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Assessing fire regimes on Grand Canyon landscapes with fire-scar and fire-record data

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Abstract. Fire regimes were reconstructed from fire-scarred trees on five large forested study sites (135–810 ha) on the North and South Rims at Grand Canyon National Park. Adequacy of sampling was tested with cumulative sample curves, effectiveness of fire recording on individual trees, tree age data, and the occurrence of 20th Century fires which permitted comparison of fire-scar data with fire-record data, a form of modern calibration for the interpretation of fire-scar results. Fire scars identified all 13 recorded fires >8 ha on the study sites since 1924, when record keeping started. Records of fire season and size corresponded well with fire-scar data. We concluded that the sampling and analysis methods were appropriate and accurate for this area, in contrast to the suggestion that these methods are highly uncertain in ponderosa pine forests. Prior to 1880, fires were most frequent on low-elevation 'islands' of ponderosa pine forest formed by plateaus or points (Weibull Median Probability Intervals [WMPI] 3.0–3.9 years for all fires, 6.3–8.6 years for 'large' fires scarring 25% or more of the sampled trees). Fires were less frequent on a higher-elevation 'mainland' site located further to the interior of the North Rim (WMPI 5.1 years all fires, 8.7 years large fires), but fires tended to occur in relatively drier years and individual fires were more likely to burn larger portions of the study site. In contrast to the North Rim pattern of declining fire frequency with elevation, a low-elevation 'mainland' site on the South Rim had the longest fire-free intervals prior to European settlement (WMPI 6.5 years all fires, 8.9 years large fires). As in much of western North America, surface fire regimes were interrupted around European settlement, 1879 on the North Rim and 1887 on the South Rim. However, either two or three large surface fires have burned across each of the geographically remote point and plateau study sites of the western North Rim since settlement. To some extent, these sites may be rare representatives of nearly-natural conditions due to the relatively undisrupted fire regimes in a never-harvested forest setting.

Additional keywords: Ponderosa pine; Gambel oak; mixed conifer; Kaibab Plateau; Coconino Plateau; modern calibration.

Introduction

Fire scars on a tree, if correctly identified as originating from fire and cross-dated to the exact year of the injury, provide incontrovertible evidence of the past occurrence of fire at the tree's location. Since fire-scarred trees persist for hundreds to thousands of years, they have been fundamental to understanding past fire disturbance regimes (e.g. Swetnam 1993). In ponderosa pine and closely related forests across western North America, fire regimes reconstructed from fire scars have been remarkably consistent in finding frequent fire recurrence with mean fire return intervals of 2–25 years (Swetnam and Baisan 1996; Baker and Ehle 2001; Heyerdahl *et al.* 2001). Together with other historical, photographic, relict site, and paleoecological evidence, these studies have contributed to the interpretation of an evolutionary environment in which frequent, low-intensity fire maintained relatively open forests dominated by large trees and diverse, productive understory vegetation (Cooper 1960; Moore *et al.* 1999). Current recommendations for ecological restoration and ecosystem management of forests are therefore based in large part on fire-scar studies (e.g. Swetnam and Baisan 1996; Kaufmann *et al.* 1998). The choice of management policy is important since large and intense wildfires in ponderosa pine forests have been increasingly costly and are perceived as ecologically destructive (Covington 2000).

Recently the basic premises of fire-scar sampling and interpretation have been questioned (Johnson and Gutsell 1994; Fall 1998; Minnich *et al.* 2000; Baker and Ehle 2001). Although the presence of a fire scar is evidence of fire, the

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absence of a scar does not prove that fire did not occur. Therefore the scattering of point-locations (fire-scarred trees) over a landscape leaves the areal extent of the fire(s) burning between these points uncertain (Minnich *et al.* 2000). Second, fire return intervals are longer if one considers the average of fire intervals per tree rather than the composite of fire intervals per site (Baker and Ehle 2001). Third, the common practice of seeking out trees with multiple scars and long records of fire has been criticized as non-random sampling leading to biased results because of spatial segregation of sample trees, inadequate sample depth, or simply missed fires (Johnson and Gutsell 1994; Fall 1998). As a consequence, Johnson and Gutsell (1994: 268) argued that essentially all fire-scar studies to date were 'not arrived at by a statistically valid sampling design, [so] it is impossible to know how accurate and precise the calculations are'.

Accurate information about fire occurrence over long periods in ecosystems with surface and mixed-severity fire regimes is usually limited to fire-scar interpretation because fire records or 'fire atlas' data are usually short, incomplete, and overlap with modern fire-exclusion periods. Grand Canyon National Park is a unique area in which to measure patterns of fire disturbance on large landscapes because it includes rare examples of south-western forests with 20th Century fires, allowing the use of historical fire records since 1924 to assess the validity of fire-scar analysis methods. The rims of Grand Canyon National Park support the largest area of never-harvested forest in Arizona, approximately 50 000 ha of ponderosa pine and higher elevation forests (Warren *et al.* 1982). Livestock grazing was eliminated early in the 20th Century and there are few roads. Although complete fire suppression was official policy for most of the past century, the difficult access to remote sites limited firefighting capabilities.

It is useful to reconstruct fire regimes over large landscapes because variability in fire disturbance interacts with vegetation over geographic and elevational gradients to create complex landscape patterns (e.g. Romme and Knight 1981; Veblen *et al.* 1992). Geographic 'islands' such as isolated mesas or peninsulas affect the spread of contagious processes such as fire (Turner *et al.* 1989), suggesting that the fire frequency in isolated forest patches would probably be less than that of similar vegetation on 'mainland' forests. This hypothesis was supported at Zion National Park in Utah, where Madany and West (1983) found that a ponderosa pine forest on a small (150 ha) mesa had a pre-European mean fire return interval (MFI—all fires included) of 69 years, up to 10 times longer than a nearby large plateau and far longer than any other south-western ponderosa site. Another site with relatively long MFI (16.5 years—all fires included), Hidden Kipuka at El Malpais National Monument, New Mexico, is an island-like patch of forest surrounded by lava flows (Grissino-Mayer 1995). But forested islands in a Quebec lake burned more frequently than the lakeshore, although with smaller fires (Bergeron 1991) and fires were more frequent and smaller on an isolated mountain range on the Idaho/Montana border than on large contiguous ranges (Murray *et al.* 1998).

Elevational gradients influence fire by affecting fuel moisture, ignition potential, and vegetation composition and productivity (i.e. the amount and arrangement of biomass available for burning). Productivity and biomass generally increase with higher moisture availability at increasing elevation (Gosz 1992). In southern Arizona, for example, biomass rose from 162 to 250 Mg/ha in ponderosa pine forests around 2200 m elevation to 357 Mg/ha in mixed conifer forest around 2700 m elevation (Whittaker and Niering 1975). Despite the abundant quantity of fuel at higher elevations, pre-European fire frequencies across the Southwest tended to decrease with increased elevation, probably limited by higher fuel moisture and relatively compact surface fuel beds (due to short-needled conifers) at higher elevations (Touchan *et al.* 1996; Brown *et al.* 2001).

On a geographic and elevational gradient starting from remote canyon rim sites into the mainland of the Kaibab and Coconino Plateaus, we asked the following questions:

1. Did fire-scar methods accurately reconstruct fire history, as compared with historical fire records?
2. How did fire regimes change, in terms of fire frequency, size, and climate-fire relationships, over the geographic/elevational gradient prior to recent fire regime disruption associated with European settlement?
3. After European settlement, did the fire regime of sporadic burns on remote North Rim sites maintain a near-natural disturbance pattern?

Methods

Study sites

We chose to sample large landscapes over an elevational and biogeographical gradient in order to capture large-scale fire patterns. This choice limited the scope of inference to the study region. An alternative approach, of sampling smaller replicated stands, could have provided estimates of variability in fire regime statistics. This approach was not selected for two reasons: first, the great majority of south-western fire histories have focused on stands or even smaller scales (Swetnam and Baisan 1996), not necessarily providing the most useful information for landscape-scale ecosystem management. Second, the large areal extent of fires as documented in this study and others (e.g. Rollins *et al.* 2000) means that 'replicated' stands in a contiguous forested region are not actually independent, having shared numerous fires, so a statistical treatment based on presumed replication and extrapolation of results would be inappropriate. Ultimately, repeated landscape-scale studies at numerous sites will provide the most robust understanding of the variability and generality of fire patterns (Heyerdahl *et al.* 2001).

Table 1. Summary of study site characteristics, listed from lowest to highest elevation
The Grandview site is located on the South Rim. The following four sites form a geographic and elevational transect from west to east on the North Rim

Study site	Code	Area (ha)	Elevation (m)	Average slope (%)	Vegetation type	No. of fire-scarred samples/Total fire scars/Total fire years
Grandview	GV	810	2244–2284	11.5	Ponderosa pine/Gambel oak	44/308/35
Powell Plateau	PP	315	2256–2336	11.5	Ponderosa pine/Gambel oak	46/443/64
Fire Point	FP	135	2308–2368	9.9	Ponderosa pine/Gambel oak	39/317/46
Rainbow Plateau	RP	225	2305–2335	23.2	Ponderosa pine/Gambel oak	34/238/50
Swamp Ridge	SR	270	2427–2537	13.3	Mixed conifer	30/208/32

Using fire records and field reconnaissance, we identified the three remote areas on the north-western edge of the North Rim where fire regimes were the least disrupted by fire management. 'Least disruption' was defined by management history, not by fire-scarred tree density or tree age. Four sites representing a biogeographical gradient (island [Powell Plateau] → peninsula [Rainbow Plateau, Fire Point] → mainland [Swamp Ridge]) were selected on the North Rim (Table 1; Fig. 1). Elevation increased along the gradient from 2256 m (ponderosa pine/Gambel oak forest) to 2537 m (mixed conifer forest). To distinguish geographic from elevational effects, we also selected a low-elevation (2264 m) pine/oak mainland site at Grandview on the South Rim. Although the total elevational change was small ($\sim$300 m), the North Rim study sites were situated directly over the major transition from ponderosa pine to mixed conifer forest. The total study site area was 1755 ha. All the sites were within Grand Canyon National Park, except 207 ha of the southern portion of the Grandview site, in the Kaibab National Forest. Within each study site, vegetation and topography were relatively homogeneous and there were no natural barriers to fire spread within sites.

Soil information was derived from an ongoing soil survey (A. Dewall, National Resource Conservation Service, personal communication 2002). Soils at the North Rim sites were tentatively classified as Typic Paleustalfs. Soils at the Grandview site were classified as Vertic Paleustalfs and Haplustalfs, clay soils weathered from calcareous sandstone parent material. Average annual precipitation at the North Rim ranger station (elevation 2564 m) is 64.7 cm, with an average annual snowfall of 356 cm. Temperatures range from an average July maximum of 25.1°C to an average January minimum of −8.2°C. At the South Rim (elevation 2070 m), average annual precipitation is 44.0 cm with an average annual snowfall of 177.6 cm; average July maximum temperature is 28.9°C and average January minimum temperature is −8.2°C (Western Regional Climate Center, www.wrcc.dri.edu). Forest vegetation included ponderosa pine (*Pinus ponderosa* var. *scopulorum* P. & C. Larson), Gambel oak (*Quercus gambellii* Nutt.), and New Mexican locust (*Robinia neomexicana* Gray) trees, with an understory of forbs and perennial grasses. At the higher-elevation Swamp Ridge site, oak and locust were not encountered but white fir (*Abies concolor* (Gord. & Glen.) Hoopes.), Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Mirb.) Franco), and aspen (*Populus tremuloides* Michx.) were found. All sites were dominated by ponderosa pine. Although the contemporary vegetation at Swamp Ridge was a mix of species, dendroecological reconstruction of the site showed that pine comprised 75% of the basal area in 1879, the year of the last widespread fire at the site (Fulé *et al.* 2002).

Native Americans populated the lower elevations of the canyon rims until a regional abandonment around A.D. 1250–1300 (Altschul and Fairley 1989). On Wahalla Plateau (eastern North Rim, similar in elevation and vegetation to Powell Plateau, Rainbow Plateau, and Fire Point), Schwartz *et al.* (1981: 126) stated that 'fairly intensive use of the area is unquestionable', even though precise population numbers could not be estimated from the archeological evidence. We encountered ruins on most of the ridges on Powell and Rainbow Plateaus. Several tribes, including the Paiute, Hopi, Havasupai, Hualapai, Navajo, and Zuni, have ancestral and current connections to the rim habitat.

European settlement of southern Utah was begun by Mormon pioneers in 1854 but fighting with Utes and Navajos kept them out of the Kaibab plateau until 1869. European settlement on the South Rim began around 1885 with homesteading, construction of the first tourist hotel (near the Grandview study site), and prospecting (Verkamp 1940). Surface fire regimes were disrupted in forested highlands as early as 1870 in the Mt Trumbull area (P.Z. Fulé, unpublished data), about 85 km west of the Kaibab Plateau, and between 1876 and 1883 in the Flagstaff area, about 100 km south-east of the Grandview site (Dieterich 1980; Fulé *et al.* 1997). Early livestock grazing was excessive (Altschul and Fairley 1989) and removed fine herbaceous fuels, limiting fire spread across most of the Southwest (Dieterich 1980; Savage and Swetnam 1990).

Grand Canyon Forest Reserve was designated in 1893, followed by creation of Grand Canyon National Park (GCNP) in 1919. In North Rim forests, Wolf and Mast (1998) found complete fire exclusion by about 1920. Livestock were fenced out of the North Rim by 1938 (M. Schroeder, GCNP archeologist, personal communication, 1999). Park management policy advocates restoration of natural ecological processes,

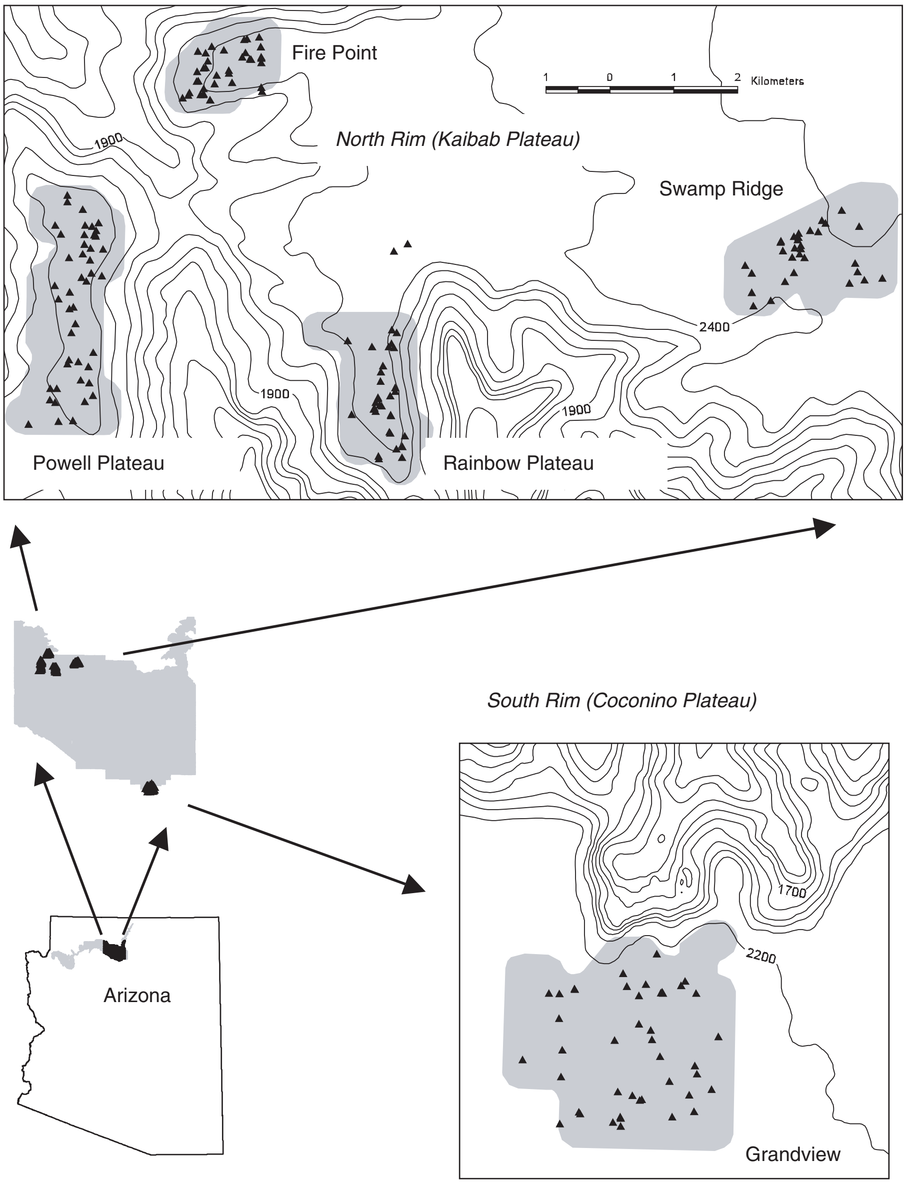

Fig. 1. Study sites (shaded gray) on the North and South Rims of Grand Canyon National Park. The Grandview study area extends into the Kaibab National Forest. Dark triangles are locations of fire-scar samples. Scale is identical in each topographic inset; contour interval is 100 m.

especially fire, but the presently dense forests and heavy fuel loads hinder effective re-introduction of fire on much of the North Rim (Pyne 1989).

Field and laboratory methods

Sampling

Fire-scarred tree sampling was done in October–November 1997, at the Grandview and northern Swamp Ridge sites, and June–July 1998, at the three remaining sites. Sampling was completed at the southern portion of the Swamp Ridge site in July and September 1999. The intent of sampling was to obtain as complete as possible an inventory of fire dates and point locations (i.e. scarred tree locations) where these fires occurred (Swetnam and Baisan 1996). We reconstructed comprehensive fire histories over large study areas. Each study site was completely surveyed along parallel transects to observe all fire-scarred trees. Trees with the longest series of fire scars were selected, an example of 'targeted' sampling (Baker and Ehle 2001). Partial cross-sections were cut from scarred 'catfaces' on trees, logs, and stumps of conifers. Samples were mapped when collected and were well-distributed throughout the study areas (Fig. 1). In a companion study, we measured vegetation, tree age structure, and fuels on 0.1-ha plots located on a 300 × 300 m sampling grid at the same study sites (Fulé *et al.* 2002).

Dendrochronology

In the lab, samples were mounted, surfaced with fine-grit sandpaper, and cross-dated (Stokes and Smiley 1968) using characteristic patterns of narrow marker years: 1722, 29, 35, 48, 52, 72, 82; 1810, 13, 20, 22, 45, 47, 73, 79, 96, 99; 1902, 04, 51, 63, 77, 96. All dates were independently confirmed by another dendrochronologist. The season of fire occurrence (Baisan and Swetnam 1990) was estimated based on the relative position of each fire lesion 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), as conventionally done in the Southwest (Baisan and Swetnam 1990).

Sampling adequacy

Since fire scars are recognized as minimum recorders of fire occurrence (some fires leave no scars: Dieterich and Swetnam 1984), the adequacy of field sampling was tested by examining the cumulative fire dates added by successive samples in random order at each study site. In a manner analogous to a species–area curve, the number of new fire dates would be expected to reach a plateau before all fire-scarred samples were included if the sampling had in fact captured all of the fires. In contrast, if the number of new fire dates rose proportionally with the addition of new samples, then the sampling would have been inadequate to inventory the fires. The value of multiple-recording fire-scar samples was also tested at each site by selecting the best (most scars per sample) and worst (fewest scars per sample) 10% of recorders in each sample set, comparing the number and proportion of fire years captured by each group. Since tree bark typically grows thicker with age, the ability of a scarred tree to record fires might decrease given a long fire-free period (although note that all of our sampled trees had open 'catfaces' or scars; none had completely healed over). If this were true, the sampling of the oldest possible recording trees could be biased against recent fires that would be recorded on younger trees with thinner bark (Baker and Ehle 2001). We tested this hypothesis by calculating the proportion of recorders that covered long gaps, many decades to over a century.

In some forests where stand-replacing fires occurred together with surface fires, it has been suggested that the primary ecological role of fire is carried out by infrequent, relatively severe burns, while the more frequent burns recorded on scarred trees are considered to be limited in area and/or impact (Johnson and Gutsell 1994; Shinneman and Baker 1997; Kipfmueller and Baker 2000; Minnich *et al.* 2000; Baker and Ehle 2001). In such a situation, the use of fire-scarred trees to determine fire history could overestimate the occurrence of fires that alter stand structure. The study sites were relatively homogeneous in vegetation type (Warren *et al.* 1982) and aerial photos as well as field reconnaissance showed no large patches (> 1–2 ha) that might have originated from stand-replacing fires. The fire-scarred trees themselves are multi-century fire survivors, indicating that no fire causing complete mortality had crossed the study sites over the analysis period. At a finer scale, we examined the distribution of minimum tree ages from the companion vegetation study (Fulé *et al.* 2002).

Fire data analysis

Data were analysed with FHX2 software (Grissino-Mayer 1995). Analysis at each site began with the first year with an adequate sample depth, defined as the first fire year recorded by 10% or more of the total sample size of recording trees at each site (Grissino-Mayer *et al.* 1994). 'Recording' trees are those with open fire scars or other injuries (e.g. lightning scars), leaving them susceptible to repeated scarring by fire. Agee (1993) described the mechanisms by which trees record multiple scars (resinous deposits, exposed dead wood, and thin bark next to the wound).

Fire return intervals were analysed statistically in different sub-categories that are related to the size and/or intensity of past fires. The size of past fires in frequent-fire ecosystems cannot be precisely reconstructed because most overstory trees survive such fires, precluding fire history methods based on stand ages and stand mapping. However, Swetnam and Baisan (1996) argued that fire years in which only one or two samples were scarred probably represented relatively small fires, while fire years in which a greater proportion of samples were scarred represented relatively larger fires. Accordingly, the fire data were filtered to look at progressively greater proportional 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.

The statistical analysis of fire return intervals includes several measures of central tendency: the mean fire interval (MFI, average number of years between fires); the median; and the Weibull median probability interval (WMPI). The latter statistic is a measure of central tendency in the Weibull distribution, used to model asymmetric fire interval distributions and to express fire return intervals in probabilistic terms (Swetnam and Baisan 1996; Grissino-Mayer 2000). Since fire return intervals are rarely normally distributed, the WMPI may be preferred over the MFI, although the values are often numerically similar. Regional fire occurrence among the North Rim sites was analysed from 1700 to the present. Fires *within* sites were analysed in the all-scar and 25%-scar categories, to examine possible differences in fire regime between smaller and larger fires.

Comparison of data across different-sized study sites could be problematic because more scars recording small fires might be included in larger study sites (Agee 1993; Swetnam and Baisan 1996). At 810 ha, the Grandview study area was six times larger than the smallest area sampled, Fire Point. To test the sensitivity of the Grandview fire regime to sampling area, we divided the sample set into geographically distinct quarters, divided N–S and E–W, and fire frequencies of the quarters were compared. At the regional scale, the occurrence of simultaneous or wide-spreading fires across the western North Rim *between* sites was compared in three categories: all fire years (fire at any site); fire years at 50% or more of the sites; and fire years represented at 75% or more of the sites.

To see whether fire return intervals had changed over time before European settlement, the fire records prior to recent fire exclusion were divided into earlier and later halves at each study site and compared. Fire distributions were tested for significantly different means (t-test), variances (F-test), and distributions (Kolmogorov–Smirnov test). Alpha level for all tests was 0.05. In addition, the spatial homogeneity of fires was investigated by dividing each site into geographic halves and testing the synchroneity of fire years (χ^2 tests, 2×2 and 2×1 contingency tables [Grissino-Mayer 1995]).

Climate

The relationship between climatic fluctuations and fire occurrence was compared with superposed epoch analysis (SEA), using software developed by Grissino-Mayer (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 Severity Index ($r = 0.67$) for grid point 31 in northern Arizona, A.D. 1694–1978 (Cook *et al.* 1996). The SEA superimposes fire years and summarizes the climate variable for fire years as well as preceding and succeeding years. Confidence intervals were developed using bootstrapping methods with 1000 simulations based on random windows with the actual fire events. Reconstructed positive or negative extreme years of the Southern Oscillation Index (Stahle and Cleaveland 1993), which has been shown to be associated with fire activity in the Southwest (Swetnam and Betancourt 1990) were also compared with years in which fires burned at a majority of the Grand Canyon study sites.

Fire records

At Grand Canyon, many fires occurred during the 20th Century, permitting us to test the accuracy of the fire-scar record using fire records back to 1924. In contrast, the lands where the majority of south-western fire history studies have been carried out have good fire records but few or no 20th Century fires (Swetnam and Baisan 1996). Some forests in northern Mexico have had many 20th Century fires, but the written fire records are inadequate for comparison (Fulé and Covington 1997, 1999).

The fire-record data were used with caution. The historical data were patchy in the early years, so the observed long-term trend toward increasing fire occurrence may be a real phenomenon or may be due to increasingly sophisticated detection methods and better record-keeping. Many recorded fire sizes and geographic locations were considered approximate and some evident errors were observed, such as coordinates that placed fires well outside the park boundaries. Nonetheless, the database was a valuable independent source of fire history information. After completing the fire-scar analysis without reference to the database, we selected records of fires occurring in and around (within 1 km) the study sites for comparison with the fire-scar data.

Results

Sampling adequacy

Cumulative sample curves (Fig. 2*a*) showed that 100% of fire dates were captured with less than 100% of samples at all study sites. Fifty percent of the samples recorded 94% of fires at Grandview, 72% at Fire Point, 78% at Powell Plateau, 86% at Rainbow Plateau, and 84% at Swamp Ridge. The top 10% of recording samples averaged 68% of the total number of fire dates, while the bottom 10% of samples averaged only 17% (Table 2). Fire-scarred sample depth over time is shown in Fig. 2*b* and summarized in Table 1.

Bark thickening or other changes with age did not degrade the ability of trees with open, unhealed scars to record fires, as many were scarred before and after long fire-free intervals, so there is no evidence that selection of old trees for sampling would cause recent fires to be missed. At Fire Point, 20 recorders of 25 potentially recording sample trees (80%) covered the 44 year fire-free gap from 1879 to 1923 and 100% (4 recorders/4 potential) covered the 66 year gap from 1923 to 1989 (fire-free gaps are shown in Fig. 3). At Powell Plateau, 14/24 (58%) of trees recorded over the combination of fire-free gaps from 1892/1895/1923/1924 to 1986/1987/1988. At Rainbow Plateau, 4/7 (57%) recorded over the 1900–1970 gap and 12/17 (71%) over the 1900–1985 gap. The longest fire-free periods were encountered at Grandview, where 8/11 (73%) recorded over the gap between 1887 and the fires in 1981/1985/1986.

Minimum ages of trees in plots on a 300 × 300 m grid across each study site predated 1800 on an average of 72% of plots and predated 1700 on an average of 20% of plots (Table 3). The exception was the previously harvested Kaibab National Forest portion of the Grandview site, where only 22% of plots had trees predating 1800.

Comparison of fire-scar data with fire records

Fire scars were highly accurate in identifying historical fires: *each of the 13 recorded fires on the study sites larger than*

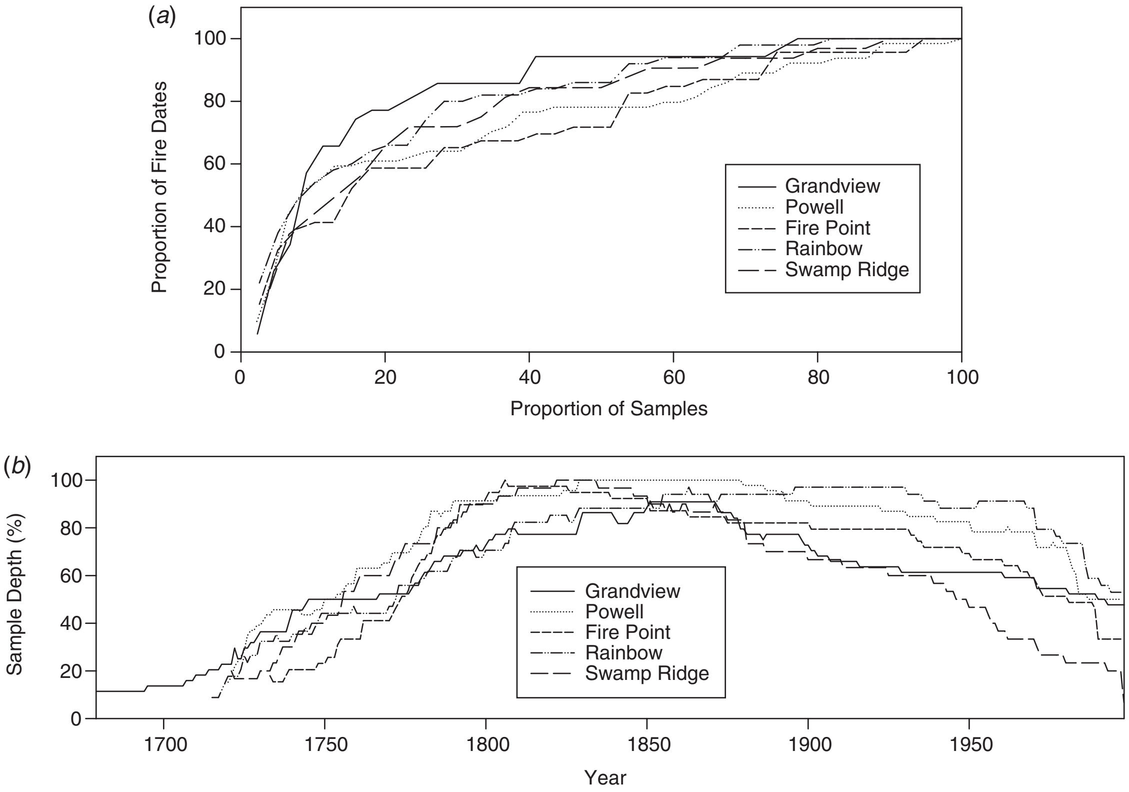

Fig. 2. (*a*) Cumulative fire dates expressed as a proportion of total fire dates versus cumulative proportion of total fire-scarred sample size. Fire-scarred sample sizes are shown in Table 1. (*b*) Sample depth (number of recording samples in each year) as a proportion of total fire-scarred sample size. Fire-scarred sample sizes are shown in Table 1.

Table 2. Number and proportion of fire years captured by the 10% of samples at each study site with the greatest number of fire dates ('best recorders') and the 10% of samples with the fewest number of fire dates ('worst recorders')

Site	No. of fire years	Percentage of fire years
GV best	22	63
GV worst	6	17
PP best	43	80
PP worst	14	21
FP best	37	80
FP worst	8	21
RP best	27	54
RP worst	6	12
SR best	25	78
SR worst	4	13

8 ha since 1924 was identified from fire scars (Table 4). Wildfires, prescribed natural fires, and prescribed fires—differing in season and arguably also in intensity—were all correctly identified. The largest fire recorded in the database but missed in the fire-scar reconstruction was an 8-ha prescribed natural fire on the Rainbow Plateau (6/87). Numerous small fires suppressed at sizes of 0.04–0.4 ha did not show up in the fire-scar record. For example, approximately 25 fires of 1 ha or smaller in size were documented in historical records on the Powell Plateau study area since 1924. (The number of fires is approximate because of possible inaccuracies in recorded locations; other clues, such as fire names, were also used to assess whether a fire's recorded location may have been incorrect). The proportion of scarred trees was generally related to recorded fire size [see Fulé *et al.* (2000) for a graphical comparison of fire-scarred sample locations to mapped fire size for the Emerald fire on Rainbow Plateau (8/93, 138 ha)]. The greatest discrepancy between fire size and scarring proportion occurred with the 1931 Fire Point fire; it burned 65 ha (some of which may have been below the rim) but was recorded only on a single scarred sample. Season of fire occurrence, as identified on the fire-scarred samples, corresponded well with the recorded fire dates (Table 4). A few fires represented by dormant season scars were moved back a calendar year, as noted in the Grandview section below. Several fire scars did not correspond to any fire records, such as a 1950 fire that scarred a single sample tree on Powell Plateau. In other cases, there was a discrepancy between the scar sample location and the mapped fire location. For example, a 2-ha fire occurred near the north-eastern corner of Powell Plateau in June, 1953, according to the database. We found a single sample scarred in 1953 located approximately

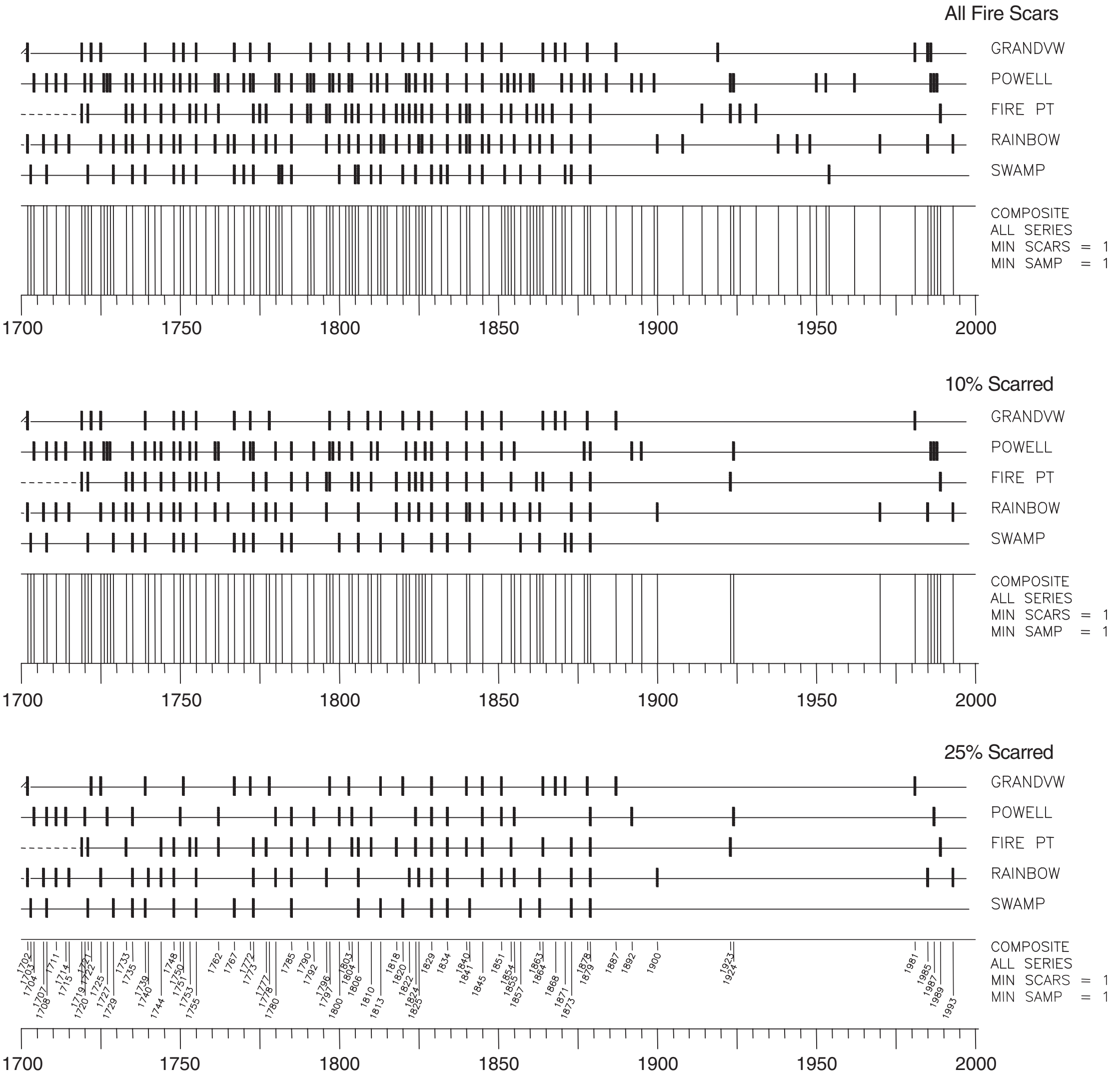

Fig. 3. Fire history results are summarized in these graphs, with each horizontal line representing the composite of all sampled trees on a site and the short vertical lines noting the year of fire occurrence. Fire regimes are compared in three categories: *all fires*, including even those which scarred only a single sample tree (top graph); fires scarring *10% or more* of the sample trees on each site (middle graph); and fires scarring *25% or more* of the sample trees (bottom graph).

1 km to the south-west of the database fire location. The earlier practice of recording fire locations by township, range, and section may have contributed to location errors. Since the Grand Canyon is not surveyed into townships, firefighters had to estimate legal descriptions by extending township lines from adjacent areas on maps.

Table 3. Proporation of plots in a companion study containing trees predating 1800, 1700, or 1600

Sample plots were 20 × 50 m in size located on a 300 × 300 m grid. The Kaibab National Forest site is adjacent to the southern portion of the Grandview site

Site	No. of plots	Percentage of trees predating		
		1800	1700	1600
Grandview	67	64	37	1
Kaibab National Forest	23	22	1	0
Powell Plateau	36	67	22	3
Fire Point	15	93	20	0
Rainbow Plateau	25	72	20	8
Swamp Ridge	30	63	3	0

Fire regime data

The following results are presented from lowest-elevation (Grandview) to highest-elevation (Swamp Ridge) study sites.

Grandview

Fire frequency (WMPI) averaged 6.5 years at the Grandview study site from 1679 to 1887 (Table 5), when fires stopped abruptly (Fig. 3). Grandview had the smallest

Table 4. Comparison of historical fire dates from GCNP records with fire seasonality estimated from scar location within the tree ring

Fire-scar seasonality codes are: EE: early earlywood; ME: middle earlywood; LE: late earlywood; L: latewood; D: dormant; and U: unidentifiable season

Site	Fire name	Fire date (month/year)	Fire size (ha)	Seasonality of scars[A]
GV	Hearst	11/81	174	L, U, U, U, U, U
GV	Hearst	8/85	243	LE, L
GV	B Block	4/86	61	D, D
PP	Powell	7/24	650	ME, ME, ME, ME, ME, LE, LE, LE, L, U
PP	Powell 2	12/62	23	U
PP	Zephyr	9/86	146	U, U, U
PP	Muav	7/87	324	ME, ME, LE, L, U, U, U
PP	Dutton	7/88	1332	ME, ME, U, U
FP	Fire Point	8/31	65	U
FP	Muav	7/89	708	LE, U, U, U
RP	Rainbow Pl.	10/48	7	U
RP	Rainbow	5/70	19	D, U, U, U
RP	Rainbow	10/85	526	LE, L, D, D, D, D, D, U, U, U, U, U, U
RP	Emerald	8/93	138	ME, LE, LE, L, L, L

[A] Number of codes shown equals the number of recording trees.

Table 5. Fire return intervals at the study sites

Statistical analysis was carried out in three categories: (1) all fire years, including those represented by a single fire scar; (2) fire years in which 10% or more of the recording sample trees were scarred; and (3) fire years in which 25% or more of the recording sample trees were scarred. s.d.: standard deviation; WMPI: Weibull Median Probability Interval

Site/analysis period	No. of intervals	Mean (MFI)	Median	s.d.	Min.	Max.	WMPI	Ratio WMPI$_{25\%}$:WMPI$_{All}$
Grandview/1979–1887								
All scars	30	6.9	6	3.8	2	17	6.5	1.4
10% scarred	29	7.2	6	4.4	2	19	6.6	
25% scarred	22	9.5	8	5.2	3	20	8.9	
Powell Plateau/1720–1899								
All scars	54	3.2	3	2.0	1	9	3.0	2.9
10% scarred	39	4.5	4	3.9	1	22	3.8	
25% scarred	19	9.2	7	5.6	3	24	8.9	
Fire Point/1733–1879								
All scars	40	3.7	3.5	2.0	1	11	3.4	1.8
10% scarred	30	4.9	4.5	2.5	1	11	4.6	
25% scarred	23	6.4	6	2.5	2	11	6.3	
Rainbow Plateau/1715–1879								
All scars	41	4.0	4	2.0	1	11	3.9	2.0
10% scarred	31	5.3	4	2.8	1	12	5.1	
25% scarred	21	7.8	7	4.0	3	18	7.5	
Swamp Ridge/1721–1879								
All scars	31	5.5	5	3.4	1	15	5.1	1.7
10% scarred	24	7.1	6.5	3.8	2	16	6.8	
25% scarred	19	9.0	7	4.2	4	21	8.7	

difference of any study site between the all-scar and 25%-scarred distributions, implying that most fires were relatively large. The maximum fire-free period before European settlement was 17 years for all fires, 20 years for 25%-scarred fires. Fire seasonality was determined on 53% of the samples (Table 6). Because narrow tree rings were the most common reason for failure to identify the season, the determination of seasonal distribution might be biased toward years in which relatively good conditions for tree growth produced wider rings. Few samples recorded dormant season fires (12%) and none recorded latewood fires, but overall the site was nearly evenly divided between spring fires (54%) and summer fires (46%). Temporal and spatial divisions of the fire record prior to European settlement were not significantly different at Grandview or any of the other study sites. Division of the Grandview fire data into geographically distinct

Table 6. Seasonal distribution (number and percentage) of fire scars based on the position of the fire lesion within the scarred ring

Site	Season		Dormant	Early	Earlywood		Latewood	D + EE	ME + LE + L	EE + ME + LE
	Determined	Undetermined			Middle	Late		(spring)	(summer)	(earlywood fires)
GV	164 (53%)	144 (47%)	19 (12%)	70 (43%)	62 (38%)	13 (8%)	0	89 (54%)	75 (46%)	145 (88%)
PP	311 (70%)	132 (30%)	41 (13%)	7 (2%)	134 (43%)	90 (29%)	39 (13%)	48 (15%)	263 (85%)	231 (74%)
FP	238 (75%)	79 (25%)	38 (16%)	5 (2%)	116 (49%)	66 (28%)	13 (6%)	43 (18%)	195 (82%)	187 (79%)
RP	141 (59%)	97 (41%)	17 (12%)	9 (6%)	72 (51%)	36 (26%)	7 (5%)	26 (18%)	115 (82%)	117 (83%)
SR	169 (81%)	39 (19%)	9 (5%)	11 (7%)	61 (36%)	51 (30%)	37 (22%)	20 (12%)	149 (88%)	123 (73%)

groups caused no significant difference in fire occurrence. The $\mathrm{MFI}_{\mathrm{All}}$ values for each group differed from the overall $\mathrm{MFI}_{\mathrm{All}}$ by less than 1 year (average = 0.4 year), indicating that the all-scar fire frequency at Grandview was not artificially inflated due to the large sampling area.

Fires were excluded through the early 20th Century, except for two samples scarred in 1919. The scarred trees were located about 1.3 km apart near the Hearst Tanks (north end of the study area). Beginning in 1981, prescribed burns scarred a number of trees on the site. Correlating GCNP records with the fire-scar dates, we identified the Hearst burn (11/81, 174 ha), another Hearst burn (8/85, 243 ha), and the B Block burn (4/86, 61 ha). Note that the same name (e.g. 'Hearst') was often used for fires in multiple years because of the practice of identifying fires by nearby features on topographic maps [also see Pyne (1989) for a discussion of less orthodox fire names]. Since the 1981 fire occurred in November, dormant-season scars occurring after the 1981 latewood were assigned the calendar year 1981. The prescribed burns did not overlap geographically. Together they covered approximately the northern third of the study site. The overall 20th Century fire history for the Grandview site thus includes:

(1) A portion which has not burned in the past 110 years (1887–1997 sample collection date);
(2) Portions which have burned once in one of three prescribed fires in the 1980s; and
(3) A portion which burned in 1919 as well as in a prescribed fire.

The fire-scar data for Grandview were also compared with a previous fire history by Duhnkrack (1982), who used the fire history procedure of Arno and Sneck (1977) to estimate fire dates for nine scarred samples from the GCNP portion of the study area. His fire dates did not coincide with the dates we found because his samples were not cross-dated. However, he calculated a mean fire interval of 7.3 years for the period 1750–1900, which is within 6% of the MFI of 6.9 years in our study (Table 5).

North Rim sites

Powell Plateau. Fire regimes on the Powell Plateau showed the greatest variability of all the study sites between the all-scar and 25%-scar fire interval distributions, implying that most fires were relatively small. The WMPI for all fires between 1720 and 1899 was the lowest of all the study sites, 3.0 years, but rose to 8.6 years for fires scarring 25% or more of the samples (Table 5). The maximum fire-free interval was 9 years for all fires, the lowest of all study sites, but Powell had the highest maximum for 25%-scarred fires (24 years). Fire seasonality at Powell and all the North Rim sites was strongly skewed toward later-season fires, averaging only 15–20% spring fires (Table 6).

Disruption of the Powell fire regime was complex. A relatively long fire-free period of 24 years began as early as 1855 in the 25%-scarred record, but Powell burned in 1879 in a large fire that scarred 31 of the 45 recording trees, covering the whole site. Approximately the northern two-thirds of the site (based on the mapped locations of fire scars) burned in 1892, with the remaining third burning in 1895. Twenty-nine years later, in July 1924, the 'Powell' fire crossed much of the site, burning about 650 ha. This fire is the first entry in the GCNP fire records. Small fires (scarring single trees) were recorded in 1950, 1953, and 1962 (Powell2 Fire, 12/62, 23 ha). The next large fires on the Powell site were the Zephyr (9/86, 146 ha), Muav (7/87, 324 ha), and Dutton (7/88, 1332 ha). The latter two fires were managed with prescribed natural fire (PNF) and confine/contain strategies, respectively. The 1987 Muav fire was the first large PNF on the Powell site.

Fire Point. Fires recurred with a WMPI of 3.4 years (all scars) to 6.3 years (25%-scarred) between 1733 and 1879 at Fire Point (Table 5). After 1879, the fire regime was disrupted for 34 years until a 1923 fire burned across approximately the western two-thirds of the study site. None of the eight recording samples in the eastern third of the study site was scarred by this fire, suggesting that the eastern portion had not burned since 1879. The 'Fire Point' fire of 8/31 burned about 65 ha, also in the western portion of the site, but was represented in the fire-scar data by only a single sample. In July 1989, the 708-ha Muav fire scarred trees on Fire Point but was contained to the south-western corner of the study site. After sampling for the present study was completed, the entire site was burned in the Boundary fire (9/99, 156 ha).

Rainbow Plateau. The WMPI was 3.9 years (all scars) and 7.5 years (25%-scarred) between 1715 and 1879 on the Rainbow Plateau site. Maximal fire-free intervals prior to European settlement ranged from 11 years (all scars) to 18

Table 7. North Rim regional fire interval analysis comparing pre-disruption fire years over multiple study sites

The analysis includes fire years represented *within* sites by the all-scars and 25% scarred categories. Within these categories, fire years are analysed *between* sites in three groups: (1) all fire years; (2) fire years represented on 50% or more of the sites; and (3) fire years represented on 75% or more of the sites. Fires after 1879 never occurred on more than one study site per fire year, so only the 'all fire year' category is reported. Swamp Ridge had no fires after 1879, except for a single scarred tree in 1954, so it was not included in the 1880–1997 analysis

Site/Analysis period Scar category	No. of intervals	Mean (MFI)	Median	s.d.	Min.	Max.	WMPI
All North Rim sites/1721–1879							
All scars within sites							
All fire years	83	1.9	2	1.1	1	5	1.8
50% years	49	3.2	3	1.6	1	8	3.1
75% years	20	5.5	5.5	5.6	1	22	6.3
25% scarred within sites							
All fire years	46	3.5	3.5	1.9	1	9	3.3
50% years	20	7.9	7	4.2	2	19	7.5
75% years	10	14.4	12.5	7.8	5	28	13.7
Powell, Rainbow and Fire Point/1880–1997							
All scars within sites							
All fire years	24	4.7	4	3.5	1	15	4.0
25% scarred within sites							
All fire years	8	13.1	4	20.6	1	61	6.8

years (25%-scarred). Only 21 years after 1879, a fire in 1900 burned over the entire study site. Smaller fires confined to the southern tip of the plateau burned in 1908, 1938, 1944, 1948 (Rainbow Plateau fire, 10/48, 7 ha), and 1970 (Rainbow fire, 5/70, 19 ha). The entire study site was burned in the Rainbow fire (10/85, 526 ha), which was suppressed, and again in the Emerald prescribed natural fire (8/93, 138 ha).

Swamp Ridge. WMPI values ranged from 5.1 years (all scars) to 8.7 years (25%-scarred) between 1721 and 1879 (Table 5). Maximum fire-free intervals were also relatively long, 15–21 years for the all-scar and 25%-scarred distributions, respectively. The Swamp Ridge site has undergone the longest fire exclusion period of any of the study sites, with no fires recorded after 1879, except for a fire scarring a single sample tree in 1954.

Gradient analysis of fire regimes

Fire frequency and variability prior to European settlement declined over the geographic and elevational gradient from Powell Plateau to Swamp Ridge, a region encompassing approximately 96 km^2. Fire intervals increased by 150–200% (depending on the site and proportional scarring category). The westernmost site, Powell Plateau, had the greatest difference in frequency of large vs. small fires, with the $\mathrm{WMPI}_{25\%}$ nearly 300% greater than the $\mathrm{WMPI}_{\mathrm{All}}$. The difference dropped to 180–195% at Fire Point and Rainbow Plateau, respectively, and was only 150% at Swamp Ridge (Table 5). On the North Rim, average site elevation was correlated with $\mathrm{WMPI}_{\mathrm{All}}$ ($r = 0.94$) and the ratio of large to small fires ($\mathrm{WMPI}_{25\%}$:$\mathrm{WMPI}_{\mathrm{All}}$, $r = -0.63$), but $n = 4$. The pattern did not extend to the South Rim: the highest $\mathrm{WMPI}_{25\%}$ and $\mathrm{WMPI}_{\mathrm{All}}$ values were recorded at Grandview, the lowest-elevation study area. In general, geographic position was related to fire frequency: island most frequent → point/peninsula → mainland least frequent. But when fires occurred, mainland sites were as much as twice as likely to have large fires, as indicated by the lower ratios of $\mathrm{WMPI}_{25\%}$:$\mathrm{WMPI}_{\mathrm{All}}$ in Table 5.

Before 1879, a fire burned in at least one of the North Rim study sites nearly every 2 years (Table 7). In the 'all scar' category, fires burned in two of the four sites with a WMPI of 3.1 years and in three or more sites with a WMPI of 6.3 years. Restricting the analysis to years in which 25% or more of the samples were scarred—that is, years in which most sites burned with large fires—intervals were approximately twice as long (3.2–13.7 years).

The climate–fire relationship differed over the gradient of study sites (Fig. 4). At all sites, fires tended to occur in dry years following wet years. But the fire years at Grandview, the lowest elevation site, were not significantly dry. At the highest-elevation site, however, the fire years were significantly drier than the 99th percentile of the bootstrapped sample. A 'dryness' index for each site was estimated by taking the ratio of the mean tree-ring width index during fire years to the bootstrapped—99th percentile tree-ring width index. Elevation was highly correlated with 'dryness', with $r = 0.97$ for a declining polynomial relationship.

Major fire years, defined as those in which at least three of the four North Rim study sites burned, are listed in Table 8. Twelve of the 20 major fire years were relatively dry, consistent with the SEA results. The driest year in the 1721–1879 period, 1847, was not a major fire year, but three out of the four sites burned in the second-driest year, 1822. None of the major fire years coincided with reconstructed positive or negative extreme years of the Southern Oscillation Index (Stahle and Cleaveland 1993). Fires occurred on the Grandview site on only 20% (4 out of 20) of the North Rim's major fire years.

After 1879, fire regimes were disrupted at all the North Rim study sites (with the exception of Powell Plateau, Fig. 3). No further fires occurred at the Swamp Ridge site except the single-scarring fire in 1954. Fire-free intervals for the other three sites between 1879 and 1997 were longer than intervals prior to European settlement (Table 7) and no two sites have had fires in the same year since 1879 (Fig. 3).

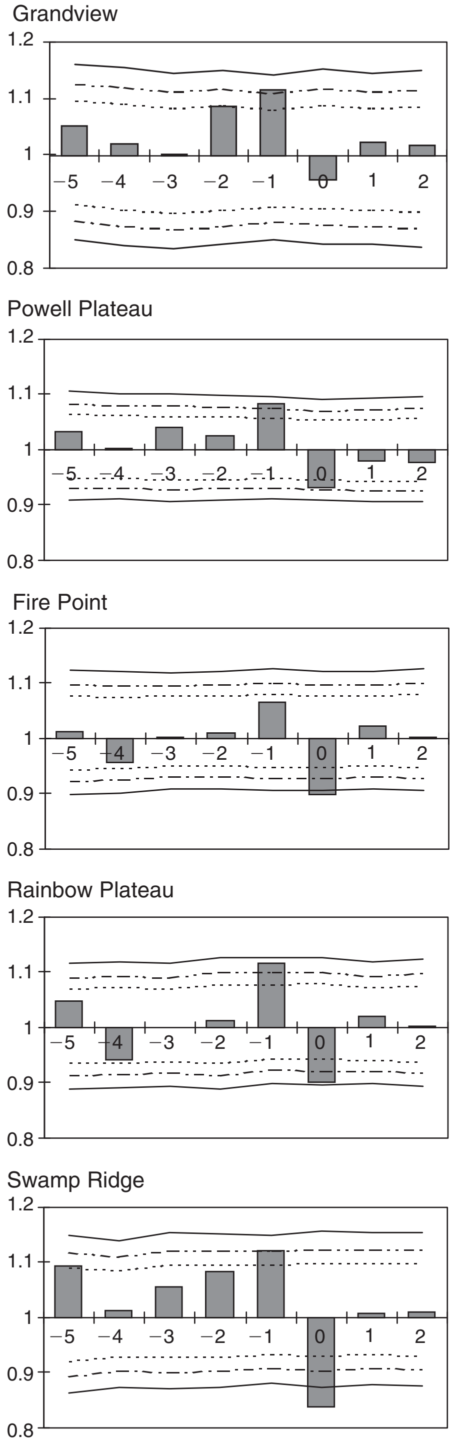

Fig. 4. Superposed epoch analysis (SEA) showing the relationship between local climate (tree-ring width index) and fire occurrence. Sites are listed from lowest elevation (Grandview) to highest (Swamp Ridge). The average climate value is scaled to 1. Bootstrapping procedures were used to assess the statistical significance of climate departures above the mean ('wet years') and below the mean ('dry years') in the fire years (year 0), the 5 years preceding fires (−5 through −1), and the 2 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%.

Discussion

Validity of fire-scar sampling and analysis

The reliability of fire-scar analysis as a means for reconstructing fire patterns has been an important question for decades (Stokes and Dieterich 1980; Agee 1993; Baker and Ehle 2001). Fire-scar methods are inherently limited because not every fire scars trees, even those with open 'recording' scars (Dieterich and Swetnam 1984), fire-scarred trees are not uniformly distributed across the landscape, and individual scarred trees differ greatly in the number of fires and temporal period recorded. Johnson and Gutsell (1994: 268) criticized the 'informal' sampling of fire scars, arguing that random (or stratified) sampling was necessary to develop valid quantitative estimates of fire frequency. In a detailed treatment of all south-western fire-scar studies to date, Swetnam and Baisan (1996, 2003) reviewed the assumptions, limitations, and statistical approaches, focusing on the mechanisms through which the landscape-scale process of fire is recorded in point locations. The central argument was that the object of study was the fire events, not the trees that record fires, suggesting that random tree sampling was not helpful. Instead, assuming that study areas were well-chosen (relatively homogeneous, without barriers to fire spread, etc.), sampling of well-distributed trees with multiple scars would provide the most complete and extensive fire record.

Fall (1998) identified three sources of uncertainty in fire-scar studies:

(1) A fire may fail to leave a record (scar) in every burned location;
(2) A severe fire may erase previous records; or
(3) Sampling may not detect all past fires, even if a record exists.

The first source is an inherent limitation (Dieterich and Swetnam 1984). The second source of uncertainty, severe fire, appears not to have occurred in the temporal period of this study. Sites were homogeneous in vegetation type, no large patches (>1–2 ha) that may have been fire-caused were detected, fuel accumulation would have been limited by

Table 8. Major fire years based on the percentage of fire occurrence (all fires) at all the North Rim study sites between 1721 and 1879

Palmer Drought Severity Index (PDSI) values were reconstructed by Cook *et al.* (1996, grid point 31). Negative PDSI values indicate dry conditions

Year	No. of sites burned	No. of recording sites	% of sites burned	Fire interval	PDSI
1733	3	4	75	–	−0.99
1735[A]	4	4	100	2	−4.83
1739[B]	3	4	75	4	−1.87
1744	3	4	75	5	0.27
1748[A,B]	4	4	100	4	−2.38
1755[A,B]	4	4	100	7	−3.61
1773[A]	4	4	100	18	−3.42
1785[A]	4	4	100	12	−1.09
1800	3	4	75	15	−2.83
1806[A]	3	4	75	6	−1.52
1810	3	4	75	4	−0.61
1822	3	4	75	12	−2.48
1829[A,B]	4	4	100	7	−0.79
1834[A]	4	4	100	5	−1.06
1840	3	4	75	6	3.42
1841	3	4	75	1	−1.51
1845[A]	3	4	75	4	−3.58
1851	3	4	75	6	−0.83
1873[A]	4	4	100	22	−2.11
1879[A]	4	4	100	6	−4.66

[A] Also a major fire in the 25%-scarred category.

[B] Also a fire year at the Grandview (South Rim) study site.

frequent surface fires, old trees were found at most points on 300 × 300 m grids, and all sites were highly uneven-aged (Table 3, complete age structure in Fulé *et al.* 2002). However, small patches of severe burning or other disturbance causing mortality cannot be excluded.

Incomplete detection, the third source of uncertainty, cannot be verified without complete sampling of all fire-scar evidence, presumably including buried scars in intact trees (McClaran 1988). A scar census to test the detection threshold would be a useful contribution but such sampling would have been beyond the scope, authorization, and ethical constraints of this study, requiring cutting into large numbers of old-growth trees in a national park. However, the cumulative sample curves (Fig. 2) indicated that the samples collected captured most of the fire years, i.e. that continued sampling would have contributed very few additional fire dates. Furthermore, the facts that the 10% of best recorders captured 54–80% of fire dates and that the first 50% of random recorders captured 72–94% of fire dates support Swetnam and Baisan's (1996) contention that fire history information should be sought specifically in the best recorders, not in random scarred trees. Since the sample set as a whole contains the best recorders from each study site, adding more poor-recording samples would have produced diminishing returns even below the level suggested by the cumulative sample curves. The hypothesis that old trees with open, unhealed fire scars would be poor recorders of recent fires because of thickening bark was not supported by evidence of high fire recording rates across multi-decadal to century-long fire-free gaps.

In their critical review of fire-scar analysis, Baker and Ehle (2001) argued that the uncertainty associated with sampling problems and extrapolation between scarred points was so large that mean fire interval statistics should be bracketed as much as 1100–1200%. This concept was not supported in the present study. The acid test of fire-scar validity was the detection of all 13 historical fires >8 ha. There was no evidence of overestimation of fire occurrence (Minnich *et al.* 2000), as long as the proportional filtering of fire size is taken into account so that all-scar fire statistics are considered separately from statistics for larger fires, as done here. Thus for 75 years (1924–1999) over 1755 ha, we correctly identified fires down to an 8-ha patch size. Unless one assumes that the mechanisms of fire-tree interaction were different prior to 1924, there is no need to 'bracket' the fire history statistics, other than explicitly to make two points:

(1) Some additional small fires were probably missed; and
(2) Virtually all fires, including those prior to 1880 as well as at present, burn with a mosaic of intensities and include unburned areas within the overall fire perimeter.

In sum, within the understood limitations of the physical evidence, sampling capability, and burning variability, the methodology of this study appears to be a consistent and accurate approach to detailed reconstruction of approximately 300 years of fire disturbance at these study sites.

The reliability of fire-scar analysis has broad implications for management because plans for restoration of ponderosa pine and forests with similar fire ecology characteristics are predicated on the view that frequent, low-intensity fires and low-density forests were natural and desirable features (Covington 2000; McIver *et al.* 2001; USDA/USDI 2002). If Baker and Ehle's (2001) alternative interpretation of the same data were correct, with fire intervals as much as 10 times greater, managers would need to re-evaluate the ecological underpinning of forest restoration. Presumably plans for tree thinning and prescribed burning would be scaled back, while high-intensity fire might be more widely considered acceptable. There are both ecological and social reasons why a range of forest conditions may be suitable in specific times and places to meet management goals (e.g. Shinneman and Baker 1997; Brown *et al.* 1999; Tiedemann *et al.* 2000). But the high precision of the Grand Canyon data in this study indicates that the range of uncertainty perceived by Baker and Ehle (2001) was excessive. Management decisions at Grand Canyon and similar south-western forests should continue to rest on the regional range of historical variability in fire regimes, such as the data summarized by Swetnam and Baisan (1996), as a point of reference for evaluating ecological change and selecting restoration alternatives.

Fire regimes over the environmental gradient

Geographical location (island → point/peninsula → mainland) was weakly associated with fire frequency prior to European settlement (all fires) and the ratio between small and large fires at the Grand Canyon study area. Considering only the North Rim sites, fire frequency (all fires) declined moderately with increasing elevation and fires occurred in relatively drier years at higher elevations, consistent with the general trends throughout the Southwest (Swetnam and Betancourt 1990, 1998; Swetnam and Baisan 1996; Touchan *et al.* 1996; Brown *et al.* 2001). Using the 25%-scarred filter instead of all fires, however, mean fire intervals at Grandview, Powell Plateau, and Swamp Ridge were all within 0.5 year (range 9.0–9.5 years), with lower values only at Fire Point (6.4 years) and Rainbow Plateau (7.8 years). The inconsistency in the relationship between geographical location and fire frequency suggests that the biogeographical gradient is not a strong influence on fire occurrence and that apparent trends may depend on the choice of filter (e.g. all-scarred versus 25%-scarred).

A possible explanation for the high fire incidence on the western North Rim is that the topographically prominent points and plateaus are well-placed to receive lightning strikes, similar to the islands studied by Bergeron (1991), although the likelihood of ignition depends not only on lightning occurrence but also fuel conditions (continuity, moisture) (van Wagtendonk 1991). The historical lightning fire density of the western North Rim is high, reaching 2.7 fires/km^2 in the 1955–1980 period at the south end of Rainbow Plateau (unpublished fire density map, on file at Fire Management Office, GCNP). However, the data from the Grandview study site contradict the North Rim pattern.

The fire regime prior to European settlement at the Grandview area presented a distinct contrast to the North Rim pattern. Grandview was at the lowest elevation of all the study areas, having environmental characteristics most similar to Powell Plateau, but had the lowest fire frequency and the lowest ratio (1.37) between large and small fires, thereby displaying fire regime characteristics most similar to the high-elevation Swamp Ridge study area. The reasons for the differences are not clear. The South Rim may appear to be less well-placed for lightning than the prominent North Rim features, but historical records show that the highest lightning fire density in the park, 4.2 fires/km^2, is on the South Rim (top of Long Jim Canyon) and the lightning fire density across the Grandview study area is similar to that of Powell Plateau, up to 2.3 fires/km^2 in the 1955–1980 period (unpublished fire density map, on file at Fire Management Office, GCNP). We can speculate that the historical record might be more accurate for small lightning fires at Grandview, such as fires burning single snags before being extinguished by rain, because detection would be more likely on the populous South Rim than on the remote western North Rim. The Grandview study area is located immediately north of a lookout tower, facilitating detection of small fires. Other possible explanations might be differences in topography or fuels, but average slopes were identical at Powell Plateau and Grandview (Table 1) and vegetation communities and fuel loads are similar (Fulé *et al.* 2002).

Native Americans may have influenced fire regimes at all of the sites. There is extensive archeological evidence of people residing and farming at all of the study areas except Swamp Ridge until A.D. 1300. Many tribes used natural resources in the region up through early European settlement (Altschul and Fairley 1989). The historical record of lightning fires—dozens to over 100 ignitions per year—suggests that lightning alone may always have been sufficient to maintain frequent fire regimes. The occurrence of fires outside the typical fire season has been used to infer human-caused ignition (e.g. Baisan and Swetnam 1997; Kaye and Swetnam 1999); no pattern of unusual seasonal burning was observed in the present study. Human-caused fires have probably always been a factor in Grand Canyon ecosystems, but the extent and ecological importance of native burning remains uncertain.

Fire sizes prior to European settlement reached at least hundreds of hectares, for fires scarring 25% or more of the samples distributed across the study areas, and probably reached many thousands to tens of thousands of hectares. The 810-ha Grandview site is surrounded on the west, south, and east by contiguous ponderosa pine forest, providing opportunities for regional fires to spread across much larger areas.

The major North Rim fire years (Table 8) provide evidence of widespread fire in many years. The four North Rim study areas span an area of 96 km^2, of which 59% or 57 km^2 is forest (the remainder is below-rim vegetation). In years such as 1873 and 1879 it is likely that fire burned over most of this area. Since the typical wind direction in the fire season is from the south-west, fire sizes in such years may have grown much larger than the area covered by the east–west transect of our study areas. Multiple ignitions of fires in the same year or season are also likely. In the historical record, the maximum number of lightning fires, 125, occurred in 1988. Seventy-one lightning fires started that June with a record of 31 lightning starts on one day (17 June 1988). The second-closest month was July of 1970, with 41 lightning fires. In the absence of suppression activities, the role of multiple ignitions may have been moot in areas where fires could burn together. However, multiple ignitions were evidently important where fire spread was otherwise impossible, such as the 1748 fires on both North and South Rim sites.

Fire regime disruption and restoration

How big of a change in the natural fire regime constitutes a 'disruption' of this disturbance process? The absolute values of fire-free periods are probably less ecologically significant than the relative length of such periods compared with natural variability (Stephenson 1999). The modern fire-free periods at Swamp Ridge and Grandview are about 5.5 times longer than the maximum interval prior to European settlement for large (25%-scarred) fires. Across much of western North America, changes of this magnitude have been associated with increased living and dead fuels reaching a threshold beyond which fires become large-scale crown fires (Covington *et al.* 1994). In the absence of adaptations to permit regeneration or mechanisms to retain soil and propagules after large disturbances, forest conditions may be indefinitely altered (Romme *et al.* 1998).

Although fire frequency at the three non-mainland sites was clearly reduced after 1879, each experienced either two or three large surface fires since European settlement. These relatively uninterrupted fire regimes are highly unusual in the Southwest (Swetnam and Baisan 1996), even in comparison with the other large unharvested forest area, the Gila Wilderness in New Mexico (Swetnam and Dieterich 1985; but also see Rollins *et al.* 2000). Taking all three western North Rim sites together, regional fire intervals appear to have only approximately doubled since 1879 (Table 7), seeming to fall well within the pre-disruption maximum fire-free intervals (Table 5). However, such a comparison would obscure key differences between the pre-1879 and post-1879 fire regimes. Most importantly, since 1879 no fire has occurred at more than one study site per year.

Understanding the disturbance patterns that influenced an ecosystem is a critical first step for management. The next issue is how to apply the information. Even if perfect knowledge of past fire regimes were available, future actions must consider today's unique situation. Prior to 1880, Grand Canyon forests were characterized by large fire sizes, high fire frequency even on geographically isolated sites, and strong connection between extensive fires and dry years, implying that huge regions burned during droughts and that burned area and smoke production varied widely between years. In contrast, most modern management fires are either ignited or allowed to burn under 'safer' conditions, usually at much smaller sizes. Managers are unlikely to try to imitate the pre-1880 fire regime, but a thoughtful quantitative comparison of the past and present fire regimes could support adaptive testing of alternatives. There are several challenges.

First, smoke and the threat of escaped fire are major constraints, especially because the park boundaries are arbitrary east–west lines across the Kaibab and Coconino Plateaus.

Second, the change in forest composition since fire exclusion has been exactly opposite to the predicted direction of climate change: mesic species expanded to lower elevations. In contrast, future conditions are expected to be warmer and drier, more conducive to longer fire seasons and increasing total fire activity (Flannigan *et al.* 2000), reduction in range of temperate forest species like ponderosa pine and Douglas-fir (Shafer *et al.* 2001), and the likelihood that climate change will interact with fire and other disturbances in novel and possibly severe ways (Flanningan *et al.* 2000; Dale *et al.* 2001).

The remote North Rim sites may present a valuable example. Although fire frequency on the north-western points and plateaus prior to European settlement was much higher than the post-1879 fire occurrence, these sites may still be the best existing representatives of natural ponderosa pine forest landscapes in the Southwest. It would be useful to test the hypothesis that a few widely spaced fires can have ecological effects reasonably similar to those of the natural fire regime. If so, managers might be able to foster safe, low-smoke, and cost-efficient modern fire regimes by using wildland fire at longer intervals.

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