7. Influence of Climate and Land Use on Historical Surface Fires in Pine-Oak Forests, Sierra Madre Occidental, Mexico

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The rugged mountains of the Sierra Madre Occidental, in north-central Mexico, support a mosaic of diverse ecosystems. Of these, the high-elevation, temperate pine-oak forests are ecologically significant for their extensiveness and biodiversity. They cover nearly half the land area in the states of Durango and Chihuahua (42%), and comprise a similar percentage of the temperate coniferous forest in Mexico as a whole (45%; World Forest Institute 1994; SARH 1994). These forests are globally significant centers of vascular plant diversity, and of endemism in both plant and animal species (Bye 1993; Manuel-Toledo and Jesús-Ordóñez 1993). For example, they have the highest number of pine and oak species in the world (Rzedowski 1991) and contain many of Mexico's *Pinus*, *Quercus*, and *Arbutus* species (33%, 30%, and 66%, respectively; Bye 1995). Surface fires were historically frequent in these forests, and variations in their frequency may have contributed to the maintenance of this biodiversity (Dieterich 1983; Fulé and Covington 1997, 1999; Park 2001). However, we know little about the drivers of variation in historical fire regimes.

Forest fires are controlled by processes acting across a broad range of spatial scales (Tande 1979; Payette et al. 1989; Swetnam and Baisan 1996; Taylor and Skinner 1998; Heyerdahl, Brubaker, and Agee 2001). At coarse spatial scales, annual extremes in regional climate can synchronize the occurrence of fires across broad areas (Swetnam and Betancourt 1998; Swetnam and Baisan, Chapter 6, this volume). For example, fires were widespread during years of regionally low precipitation at sites in North and South America (Veblen et al. 1999; Veblen, Kitzberger, and Donnegan 2000; Kitzberger, Swetnam, and Veblen 2001; Heyerdahl, Brubaker, and Agee in press; Swetnam and Baisan, Chapter 6, this volume). Climate varies at annual scales in Mexico, partly in response to the El Niño–Southern Oscillation (ENSO), which significantly affects precipitation in the Sierra Madre Occidental (Ropelewski and Halpert 1986, 1987, 1989; Kiladis and Diaz 1989; Cavazos and Hastenrath 1990; Stahle et al. 1998, 1999). We would expect such temporal variations in climate to synchronize the occurrence fire across this region by affecting the amount and moisture content of the fine fuels that carry surface fires. Assessing the annual relationship between climate and fire requires long accurate records. Unfortunately, detailed archival records of fire occurrence and climate are rare for much of the Sierra Madre Occidental. However, multicentury records of both can be reconstructed from annually dated tree-ring series for the region (Fulé and Covington 1997, 1999; Stahle et al. 1998, 1999).

Climate is not the only factor that drives variation in fire regimes through time. In the western United States, for example, fire regimes were dramatically affected by late nineteenth- and early twentieth-century changes in land use, such as grazing, road building, and timber harvesting (e.g., Leopold 1937; Savage and Swetnam 1990; Baisan and Swetnam 1997; Fulé and Covington 1997, 1999; Kaib 1998; Veblen et al. 1999; Veblen, Kitzberger, and Donnegan 2000; Heyerdahl, Brubaker, and Agee, in press). These land-use activities also intensified in the Sierra Madre Occidental in the mid-1900s with changes in the *ejido* system of land tenure in Mexico and may have affected fire regimes there.

Our objective was to infer the role of annual variation in regional climate and changes in land use in driving the occurrence of widely synchronous surface fires in pine-oak forests of the Sierra Madre Occidental of Mexico. Specifically, we reconstructed a multicentury history of fire from tree rings and fire scars at eight sites in the states of Durango and Chihuahua. We compared this history to existing tree-ring reconstructions of precipitation and ENSO activity (Stahle et al. 1998, 1999) and to archival records of land use.

Study Area

Sampling Sites

We relied on the knowledge of local foresters and researchers to judgmentally locate eight largely unlogged sites (2–6 ha each) containing relatively old, fire-scarred trees. The sites are distributed over nearly 700 km on the dry east side of the crest of the Sierra Madre Occidental in north-central Mexico (Fig. 7.1). All the sites are high in elevation (2440–2950 m, Table 7.1), but vary in slope (16–65%), aspect (3–343°) and topographic position (hill slopes: SSP, AJT, FCT, CHI, LBA; mesas: CAR, MLC; rocky ridge: ALF). The shallow, coarse-textured volcanic soils at most of our sites are typical of the region in general (Challenger 1998; Ferrusquía Villafranca 1998).

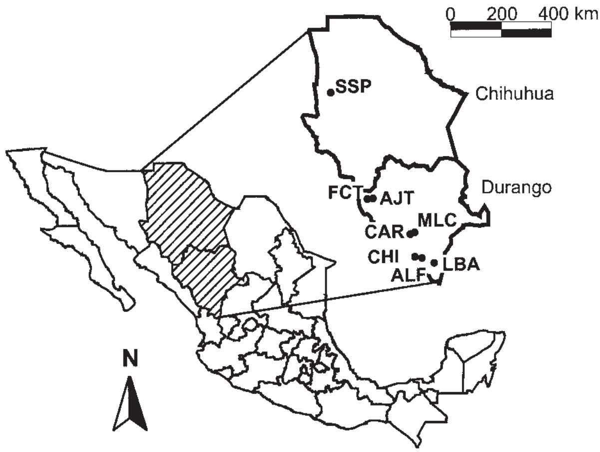

Figure 7.1. Mexico and the states of Durango and Chihuahua, showing the location of the eight sites at which we reconstructed fire history.

Forest composition at these sites, typical of this portion of the Sierra Madre Occidental (Bye 1995), was dominated by four pine species (*Pinus durangensis* Mart., *P. teocote* Schl. & Cham., *P. ayacahuite* Ehren., or *P. engelmannii* Carr.), but other species also occurred (*P. arizonica* Engelm., *P. herrerai* Mart., *P. lumholtzii* Robins. & Fern. and *Pseudotsuga menziesii* Mirb. Franco). Several species of *Quercus* were common at all sites, and a few species of *Arbutus* and *Juniperus* occurred at some southern sites. The understory was dominated by grasses and herbs.

Table 7.1. Location and topographic position of the sampling sites

Site name	Site code	Ownership	Nearby town	Elevation (m)	Aspect (degrees)	Slope (%)	Area sampled (ha)
Salsipuedes	SSP	El Largo	Madera	2620	314	47	2
Alto del Jiguital	AJT	El Tecuan	Tamazula	2440	18	34	3
Falda de la Cañada	FCT	Santa Ana	Tamazula	2660	212	26	4
El Carpintero	CAR	La Victoria–Miravalles	San Miguel	2790	295	18	4
Mesa de los Ladrónes	MLC	La Victoria–Miravalles	San Miguel	2830	179	16	3
Las Chivas	CHI	La Victoria	El Salto	2950	224	42	6
Arroyo de las Flores	ALF	La Campana	El Salto	2800	3	65	5
Las Bayas	LBA	UJED Research Forest	La Flor	2900	343	38	3

Note: Sites are ordered from north to south (top to bottom). All sites but LBA are owned by the *ejidos* indicated. UJED is the Universidad Juárez del Estado de Durango. All sites except SSP are in Durango.

Instrumental Climate

The Sierra Madre Occidental has a monsoonal climate with warm, wet summers, a long dry period in the spring and a shorter one in the fall (Fig. 7.2; Mosiño Alemán and García 1974). Most annual precipitation (70–80%) falls during the summer (June–September) as a result of the monsoon that develops over southern Mexico in May and spreads north along the Sierra Madre Occidental to reach Arizona and New Mexico by July (Mosiño Alemán and García 1974; Hales 1974; Douglas et al. 1993). Annual precipitation, derived from low-elevation stations for the states of Durango and Chihuahua, averages 40 and 56 cm, respectively (1945–1993; Douglas and Englehart 1995). While the seasonal distribution of precipitation at our high-elevation sampling sites is probably similar to these statewide averages, total precipitation is likely higher. For example, El Salto (elevation ca.2500 m), near the southern end of our sampling area, annually receives 92 cm of rain (1940–1993; Fig. 7.2). Winter precipitation can fall as snow at high elevations in the Sierra Madre Occidental, but persistent snow packs are rare (Mosiño Alemán and García 1974; Challenger 1998). Precipitation in the Sierra Madre Occidental varies through time, partly in response to global processes like ENSO. Winters are wetter than average during El Niño years and drier than average during La Niña years (Ropelewski and Halpert 1986, 1987, 1989; Kiladis and Diaz 1989; Cavazos and Hastenrath 1990). Temperatures are generally mild in this region, with an annual maximum in June (e.g., 16°C at El Salto, Fig. 7.2; Mosiño Alemán and García 1974).

Most modern fires in our study area burn in the spring (January–May, SEMARNAP 2000) as temperatures warm and fine fuels dry, but before monsoon rains increase fine-fuel moisture and encourage new growth of grasses and herbs. Lightning is most common from April to October and has been inferred

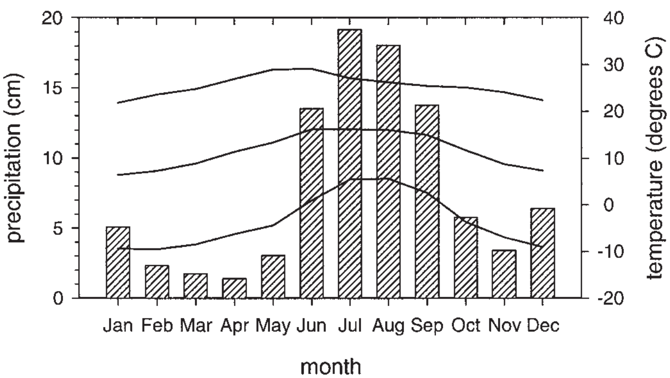

Figure 7.2. Climate of El Salto, Durango (1940–1993; elevation ca.2500 m). Total monthly precipitation is shown as bars, average monthly minimum, mean, and maximum temperatures are shown as lines.

as an ignition source for fire elsewhere in the Sierra Madre Occidental (Turman and Edgar 1982; Fulé and Covington 1999).

Historical Climate from Tree Rings

Precipitation has been reconstructed from tree rings for Durango (1386–1995; Stahle et al. 1999). These reconstructions explain 56% of the variance in the instrumental record of winter precipitation (previous November–March) and 53% of that in early summer (May–June, 1942–1983). For each of these seasons, modern precipitation varies similarly in Durango and Chihuahua ($r = 0.57$ and 0.59, for winter and early summer, respectively, $p < 0.01$, 1945–1994; Douglas and Englehart 1995). Consequently the reconstruction for Durango probably captures variation in precipitation at our sites in both states.

Variation in the strength and phase of ENSO is captured by an index of the Southern Oscillation, computed as the normalized difference in monthly surface pressure between Tahiti and Darwin, Australia, two measurement stations near the oscillating centers of high and low pressure (Enfield 1992; Allan, Lindesay, and Parker 1996). Years of low (high) values of the Southern Oscillation Index (SOI) are typically El Niño (La Niña) years (Deser and Wallace 1987). Winter SOI (December–February) has been reconstructed from tree rings and explains 53% of the variance in instrumental SOI (1706–1977, Cook 1985; Allan, Lindesay, and Parker 1996; Stahle et al. 1998).

Methods

Fire Regimes

Over an area of 2 to 6 ha per site, we used a chain saw to remove scarred sections from 19 to 32 of those trees that we judged to have the greatest number of visible, well-preserved scars (Arno and Sneck 1977). More than half of these trees (56%) were alive when sampled. We sanded the scarred sections until the cell structure was visible with a binocular microscope and assigned calendar years to tree rings using a combination of visual crossdating of ring widths and crosscorrelation of measured ring-width series (Holmes 1983). The crossdating was confirmed by another dendrochronologist for nearly half the dated sections (47%). We excluded 13% of the sampled trees from further analyses because they could not be crossdated.

We used fire scars as evidence of surface fires and identified them as discontinuities between cells, within a ring or along a ring boundary, where the cambium had been killed but not mechanically damaged, followed by overlapping, curled rings (Dieterich and Swetnam 1984). Additionally we obtained a small amount of supporting evidence of surface fires (5% of fire-scar dates) from abrupt changes in the width of annual rings (e.g., Landsberg et al. 1984; Sutherland, Covington, and Andariese 1991). However, because factors other than surface fires can cause abrupt changes in cambial growth (e.g., Brubaker 1978), we used such a change in a given sample as evidence of a surface fire only when it coincided with a fire scar in other samples at the same site.

We identified the calendar year in which each scar formed to determine the year of fire occurrence, and the position of each scar within the ring (ring boundary, earlywood, latewood, or unknown) as an indication of the season of fire occurrence (Dieterich and Swetnam 1984; Baisan and Swetnam 1990). In the Northern Hemisphere the season of cambial dormancy (i.e., the period corresponding to the ring boundary) spans two calendar years: from the time the cambium stops growing in the fall of one year until it resumes in the spring of the following year. For this study we assigned ring-boundary scars to the *following* calendar year because modern fires in the Sierra Madre Occidental generally burn in the spring, as they do under monsoonal climates elsewhere (Baisan and Swetnam 1990; Fulé and Covington 1997, 1999; SEMARNAP 2000). Scar position could not always be determined where it was obscured by rot or insect galleries or where rings were narrow.

For each site we composited the dates from all trees into a single record of fire occurrence (Dieterich 1980) and computed the intervals between years in which a fire scarred at least one tree at that site. We analyzed fire intervals for the period after which at least five trees (17–29% of trees) per site had scarred at least once and before any major recent shifts in fire regimes (Table 7.2). Two-parameter Weibull distributions fit the fire-interval density distribution at seven of the sites ($p > 0.05$, one-sample Kolmogorov-Smirnov goodness-of-fit test) and marginally fit the distribution at the remaining site (AJT, $p = 0.03$). Consequently we used percentiles of the fitted Weibull distribution to characterize the distribution of fire intervals at each site (Grissino-Mayer 1999, 2001).

Table 7.2. Size of sampling areas and amount of fire evidence collected

Site	Number of trees crossdated	Number of fire scars	Abrupt changes in ring width	Earliest year sampled	Analysis start year	Analysis end year
SSP	18	212	9	1629	1785	1951
AJT	22	191	18	1669	1772	1893
FCT	25	86	6	1754	1857	1994
CAR	24	234	8	1700	1795	1951
MLC	29	222	13	1729	1797	1951
CHI	23	165	11	1791	1898	1994
ALF	22	236	0	1779	1841	1994
LBA	17	123	4	1687	1817	1951
Total	180	1469	69			

Note: Earliest years are dates of first rings found at each site, while analysis start year is the first year for which at least five trees at the site had scarred at least once. Analysis end year is either the last year of record or the approximate year of an abrupt decrease in fire frequency at each site. Number of scars are for the entire period of record.

Drivers of Temporal Variation in Historical Fire Regimes

To identify climate drivers of fire at annual scales, we determined whether variation in regional climate was associated with variation in the occurrence of widespread surface fires in our study area. Specifically, we assessed whether climate during widespread- and non-fire years was significantly different from climate during the preceding and following years (±5 years), using superposed epoch analysis (SEA; Baisan and Swetnam 1990; Swetnam and Betancourt 1992; Grissino-Mayer 1995). We used this analysis to test for departures in climate during two sets of years at our eight sites: *widespread fire years*, namely those with at least 50% of sites recording a fire (~1 standard deviation above the mean; 31 years); and *non-fire years*, namely those with no sites recording fire (68 years). For both sets of years, we computed departures in three climate parameters: *winter precipitation* (previous November–March; Stahle et al. 1999), *early summer precipitation* (May–June; Stahle et al. 1999), and *winter SOI* (December–February; Stahle et al. 1998). We identified significant departures as those with $p < 0.05$, determined by bootstrapping (1000 trials; Swetnam and Betancourt 1992; Mooney and Duvall 1993; Grissino-Mayer 1995). We conducted this analysis from 1772 to 1977, the period after which at least five trees per site had scarred at least once (17–29% of trees per site; Table 7.2) to the end of the record of reconstructed SOI (1977). However, the tree-ring record started after 1772 for some sites, so we computed the percentage of sites burning during a given year as a percentage of those sites that had a record for that year. Finally, we repeated these SEA analyses but included existing fire history reconstructions from an additional four sites in Durango (Fulé and Covington 1997).

To identify nonclimatic drivers of surface fire, we determined whether changes in land use were synchronous with variation in surface fire occurrence in our study area. We used regional trends in land use to make inferences about the effects of land use on the history of fire at our sites because we lack site-specific land-use histories. Specifically, we used a national record of the amount of land redistributed via the *ejido* system (Sanderson 1984), as an indication of likely settlement in the forests of the Sierra Madre Occidental. We compared this time series to that of percentage of sites recording fire per year. To emphasize decadal variation, we smoothed the time series of fire occurrence using a cubic spline that retained 50% of the variance present in the original series at periods of 20 years (Diggle 1990).

Results

Fire Regimes

We removed fire-scarred sections from 206 trees, most of which were *Pinus durangensis* (40%), *P. teocote* (14%), *P. ayacahuite* (10%), *P. engelmannii* (6%) or unknown species (26%; Table 7.2). The remaining samples came from

P. arizonica (1%), *P. herrerai* (1%), *P. lumholtzii* (1%) or *Pseudotsuga menziesii* (1%). We were able to crossdate 180 of these trees, yielding 1469 fire scars, and 69 abrupt changes in ring width (Fig. 7.3; Dieterich 1980; Grissino-Mayer 2001).

We were able to assign an intra-ring position to most scars (73% of 1341 scars during the analysis periods; Table 7.2). The distribution of scars by intra-ring position was similar among sites. Of the scars to which we could assign an intra-

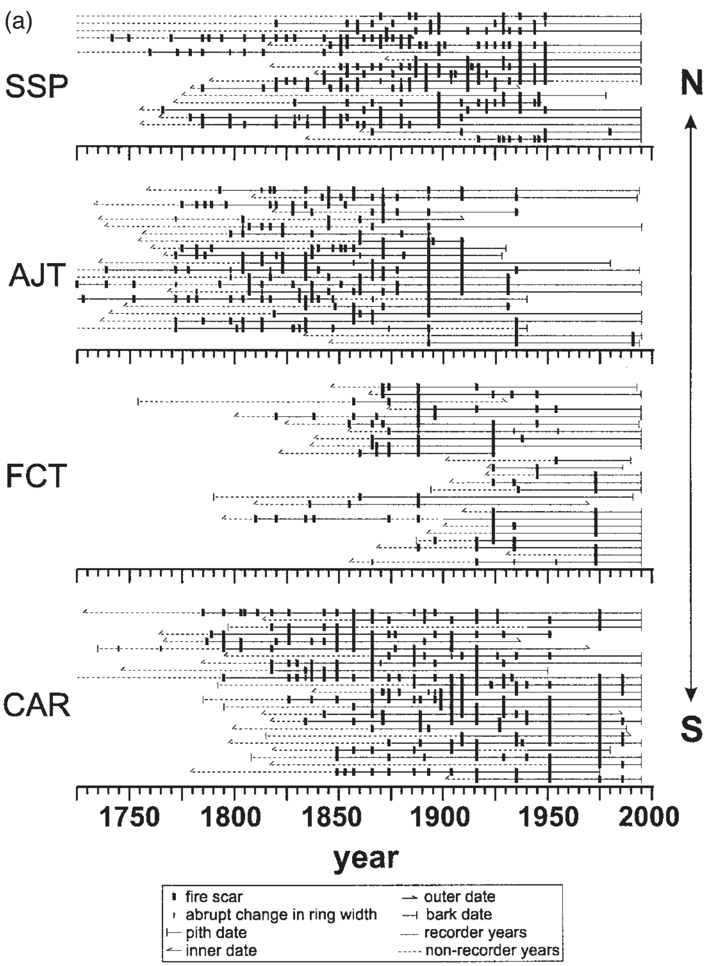

Figure 7.3. Fire charts. Each horizontal line shows the fires recorded by a single tree through time. Recorder years generally follow the first scar on each tree. Nonrecorder years precede the formation of the first scar on each tree but also occur when tree rings are consumed by subsequent fires or rot. Inner and outer dates are the dates of the earliest or latest rings sampled for trees where pith or bark were not sampled.

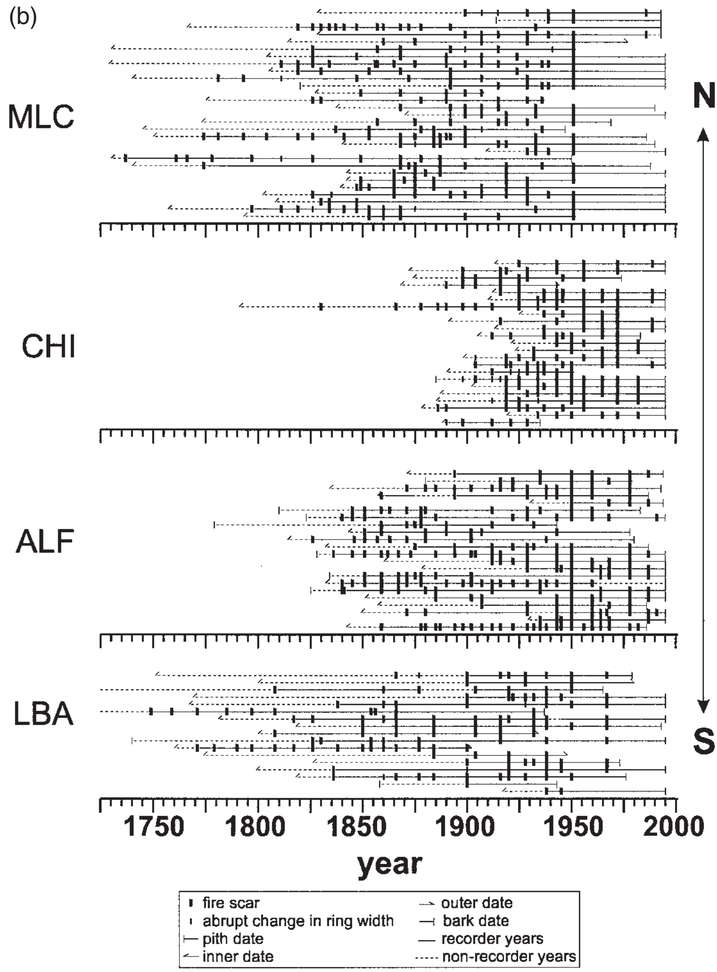

Figure 7.3. *Continued*

ring position, most were created by fires burning when the cambium was dormant (63% ring-boundary scars; Fig. 7.4). Most of the rest of the scars were created during the growing season (35% earlywood scars), and of these, most were formed early in that season (51% in the first third of the earlywood, 35% in the middle third). Only a few scars were created by fires burning late in the cambial growing season (2% latewood scars).

The distribution of intervals was similar for the composite surface fires from our sample of trees at most sites, although intervals were slightly longer and more variable, at FCT and LBA than at the other sites (sampled areas 2–6 ha; Fig. 7.5). Weibull median intervals were 3 to 6 years, minimum intervals 1 to 2 years and maximum intervals 9 to 20 years. Most fires (76–100% per site), were recorded

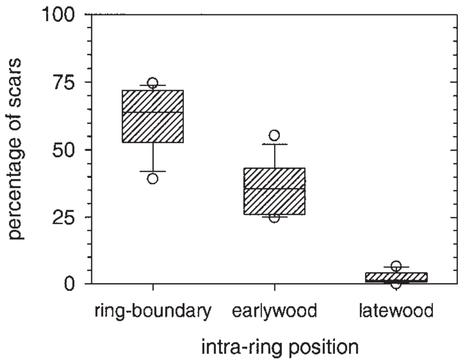

Figure 7.4. Distribution among sites of intra-ring position of fire scars, as a percentage of scars per site for which position could be determined (974 scars or 56–83% per site). Ring-boundary scars were formed by fires that burned between growing seasons, when the cambium was dormant, whereas earlywood and latewood scars were formed by fires that burned during the growing season. The boxes enclose the 25th to 75th percentiles of the distribution. The whiskers enclose the 10th to 90th percentiles and the horizontal line across each box indicates the 50th percentile. Circles mark all values lying outside the 10th to 90th percentiles.

by more than one tree, with an average of 5 trees recording a fire per site (range: 1–23).

At some sites surface fire regimes changed abruptly in the late nineteenth to midtwentieth century, with sites near one another generally experiencing syn-

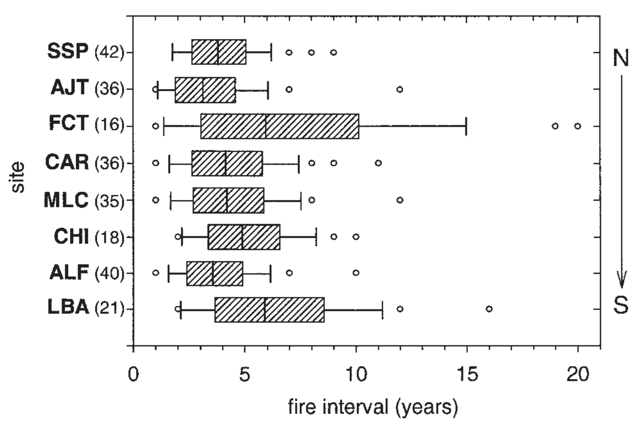

Figure 7.5. Composite fire intervals by site, with the number of intervals in parentheses. The box-and-whisker sets are as defined for Figure 7.4, but mark the percentiles of Weibull distributions fit to the composite fire intervals at each site, for the analysis periods indicated in Table 7.2. Trees were sampled over 2 to 6 ha per site (Table 7.1).

chronous changes. Specifically, fires nearly ceased after the late 1800s at AJT and after about 1950 at SSP, CAR, MLC, and LBA (Fig. 7.3). In contrast, surface fires remained frequent until the time of sampling at CHI and ALF. The abrupt cessation of fire at some sites is not likely an artifact of sampling dead trees, and hence low twentieth-century sample size, because an average of 14 trees (range: 7–20) had a record extending into the late twentieth century at each site. Fires may have been frequent at FCT before about 1950, as they were at nearby AJT. However, the record at FCT is less than 150 years for most trees, which is too short to determine if the fire regime changed at this site around 100 years ago, as it did at AJT.

Drivers of Temporal Variation in Historical Fire Regimes

Annual variation in climate was a strong driver of surface fires in the Sierra Madre Occidental. Not surprisingly, fires were widespread in years with significantly dry winters and early summers, but did not burn during significantly wet years (Fig. 7.6a, b). Consistent with these results, fires were widespread during years of significantly high SOI (Fig. 7.6c), which tend to be La Niña years and have dry winters. In contrast, variation in SOI was not significantly associated with non-fire years.

Climate in preceding years was also an important driver of surface fires in our study area. Specifically, fires were widespread following several years with wet

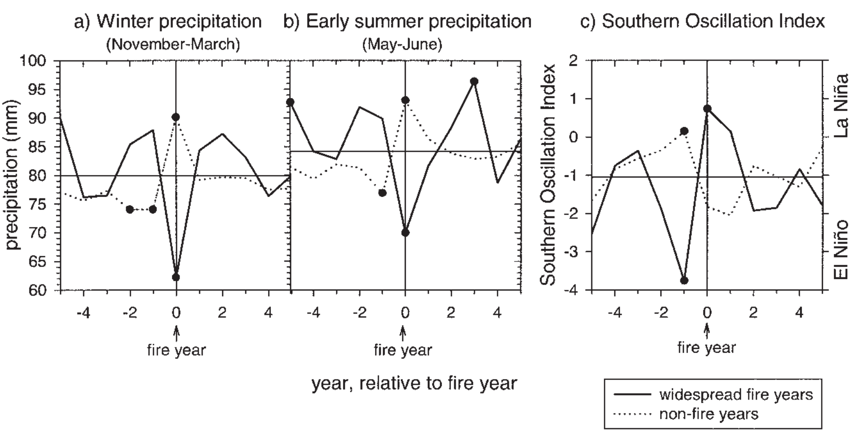

Figure 7.6. Annual association of fire and climate. Average departure from climate during widespread fire years (31 years, >50% of sites recording fire) and non-fire years (68 years, no sites recording fire), and for years immediately before and after these years. Solid dots mark departures that fall outside the 95% confidence interval, determined by bootstrapping. The horizontal lines indicate average precipitation or SOI for the analysis period (1772–1977).

winters and early summers (although not significantly wet), while fires did not burn following 1 to 2 significantly dry years (Fig. 7.6a, b). Consistent with these results, fires were widespread following a year with significantly low SOI (Fig. 7.6c), which tend to be El Niño years and have wet winters. This association is reversed for non-fire years, which followed a year of significantly high SOI (La Niña years).

Surface fires over a broader area were similarly driven by climate. When we repeated the SEA analyses including four additional existing fire history reconstructions from Durango (Fulé and Covington 1997), we found nearly identical patterns of significant climate departures for both widespread and non-fire years.

In addition to varying at annual time scales, the occurrence of widespread fires varied at decadal time scales, sometimes due to variation in the synchrony of fires among sites but sometimes to a lack of fire (Fig. 7.7). Compared to the period from the late 1700s to about 1930, fires were somewhat less synchronous among sites for brief periods around 1810 and 1910. However, the decrease in synchrony around 1810 could be due to low sample size because few of the sampled trees have a record before this time. The occurrence of widespread fires declined sharply beginning around 1930, due to an abrupt cessation of fires at some sites (Fig. 7.3). This abrupt decline was synchronous with the beginning of extensive distribution of *ejido* lands in Mexico.

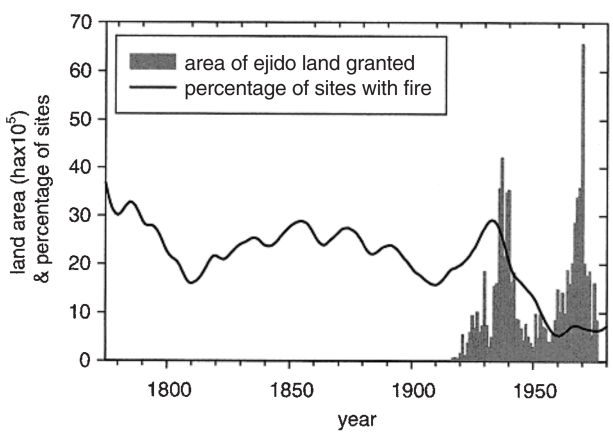

Figure 7.7. Decadal variation in the occurrence of synchronous fires, compared to changes in land tenure in Mexico. The percentage of sites recording fire per year was determined from the combined composite records of fire occurrence for the analysis periods identified for each site in Table 7.2, smoothed using cubic splines with a 50% frequency cutoff at 20 years. Land tenure is the amount of land distributed to *ejidos* (Sanderson 1984).

Discussion

Fire Regimes

Based on our sample of trees, composite surface fire intervals were remarkably similar across the study area, despite topographic variation among the sites (Fig. 7.5, Table 7.1). Topographically driven variation in solar insolation was an important driver of spatial variation in historical surface fire regimes farther north (e.g., Taylor and Skinner 1998; Heyerdahl, Brubaker, and Agee 2001). However, differences in solar energy input to steep slopes of different aspect are not as great in Mexico as they are at higher latitudes (Holland and Steyn 1975) and so may not drive differences in fire frequency as they do farther north. Furthermore the frequency of fire at these sites may not be driven only by the topographic characteristics of the sampled area but may also depend on the frequency of fire in surrounding areas because our sites are not surrounded by fire breaks (Agee, Finney, and de Gouvenain 1990; Bergeron 1991; Heyerdahl, Brubaker, and Agee 2001). We do not have a clear explanation for the long and variable intervals that we found at FCT and LBA, relative to the other sites. The record at FCT may entirely postdate a change in fire intervals because this site is near AJT. Fires at AJT nearly ceased in the late 1800s and major changes in fire regimes are generally synchronous among sites that are near one another. However, we compare fire intervals among our sites cautiously because these sites were not selected to capture spatial variation in fire frequency. Rather, we selected sites and trees that we expected to yield relatively long records of surface fires in order to explore the role of climate in driving widespread fires. Consequently we may not have captured the full range of variability in fire frequency across the landscape (Baker and Ehle 2001; Lertzman, Fall, and Dorner 1998). Furthermore the fire intervals we report may be affected by the small differences in area over which they were composited (2–6 ha; Table 7.1; Arno and Petersen 1983; Baker and Ehle 2001).

The intervals we report probably include fires of different sizes, although we did not reconstruct this parameter of fire regimes. The number of scarred trees per fire at our sites yields little information about the size of those fires because we sampled trees over relatively small areas (2–6 ha). Most fires were recorded by at least several trees at a site (average of 73% of fire years per site recorded by ≥3 trees). However, even fires recorded by a single tree may be extensive because our sites are not surrounded by fire breaks so that fires may have spread into them from surrounding areas.

Most of the fires we reconstructed probably burned in the spring, before the onset of the monsoon rains that wet litter fuel and encourage new growth of grasses and herbs. This is consistent with the seasonality of most modern fires in the Sierra Madre Occidental which burn during the dry spring when lightning is most common (Mosiño Alemán and García 1974; Hales 1974; Turman and Edgar 1982; Douglas et al. 1993; SEMARNAP 2000), and with written reports of spring burning by indigenous people (Sheridan and Naylor 1978; Graham 1994). Most fire years with ring-boundary scars on some trees also had scars in the first third of the earlywood on other trees (62%), consistent our assumption that most fires burned early in the year, when some of the trees had begun growing. Likewise, no fire years had ring-boundary scars on some trees and latewood scars on others, suggesting that few fires burned late in the year. However, some fall or winter fires may have burned in our study area because some fire years (24%) had only ring-boundary scars. Consequently we cannot determine whether these fires burned during the fall, after growth ceased, or during the following spring, before growth began again. Although lightning is not as common in the fall and winter as in the summer, humans could have ignited fires in these forests during the brief fall dry season.

Historically surface fires in our study area, and at sites elsewhere in Durango (Fulé and Covington 1997, 1999) probably burned earlier in the year than surfaces fires in the Mexico/U.S. borderlands. Most historical fires in our study area burned during the season of cambial dormancy whereas in the borderlands, they burned during the cambial growing season (Swetnam, Baisan, and Kaib 2001). Based on the few existing studies of cambial phenology, fires in the borderlands burned during the warm spring dry period (April–June) consistent with the seasonality of lightning and modern fires in that region (Baisan and Swetnam 1990; Swetnam, Baisan, and Kaib 2001). We know of no studies of cambial phenology in the pine-oak forests of the Sierra Madre Occidental, but the early spring seasonality we inferred from fire scars for this region is also consistent with the seasonality of modern precipitation, lightning, and fires. However, these differences in the intra-ring position of fire scars could result from differences in cambial phenology between the two regions, rather than from a difference in the season of burning.

Climate Was a Strong Driver of Surface Fire Regimes

Current year's climate synchronized the occurrence of widespread surface fires among our sites in the Sierra Madre Occidental, probably by affecting fuel moisture and perhaps by affecting fuel amount (Fig. 7.6). In this region, where winters are relatively dry and cold, fires burn primarily in the spring, before the flush of live surface fuels and the onset of monsoon rains in early summer which wet surface fuels and inhibit fire ignition and spread. Winter precipitation probably affects fire by influencing soil moisture and hence the growth of live surface fuels. Consequently, after dry winters, the spring flush of grasses and herbs may be delayed, lengthening the fire season and increasing the likelihood of widespread fires in this region. The opposite may occur after wet winters, when high soil moisture leads to an early spring flush and a relatively short fire season. Winter precipitation probably does not affect the moisture content of fine fuels during the subsequent fire season because any increased moisture will evaporate quickly with warm, dry weather. However, the onset of monsoon rain in early summer can affect fine fuel moisture at the beginning of the fire season. During years when the onset of the monsoon rains was delayed (i.e., years with low early summer precipitation), fine fuels remained dry. As a result the fire season was relatively long and the probability of synchronous fires was greater than during years when the monsoon rains began early. These relationships are consistent with the effect of precipitation on fire regimes in monsoonal climates elsewhere (Swetnam and Baisan, Chapter 6, this volume).

The current year associations we found between surface fire and ENSO are generally consistent with those we found between fire and precipitation, because these two measures of climate are strongly associated in the study area. In the Sierra Madre Occidental, dry La Niña winters may have resulted in a delay in the spring flush of grasses and herbs and hence a relatively long fire season, increasing the probability of widespread fires, as described above. Historical ENSO activity also affected the length of the fire season elsewhere in North America (Heyerdahl, Brubaker, and Agee, in press). We would expect wet El Niño winters to have the opposite effect, suppressing widespread fire activity, as they do in the American Southwest (Swetnam and Betancourt 1990). However, El Niño years were not significantly associated with non-fire years, perhaps because the effect of ENSO on weather, and hence fire, varies from one event to the next (Enfield 1992; Allen 2000; Kitzberger, Swetnam, and Veblen 2001). Specifically, in the Sierra Madre Occidental, ENSO activity sometimes affects winter temperature as well as winter precipitation. For example, the El Niño winters of 1982–1983 and 1997–1998 were very cold as well as wet in northern Mexico (SEMARNAP 2000). Consequently heavy snow broke tree limbs and tops, increasing fuel loads so that extensive areas burned when these fuels dried in the spring (Alvarado 1984). We do not know how common these cold El Niño winters were historically, because there are no reconstructions of winter temperature for this region. However, the occurrence of some cold El Niño winters would explain why fire activity is not strongly suppressed during El Niño years when viewed over several centuries in our study area.

Prior year's climate also strongly synchronized the occurrence of widespread surface fires among our sites in the Sierra Madre Occidental, probably by affecting fuel amount, rather then fuel moisture. The growth of grasses and herbs was probably enhanced during wet years, increasing the amount of fine-fuel available to carry surface fires in subsequent dry years. This enhanced growth may also have increased fuel continuity so that fires spread more effectively, similar to the effect of wet years on fine-fuel production inferred for dry pine forests elsewhere (Swetnam and Baisan 1996; Baisan and Swetnam 1997; Swetnam and Betancourt 1998; Veblen, Kitzberger, and Donnegan 2000). In contrast, these fine live fuels were probably reduced during prior dry years. Specifically, dry winters may have delayed or inhibited the spring flush of grasses and herbs, especially given the poor moisture retention of the coarse soils at our sites. Fires during dry prior years probably also consumed these fuels, further limiting the amount of fine fuel available to carry fire in subsequent years (Swetnam and Betancourt 1998).

The prior year associations we found between surface fire and ENSO are generally consistent with those we found between fire and precipitation. At our sites, fires were widespread in years following wet El Niño years but did not burn in years following dry La Niña years, consistent with the effect of precipitation on the growth and consumption of fine live fuels, discussed above. ENSO varies with a period of two to five years (Enfield 1992; Stahle 1998), so the association we found between widespread fire and prior year's ENSO activity is probably not an artifact of the intrinsic scale of variation in ENSO. Last, fires were widespread during La Niña years and following prior El Niño years. This switching from one atmospheric state to another is characteristic of the ENSO system (Kiladis and Diaz 1989), and it drives widely synchronous fires elsewhere in North and South America (Swetnam and Betancourt 1998; Kitzberger, Swetnam, and Veblen 2001).

Land-Use Change Caused Recent Cessation of Surface Fires

The recent abrupt cessation of surface fires at some of our sites likely resulted from a complex mix of local changes in land use rather than from regional variation in climate, since fires did not cease synchronously at all sites (Fig. 7.3). Fire at individual sites can be dramatically impacted by grazing, fire use or suppression, timber harvesting, and the construction of roads and railways (e.g., Leopold 1937; Dieterich 1983; Savage and Swetnam 1990; Baisan and Swetnam 1997; Fulé and Covington 1997, 1999; Kaib 1998; Veblen et al. 1999; Veblen, Kitzberger, and Donnegan 2000; Heyerdahl, Brubaker, and Agee, in press). However, local variation in the intensity of these activities can impact fire regimes differently among sites, particularly for small, widely dispersed sites such as those we sampled. We lack local land-use histories for our sites but speculate that the differences in timing of fire exclusion among them probably resulted from differences in the type and timing of changes in land use.

Mid-twentieth-century changes in Mexican land tenure probably resulted in local increases in human occupation of the high-elevation pine-oak forests at some of our sites (Fulé and Covington 1997). There is little quantitative information on human use of the remote and rugged Sierra Madre Occidental before the twentieth century. However, before 1900 these mountains were sparsely populated by indigenous people, such as the Tarahumara, Tepehuano, Mayo, and Yaqui, who occupied the lower valleys and deep canyons in winter and the upper mountains in summer. They practiced slash-and-burn agriculture and used fire for hunting and religious purposes (Bye 1976; Sheridan and Naylor 1978; Graham 1994). There is little evidence that the high-elevation pine-oak forests of this region were densely occupied until the mid-twentieth century, in response to reform in the land tenure system in Mexico (Sanderson 1984; Thompson and Wilson 1994). In the early 1900s, shortly after the Mexican Revolution, new legislation (Agrarian Law 1915; Mexican Constitution 1917) legalized the *ejido* system, the reallocation of land to small communities of landless people. Despite this legalization not much land was actually distributed until the administration of Lazaro Cárdenas (1934–1940) when nearly 800,000 people in Mexico received land grants of about 20 million hectares (Sanderson 1984; Thompson and Wilson 1994). The distribution of *ejido* lands brought a wave of people from low-elevation agricultural areas to settle the forested mountains, resulting in a change from traditional land use. Today all but one of our sites are owned by *ejidos* (Table 7.1).

The movement of people to forest *ejidos* in the Sierra Madre Occidental in the mid-1900s may have affected fire regimes by introducing, or intensifying, cattle grazing, road building, or logging (Fulé and Covington 1997; Kaib 1998), and perhaps by changing traditional uses of fire. We speculate that some or all of these changes in land use may have caused the mid-1900s cessation of fire at four of our sites (SSP, CAR, MLC, and LBA). Cattle were introduced to southern Mexico in the early 1500s and rapidly spread north (Rouse 1977; Jordan 1993). However, while cattle grazed on the lower slopes of the Sierra Madre Occidental (Leopold 1937), they were probably not grazed in great numbers in the high elevations of our sampling sites until the major distribution of *ejido* land in the mid-1900s. The introduction of livestock grazing may have resulted in fire exclusion at some of our sites at this time, as it has elsewhere in Mexico and the American Southwest, by reducing both the amount and continuity of the fine fuel that carries surface fires in these forests (Baisan and Swetnam 1997; Leopold 1924, 1937; Madany and West 1983; Savage and Swetnam 1990; Grissino-Mayer and Swetnam 1997; Kaib 1998; Mast, Veblen, and Linhart 1998; Fulé and Covington 1999; Swetnam, Baisan, and Kaib 2001). Grazing may not be the only cause of change in fire regimes at this time. Roads and trails built to access *ejido* lands, and harvest timber can interrupt fuel continuity and may have reduced the number of fires that spread into our sites. Changes in human use of fire may also have contributed to the exclusion of fire in the mid-1900s at some of our sites. We have little quantitative information on the use of fire by indigenous people, but the occupation of *ejido* lands probably curtailed their ignition of fire. This may have contributed to the decline in fire if these ignitions were an important cause of the fires we reconstructed at our sites. Twentieth-century fire suppression is not a likely cause of the changes we reconstructed in fire regimes because fire-fighting resources were limited during this time (Leopold 1937; Dieterich 1983; González-Cabán and Sandberg 1989; Fulé and Covington 1999; Kaib 1998).

We speculate that the abrupt cessation of fire at some of our sites (AJT and perhaps FCT) in the late 1800s could have been caused by a dramatic increase in travel routes, decades before the major distribution of *ejido* lands. The Sierra Madre Occidental is a high and rugged mountain range (200–3000 m) over which few easy travel routes exist (Jordon 1993). Consequently few roads crossed it in the early twentieth century (Leopold 1937). In Mexico, a few kilometers of railroad were constructed in the nineteenth century, but the major construction of rail lines, including those from southern Mexico northward into the central highlands, began in 1880 (Coatsworth 1981). In that year, there were 770 km of railroad but this had expanded to 24,700 km by 1911 (Powell 1921). These roads may have allowed access to parts of the Sierra Madre Occidental, resulting in changes in land use that affected fire regimes. For example, silver mines near AJT and FCT may have been established at this time and resulted in timber harvesting, leading to a decrease in surface fires.

We speculate that frequent surface fires continued to burn into the late 1990s at two sites (CHI and ALF) because they were relatively inaccessible and ignition of fires remained frequent. ALF is a rocky ridge that may have been a poor site for grazing or a difficult area for road building and timber harvesting. At CHI, most of the trees are young. Perhaps this forest regenerated after logging or a stand-replacing fire in the mid-1800s and may not have been suitable for harvesting or grazing during the time of major *ejido* land distribution in the mid-1900s.

Conclusion

Our objective was to infer the drivers of temporal variation in fire regimes in pine-oak forests of the Sierra Madre Occidental in north-central Mexico. We reconstructed a multicentury history (1772–1994) of the occurrence of surface fires from 1469 fire scars on 180 trees sampled at 8 sites over nearly 700 km in the states of Durango and Chihuahua. We compared our fire histories to existing tree-ring reconstructions of winter and early summer precipitation and the Southern Oscillation Index. Fire intervals were similar among our sites, with Weibull median fire intervals of 3 to 6 years. Most fires probably burned in the warm, dry spring, based on the intra-ring position of fire scars (98% formed during the season of radial dormancy or early in the growing season) and the seasonality of precipitation, lightning, and modern fires in this region. However, some fall or winter fires may have occurred. Annual variation in precipitation and El Niño–Southern Oscillation were strong drivers of current year's fire, probably through their effects on fuel moisture. Extensive fires generally burned during dry years but not during wet ones. Extensive fires also typically burned during La Niña years, which tend to have dry winters in this region. Climate in prior years was also a strong driver of fire, through its effect on fuel amount. Widespread fires often burned following one to two wet years and also following El Niño years, which tend to have wet winters in this region. Likewise fires were not widespread following dry years and following La Niña years. Prior year's climate probably affected the growth of grass and herbaceous fuel. Changes in land use, rather than climate, probably caused the near cessation of fire that we reconstructed at some sites because these shifts did not occur synchronously (some ca.1900, some ca.1950). Frequent surface fires continued to burn until the time of sampling at two of our sites.

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