Comparing modern and past fire regimes to assess changes in prehistoric lightning and anthropogenic ignitions in a Jeffrey pine – mixed conifer forest in the Sierra San Pedro Mártir, Mexico

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Abstract: Fire histories of Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) – mixed conifer forests in the Sierra San Pedro Mártir, Baja California, Mexico, recently described through analysis of 300 years of tree-ring fire-scars, indicate there have been four distinct fire-regime periods based on fire frequency and size. We used modern lightning and fire data to assess whether the current lightning regime could have supported the prehistoric fire regime. Although there are several sources of uncertainty, the present lightning regime, concentrated in the summer with little spring activity, may be insufficient to support the high number and spring seasonality of fires recorded during some periods in the past. Changes in the ignition regime recorded during the past 300 years could have been due to anthropogenic and (or) climatic factors; available evidence suggests periods of frequent fire were dominated by anthropogenic ignitions.

Résumé : L'historique des feux dans les forêts résineuses mixtes de *Pinus jeffreyi* Grev. & Balf. de la Sierra San Pedro Mártir, dans l'État de la Basse-Californie au Mexique, décrit récemment par l'analyse des cernes annuels pour la présence de cicatrices de feu sur une période de 300 ans indique qu'il y a eu quatre périodes distinctes de régime de feux sur la base de la fréquence et de la dimension des feux. Nous avons utilisé les données modernes sur la foudre et les feux pour évaluer si le régime actuel de foudre aurait pu supporter le régime préhistorique de feux. Bien qu'il y ait de nombreuses sources d'incertitude, le régime actuel de foudre, concentré durant l'été avec peu d'activité au printemps, est possiblement insuffisant pour supporter le nombre élevé et l'occurrence printanière des feux notés durant certaines périodes dans le passé. Les changements dans le régime d'allumage notés au cours des 300 dernières années pourraient être dus à des facteurs anthropiques et climatiques; les indices disponibles indiquent que les périodes où les feux ont été fréquents étaient dominées par des allumages d'origine humaine.

[Traduit par la Rédaction]

Introduction

Tree-ring fire scars (TRFS) have been used to reconstruct prehistoric fire regimes in coniferous forests extending back several hundred to over 1000 years in the region influenced by the North American monsoonal system (NAMS) in the southwestern United States and northwestern Mexico (Baisan and Swetnam 1995; Swetnam et al. 2001; Swetnam and Baisan 2002; Stephens et al. 2003). One of the goals of fire-history reconstruction is to provide land managers with reference conditions, describing the fire regime of a forest prior to European settlement disturbances, to serve as a template for current fire management (Swetnam et al. 1999). Land managers make the assumption that, in the absence of human disturbance, the prehistoric fire regime recorded by TRFS would have continued to the present day, despite known complex interactions between fire regimes and climatic variation (Swetnam 1993; Grissino-Mayer and Swetnam 2000). Testing this assumption has not been possible because there are no good controls; nearly all mixed-conifer forests in California have been extensively disturbed for over 150 years by fire suppression, timber harvesting, and the introduction of grazing animals, resulting in dramatic changes in fire regimes. One region, presumed to be largely free of human disturbance, has been proposed as a control for fire history in California: the Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) – mixed conifer forest in the Sierra San Pedro Mártir (SSPM) in north-central Baja California, Mexico (Minnich et al. 2000*a*; Stephens et al. 2003). The SSPM is highly unusual within the Californian floristic province, because the forest was burned by uncontrolled, presumably lightning-ignited, fires until approximately 1970, and timber harvesting has been minimal (Stephens et al. 2003).

Stephens et al. (2003) completed a TRFS study in the

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SSPM, sampling 105 fire-scarred specimens, mostly live Jeffrey pine, from two 0.8 km^2 sites approximately 1.5 km apart near Vallecitos Meadow on the upper plateau in the SSPM. They found 1034 cross-dated fire scars and identified 105 years between 1521 and 1998 when a recorded fire occurred on at least one of the sites (Fig. 1). Approximately 40% of the fires scarred only one tree. The calculated fire-return interval, depending on the scale of composite fire chronology used and time period analyzed, was between 5.7 and 14.5 years, but most composites were less than 10 years, suggesting a frequent, low-intensity fire regime (Fig. 1). The mean fire-return interval for single trees, equivalent to the fire-rotation period calculated by Minnich et al. (2000*a*), was 24.4 years. Fire seasonality, estimated from scar position in the annual growth rings, was dominated by early-wood fires, interpreted as late spring to midsummer.

The TRFS record for these two sites indicated there have been four distinct fire regimes during the past 400 years: (*i*) 1600–1789 (very frequent small fires), (*ii*) 1790–1831 (infrequent small fires), (*iii*) 1832–1946 (frequent larger fires), and (*iv*) 1947–present (infrequent small fires). Less intensive TRFS data from sites throughout the SSPM (Skinner et al. 2004) confirmed this general pattern of fire frequency and seasonality.

Stephens et al. (2003) proposed three hypotheses for observed changes in the fire regime in the SSPM in the late 18th century: (*i*) the introduction of livestock grazing, resulting in reduced grass cover and a change in fine fuel characteristics, (*ii*) changes in human-caused ignitions, and (*iii*) changes in regional climate. We have used phytolith analysis to reject the first hypothesis: there was probably no substantial prehistoric grass cover in SSPM forests (Evett et al. 2007).

In this paper, we evaluate the other two hypotheses by determining whether the modern lightning and fire ignition regime in the SSPM could support the prehistoric fire regime indicated by the TRFS record. We examine data describing the modern lightning and fire regime in the SSPM compared with TRFS fire-history data. If the number and seasonality of ignitions resulting from the current lightning regime do not match the number and seasonality of fires in the past recorded in the TRFS data, a change in the ignition regime, of anthropogenic or climatic origin, is inferred.

Climate is a crucial factor for any fire regime regardless of ignition source; anthropogenic fires are constrained by the same climatic conditions as lightning fires. Even if there are strong correlations between periods with widespread fires and climatic drivers, lightning was not necessarily the primary ignition source, because anthropogenic ignitions would also lead to widespread fires during these periods. To distinguish anthropogenic from lightning fires in the TRFS record, one must assess the likelihood the lightning regime could support the number and as well as the seasonality of fire ignitions. Very large discrepancies between the modern and prehistoric fire regimes in the absence of evidence of substantial climate change or an altered vegetation type would suggest anthropogenic ignitions were an important component. If this is the case, the SSPM may not be a suitable control for California land managers desiring reference conditions based on a continuing natural fire regime.

Materials and methods

Study area

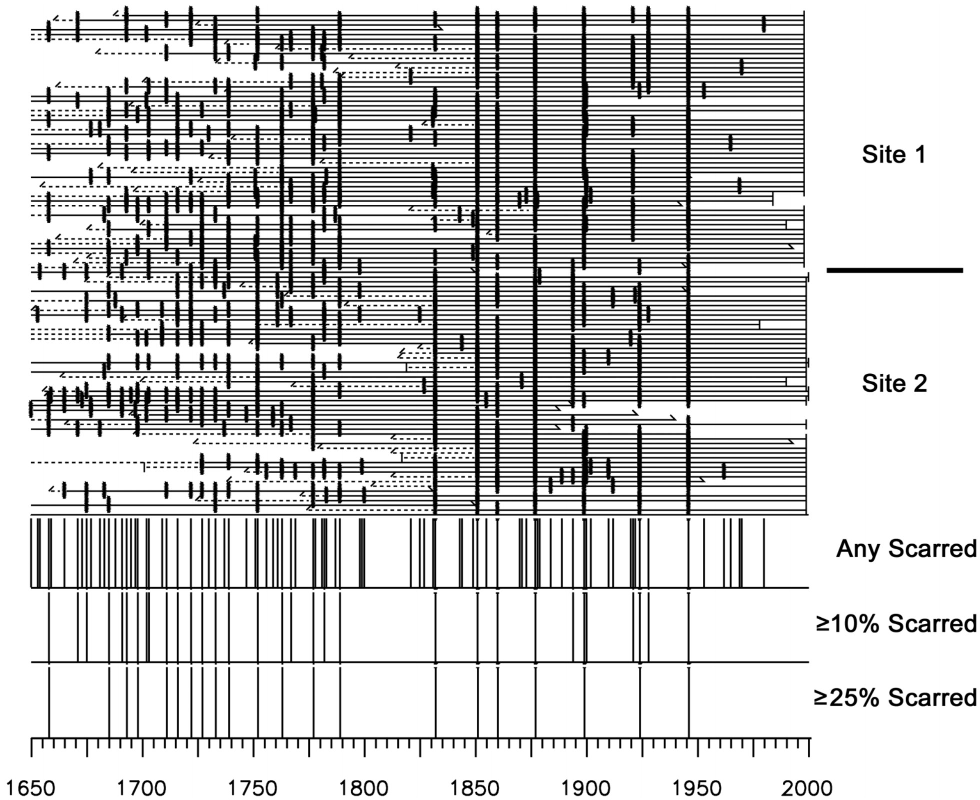
The study was located in San Pedro Mártir National Park within the SSPM mountain range in north-central Baja California, Mexico, 100 km southeast of Ensenada (Fig. 2). The SSPM, the southernmost extension of the Peninsular Range, is dominated by a sloping plateau averaging 2600 m in the north, decreasing to 1800 m in the south. Coniferous forests, comprising approximately 40 655 ha (Minnich et al. 2000*a*), dominate the plateau. Major tree species on and near the study sites include (from Wiggins 1980): Jeffrey pine, white fir (*Abies concolor* (Gord. & Glend.) Lindl.), sugar pine (*Pinus lambertiana* Dougl. ex Loud.), lodgepole pine (*Pinus contorta* var. *murrayana* Dougl. ex Loud.), and incense-cedar (*Calocedrus decurrens* (Torr.) Floren.). Common understory species on the study sites include mountain snowberry (*Symphoricarpos oreophilus* Gray), greenleaf manzanita (*Arctostaphylos patula* Greene subsp. *platyphylla* (Gray) P.V. Wells), whitethorn ceanothus (*Ceanothus cordulatus* Kell.), and blue sage (*Salvia pachyphylla* Epling ex Munz). Grasses currently found on the sites include cheatgrass (*Bromus tectorum* L.), squirreltail (*Elymus elymoides* (Raf.) Swezey subsp. *elymoides*), deergrass (*Muhlenbergia rigens* (Benth.) A.S. Hitchc.), New Mexico muhly (*Muhlenbergia pauciflora* Buckl.), and pine dropseed (*Blepharoneuron tricholepis* (Torr.) Nash). Jeffrey pine, Jeffrey pine – mixed conifer, and mixed white fir are the most common forest types (Minnich and Franco-Vizcaino 1998). These forests have never been extensively logged. Limited fire suppression, with hand crews in the summer and fall, began in the 1970s, but there has never been large-scale fire suppression.

The soils of the SSPM are unclassified, but those derived from diorite parent materials in forested upland sites near the study area are Typic Xeropsamments (Franco-Vizcaino et al. 2002; Stephens and Gill 2005). Soils are shallow, well to excessively drained, and relatively acidic (pH 5.3). The most common soil texture is loamy sand. Soil chemistry and texture in this study are typical of granite-derived soils in similar forests in California (Potter 1998).

The SSPM is at the southern margin of the North American Mediterranean climate zone (Pyke 1972; Markham 1972; Minnich et al. 2000*a*). Accurate climatic data for the plateau is very limited, but the mean precipitation from 1989 to 1992 (a period with two regional drought years and one wet year) at Vallecitos Meadow, near our study sites, was 55 cm (Minnich et al. 1997, 2000*a*). Most precipitation occurs during the winter months, but there is a secondary peak from July to August when moisture derived from the North American monsoonal system (NAMS) commonly extends to the SSPM (Minnich et al. 1993, 2000*b*). The Mediterranean climate in the SSPM possibly includes higher amounts of summer precipitation than most areas of California but probably less than most areas within the region influenced by the NAMS.

The TRFS fire-history study (Stephens et al. 2003) was done on two 0.8 km^2 sites separated by 1.5 km at 2400–2600 m elevation on the upper plateau at 31°02′N, 115°27′W. The vegetation at site 1, located on granitic parent material, is Jeffrey pine – mixed conifer with patchy greenleaf manzanita and very little grass in the understory.

Fig. 1. Fire activity recorded by tree-ring fire scars with multiple-scale composite fire chronologies at two sites in Jeffrey pine – mixed conifer forest in the Sierra San Pedro Mártir, Baja California, Mexico (adapted from Stephens et al. 2003). Each horizontal line is an individual tree and each short vertical line is a dated fire scar.



Site 2, located on metamorphic quartz schist, is dominated almost exclusively by Jeffrey pine with patchy greenleaf manzanita and areas of grass with <5% cover in the understory.

Lightning data

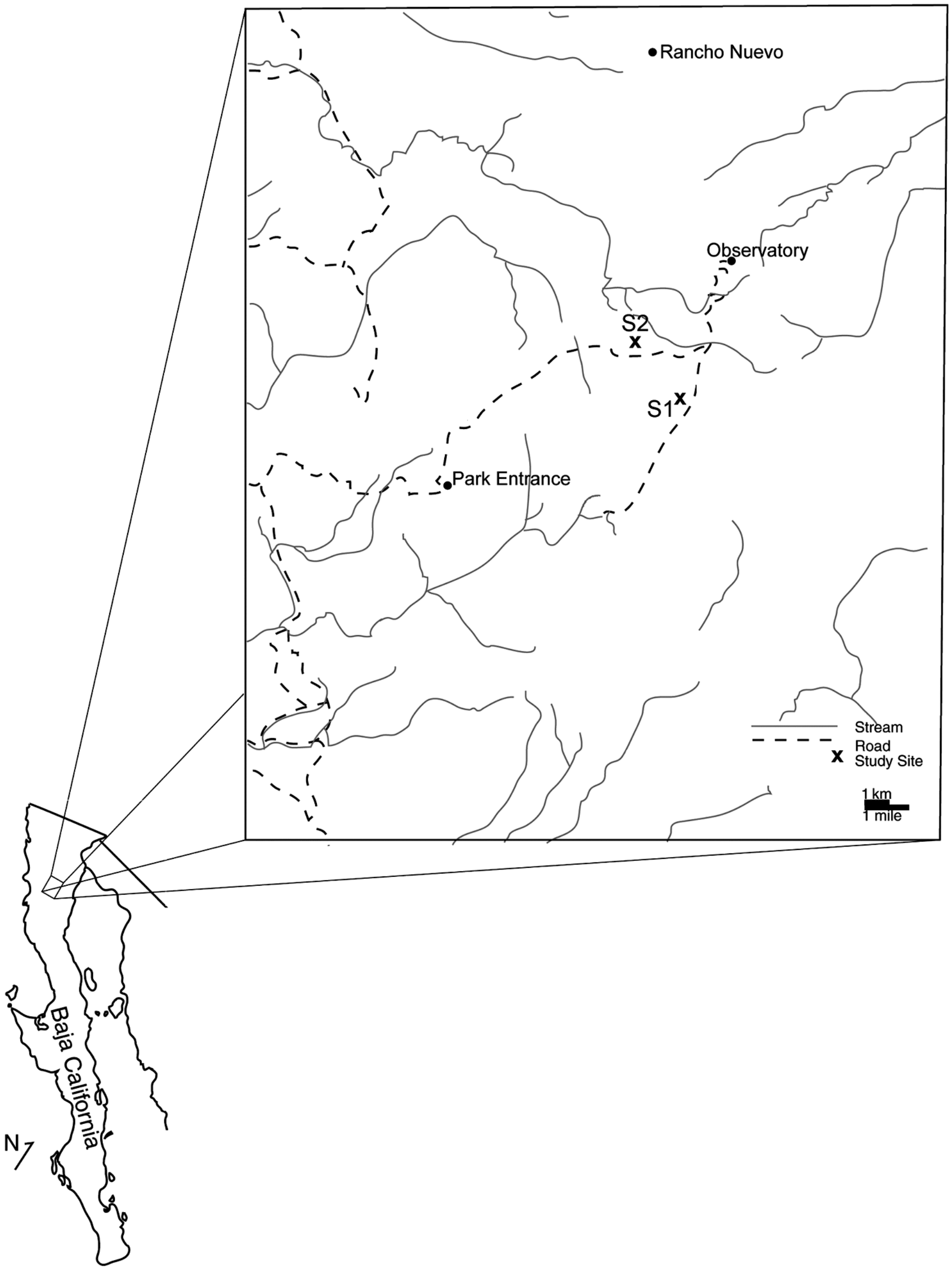
Monthly cloud-to-ground lightning flash density data for 1996–2002, based on data from the U.S National Lightning Detection Network (NLDN), the most accurate lightning data available (Cummins et al. 1998; Orville and Huffines 2001), were purchased from Vaisala Inc. (2705 East Medina Road, Tucson, Ariz.). Data were for a 2300 km^2 rectangle that included almost all of the SSPM, bounded by 30°40′N to 31°10′N and 115°10′W to 115°40′W. To narrow the analysis to the most relevant region, we used a subset of the monthly flash density data for an 865 km^2 quadrilateral subset of the rectangle (encompassing most of the Jeffrey pine – mixed conifer and mixed conifer vegetation types in the SSPM, according to the GIS map in Minnich et al. (2000*a*)), with coordinates 31°10′N, 115°30′W; 30°58′N, 115°38′W; 30°40′N, 115°20′W; and 30°42′N, 115°15′W. Because all NLDN lightning sensors are located north of the United States – Mexico border, flash detection is compromised. Lightning flash detection efficiency for the NLDN data for this location is estimated at 30%, with high confidence that the actual value is in the interval between 20% and 40% (K. Cummins, Vaisala, Inc., Tucson, Arizona, personal communication 2003). The spatial accuracy of detected flashes is unknown but is probably not a problem, because flash density is quite uniform throughout the plateau (Minnich et al. 1993). Automated lightning detection system (ALDS) data (Western Regional Climate Center, Desert Research Institute, 2215 Raggio Parkway, Reno, Nev.), used by Minnich et al. (1993), were also obtained for 1986–1996 for the SSPM region north of 31°N, covering only one third of the SSPM Jeffrey pine – mixed conifer and mixed conifer areas. Because of fewer observation sites, increased spatial detection errors, and lower lightning flash detection efficiency, ALDS data is of lesser quality than NLDN data and is not accurate enough to be combined for a longer term quantitative flash density study (Brown and Hall 2001). However, the interannual variation in flash density and the percentage of monthly flash occurrence from ALDS data, presumably not biased by poor detection efficiency, were used to test the validity of and extend the NLDN lightning climatology over a longer time period.

Tree ring fire history data

Fire-history data from Stephens et al. (2003), based on sampling of TRFS on two 0.8 km^2 plots, were reworked to estimate the number of ignitions that occurred on each site and the seasonality of each ignition. Fires that scarred <10% of recording trees, or only one tree if there were only 5–10 recording trees, were considered small fires with ignition occurring on the plot.

Designation of fire seasonality, originally done by Stephens et al. (2003), was based on the position of the fire scar in the annual cambial growth. By convention, scars found in the first third of the earlywood were considered

Fig. 2. Location of Sierra San Pedro Mártir and study sites.



early earlywood fires, those in the second third were middle earlywood, and those in the last third were late earlywood (Dieterich and Swetnam 1984; Swetnam and Baisan 1989; Baisan 1990). Scars in the latewood were designated latewood fires, whereas scars at the border of the latewood and the following earlywood were interpreted as dormant season fires. Calendar dates were assigned to fire scar positions using phenological data for Jeffrey pine at a site at the same elevation in the Sierra Nevada, 5° latitude farther north (Royce and Barbour 2001).

For this study, fire-scar seasonality data were simplified with the assumption that all fire scars on a plot dated to the same year came from only one ignition event. Each fire year was assigned a ring-position seasonality based on the dominant ring position of fire scars for that year. Dominant was defined as a ring position having twice or more the number of fire scars as any other position. If no ring position was dominant in a fire year, two or more ring positions were credited with appropriate percentages.

Modern fire data

The lightning ignition regime depends on lightning flash density and the lightning fire ignition rate. Climatically determined lightning flash density, particularly for a region such as SSPM, influenced sporadically by the NAMS, could vary considerably over decadal, centennial, and millennial scales. The lightning fire ignition rate, the proportion of lightning flashes resulting in a detectable ignition event (Minnich et al. 1993), is determined by several factors, including characteristics of the litter of the vegetation type (Latham and Schlieter 1989; Anderson 2002) and fuel moisture, largely dependent on long-term climate and short-term weather conditions.

We used two approaches to estimate the modern lightning ignition rate for the SSPM: (*i*) combined modern estimated lightning flash density data with the historical fire record in the SSPM and (*ii*) estimated likely ignition rates for the SSPM by applying the above approach to possible SSPM analogs in southern California and New Mexico, regions in the western United States with higher quality lightning flash density and historical fire ignition data that span the gradient of monsoonal influence.

Lightning fire ignition rates were estimated by combining lightning flash density data with the historical fire record for 1996–2002 in the SSPM. Fire records (including fire location name; dates fire started and was extinguished; number of hectares of trees, shrubs, and grassland burned; and cause of fire) were obtained from the Mexican Comisión Nacional Forestal (CONAFOR). The quality of the CONAFOR data is unknown; there may have been some small or inaccessible fires that were not observed. SSPM fire data in Minnich et al. (2000*a*) was not useful for this study, because they did not detect fires <5 ha and were forced to aggregate years because of the time between aerial photograph flights.

Analog lightning fire ignition rates were calculated using monthly NLDN lightning data (obtained from Vaisala) and agency fire-history data for 1986–1997 for a 130 km^2 quadrangle above 1800 m (approximating the distribution of the mixed conifer forest) in the San Jacinto Mountains (SJM) and yearly lightning data for a 168 km^2 polygon above 1800 m in the San Bernardino Mountains (SBM), both in San Bernardino National Forest in southern California, a region typical of the North American Mediterranean climate region zone (little summer rainfall and low summer lightning flash density). Additional ignition rate data for the Gila – Aldo Leopold Wilderness Complex (GW), New Mexico, where the climate is typical of the NAMS region (considerable summer rainfall and high summer lightning density), were obtained from Rollins (2000, 2001). The detection efficiency of the agency fire data is unknown, but many small fires <1 ha were recorded. These two regions are the closest analogs to the SSPM for which data are available.

Results

Lightning data

Based on NLDN data, uncorrected mean annual flash density for 1996–2002 for most pixels (3 km × 3 km, included in the Vaisala grid data) within the 2300 km^2 rectangle including most of the SSPM was between 0.5 and 2.0 flashes·km^{-2}·year^{-1}. A map of flashes indicated that they were spread evenly over the SSPM plateau with no evidence that the TRFS history sites had unusual lightning activity. When corrected for the estimated 30% detection efficiency (multiplying corrected values by 3.33 and dividing by 7 years of record), mean flash density for the smaller quadrangle (865 km^2), focusing on the Jeffrey pine – mixed conifer forest, was 2.58 flashes·km^{-2}·year^{-1}, with 20% and 40% detection efficiency intervals between 1.94 and 3.87 flashes·km^{-2}·year^{-1} (Table 1). Interannual variation in total number of flashes was high, ranging from 4947 in 1996 to 633 in 2002. Only 8% of lightning flashes occurred during May and June; 91% of flashes occurred during the July–September period influenced by the NAMS. ALDS lightning data for the period 1986–1996 confirmed that only a small percentage of flashes occurred in May and June (Table 1). Data from the SJM and SBM above 1800 m in southern California showed considerably less lightning flash density during all months and almost all years, averaging 0.39 and 0.92 flashes·km^{-2}·year^{-1}, respectively (Table 1).

Fire size and seasonality data based on fire-scar record

The majority of fires (54%) on both fire history sites scarred <10% of the trees (Table 2; Fig. 1). These were interpreted as microfires with ignition occurring on-site. The proportion of microfires fluctuated over time; the period 1700–1799 had approximately half the percentage of microfires as the period 1900–1998.

The majority of fire years (56%) on both sites were recorded in early earlywood followed by middle earlywood (23%) (Table 2). Only 11% of the fire years recorded on the two sites were in latewood.

Modern fire and ignition data

During the period 1996–2002, there were 73 lightning-caused fires reported in the SSPM (Table 3), ranging from 3 in 1999 to 26 in 1997. Causes of the fires were not given in 1996 and 1998, but because nearly all fires in other years in the SSPM were caused by lightning, all fires in these 2 years were conservatively assumed to be lightning caused. Only 25% of the fires occurred during May and June. Combining reported fire data with lightning flash data (Table 1), the estimated lightning fire ignition rate for 1996–2002 was 0.0047 fires/flash (Table 3). Interannual variation was nearly an order of magnitude from 0.0016 fires/flash in 1999 to 0.0142 fires/flash in 2002. Ignition rates were highest in May and June and lowest in August and September, possibly reflecting the dampening effect of the NAMS.

Based on estimates of lightning flash and fire data from charts in Rollins (2001), the annual ignition rate in the GW within the mixed conifer vegetation type was 0.0031 fires/flash (Table 4). Ignition rates peaked in June at 0.0133 fires/flash and declined with the onset of the NAMS (Table 3). The annual ignition rate above 1800 m in southern California mountains was considerably higher, approaching 0.060 fires/flash (Table 4); however, the peak (0.088 fires/flash) was in August, probably reflecting the much smaller NAMS dampening effect (Table 3). Despite a total of 30 lightning flashes in May and June during 1996–2002 on the 130 km^2 SJM quadrangle, there were no fires recorded. These data suggest the ignition rate during May and June may be lower than 0.060 fires/flash.

Based on modern lightning flash data, there are 2.58 flashes·km^{-2}·year^{-1} in the SSPM (Table 1). Combining this with an ignition rate of 0.0047 fires/flash calculated from CONAFOR data (Table 3) produces an estimated 0.012 fires·km^{-2}·year^{-1}. If the current lightning ignition regime existed in the past, each 0.8 km^2 site in the study area would be expected to have ∼1.0 fire ignitions/century. The 300 year TRFS history recorded a mean of 9 fires ignitions/

Table 1. NLDN and ALDS lightning flash data for a 86 500 ha quadrangle in the Sierra San Pedro Mártir (SSPM), 1996–2002.

	NLDN data											NLDN (flashes·km^{-2}·year^{-1})	
	1996	1997	1998	1999	2000	2001	2002	30% DE (flashes/ year)	Confidence interval (flashes/ year)	30% DE flashes/ month (%)	ALDS data 1986–1996 flashes/ month (%)	SSPM	SJM
January	0	0	0	0	0	0	0	0	0	0.0	0.2	0.00	0.00
February	1	0	3	0	7	0	0	5	8	0.2	0.5	0.01	0.00
March	0	0	0	0	0	0	0	0	0	0.0	0.7	0.00	0.00
April	0	1	0	0	0	0	0	0	0–1	0.0	0.8	0.00	0.00
May	0	177	0	0	0	6	0	87	65–131	3.9	1.2	0.10	0.03
June	0	0	0	3	35	159	0	94	70–141	4.2	1.4	0.11	0.01
July	368	8	78	107	51	83	120	388	291–582	17.4	23.3	0.45	0.12
August	799	350	266	363	547	217	14	1217	913–1826	54.5	49.3	1.41	0.11
September	297	403	54	72	4	3	51	421	316–631	18.9	21.8	0.49	0.11
October	14	0	0	4	9	0	0	13	10–19	0.6	1.5	0.01	0.01
November	5	0	0	0	0	0	5	5	4–7	0.2	0.0	0.01	0.00
December	0	1	4	0	0	0	0	2	2–4	0.1	0.0	0.00	0.00
Total raw flashes/year	1484	940	405	549	653	468	190	2233	1675–3349	100.0	100.0		
30% DE flashes/year	4947	3133	1350	1830	2177	1560	633						
Lower CI flashes/year	3710	2350	1013	1373	1633	1170	475					1.94	
Upper CI flashes/year	7420	4700	2025	2745	3265	2340	950					3.87	
SSPM flashes·km^{-2}·year^{-1}	5.72	3.62	1.56	2.12	2.52	1.80	0.73					2.58	
SJM flashes·km^{-2}·year^{-1}	0.08	0.64	0.25	0.52	0.82	0.41	0.01						0.39
SBM flashes·km^{-2}·year^{-1}	0.42	0.34	2.39	1.08	1.46	0.66	0.08						0.92

Note: NLDN number of flashes are shown as raw data and with correction for expected 30% flash detection efficiency (DE) and confidence interval of 20%–40% DE. Also shown are uncorrected monthly and yearly flash data for a 13 000 ha quadrangle in the San Jacinto Mountains (SJM) and yearly flash data for a 16 800 ha polygon in the San Bernardino Mountains (SBM).

Table 2. Number of fire years by percentage of recording trees scarred by fires by estimated season of fire based on dominant position of fire scars within annual growth rings for each fire year for two sites in SSPM mixed conifer forest.

		Annual ring position							
		D	EE	ME	LE	LW	U	Fire years	% of total
Site 1									
1700–1799	<10%	0	2	1	0	0	4	7	32
	10%–24%	0	2	0	0.5	0	0	2.5	11
	25%–49%	0	4	4	0.5	0	0	8.5	39
	>49%	0	3	1	0	0	0	4	18
	Total	0	11	6	1	0	4	22	
	% of known	0	61	33	6	0			
1800–1899	<10%	0	4	0	0	1	5	10	67
	10%–24%	0	0	0	0	0	0	0	0
	25%–49%	0	1	0.5	0.5	0	0	2	13
	>49%	0	1	0.5	1	0.5	0	3	20
	Total	0	6	1	1.5	1.5	5	15	
	% of known	0	60	10	15	15			
1900–1998	<10%	1	1	1	1	1	4	9	69
	10%–24%	0	0	1	0.5	0	0	1.5	12
	25%–49%	0	1	0.5	0	0	0	1.5	12
	>49%	0	0	0.5	0.5	0	0	1	8
	Total	1	2	3	2	1	4	13	
	% of known	11	22	33	22	11			
Site 2									
1700–1799	<10%	0	3	2	0	2	3	10	40
	10%–24%	0	4	1	1	0	0	6	24
	25%–49%	0	5	2	0	0	0	7	28
	>49%	0	1	1	0	0	0	2	8
	Total	0	13	6	1	2	3	25	
	% of known	0	59	27	5	9			
1800–1899	<10%	0	6	0	1	1	1	9	56
	10%–24%	0	0	0	0	0.5	0	0.5	3
	25%–49%	0	1	0	0	1	0	2	13
	>49%	0	2	1	1	0.5	0	4.5	28
	Total	0	9	1	2	3	1	16	
	% of known	0	60	7	13	20			
1900–1998	<10%	0	4	0.5	0	1.5	5	11	85
	10%–24%	0	0	0	0	0	0	0	0
	25%–49%	0	0	0	0	0	0	0	0
	>49%	0	1	1	0	0	0	2	15
	Total	0	5	1.5	0	1.5	5	13	
	% of known	0	63	19	0	19			
Both sites									
1700–1998	<10%	1	20	5	2	7	22	56	54
	10%–24%	0	6	2	2	1	0	11	10
	25%–49%	0	12	7	1	1	0	21	20
	>49%	0	8	5	3	1	0	17	16
	Total	1	46	19	8	9	22	104	
	% of known	1	56	23	9	11			
Southern California sites									
Black Mountain, SJM (%)		0	0	4	17	78	0	132	100
Big Pine Flat, SBM (%)		0	0	0	38	62	0	109	100

Note: Seasonality data for Black Mountain (San Jacinto Mountains; SJM) and Big Pine Flat (San Bernardino Mountains; SBM) are from a tree-ring fire-scar study (Everett 2003) in southern California. Annual ring positions are as follows: D, dormant; EE, early earlywood; ME, middle earlywood; LE, late earlywood; LW, latewood; U, undetermined.

century (Table 2: 56 total fires divided by 6 total centuries of record) scarring <10% of recording trees for each site.

Analog data suggest that, depending on the degree of influence of the summer monsoon, the ignition rate in the SSPM is between 0.0036 fires/flash (GW) and 0.0565 fires/flash (SJM) (Table 4). Given SSPM modern lightning flash

Table 3. Lightning-caused fire history data compiled by Comision Nacional Forestal with estimated ignition rates for SSPM for the period 1996–2002.

	May		June		July		August		September		October		Total			
	No.	Burn area (ha)	No.	Burn area (ha)	No.	Burn area (ha)	No.	Burn area (ha)	No.	Burn area (ha)	No.	Burn area (ha)	No.	Burn area (ha)	30% DE (flashes/ year)	Ignition rate (fires/ strike)
1996	0	0.00	0	0.00	1	0.01	8	59.50	0	0.00	1	1.00	10	60.51	4 947	0.0020
1997	9	33.00	1	8.00	2	0.01	8	6.00	6	3.00	0	0.00	26	50.01	3 133	0.0083
1998	0	0.00	0	0.00	0	0.00	3	0.01	2	0.01	0	0.00	5	0.02	1 350	0.0037
1999	0	0.00	0	0.00	0	0.00	1	0.05	2	0.50	0	0.00	3	0.55	1 830	0.0016
2000	0	0.00	0	0.00	2	3.00	3	0.58	0	0.00	0	0.00	5	3.58	2 177	0.0023
2001	2	2.00	6	0.01	1	1.00	5	1.00	1	0.50	0	0.00	15	4.51	1 560	0.0096
2002	0	0.00	0	0.00	8	6.50	1	0.03	0	0.00	0	0.00	9	6.53	633	0.0142
Total	11	35.00	7	8.01	14	10.52	29	67.17	11	4.01	1	1.00	73	125.71	15 630	0.0047
Total (%)	15.1	27.8	9.6	6.4	19.2	8.4	39.7	53.4	15.1	3.2	1.4	0.8				
30% DE																
Flashes/year	87		94		388		1217		421		13					
Flashes 1996–2002	610		657		2717		8520		2947		90					
Fires 1996–2002	11		7		14		29		11		1					
Ignition rate	0.0180		0.0107		0.0052		0.0034		0.0037		0.0111					
SJM ignition rate	No fires		No fires		0.037		0.088		0.070							
GW ignition rate	0.0075		0.0133		0.0038		0.0015		0.0004							

Note: Estimated ignition rates for two potential SSPM analogs, the San Jacinto Mountains (SJM) and the Gila Wilderness (GW), are also shown.

density, this translates to 0.73–11.6 fire ignitions/century. The upper end is in line with TRFS estimates, whereas the lower end is an order of magnitude less.

Although phenological data for Jeffrey pine has not been collected in the SSPM, data from a site 5° latitude farther north indicates that, for all but very wet years when there are very few fires, early earlywood and middle earlywood cambial growth in Jeffrey pine begins in early May (Table 5) 5) and is completed by the end of June (Royce and Barbour 2001). Cambial growth dates for the SSPM sites are probably earlier because they are at approximately the same elevation but several hundred kilometres south, but no correction factor was applied.

According to the TRFS record, 79% of SSPM fires recorded during the past 300 years for which seasonality was assignable were in early and middle earlywood (Table 2). In contrast, based on the NLDN lightning climatology for the SSPM, only 8.1% of lightning flashes, or 0.21 flashes·km^{-2}·year^{-1}, occurred during May and June (Table 1). ALDS lightning data indicate the proportion of May and June lightning is even less (2.6%) (Table 1). These percentages should not be affected by higher or lower detection efficiency if one assumes there is no seasonal bias in lightning flash detection efficiency. From 1700 to 1998, there were 25 years with a fire scar assignable to early or middle earlywood that scarred <10% of the trees on one of the two 0.8 km^2 TRFS history sites (Table 2). This means there was a May–June fire ignition recorded on the combined 1.6 km^2 every 12 years. According to the NLDN lightning climatology, only four flashes would be expected every 12 years on those 1.6 km^2 in May–June (Table 1). Using a maximum likely ignition rate of 0.02 fires/flash (Table 3), a May–June fire ignition event would be expected on one of the two sites every 150 years; lesser ignition rates yield larger intervals between expected fires and larger disparities compared with TRFS data.

Discussion

Sources of error in modern lightning, fire, and ignition data

Estimates of the modern SSPM lightning regime, determined from 7 years of NLDN data and partially confirmed with 10 more years of ALDS data, may have at least two possible sources of error as follows. (*i*) The 7 year period of record spanned by the NLDN lightning data may be too short to estimate the long-term mean flash density. ALDS data overlap with NLDN data for only one year (1996). NLDN data indicate that 1996 was the highest of the 7 year record, with 1484 raw flashes, more than twice the 7 year average of 670 flashes/year (Table 1). ALDS flash data indicate 1996 was 27% below average for the period 1986–1996. Based on this very limited comparison, the longer term mean flash density calculated for the 17 year period of combined record may be two to three times the 7 year NLDN mean, but an order of magnitude difference is unlikely. More importantly for this study, there is no indication from ALDS data that May and June mean flash density is higher than the NLDN mean. In fact, the evidence suggests the long-term average may be less: the ALDS average was

Table 4. Estimated lightning fire ignition rates and time between lightning ignition events on a square-kilometre plot, based on NLDN flash data and agency fire records for the period 1996–2002, for polygons above 1800 m within the San Jacinto and San Bernardino Mountains, southern California, and the period 1986–1997 for the Gila Wilderness, New Mexico (Rollins 2001).

	Area (ha)	No. of lightning flashes	No. of lightning fires	Ignition rate (fires/ flash)	Estimated time between lightning ignition events on 1 km^2 plot (years)
Gila Wilderness (1986–1997)					
Mixed conifer	34 000	35 000	110	0.0031	37.1
Ponderosa pine	98 000	85 000	260	0.0031	45.2
May (whole wilderness area)	317 000	20 000	150	0.0075	253.6
June (whole area)	317 000	30 000	400	0.0133	95.1
July (whole area)	317 000	130 000	500	0.0038	76.1
August (whole area)	317 000	120 000	175	0.0015	217.4
September (whole area)	317 000	40 000	15	0.0004	2536.0
Total	317 000	340 000	1240	0.0036	30.7
San Jacinto Mountains (1996–2002)	13 000	354	20	0.0565	45.5
San Bernardino Mountains (1996–2002)	16 800	922	39	0.0423	24.0

2.5% (compared with 8.1% for NLDN), 5 of 11 ALDS years recorded no May and June lightning and the only year with more than 4% of flashes in May and June was 1990 (8%). (*ii*) There may be considerably more flashes in the SSPM than the NLDN detects. Because the NLDN sensors are all north of the United States – Mexico border, detection efficiency is problematic. The 30% detection efficiency assigned to the SSPM is the best estimate based on an established algorithm (K. Cummins, personal communication, 2003). Lightning data from mountainous regions in the heart of the NAMS region north of the border, where detection efficiency has been tested and is much higher, shows the SSPM data, with a range of 1–4 flashes·km^{-2}·year^{-1} and <10% of flashes occurring in May and June, are very comparable (Orville and Huffines 2001; Kaney et al. 2001). An order of magnitude increase in May–June lightning would result in ~1800 flashes/year during this period, more than currently occur in July–August at the height of the monsoonal influence (Table 1), a highly unlikely situation. We have concluded the 30% detection efficiency used to calculate actual flash density for the SSPM gives reasonable estimates of flash density that are unlikely to be inaccurate by an order of magnitude.

An argument can be made that the Mexican Comision Nacional Forestal (CONAFOR) fire data underestimated the number of fires in the SSPM by an order of magnitude. Minnich et al. (2000*a*) observed 204 ash beds from aerial photographs taken on 20 July 1991, the result of fires ignited presumably between the time of snowmelt (probably April or May) and 20 July. This suggests that, for 1991 (prior to CONAFOR data records), there were a large number of unreported microfires, an order of magnitude more than the maximum annual number of fires recorded by CONAFOR (26 fires in 1997). Although we acknowledge considerable uncertainty stemming from the short period of record for our lightning and fire data, we are skeptical that our data is inaccurate by the order of magnitude suggested by the ash bed data for the following reasons. (*i*) Microfires were not ignored in the CONAFOR database. Fires in the SSPM were often recorded at the scale of number of individual trees burned. (*ii*) The approach of Minnich et al. (2000*a*), estimating the year of fire occurrence from ash beds identified on aerial photographs, is untested for accuracy. Based on ALDS data (uncorrected for detection efficiency errors, covering only the northern one-third of the SSPM, but useful for relative comparison between years), there were only 27 lightning flashes between April and July 1991, the third lowest total for this period in the 11 years of record. However, there were 443 lightning flashes in 1990, the highest year recorded, suggesting that, unless they were concentrated in the southern SSPM outside the range of ALDS detection, many of the ash beds observed on aerial photographs came from fires occurring at least 1 year, and possibly several years, previously. (*iii*) There is the possibility that 1991 (although the ALDS data suggests 1990 was a more likely candidate) was a rare year in the SSPM, with exceptionally large amounts of lightning and (or) much higher ignition rates, a phenomenon observed in 1987 in the Stanislaus National Forest in California (Minnich et al. 1993). Because one of these rare years was not included in the short-term lightning and fire records for the SSPM, long-term lightning fire ignition rates were probably underestimated. Long-term fire records from California forests suggest these exceptional lightning ignition episodes are not frequent enough to explain the frequent small fire regime seen in the SSPM tree-ring fire-scar record. (*iv*) Because issues concerning the quality of CONAFOR fire data could not be definitively resolved without further testing of Minnich et al.'s (1993) aerial photograph ash bed approach, we indirectly tested the CONAFOR data quality by comparing the calculated SSPM lightning fire ignition rate with the ignition rates for two potential analog sites: the GW and the SJM. Because there is a large disparity in ignition rates between the two analog sites, accurately estimating the SSPM ignition rate from analog data depends on where the SSPM lies on the monsoonal moisture gradient. There are clear differences in the pattern of monthly fire ignition rates that are probably related to this gradient. Ignition rates in the GW, strongly influenced by the NAMS, peaked at 0.0133 in May and declined steadily to 0.0004 in September (Table 3). For the SJM, only slightly influenced by the NAMS, ignition rates increased from 0 in June, peaked at 0.088 in August, and stayed high in September. The observed sharp decline in monthly ignition rates in regions heavily influenced by

Table 5. Estimated calendar dates for SSPM tree-ring fire-scar seasonal designations based on a study of Jeffrey pine phenology in the southern Sierra Nevada (Royce and Barbour 2001).

Scar location	Dry year	Wet year
Early earlywood	1 May – 4 June	28 May – 25 June
Middle earlywood	5 June – 20 June	26 June – 10 July
Late earlywood	21 June – 16 July	11 July – 16 August
Latewood and dormant	17 July – April	17 August – April

the NAMS may be more closely related to a threshold in atmospheric moisture (measured by dew point and relative humidity) accompanying the arrival of the monsoon rather than the amount of precipitation recorded (Mohrle 2003; R. Evett, unpublished data). During the 1996–2002 period of CONAFOR records in the SSPM, the fire ignition rate steadily decreased from 0.018% in May to 0.0034% in August (Table 3). This pattern of monthly fire ignition rates more closely matches the GW, suggesting that, despite having considerably less summer rainfall and thunderstorm days than the GW (Changnon 2003), the SSPM may lie closer to the GW than the SJM on the monsoonal atmospheric moisture gradient. Although the ignition rates in the SSPM may be higher than the CONAFOR data indicates, the very high ignition rates seen throughout the summer in southern California mountains are probably not accurate for the SSPM. More importantly, both analogs agree with the CONAFOR data: the ignition rate in May and June in the SSPM does not exceed 2% (Table 3).

There are other sources of uncertainty in the SSPM ignition rate estimates. The lightning flash detection efficiency for the SSPM is poor, so flash estimates have wide confidence intervals. Despite this, using the 30% detection efficiency correction gives an estimate of 2.58 flashes·km^{-2}·year^{-1}, well within the 1–6 flashes·km^{-2}·year^{-1} observed in mountains in the NAMS region, and more than the <1.0 flashes·km^{-2}·year^{-1} observed in mountains in California (Orville and Huffines 2001). Many lightning flashes have two or more strokes; one flash can cause more than one fire (Rakov and Huffines 2003). There is no data suggesting that the mean number of strokes per flash varies in this part of western North America, so the comparison of SSPM and analog data should be valid.

In summary, there is considerable uncertainty regarding the accuracy of calculated ignition rates. Our data are not unequivocal and need to be tested further, both in the SSPM and in other possible analogous regions. However, based on the best available data from recent SSPM lightning and fire records (Tables 1 and 3) buttressed with data from the potential analogs (Table 4), a mean lightning ignition rate between 0.0030 and 0.0500 fires/flash, probably closer to the lower end of the range, is reasonable. All available evidence suggests that the maximum likely ignition rate during the months of May and June is 0.0200 fires/flash. Unless there was a change in climate or vegetation type, these long-term ignition rates would be expected to remain relatively stable over time.

Anomalies in estimated number of fire ignitions and fire seasonality between the TRFS record and modern lightning ignition data

Using the ignition rate indicated by modern lightning flash density and CONAFOR data, there is ninefold discrepancy between 1 fire ignition/century expected on each 0.8 km^2 SSPM study site given the current lightning regime and 9 small fires/century recorded in the 300 year TRFS record. There is a 12-fold discrepancy in the estimated time between May–June ignitions (150 years vs. 12 years) based on the modern lightning regime and the TRFS record. Possible errors in flash-density estimates, fire data, and ignition rates have been discussed in previous sections. Although there is the possibility that the anomalies described are an artifact of analytical imprecision, the evidence suggests it is unlikely that these sources of error would all be cumulative in the same direction to account for the order of magnitude discrepancies.

The 1.2 fire ignitions·km^{-2}·century^{-1} estimated from the current lightning regime for the SSPM is in line with coniferous forests in southwestern North America, making it unlikely the modern SSPM fire and lightning regime estimates are underestimated by an order of magnitude. Analysis of over 30 years of fire data for several large western national forests produced estimates ranging from a maximum 3.8 fire ignitions·km^{-2}·century^{-1} in the SJM, to 2.4 fire ignitions·km^{-2}·century^{-1} in Gila National Forest, an area with one of the highest lightning densities in the region influenced by the NAMS (Orville and Huffines 2001), to 1.0 fire ignitions·km^{-2}·century^{-1} in Lincoln National Forest in south-central New Mexico (R. Evett, unpublished data).

Most of the possible sources of error in the TRFS record lead to underestimating the actual number of ignitions that occurred on the 0.8 ha sites. (*i*) Recording trees are nonrandomly dispersed on each site, with each tree representing ~2 ha. Even though trees with multiple fire scars were preferentially sampled, smaller fires may not have burned an area with a recording tree. (*ii*) Because of the patchy nature of fires (Stephens 2004), not all fires burning around a recording tree were recorded. (*iii*) Some fires scarring >10% of recording trees ignited on the site. (*iv*) Multiple small fires ignited on a site during a single year were treated in the TRFS record as a larger fire. (*v*) Some larger fires ignited outside the boundary of the site and burned only one or two recording trees on the site perimeter before being extinguished. An examination of spatial burning patterns for each recorded fire year indicated this was probably not common. Because most of the potential sources for error suggest there were considerably more ignitions that were not recorded in the TRFS fire history, the 12-fold discrepancy between recorded and expected fires in May–June may be a conservative estimate.

Reconciling fire ignition and seasonality anomalies

The most plausible explanation for the anomalies between the modern ignition record and the TRFS data in the SSPM is the fire ignition regime has changed considerably over time; there were an order of magnitude more May and June ignitions during periods in the past compared to the present. We have shown with phytolith data that grasses were not an important prehistoric component of the forest understory (Evett et al. 2007). It is unlikely that changes in fuel characteristics caused changes in the fire regime.

Increased ignitions in May–June in the past could have been due to increased lightning flash density, altered climate leading to lower fuel moisture in the spring and an increased lightning ignition rate, and (or) more anthropogenic ignitions.

There are several possible changes in climate that could lead to an increase in May–June fires. Dry lightning during the premonsoonal May–June period, when fuel moisture is at a minimum and ignition rates are highest, can spark numerous fires (e.g., Rorig and Ferguson 1999, 2002*a*, 2002*b*). The climate mechanism leading to increased May–June lightning in the SSPM is unknown. We are not aware of evidence from anywhere in the surrounding region that spring lightning was an order of magnitude more frequent prior to the 1950s.

Climate can have a strong effect on spring fuel moisture and fire ignition rates. Years with considerably less than the mean winter precipitation would be expected to have higher lightning ignition rates because fuels are drier for a longer period of time. We found the average lightning ignition rate for drought years 1996, 1997, 2000, and 2002 (determined by PDSI values less than –2.0 for grid 74; Cook et al. 2004) was almost twice the rate for 1998, a wet year (Table 3). Although May and June precipitation in northern Baja California is very low and apparently not strongly influenced by the El Niño – Southern Oscillation (ENSO) cycle (Minnich et al. 2000*b*), ENSO does influence snow depth; an unusually wet (usually El Niño in this region) year leads to greater snow depth, delaying the drying of fuels, whereas a dry (usually La Niña) year leads to earlier and more complete drying of fuels. However, analysis of the annual PDSI and the TRFS record of fires revealed only weak correlation between drought years and fire years, particularly after 1800 (Stephens et al. 2003). The evidence does not indicate decadal periods of reduced fire frequency were wetter than periods with frequent fire.

A largely anthropogenic explanation for observed changes in the fire regime, while circumstantial, fits the evidence better and may be more plausible than a climatic explanation. (*i*) Archaeological evidence indicates there was considerable seasonal use of the SSPM by native populations (Meigs 1935; Stephens et al. 2003). (*ii*) Native populations in the surrounding region had many documented uses for fire (Lewis 1973; Bean and Lawton 1993; Pyne 1997; Kaib 1998; Allen 2002). (*iii*) The modern lightning regime in the SSPM does not support the order of magnitude more May–June ignitions recorded in the TRFS record, suggesting a large anthropogenic component in the past unless there were substantial changes in climate. (*iv*) The TRFS seasonality record from mixed conifer forests in southern California mountains (Everett 2003), the nearest available fire-history analog for the SSPM, with similar vegetation and climate, indicates most prehistoric fires probably occurred in August–September (Table 2), currently the period of peak lightning density (Table 4), whereas the TRFS record for the SSPM indicates most prehistoric fires occurred in May–June, currently a period of greatly reduced lightning density. (*v*) The number of modern anthropogenic fires in the region with some NAMS influence peaks during the May–June period, while lightning fire numbers peak in July–August, suggesting May–June prehistoric fires in the SSPM could also have been human caused (Bartlein et al. 2003; Mohrle 2003; R. Evett, unpublished data). (*vi*) Changes in the TRFS record of fire history roughly coincide with known historical events affecting human populations in the SSPM. An anthropogenic ignition scenario for the TRFS record suggests that, prior to 1790, members of the native population intentionally set fires in SSPM forests in May and June, when fires were more likely to ignite and burn larger areas than during the monsoon-dampened summer months, perhaps to maintain the open forest structure favorable for hunting or other resource objectives. They would have been most successful setting fires during drought years when spring fuel moisture was minimal; superposed epoch analysis of the pre-1800 SSPM TRFS record supports this (Stephens et al. 2003). The period 1790–1831 saw the establishment of the Spanish mission in 1796, the spread of the Spanish colonists' negative view of fire (Kaib 1998), and rapid decline in native populations through disease (Meigs 1935; Aschmann 1959). The few fires that ignited from 1790–1831 may have been lightning-caused. Two of the five fires recorded with assignable seasonality in the TRFS record during this period were latewood fires, a much higher percentage than during other periods. The TRFS record for the period 1832–1946 may reflect a rancher-driven anthropogenic fire regime. During this period, there was an increase in the number of livestock seasonally moved into the mountains in the spring as snows melted and forage became available in the large meadows (Minnich and Franco-Vizcaino 1998). Ranchers in western North America commonly used fire to favor grasses and prevent shrub invasion (Kaib 1998). There is some evidence that ranchers set intentional fires in the SSPM (Minnich and Franco-Vizcaino 1998); with people building campfires in the mountains, accidental ignitions were also inevitable. Around the middle of the 20th century in the SSPM, or perhaps coinciding with the establishment of the National Park in 1947, the change in the TRFS record may have been due to decreased anthropogenic ignitions and a return to a lightning-dominated regime. Only two of five fires on the study sites since 1946 with assignable seasonality in the TRFS record were ignited during the May-June period.

Conclusion

Our data show changes have occurred over time in the SSPM fire ignition regime, reflected in both the number and seasonality of fires, and that the modern lightning regime probably does not support the TRFS record of the fire regime for most of the past 300 years. These results must be interpreted with considerable caution, because the period of record of the modern lightning regime only spans 17 years, ignition rates were calculated from only 7 years of data, and many of the estimated and calculated parameters have substantial uncertainties.

Assessing the relative importance of prehistoric anthropogenic and lightning-caused ignitions in the SSPM is difficult, but we believe the existing evidence suggests the prehistoric fire regime in the SSPM had a substantial anthropogenic component. Even though they cannot be ruled out, climatic explanations for changes in the TRFS record in the SSPM, requiring an order of magnitude increase in May–June lightning for decades-long periods that does not appear to have occurred elsewhere in southwestern North America, do not easily fit the available evidence.

These conclusions suggest the TRFS record in the SSPM may not reflect a centuries-long lightning ignition fire regime, free of human-caused disturbance. Because anthropogenic ignitions may have been important during much of the TRFS record, land managers in California should be aware that the SSPM, despite similarities in climate and vegetation, may not be a good analog to use to estimate modern natural fire regimes for mixed conifer forests in southern California and the Sierra Nevada.

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References

Allen, C.D. 2002. Lots of lightning and plenty of people: an ecological history of fire in the upland Southwest. *In* Fire, native peoples, and the natural landscape. *Edited by* T.R. Vale. Island Press, Washington, D.C. pp. 143–193.

Anderson, K. 2002. A model to predict lightning-caused fire occurrences. Int. J. Wildland Fire, **11**: 163–172. doi:10.1071/WF02001.

Aschmann, H.H. 1959. The central desert of Baja California: demography and ecology. University of California Press, Berkeley, Calif.

Baisan, C.H. 1990. Fire history of the Rincon Mountain Wilderness, Saguaro National Monument. University of Arizona, School of Renewable Natural Resources, Cooperative National Park Resources Studies Unit, Tucson, Ariz. Tech. Rep. No. 29.

Baisan, C.H., and Swetnam, T.W. 1995. Historical fire occurrence in remote mountains of southwestern New Mexico and northern Mexico. *In* Proceedings of the Symposium on Fire in Wilderness and Park Management, 30 Mar. – 1 Apr. 1993, Missoula, Mont. *Technical coordinators*: J.K. Brown, R.W. Mutch, C.W. Spoon, and R.H. Wakimoto. USDA For. Serv. Gen. Tech. Rep. INT-GTR-320. pp. 153–156.

Bartlein, P.J., Hostetler, S.W., Shafer, S.L., Holman, J.O., and Solomon, A.M. 2003. The seasonal cycle of wildfire and climate in the western United States. *In* Preprints, 2nd International Wildland Fire Ecology and Fire Management Congress, and 5th Symposium on Fire and Forest Meteorology American Meteorological Society, 16 - 20 November 2003, Orlando, Fla.

Bean, L.J., and Lawton, H.W. 1993. Some explanations for the rise of cultural complexity in Native California with comments on proto-agriculture and agriculture. *In* Before the wilderness: environmental management by native Californians. *Edited by* T.C. Blackburn and K. Anderson. Ballena Press, Menlo Park, Calif. Anthropol. Pap. No. 40. pp. 27–54.

Brown, T.J., and Hall, B.L. 2001. Climate and ecosystem studies and product development for wildland fire and resource management: annual report. Desert Research Institute, Reno, Nev. CEFA Rep. No. 01-04. Available from http://www.cefa.dri.edu/Publications/publications_index.htm [Accessed 9 Dec. 2004].

Changnon, S.A. 2003. Thunderstorm rainfall in the conterminous United States. Bull. Am. Meteorol. Soc. **82**: 1925–1940.

Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., and Stahle, D.W. 2004. Long-term aridity changes in the western United States. Science (Washington, D.C.), **306**: 1015–1018. doi:10.1126/science.1102586. PMID:15472040.

Cummins, K.L., Murphy, M.J., Bardo, E.A., Hiscox, W.L., Pyle, R.B., and Pifer, E. 1998. A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network. J. Geophys. Res. **103**(D8): 9035–9044. doi:10.1029/98JD00153.

Dieterich, J.H., and Swetnam, T.W. 1984. Dendrochronology of a fire-scarred ponderosa pine. For. Sci. **30**: 238–247.

Everett, R.G. 2003. Grid-based fire-scar dendrochronology and vegetation sampling in the mixed-conifer forests of the San Bernardino and San Jacinto Mountains of southern California. Ph.D. dissertation, University of California, Riverside, Calif.

Evett, R.R., Franco-Vizcaino, E., and Stephens, S.L. 2007. Phytolith evidence for the absence of a prehistoric grass understory in a Jeffrey pine – mixed conifer forest in the Sierra San Pedro Mártir, Mexico. Can. J. For. Res. **37**. This issue. doi:10.1139/x06-280.

Franco-Vizcaino, E., Escoto-Rodriguez, M., Sosa-Ramirez, J., and Minnich, R.A. 2002. Water balance at the southern limit of the Californian mixed-conifer forest and implications for extreme-deficit watersheds. Arid Land Res. Manage. **16**: 133–147.

Grissino-Mayer, H.D., and Swetnam, T.W. 2000. Century-scale climate forcing of fire regimes in the American Southwest. Holocene, **10**: 213–220. doi:10.1191/095968300668451235.

Kaib, J.M. 1998. Fire history in the riparian canyon pine-oak forests and the intervening desert grasslands of the Southwest borderlands: a dendroecological, historical, and cultural inquiry. Master's thesis, University of Arizona, Tucson, Ariz.

Kaney, B.T., Howard, K.W., Maddox, R.A., and Langston, C. 2001. Investigation of lightning and terrain in the Four Corners region (Arizona, Colorado, New Mexico and Utah), summer monsoon season 1995–1999. Available from http://www.nssl.noaa.gov/wrd/wish/kaney/. [Accessed 15 December 2004].

Latham, D.J., and Schlieter, J.A. 1989. Ignition probabilities of wildland fuels based on simulated lightning discharges. USDA For. Serv. Intermountain For. Range Exp. Stn. Res. Pap. INT-366.

Lewis, H.T. 1973. Patterns of Indian burning in California: ecology and ethnohistory. Ballena Press, Ramona, Calif. Anthropol. Pap. No. 1.

Markham, C.B. 1972. Baja California's climate. Weatherwise, **25**: 64–76.

Meigs, P. 1935. The Dominican missions frontier of Lower California. Univ. Calif. Publ. Geogr. No. 7.

Minnich, R.A., and Franco-Vizcaino, E. 1998. Land of chamise and pines: historical accounts and current status of northern Baja California's vegetation. Univ. Calif. Publ. Bot. No. 80.

Minnich, R.A., Franco-Vizcaino, E.F., Sosa-Ramirez, J., and Chou, Y.H. 1993. Lightning detecton rates and wildland fire in the mountains of northern Baja California, Mexico. Atmosfera, **6**: 235–253.

Minnich, R.A., Franco-Vizcaino, E., Sosa-Ramirez, J., Barry, W.J., Burk, J.H., Barbour, M.G., and de la Cueva Salcedo, H. 1997. A land above: protecting Baja California's Sierra San Pedro Martir within a biosphere reserve. J. Southwest, **39**: 613–695.

Minnich, R.A., Barbour, M.G., Burk, J.H., and Sosa-Ramirez, J. 2000*a*. Californian mixed-conifer forests under unmanaged fire regimes in the Sierra San Pedro Martir, Baja California, Mexico. J. Biogeogr. **27**: 105–129. doi:10.1046/j.1365-2699.2000.00368.x.

Minnich, R.A., Franco-Vizcaino, E., and Dezzani, R.J. 2000*b*. The El Nino/Southern Oscillation and precipitation variability in Baja California, Mexico. Atmosfera, **13**: 1–20.

Mohrle, C.R. 2003. The Southwest monsoon and the relation to fire occurrence. Master's thesis, University of Nevada, Reno, Nev.

Orville, R.E., and Huffines, G.R. 2001. Cloud-to-ground lightning in the United States: NLDN results in the first decade, 1989–1998. Mon. Weather Rev. **129**: 1179–1193. doi:10.1175/1520-0493(2001)129<1179:CTGLIT>2.0.CO;2.

Potter, D.A. 1998. Forested communities of the upper montane in the central and southern Sierra Nevada. USDA Forest Serv. Gen. Tech. Rep. PSW-169.

Pyke, C.B. 1972. Some meteorological aspects of the seasonal distribution of precipitation in the western United States and Baja California. University of California Water Resources Center, Los Angeles, Calif. Contrib. No. 139.

Pyne, S.J. 1997. Fire in America: a cultural history of wildland and rural fire. University of Washington Press, Seattle, Wash.

Rakov, V.A., and Huffines, G.R. 2003. Return-stroke multiplicity of negative cloud-to-ground lightning flashes. J. Appl. Meteorol. **42**: 1455–1462. doi:10.1175/1520-0450(2003)042<1455:RMONCL>2.0.CO;2.

Rollins, M.G. 2000. Twentieth-century fire patterns in the Gila/Aldo Leopold Wilderness Areas, New Mexico and the Selway-Bitterroot Wilderness Area in Idaho/Montana. Ph.D. dissertation, University of Arizona, Tucson, Ariz.

Rollins, M.G. 2001. Lightning and fire occurrence (LFC) in two, large Rocky Mountain wilderness complexes. Final report to the Joint Fire Science Program. Available from http://www.firelab.org/fep/research/mrollins/intro.htm [Accessed 9 Dec. 2004].

Rorig, M.L., and Ferguson, S.A. 1999. Characteristics of lightning and wildland fire ignition in the Pacific Northwest. J. Appl. Meteorol. **38**: 1565–1575. doi:10.1175/1520-0450(1999)038<1565:COLAWF>2.0.CO;2.

Rorig, M.L., and Ferguson, S.A. 2002*a*. Predicting risk of dry lightning. Bull. Am. Meteorol. Soc. **83**: 1140–1141.

Rorig, M.L., and Ferguson, S.A. 2002*b*. The 2000 fire season: lightning-caused fires. J. Appl. Meteorol. **41**: 786–791. doi:10.1175/1520-0450(2002)041<0786:TFSLCF>2.0.CO;2.

Royce, E.B., and Barbour, M.G. 2001. Mediterranean climate effects. II. Conifer growth phenology across a Sierra Nevada ecotone. Am. J. Bot. **88**: 919–932. doi:10.2307/2657045. PMID: 11353717.

Skinner, C.N., Burk, J., Stephens, S.L., Franco-Vizcaino, E., and Minnich, R.A. Fire and climate interactions in the Sierra San Pedro Martir, Baja California, Mexico. Mountain Climate Sciences Symposium, 25–27 May 2004, Lake Tahoe, Caif. [Abstr.] Available from http://www.x-cd.com/mcss04/P59.html [Accessed 7 October 2005].

Stephens, S.L. 2004. Fuel loads, snag density, and snag recruitment in an unmanaged Jeffrey pine – mixed conifer forest in northwestern Mexico. For. Ecol. Manage. **199**: 103–113.

Stephens, S.L., and Gill, S.J. 2005. Forest structure and mortality in an old-growth Jeffrey pine – mixed conifer forest in northwestern Mexico. For. Ecol. Manage. **205**: 15–28. doi:10.1016/j.foreco.2004.10.003.

Stephens, S.L., Skinner, C.N., and Gill, S.J. 2003. Dendrochronology-based fire history of Jeffrey pine – mixed conifer forests in the Sierra San Pedro Martir, Mexico. Can. J. For. Res. **33**: 1090–1101. doi:10.1139/x03-031.

Swetnam, T.W. 1993. Fire history and climate change in sequoia groves. Science (Washington, D.C.), **262**: 885–889. doi:10.1126/science.262.5135.885.

Swetnam, T.W., and Baisan, C.H. 1989. Fire history of Rhyolite Canyon, Chiricahua National Monument. University of Arizona, School of Renewable Natural Resources, Cooperative National Park Resources Studies Unit, Tucson, Ariz. Tech. Rep. No. 32.

Swetnam, T.W., and Baisan, C.H. 2002. Tree-ring reconstructions of fire and climate history in the Sierra Nevada and southwestern United States. *In* Fire and climatic change in the Americas. *Edited by* T.T. Veblen, W. Baker, G. Montenegro, and T.W. Swetnam. Springer-Verlag, New York.

Swetnam, T.W., Allen, C.D., and Betancourt, J.L. 1999. Applied historical ecology: using the past to manage the future. Ecol. Appl. **9**: 1189–1206. doi:10.2307/2641390.

Swetnam, T.W., Baisan, C.H., and Kaib, J.M. 2001. Forest fire histories of the sky islands of *La Frontera. In* Changing plant life of *La Frontera*: observations on vegetation in the United States/Mexico borderlands. *Edited by* G.L. Webster and C.J. Bahre. University of New Mexico Press, Albuquerque, N.M. pp. 95–123.

Wiggins, I.L. 1980. Flora of Baja California. Stanford University Press, Stanford, Calif.