Fire History and Climatic Patterns in Ponderosa Pine and Mixed-Conifer Forests of the Jemez Mountains, Northern New Mexico

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Abstract.—We reconstructed fire history in ponderosa pine and mixed-conifer forests across the Jemez Mountains in northern New Mexico. We collected fire-scarred samples from ten ponderosa pine areas, and three mesic mixed-conifer areas. Prior to 1900, ponderosa pine forests were characterized by high frequency, low intensity surface fire regimes. The mixed-conifer stands sustained somewhat less frequent surface fires, along with patchy crown fires. We also examined the associations between past fires and winter-spring precipitation. In both ponderosa pine and mixed-conifer forests, precipitation was significantly reduced in the winter-spring period immediately prior to fire occurrence. In addition, winter-spring precipitation during the second year preceding major fire years in the ponderosa pine forest was significantly increased. The results of this study provide baseline knowledge concerning the ecological role of fire in ponderosa pine and mixed-conifer forests. This information is vital to support ongoing ecosystem management efforts in the Jemez Mountains.

INTRODUCTION

Fire has played a dominant role in controlling the formation and maintenance of species and age structure patterns in forest communities (Weaver 1951; Dieterich 1983; Baisan and Swetnam 1990). In order to understand the modern landscape and to manage it effectively, fire managers require specific information about the spatial and temporal variability of past fire regimes (Allen 1994). Historical reconstructions, such as fire history analysis, provide specific information on the range and variability of the fire process, which can be a useful guide to reintroduction of fire for long-term sustainability of forests (Swanson *et al.* 1993; Kaufmann *et al.* 1994).

During the past century, the ecology of Southwestern forests, including the Jemez Mountains in northern New Mexico, has been altered by anthropogenic factors. Anthropogenic effects include intensive grazing by sheep and cattle and effective fire suppression by the U.S. Forest Service (deBuys 1985; Carlson 1969; Allen 1989; Touchan *et al* - in press). Natural factors also have an effect on fire regimes. On a regional scale, climate causes variations in fire regimes because it has a significant influence on fire frequency, extent, and intensity. On a local scale, topography, aspect, and elevation have site specific influences on fire regimes.

In this study we investigate the past fire regimes of ponderosa pine and mixed-conifer forest types in the Jemez Mountains. We employ dendrochronological methods to determine exact fire dates and approximate establishment dates of aspen stands. We assess and discuss the influence of land-

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use and topography on observed fire regime patterns. We also identify year-to-year climatic variations associated with fire occurrence in each forest type by comparing tree-ring reconstructions of fire history and climatic variations (Baisan and Swetnam 1990; Swetnam and Betancourt 1990; Swetnam 1993).

STUDY AREA

The Jemez Mountains are located in north-central New Mexico (Figure 1). Elevations range from 1,590 m at the Rio Grande to 3,526 m at the summit of Tschicoma Peak (the highest point in the Jemez Mountains), with a geologic boundary enclosing about 543,522 ha (Smith *et al* 1976). The elevation of the sampled area varies between 2,250 m and 3,000 m (Table 1). Soil parent material varies from rhyolites and andesites with some dacites and latites, to tuff and pumice on the plateaus and basalt near the Rio Grande (Nyhan et al 1978).

The length of the frost-free growing season in Los Alamos is 157 days, or around five months (Bowen 1989). July is the warmest month at Los

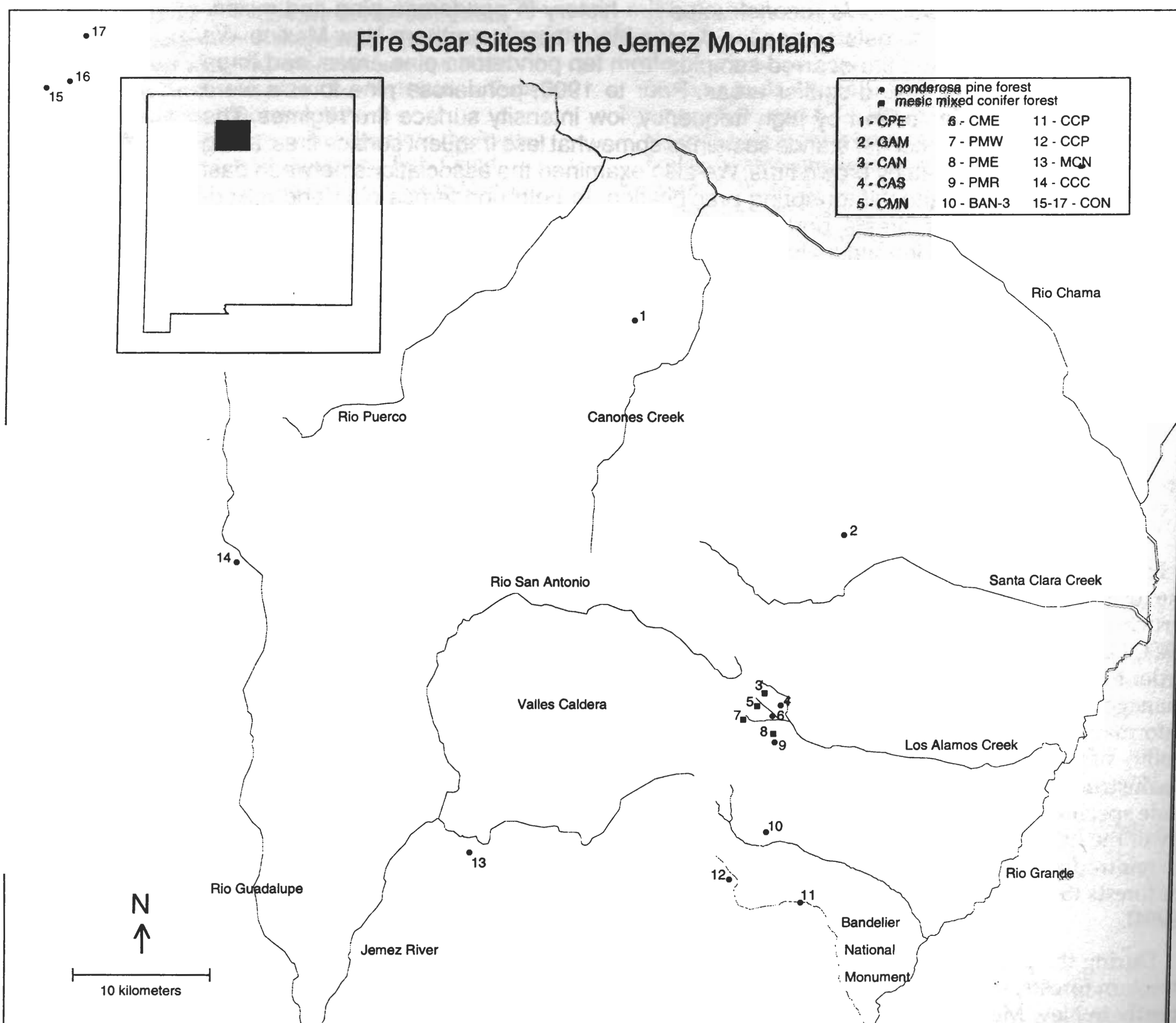

Figure 1. Locations of fire history study sites in the Jemez Mountains, northern New Mexico.

Alamos, with a mean temperature of 28° C, and January is the coldest month, with a mean temperature of –1.6° C. Annual precipitation ranges from about 30 cm at the lower elevations to about 90 cm at higher elevations. Yearly precipitation is bimodal, with maxima in winter (December-January) and summer (July-August). Winter precipitation falls primarily as snow, with average accumulations of about 130 cm. This moisture has its origin in eastern-moving storms coming from the Pacific Ocean. Summer precipitation results from a southeasterly wind pattern that typically transports moisture from the Gulf of Mexico to New Mexico. This moisture, combined with strong heating, produces an unstable atmosphere that leads to convective storms. Forty percent of the total annual precipitation falls in July and August during the height of the summer rainy season.

In a summary of forest fire statistics for the period 1960 to 1975, Barrows (1978) found that 80% of New Mexico fires were ignited by lightning, and about 20% were anthropogenic fires. Foxx and Potter (1978) and Allen (1984) found that 86% of the fires recorded at Bandelier were ignited by lightning, with a peak in July and smaller peaks in June and August. Generally all local fires occurred between April and September. Barrows (1978) found that this seasonal pattern of ignitions occurred throughout the Southwest, but fires that start in June cause the greatest area burned. For example, approximately 72% of the area burned in New Mexico was due to lightning fires which started in June.

Sampled forests range from pure ponderosa pine (*Pinus ponderosa)* stands to high elevation, mesic, mixed-conifer forests (Table 1, Figure 1). Six of the sampled sites occur in ponderosa pine forests, including Monument Canyon Research Natural Area (MCN), Bandelier-Group 3 (Ban-GR3), Pajarito Mountain Ridge (PMR), Cerro Pedernal (CPE), Continental Divide (CON), and Clear Creek Campground (CCC). CON includes three adjacent subsites called Laguna Jaquez (LJA), Laguna Gurule (LGU), and Continental Divide (CON). The sampled mixed-conifer forests are dominated by Douglas-fir (*Pseudotsuga menziesii*), Engelemann spruce (*Picea engelmannii*), and quaking aspen (*Populus tremuloides*), with Rocky Mountain maple (*Acer glabrum* var. *neomexicana*) and either white fir (*Abies concolor*) or corkbark fir (*Abies lasiocarpa* var.

Table 1. Jemez Mountains fire scar site locations. The area of each study site was estimated within a perimeter of an area defined by the sampled trees. Sites are listed by forest type (PIPO = ponderosa pine, PIPO/MC = ponderosa pine/mixed conifer, and MC = mixed conifer).

Name of site	Ranger District/Park	Latitude	Longitude	Veg. type	Area (ha)	Elevation (m)	No. of samples
Monument Canyon Natural Area	Jemez RD	35° 48' 12" N	106° 37' 3" W	PIPO	259	2,600	30
Ban-Group 3 (Apache Mesa)	Bandelier NM	35° 49' 20" N	106° 23' W	PIPO	110	2,510	18
Pajarito Mountain Ridge	Española RD	35°53'04"N	106° 22' 49" W	PIPO	3.5	2,985	26
Cerro Pedernal	Coyote RD	36°9'43"N	106°30'12"W	PIPO	16	2,865	26
Continental Divide	Cuba RD	36° 18' 42" N	106° 57' 30" W	PIPO	27	2,300	27
Clear Creek Campground	Cuba RD	36° N	106° 49' 4" W	PIPO	130	2,500	20
Capulin Canyon	Bandelier NM	35° 47' 12" N	106° 24' 2" W	PIPO/MC	103	2,250	23
Gallina Mesa	Espanola RD	36° 1' 26" N	106° 19' 42" W	PIPO/MC	285	2,700	25
Cañada Bonito South	Española RD	35°54'25"N	106°22'22"W	PIPO/MC	2	2,800	31
Camp May East	Española RD	35°54'N	106° 22' 57" W	PIPO/MC	1.3	2,710	6
Pajarito Mountain North East	Española RD	35° 53' 09" N	106° 22' 09" W	MC	7.6	2,925	14
Pajarito Mountain North West	Española RD	35°53'13"N	106°24'14"W	MC	7	3,000	11
Camp May North	Española RD	35°54'25"N	106°23'53"W	MC	8	3,000	20
Cañada Bonito North	Española RD	35°54'56"N	106°23'15"W	MC	4.8	2,980	28

arizonica) also present. The four mixed-conifer sample sites are Pajarito Mountain North (PMN), which includes two sub-sites called Pajarito Mountain East (PME) and Pajarito Mountain West (PMW), and Camp May North (CMN) and Cañada Bonito North (CAN). Four sites were sampled in transitional situations where mixed-conifer species like Douglas-fir and white fir were co-dominants with ponderosa pine: at Capulin Canyon (CCP), Gallina Mesa (GAM), Camp May East (CME), and Cañada Bonito South (CAS). At CME and CAS limber pine (*Pinus flexilis*) was also a dominant component of the forest. CCP includes two sub-sites, in the upper and middle reaches of the canyon, which are lumped in this treatment. These four PIPO/MC sites (Table 1) were analyzed as ponderosa pine sites.

METHODS

During 1988–1993, we collected fire-scarred samples from a total of 13 sites (including sub-sites) (Table 1). Full or partial cross-sections were cut with a chainsaw from fire-scarred boles of downed logs, snags, and stumps. Partial sections were also taken from living trees as described by Arno and Sneck 1977. The primary criterion for sample tree selection within study areas was the presence of a maximum number of well preserved scars showing evidence of fire by the number of healing ridges observed on the scarred surface ("cat face") (Dieterich and Swetnam 1984, Baisan and Swetnam 1990).

In addition to collecting fire-scarred samples in the mixed-conifer sites, we cored 202 quaking aspen since these trees often sprout abundantly after fire disturbance in mixed-conifer forests (Moir and Ludwig 1979). We sampled dominant and co-dominant aspen trees in aspen stands which were adjacent to the old-growth mixed-conifer stands which were sampled for fire scars. Hence, we determined both fire dates and tree recruitment dates to reconstruct fire and stand development histories.

In the laboratory, samples were fine-sanded and cross-dated using standard dendrochronological techniques (Stokes and Smiley 1968). In some cases, the aspen growth was very suppressed after 1979 because of a tent caterpillar outbreak that occurred in the early 1980's (Allen 1984). Because of this growth suppression the tree-rings on some cores were difficult or impossible to cross-date during this period. In these cases, the period from 1979 to 1993 was estimated by simple ring counts. If a particular core was near, but did not contain, the pith, a pith locator (Applequist 1958) was used to estimate the pith dates.

All fire-scar dates from individual trees within each site were compiled into master chronologies in order to examine both temporal and spatial patterns of past fire occurrence. The FHX2 fire history analysis program was used to compute descriptive statistics (H. Grissino-Mayer - unpublished software documentation). These included fire frequency (number of fires per time period), fire-scar index ([number of trees scarred / Number of trees sampled] X 100), Weibull median probability intervals (WMPI), maximum and minimum fire interval (Max. FI and Min. FI), and standard deviation (STD) of fire intervals. These statistics were computed separately for (1) all fire dates and (2) fires recorded by 10% or more of the sampled trees and (3) fires recorded by 25%. Because fire scarred trees are spatially dispersed within the sites, the =>10% and =>25% categories generally emphasize the relatively larger, more widespread fires within the sites.

The WMPI is calculated using the Weibull distribution, a very flexible distributional model that may be fitted to a variety of negatively and positively skewed distributions. The Weibull distribution often provides a superior fit to fire interval data than does the normal distribution (Johnson 1992; Baker 1992; Grissino-Mayer *et al.*, 1994). The WMPI is used here in addition to the Mean Fire Interval (MFI) because fire interval data are usually positively skewed (Baker 1992; Grissino-Mayer *et al.* 1994), Hence, simple averages (e.g. mean fire intervals) often provide a less robust estimate of the central tendency of the fire interval distribution. In this case, we report the fire interval associated with the 50% exceedance probability of the WMPI, which is the interval (in years) at which there was a 50% probability of fire intervals exceeding or being less than this interval (Grissino-Mayer *et al.* 1994).

Changes in fire frequency through time were graphically examined by computing and plotting moving-period fire frequencies. The moving periods were overlapping time periods of different lengths (51 and 21 years), during which the total number of recorded fires were summed. Each sequential value was the sum of fire events in the time period lagged one year forward from the previous period. The fire frequencies in these moving periods were plotted on the central-year of the period (i.e., 25th and 11th years respectively).

The computation of WMPI, Max. and Min. FI, and STD were based on a time span we termed the "period of reliability". This is the number that included a minimum number of fire scar samples deemed sufficient to reliably estimate fire regime parameters. Generally this period included at least three to four samples recording the fire events (Table 2). This was a somewhat subjective determination, but given the degree of replication of fire dates among the sampled trees, and relatively small size of the study sites we are confident that these are reasonable time periods to confidently base our descriptive analyses.

Finally, we used superposed-epoch analyses (Baisan and Swetnam 1990; Swetnam and Betancourt 1990; Swetnam 1993) to compute the mean climate conditions before, during, and after sets of fire years in both the ponderosa pine and mixed-conifer forests. In this analysis, fire years were "superposed" on reconstructed precipitation. Precipitation values were obtained from a 333-year-long dendroclimatic reconstruction of December through June precipitation based on seven tree-ring width index chronologies developed from ponderosa pine that were collected from four different watersheds in northern New Mexico (Swetnam and Lynch 1993; Touchan and Swetnam, unpublished data). The winter-spring seasonal precipitation values used in this analyses are assigned to the calendar year corresponding with the spring months. Precipitation values (expressed as departures from the long term mean) are computed for the fire year and lagged years and then plotted. We conducted 1,000 Monte Carlo simulations to estimate confidence intervals for the mean departures at the 95% and 99% probability levels based on the normal approximation and percentile-rank methods (Mooney and Duval 1993).

RESULTS

Ponderosa Pine Fire Regimes

The fire-scarred samples in the ponderosa pine and transitional forests contained abundant and well preserved fire history records. We identified 1,858 fire events representing 221 separate fire

Table 2. Jemez Mountains fire scar dates. Period of reliability is the period when the number of samples was deemed sufficient to reliably estimate presuppression fire regime characteristics. Generally this was the period during which at least three or four samples recorded fire events. Sites are listed by forest types (PIPO = ponderosa pine, PIPO/MC = ponderosa pine/mixed conifer, and MC = mixed conifer).

Site name	Site code	Veg. type	Tree-ring date		Earliest fire-scar date	Latest fire-scar date	No. of fire-events (years)	Period of reliability	
			Earliest	Latest				Beginning date	Ending date
Monument Canyon Natural	MCN	PIPO	1408	1972	1493	1909	57	1648	1892
Ban-Group 3 (Apache Mesa)	BAN-GR3	PIPO	1459	1988	1480	1939	66	1614	1890
Pajarito Mountain Ridge	PMR	PIPO	1626	1993	1632	1912	39	1685	1875
Cerro Pedernal	CPE	PIPO	1380	1993	1522	1959	30	1598	1873
Continental Divide	CON	PIPO	1387	1979	1601	1899	54	1654	1870
Clear Creek Campground	CCC	PIPO	1538	1978	1548	1881	45	1664	1860
Capulin Canyon	CCP	PIPO/MC	1554	1990	1624	1955	44	1664	1893
Gallina Mesa	GAM	PIPO/MC	1531	1979	1558	1921	66	1663	1870
Cañada Bonito South	CAS	PIPO/MC	1378	1993	1480	1966	33	1672	1893
Camp May East	CME	PIPO/MC	1660	1993	1709	1880	11	1709	1879
Pajarito Mountain North-East	PME	MC	1702	1993	1773	1949	13	1801	1879
Pajarito Mountain North-West	PMW	MC	1617	1993	1669	1925	10	1841	1879
Camp May North	CMN	MC	1683	1993	1729	1880	7	1847	1879
Cañada Bonito North	CAN	MC	1655	1993	1685	1914	12	1801	1893

years (Figure 2, Table 2). The average, maximum, and minimum number of fire scars per tree was 8, 31, and 1 respectively. Long-lived specimens extended the record to more than 600 years before present in a few sites, but most of the samples began consistently recording fires after about AD 1600. Major fires ceased after the 1890's.

The pre–1900 WMPI varied at each site for the three different percentage scarred classes examined (Table 3). For example, the WMPI for major fire years (at least 10% of the trees scarred) ranged from 6.5 to 22.1 years. At CME and CAS the WMPI values for major fire years were much higher than at the other ponderosa pine sites.

Fire intervals varied considerably among the sites. The minimum fire intervals (Min. FI) for major fires ranged from 1 to 12 years (Table 3). The maximum fire intervals (Max. FI) for major fires ranged from 16 to 51 years. There were unusually long maximum fire intervals at CPE and CON.

The WMPI for all trees regardless of percentage scarred was lower in most cases than the MFI values derived from the arithmetic mean (Table 3). The MFI overestimate is due to a few longer fire intervals, which skew the distribution (Grissino-Mayer *et al*. 1994). During the pre-settlement period, the differences between the MFI and the WMPI for major fire events ranged from zero (i.e., no difference) at CAS to 3.9 years at CPE. Most of the differences were between 1 and 2 years. Thus, although WMPI is a more statistically robust estimation of central tendency, it only differs appreciably from MFI when the distributions are highly skewed.

Mixed-Conifer Fire Regimes

Samples collected from the mixed-conifer sites were not as well preserved as the samples from the ponderosa pine sites. For example, at the Cañada Bonito North (CAN) site, 33 fire-scarred samples were collected, but due to advanced decay only 28 samples could be dated. Many of these samples were fire scarred Douglas-fir and white fir, which are generally less resinous than ponderosa pine and seem to decay more rapidly following scarring. The composite of master fire chronologies for the four sites yielded a total of 113 individual fire scars representing 28 separate fire years (Figure 3).

The mixed-conifer sites presented a shorter tree-ring record than the ponderosa pine sites, extending to a maximum of 377 years before present *versus* over 600 years at some pine sites (Table 2). Note that the period of reliability was relatively short for all the mixed-conifer sites, ranging from only 38 years to 92 years, *versus* over 200 years for most ponderosa pine sites.

The pre-1900 WMPI for major fire events (at least 10% of trees scarred) ranged from 9.7 to 14 years (Table 3). The Max. FI and Min. FI for all percentage classes varied between sites. The Max. FI for major fire events ranged from 18 to 32 years. The Min. FI. for major fire events ranged from 4 to 6 years.

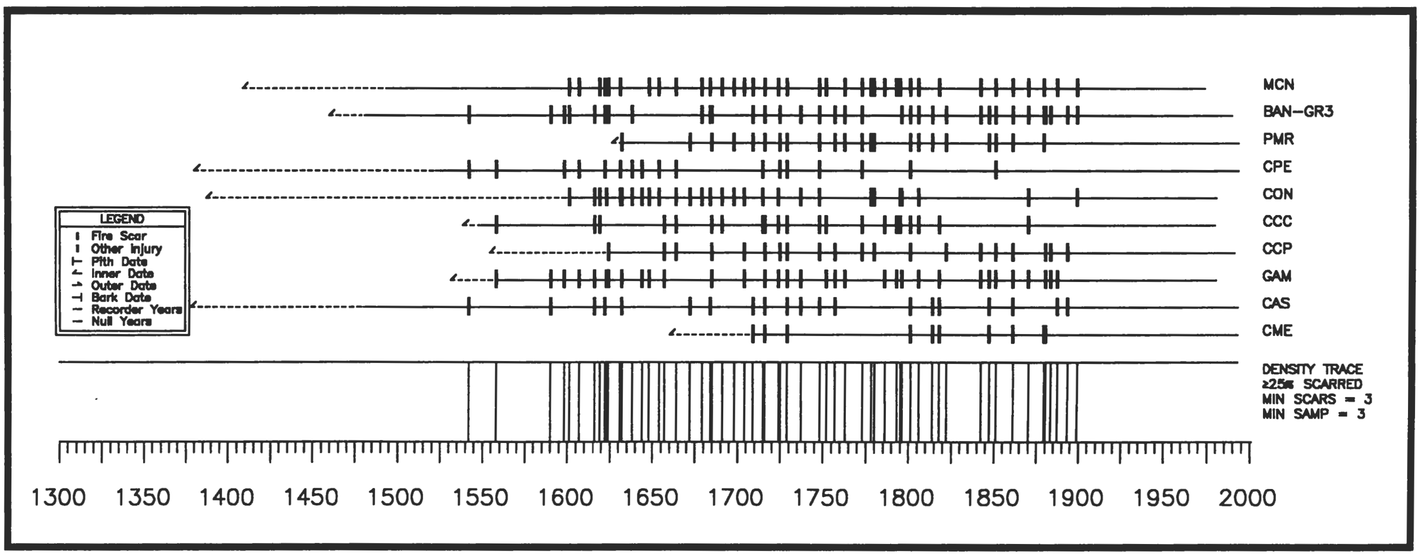

Figure 2. Composite of all fire chronologies for the ponderosa pine and transitional forests. Horizontal lines are maximum life span of trees within each site. Vertical lines are composite fire dates recorded by 25% or more of the trees within each site.

Aspen Age Distributions

The age distributions for the quaking aspen stands we sampled showed tree recruitment occurred sporadically from 1795 to 1918, but most of the regeneration concentrated in the period between 1850 to 1910 (Figure 4). Some of the fire scar dates obtained near the stands seem to correspond with the major recruitment episodes, but others do not. We hypothesize that most recruitment episodes in the late 1800's correspond to relatively intense, patchy, stand opening fires.

Precipitation-Fire Relations: Superposed-Epoch Analysis

The superposed epoch analysis revealed that both mixed-conifer and the ponderosa pine forest types exhibited significantly negative (dry) mean winter-spring precipitation departures during fire years (Figure 5). For example, in the mixed-conifer forests the mean precipitation departure during the fire years was -1.48 inches; in the ponderosa pine forests the mean precipitation departure during the fire year was -0.84 inches. In the ponderosa pine

Table 3. Summary of fire interval statistics for different sites in the Jemez Mountains for the period of reliability. Weibull median probability interval (WMPI), Mean Fire Interval (MFI), Standard deviation (STD), and maximum and minimum fire interval for all trees scarred and at least 10%, and 25% of all trees scarred. All values are expressed in years. Sites are isted by forest type (PIPO = ponderosa pine, PIPO/MC = ponderosa pine/mixed conifer, and MC = mixed conifer).

		WMPI			MFI			STD			Maximum fire interval			Minimum fire interval		
Site name (veg. type)	Site code	All fires	10% trees scarred	25% trees scarred	All fires	10% trees scarred	25% trees scarred	All fires	10% trees scarred	25% trees scarred	All fires	10% trees scarred	25% trees scarred	All fires	10% trees scarred	25% trees scarred
Monument Canyon Natural Area (PIPO)	MCN	5.4	6.5	8.1	5.5	6.6	8.4	2.5	2.9	4.3	12	16	18	1	2	3
Bandelier-Group 3 (PIPO)	BAN-GR3	5.2	6.7	9.8	6.1	7.7	9.5	4.4	5.1	6.8	21	23	24	1	1	1
Pajarito Mountain Ridge (PIPO)	PMR	5.6	7.0	13.0	6.1	7.6	13.6	4.0	4.7	6.9	21	21	27	1	1	5
Cerro Pedernal (PIPO)	CPE	8.8	12.3	20.1	11.5	16.2	22.9	11.5	15.2	17.8	51	51	53	1	1	9
Continental Divide (PIPO)	CON	4.7	6.9	11.3	6.2	9.8	15.4	6.8	12.7	18.0	28	48	64	1	2	2
Clear Creek Campground (PIPO)	CCC	4.3	7.2	12.6	5.6	8.2	13.1	5.5	5.6	6.5	24	24	25	1	1	5
Capulin Canyon (PIPO/MC)	CCP	5.4	6.8	10.6	6.5	8.2	11.5	5.3	6.2	6.4	21	21	23	1	1	2
Gallina Mesa (PIPO/MC)	GAM	4.6	7.5	11.5	5.0	8.0	11.5	3.4	4.2	4.0	16	16	19	1	1	5
Cañada Bonito South (PIPO/MC)	CAS	9.8	22.1	22.1	11.1	22.1	22.1	7.8	7.7	7.7	29	33	33	2	12	12
Camp May East (PIPO/MC)	CME	17.1	17.1	20.0	18.9	18.9	21.3	13.0	13.0	13.0	46	46	46	4	4	7
Pajarito Mountain North-East (MC)	PME	9.7	9.7	19.9	11.1	11.1	19.5	8.1	8.1	4.7	22	22	25	3	3	14
Pajarito Mountain North-West (MC)	PMW	12.6	12.6	10.0	12.7	12.7	10.0	6.1	6.1	5.7	18	18	14	6	6	6
Camp May North (MC)	CMN	10.2	10.2	16.0	10.7	10.7	16.0	7.0	7.0	2.8	18	18	18	4	4	14
Cañada Bonito North (MC)	CAN	14.0	14.0	20.4	15.3	15.3	20.0	10.1	10.1	5.6	32	32	25	4	4	14

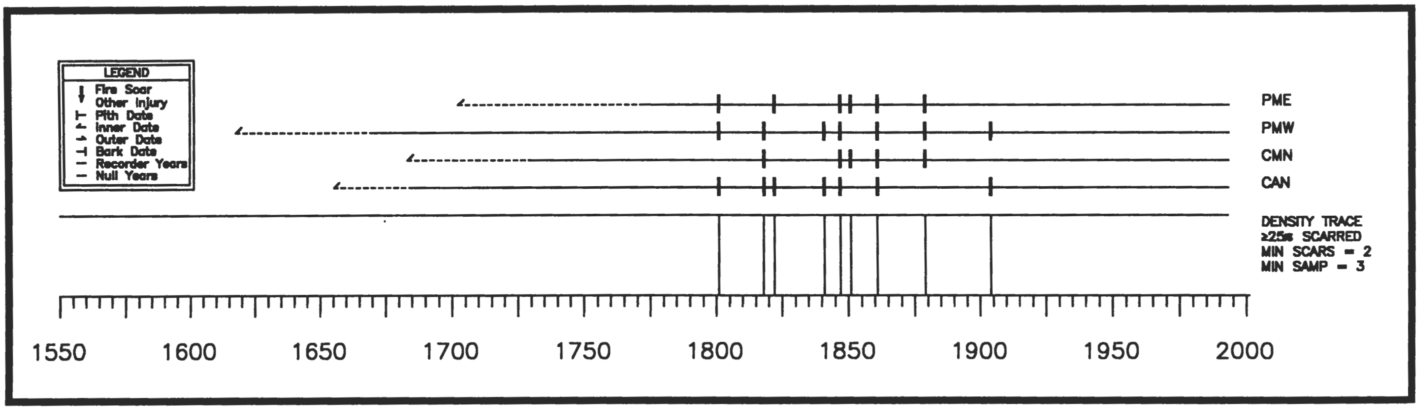

Figure 3. Composite of all fire chronologies from the mixed-conifer forests. Horizontal lines are maximum life span of trees within each site. Vertical lines are composite fire dates recorded by 25% or more of the trees within each site.

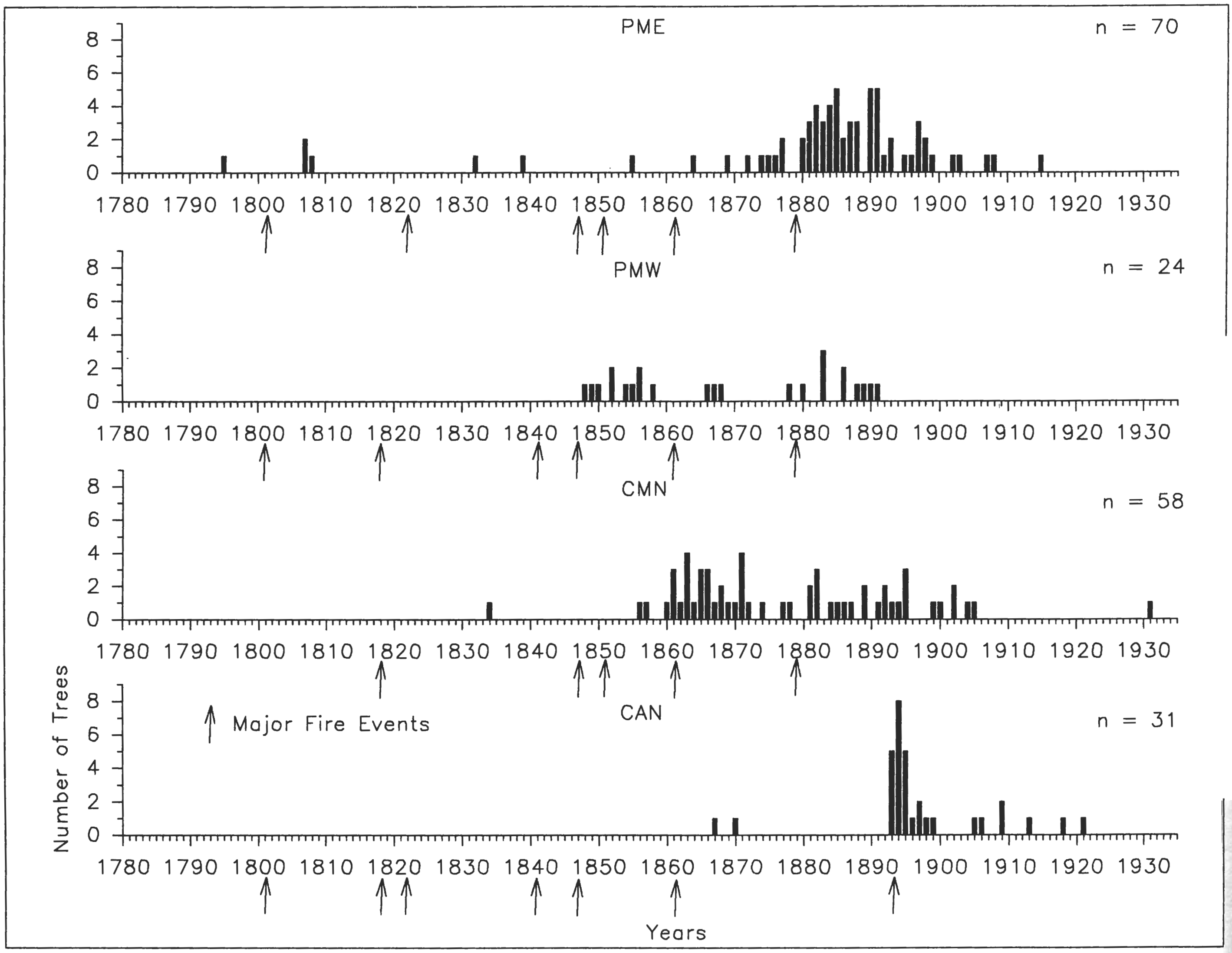

Figure 4. Aspen age structure and fire events (arrows) in the mixed-conifer forest sites. Graph shows inside tree-ring dates for sampled aspen stems, indicating establishment years.

forests, the first and the second years prior to the fire year were noticeably wet, with the second year significantly wetter than normal at the 95% confidence level.

DISCUSSION

Prior to 1900, fire regimes in ponderosa pine forests were characterized by high frequency, low intensity surface fires (Figures 6 and 7). At seven of the sites, the WMPI for major fire years (6.5 to 7.5 years, Table 3) falls within the range found in other Southwestern ponderosa pine forests. At three sites, CAS, CME, and CPE the WMPI values were greater (12.7 to 22.1 years) than for most other southwestern ponderosa pine forests (Swetnam and Baisan, This Volume). The MFI intervals for other southwestern ponderosa pine forests ranged between 4.9 to 10.2 years (Weaver 1951; Dieterich 1980; Swetnam and Dieterich 1985; Swetnam *et al.* 1989; Allen 1989; Baisan and Swetnam 1990; Grissino-Mayer and Swetnam 1992).

Variations in fire intervals between sites and through time were probably due to differences in topographic situation, site-specific histories of intensive livestock grazing, and climatic variability (Figures 2 and 3). Each of these factors are discussed below.

The CON sub-sites all show high fire frequency in the 1600's and early 1700's, with a clear reduction in fire frequency after 1752 and early cessation of major fires (Figure 2). These early reductions in fire frequency could be due to early sheep grazing by Navajo communities at CON (Touchan *et. al* - in press). Intensive livestock grazing removes grasses and herbs necessary for fire spread in the high frequency fire regimes. Trails created by the herding of animals would also disrupt fuel continuity and hence fire spread patterns. Baydo (1970) and Bailey

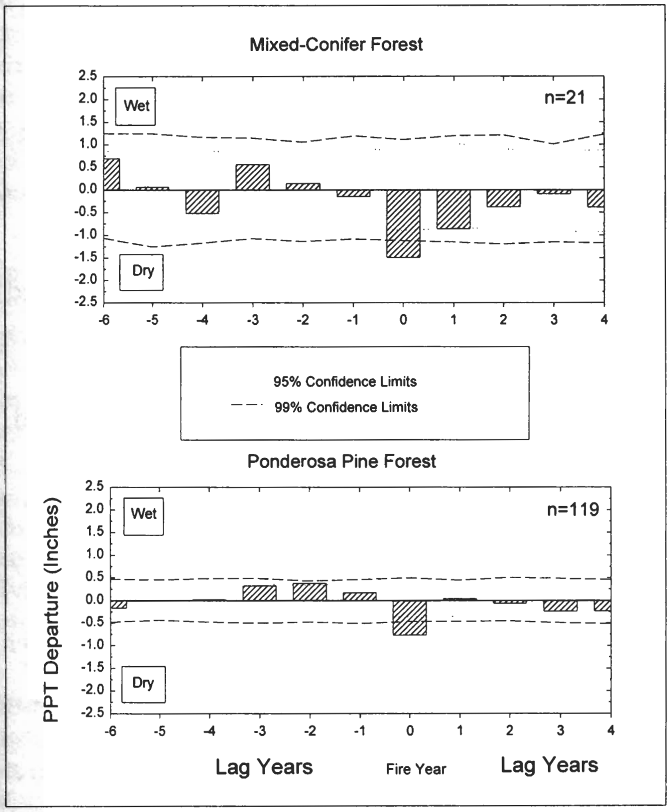

Figure 5. The superposed-epoch analysis for both the mixed-conifer (all fire dates) and the ponderosa pine forests (fire dates based on at least 10% trees scarred) for the period 1653–1986. The precipitation time series used was based on a tree-ring reconstruction of December-June precipitation. Departures were computed as the difference between the long-term mean precipitation level (1653–1986) and the observed mean precipitation during the fire years and lagged years. The "n" value is the number of fire years used in the calculations.

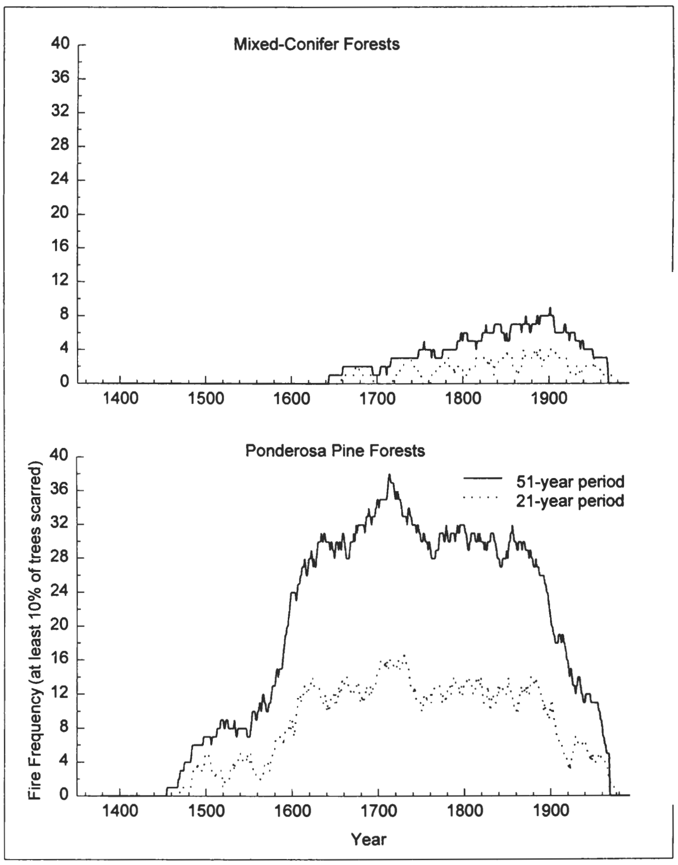

Figure 6. Fire frequency (number of fires/period, based on all fires date) for both mixed-conifer and ponderosa pine forests. Moving periods of 51 and 21-years length were used for computing the fire frequencies and are plotted on the central year of the moving period.

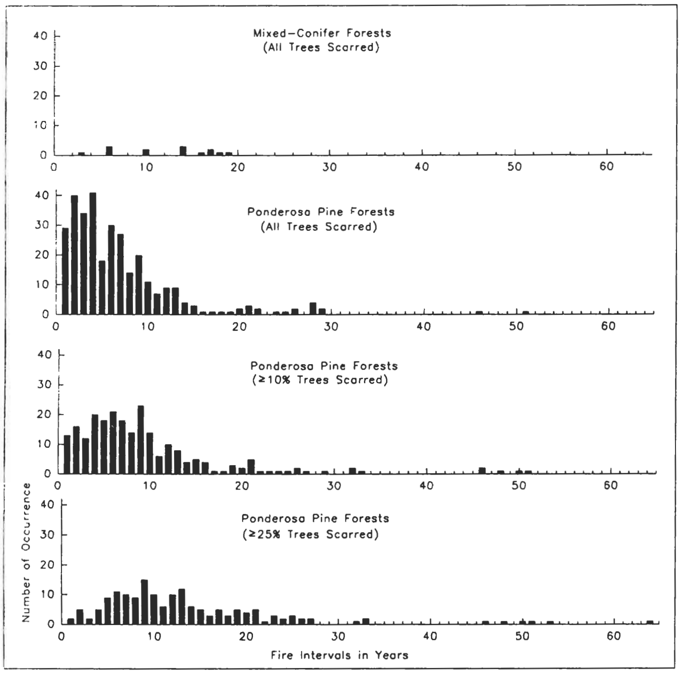

Figure 7. Distribution of fire intervals for mixed-conifer forests (all fires) and ponderosa pine forests (all fires and at least 10% and 25% of all trees scarred).

(1980) reported that early grazing of sheep and other livestock by the Navajo began in northern New Mexico in the mid 18th century. Savage and Swetnam (1991) documented an early decline in fire frequency beginning around the mid 1800s in ponderosa pine forests in the Chuska Mountains, and hypothesized that this change in fire regime was due to the rise of intensive sheep herding by the Navajo in this area.

The Cerro Pedernal site (CPE) also displays high frequency fire events during most of the 1600's and early 1700's, again with an obvious reduction in fire frequency after 1748 and early cessation of major fires by 1873 (Figure 2). Portions of the CPE area were grazed by Hispanic/genizaro peoples since the 1720s, and the initial Spanish land grant for Cañones (immediately northeast of CPE) was provided in 1731 (Van Ness 1987). These lines of evidence suggest Hispanic grazing practices might have caused the reduction in fire frequency which is apparent after 1748 in this area. In addition, CPE displays an unusually long, 51-year gap without any recorded fires between 1664 and 1715. This long fire interval may be due to utilization of the CPE area for livestock husbandry by Tewa Native Americans during the unsettled years immediately before and after the 1680 Pueblo Revolt, as indicated by Piedra Lumbre phase archeological sites in the adjoining Chama River Valley (Wozniak 1992, Kemrer 1992) and historic documentation of Tewa Puebloans taking refuge from the Spanish reconquest in 1696–1697 "at the foot of the Cerro de los Pedernales" (Wozniak 1992:59–60). Potential explanations for this odd, long fire interval must remain speculative until additional historical information and comparative fire history data are gathered and analyzed for this locality.

The CAS and CME sites had much lower fire frequencies than the other ponderosa pine sites, and their Max. and Min. FI's were also relatively high (Table 3). Both stands are topographically isolated at relatively high elevations by unvegetated, steep, rocky cliffs in upper Los Alamos Canyon from fires which could otherwise have spread to these sites from the extensive ponderosa pine forests found on lower elevation uplands. Further, the adjoining north-facing slopes of these two mountains are quite mesic and are dominated by mixed-conifer forests which had somewhat lower fire frequencies than most ponderosa pine forests. Consequently, we suggest that topographic isolation from more extensive ponderosa pine stands (and their spreading fires), combined with the lower frequency of fire in the mixed-conifer forests on the adjoining north-facing slopes, led to lowered fire frequencies at these two sites.

There was a clear cessation in widespread fire occurrence at all sites after 1893 (Figure 2). The end of the frequent and extensive fires coincided with the onset of the documented period of intensive livestock grazing across northern New Mexico (Wooton 1908; Allen 1989:145–148), which reduced the continuity of herbaceous fine fuels (e.g., grasses) and hence the ability of fires to spread. Because the buildup of livestock numbers in the late 1800's was also a regional phenomenon, concurrent and similarly sharp declines in fire frequency are observed in most other southwestern fire scar studies (Weaver 1951; Dieterich 1980; Allen 1989; Swetnam 1990; Swetnam and Baisan, This Volume). However, fire histories show earlier cessation of fires at sites with earlier periods of intense grazing (e.g. Savage and Swetnam 1991; Touchan *et al.* 1993), and conversely fire regimes have continued little-changed well into the 20th Century at a few sites where grazing and fire suppression were limited (e.g., Dieterich 1983; Swetnam 1983; and Grissino-Mayer *et al.* 1994).

Our results indicate that fire during the presettlement period was less frequent in the mesic mixed-conifer forests in the Jemez Mountains than in the ponderosa pine forests (Figure 6). Fire frequency is generally thought to decrease with increasing elevation in the southern and central Rockies (Wright and Bailey 1982), due to the cooler and wetter conditions that prevail at higher elevations. The fire frequencies for major fires in the Jemez mixed-conifer forests varied between sites, but they were similar to those found in other southwestern mixed-conifer forests where the MFI's were estimated to vary between about 7 and 22 years (Dieterich 1983; Ahlstrand 1980; Baisan and Swetnam 1990). However, our Jemez "mixed-conifer" stands are colder and more mesic than the other cited Southwestern sites, as PMN, CMN, and CAN all lack any pine species and include a significant Engelmann spruce component. Further, Grissino-Mayer *et al.* (1994) have recently reported high frequency fire regimes from upper-elevation, mixed-conifer forests on Mount Graham (3,267 m) in the Pinaleños Mountains of southeastern Arizona (the WMPI for at least 25% of all trees scarred was 7.9 years). This recent work indicates that great variability in past fire regimes existed among mixed-conifer forests in the Southwest, commensurate with the variability in species composition, stand structure, and landscape position of this forest "type". A linear model of changes in fire frequency as a function of elevation is too simplistic.

Our results for the age structure of aspen stands in Jemez Mountains mesic mixed-conifer forests indicates that aspen regeneration was the result of patchy crown fires. For example, at CAN the presence of a large aspen stand which displays a major pulse of aspen regeneration in the 1890's adjacent to the fire-scar-sampled conifer forest suggests that the widespread 1893 fire probably crowned across much of this slope (Figure 4). Other fire dates recorded on nearby conifer trees do not obviously correspond temporally with recruitment pulses. We conclude that a combination of surface and crown fires occurred in these mixed-conifer forests.

In the past century, both the ponderosa pine and mesic mixed-conifer forests sustained changes in species composition and stand structure. For example, changes in the ponderosa pine forest include the formation of dog-hair thickets, decreased understory cover, and increased fuel-loading (Covington and Moore 1994). Evidence of such changes are very obvious at the MCN site (Moir and Dieterich 1988). These changes are most likely a result of natural and anthropogenic factors such as grazing, good seed crop years, and fire suppression (deBuys 1985; Carlson 1969; Allen 1989; Touchan *et al.*, in press). In the mesic mixed-conifer forests, these anthropogenic changes have favored the establishment of the shade tolerant, less fire resistant white fir within many portions of these stands (Allen 1984:70–75). As in ponderosa pine forests, fire suppression over the past century has allowed the development of a densely stocked, younger, understory ("doghair thickets") that would previously have been thinned by repeated surface fires (Harrington and Sackett 1990). These changes in forest structure and species composition have increased the probability of high intensity fires. In addition, these structural changes have probably resulted in other kinds of disturbance regime changes, such as increased synchrony and severity of regional spruce budworm outbreaks in mixed-conifer forests of the Southern Rockies (Swetnam and Lynch 1993).

Precipitation-Fire Relations: Superposed-Epoch Analysis

Climatic variation has an important influence on fire regimes in the Southwestern United States. On a regional basis fires are more likely to occur in years of below average moisture. For example, the regional drought years of 1748 and 1879 show up repeatedly as fire dates in fire history studies across the Southwest (Swetnam 1990; Swetnam and Betancourt 1990; Swetnam and Baisan, This Volume). Another factor that may play a role in regional fire occurrence is the influence of winter-spring precipitation on the accumulation and moisture content of the fuels. A dry spring may be followed by numerous lightning strikes at the onset of the summer precipitation season, which ignite the accumulated dry fuel (Baisan and Swetnam 1990). In contrast wet springs result in high fuel moisture which may persist into the early fire season inhibiting fire spread.

In our study, we found that the winter-spring season immediately preceding fire occurrence was significantly drier than normal in both the ponderosa pine and mixed-conifer forests (Figure 5). In the ponderosa pine forests, winter-spring seasons several years prior to fires were characterized by above average precipitation, but only the second year prior to the fire was significantly above average at the 95% confidence limit. This general pattern suggests that during wet years the build up of fine fuels is an important pre-condition for fire ignition and spread. Baisan and Swetnam (1990) documented a similar pattern in their study of pine forests in southeastern Arizona. They concluded that two unusually wet years prior to a fire season increased fine fuel production and enhanced the probability of fire spread.

A consequence of the normally mesic, relatively productive conditions and lower fire frequencies on north facing slopes is that fuel is usually available in the mixed-conifer forests. Our analysis of climate/fire relationships in mixed-conifer forests of the Jemez Mountains suggests that the winter-spring season immediately preceding the fire season was much drier than normal, but found no significant relationships with preceding years (Figure 5). Therefore, we suggest that fuel moisture was the most important factor determining fire spread in these mesic forests. If fuels were dry enough, then there was a high probability of fire spread in this forest type. In contrast to ponderosa pine forests, fine fuel accumulation resulting from plant growth in preceding years was less important.

An unusually long fire-free interval in the 1820's and 1830's occurred at almost all of the Jemez sites (Figure 2). A similar decrease in fire occurrence during approximately the same period has been noted in several other southwestern fire history studies (Swetnam 1983; Swetnam and Dieterich 1985; Swetnam *et al*. 1989; Baisan and Swetnam 1990; Grissino-Mayer *et al*. 1994). Swetnam and Dieterich (1985) hypothesized that lack of fire during this period may have been due to regional climate changes. Fritts' (1991) regional precipitation reconstruction for the western US shows that the 1830's period was one of the wettest periods in the past two to three centuries. Our winter-spring reconstruction for the Jemez Mountains shows that 1824–1827 was very dry, followed by a wet period in the 1830's. Grissino-Mayer *et al*. (1994) also report that a severe drought occurred between 1817 to 1832 in southeastern Arizona; they hypothesize that this drought resulted in a decline in the herbaceous vegetation, and that the average to wet conditions that followed perhaps reduced both successful ignitions and the spread of fire. Hence, a combination of extreme drought and wetness is a plausible explanation of this regional scale, anomalously long fire-free interval. The extensiveness of this pattern across the Southwest also argues for a climatic, rather than an anthropogenic explanation.

CONCLUSIONS

Our data show that pre-1900 fire regimes in ponderosa pine forests were characterized by high frequency, low intensity fires. Fire regimes in the mixed-conifer forests were characterized by somewhat lower fire frequencies than in the ponderosa pine forest. Patchy crown fires occurred during some years in the mixed-conifer forests. The variability of fire documented in both the mixed-conifer and the ponderosa pine forest was probably caused by three main factors.

First of all, anthropogenic factors, such as intense livestock grazing, reduced fine fuels necessary for the spread of fire in the high frequency fire regimes. Overall, one of the most important anthropogenic disturbances in the Jemez Mountains in the last century is fire suppression. Fire suppression has allowed changes in species composition and stand structure in both the ponderosa pine and the mixed-conifer forests. Fire suppression has caused both the build-up of woody and fine fuels and the increase in woody vegetation, such as the formation of densely overstocked understory thickets. These factors have also contributed to the decline of native grasses, due to the increased shading and accumulation of thick mats of pine needle litter. The current policy of fire suppression will result in further fuel buildups in both forest types, threatening modern forests with high-intensity conflagrations such as the La Mesa Fire of 1977 (Foxx and Potter 1978).

Second, on a local scale, topography and moist north facing slopes played an important role in lowering the frequency of fire at two ponderosa pine sites. Our study shows that forest type and elevation are sometimes less important than topographic situation in determining historic fire regimes.

Third, on a regional scale, climate played an important role in the fire regimes in both the ponderosa pine and the mixed-conifer forests. Major fire years in both forest types tended to be significantly drier than normal. Moreover, our analysis of climate/fire relationships suggests that the availability of fine-textured surface fuels was an important factor controlling the spread of fires in ponderosa pine forests. Similar patterns have been observed in modern fire occurrence patterns; e.g., the 1994 fire season has been particularly extensive in the southern portion of the Southwest, following three years of herbaceous and needle litter fuel buildups in the wet conditions of 1990, 1991, and 1992. In the sampled mixed-conifer forests fuel moisture is probably more important than fine fuel availability in determining fire occurrence. Usually, long intervals between fires in many sites across the Southwest could be important in synchronizing forest structures, since these were concurrent periods when many trees may have established.

This study provides a baseline for planning and justifying ecosystem management programs. For example, an understanding of the pre-settlement fire regimes for specific areas can be used to design the appropriate prescribed burning plan to affect ecosystem dynamics in a fashion similar to the natural fire regime that existed before human disturbance (i.e., low-intensity surface fires). Such a management plan is not intended to strictly mimic the natural fire regime, but to meet ecological objectives by bringing the range of existing conditions in a landscape to within the historic "natural" range. This natural range of conditions, as defined by the pre-settlement, historical states, may not be the most desirable, or practical conditions for current forest ecosystems. On the other hand, in many cases the natural range of variability is the best template we have for longer-term sustainable conditions (Allen 1994).

In summary, this study demonstrates that the fire regimes in the Jemez Mountains are the result of complex interactions between combinations of anthropogenic and natural factors, and regional as well as local factors.

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