HISTORIC FIRE REGIMES ALONG AN ELEVATIONAL GRADIENT ON THE WEST SLOPE OF THE SIERRA NEVADA, CALIFORNIA

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The vegetation of Sequoia National Park, and the Sierra Nevada in general, has been greatly altered since the arrival of large numbers of Europeans in the nineteenth century. This change was largely due to the modification of the historic fire regimes (Kilgore and Sandro 1975; Vankat and Major 1978; Parsons and DeBenedetti 1979). The "natural" fire regime in the past was one of low severity surface fires with crown fires uncommon (Show and Kotok 1924; Kilgore 1973). As elsewhere in the western United States, suppression of pre-European fire regimes resulted in shifts in successional patterns and, in some cases, produced undesirable changes in vegetation composition and structure. The modification of historic fire patterns were due to a variety of land use practices and fire suppression efforts (Biswell 1959; Vankat 1977; Shaman and Warren 1988). Because no documentary records of fire regimes exist prior to European settlement, "proxy" data must be sought to provide this information. One type of proxy data exists as fire scars on trees that survived but were injured by past fires. These injuries are usually visible as open scars or "cat-faces" at the base of a tree and may contain multiple fire-caused lesions (Lachmund 1921; Dieterich and Swetnam 1984).

Fire scars have been widely used in determining occurrence of past fires in the western United States (Clements 1910; Keen 1937; Houston 1973; Arno and Sneck 1977; Swetnam and Dieterich 1985; and many others). Previous fire history studies in the ponderosa pine and Jeffrey pine forests (yellow pine forests) in southern California relied on ring-counting methods for dating fire scars (Show and Kotok 1924; Wagener 1961; Kilgore and Taylor 1979; Warner 1980; McBride and Jacobs 1980; Pitcher 1987). Although for some purposes this method provides adequate estimates of fire frequency, for other purposes the resulting approximate fire dates lack the necessary level of precision. In contrast to ring counting, dendrochronologically crossdated fire histories are accurate to the year because each annual ring is precisely dated to the year of formation. Thus, there is accurate placement of each fire event in space and time, which is particularly important for forest ecosystems with high fire frequency (<5 yrs) (Madany et al. 1982). This allows precise comparisons of fire dates within and among sites and regions which provide a sound basis for inferring fire spread, size, and extent patterns. Additionally, because fire dates are accurate to the year they can be compared to seasonal or annual climatic data leading to better understanding of fire climatology (Swetnam and Betancourt 1990; Baisan and Swetnam 1990). Finally, use of crossdating techniques permits the utilization of remnant logs and snags, greatly reducing the number of samples that need to be removed from living trees. This is an important consideration when sampling must be conducted in parks or wilderness areas.

The goal of this study was to document fire occurrence patterns in montane forest stands on the west slope of the Sierra Nevada for the last 300-400 years using dendrochronological analysis of tree-ring samples. We investigated historic fire regimes by collecting fire-scarred specimens from logs, snags or living trees in Sequoia National Park along an elevational gradient. Our interpretation of this fire-history record provides a historical perspective on the past fire regime in this area, including estimates of fire frequency, spatial extent and spread patterns, fire synchrony among sites, and seasonality of fires. This fire history was also compared to fire chronologies constructed from dead giant sequoias (*Sequoiadendron* ***giganteum***) obtained in the Giant Forest (Swetnamet al. 1992). These data provide resource managers and researchers detailed information on fire occurrence and variability across a range of temporal and spatial scales. Such information is important for improving our understanding of current and past vegetation

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composition and processes in parks and wilderness areas. This was the first of several fire-history transects that we plan to develop on the west slope of the Sierras. Additional sampling is also underway to extend this transect to higher elevation sites. Our ultimate goal is to develop a network of fire history sites and transects that will be useful in the study of climate-fire interactions in the central and southern Sierra Nevada over the past several hundred years. This work is part of a larger research effort, funded by the National Park Service Global Change Program, to understand and predict climate-related changes in ecosystems of the Sierra Nevada (Stephenson and Parsons 1993).

STUDY AREA

The transect was located in the Kaweah River watershed on the west slope of the Sierra Nevada in Sequoia National Park (Fig. 1). Collections were made at 15 sites along the transect. Data from 12 of these sites are reported here. Area encompassed by each site ranged from about 0.25 to 2 ha. No obvious fire spread barriers were present within sites. In general, the sites were selected so as to reduce possible effects the size of area sampled or within site variations on fire frequency estimates (Arno and Peterson 1984). Within site characteristics were generally homogenous with respect to current vegetation, topography, and aspect. All sites were located on the south facing slope of the ridge forming the north flank of the Middle Fork of the Kaweah River. Elevations along the transect ranged from 1550 to 2200 m and extended from the upper edge of chaparral, black oak, and grassland communities into mid-elevation mixed conifer forest. There was a west-to-east elevation increase along the transect, although the transect was bisected by the Marble Fork of the Kaweah River.

Lower elevation sites were located along the Old Colony Mill Road near Ash Peak Ridge (APR) and on the ridge at the head of Cedar Creek (CMW, CMN, CMM, CME). The Crystal Cave Road site (CCR) was located along a dry ridge midway between the Marble Fork bridge and the Generals Highway. The Moro Rock site was located on the crest of the slope forming the west margin of the Giant Forest. The Bobcat Point sites were situated on the upper portions of a slope, near Bobcat Point, south of Giant Forest. Bobcat East (BOE) was located on the east side of Crescent Creek and Bobcat West (BOW) on the west side. The Huckleberry site (HUK) was located on the south margin of Giant Forest and Giant Forest Pine (GFP) within the interior of the sequoia grove. The High Sierra Ridge site (HSR) was located on a ridge forming the southeast boundary of the grove. Previously developed giant sequoia fire histories at eight sites from three larger areas are located in Giant Forest. Species sampled along the transect were predominantly ponderosa pine (*Pinus ponderosa*), Jeffrey pine (*P. jeffreyi*), and sugar pine (*P. lambertiana*) but also included incense cedar (*Callocedrus decurrens*) and California black oak (*Quercus kelloggii*).

METHODS

Fire scar collections were made from multiple trees at each site since we seldom find any single tree that has recorded all fires that burned in the vicinity. Sample size varied from four to fourteen fire-scarred trees per site with a total of 91 trees sampled. This included the collection of 76 samples from logs and snags (at low elevation sites we sampled many recently

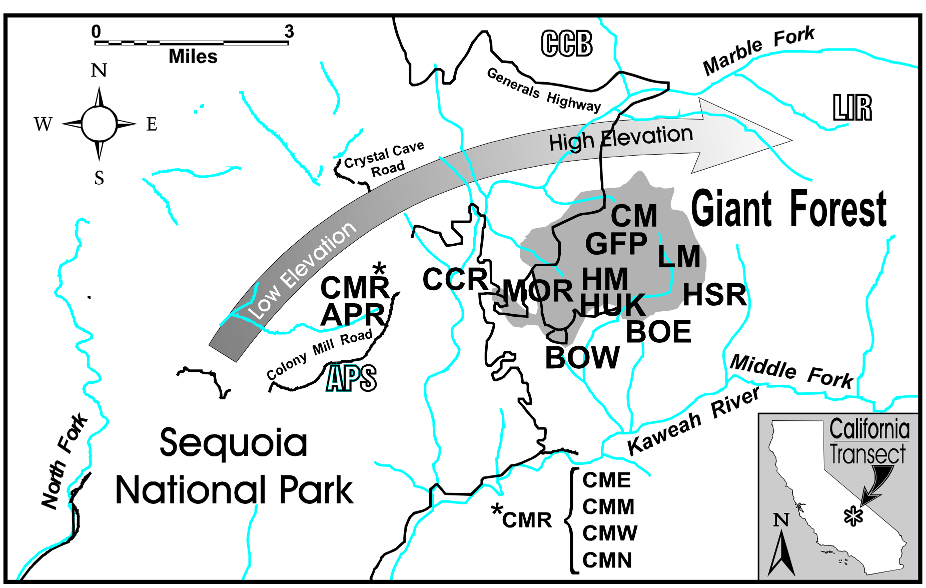

Figure 1—Study area on the west slope of the Sierra Nevada in Sequoia National Park. Location of the Giant Forest is shown by the shading. The west-to-east elevational increase along the transect is indicated by the large arrow. The map shows the locations of the 15 pine sites sampled (three letter codes) with the 12 used in this analysis shown with solid letters. Three areas where eight giant sequoia sites were sampled have two letter codes.

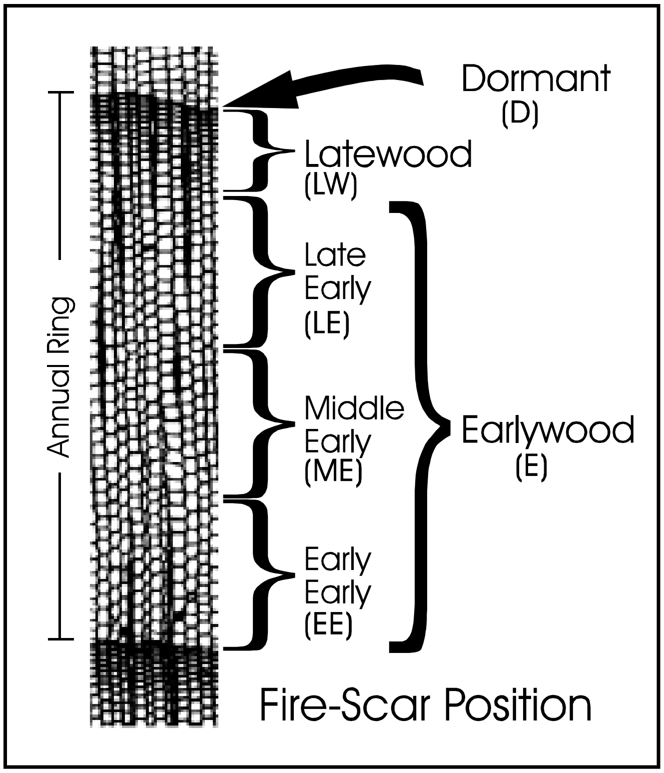

Figure 2— Areas of an annual ring used in designating intra-annual fire-scar positions.

dead trees which appeared to have died as a result of the 1980's drought). Samples were removed from 15 living trees as partial sections (Arno and Sneck 1977), for the purpose of crossdating the remnant material and documenting the location and timing of recent fires.

Samples were surfaced and crossdated using standard dendrochronological techniques (Glock 1937, Stokes and Smiley 1968). Fire scars were assigned to the year of occurrence, and where possible, to a position within the annual ring. Intra-annual position of fire scars can provide an estimate of the season of past fire occurrence (Ahlstrand 1980; Barrett 1981; Dieterich and Swetnam 1984). Intra-annual positions of scars were recorded as "early in the earlywood" (EE), "middle of the earlywood" (ME), "late in the earlywood" (LE), "latewood" (L), or "dormant" (D) for the period when cambial growth has become inactive (Fig. 2). Dormant season scars in the Sierra Nevada r egion were interpreted to have occurred in the calendric year corresponding to the adjacent latewood cells. This convention was established after observing, that dormant season scars were always associated with late season scars (latewood) in nearby trees. In other words, in this region we interpret dormant season scars to represent fires occurring in late summer or fall after cambial cell division has ceased. This convention was also supported by our knowledge of the modern seasons of peak burning in this region (Show and Kotok 1923; Parsons 1981; NPS fire records for Sequoia National Park).

RESULTS AND DISCUSSION

Spatial Patterns

Master fire chronologies were developed for each sampled stand. Fire scar dates spanned the period from 1402 to 1988. From these chronologies a composite inter-site fire chronology was constructed which summarized the fire-history dates from all sites along the transect for the period extending back to 1600 AD (Figure 3). Prior to about 1700 our sample depth (number of sampled trees) declined at most sites and past fire history and frequency estimates became less reliable. Widespread fire events (peaks in the fire-scar

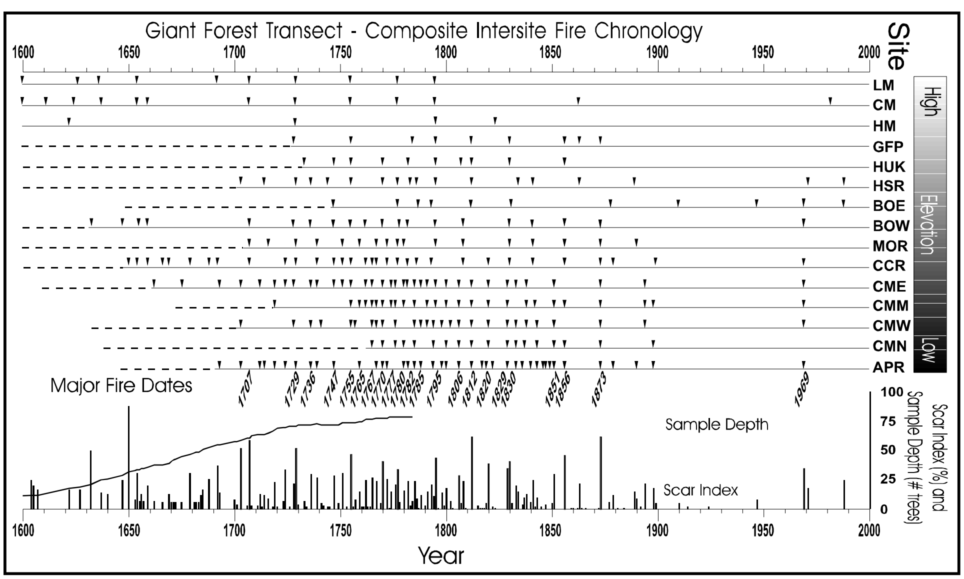

Figure 3. Composite intersite fire chronology for the Giant Forest transect. Each horizontal line is a composite fire record of all trees at a site. Only fire-scars found on two or more trees at a site are shown (solid triangles). The three upper horizontal lines (open text at left) show the fire-scar record from giant sequoias in three areas of the Giant Forest. Major fire dates are synchronous fire events that occurred at five-or-more sites. Lower graph gives scar index-values (bars) for all fire scars recorded at all sites and the change in sample depth through time (curve).

index with fires occurring over a broad range of elevations) were recorded in 1729, 1755, 1770, 1795, 1812, 1856, and 1873. Other less widespread events occurred in 1707, 1736, 1747, 1765, 1767, 1777, 1780, 1782, 1785, 1806, 1820, 1829, 1830, and 1851. The last widespread fire we recorded was in 1898. This last date and the location of the scarred trees correspond to a documentary record of a 8,098 ha (20,000 ac) burn along the North Fork and Marble Forks of the Kaweah River in 1898 (Barrett 1935). Fire scars from twentieth century wildfires were dated to 1910, 1947, and 1988 and prescribed burns to 1969 and 1971. All of these dates were recorded by National Park Service fire records or superintendents reports.

The coinciding dates of many fire events over much of the transect indicate that during the pre-settlement era many fires burned across the elevational gradient through a variety of habitats and vegetation types. These patterns suggest interconnections among the different vegetation types along the elevational gradient though the linkage of fire. Changes in the fire regime and associated vegetation patterns in one elevation zone could have important effects on fire regimes and vegetation patterns in other zones through a shift in fire spread patterns. For example, the alteration of mixed conifer forests may not entirely be a result of fire suppression in these forests but may partially be a result of settlement and development in lower elevation zones which prohibited fire spread in these areas. Thus historic fire regimes and events should not be perceived as solely a feature of a specific vegetation type but should be viewed in the context of a variety of vegetation types over a landscape through which fire may spread.

Comparison of fire dates from sites located within Giant Forest (GFP, LM, CM, HM) showed that nearly all of these fires were recorded by sites outside the sequoia grove, but conversely, many fires recorded outside the grove were not recorded within the grove. This finding suggests that many fires recorded in the grove originated outside the grove, but not all fires burning up to the grove boundary successfully burned into the grove.

An inverse relationship was found between elevation and fire frequency for the 12 non-sequoia and eight Giant Forest sequoia sites (Table 1). The pattern of fire occurrence we observed does not necessarily imply that fire ignitions in the past were more frequent at lower elevations. This pattern was also inverse to the incidence of lightning ignitions recorded since 1921, where on the west slope of the Sierras in Sequoia National Park most lightning ignitions occurred at higher elevation ridge tops, above 2,500 m (Vankat 1985). This discrepancy might be explained, even with a reduced ignition rate at lower elevations, if fires typically were larger in these areas resulting in an overall higher fire frequency at any one location through time. We hypothesize that understory vegetation at these elevations consisted of a high proportion of flammable surface fuels (e.g. graminoids) with quick recovery rates following fires. This would enable fire to spread rapidly over large areas and to recur frequently. Although fires of large size might originate at any elevation we would expect the probability of an ignition becoming a large fire at lower elevations to be greater than at higher elevations. A similar interpretation was expressed by Parsons (1981) based on a study of fire records for Sequoia and Kings

Table 1— Fire interval estimates from the 12 pine sites and eight sequoia sites for the period from 1700 to 1900 AD giving number of fires, mean fire interval (MFI), number of trees used in chronology development, and elevation (m). The long MFI estimates for sequoia for this full period are primarily a result of the decline in fire occurrence in Giant Forest beginning in the early-to-mid nineteenth century, generally earlier than in pine sites (see Fig. 3).

Pine Site	No.	MFI	N	Elev.	Sequoia Site	No.	MFI	N	Elev.
HSR	24	7.75	12	2180	CMN - sequoia	6	32.4	5	2103
GFP	20	9.65	9	2133	CMC	5	22.0	4	2097
HUK	26	6.58	6	2000	LMN	8	22.3	5	2090
BOE	16	10.65	5	1940	CME - sequoia	7	26.0	6	2073
BOW	22	7.82	4	1940	CMW - sequoia	6	31.2	4	2060
MOR	28	6.57	12	1940	LME	7	13.8	4	2045
CMN - pine	41	4.68	6	1670	HKW	11	15.8	3	2045
CCR	29	6.62	14	1640	HKE	6	22.6	2	2030
CMM	31	5.77	6	1640					
CMW - pine	41	4.78	6	1640					
CME - pine	37	5.24	7	1640					

Canyon National Parks. "When ignited under the proper conditions, few ignitions are needed to burn large areas of highly flammable chaparral and oak woodland." Additionally, as a result of their size and the fuels they were burning in, many of these low elevation fires could subsequently spread into more high elevation areas. If this interpretation is correct then lower elevation vegetation types were an important dynamic linkage between different elevation zones through fire spread patterns.

Temporal Patterns

Intervals between fires at particular sites ranged from one to 36 years. We observed changes in fire frequency in individual master fire chronologies and the composite inter-site transect chronology (Fig. 3). This is also apparent from a comparison of the fire interval frequency distributions for the 1700's and 1800's at three representative sites along the transect (Fig. 4). Fire frequency was high during the 1700's and began to decrease around 1800. It increased again at some lower elevation sites from about 1830 to 1850. Fire frequencies generally declined at all sites after this time. The decrease was most apparent and began earlier at the higher elevation sites than at the lower elevation sites (Fig. 3). The cause of the early fire frequency decline (ca. 1800-1830) was unknown, while the more obvious decrease in fire frequency at the end of the nineteenth century was probably due to grazing and subsequent fire suppression policies (Vankat and Major 1978; Kilgore and Taylor 1979). A similar historical pattern of increased domestic livestock grazing associated with decreases in fire frequency has been hypothesized for southwestern ecosystems (Foster 1917; Leopold 1924; Humphrey 1958; Swetnam 1990). Additionally, decline in local Native American populations (and their burning practices) around 1860 may also have been important (Vankat 1977; Kilgore and Taylor 1979). Given the specific life history attributes of each plant species, such shifts in fire frequency over time have important implications for mortality and recruitment patterns within an ecosystem with long lasting consequences for vegetation structure and composition. Furthermore, the historical fact that shifts in fire frequency occurred prior to European settlement suggests that these systems have been dynamic for many centuries.

Fire regimes also varied spatially along the elevational transect (Fig. 4). As elevations increased along the transect there was a general increase in MFI and an increased range in the fire frequency distribution. The MFI differences across the gradient may not be as ecologically important as differences in the fire interval distributions. These distributions have important ramifications for ecological patterns because the life history attributes of many plant species are closely tied to their tolerance and intolerance to fire (Noble and Slatyer 1980; Zedler et al. 1983; Bradstock and Myerscough 1988). While the MFI value only gives a simple estimate of fire intervals at a specific site, consideration of the fire interval distribution provides a more complete characterization of the range and inherent variability in a fire regime. This variability is also important in designing prescribed urning programs because fire regimes with a similar MFI could have very different fire interval distributions that might produce distinct differences in fire effects and vegetation responses.

Another important component of fire regimes is seasonality of fire occurrence. Seasonal fire-scar positions at the sampled sites were almost always found in the latter portion of annual rings (Fig. 5). This indicated that most fires occurred late in the growing

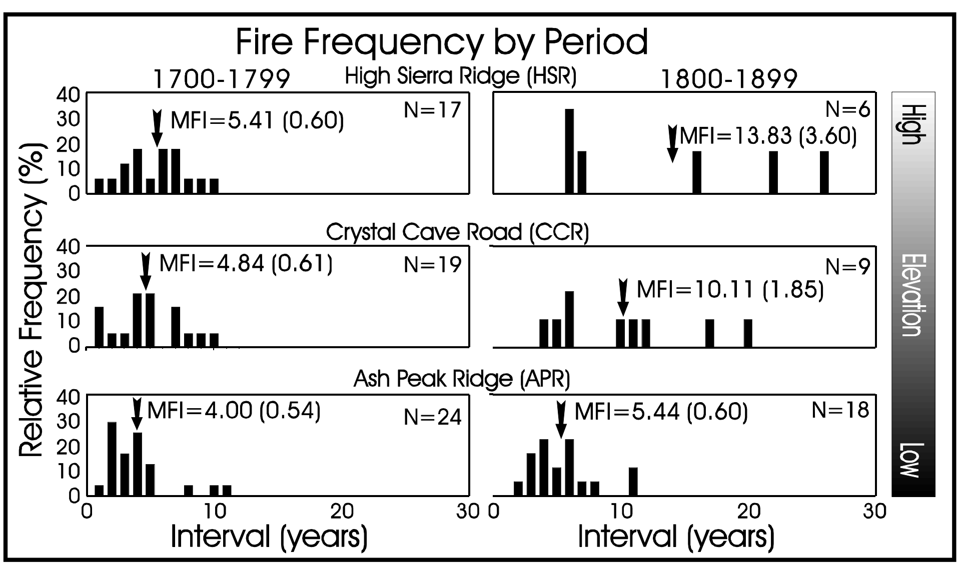

Figure 4— Fire interval frequency distributions for the 1700's and 1800's at three sites representing low, medium, and high elevations along the transect. Also given are mean fire interval (MFI) and standard error.

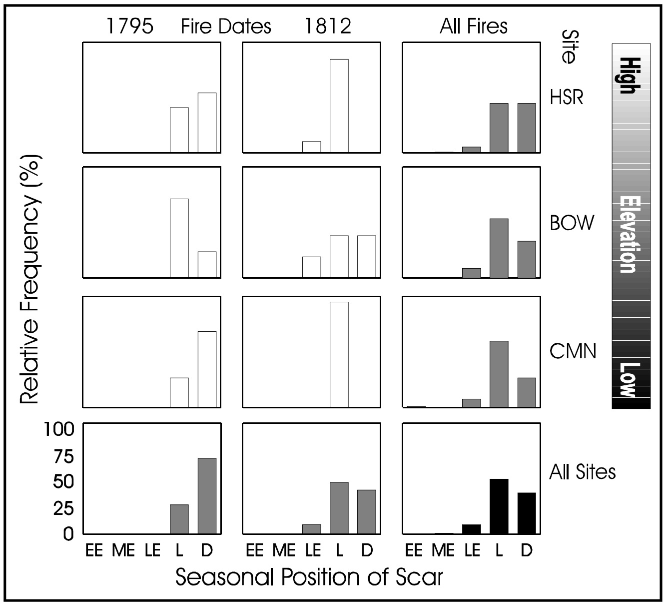

Figure 5 — Histograms of the seasonal timing of past fires based on fire scar position within an annual ring. Data shown is for three sites and all sites combined for fires recorded in 1795 and 1812 and for all fire dates recorded along the transect combined.

season, probably from mid-summer to early fall. Accurate seasonal interpretation of these scar positions requires tree phenology studies to characterize tree-ring growth within a year at different locations and elevations along the transect. However, recent fire events of known dates provided us with benchmarks upon which to evaluate the seasonal position of scars produced by these events. The scar positions agree well with existing records of lightning and fire occurrence in the Sierra Nevada recorded since the beginning of the twentieth century. The peak period of lightning ignitions is between July and August with the greatest area generally burning in August, although large fires may occur at any time between June and September (Show and Kotok 1923; Parsons 1981; Vankat 1985). The peak in lightning ignitions occurs during the period of low and decreasing foliage moisture content, maximum temperatures, and minimal precipitation (Parsons 1981).

SUMMARY

Well dated and replicated fire histories, extending back to 1700 AD, were reconstructed for 12 sites. These histories document the occurrence of widespread fires with temporally variable fire frequencies. Fire frequency was inversely related to elevation; frequencies were relatively high in low elevation forest stands compared to higher elevation stands. The highest fire frequencies were observed in the mid-to-late 1700's, followed by a decline in fire occurrence that accelerated around the beginning of the settlement era, with a nearly complete cessation of fires by the start of the twentieth century. Decreases in fire frequency also occurred earlier at higher sites. Major fire years were recorded at many sites as synchronous fire dates across most of the elevational transect in the years 1729, 1755, 1770, 1795, 1812, 1856, and 1873. Our observations of intra-annual positions of fire scars within the tree rings indicate that past fires usually occurred late in the growing season.

Knowledge of past fire regimes is important to managers in developing and implementing appropriate resource management policy. For one, fire histories provide basic information, such as past frequency and seasonality estimates of past fires. Secondly, they give a better understanding of how fire as a landscape shaping process has changed since the "natural" fire regime has been altered. This information is useful in understanding what the fire effects and vegetation response might be when reintroducing fire into an area, and in the planning and management of prescribed burning programs.

Our findings underscore the importance of historic fire patterns across elevational gradients, forest types, and current management boundaries. Fire spread patterns across these gradients and boundaries in pre-settlement times were probably an important mechanism of ecosystem connectivity, influencing many different ecosystem processes and structures. Re-establishing this connectivity may be especially important in conditions of changing climate, because landscape connectivity may facilitate biotic adjustment in space and time to new environmental conditions. This will require fire management plans to include (and even encourage) burns of greater size and frequency than those that have been accomplished in the past two decades.

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