 1879 in the 4,400 ha site, especially on S and W aspects. Fire dates frequently coincided with fire dates measured at study sites at lower elevation, suggesting that pre-1880 fire sizes may have been very large. Large fires, those scarring 25% or more of the sample trees, were relatively infrequent, averaging 31 years between burns. Four of the five major regional fire years occurred in the 1700s, followed by a 94-year gap until 1879. Fires typically occurred in significantly dry years (Palmer Drought Stress Index), with severe drought in major regional fire years. Currently the forest is predominantly spruce-fir, mixed conifer, and aspen. In contrast, dendroecological reconstruction of past forest structure showed that the forest in 1880 was very open, corresponding closely with historical (1910) accounts of severe fires leaving partially denuded landscapes. Age structure and species composition were used to classify sampling points into fire-initiated and non-fire-initiated groups. Tree groups on nearly 60% of the plots were fire-initiated; the oldest such groups appeared to have originated after severe fires in 1782 or 1785. In 1880, all fire-initiated groups were less than 100 years old and nearly 25% of the groups were less than 20 years old. Non-fire-initiated groups were significantly older (oldest 262 years in 1880), dominated by ponderosa pine, Douglas-fir, or white fir, and occurred preferentially on S and W slopes. The mixed-severity fire regime, transitioning from lower-elevation surface fires to mixed surface and stand-replacing fire at higher elevations, appeared not to have been stable over the temporal and spatial scales of this study. Information about historical fire regime and forest structure is valuable for managers but the information is probably less specific and stable for high-elevation forests than for low-elevation ponderosa pine forests.

Introduction

The concept of fire severity, the effects of a fire on biota, is distressingly qualitative (Johnson and Miyanishi 2001) but very useful for ecologists and managers. Defining severity in terms of survival of dominant trees, the extremes are low-severity fire regimes where most trees survive (e.g., surface fires in ponderosa pine; Swetnam and Baisan 1996) and high-severity fire regimes in which most perish, initiating a new stand (e.g., crown fires in jack pine; Heinselmann 1973). In the southwestern USA, low- and high-severity fire regimes are often found in close proximity on steep elevational gradients. Grissino-Mayer et al. (1995) found frequent fire occurrence (mean fire interval [MFI] of 6.2 years) in an Arizona mixed conifer forest located below a spruce-fir stand that had not burned in > 300 years. In a similar example of abrupt differences in fire regime over a short distance, Stephens (2001) in California reported a MFI of 9 years in a Jeffrey pine stand and nearly 25 years in a fir-dominated stand located only 100 m away. The nature of the transition between low- and high-severity fire is poorly understood. A moderate-severity fire regime, intermediate in mortality, may exist in some circumstances (Agee 1993). However, heterogeneity in aspect, slope, and elevation at fine scales can influence differences in vegetation and fuel moisture, leading to topographically distinct burning patterns (Beaty and Taylor 2001). This alternative is a *mixed-severity* fire regime, where forest patches affected by low- and high-severity burning are closely juxtaposed.

The never-harvested forest on the North Rim of Grand Canyon National Park is an ideal site to measure fire regime transition. Frequent surface fires burned throughout ponderosa pine and lower mixed conifer forests of the canyon's North Rim on the Kaibab Plateau until disruption of the fire regime *circa* 1880 (Wolf and Mast 1998; Fulé et al. 2000 and in press). At higher elevation, White and Vankat (1993) used tree age data to show increased spruce-fir forest density since 1880. The North Rim has never been harvested and livestock grazing was excluded around 1938, affording a unique opportunity to assess forests over an elevational gradient in a near-natural setting (Fulé et al. 2002 and in press).

The appropriate sampling methods in a setting where fire regimes include both surface and canopy burning are a combination of fire-scar dates, age structure, and species composition of fire-initiated stands (Johnson and Gutsell 1994). All these approaches have strengths and limitations. Fire scars are precisely dated but they represent points on the landscape; age and species data are constrained by imprecision in stand boundaries, fire survivors within stands, imprecision of tree establishment date, immediacy of post-fire colonization, and interpretation of successional pathways (Johnson and Gutsell 1994; Swetnam and Baisan 1996; Swetnam et al. 1999; Baker and Ehle 2001). Recent studies in forests with mixed burning patterns have emphasized different aspects of methodological certainty. For instance, Kipfmueller and Baker (2000) calculated fire rotation (FR, the time required to burn an area equivalent to 100% of the study site), MFI, and mean point fire intervals (a per-tree measure of average intervals between fire scars) in a Wyoming lodgepole pine forest, suggesting that the composite MFI overestimated fire occurrence. Minnich et al. (2000) reconstructed twentieth century fire history in a Baja California mixed conifer forest from aerial photography, arguing that infrequent, severe fires regulated forest structure, rather than the more-frequent surface fires detected from fire scars. Taylor (2000) suggested a closer integration between MFI and FR data along a gradient from low-elevation Jeffrey pine to high-elevation mesic forests by showing that the mean point fire interval (i.e., fire interval on a per-sample basis) corresponded closely with FR values.

We applied multiple methods (fire scars, tree age and species, spatial patterns of forest stands) to measure spatial and temporal patterns of fire on the North Rim. Our first objective was to reconstruct fire regime characteristics across the transition from surface to stand-replacing fires, asking:

1. Did fire occurrence differ by aspect, elevation, and forest type at high elevation?
2. Were fire events synchronized between low-elevation and high-elevation sites?
3. Could severe fires be identified by detecting fire-initiated tree groups using remote sensing, tree age, or species composition data?

The second objective was to compare current forest conditions with forest structure at the onset of fire exclusion, *circa* 1880, asking:

1. What is the accuracy of forest reconstruction, compared with historical data?
2. What are the implications of forest structural change for future management?

Methods

Study area

Two sites were studied. The larger site was the upper mixed conifer and spruce-fir forests covering ~ 4,400 ha at Little Park, comprising the highest elevations on the Kaibab Plateau, up to 2,794 m (Figure 1). The Little Park site lay to the east of previously sam-

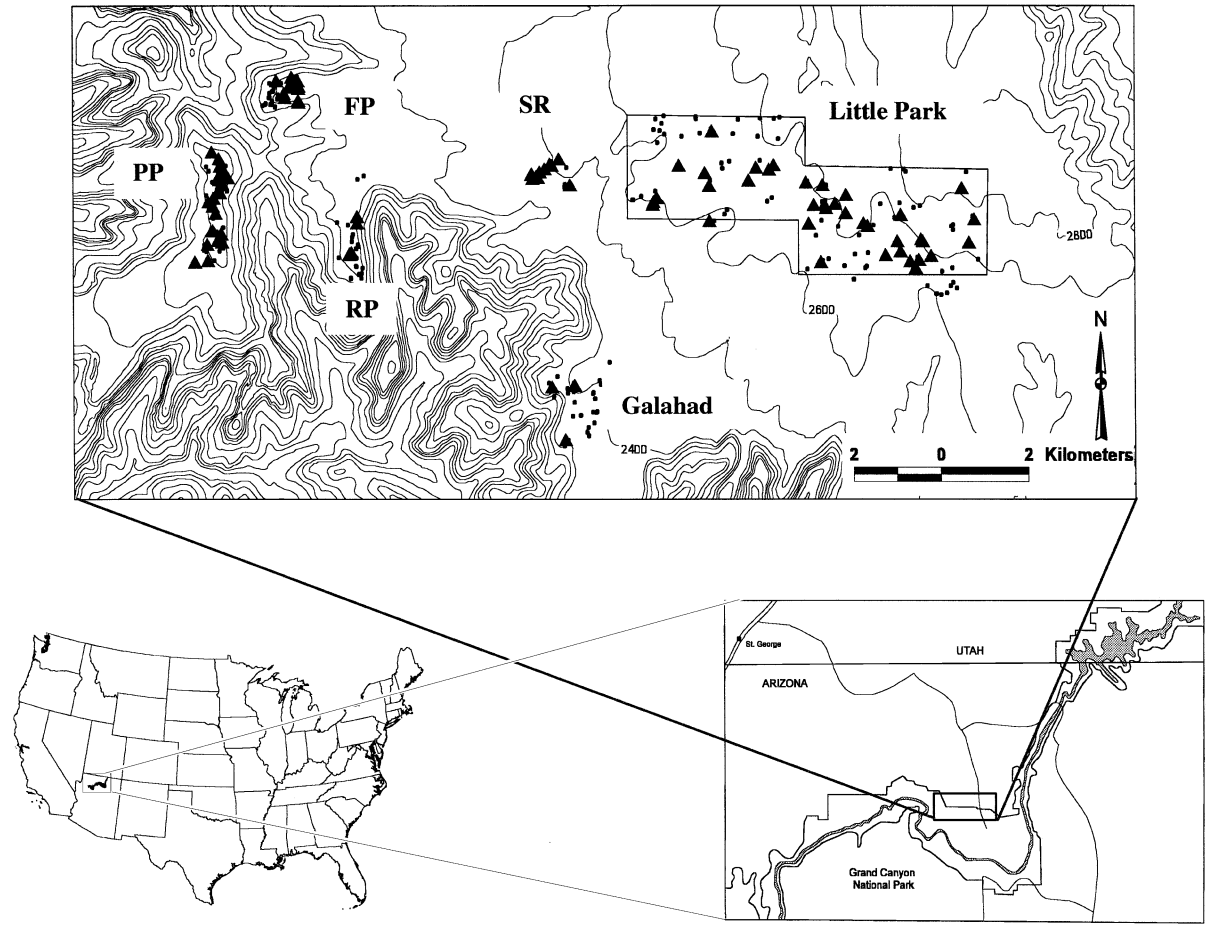

Figure 1. Study sites on the North Rim of Grand Canyon National Park. From west to east, sites are Powell Plateau (PP), Fire Point (FP), Rainbow Plateau (RP), Swamp Ridge (SR), Galahad Point, and Little Park. Forest structure and fire regimes of the first four sites were described by Fulé et al. (2002 and in press). Galahad and Little Park are described in this study. Symbols scattered across the study sites indicate locations of fire-scarred sample trees. Large triangles are trees that were scarred by fire in 1785. Smaller circles are trees not scarred in 1785. The contour interval is 100 m.

pled study sites (Fulé et al. 2002) ranging from Powell Plateau (PP), Fire Point (FP), and Rainbow Plateau (RP), each at ~2,300 m elevation, through Swamp Ridge (~2,500 m) (Figure 1). These sites are arranged west–east on an elevational gradient along the northern border of Grand Canyon National Park, permitting the comparison of fire regimes over the gradient. However, the prevailing summer winds are from the southwest, so fires might not necessarily be expected to burn from the low-elevation sites into Little Park. Therefore we added a second study site, Galahad Point, at the base of Kanabownits Canyon (~2,350 m elevation) (Figure 1). The 410-ha Galahad site lay directly downcanyon and upwind (i.e., SW) from Little Park, so fires at Galahad would be expected to burn toward Little Park. Adding the Galahad site allowed us to test whether fire dates differed among low-elevation sites southwest vs. due west of the high-elevation site.

Average annual precipitation at the North Rim ranger station (elevation 2,542 m) is 58 cm, with an average annual snowfall of 328 cm. Temperatures range from an average July maximum of 26 °C to an average January minimum of −2 °C (White and Vankat 1993). Soil information was derived from an ongoing soil survey (A. Dewall, National Resource Conservation Service, personal communication 2002). Soils at the Galahad site were Typic Paleustalfs. At the Little Park site, soil textures ranged from coarse to fine loams. Valley soils at the Little Park site were Cumulic Haplustolls, soils on 15–40% slopes

Table 1. Tree species found on sampling plots at Grand Canyon study sites.

Species	Common Name	Code
Abies lasiocarpa (Hook.) Nutt.	Subalpine fir	ABLA
Abies concolor (Gordon & Glendinning) Hoopes.	White fir	ABCO
Picea engelmannii Parry ex Engelm.	Engelmann spruce	PIEN
Picea pungens Engelm.	Blue spruce	Combined with PIEN
Pinus ponderosa var. *scopulorum* P. & C. Lawson	Ponderosa pine	PIPO
Populus tremuloides Michx.	Quaking aspen	POTR
Pseudotsuga menziesii (Mirb.) Franco var. *glauca* (Beissn.) Franco	Rocky Mountain Douglas-fir	PSME
Quercus gambelii Nutt.	Gambel oak	QUGA
Robinia neomexicana Gray	New Mexican locust	RONE

were Oxyaquic Paleustalfs, and flatter upland areas (2–15% slopes) were Cumulic Haplustolls.

Forests in the Galahad study site were dominated by ponderosa pine with Gambel oak and New Mexican locust (scientific names and species codes are given in Table 1). At Little Park, tree species included ponderosa pine, aspen, white fir, and subalpine fir. Engelmann and blue spruce were combined in this study because of difficulties in distinguishing young trees (Moore and Huffman (unpublished)) and our observation of trees at the study site that had characteristics intermediate between the two species. For the remainder of this paper, species codes are used to refer to individual tree species (e.g., ″PIPO″), while names of dominant tree species are used to refer to vegetation types (e.g., ″spruce-fir vegetation type″).

Field sampling

Fire-scarred trees were sampled in 2000 and 2001 to obtain an inventory of fire dates from scarred trees distributed across the study sites (Swetnam and Baisan 1996). The Galahad study site (410 ha) was systematically surveyed along parallel transects to search 100% of the site. At the much larger Little Park site (4,400 ha), fire-scarred trees were encountered predominantly on ridgetops and SW-S-SE aspects. These topographic features were completely traversed for sample collection. In addition, representative transects were sampled across northern aspects on each ridge. Trees with the longest and most complete fire records were selected, an example of ″targeted sampling″ (Baker and Ehle 2001). Samples were mapped when collected and were well-distributed throughout the study areas (Figure 1).

Forest sampling was carried out at the Little Park site. In many forests, sampling can be stratified by even-aged patches originating from fire (e.g., Johnson and Gutsell 1994). The first step was to attempt to identify such stands across the study area using current and the oldest available aerial photographs (1956), vegetation maps (Warren et al. 1982), data from adjacent stands (White and Vankat 1993), and field surveys. However, all these sources of information showed that forest structure at Little Park was highly diverse, suggesting a mixture of surface fire together with fire-initiated groups or patches that may have contained many fire survivors. Therefore we sampled on a systematic grid to capture forest age structure and species composition proportional to occurrence.

Sixty sampling plot centers were located systematically on a 600 m (E–W) by 1,200 m (N–S) grid. The shorter grid distance was chosen in order to measure with greater sampling density along the prevailing elevational gradient, roughly E–W. Vegetation was measured on plots based on the National Park Service's Fire Monitoring plots (Reeberg 1995), with modifications to collect detailed tree condition and dendroecological data. This plot design was chosen to correspond with NPS monitoring and because the relatively large plots are useful for capturing variability of clumps of old trees (Fulé et al. 1997). Sampling plots were 0.1 ha (20 × 50 m) in size, oriented with the 50-m sides uphill-downhill to maximize sampling of variability along the elevational gradient and to permit correction of the plot area for slope. Plots were permanently marked to permit re-measurements in the future. Iron stakes were sunk flush to the forest floor at the corners and center of each plot and a large tree was tagged with the distance and bearing to the plot center. Photos were taken at the corners and quarter-corners of each plot.

Trees larger than 15 cm diameter at breast height (dbh) were measured on the entire plot (1000 m^2) and trees between 2.5–15 cm dbh were measured on one quarter-plot (250 m^2); all trees were tagged. Tree attributes measured were: species, dbh, height, crown base height, dwarf mistletoe rating (0–6, Hawksworth and Geils (1990)), and tree condition. To assess changes in forest structure, we differentiated between trees established prior to 1880 and those that established later. Previous research in northern Arizona showed that ponderosa pines with dbh > 37.5 cm or ponderosa of any size with yellowed bark could be conservatively identified in the field as being of pre-1880 origin (White 1985; Mast et al. 1999). We used the same diameter breakpoint, 37.5 cm, for other conifers (Fulé et al. 2002) and > 20 cm for aspen trees. ″Conservative″ identification meant that these criteria included all pre-1880 trees as well as numerous post-1880 trees. Tree status (pre/post 1880) was later corrected in the laboratory using age data. All living trees meeting the field criteria above were considered potentially pre-1880 trees and were cored. A random 10% sample of all trees that did not meet the field criteria was also cored. Coring height was 40 cm above ground level. This height was chosen to meet two objectives: first, to measure tree age, and second, to measure growth between the fire regime disruption date and the present (needed for the forest reconstruction). The two objectives conflict because the best coring height for age is ground level, but the butt swell and irregular growth around the root collar make this an inappropriate height for growth measurement. The 40-cm height is a compromise, the lowest position on the bole where consistent tree form allows a good measurement of growth. Seedling trees, those below 2.5 cm dbh, were tallied by species, condition, and height class in a 50 m^2 subplot. Canopy cover measured by vertical projection (Ganey and Block 1994) was recorded at 30 cm intervals along the two 50-m sidelines of each plot.

Laboratory methods

Fire scars

Samples were mounted on plywood backing and surfaced with sandpaper to 400 grit. Tree rings were crossdated (Stokes and Smiley 1968) with marker years listed in Fulé et al. (2002). Dates were independently confirmed by another dendrochronologist or ring widths were measured and dating was checked with the Cofecha software (Holmes 1983). Following the procedure of Baisan and Swetnam (1990), the season of fire was estimated based on the relative position of fire injury within the annual ring according to the following categories: EE (early earlywood), ME (middle earlywood), LE (late earlywood), L (latewood), and D (dormant). Dormant season scars were assigned to the year of the following earlywood (i.e., spring fires).

Data were analyzed with FHX2 software (Grissino-Mayer 2001). Analysis at each site began with the first fire year with an adequate sample depth, defined as 10% or more of the total sample size of recording trees at each site (Grissino-Mayer et al. 1995). ″Recording″ trees are those with open fire scars or other injuries (e.g., lightning scars), leaving them susceptible to repeated scarring by fire (Dieterich and Swetnam 1984). At Galahad, the first year of fire regime analysis was 1744; at Little Park the first year was 1700. Statistical summaries of fire occurrence data included the mean fire interval, median, and Weibull median probability interval (Grissino-Mayer 1999), minimum/maximum fire-free intervals, and standard deviation. Comparison of data across different-sized study sites could be biased because more scars recording small fires are likely to be included in larger study sites (Agee 1993; Swetnam and Baisan 1996). The practice of proportional filtering of the data set provides a reasonably consistent basis of comparison by removing small fire events that scarred only one or a few trees (Swetnam and Baisan 1996; Baker and Ehle 2001). Our fire data were filtered to look at three levels of progressively higher proportions of scarring. First, all fire years, even those represented by a single scar, were considered. Then only those fire years were included in which respectively 10% or more, and 25% or more, of the recording samples were scarred. Finally, we also calculated the per-sample or ″point″ fire frequency, suggested by Baker and Ehle (2001) as another approach for consistent comparisons between study areas. This interval was calculated from the first to last fire date, not from the pith date.

The relationship between climatic fluctuations and fire occurrence was evaluated with superposed epoch analysis (SEA), using software developed by Grissino-Mayer et al. (1995). A locally developed tree-ring chronology served as a proxy for climate (19 ponderosa pine trees from Powell Plateau, Rainbow Plateau, and Fire Point, master series 1559–1997, series intercorrelation = 0.70, average mean sensitivity = 0.34). The chronology was significantly correlated with reconstructed Palmer Drought Stress Index (r =

0.67) for grid point 31 in northern Arizona, A.D. 1694–1978 (Cook et al. 1996). The SEA superimposes all fire years and mathematically summarizes the climate data for fire years, as well as a window of 5 preceding and 5 succeeding years. Bootstrapped distributions of climate data in 1000 random windows were used to create confidence intervals.

From 1924 onward, Grand Canyon National Park maintained records of fire occurrence. After determining fire dates on fire-scarred samples, we compared the tree-ring fire history against the recorded fire history.

Forest structure

Forest plot area was corrected for slope by multiplying the 50-m dimension by the slope correction factor. Tree increment cores were surfaced and visually crossdated (Stokes and Smiley 1968) with tree-ring chronologies we developed. Rings were counted on cores that could not be crossdated, especially younger trees. Additional years to the center were estimated with a pith locator (concentric circles matched to the curvature and density of the inner rings) for cores that missed the pith (Applequist 1958). From previous studies (Fulé et al., 2000, 2002 and in press), we know that fire exclusion began after 1879 on most of the North Rim. Forest structure in 1880 was reconstructed using dendroecological methods (Fulé et al. 1997) as follows: tree size at the time of fire exclusion was reconstructed by subtracting the radial growth measured on increment cores since 1879. We developed local species-specific relationships between tree diameter and basal area increment (r^2 = 0.45 to 0.90) and applied these relationships to estimate past size for trees without increment cores (dead or rotten centers). For dead trees, the date of death was estimated based on tree condition class using diameter-dependent snag decomposition rates (Thomas et al. 1979). A total of 4,719 trees were present on the plots in 1880; of this number, 3,153 trees or 67% are still living. The accuracy of the dendroecological reconstruction methods is assessed in *Changes in forest structure*, below.

Fire-initiated/non-fire-initiated plots

We were unable to use remotely sensed data or field reconnaissance to identify homogeneous stands of trees originating after fire, as noted above. However, at the finer scale of the 20 × 50-m plots we were able to detect differences associated with effects of fires of differing severity. Fire-initiated and non-fire-initiated plots were distinguished by age and species composition data, following methods similar to Murray et al. (1998). In some sense, all forests on the North Rim might be considered ″fire initiated,″ because of fire's importance in regeneration (e.g., White 1985), but the terminology is used here to separate groups of trees that originated following a stand-replacing fire from trees that established as individuals or small cohorts under an overstory of fire-resistant trees. All age cohorts within each plot were taken into consideration but the greatest weight was given to the oldest trees. When the oldest tree or trees were the fire-resistant species PIPO and PSME, the plot was classified as non-fire-initiated. When the oldest trees were the fire-susceptible species POTR, PIEN, or ABLA, the plot was classified as fire-initiated. ABCO was considered intermediate in fire resistance and old-ABCO plots were classified as non-fire-initiated when accompanied by uneven-aged PIPO or PSME, and as fire-initiated when accompanied by approximately equal-aged POTR. In general, the non-fire-initiated classification corresponded to ″uneven-aged″ structure, but the fire-initiated classification was not interpreted as ″even-aged″—plots with fire-susceptible old trees often had one or more cohorts of younger trees, a category called ″mixed severity″ by Murray et al. (1998).

Remote sensing

Vegetation at the Little Park study area was classified from satellite imagery (Landsat Enhanced Thematic Mapper image, acquired 6 June 2000) in order to compare topographic characteristics (slope, aspect, elevation) with vegetation type. The classification scheme was designed under the National Vegetation Classification Standards (NVCS) framework (USGS [United States Geological Survey] 2000). The plot data were used as training sites for image classification. The species label for each training site was 'importance value' (Taylor 2000), calculated as the sum of the relative frequency (percent stems) and relative abundance (percent basal area) for each species. This approach was similar to the classification method used by White and Vankat (1993) on an adjacent study area, but differed in that we chose to include aspen as a distinct forest type, because of its prevalence in the study area and importance in assessing post-fire succession, and we did not differentiate the two spruce species. Four forest types were used in this study: aspen, mixed conifer, ponderosa pine, and

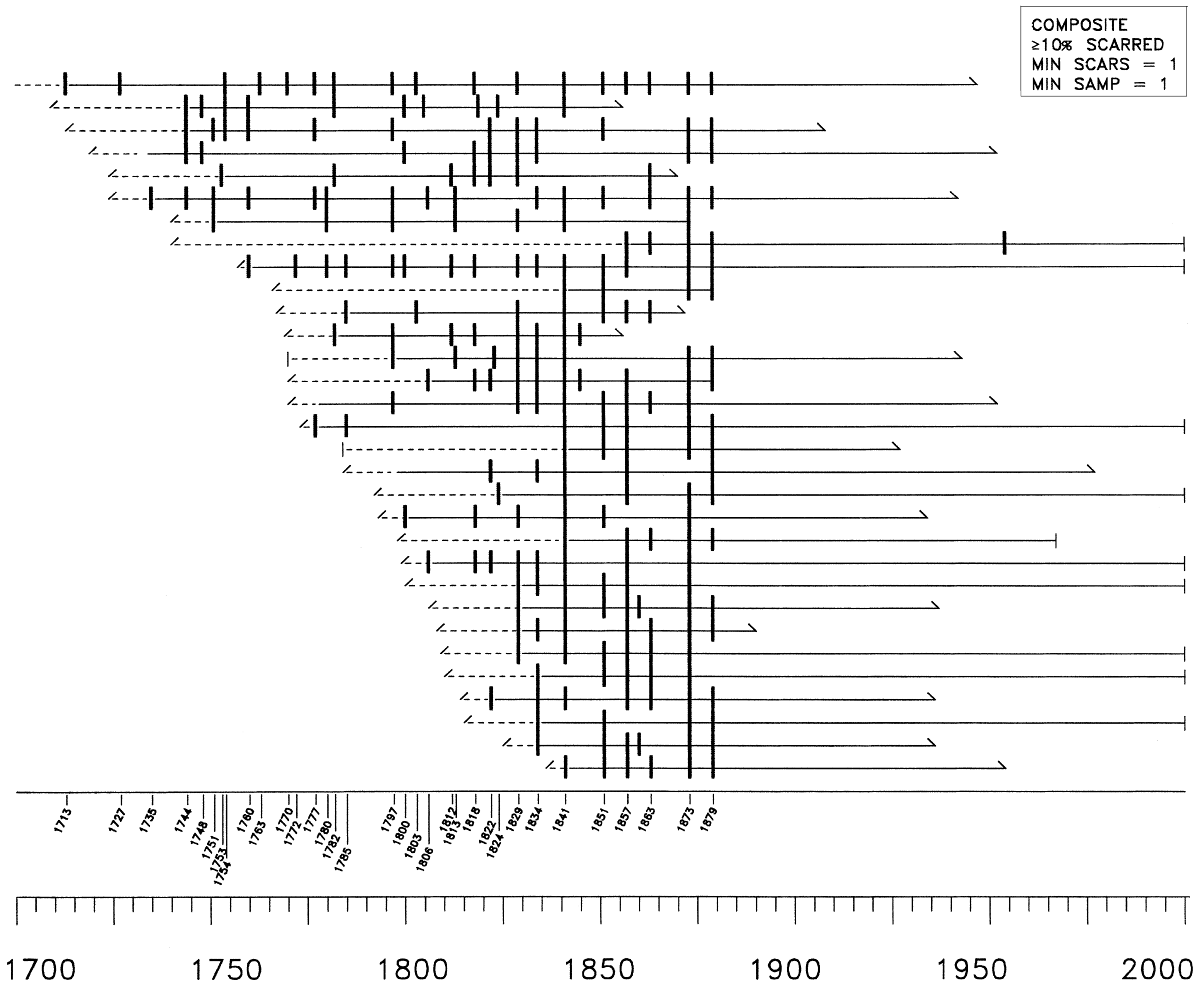

Figure 2. Fire chart for 31 fire-scarred trees from the Galahad study site. Horizontal lines represent the time period of each scarred sample tree; vertical bars are fires. Years in which fires scarred 10% or more of the samples are shown on the lower axis.

spruce-fir. A non-forested grass type was also identified.

Results

Fire scar data

Galahad point

Fire history was reconstructed for the period 1744–2000 from 31 fire-scarred trees (Figure 2). Fires occurred frequently until 1879; only one scar occurred after 1879 (1954). The following statistics apply to the 1744–1879 period: the mean fire interval (MFI) calculated from all fire scars was 4.0 years (Table 2). The Weibull median probability interval (WMPI) for the same data was 3.6 years. For fires scarring 25% or more of the samples, average fire intervals increased by approximately 70% to MFI = 6.8 years, WMPI = 6.1 years. The minimum fire-free interval was 1 year, maximum 12 years, rising to 2 and 18 years, respectively, under the 25%-scarred filter. The mean point (or per-sample) fire interval was 11.3 years (minimum 6.5 years, maximum 20.3 years).

The season of fire occurrence was determined on approximately 75% of the fire scars. Over 85% of the scars occurred in the middle earlywood to latewood; dormant season scars accounted for < 5%. Fire years in which 25% or more of the samples were scarred matched 11 of the 17 major fire years in which fires burned at 3 or all 4 of the sites previously studied on the North Rim transect (Table 3, see Figure 1 for

Table 2. Statistical summaries of fire occurrence data from fire-scarred trees. Weibull median probability values are not reported (n/a) where the Weibull model failed to fit the fire interval data adequately (Kolmogorov-Smirnov test, alpha = 0.05).

Site / Analysis Period / Number of fire-scarred sample trees	No. of Intervals	Mean (MFI)	Median	Minimum	Maximum	Standard Deviation	WMPI (Weibull median probability interval)
Galahad / 1744–1879 / N = 31							
All scars	34	4.0	3	1	12	2.6	3.6
10% scarred	29	4.0	4	1	12	2.7	4.3
25% scarred	20	6.8	6	2	18	4.6	6.1
Little Park / 1700–1879 / N = 132							
All scars	69	2.6	2	1	12	1.8	n/a
10% scarred	22	8.0	6.5	2	25	6.6	6.8
25% scarred	5	31.0	13	11	94	35.7	23.4
Little Park by Forest Type (1700–1879, 10% scarred)							
Aspen (N = 38)	31	5.7	4	1	16	4.2	4.9
Mixed Conifer (N = 15)	15	8.7	5	1	28	8.3	6.6
Ponderosa Pine (N = 9)	21	7.4	6	2	25	5.2	6.6
Spruce-fir (N = 53)	20	8.8	7	2	32	7.7	7.2
Little Park by Aspect (1700–1879, 10% scarred)							
North (N = 6)	10	13.1	11	1	34	11.4	9.8
East (N = 23)	23	7.7	6	1	24	6.9	6.0
South (N = 61)	32	5.5	5.5	1	13	3.4	5.0
West (N = 27)	18	9.8	5.5	1	28	8.7	7.7
Little Park by Elevation (1700–1879, 10% scarred)							
2550–2650 m (N = 31)	28	6.3	6	2	19	4.2	5.7
2650–2750 m (N = 66)	24	6.7	5	1	21	5.1	5.7
> 2750 m (N = 18)	11	15.9	11	2	36	12.9	12.7

study sites). Superposed epoch analysis showed that fire years were significantly dry (Figure 4). The year preceding fire tended to be relatively wet but the proxy climate variable did not exceed the 90% confidence interval (Figure 3).

Contemporary fire records for the Galahad Point area (410-ha study site buffered by 1 km to allow for imprecision in recorded fire locations) contained 40 lightning-caused fires between 1936 and 1990. A 3.3-ha wildfire, the Bedivere fire, burned in 1954 and was detected in the tree-ring fire history. However, the largest fire that burned within the sampling area was the 12-ha Bedivere fire in 1990 (fires were often named for nearby map features so names commonly reappeared from year to year); this fire was not detected in the tree-ring fire history. All other wildfires were 3.7 ha or less, most commonly recorded as 0.04 ha, the minimum reporting size. All wildfires were suppressed until 1986, when a lightning ignition was allowed to burn, reaching 1.2 ha in size. Taking recent years as the most reliable period of record (1967–1996), 25 lightning fires or 0.8 lightning fires/year occurred.

Little Park

Fire history was reconstructed for the period 1700–2000 from 132 fire-scarred trees (Figure 4). Scarred trees were predominantly encountered on S aspects (53%) followed by W (23%) and E (19%) aspects. Only 5% of samples were collected from N-facing slopes. A number of additional scarred samples were collected but could not be crossdated confidently, due to complacent ring series (wide rings that do not cross-match well with climate-induced narrow rings in other trees).

In a similar pattern to the other North Rim sites, fires ceased after 1879 with only two subsequent fire dates: 1893 (one scarred sample) and 1921 (two scarred samples). The following statistics apply to the 1700–1879 period. The all-scars MFI and WMPI showed the highest fire frequency of any North Rim site, 2.6 and 2.3 years, respectively (Table 2). In con-

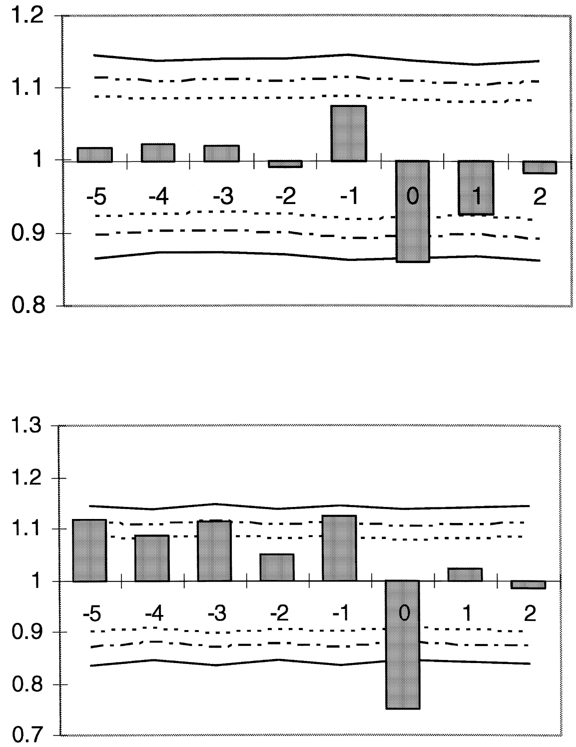

Figure 3. Fire years were significantly dry, as shown by superposed epoch analysis (SEA) showing the relationship between local climate (tree-ring width index) and occurrence of fires scarring 10% or more of the sample trees at the Galahad (top) and Little Park (bottom) study sites. The average climate value is scaled to one. Bootstrapping procedures were used to assess the statistical significance of climate departures above the mean ("wet years") and below the mean ("dry years") in the fire years (year 0), the five years preceding fires (−5 through −1), and the two years after fires (1 and 2). The three lines above and below the x-axis in each graph represent confidence intervals of 90%, 95%, and 99%.

trast, applying the 25%-scarred filter led to the longest fire-free intervals, MFI = 31.0 years and WMPI = 23.4 years, an increase of approximately 900–1100% over the all-scar intervals. The change in minimum and maximum fire-free years among the different fire categories was also striking: for all scars, the minimum fire-free interval was 1 year and the maximum was 12 years, identical to the Galahad site. But for the 25%-scarred category, the minimum interval rose to 11 years and the maximum to 94 years (1785 to 1879). The mean point fire interval was 31.9 years (minimum 8.9 years, maximum 99.0 years), nearly three times as long as the Galahad mean point fire interval.

Using the forest data measured at the Little Park site, the fire-scarred samples were subdivided by the forest type, aspect, and elevation, taking the 10%-scarred filter as a standard of comparison (Table 2). For the entire data set, with the 10%-scarred filter, MFI = 8.0 years and WMPI = 6.8 years. Differences were relatively minor among the subdivided groups. By forest type, the MFI values for the 10%-scarred groups ranged from 5.7 to 8.8 years, with samples collected in the aspen type having the shortest average fire-free intervals and samples collected in the spruce-fir type having the longest (WMPI values and min/max intervals for these groups are shown in Table 2). By aspect, MFI values for the 10%-scarred groups ranged from 5.5 to 13.1 years, with samples collected on south aspects having the shortest average fire-free intervals and samples from north aspects having the longest. By elevation, MFI values for the 10%-scarred groups ranged from 6.3 to 15.9 years, with samples collected below 2,650 m having the shortest average fire-free intervals and samples collected above 2,750 m having the longest.

The season of fire occurrence was determined on 67% of the fire scars. The majority of the scars occurred in the middle earlywood to latewood but the proportion of these scars was only 64%, compared to 85% at Galahad.

Synchrony between low- and high-elevation fires was found in the five fire years in which 25% or more of the samples were scarred (Table 3). All five years—1735, 1748, 1773, 1785, and 1879—matched major fire years in which fires burned at 3 or all 4 of the sites previously studied on the North Rim (Fulé et al. 2000 and in press) as well as at the Galahad site (Table 3). Fire years were significantly dry, as shown by superposed epoch analysis, but pre-fire years were wet. Four of the five pre-fire years were significantly wet at the 90% confidence interval and two exceeded the 95% confidence interval (Figure 3).

Contemporary fire records for the Little Park area (buffered by 1 km) contained 71 lightning-caused fires between 1933 and 1996. None was detected in the tree-ring fire history. The largest historical fire was the 5.1-ha Upper Big Spring Canyon fire (1940). All other wildfires were 1.6 ha or less, most commonly recorded as 0.04 ha, the minimum reporting size. All wildfires were suppressed until 1981. A total of 4 lightning ignitions were allowed to burn in 1981, 1986, and 1988, but none exceeded 0.04 ha in size. For the reliable historical period (1967–1996), 38 lightning fires or 1.3 lightning fires/year occurred.

Table 3. Major fire years based on the percentage of fire occurrence (all fires) at four North Rim study sites between 1721 and 1879. The four sites are Powell Plateau, Fire Point, Rainbow Plateau, and Swamp Ridge (Fulé et al. 2002). Fire years recorded by 25% or more of fire-scarred samples at Galahad and Little Park are indicated by the date. Underlined rows are major regional years at low and high elevation. Reconstructed Palmer Drought Stress Index (PDSI) values are shown for northern Arizona (grid point 31, Cook et al. (1996)). Negative PDSI values indicate dry years.

Major fire years at 4 North Rim study sites	No. of sites with fire	Total no. of sites	Percent	Fire at Galahad Point (⩾ 25% scarred)	Fire at Little Park (⩾ 25% scarred)	Palmer Drought Stress Index (PDSI)
1733	3	4	75%			−0.10
1735[A]	4	4	100%		1735	−4.83
1739[B]	3	4	75%			−1.87
1744	3	4	75%	1744		0.27
1748[A,B]	4	4	100%	1748	1748	−2.38
				1754		−1.78
1755[A,B]	4	4	100%			−3.61
				1760		0.73
1773[A]	4	4	100%		1773	−3.42
				1777		−3.31
				1780		−3.40
				1782		−4.53
1785[A]	4	4	100%	1785	1785	−1.09
				1797		0.95
1800	3	4	75%	1800		−2.83
1806[A]	3	4	75%			−1.52
1810	3	4	75%			−0.61
				1818		−0.46
1822	3	4	75%	1822		−2.48
1829[A,B]	4	4	100%	1829		−0.79
1834[A]	4	4	100%	1834		−1.06
1840	3	4	75%			3.42
1841	3	4	75%	1841		−1.51
1845[A]	3	4	75%			−3.46
1851	3	4	75%	1851		−0.83
				1857		−5.44
				1863		−2.32
1873[A]	4	4	100%	1873		−2.11
1879[A]	4	4	100%	1879	1879	−4.66

[A] Also a major fire in the 25%-scarred category.
[B] Also a fire year at Grandview on the South Rim (Fulé et al. (in press)).

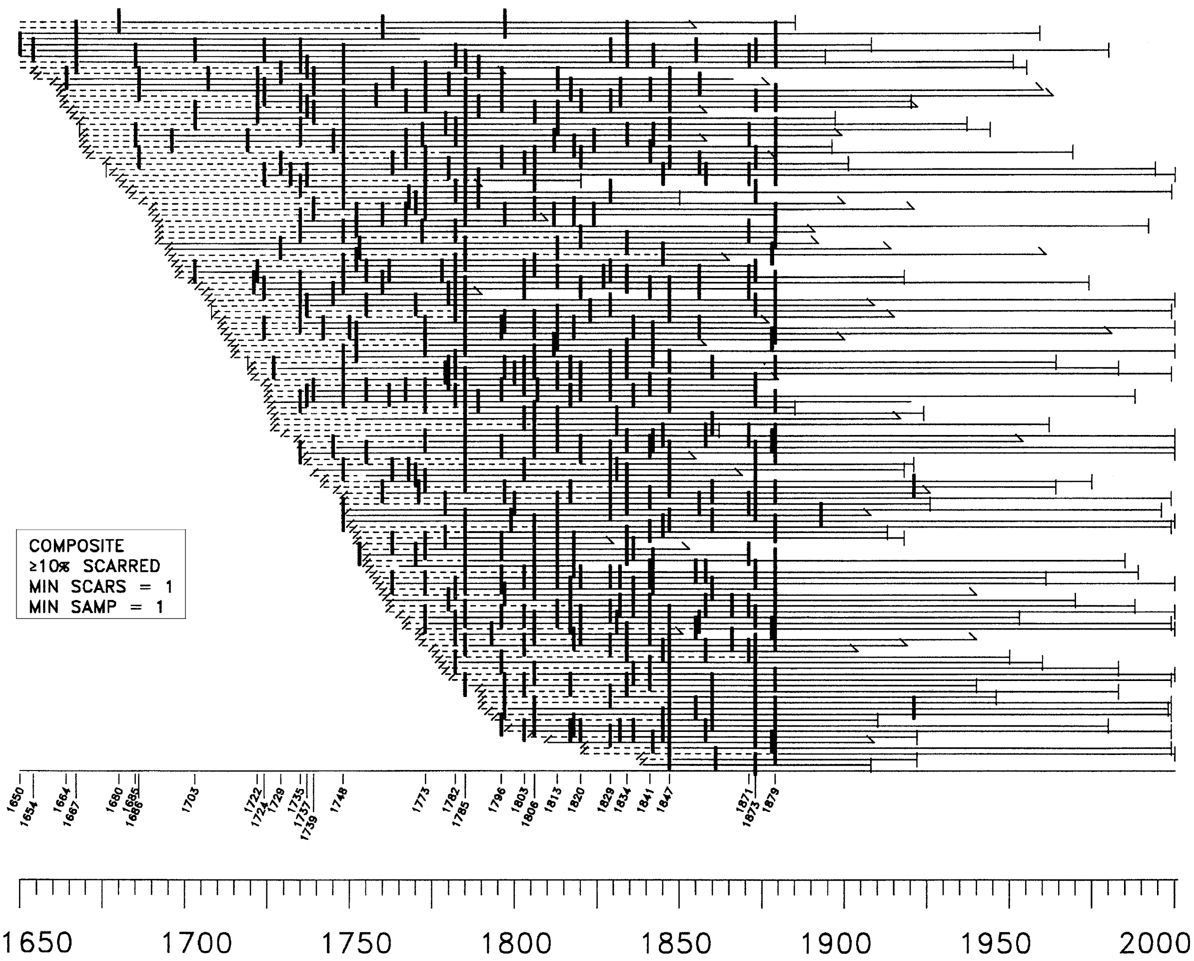

Figure 4. Fire chart for 132 fire-scarred trees from the Little Park study site. Years in which fires scarred 10% or more of the samples are shown on the lower axis.

Overstory forest structure—Little Park

Spruce-fir was the predominant forest type classified from Landsat imagery, representing 2,860 ha or 67% of the forested area (Table 4). The remaining types, aspen, mixed conifer, and ponderosa pine, represented 17%, 11%, and 3%, respectively. Average elevation increased from ponderosa pine through mixed conifer and aspen to spruce-fir, but the differences were slight (range 68 m) (Table 4).

Species composition and tree age were the key variables used to categorize plots as fire-initiated or non-fire-initiated. Forest composition was highly varied within forest types (Table 5), with all six dominant tree species occurring in all four forest types. Only RONE was limited to a single forest type (mixed conifer). In contrast, ABLA averaged over 100 trees/ha in all four types, although the trees were relatively small, as indicated by the low basal area values (< 3.2 m^2/ha except in the spruce-fir type). POTR trees were actually outnumbered by PIEN trees in the aspen type, although POTR dominated in basal area. Average tree densities ranged from a minimum of 946 trees/ha (spruce-fir type) to a maximum of 1382 trees/ha (aspen type) and basal areas ranged from approximately 28 to 39 m^2/ha. Mean canopy cover values and standard errors were 60.9% (± 3.6%) in aspen, 55.3% (± 3.4%) in mixed conifer, 53.0% (± 10.8%) in ponderosa pine, and 51.6% (± 2.3%) in spruce-fir. The highest average (60.9%) and maximum cover on a single plot (84.6%) both occurred in the aspen type. The spruce-fir type had the greatest range in cover values, 63% (minimum 18.7%, maximum 81.2%). Tree regeneration was

Table 4. Vegetation types were classified from Landsat imagery. Plot data includes the number of plots classified as each forest type, average slope, and the number of plots in each with north, east, south, and west aspects. No plots were located in the grass vegetation type.

Forest Type	Area (ha)	Average Elevation	No. of Sample Plots	Average Slope (%) on plots	N Aspect	E Aspect	S Aspect	W Aspect	No. of Trees Aged
Aspen	712	2,692	13	16.6	5	1	5	2	146
Mixed Conifer	453	2,666	15	14.5	2	3	5	5	130
Ponderosa Pine	248	2,629	4	19.0	0	0	3	1	47
Spruce-fir	2,860	2,697	28	16.6	2	8	8	10	168
Subtotal	**4,273**				**9**	**12**	**21**	**18**	
Grass	108	2,690	n/a	n/a	n/a	n/a	n/a	n/a	
Total	**4,381**		**60**		**9**	**12**	**21**	**18**	**491**

dense, from > 5,000 to > 12,000 seedlings or sprouts per ha (Table 5). POTR was the most prolific species, averaging > 2,000 small trees/ha in each forest type. At the other extreme, PIPO had no recorded regeneration in the aspen and spruce-fir types, which make up 78% of the landscape. No PIEN seedlings were found in the ponderosa pine vegetation type, but it only comprised 3% of the study area.

Age distributions (center date at the 40-cm sampling height of 491 increment cores) are expressed on a per-hectare basis by forest type in Figure 5. The number of sample plots and number of trees aged for each forest type are listed in Table 4. All forest types had numerous old trees of several species but were numerically dominated by post-1880 regeneration. The oldest trees by species were: ABCO 1735, ABLA 1811 (ABLA was never the oldest tree on any plot), PIEN 1788, PIPO 1618, POTR 1770, and PSME 1693.

Fire-initiated plots were identified on 58% of the plots (35/60 plots) (Table 6). North and east aspects had higher proportions of fire-initiated plots (71% of the N- and E-facing plots), while south and west aspects were nearly equal in fire-initiated versus non-fire-initiated plots (51% and 49%, respectively, of the S- and W-facing plots). The aspen and spruce-fir types had predominantly fire-initiated plots (73% of the plots in these two forest types), the ponderosa pine type was evenly split (50% each), and the mixed conifer type had predominantly non-fire-initiated plots (80%). The two oldest plots classified as fire-initiated were PIEN-dominated, with oldest trees dating to 1788 and 1791. The oldest POTR plot dated to 1792 and ten additional old-POTR plots predated 1860. Given the imprecision of age sampling at 40 cm above ground level and estimating rings to pith on many of the increment cores, we did not attempt to finely delineate age cohorts within plots. However, clearly distinct cohorts of POTR were evident on 9 plots. Five of these plots were classified as non-fire-initiated; the remaining four were classified as fire-initiated, with POTR as the oldest tree species. The oldest trees on fire-initiated plots were significantly older than on non-fire-initiated plots (mean = 1754 vs. 1851, t-test $P < 0.001$). Fire-initiated plots also occurred on steeper slopes (mean = 18.8% vs. 12.7%) but the difference was not statistically significant. Mean elevations of fire-initiated and non-fire-initiated plots were nearly equal (2,690 m vs. 2,682 m).

Reconstruction of forest structure in 1880 (Table 5) showed that past forests were significantly less dense and had significantly lower basal area than the contemporary forest (paired *t*-test). Total tree densities ranged from 150 to 337 trees/ha, only 16–24% as dense as the contemporary forest. Basal areas in 1880 ranged from approximately 10 to 18 m^2/ha, about 36–46% as dense as the contemporary forest. Basal area values for PIPO, POTR, and PSME were the least changed over the 1880–2000 period, but ABCO, ABLA, and PIEN were sparse in the 1880 forest, in contrast to their current dominance.

Table 5. Forest structure by vegetation type. Species codes are **GE**nus + **SP**ecies (e.g., *Abies concolor* = ABCO). Two species of spruce, *Picea engelmannii* and *Picea pungens*, are grouped together under the code PIEN. Past forest structure reconstructed in 1880 is shown in the lower sections of the table. Numbers in parentheses are standard errors.

Forest Type	ABCO	ABLA	PIEN	PIPO	POTR	PSME	RONE	Total
	Current Tree Density (trees/hectare)							
Aspen	196.4 (61.6)	306.1 (114.7)	419.1 (122.3)	68.8 (23.4)	352.5 (29.6)	39.3 (8.9)	0	1382.2 (170.6)
Mixed Conifer	216.1 (57.1)	159.9 (66.9)	190.8 (51.4)	46.6 (9.9)	170.1 (52.3)	76.2 (15.5)	13.7 (13.7)	873.4 (88.9)
Ponderosa Pine	199.4 (103.8)	108.7 (108.7)	2.8 (2.8)	228.2 (46.2)	222.6 (128.6)	20.6 (7.1)	0	782.3 (117.2)
Spruce-Fir	17.8 (7.2)	241.3 (43.2)	440.3 (71.7)	22.1 (7.5)	207.4 (38.7)	17.0 (5.4)	0	946.0 (99.1)
	Current Basal Area (m^2/hectare)							
Aspen	3.6 (1.1)	3.1 (0.9)	7.6 (1.2)	3.8 (0.8)	11.3 (1.2)	2.2 (0.5)	0	31.6 (1.7)
Mixed Conifer	14.3 (3.5)	2.1 (0.6)	5.4 (1.2)	4.6 (0.7)	3.2 (0.7)	9.2 (2.5)	0.02 (0.02)	38.8 (2.7)
Ponderosa Pine	8.2 (3.9)	1.5 (1.5)	0.06 (0.06)	18.9 (4.3)	6.0 (2.4)	0.6 (0.2)	0	35.3 (4.6)
Spruce-Fir	0.8 (0.4)	5.7 (1.0)	13.9 (1.3)	2.2 (0.8)	3.6 (0.5)	1.7 (0.5)	0	27.8 (1.8)
	Current Regeneration (seedlings or sprouts < 2.5 cm diameter, trees/ha)							
Aspen	1,025 (458)	3,176 (1,169)	2,038 (756)	47 (25)	5,846 (1,497)	139 (100)	0	12,271
Mixed Conifer	1,933 (975)	1,166 (505)	270 (122)	0	3,828 (839)	270 (148)	550 (550)	8,017
Ponderosa Pine	1,662 (1,589)	50 (50)	0	1,062 (1,062)	2,304 (1,320)	50 (50)	0	5,128
Spruce-Fir	211 (112)	1,847 (475)	1,199 (420)	0	4,187 (819)	129 (101)	0	7,573
	Reconstructed 1880 Tree Density (trees/hectare)							
Aspen	12.0 (5.3)	5.4 (2.7)	12.4 (4.0)	43.9 (11.4)	167.7 (29.5)	10.0 (4.1)	n/a	251.4 (37.9)
Mixed Conifer	59.3 (15.1)	2.7 (1.6)	10.9 (3.6)	64.9 (7.3)	59.4 (11.9)	45.8 (13.2)	n/a	242.8 (14.4)
Ponderosa Pine	30.3 (20.3)	0	0	159.1 (48.5)	142.1 (50.0)	5.0 (5.0)	n/a	336.5 (49.6)
Spruce-Fir	10.1 (5.6)	11.9 (2.9)	39.1 (6.4)	14.3 (5.3)	60.3 (10.3)	14.2 (5.0)	n/a	149.8 (14.8)
	Reconstructed 1880 Basal Area (m^2/hectare)							
Aspen	1.0 (0.5)	0.3 (0.2)	1.0 (0.4)	4.9 (1.1)	2.5 (0.7)	1.2 (0.7)	n/a	10.8 (1.8)
Mixed Conifer	5.5 (1.3)	0.1 (0.1)	0.6 (0.3)	5.4 (1.0)	0.7 (0.2)	5.4 (1.8)	n/a	17.6 (2.1)
Ponderosa Pine	1.9 (1.3)	0	0	9.6 (4.1)	1.4 (0.5)	0.4 (0.4)	n/a	13.3 (5.3)
Spruce-Fir	1.1 (0.6)	0.9 (0.2)	3.9 (0.8)	0.9 (0.3)	0.9 (0.2)	2.0 (0.8)	n/a	9.7 (1.2)

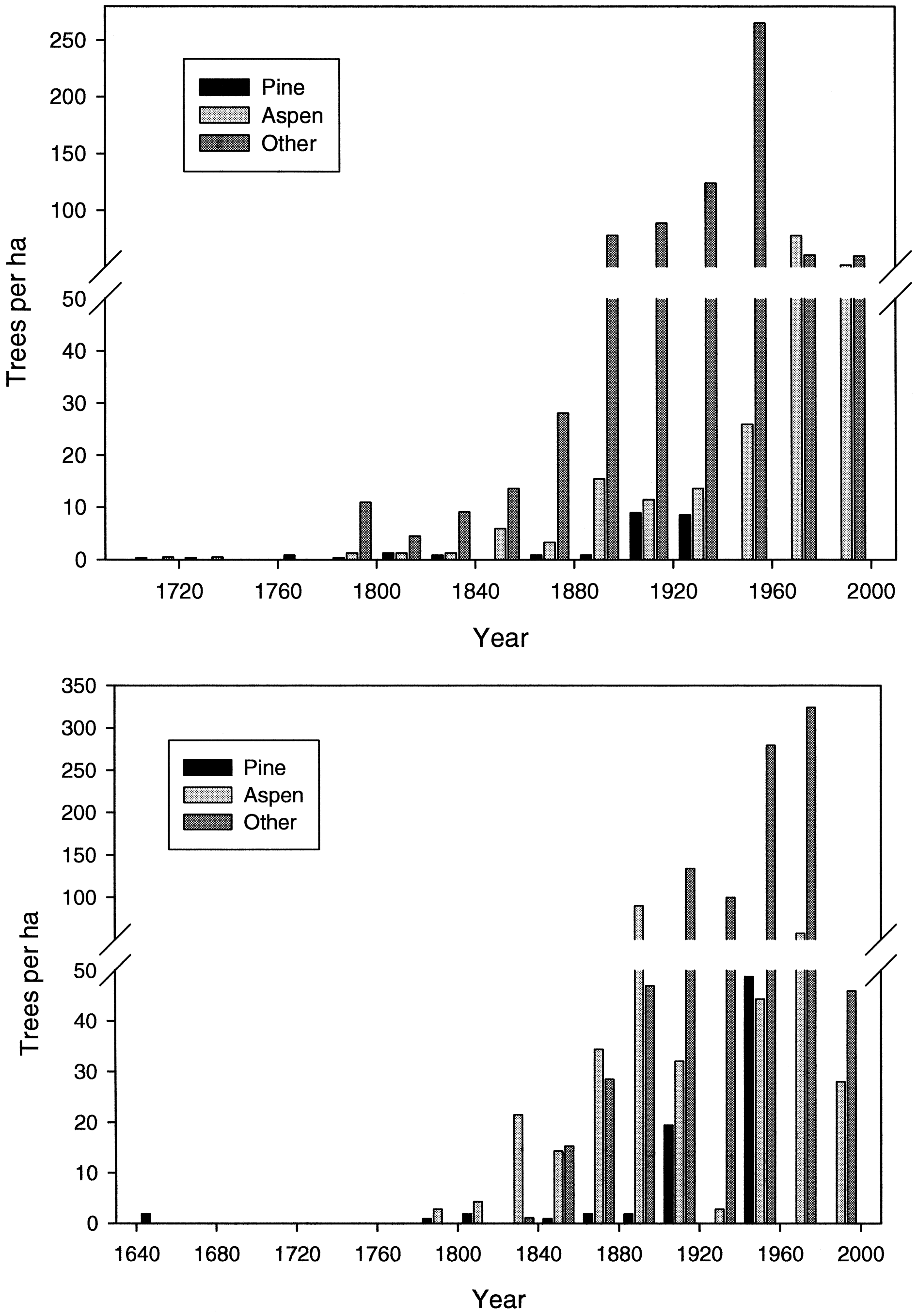

Figure 5. a. Age distribution in spruce-fir forest; b. Age distribution in aspen forest; c. Age distribution in pine forest. The sample size of dated trees in pine forest (N = 47) was inadequate to correctly express the data on a trees-per-hectare basis (see text). The ponderosa pine age structure was artificially truncated because through random chance no pole-sized trees were sampled (10% subsampling) on the four ponderosa pine forest type plots; d. Age distribution in mixed-conifer forest.

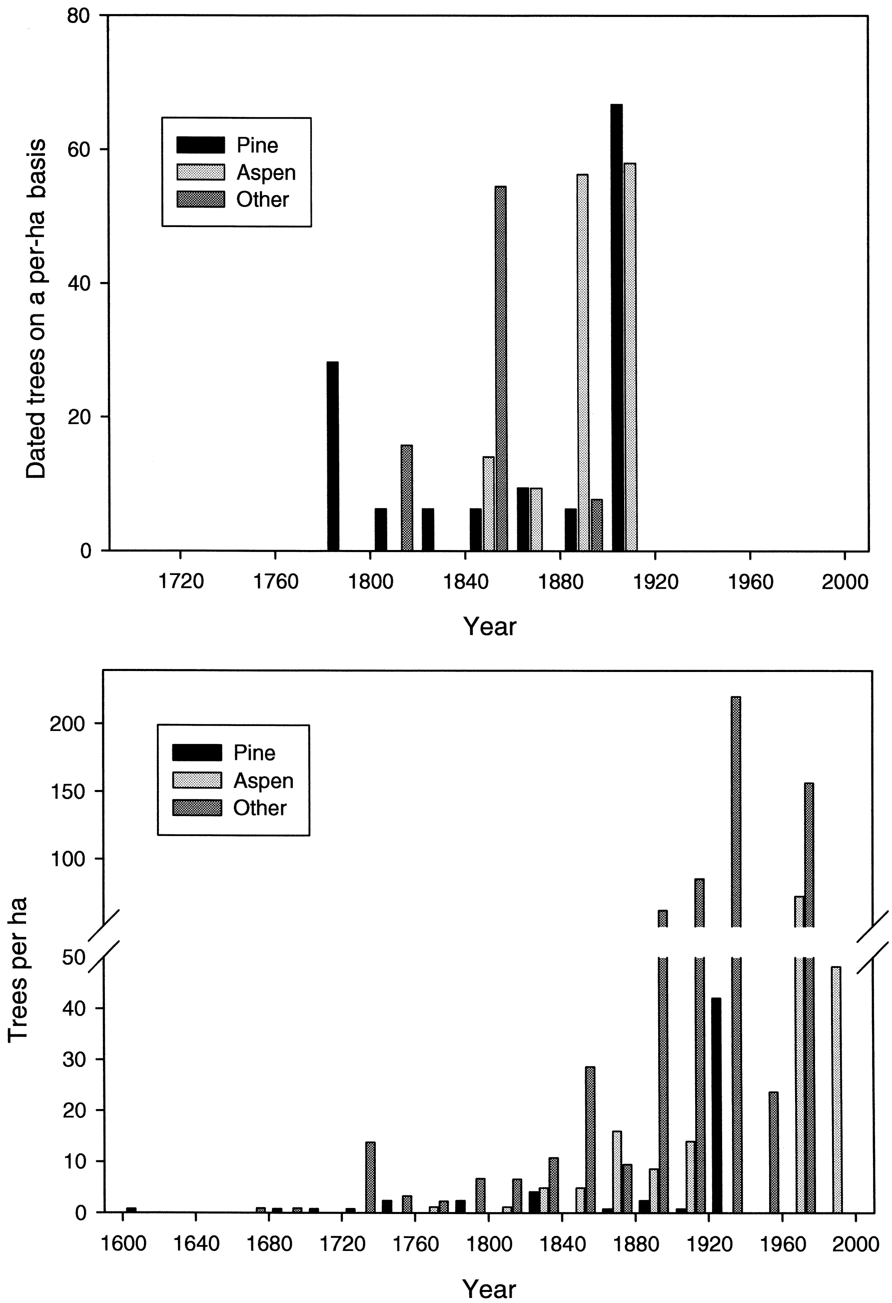

Figure 5. Continued.

Discussion

Fire regime

Fire-scar data

A pattern of numerous small fires but few larger fires emerged from the fire-scar data at the Little Park site. Seventy fire years were identified between 1700 and 1879 at the Little Park study area, resulting in the lowest mean fire interval (2.6 years) of any study site on the North Rim. This extraordinarily high fire frequency supports the idea that total fire occurrence is likely to increase with increasing size of the study area, simply because more and more small fires are

Table 6. Data from 60 field plots classified as fire-initiated or non-fire-initiated based on tree age and species composition.

	Fire-Initiated	Non-Fire-Initiated
All plots (N = 60)	35	25
Aspect		
N	7	2
E	8	4
S	9	9
W	11	10
Forest Type		
Aspen	10	3
Mixed Conifer	3	12
Ponderosa Pine	2	2
Spruce-Fir	20	8
Species of Oldest Tree		
ABCO	2	4
PIEN	12	0
PIPO	0	17
POTR	21	0
PSME	0	4

encountered (Minnich et al. 2000; Baker and Ehle 2001). But the majority of the fires scarred a low proportion of the sample trees. With a 10%-scarred filter, the MFI rose to 8.0 years, slightly higher than the 4.0 years at Galahad and 4.5–7.1 years at the 4 other North Rim study sites described by Fulé et al (2000 and in press). However, it was the 25%-scarred filter that distinguished Little Park from all the lower-elevation sites: 31.0 years versus 6.4–9.0 years. The composite fire frequencies calculated under the 25%-scarred filter were similar to mean point fire intervals at Galahad and Little Park, 11.3 and 31.9 years, respectively.

Little Park had a lower fire frequency under the 10% and 25%-scarred filters than other high-elevation forests in the Southwest. MFI values using the 10%-scarred filter ranged from approximately 10–26 years in 21 fire history studies in mixed conifer forests listed by Swetnam and Baisan (1996). With the 25%-scarred filter, the MFI values rose only slightly, to approximately 15–26 years (Swetnam and Baisan 1996). The fire-scar fire history at Little Park is also qualitatively different from lower-elevation fire histories because samples were not evenly distributed by aspect, so surface fire occurrence cannot be assumed to have occurred uniformly over the landscape. Where fire-scarred trees were not found, it would not be appropriate to infer that fire had not occurred. Instead, the presence of fire-initiated plots is evidence of severe fire. Even where trees were fire-scarred, the relatively long mean point fire intervals compared to Galahad suggest that individual locations on the ground were burned much less frequently at Little Park, similar to the pattern of increasing mean point fire intervals with elevation observed by Taylor (2000) in California.

Forest structure data

Approximately 58% of the plots appeared to have been fire-initiated. Aspen plots would provide the clearest evidence of past severe fire if the oldest aspens reliably represent a post-fire cohort. This interpretation may be confounded by the observation of multiple aspen cohorts on four of the old-aspen groups classified as fire-initiated. If uneven-aged aspen regeneration occurred, as suggested by Ripple and Larsen (2000), old aspens would indicate a minimum fire-free period but not necessarily the date of a stand-replacing fire. One or more aspen cohorts were also encountered on five plots (20%) with old fire-resistant trees, classified as non-fire-initiated, a finding that suggests that fire severity variation even at the sub-plot scale (< 0.1 ha) may have influenced the relationship between fire survivors (PIPO or PSME) versus fire-initiated POTR groups.

Spruce age data are also subject to alternative interpretations depending on possible differences in successional pathways. The oldest spruce groups, dating to *circa* 1790, might represent immediate post-fire regeneration following fires in 1773, 1782 or 1785. The possibility that spruce could colonize post-fire openings immediately is supported by the fact that the old-spruce age distribution is narrow (1788, 1791, 1795, 1796). However, if the spruce succeeded an aspen stand, the date of an original stand-replacing fire might precede 1790 by 100 or more years.

The most reliable interpretation of the age data from fire-susceptible trees is in terms of minimum fire-free periods. By this criterion, the two old-age PIEN groups and the oldest POTR group (1770) show that approximately 5% of the Little Park site has not had a fire severe enough to kill fire-susceptible trees for 210–230 years. The post-1879 fire-free period is an artifact of land management practices introduced by European settlers (Altschul and Fairley 1989; Wolf and Mast 1998; Fulé et al. 2002), so 1880 would serve as a better endpoint for calculating the fire-free period. In 1880, 5% of the landscape had been fire-free for at least 90–110 years, 10% of the landscape was fire-free for at least 60–80 years in 1880, 12%

was fire-free for at least 40–60 years, 8% was fire-free for at least 20–40 years, and 18% was fire-free for less than 20 years. Finally, an additional 5% of the landscape was unforested in 1880 and regenerated with fire-susceptible species between 1890–1930.

If the sampling proportions and tree ages of fire-initiated plots were translated directly into proportional area, the data listed above could be used to create a time-since-fire map and calculate fire rotation (e.g., Heinselmann 1973, Agee and Krusemark 2001). Several studies have used fire scars in conjunction with stand mapping, species composition, and tree age measurements for developing comprehensive fire regime studies (e.g., Niklasson and Granstrom 2000, Taylor 2000). However, the assumptions underlying fire rotation analysis are substantial: ″distinct boundaries between different aged burns″ (Johnson and Gutsell 1994:243) and clear dating of stand origins, or, in the case of fire sizes calculated from fire-scar data, assigning fire areas around point locations of scarred trees (Agee 1993). These assumptions were not well-supported in this study, where distinct stands could not be clearly delineated, fire-initiated groups were intermixed with non-fire-initiated groups, and fire-scarred trees were not encountered evenly across the landscape.

The weighted average of the fire-free periods, about 22 years, is reasonably close to the MFI of 31 years for the fire-scar data with the 25%-scarred filter and the mean point fire interval of 31.9 years. Taken together, the fire-scar and forest structural approaches are consistent with a mixed-severity fire regime at the Little Park site. On approximately 40% of the landscape, notably on S and W aspects, predominantly surface fires occurred in the 1700–1879 period represented by our samples. Even where these fires burned severely enough to initiate POTR groups at the < 0.1 ha scale, old PIPO, PSME, and ABCO trees survived. On approximately 60% of the landscape, severe fires occurred in the Little Park site at intervals that averaged 20–30 years in the century preceding 1880. During that period, at least 5% of the landscape had not burned at all and at least 23% (14/60 plots) had burned within the past 20 years.

Fire-climate relationship and fire extent

Fires at Little Park and Galahad tended to occur in drier years, as seen throughout the Southwest (Swetnam and Baisan 1996; Swetnam et al. 2001; Allen 2002). Swetnam and Baisan (1996) observed a pattern of a wet pre-fire year followed by a dry fire year, suggesting that fine fuel production in wet years might facilitate burning. We saw a trend toward wet conditions in the pre-fire year at Galahad (Figure 4), but the observation that several years before fire were significantly wet at Little Park was surprising. Similar trends were seen with the 25%-scarred Little Park fire chronology, but there were only five such fire dates between 1700–1879, limiting the reliability of the fire-climate relationship. It will be helpful to compare further studies from high-elevation southwestern forests to assess whether the pre-fire moist conditions are a regional or just a local phenomenon.

Fire years were synchronized between Little Park, Galahad, and the previously studied sites. All five major fire years at Little Park (25%-scarred filter) coincided with major regional fire years (Table 3). The dry PDSI values reconstructed in regional fire years (Table 3) support Swetnam and Baisan (1996) contention that climate must have been the major factor underlying regionally synchronous burning. The reconstructed PDSI values do not have the accuracy of measured weather data (see Cook et al. (1996) for validation data), but comparisons may be useful in relative terms. The average PDSI value for all the fire years listed in Table 4 was −1.89, compared to an average of −0.37 for the entire 1700–1879 period. Average PDSI in the five major regional fires at both low and high elevation (shaded rows in Table 4) was −3.28, corresponding to severe drought conditions (Cook et al. 1996).

Considering only the actual sampled areas, fires in major regional fire years such as 1785 (Figure 1) appear to have covered at least 5,000 ha, either as one large fire or several separate ignitions. The Galahad site (410 ha) was actually less linked to Little Park (4,400 ha), located upslope and downwind, than were the four western sites in 1773, a major regional fire year in which fire was not detected at Galahad (Table 3). Continuous fuels existed *between* all the sites and Little Park shared major fire years with the sites located directly west, so fire in years such as 1785 could have burned at least 24,000 ha, the between-site area. But fuels extend to the north and east well beyond the extent of all the sampled areas, suggesting that fires may have been much larger.

Changes in forest structure

Dendroecological reconstruction showed that forest tree structure had changed substantially since 1880.

Table 7. Forest reconstruction in 1880 compared with Lang and Stewart's (1910:12) ″spruce-balsam″ or ″mixed type″ stand averages, trees/ha. Lang & Stewart used the common name ″balsam fir″ for both *A. concolor* and *A. lasiocarpa*. Lang & Stewart did not report POTR density.

	PIPO	PSME	Firs	PIEN	Total
Reconstruction: Trees ⩾ 15.24 cm dbh	34.2	20.8	29.8	22.2	107.0
Lang & Stewart: Trees ⩾ 15.24 cm dbh	45.7	19.3	30.5	21.9	117.4
Percent Difference	**–25.0%**	**7.7%**	**–2.3%**	**1.4%**	**–8.9%**
Reconstruction: Trees ⩾ 30.48 cm dbh	20.2	12.4	12.6	9.6	54.8
Lang & Stewart: Trees ⩾ 30.48 cm dbh	23.1	10.6	13.4	10.5	57.7
Percent Difference	**–12.6%**	**17 %**	**–6 %**	**–8.6%**	**–5 %**

The accuracy of the forest reconstruction procedure used here was discussed by Fulé et al. (1997, 2002). In general, reconstructions are reliable if the site has not been disturbed, if the period of reconstruction is not excessive relative to the lifespan of the trees, and if dead tree evidence (stemwood, bark, and/or rootball) is likely to persist (e.g., Habeck 1990, Foster et al. 1996). In the present case, the Little Park study site has never been harvested and was not burned over the reconstruction period. Individuals from all six dominant tree species had lifespans 200–300% of the reconstruction period (Figure 5). The persistence of dead tree evidence is well-established for ponderosa pine in northern Arizona (Mast et al. 1999; Huffman et al. 2001). The persistence of other species is less documented, especially for small trees. However, the striking changes in forest structure would still be evident even if dense small tree groups had been present in 1880 and subsequently disappeared. As an example of the upper boundary of error, assume that all the trees < 15 cm dbh present today were to be added to the 1880 forest. The tree density would rise by an average 526 trees/ha but the basal area would increase by only 1.3 m^2/ha, accounting for only about 6.5% of the rise in basal area from 1880 to 2000.

The oldest forest survey of the Kaibab Plateau, by Lang and Stewart (1910), was in remarkably close agreement with the forest reconstruction results (Table 7). Lang and Stewart (1910) ″spruce-balsam″ stand average tree densities were within 5–9% of reconstructed tree density values. The ″spruce-balsam″ (spruce-fir) was described as occupying ″only northern aspects up to 8,800 feet [2,683 m] elevation where it extends over the ridges. Occasionally large veteran yellow pine [old-growth ponderosa pine] occur among the balsam and spruce, a strong evidence that the primeval forest was pine. It is thought that the mixed type has succeeded the original yellow pine on account of the cumulative effects of severe fires, and is still advancing upon it″ (Lang and Stewart 1910:9). With respect to fires, they commented on ″vast denuded areas, charred stubs and fallen trunks … The old fires extended over large areas at higher altitudes, amounting to several square miles on either side of Big Park [now called DeMotte Park, immediately N of the present Little Park study site] and to numerous smaller irregular areas over the remainder of the forest″ (Lang and Stewart 1910:18–19). Aspen was described as ″exceedingly active in restocking burns″ and they photographed ″Spruce-Balsam coming in under aspen on northern exposure of old burns″ (Lang and Stewart 1910:9, 18–19). In contrast, at lower elevation, ″evidence indicates light ground fires over practically the whole forest…″ (Lang and Stewart 1910:19).

The oldest PIEN tree on the Little Park site had a center date of 1788 at the 40-cm coring height. Much older spruce stands were reported by Grissino-Mayer et al. (1995) in southern Arizona (300+ years) and Aplet et al. (1988) in Colorado, where four out of five study sites had trees in the 251–275 year category and the oldest trees were in the 601–625 year category. The oldest ABLA at Little Park had a center date of only 1811, well below the 200–500 year age range of ABLA in Colorado (Aplet et al. 1988). The oldest POTR tree was about 230 years (1770 center date) but the majority of POTR were also young. A notable reduction in POTR regeneration occurred around the 1920–1940 age class (Figure 5). POTR cohorts from this period may have been killed by heavy deer browsing during the 1920s and 30s (Rasmussen 1941; Merkle 1954, 1962; Mitchell and Freeman 1993; Fulé et al. 2002). Apart from this period of reduced regeneration, POTR regeneration was consistent in all forest types since the early 1800s and heavy POTR regeneration also occurred through the mid-1900s

(Figure 5), with several plots supporting multiple age cohorts of POTR. These findings tend to support the hypothesis of Ripple and Larsen (2000) that aspen is capable of uneven-aged regeneration in the absence of heavy herbivore pressure, notably elk. Unlike most regions with aspen in the West, the Kaibab Plateau has been free of elk until recently and the current population is small (S. Germaine, Arizona Game and Fish Department, personal communication 2001).

The intersecting evidence of intermittent broad-scale fires recorded on fire scars, relatively young age structure of all fire-susceptible species, low forest density, and historical accounts reinforce a picture of a very open forest of many young trees in 1880, with more than half of the Little Park site in early post-fire successional stages. At a scale of centuries, the mixed-severity fires may have exhibited an unstable or non-equilibrium pattern dominated by drought influences. Meko et al. (1995) identified the periods 1879–1883 and 1773–1782 as the driest 5- and 10-year periods in Arizona since 1600. Salzer (2000) bristlecone pine chronology from northern Arizona did not identify exactly the same periods as Meko et al. (1995), but recorded several warm/dry episodes in the 1700s and none in the 1800s. At Little Park, relatively frequent large fires in the 1700s (4 fire dates: 1735, 1748, 1773, and 1785) contrast with a single large fire in the 1800s (1879, although fires in 1806, 1847, and 1873 were also widespread, scarring ~23% of the samples, nearly meeting the 25%-scarring criterion). One interpretation of the fire and climate data is that wetter conditions in the 1800s made possible the 94-year period without a major fire from 1785 to 1879. Fuel accumulation in this period could have supported more severe fire effects at the landscape scale during the 1879 fire event than the shorter fire-free periods prior to 1785, leading to the open post-fire forest conditions reconstructed in 1880 and observed by Lang and Stewart (1910). However, if 1806, 1847, and 1873 are also considered as major fire years, the apparent difference between the burning patterns in the 1700s and 1800s disappears. Under this alternative interpretation, the open forest conditions and young stand age may have been typical of both centuries. Given the relatively short temporal period of these data, it is not possible to say which pattern was characteristic of the long-term fire regime at high elevations.

Currently a very dense spruce-fir forest predominates at Little Park. All forest types—even those that predominantly contain non-fire-initiated groups—exhibit high densities (782–1,382 trees/ha), basal areas (28–39 m^2/ha), canopy cover (52–61%), and woody debris (99–142 Mg/ha). These characteristics can support high-intensity, severe, stand-replacing fires. The Outlet fire, ignited in a prescribed burning operation on May 9, 2000, burned over 5,260 ha of Grand Canyon National and Kaibab National Forest lands SE of Little Park (Bertolette and Spotskey 2001). Within the park, approximately 30% of the fire area burned with low severity (tree scorching but no overstory mortality), 34% with moderate severity, 35% with high severity (complete overstory mortality), and less than 2% unburned (Bertolette and Spotskey 2001, and D. Bertolette, personal communication, 2002). The post-fire distribution of burn severities appears similar to the distribution of fire-initiated/non-fire-initiated groups at Little Park in 1879, suggesting that fires similar to the Outlet fire are not unprecedented in the high-elevation forest. However, the high severity burning in the Outlet fire was concentrated in the center of the wind-driven burn area (Bertolette and Spotskey 2001), in contrast to the highly mixed spatial pattern of fire-initiated/non-fire-initiated groups at Little Park.

Park managers should recognize the near certainty that fire behavior similar to that observed on the Outlet fire will also occur at Little Park and other high-elevation forests under windy drought conditions. Severe burning is historically precedented in many of these forests, as shown in this study, but the vegetation types dominated by PIPO, PSME, and ABCO appear to have become unusually dense with young fir and spruce trees. Instead of mixed-severity fire effects in a patchwork of stand densities, the modern forest forms a homogenous fuel complex (White and Vankat 1993) that appears likely to burn with high severity over a greater fraction of the landscape than in 1785, 1879, or other past fire years. Managers may wish to consider prescribed burning and fuel reduction treatments on S and W aspects, as well as extensive use of wildland fires managed for resource benefits, if they choose to try to restore fuel conditions similar to historic conditions. We were able to reconstruct past forest structure with high accuracy, as supported by Lang and Stewart (1910) measurements, and to some extent these reconstructions can serve as a guide to developing appropriate restoration targets. However, our understanding of historical conditions in a broader sense is likely to always remain imprecise for two reasons. First, while the combination of fire scar analysis, remote sensing, tree age, and forest structure measurements applied here served to provide a relatively detailed and multifaceted assessment of past fire regimes, there are inherent limitations to all these methods that circumscribe inferences about the severity and exact geographical extent of past fire events. The transition zone studied here, changing from surface to stand-replacing fires, may be the most complex case for fire regime reconstruction. Second, even if we were fully able to reconstruct the details of every fire from 1700 to 1879, the pattern of severe burning did not appear to be stable over the spatial and temporal scale of the study. These considerations imply that managers may be best advised to view the historical condition in high-elevation southwestern forests as a relatively general guide to reference conditions, in contrast to the more specific and temporally stable reference data available for lower-elevation ponderosa pine forests.

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