Quaternary Research **51,** 295–305 (1999)
Article ID qres.1999.2035, available online at http://www.idealibrary.com on IDEAL®

A 560-Year Record of Santa Ana Fires Reconstructed from Charcoal Deposited in the Santa Barbara Basin, California

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Received February 4, 1998

Microscopic charcoal from varved Santa Barbara Basin sediments was used to reconstruct a 560-yr record (A.D. 1425 to 1985) of Santa Ana fires. Comparison of large (>3750 μm²) charcoal with documented fire records in the Santa Barbara Ranger District shows that high accumulations correspond to large fires (>20,000 ha) that occurred during Santa Ana conditions. The charcoal record reconstructed a minimum of 20 large fires in the Santa Barbara region during the study period. The average time between fires shows no distinct change across three different land use periods: the Chumash period, apparently characterized by frequent burning, the Spanish/Early American period with nominal fire control, and the 20th century with active fire suppression. Pollen data support the conclusion that the fire regime has not dramatically changed during the last 500 yr. Comparison of large charcoal particle accumulation rates and precipitation reconstructed from tree rings show a strong relationship between climate and fire history, with large fires consistently occurring at the end of wet periods and the beginning of droughts.

Key Words: **Santa Ana; fire history; microscopic charcoal; Santa Barbara Basin; varved sediments.**

INTRODUCTION

Wildland fires consume thousands of hectares annually throughout California. Periodically, large fires burn >20,000 ha. In southern California, such fires typically occur in late summer and early fall during Santa Ana conditions, characterized by low relative humidity, high temperatures, and strong northeasterly winds (Davis and Michaelsen, 1995). Conflagrations in southern California have been suggested to be an artifact of fire suppression, begun in the early 1900s (Minnich, 1983). Minnich argued that the natural fire regime in southern California was one of small frequent fires that created a fine-grained vegetation mosaic, which prevented large fires. Landsat images from southern California and Baja California for the period A.D. 1972–1980 showed that Baja fires were frequent and small, whereas southern California fires were fewer and much larger. Baja California has no policy of fire suppression, and Minnich reasoned that, without fire suppression, the prehistoric fire regime for southern California would have been similar to the pattern found today in Baja. In contrast, Sauer (1977) suggested that because chaparral commonly burns during Santa Ana conditions the fire regime has probably not been substantially altered by human intervention.

Efforts to determine long-term fire history in chaparral have relied largely on proxy evidence. Standard fire-scar methodology can not be used because fires are stand-replacing and shrubs are short-lived (<100 yr). Charcoal in sediments provides another method of reconstructing fire history (Swain, 1973; MacDonald *et al.*, 1991; Millspaugh and Whitlock, 1995; Bradbury, 1996; Clark and Royall, 1996; Clark *et al.*, 1997).

Byrne *et al.* (1977, 1979) analyzed charcoal accumulation rates in varved sediments from the Santa Barbara Basin for the period A.D. 1931–1970. They reported a significant correlation between total acreage burned per year in the Santa Barbara Ranger District of the Los Padres National Forest (LPNF) and the accumulation rate of large particles of charcoal (>3750 μm²).

Two major peaks in large charcoal particle accumulation rate were associated with the two largest fires within the Santa Barbara Ranger District, in A.D. 1955 and 1964 (Figs. 1 and 3). Both fires occurred in late summer/early fall under Santa Ana conditions (Table 1). Large fires >50 km from the core

TABLE 1
Fires Greater than 12,000 Hectares for the Period 1911 to 1990 on the Los Padres National Forest and Adjacent Areas in the Santa Barbara Region

Start date	Total ha (acres) burned	Cause	Name	District
9/28/1917	12,800 (32,000)	Unknown	Piru-Sespe	ORD
8/7/1921	27,872 (69,680)	Brush burning	Creston	SLRD
9/14/1922	23,840 (59,600)	Incendiary	Kelly Canyon	SLRD
9/1/1923	28,000 (70,000)	Smoking	Oso Canyon	SBRD
9/1/1928	17,152 (42,880)	Smoking	Aliso Canyon	MPRD
8/19/1933	12,320 (30,800)	Smoking	Indian Canyon	SBRD
9/7/1932	87,701 (219,254)	Campfire	Matilija	ORD
7/10/1953	29,400 (73,500)	Powerline	Big Dalton	SLRD
9/6/1955	33,908 (84,770)	Burning bldg.	Refugio	SBRD
9/22/1964	26,800 (67,000)	Unknown	Coyote	SBRD
6/11/1966	37,440 (93,600)	Plane crash	Wellman	SLRD
7/1/1985	47,744 (119,361)	Incendiary	Wheeler #2	ORD
10/14/1985	18,284 (45,710)	Incendiary	Ferndale	ORD

Note. Data were obtained from the Los Padres National Forest fire database. Ranger districts are as follows: SBRD, Santa Barbara Ranger District; ORD, Ojai Ranger District; SLRD, Santa Lucia Ranger District; MPRD, Mount Pinos Ranger District. Fires listed are mapped in Figure 1.

site were not clearly evident in the charcoal record. They suggested that large charcoal particles were most likely deposited by Santa Ana winds associated with conflagrations near the coast (Byrne *et al.*, 1977). Analysis of a core spanning A.D. 730–1505 identified large charcoal accumulation peaks equal to or greater than those from the A.D. 1955 and 1964 samples (Byrne *et al.*, 1977). The authors suggested that very large fires must have a long history in the Santa Barbara region; however, they had no data documenting the critical prehistoric/historic transition.

This paper presents new charcoal evidence from the Santa Barbara Basin and represents the first high-resolution charcoal study spanning the prehistoric and historic periods in southern California. First we replicate the study of Byrne *et al.* (1977) for the period A.D. 1931–1970 and compare our results to the LPNF wildland fire database. We then reconstruct a 560-yr record of Santa Ana fires >20,000 ha for the period A.D. 1425–1985. Finally, we compare the charcoal record with a climate record reconstructed from tree rings to see if there is any relationship between climate and fire history.

STUDY SITE AND METHODS

Study Site

Santa Barbara (Fig. 1) has a winter-wet, summer-dry Mediterranean-type climate. Physiographically, the region is atypical of coastal California because of the east/west trending mountain ridges (Transverse and Peninsular Ranges). The Santa Ynez Mountains rise abruptly north of the coastal plain. Vegetation is dominated by fire-adapted chaparral taxa, including *Adenostoma fasciculatum, A. sparsifolium, Arctostaphylos glandulosa, A. tomentosa, Ceanothus megacarpus, C. spinosus*, and *C. cuneatus* (Keeley, 1992; Hickman, 1993).

The eastern flank of the Pacific high-pressure cell dominates summer weather in coastal southern and central California. Circulation around the high produces persistent northwesterly surface winds that flow roughly parallel to the coast. As the Pacific High weakens and shifts southward in early fall, traveling high- and low-pressure centers associated with the North Pacific storm track begin to affect the orientation of pressure gradients along the northern and eastern edge of the Pacific High. An anticyclone trailing a traveling cyclone through the Pacific Northwest can push the eastern edge of the Pacific High into the Great Basin, shifting large-scale wind patterns from northwesterly to northeasterly. This pattern leads to warm, dry air moving from the interior into coastal southern California. As these northeasterly winds move downslope, temperature and wind speed increase and humidity decreases. These are classic ingredients of the hot, dry Santa Ana winds. Typically, Santa Ana episodes will persist for about 2–3 days (Bailey, 1966).

While the wind-driven wildfire events occur in late summer and early fall, the Santa Ana meteorological pattern is most common during winter. Hourly readings at the Santa Barbara Airport show winds between compass headings 330°–60° (north-northwest to east-northeast) 15–17% of the time between October and March, 13% in April, 10% in May, <9% in June–August, and 10% in September.

Santa Ana winds and related downslope wind events are an important part of the current climate of the region. While the synoptic meteorological conditions that produce them are well known, there has been no research on variability in the frequency of events on interannual and longer time scales. The meteorological conditions are not particularly unusual, however, requiring that the North Pacific storm track be active in the Pacific Northwest and Great Basin. It seems likely, there-

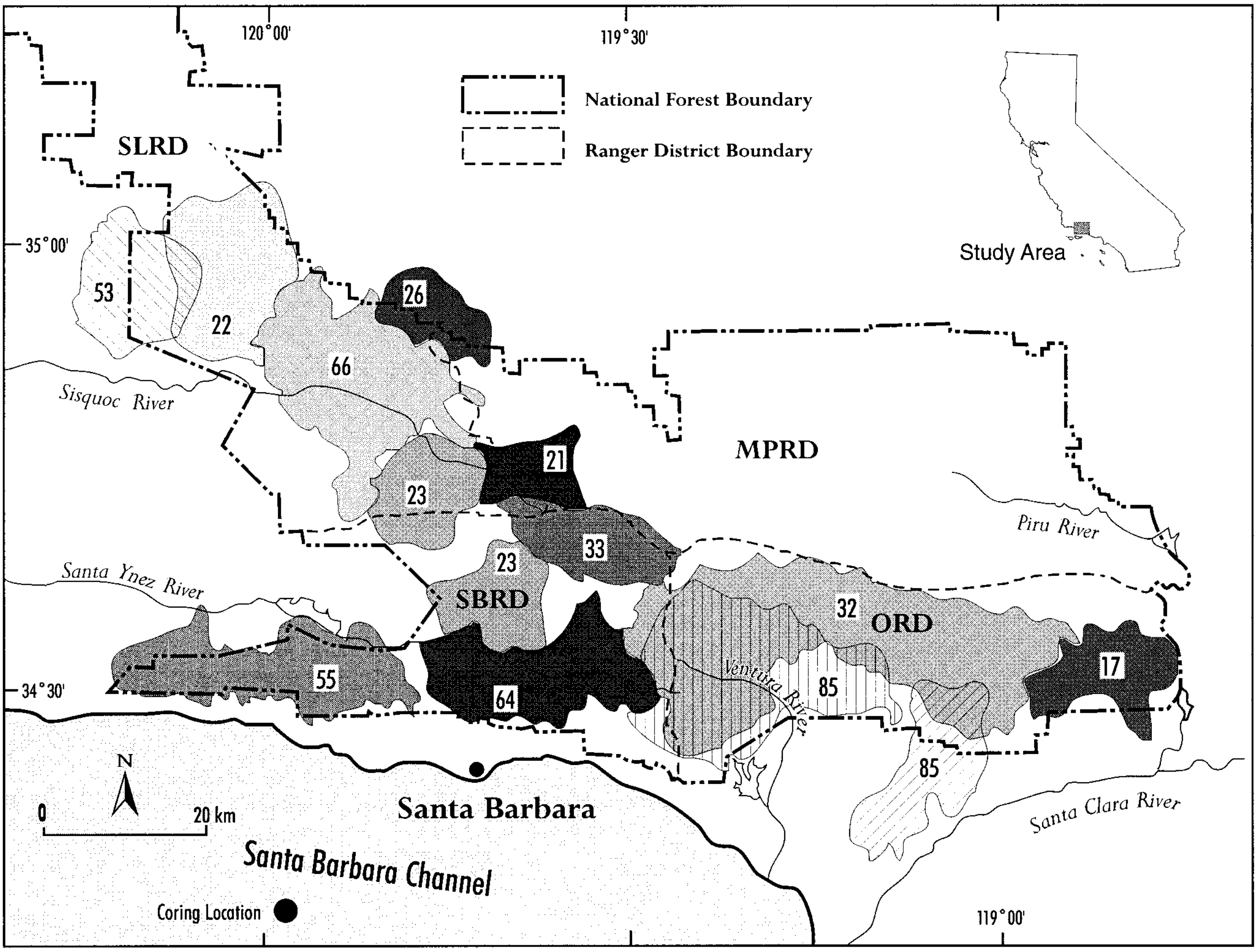

FIG. 1. Map showing the study area and major fires. The coring location identifies the area where core SABA 87-1/88 and core 262 (Byrne *et al.*, 1979) were taken. Fires shown are >12,000 ha and numbers refer to the year of the fire (Table 1). Ranger districts shown within the Los Padres National Forest are Santa Barbara (SBRD), Santa Lucia (SLRD), Ojai (ORD), and Mount Pinos (MPRD). The Los Padres National Forest, Santa Barbara District regional office, provided fire maps. The different gray tones are intended to help separate the different burned areas. Modified from Byrne *et al.* (1979).

fore, that Santa Ana conditions have occurred periodically throughout the period of this study.

The sediment cores upon which this study is based (SABA 87-1 and 88-1) were collected in the Santa Barbara Basin (34° 11′–34° 16′N: 120° 01′–120° 05′W) (Fig. 1) by investigators from Scripps Institute of Oceanography. Water depth in the central basin is ca. 590 m and the bottom waters are normally anoxic. The absence of bottom fauna allows differences in seasonal sediment density to be preserved as seasonal laminations or varves. Laminated anaerobic sediments are found only below 570-m depth in a relatively small region (110 km^2) of the basin (Soutar and Crill, 1977). A continuous high-resolution varve chronology has been developed for the last 560 yr (Soutar and Crill, 1977; Schimmelmann *et al.*, 1990). The chronology has been corroborated by radiometric dating (Emery, 1960; Koide *et al.*, 1972; Krishnaswami *et al.*, 1973; Bruland, 1974) and cross-correlation with tree ring and hydrological data (Soutar and Crill, 1977). Core recovery and sampling are described in Schimmelmann *et al.* (1990, 1992). The precision of the time scale is ± 1 yr for the period A.D. 1900–1987 and ± 2 yr at the A.D. 1840 level (Schimmelmann *et al.*, 1992). Downcore, the precision deteriorates to approximately ± 10 yr at the A.D. 1425 level (C. Lange and A. Schimmelmann, personal communication, 1992).

Microscopic Charcoal Analysis

A. Schimmelmann kindly provided us with freeze-dried sediment. Sediments from A.D. 1931–1970 were subsampled at ca. annual intervals to replicate the study by Byrne *et al.* (1977) and to compare charcoal accumulation rates with LPNF fire history. The remaining core sections (A.D. 1425–1930 and A.D. 1971–1985) were sampled in 5-yr intervals (108 pentads) to reduce the number of samples analyzed and because the downcore chronology is not sufficiently precise to justify annual sampling. Results from the A.D. 1931–1970 samples were then aggregated into eight pentads for reconstructing long-term fire history, making a total of 113 pentads. During the original sampling of the core, varves were sometimes split at subannual resolution, resulting in samples that combined portions from different years (A. Schimmelmann, personal communication, 1992). For example, the late-season portion of a varve (identified by light-colored sediments) was combined with the early season fraction (dark-colored sediments) from the following year. In one case (A.D. 1955) approximately 0.25% of the varve was initially sampled as part of the A.D. 1956 layer. Because this sampling strategy split a significant late season fire event between 2 yr, we allocated 0.25% of the A.D. 1956 charcoal fraction to the A.D. 1955 varve. In general, aggregating samples into pentads minimized sampling problems.

Samples were concentrated following standard pollen analysis procedures (Faegri and Iversen, 1975). Standard palynological procedures do not significantly alter charcoal size or abundance (Clark, 1984). A known quantity of exotic spores was introduced to calculate charcoal and pollen accumulation rates (Stockmarr, 1971). Concentrated residue was placed on glass slides for charcoal and pollen analysis.

Slides were scanned using a computerized system consisting of a video camera mounted on a compound microscope equipped with a motorized stage (Horn *et al.,* 1992). The system recognizes charcoal above a threshold optical density calibrated with known charcoal particles. Horn *et al.* (1992) found that scans of 200 fields ($<$10% total slide area) provided accurate counts. We measured 20% of the total slide area, examining a minimum of 500 fields with a 16$\times$ objective and an image capture size per field of 550 $\times$ 330 μm, or 90 mm^2. All particles $>$3750 μm^2 were individually verified to correct for system misidentification. Exotic spores were counted during pollen counts for 59 samples. For the remaining samples (54), spores were counted along transects covering a minimum of 20% of the slide. Charcoal concentration was calculated from exotic spore counts and the known volume of sediment. Charcoal concentration was divided by the number of varved years per sample to calculate charcoal accumulation rates ($mm^2\ cm^{-2}\ yr^{-1}$).

Charcoal particles were divided into two size fractions, small (312–3750 μm^2) and large ($>$3750 μm^2) following Byrne *et al.* (1979). Byrne *et al.* (1979) counted charcoal visually using a 25-μm ocular grid. In their study, large charcoal was defined as $>$6 grid squares ($>$3750 μm^2). This minimum size (approximately 0.061 mm in diameter) compares closely with the smallest of three size fractions recently tested by Whitlock and Millspaugh (1996). In that study, they found that the smallest size fraction (0.063–0.125 mm minimum diameter) identified the same trends in charcoal abundance as did much larger charcoal particles ($>$0.25 mm).

Reconstruction of fire history from microscopic charcoal requires a good understanding of the charcoal source area (Swain, 1973, 1978; Cwynar, 1978; Patterson *et al.,* 1987). Fire data for LPNF and adjacent land have been recorded since A.D. 1900 and fire extent has been mapped since A.D. 1911. Total area burned per year by ranger district on the LPNF and the mapped boundary and data on all fires $>$6000 ha were obtained from the United States Forest Service.

The correlation coefficients between total area burned per year and accumulation rates of small, large, and total particles of charcoal were calculated for each of the five LPNF ranger districts for the years A.D. 1931–1970. Correlation coefficients were also calculated for 2-yr periods (year plus one) to identify potentially significant lags in charcoal transport. To compare the charcoal record with known fire history for this century, total area burned was compared with charcoal particle accumulation rates for the same 5-yr period for the years A.D. 1901–1985.

For the period prior to 1900, charcoal peaks above a defined background level were interpreted as evidence of large fires. The background level was determined by comparing the large charcoal accumulation record with the known fire history. We used one standard deviation above the mean as the threshold value because this was slightly above the 1965 pentad large charcoal accumulation rate, which included a known large fire, and well below the 1925 pentad value, which also included a known fire. We first normalized the data to control for shifts in background accumulation rate over the record. Mean charcoal, pollen, and sediment accumulation show four distinct synchronous shifts (see Results, Fig. 4) over the last 560 yr. Transitions between these shifts are particularly abrupt (Table 4), occurring within the span of about 5 yr. We normalized the large charcoal data by dividing each value by the mean accumulation rate for that period (from Table 4). We then calculated the standard deviation for the entire period of record (A.D. 1425–1985) to determine the threshold value for inferred large fires.

Time Series Analysis

The charcoal data were compared to Santa Barbara Basin varve thickness records determined by Schimmelmann *et al.* (1990, 1992) and Santa Barbara precipitation reconstructed from tree rings (Haston and Michaelsen, 1994). Santa Barbara Basin varve thickness has been shown to represent smoothed records of regional precipitation (Soutar and Crill, 1977). The raw thicknesses show a strong decreasing trend downcore that is related to changes in water content due to compaction of the sediments. This trend was fit using an exponential trend over time and removed by dividing the raw values by the trend-line values. Biondi *et al.* (1997) fit and removed the trends using a more complex method based on singular spectrum analysis, but they report that the simple exponential fit produced very similar results. The dendroclimatic precipitation reconstruction is for rainfall season precipitation (September–August) at Santa Barbara and is based on big-cone spruce (*Pseudotsuga macrocarpa*) chronologies developed for three sites in the mountains of Santa Barbara and Ventura Counties. The overall skill

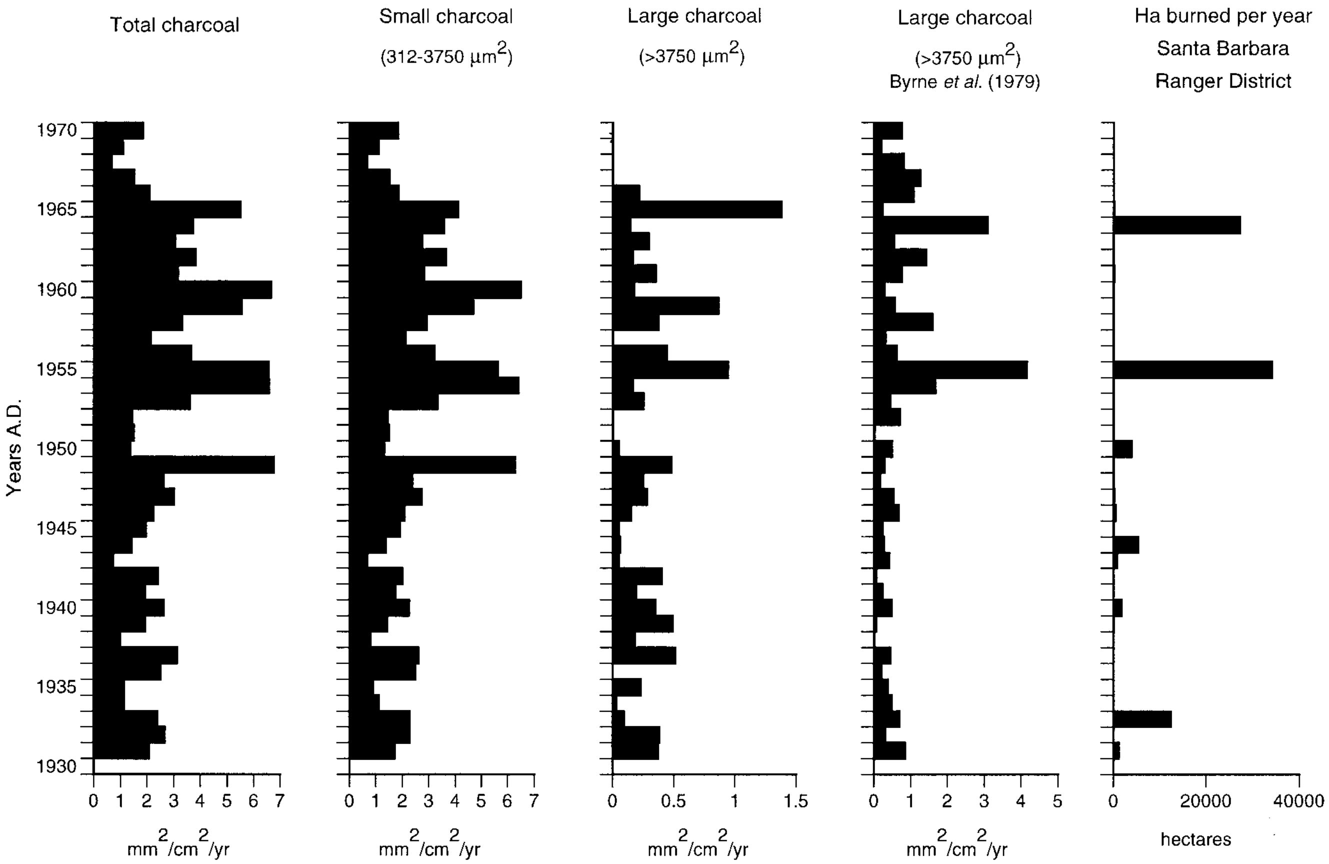

FIG. 2. Charcoal accumulation rates for the years A.D. 1931–1970 from the Santa Barbara Basin SABA 87-1/88-1 core, accumulation rates for large particles of charcoal from core 262 (Byrne *et al.*, 1977), and total acreage burned per year on the Santa Barbara Ranger District, Los Padres National Forest. Abscissa scale differs among graphs.

of the reconstruction is reasonably good, with a cross-validated variance of 54% explained (Haston and Michaelsen, 1994).

The various time series showed varying degrees of correspondence and different lead/lag relationships at different time scales, so spectral analysis was chosen as the main statistical tool for identifying and testing the relationships among the variables. Auto and cross spectra were estimated using a periodogram smoothing approach (Jenkins and Watts, 1968) with a modified Daniell smoother spanning nine frequency bands, followed with one spanning five bands (Bloomfield, 1976). The resulting spectral estimates had approximately 17.6 degrees of freedom and an effective bandwidth of 0.052 cycles/decade. The primary statistics of interest were the coherence and phase of the cross spectrum. Coherence is a measure of the percentage variance shared in common by two time series and is comparable to an r^2 value that varies as a function of frequency. Under the null hypothesis, the 0.05 significance level for an estimate with 17.6 degrees of freedom and no coherence is 0.32. The phase gives the amount by which one series leads or lags the other. The values are initially in radians but can be converted to time lags in years.

Time series were filtered using a low-pass filter that emphasizes time scales longer than 100 yr and a band-pass filter that emphasizes variations on 20- to 100-yr time scales. The filtering was accomplished by applying a Fourier transform to the time series, multiplying by the frequency response of either the low-pass or band-pass filter in the frequency domain, and inverse transforming back to the time domain (Bloomfield, 1976). This approach is directly analogous to applying appropriately weighted moving average filters in the time domain. It is used here for the convenience of being able to specify a frequency response directly rather than having to determine the shape and length of an appropriate set of moving average weights.

RESULTS

Calibration of Charcoal with Fire History

Small charcoal (312–3750 μm^2) accumulation rates range from 0.65 to 6.47 $mm^2\ cm^{-2}\ yr^{-1}$ and contribute 75–100% of the total (Fig. 2). Large charcoal (>3750 μm^2) accumulation rates range from 0 to 1.38 $mm^2\ cm^{-2}\ yr^{-1}$. No significant correlations were found between small and total charcoal ac-

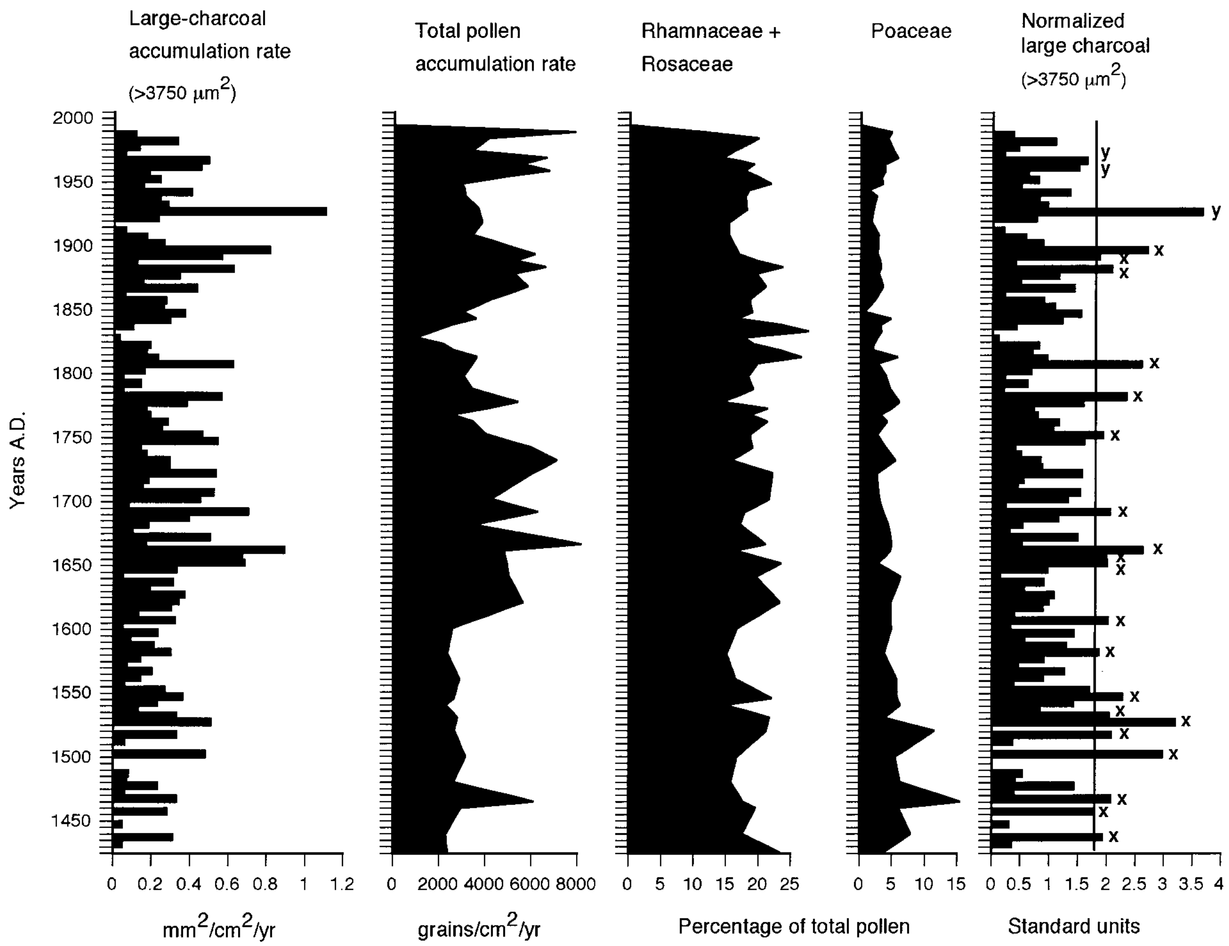

FIG. 3. Accumulation rate of large particles of charcoal, percentages of selected pollen taxa, and total pollen accumulation rate for the period A.D. 1425–1985 from the Santa Barbara Basin SABA 87-1/88-1 core. Samples are aggregated into pentads. The thin vertical line in the normalized large charcoal graph represents the threshold value for large fires, one standard deviation above the mean (1.78). Inferred large fires are marked with an **x.** Known fires from this century are marked with a **y.** Pollen values are presented as a percentage of the total terrestrial pollen sum. Rhamnaceae + Rosaceae includes the genera *Ceanothus, Adenostoma,* and *Rhamnus.* Poaceae includes all grasses.

cumulation rate and total area burned for 1-, 2-, 5-yr periods. For large charcoal, no significant correlations were identified between accumulation rate and area burned by district, in the same year; however, for the Santa Barbara Ranger District there was a significant lagged correlation between the area burned and charcoal accumulation for the year of the fire plus the following year ($r = 0.43$, $p < 0.05$). The two largest fires in the Santa Barbara Ranger District during the period A.D. 1931–1970 were in A.D. 1964 (26,800 ha) and A.D. 1955 (33,900 ha) (Table 1 and Fig. 1). The highest peaks in large charcoal accumulation rate (A.D. 1955 and 1965) coincide with or fall within 1 yr of these events. An offset of 1 yr is within the published precision of the SABA 87-1/88-1 core chronology.

The pattern of peaks in large charcoal accumulation rates corresponds well with those found in the earlier study by Byrne *et al.* (1979) (Fig. 2), although the absolute amount in our study is smaller. This may be due to differences in core handling and methodology. Byrne *et al.* (1979) worked with wet sediment and counted charcoal visually. Our study used freeze-dried sediment and counted charcoal with an automated scanning system. Automated systems create light bleed around the edges of charcoal particles that potentially cause underestimation of size and can reduce the total number and area of charcoal particles (MacDonald *et al.*, 1991; Horn *et al.*, 1992). Freeze-drying may have also caused some breakage. However, the similarity in findings between the two studies is quite good given that the analyses used different cores with independently developed chronologies and measured charcoal by different methods.

For pentads (A.D. 1901–1985) we found no significant correlation between small and total charcoal accumulation rates and hectares burned in each district. However, a significant correlation was found between large charcoal accumulation rate and total area burned on the Santa Barbara Ranger District ($r = 0.74$, $p < .001$). The A.D. 1925 pentad had the highest

TABLE 2

Pentads with Inferred Large Fire Events for the Period A.D. 1425–1900 and Known Large Fire events for the Period A.D. 1900–1985

Cultural period	Pentad with fire	Years since last fire	Average time between fires
A.D. 1900–1985	1965	10	
	1955	30	23 yr
	1925	30	
A.D. 1770–1900	1895	5	
	1890	10	
	1880	75	29 yr
	1805	25	
	1780	30	
A.D. 1425–1770	1750	60	
	1690	30	
	1660	5	
	1655	5	
	1650	45	
	1605	25	
	1580	35	21 yr
	1545	15	
	1530	5	
	1525	10	
	1515	15	
	1500	35	
	1465	10	
	1455	20	
	1435		

Note. Pentads include the years prior to the date given; i.e., 1895 includes the years A.D. 1891–1895. Cultural periods are defined in the text.

large-charcoal accumulation rate (1.1 $mm^2\ cm^{-2}\ yr^{-1}$) for the 560-yr record (Fig. 3). This pentad included the second largest fire in the Santa Barbara Ranger District (28,000 ha) in 1923 (Fig. 1, Table 1). The pentad with the second highest large charcoal accumulation rate, A.D. 1961–1965, included the third largest fire on record (26,800 ha) in A.D. 1964. The largest fire (33,900 ha) was in A.D. 1955, but was less apparent in the record, probably because our sampling strategy split the charcoal from this event between two pentads.

Normalized values for large charcoal accumulation rate by pentad are plotted in Figure 3. Despite the smoothing effect caused by averaging over 5 yr, the 1965 pentad, which included one fire >20,000 ha, had the highest accumulation rate for the A.D. 1931–1970 period. This shows that a single conflagration can deposit enough large charcoal in the Santa Barbara Basin to produce a significant peak even when annual samples are aggregated into pentads. Peaks greater than one standard deviation above the mean (1.78) were considered large fires. Charcoal peaks approaching one standard deviation may also represent large fires but were excluded from consideration in our analysis.

Reconstructed Fire History

The pre-1900 record of large charcoal accumulation rate (Fig. 3) shows 20 peaks with values one standard deviation above the mean. Each peak represents an inferred fire of >20,000 ha. Large fires occur in every century, with the longest period between fires being 75 yr (Table 2). The record has been divided into three cultural periods representative of different attitudes toward fire. Period 1 (A.D. 1900–1985) represents the period of active fire suppression and historic fire records (Minnich, 1983; USFS Santa Barbara fire data). Period 2 (A.D. 1770–1900) encompasses the early period of Spanish and American occupation characterized by a policy of fire suppression, but with little means of enforcement (Barrett, 1935). Period 3 (A.D. 1425–1770) represents the Chumash period during which fires were purposely set along the coastal plain (Timbrook *et al.*, 1982). The average interval between large fires for each period is 23, 29, and 21 yr, respectively (Table 2).

Time Series Analysis

None of the autospectra (not shown) had significant spectral peaks, indicating a lack of periodicities in the records. The autospectra did show evidence of different degrees of persistence and partitioning of variance by time scale. Table 3 gives the percentages of variance for each record on long time scales greater than 100 yr, intermediate time scales between 20 and 100 yr, and short time scales less than 20 yr. The range is quite broad, with almost no variance on long time scales for the tree ring precipitation record and large charcoal accumulation rates to substantial amounts of variance at long time scales and very little at short time scales for the varve thickness and pollen records. The small charcoal accumulation rate has variance spread fairly evenly across all time scales. These differences reflect a combination of varying sensitivities and response times to environmental forcing and different degrees of processing the data. The information in Table 3 needs to be considered when interpreting the cross-spectral results, because high coherence at time scales where there is little variance is not generally very meaningful. Large charcoal is coherent with tree ring precipitation on 20- to 40-year time scales.

The temporal record of the coherent century-scale oscillation

TABLE 3

Partitioning of Variance (%) by Time Scale

	100–500 yr	20–100 yr	10–20 yr
Precipitation	6.3%	49.0%	44.7%
Large charcoal accumulation rates	12.5%	42.3%	45.1%
Small charcoal accumulation rates	27.0%	39.3%	33.7%
Varve thicknesses	42.2%	40.3%	17.5%
Total pollen accumulation rates	59.3%	35.0%	5.7%

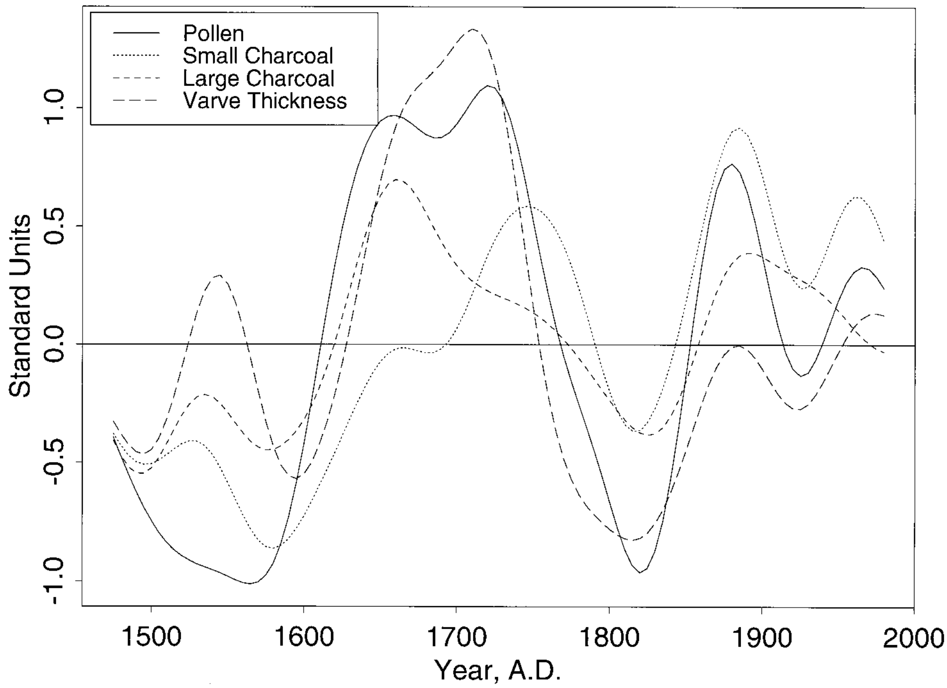

FIG. 4. Low-pass filtered versions of the records of the total pollen accumulation rate, small charcoal particle accumulation rate, large charcoal particle accumulation rate, and varve thickness records. Dividing by the standard deviation of the unfiltered record standardized each filtered series.

is depicted in the graph of the low-pass filtered records (Fig. 4). The magnitudes of the oscillations give indications of the proportion of the total variance they represent. The same pattern is present in all the records: low values prior to A.D. 1600, high values continuing to ca. A.D. 1750, low values to ca. A.D. 1850, and moderately high values to the present. The phase spectra (not shown) indicate that all four records are within one pentad of being in phase. The smoothing produced by the low-pass filter makes these oscillations appear gradual, but the unsmoothed data show abrupt transitions. This is particularly clear in the total pollen accumulation record that appears to have four regimes. The averages for the regimes are significantly different, not only in the pollen accumulation but also for several transitions in the charcoal accumulation and varve thickness records (Table 4).

TABLE 4
Means for Different Time Periods in Years A.D.

	1425–1605	1610–1745	1750–1850	1855–1980
Tree ring precipitation (cm)	47.7	45.1	44.5	44.6
Pollen accumulation (grains cm^{-2} yr^{-1})	2750	5390*	3160*	4540*
Small charcoal (mm^2 cm^{-2} yr^{-1})	1.28	2.02*	1.99	2.55*
Large charcoal (mm^2 cm^{-2} yr^{-1})	0.16	0.34*	0.24	0.30
Varve thickness (standard units)	0.93	1.22*	0.83*	0.99*

* The mean is significantly different than the mean of the preceding period.

Tree ring and large charcoal band-pass filtered time series records are shown in Fig. 5. The coherence between large particles of charcoal and tree ring widths is significant (coherence = 0.32, p = 0.05) for a broad range of periods from 25 to 39 yr. The broadness of the coherence peak indicates that the fluctuations tend to follow similar patterns but with no clear periodicity. The phase relationship shows that the two records are about one-quarter cycle out of phase, with precipitation peaks leading large charcoal peaks by about 5–10 yr. High accumulations of large charcoal tend to occur at the end of wet periods (beginning of droughts) while low accumulations of large charcoal occur at the end of droughts (beginning of wet periods).

DISCUSSION

The evidence indicates that Santa Ana fire events are recorded in the cores as peaks in the accumulation of large charcoal particles. The large charcoal is transported to the core site by Santa Ana winds during the fire and by fluvial transport within a year of the event. The evidence also indicates that large charcoal accumulates in the Santa Barbara sediments even in years without Santa Ana fires. We assume that most of this background charcoal is brought to the coast by water transport. Five drainage systems contribute sediment to the

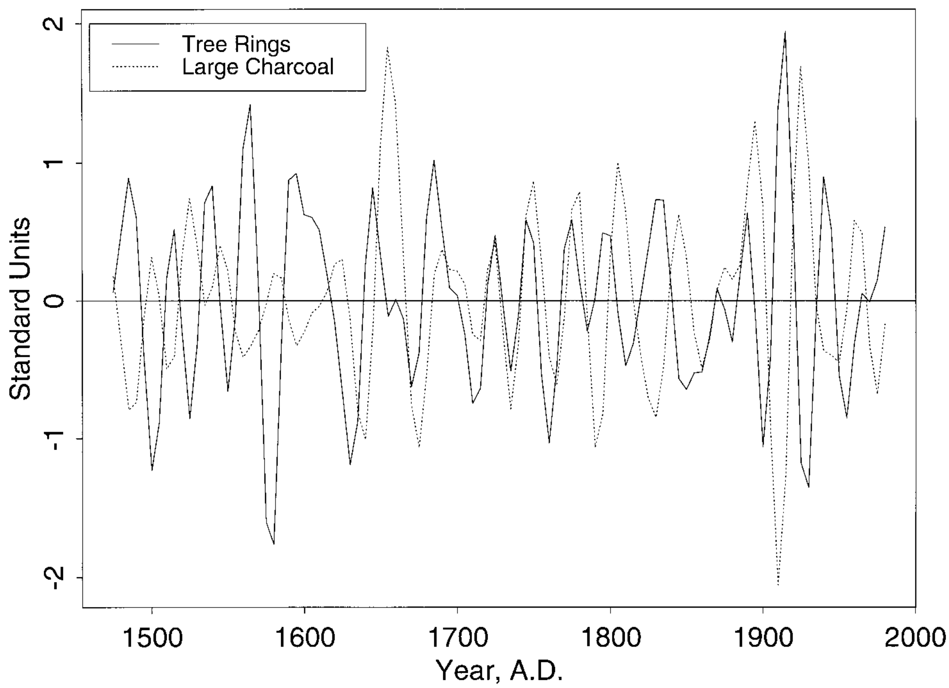

FIG. 5. Band-pass filtered versions of the tree ring precipitation record and the large charcoal accumulation rate record. Dividing by the standard deviation of the unfiltered record standardized each filtered series.

Santa Barbara Basin, the Santa Clara River (51%), the Santa Ynez River (27%), coastal streams (12%), the Ventura River (7%), and the Channel Islands (3%) (Fleischer, 1972). The correlation between runoff and net sedimentation accumulation in the Santa Barbara Basin is highest the first year, with the relationship diminishing to zero over the next 4 yr (Soutar and Crill, 1977). In 1969, record levels of runoff (174% normal) and sediment flow were measured in the Santa Clara and Ventura Rivers (Soutar and Crill, 1977); however, no charcoal peak is evident in the core sample for this year. One and one half years after the flood, one-third of the sediment deposited on the shelf remained in place (Soutar and Crill, 1977), suggesting that the process of fluvial sediment transport from the coast to the basin is slow. The significant correlation between total acreage burned in the Santa Barbara Ranger District and large charcoal accumulation lagged 1 yr lead us to conclude that large charcoal particles produced by conflagrations near the coast are rapidly transported to the Santa Barbara Basin, primarily through wind transport during the fire and secondarily by fluvial transport the following winter. The high correlation between total acreage burned per pentad on the Santa Barbara Ranger District and the accumulation rate of large charcoal in the Santa Barbara Basin suggests that large charcoal provides a good record of Santa Ana fires.

The charcoal record indicates that large fires are part of the natural fire regime in this region (Fig. 3). These results support the conclusions of Byrne *et al.* (1977) that large fires occurred prior to the modern period of fire suppression. The charcoal data show no strong periodicity. However, the average time between large fires has remained relatively consistent throughout the record, with no large differences between the three cultural periods (Table 2). Large fires occurred in every century. Neither the Chumash practice of setting fires nor the modern practice of suppressing fires appears to control the periodic occurrence of conflagrations in the region.

Ninety-five percent of the total area burned in the LPNF for the period A.D. 1950–1991 was chaparral and only six fires accounted for half of all area burned (Davis and Michaelsen, 1995). These large fires nearly always occurred during summer heat waves or during Santa Ana conditions. The probability of a wildfire >400 ha in the Santa Barbara Ranger Districts is close to zero on days when the maximum daily temperature at Santa Barbara is less than 25°C (Davis and Michaelsen, 1995). The probability increases dramatically when temperatures exceed 30°C. Human activity is responsible for most fires; however, lightning is still an important ignition source (Keeley, 1982).

Background levels of both large and small charcoal suggest that small fires are also common. Fires at this scale may have created a fine-grained vegetation mosaic in portions of the landscape, as suggested by Minnich (1983). However, there is no evidence that such a mosaic acted to prevent Santa Ana conflagrations. Such fires would have converted large portions of the landscape to an even-age, coarse-grained structure, possibly contributing to the importance of seedling-obligate chaparral taxa, such as some species of *Adenostoma* and *Ceanothus* (Keeley, 1977).

A pollen record produced from the same core suggests that there have been no significant changes in the extent of chaparral over the last 560 yr (Mensing, 1999). There is no appreciable change through time of the Rosaceae/Rhamnaceae type (representing the common chaparral genera *Ceanothus, Adenostoma,* and *Rhamnus*) (Fig. 4). Frequent low-intensity fires should have favored grasses over chaparral and resulted in an expansion of grassland (Dodge, 1975; Timbrook *et al.*, 1982; Zedler *et al.*, 1983); however, the pollen record shows a decrease in grass pollen over time. In an environment where Santa Ana fires are common events, chaparral is maintained.

Climate exerts an important control over the fire regime by increasing potential fuel loads in wet periods and providing ideal conditions for large fires in dry periods. The inferred large fires (Fig. 3 and Table 2) consistently occurred at the end of wet periods and the beginning of droughts (Fig. 5). The charcoal and precipitation records are coherent on 20- to 40-yr time scales, and although there is no clear periodicity to fires, the average length of time between large fires appears to be controlled to a large extent by precipitation trends. Mean precipitation for the region as reconstructed from tree rings shows no significant changes over the last 500 yr (Table 4) (Haston and Michaelsen, 1994). Oscillations between wet and dry phases over this period appear to contribute to large fires on a regular basis, regardless of changes in land use practices.

CONCLUSION

High accumulation rates of large charcoal in Santa Barbara Basin varved sediments compare favorably with known conflagrations that burned >20,000 ha on the nearby Santa Barbara Ranger District. These results suggest that microscopic charcoal can be used to reconstruct the long-term fire history for the region. Three fires >20,000 ha have been recorded for this century. Our reconstruction suggests that between A.D. 1425 and 1900 there were at least 20 large fires in this area. The average time between fires ranges between 20 and 30 yrs and is strongly controlled by precipitation patterns, with large fires generally occurring at the end of wet phases and the beginning of droughts. If small fires created a fine-grained vegetation pattern on the landscape, this does not appear to have prevented periodic large fires. Changes in land use practices associated with the arrival of the Spanish and the introduction of fire suppression also have not significantly altered the fire regime. Fire suppression may contribute to large fires by allowing more fuel accumulation; however, fire suppression alone does not create this type of fire. The fuel and weather conditions necessary for large fires were present prior to fire suppression and are a natural part of chaparral ecology in a Mediterranean climate.

ACKNOWLEDGMENTS

We thank Arndt Schimmelmann and Carina Lange for providing sediment samples; Fritz Cahill and Mary Blair of the Los Padres National Forest, for supplying fire maps and data; and Bob Elston Jr. for cartography. We also thank Cathy Whitlock and an anonymous reviewer for their constructive comments on an earlier version of the manuscript. Funding for this research was provided by the National Science Foundation, the California State Integrated Hardwood Range Management Program, and Sigma Xi.

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