

Spatial and temporal variability in fire occurrence within the Las Bayas Forestry Reserve, Durango, Mexico

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Abstract Patterns of fire occurrence within the Las Bayas Forestry Reserve, Mexico are analyzed in relation to variability in climate, topography, and human land-use. Significantly more fires with shorter fire return intervals occurred from 1900 to 1950 than from 1950 to 2001. However, the frequency of widespread fire years (25% filter) was unchanged over time, as widespread fires were synchronized by climatic extremes. Widespread fire years occurred during dry years that lagged wet years. Widespread fire years lagged the negative El Niño phase (wet winters) of the Southern Oscillation by 1 year, but were not synchronized by the positive, La Niña phase (dry winters) of the Southern Oscillation. The smaller, localized fires that occurred more frequently during the first half of the 20th century were attributed to changes in land tenure with the introduction of the *ejido* system in the early 1950s. *Ejido* management strategies lowered fire frequencies by suppressing fires and reducing anthropogenic fires.

There were likely more ignitions prior to the arrival of the *ejido* system as fires were ignited by lightning and indigenous people. As the movement of indigenous peoples across the landscape has been restricted by changes in land tenure, numbers of human-ignited fires subsequently decreased post 1950. After 1950, fires occurred less frequently, were more synchronized, and more restricted to years of extreme climate.

Keywords Mexico · Fire · Climate variability · Land-use changes · Forest ecology · Disturbance

Introduction

Fire is a common disturbance regulating species composition, forest structure, and regeneration potential in many xeric conifer forest types such as the long-needled pine ecosystems of western North America (Weaver 1951; Cooper 1960; Agee 1998). Fire occurrence and severity have been shown to be highly variable throughout these xeric conifer ecosystems as they are controlled by environmental processes that vary over space and time (Kaufmann et al. 2000; Ehle and Baker 2003; Sherriff and Veblen 2006). Three recent fire history studies in the Mexican state of Durango describe temporal and spatial variability in fire regimes within the mixed pine–oak region of Mexico’s Sierra Madre

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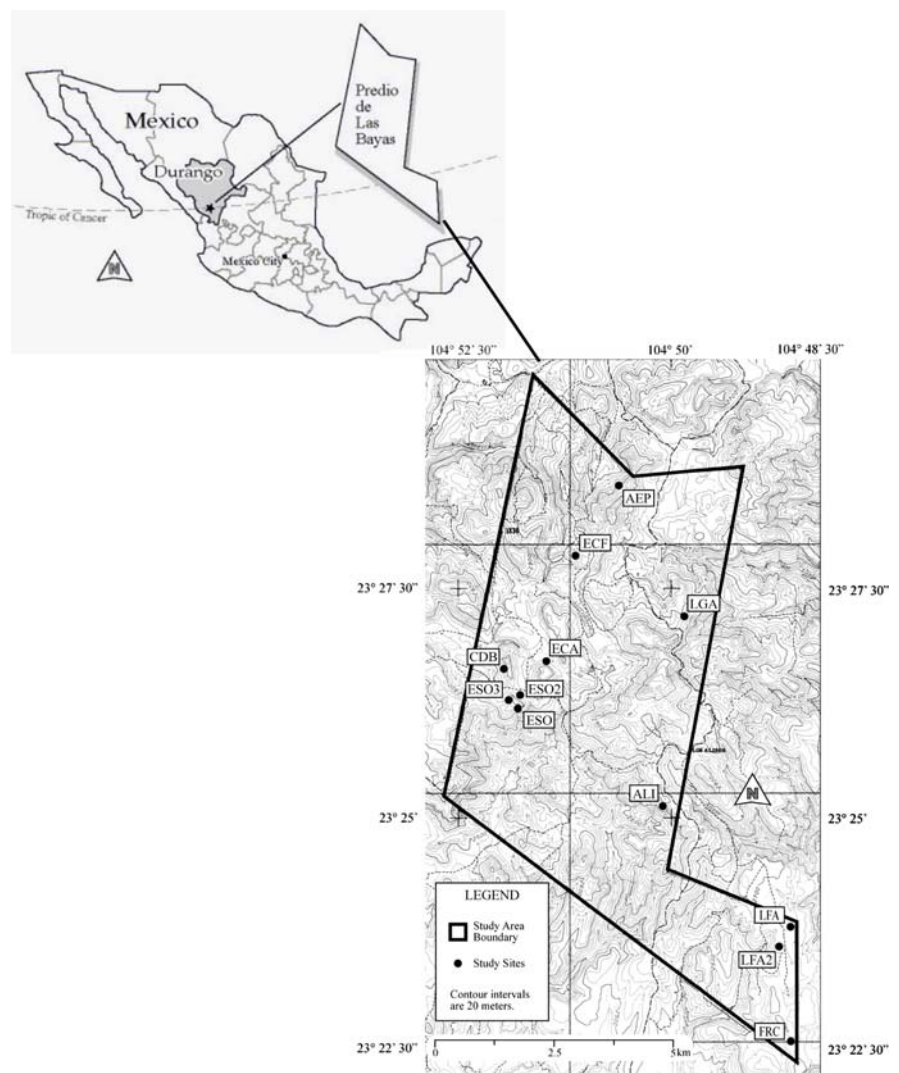
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Occidental (Fulé and Covington 1997, 1999; Heyerdahl and Alvarado 2003), yet a clear understanding of the local and regional influences on fire regimes in these forests remains elusive. Moreover, the influence of topography and habitat type on fire history and fire–climate relationships has not been systematically investigated. Thus the main objective of the current study is to elucidate the primary drivers of fire occurrence in Mexican pine–oak forests in the Las Bayas Forestry Reserve, Durango, Mexico (Fig. 1).

Our objectives are: (1) to describe the fire regime in Sierra Madreal pine–oak ecosystems within the Las Bayas Forestry Reserve and (2) to assess how climate variation, changes in land-use practices,

habitat type, and topographic position influence the fire regime. A thorough understanding of how fires occurred over time in these landscapes is necessary for land managers to make more informed land management decisions (Landres et al. 1999). Specifically, we address the following questions for the Las Bayas region: How does variation in climate influence fire occurrence and fire severity? Is the occurrence and severity of fires influenced more by the top down influence of regional climate or by the bottom up influence of topography and vegetation on microclimate? And, is there a link between changes in land-use practices and temporal and spatial patterns of fire occurrence?

Fig. 1 Locations of sample sites in the Las Bayas Forestry Reserve (Predio de Las Bayas), Mexico



Background

Fire and fire regime variability are thought to play important roles in maintaining the high diversity characteristic of Madrean pine–oak forest ecosystems in Durango (Bye 1995; Felger and Johnson 1995; Fulé and Covington 1997, 1999; Heyerdahl and Alvarado 2003). Fire in many xeric conifer ecosystems has been shown to be related to inter-annual to multi-decadal variation in climate (Swetnam and Baisan 1996; Swetnam and Betancourt 2000; Veblen et al. 2000; Heyerdahl et al. 2002; Heyerdahl and Alvarado 2003). A common pattern is that fires occur in dry years that follow wet years in association with El Niño–La Niña events (Grissino-Mayer and Swetnam 2000; Swetnam and Betancourt 2000; Heyerdahl and Alvarado 2003). Regionally widespread fires tend to occur during drier La Niña events (years) that follow wet El Niño events (years). Presumably the wetter El Niño years promote the growth of fine, herbaceous fuels, but are unfavorable for the ignition and spread of fires. During the drier La Niña years, fine fuels dry and the occurrence and spread of fires is favored by low moisture conditions.

Climate variability in the Sierra Madre Occidental and the Las Bayas Forestry Reserve

Climate in the Sierra Madre Occidental is seasonal with mild, dry winters and wet, warm summers (Douglas et al. 1993; Metcalfe et al. 2000). Much of the annual precipitation occurs during the summer months starting in late May to early June and ending in September or October depending on the year (Douglas et al. 1993; Metcalfe et al. 2000; Fig. 2). Annual climate variability tends to be associated with the ENSO phenomenon. El Niño years tend to be wetter than normal while La Niña years tend to be drier than normal (Ropelewski and Halpert 1986; Kiladis and Diaz 1989; Cavazos and Hastenrath 1990).

Multi-year droughts and multi-year periods of above average precipitation also appear to be part of the historical range of variability for northern Mexico (Diaz et al. 2002; González-Elizondo et al. 2005; Fig. 3). Multi-year droughts have been identified from tree-ring climate reconstructions for Baja California (1939–1958; Diaz et al. 2001), for Durango

(1540–1579, 1857–1872, 1950–1965; Stahle et al. 1999; Cleaveland et al. 2003), and for Chihuahua (1664–1677, 1751–1765, 1798–1810, 1948–1964; Diaz et al. 2002). A long period of drought from the late 1940s into the 1960s is reflected in many instrumental records for the state of Durango (Fig. 2).

In the state of Chihuahua, Diaz et al. (2002) noted several multi-year periods of above average precipitation during the 18th and 19th centuries, and from 1905–1932. Extended wet periods for the state of Durango have been identified by Cleaveland et al. (2003) and Stahle et al. (1999) between the years of 1477–1486 and from 1831 until 1857. These multi-annual to decadal fluctuations in precipitation may be related to the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO) as has been suggested for the southern Rocky Mountain region (Gray et al. 2003, 2004).

Previous fire history studies in Durango, Mexico

Heyerdahl and Alvarado (2003) related widespread fire occurrence prior to 1900 to climate in the northern Sierra Madre Occidental. Specifically, regionally widespread fire years tended to occur during dry La Niña events that followed wetter El Niño events. In contrast, Fulé and Covington (1999) suggested that fires in southern Durango were weakly related to the Southern Oscillation (SO), but widespread fires were not synchronized by climate as only one widespread fire year occurred during a positive SO (La Niña) in their study area.

Fire occurrence was also shown to vary spatially in some areas (Fulé and Covington 1999). In southern Durango, Fulé and Covington (1999) concluded that fire varied spatially in relation to elevation, slope gradients, and proximity to human habitation. On their higher elevation, mesic north-facing slopes, they speculated that fire occurrence was limited by humid weather conditions and/or infrequent fire ignitions. On their contrasting xeric sites they concluded that these areas were climatically dry enough to support a fire every year. However, fires were limited on these xeric sites by elevation, low slope gradients, and proximity to human settlement. In contrast, Heyerdahl and Alvarado (2003) found no relationship between fire regime and physical site differences. They speculated that due to the low latitudes of their

Fig. 2 Average monthly and annual precipitation records for El Salto and Ciudad Durango, Durango, Mexico. The heavy black lines in (c) and (d) are mean annual precipitation

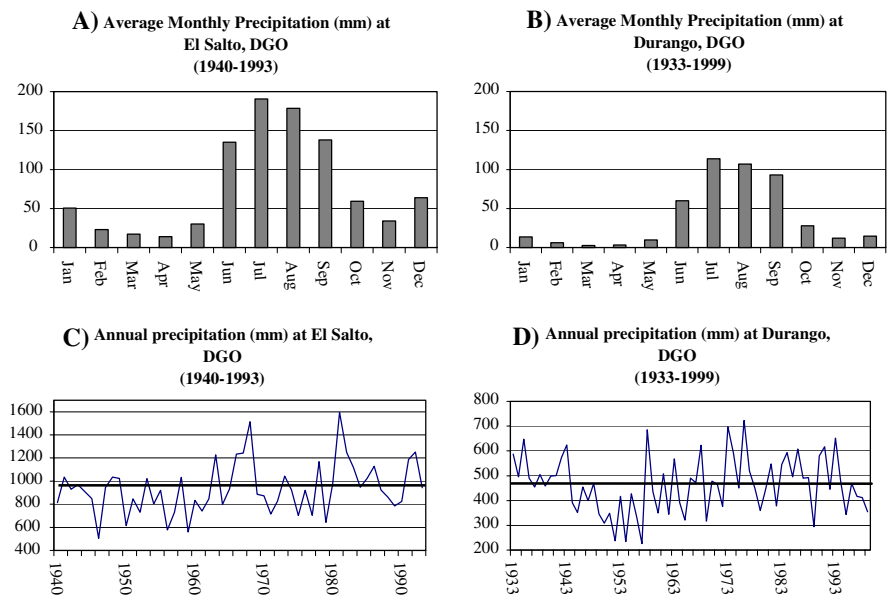
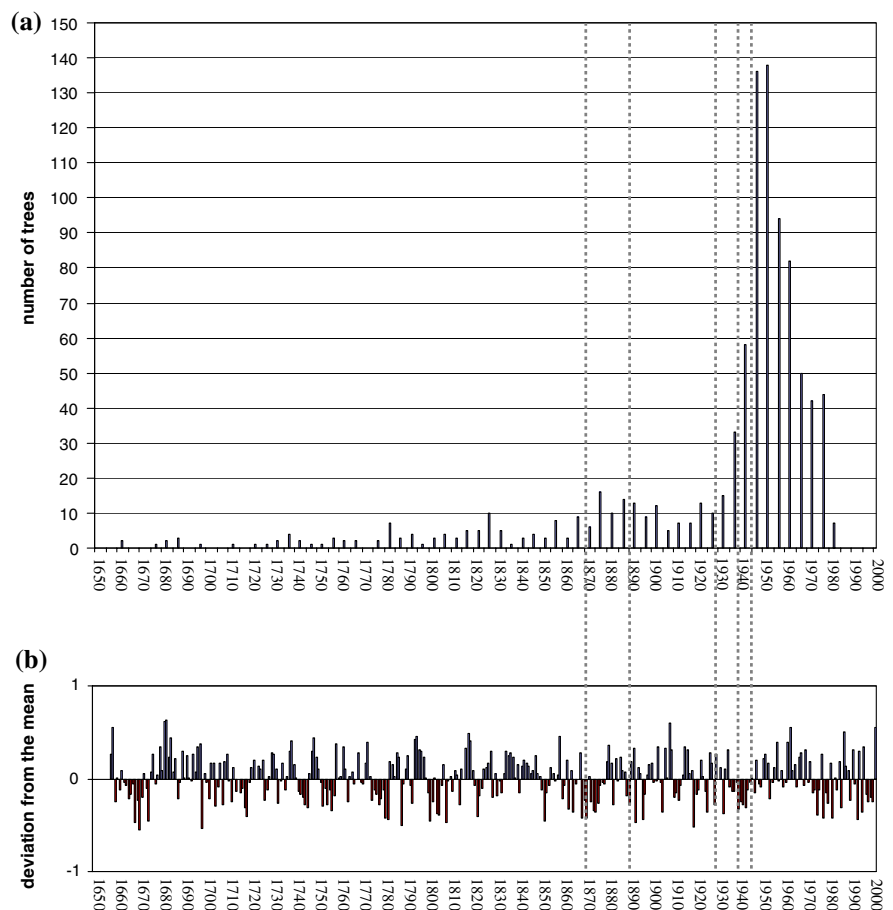


Fig. 3 (a) Numbers of conifers that established in 5-year periods from 1650 to 2000 within the Las Bayas Forestry Reserve. Vertical dashed lines indicate years classified as severe fire years (1871, 1890, 1928, 1938 and 1945—see Table 5 for list of all years identified as potentially severe fires on a study site by study site basis). (b) A climatically sensitive tree-ring chronology of *Pseudotsuga menziesii* from the Las Bayas Forestry Reserve (BAY, González-Elizondo et al. 2005) The y-axis data is percent deviation from the mean tree-ring index; positive deviations indicate greater moisture availability



sites, there was less difference in solar energy input among different slope aspects, and consequently the fuel moisture and microclimate conditions were similar on slopes with different aspects (Heyerdahl and Alvarado 2003). They also argued that topographic position may not be as important in the Sierra Madre Occidental as in more northerly areas due to the lack of fire breaks (roads, etc.). Consequently, when fires occur in areas where ignitions are common, the lack of firebreaks, the continuity of fuels, and fuel moisture similarities on slopes with different aspects enables the fire to spread from the ignition area throughout the surrounding landscape (Heyerdahl and Alvarado 2003).

In addition to climate, Fulé and Covington (1997, 1999) and Heyerdahl and Alvarado (2003) attributed some fire regime variability to changes in human land-use patterns. They attributed the abrupt cessation in fires in the 20th century that occurs in many areas throughout the Sierra Madre Occidental to changes in land access or land tenure patterns such as the establishment of community cooperative land-holdings after the Mexican Revolution (Fulé and Covington 1997, 1999; Heyerdahl and Alvarado 2003). Although the possibilities that humans could have significantly contributed to fire ignitions were addressed, these authors felt that due to the generally small indigenous population prior to *ejido* establishment, most fires during the pre-fire exclusion period were ignited by lightning.

Study area

Las Bayas Forestry Reserve

This study was conducted within the 5,000 ha Las Bayas Forestry Reserve in the Mexican state of Durango (Fig. 1) which has been owned and managed as a forestry Reserve by the University of Juarez Durango (UJED) since 1987. Lying within the Madrean pine–oak biogeographic province (Brown et al. 1995), the Reserve sustains a diverse forest vegetation that consists of multiple combinations of 6 species of *Pinus*, 8 *Quercus* species, 4 *Arbutus* species, *Pseudotsuga menziesii*, and 2 *Juniperus* species. Current forest structure is heavily influenced by harvesting and management activities under the direction of the UJED forest managers.

Methods

Individual fires were dated based on the tree rings of fire scars on live trees and dead trees (both snags and cut tree stumps; Arno and Sneek 1977; Dieterich 1980). Indices of fire history for each of 12 sample sites and for the Reserve were constructed from these fire dates. Since we wanted to address questions of how topographic variation, differences in vegetation type, land-use changes, and climatic variability influence fire occurrence, we selected sample sites based on topographic position and the presence or absence of fire. Areas that showed signs of human influences such as logging were not excluded from study. We did not restrict our study sites to mature forests but investigated fire occurrence within a range of stand ages and habitat types as most Mexican pine–oak forests are young due to extensive timber harvesting. All of our sites contained evidence of past harvesting events, although the extent of past logging was unknown due to the rapid decomposition rates in this region.

Sample sites were subjectively located to represent the full range of forest types and time since last fire (see below). There was no need to target areas of unusually abundant fire-scar evidence as fire-scarred trees were common regardless of topography, species composition, or stand structure. The ease of scarring of Madrean pine–oak species, and the large number of trees that survive scarring, reduced the problem of fires not being recorded.

Site selection

Twelve sample sites were located within the Las Bayas Forestry Reserve (Fig. 1). Six sample sites were located in areas that had burned within the last 10 years (Table 1): La Fortuna (LFA), El Solitario #1 (ESO), Arroyo El Pescador (AEP), Frenton Colorado (FRC), Los Alisos (ALI), and La Fortuna #2 (LFA 2). These six sample sites areas were further differentiated by topographic position: LFA, FRC, and LFA2 are located on a large broad mesa that lies within the southeast section of the Reserve (Fig. 1). ESO is a steep, exposed, south-facing slope in the mid-section of the Reserve, AEP is a steep, northwest-facing slope in the northwest section of the Reserve, and ALI is a very steep, exposed, southwest-facing slope in the midsection of the Reserve (Fig. 1).

The remaining six sample sites were located in areas that appeared to have not been influenced by fire within the past 20 years (Table 1): El Solitario #2 (ESO 2), Cordon de Burro (CDB), El Solitario #3 (ESO 3), El Cerro Fuera (ECF), La Grulla (LGA), and El Cerro Alto (ECA). These six sample sites occupied the following topographic positions: ESO #2 and ESO #3 are located on the northeast facing and the west-facing slopes respectively of the same hill in the mid-section of the Reserve (Fig. 1). ECA occupies a steep, north-facing slope near the ESO study sites while CDB is located on a steep, exposed south–southwest-facing slope on the western boundary of the Reserve (Fig. 1). The LGA and ECF sample sites occupy steep hillslopes in the northern section of the Reserve (Fig. 1). ECF is a cove-like southern exposure, while LGA is a steep, exposed, northeast-facing slope.

Fire-scar collection

Fire-scars were collected as evenly as possible within each 5 ha sample site (search area of uniform slope and cover type) by sampling on an 18 point-center plot grid set up to sample vegetation in a companion study (Drury 2006). A maximum of two live tree fire-scar samples and/or two dead tree fire-scar samples were collected at each point to avoid issues of data

clumping. A minimum of 15 fire-scar samples were collected within each sample site.

Fire-scar dating

Once fire-scarred trees or stumps were located in the field, a cross section was removed from each sampled tree using a chain saw as close to the tree base as possible. In addition, each fire-scar sample included the pith (innermost ring) when feasible. Some trees were sampled at higher positions based on scar location and the number of observable scars at different positions along the tree bole. Sample collection height was recorded for each fire-scar sample. Fire-scar samples were later transported to the lab, sanded with progressively finer grits of sandpaper until the individual cells could be seen using a dissecting microscope, and the individual annual ring growth increments (rings) were counted. Each fire-scarred section was visually cross-dated using the marker ring method (Stokes and Smiley 1968; Yamaguchi 1991). All fire-scarred sections that were dead when collected were cross-dated with a master tree ring chronology from the Las Bayas Forestry Reserve provided by Martha González-Elizondo (BAY; González-Elizondo et al. 2005) using the computer program COFECHA (Holmes 1986). Additionally, COFECHA was used to compare and test a subset of the live

Table 1 Characteristics of the 12 sample sites located within the Las Bayas Forestry Reserve

Study area	Transformed aspect ^a	Slope percent (%)	Canopy cover ^a (%)	Forest floor organic material depth (mm)	Time since last fire (year)
La Fortuna (LFA)	0.29	1	52	20	1
El Solitario 1 (ESO)	0.15	57	46	14	1
Arroyo El Pescador (AEP)	0.73	51	58	16	3
Frenton Colorado (FRC)	0.45	25	46	30	3
Los Alisos (ALI)	0.19	48	82	11	3
La Fortuna 2 (LFA2)	0.14	18	50	33	6
El Solitario 3 (ESO3)	0.26	52	41	47	22
El Cerro Alta (ECA)	1.56	53	34	54	23
Cordon de Burro (CDB)	0.08	58	59	33	27
El Cerro Fuera (ECF)	0.44	44	61	65	33
La Grulla (LGA)	1.2	43	43	35	34
El Solitario 2 (ESO2)	1.96	43	57	43	35

^a Cosine transformed aspect (Beers et al. 1966). Canopy cover is expressed as percent open sky. Canopy cover methodology is described in Drury (2006)

fire-scarred samples for accuracy with the master tree ring chronology. Since other disturbance events can also result in tree scars, fire years were identified and labeled as a year in which a fire occurred only if at least one of the scars on individual trees was clearly identifiable as a fire injury (Dieterich and Swetnam 1984). In addition to fire year, the season of burning was assigned to each dated fire scar whenever possible (Dieterich and Swetnam 1984; Baisan and Swetnam 1990). Fires were classified as spring fires (fire-scar tip located in the early wood section of the annual ring), summer fires (fire-scar tip located later in the early wood), late summer or fall fires (fire-scar tip located in the late wood). Fire-scar tips that were found in the boundary between annual rings were conservatively assigned to early spring of the following year.

Tree cohorts

Stand ages for conifer species (*Pinus* spp. and *Pseudotsuga menziesii*) within the study area were determined using a combination of increment cores, tree ages from fire-scarred sections that included the pith, and complete bole cross sections from dead trees and stumps within each five hectare sample site. Increment cores were not collected from angiosperms within the area due to indistinct growth ring boundaries that prevented reliable age determination. Increment cores were also collected from conifer saplings (≥ 2 cm at the base) to capture the range of conifer tree sizes and conifer tree ages within a sample site. All samples tree age samples were processed following the procedures described earlier for fire-scar sections. For samples that missed the pith, Duncan's geometric method of conifer tree growth was used to estimate the number of rings (years) missed (Duncan 1989). Samples that missed the innermost ring by more than 20 years were excluded from analysis. Each tree was cored at the lowest possible position on the tree to collect the maximum number of rings and the coring height was measured and recorded. Linear regressions were developed to calculate estimates of tree age at coring height by destructively sampling conifer seedlings within the Reserve (Drury 2006). The calculated tree ages at coring height were used to adjust the tree establishment age for each conifer tree back in time to provide a closer estimate of the actual date of tree establishment. Individual tree

establishment dates were later compiled into 5-year age classes and displayed graphically to identify successful seedling establishment.

Fire and climate relationships

The computer program FHX2 (Grissino-Mayer 1995) was used to produce composite fire history charts for each area. We used the Superposed Epoch Analysis (SEA; Baisan and Swetnam 1990) module within FHX2 and the BAY tree-ring chronology compiled by González-Elizondo et al. (2005) to test the null hypothesis that there were no significant differences in climate between fire-event years and non-fire years (Grissino-Mayer and Swetnam 2000). This chronology was significantly correlated with regional climate using instrumental meteorological records showing that tree ring growth patterns indicate climate variability, particularly moisture availability (González-Elizondo et al. 2005). Average climate conditions during widespread fire years (fires that scarred trees in at least 25% of the sample sites) were compared with the average climate for 5 years before fire and 4 years after the fire year (-5 , $+4$). SEA was also used to test for relationships between years of widespread fire and the Southern Oscillation Index (SOI). We used Stahle et al.'s (1998) reconstruction of winter (December–January) SOI, which is based on a regional tree-ring dataset from Mexico and Oklahoma. Variation in the tree-ring chronology accounts for 41% of the variability in winter SOI from 1900 to 1977.

Temporal differences in fire occurrence

We used FHX2 to calculate composite mean fire return intervals (MFI) and the Weibull Median Probability Intervals (WMPI) and to test for changes in these time intervals over time for each sample site and the entire Reserve using the student's *t*-test (Grissino-Mayer 1995). MFIs tend to be positively skewed due to a lower limit for the minimum fire return interval of 1 year and no upper limit for the maximum fire return interval (Grissino-Mayer 1995). The WMPI is viewed as an unbiased measure of the central tendency as it is associated with the 50% exceedance probability: half the fire intervals will be shorter than the WMPI and half will be longer (Johnson and Van Wagner 1985).

Two time periods were analyzed for potential differences in fire occurrence over the entire 1750–2001 time period using FHX2. The three time periods were subjectively determined based on the length of the fire record, the sample depth between time periods, and temporal changes in land use for the area (introduction of the *ejido* system of land management). Initially, the study period was divided into two halves (1750–1874, 1875–2001) to identify potential differences in fire occurrence over the length of the study. Later, the time span from 1900 to 2001 was divided into two halves which corresponded with the introduction of the *ejido* system in the early 1950s. Although the Las Bayas Forestry Reserve proper was never under *ejido* land ownership, the surrounding *ejidos* and community land tenure organizations were formed at this time. In addition, this time period was chosen because the number of sample sites recording fires and number of trees recording fires were relatively low prior to 1900.

Fire variation by habitat type

Fire occurrence from 1750 to 2001 was also compared by habitat type using the same procedures described above for the entire dataset. Habitat types were identified by Drury (2006). Mean fire-return intervals were compared among habitat types using the Students *t*-test (Grissino-Mayer 1995).

Severe fires

Indicators of fire extent, damage to individual trees, tree mortality, and post-fire tree establishment were used to assess the potential severity of past fires (Kaufmann et al. 2000; Ehle and Baker 2003; Sherriff and Veblen 2006). In the current study, “severe fires” are defined as fires that killed large numbers of canopy trees in contrast to low-severity fires that kill only juvenile trees. Assessment of past fire severity cannot be based on fire-scars alone, and instead requires a congruence of multiple lines of evidence of past fire effects on individual trees and stand structure (Baker et al. 2007). Due to disappearance of evidence of the ecological effects of past fire, no single criterion suffices to identify past fire severity and instead we used a combination of criteria. One indication of a

widespread and potentially severe fire was when a majority of recorder trees recorded a fire event. Alone, this criterion does not identify all high-severity fires but it eliminates events that did not spread to a large area. Presence of dead trees that died at the time of the fire was a strong indicator of fire severity, but due to decay could only be applied to more recent fires. If a high percentage of a tree bole was injured by the fire, it was assumed that the fire was more intense than fires that resulted in less damage to the tree. If many trees showed a high degree of bole damage in a particular event, it was interpreted as an indicator of a more severe fire. Identification of post-fire cohorts within a 20-year period after the fire-scar date (i.e., allowing for uncertainties in the determination of germination dates and lags in establishment following a fire) was a critical criterion in identifying severe fire events. Thus, we compared the percentage of tree establishments in the 20 years following a fire to the percentage in the 20 years pre-dating the fire. This procedure clearly identified major pulses of post-fire establishment (e.g., 80 to over 90% of trees in the 40-year window established in the 20 years following the fire). However, if two fires occurred in an interval of <40 years, the overlap of post-fire cohorts resulted in smaller percentages of tree establishment linked to the second fire event.

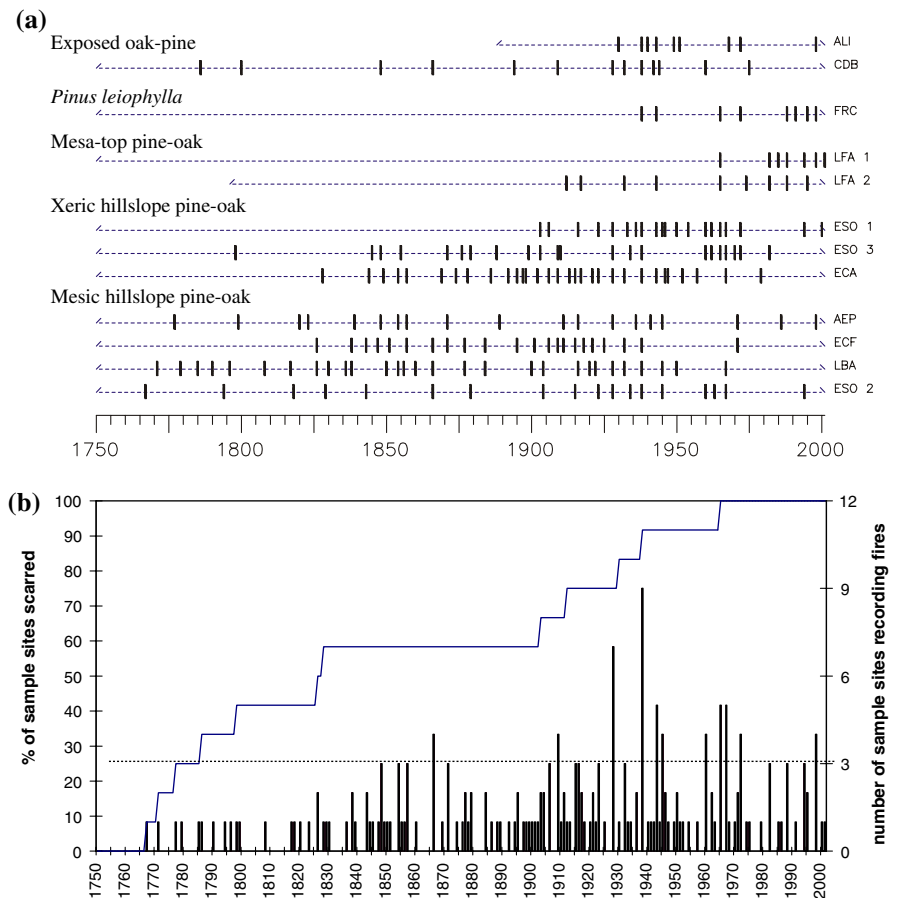
In our study as well as others in similar pine-dominated ecosystems (Kaufmann et al. 2000; Sherriff and Veblen 2006), the most useful indicator that past fires were relatively severe was age structure—e.g., evidence that many shade-intolerant trees established soon after the opening of the canopy caused by the fire. When these multiple lines of evidence converged, a fire was defined as potentially severe. However, the designation of a fire event as severe is made cautiously because individually each line of evidence can be the result of causes unrelated to the overall intensity of fire.

Results

Composite fire histories

Fires were common within the Las Bayas Forestry Reserve over the 250-year time span of this study (Fig. 4). Most fires occurred during the early growing season as spring fires. However, fire occurrence was

Fig. 4 Composite fire records for the 12 fire history sample sites (a) and percentage of sample sites recording fires in individual years from 1750 to 2001 (b) Vertical lines in (a) are years in which a minimum of two trees recorded fire in the site. In (b) the solid horizontal line is the sample depth (i.e., number of sites recording fire prior to that date); the dotted line indicates the 25% filter used to identify widespread fire (minimum 3 of 12 sites recording fire). A total of 23 fire years are identified as widespread fire years on the horizontal line: 1848, 1854, 1857, 1866, 1871, 1906, 1909, 1915, 1916, 1923, 1928, 1932, 1943, 1945, 1960, 1965, 1967, 1972, 1982, 1988, 1994 and 1998



highly variable in both time and space among sample sites with fires burning at least part of the Reserve in every decade (Fig. 4). Fires were both asynchronous and synchronous: synchronous and more extensive fires were identified with a 25% fire filter (i.e., years when fires burned at least 25% of the sample sites; Fig. 4). Using the 25% filter, we classified 23 years as widespread fire years (Fig. 4). Note that the percentage filter strength increases moving backwards in time as the number of sample sites recording fires decreases over time (Fig. 4b). For example, the La Fortuna and Los Alisos sample sites did not have large sample sizes of recorder trees prior to 1960 and 1930 respectively (Fig. 4b).

Fire occurrence and climate

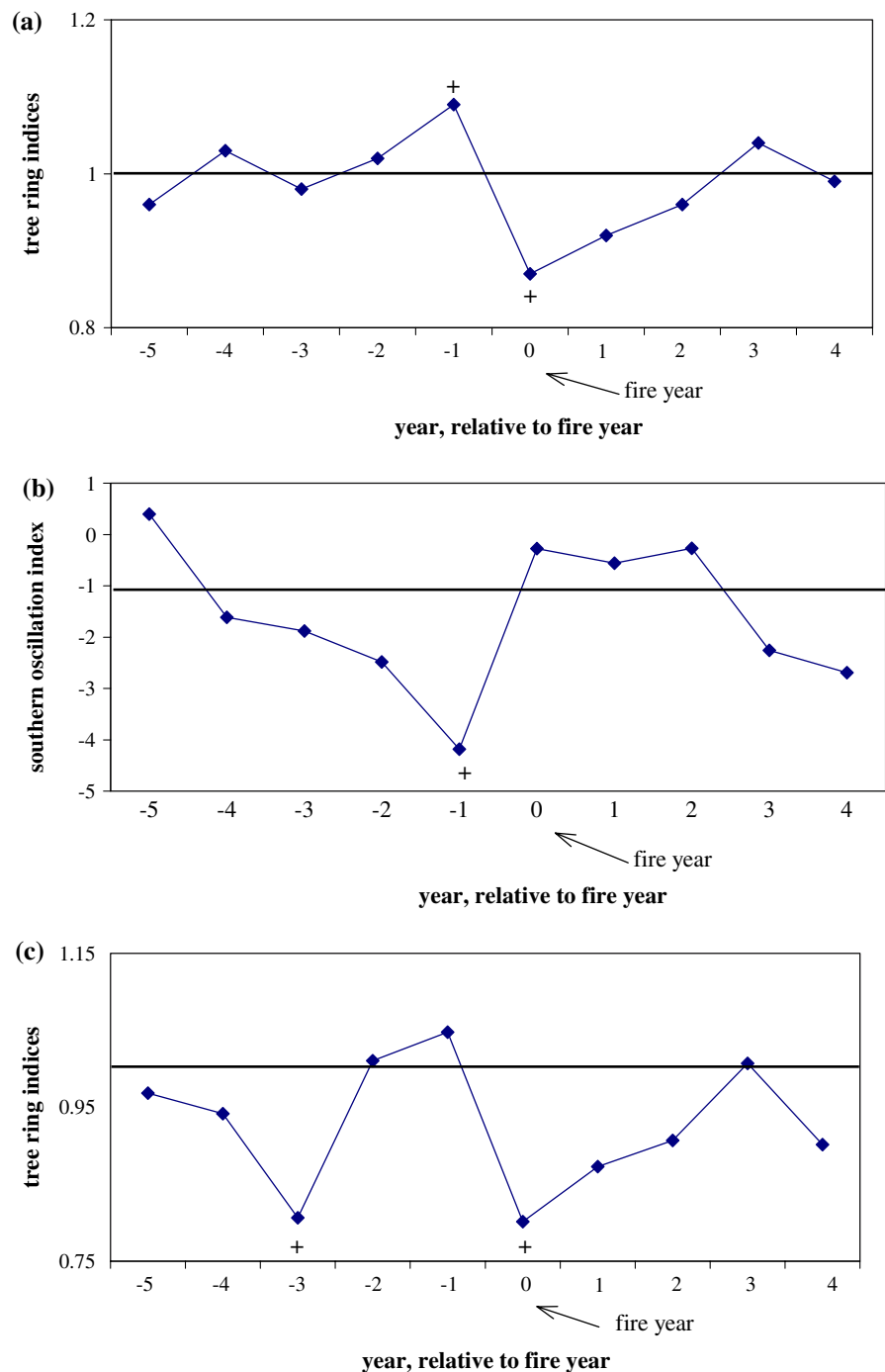
Widespread fire years tended to be dry years that were preceded by a year of above average moisture

availability (Fig. 5a). Widespread fire years followed the negative phase of the SO (typically El Niño years when winters are wet) by 1 year, but there is no statistically significant association with the positive phase of the SO (La Niña when winters are cool and dry) during the fire year (Fig. 5b). Graphically, there were no observed relationships between widespread fire occurrence and the Pacific Decadal Oscillation (PDO) or the Atlantic Multidecadal Oscillation. Similarly, superposed epoch analysis did not yield any significant statistical results for these indices (results not presented).

Fire variation according to habitat type

There was some synchronization of fire occurrence among habitat types during the widespread fire years, but the overall number of fires, and the frequency of fire as measured by mean fire return

Fig. 5 (a) Tree ring departures from the mean prior to, during, and following widespread fire years (25% filter, minimum of three sample sites recording fires) from 1750 to 2001 ($N = 23$). Fire event years and non-fire years were compared to long term climate variability using the González-Elizondo et al. (2005) tree ring chronology for the Las Bayas Forestry Reserve as a climate proxy and Superposed Epoch Analysis (SEA; Baisan and Swetnam 1990). Crosses for all figures note significant departures from chance determined by bootstrapping (1000 runs, 95% confidence interval). (b) Average departure of reconstructed winter (Dec–Feb) Southern Oscillation Indices (SOI: Stahle et al. 1998) for widespread fire years ($\geq 25\%$ trees scarred: $N = 23$) from 1750 to 1977. (c) Tree ring departures (González-Elizondo et al. 2005) from the mean prior to, during, and following years of potentially severe fires from 1750 to 2001 ($N = 5$)



interval (MFRI), differed between habitat types (Table 2; Fig. 4). The xeric and mesic hillslope communities did not differ significantly with regard to the number of fires or the mean fire return interval. However, there were significantly more fires, and these fires occurred more frequently, in the

xeric and mesic hillslope communities than in the exposed oak–pine communities, the *Pinus leiophylla* community, or the mesa-top pine–oak communities (Fig. 4). The number of fires and the interval (MFI) between fires did not differ significantly among the Exposed oak–pine communities, the *Pinus*

leiophylla communities and the Mesa-top pine–oak community (Table 2).

Temporal changes in fire regimes

Fire regimes as measured by mean fire return interval varied significantly over the time spans covered in this study (Fig. 4). Fire was encountered much more frequently with significantly shorter mean fire return intervals from 1876 to 2001 than from 1750 to 1875 (Table 3; Fig. 4). However, this result is presented cautiously as there may be a problem with missing evidence as far fewer fire-scarred trees with establishment dates prior to 1875 were encountered (Fig. 4). In addition, evidence of some early fires on fire-scarred trees that date from the 1750–1875 time period may have been removed by subsequent fires. These problems could lead to fewer fires, and longer mean fire return intervals as identified in the 1750–1875 time period. However, the frequency of widespread fire years was not significantly different between 1750–1875 and 1876–2001 (Table 3) even though fewer widespread fire years were identified during the earlier time period (5 vs. 18 fire years). More substantive conclusions can be made comparing the first and second half of the 20th century due to the much larger sample sizes (Fig. 4).

Mean fire return intervals also differed significantly between the 1900–1950 and the 1951–2001 time periods (Table 3). A total of 36 fire years (MFRI = 1 ± 1) were identified within the Reserve from 1900–1950 and 25 fire years (MFRI = 2 ± 1)

were identified from 1951–2001 (Table 3). Although fire frequency within the Reserve was lower post-1950, fires were still common within the Reserve (Fig. 4). Interestingly, the mean fire interval of widespread fire years did not differ between 1900–1950 and 1951–2001 (Table 3) providing additional evidence that regional climate is influencing widespread fire occurrence. Ten widespread fires occurred within the Reserve from 1900 to 1950 (MFRI = 4 ± 1), while eight widespread fires (MFRI = 5 ± 1) occurred from 1951–2001 (Table 3).

Temporal changes in fire regimes by habitat type

The temporal trends noted Reserve-wide tended to be maintained within the different habitat types with some exceptions (Table 4). When there was enough information for statistical analysis, there was significantly more frequent fire on the landscape from 1900 to 1950 than in the later half of the 20th century for all communities (Table 4; Fig. 4). In addition, the temporal trends for the 1750 to 2001 time periods in exposed oak–pine communities were consistent with the Reserve wide trends: significantly longer fire return intervals occurred from 1750 to 1875 than from 1876 to 2001 (Table 4) which may be an artifact of missing information as the sample size pre-1876 for this community type is considerably smaller (Fig. 4).

However, temporal trends in the xeric and mesic hillslope communities diverged from the observed Reserve wide patterns (Fig. 4) The longer fire records

Table 2 Mean fire return interval (MFRI) for the 1750–2001 by community type

Community type	Number of fire events	Weibull median probability interval (years)	Median fire return interval (years)	Mean fire return interval ($\pm$ SE) (years)	Number of fires and MFI differs significantly with (95% confidence level)
Exposed oak–pine	21	7.0	5.5	10.6 ± 2.7	Xeric hillslope pine–oak, Mesic hillslope pine–oak
<i>Pinus leiophylla</i>	8	6.7	4.0	8.6 ± 2.8	Xeric hillslope pine–oak, Mesic hillslope pine–oak
Mesa-top pine–oak	13	5.5	6.2	7.4 ± 1.8	Xeric hillslope pine–oak, Mesic hillslope pine–oak
Xeric hillslope	57	2.7	2.0	3.6 ± 0.6	Exposed oak–pine, <i>Pinus leiophylla</i> , Mesa-top pine–oak
Mesic hillslope	65	3.2	3.0	3.6 ± 0.3	Exposed oak–pine, <i>Pinus leiophylla</i> , Mesa-top pine–oak

Data are for fire years with a minimum of two scarred trees per fire at each site). Far right hand column designates the habitat type(s) that differ significantly in terms of fire numbers and mean fire return intervals with the habitat type in the far left column

Table 3 Mean fire return intervals (MFRI) from 1750 to 2001 organized by time periods for all 12 sample sites combined

	Time periods compared	Number of fire events	Mean fire return interval ($\pm$ SE) (years)	Significantly different (95% confidence level)
All fire years	1750–1874	41	2.7 ± 0.3	Yes
	1875–2001	77	1.6 ± 0.1	
Widespread fire years	1750–1874	5	5.8 ± 1.3	No
	1875–2001	18	5.4 ± 0.8	
All fire years	1900–1950	37	1.4 ± 0.1	Yes
	1951–2001	25	2.0 ± 0.2	
Widespread fire years	1900–1950	10	4.3 ± 0.7	No
	1951–2001	8	5.4 ± 0.9	
all fire years	1950–1975	16	1.7 ± 0.2	No
	1976–2001	11	2.2 ± 0.3	
Widespread fire years	1950–1975	4	4.0 ± 1.0	No
	1976–2001	4	5.3 ± 0.7	

Data are for all fire years in a minimum of two trees were scarred per fire per sample site. Widespread fire years were determined using a 25% filter (fires occurred in at least 3 of the 12 sample sites)

and larger sample sizes for identified fire scars (Fig. 4) allow for a more complete comparison between the 1750–1875 and the 1876–2001 time periods. There were no significant differences in fire occurrence between the earlier and later halves of the

study time frame in these community types (Table 4). Numerous fires were encountered in both time periods and the mean fire return intervals between these time frames did not differ significantly (Table 4).

Table 4 Mean fire return intervals organized by habitat type and time periods for 1750 to 2001

Community type	Sample sites	Time periods compared	Number of fire events	Mean fire return interval ($\pm$ SE) (years)	Significantly different (95% confidence level)
Exposed oak–pine (all fire years)	ALI, CDB	1750–1874	4	26.7 ± 10.8	Yes
		1875–2001	17	6.5 ± 1.7	
Exposed oak–pine (all fire years)		1900–1950	10	4.4 ± 1.9	Yes
		1951–2001	6	9.4 ± 3.6	
<i>Pinus leiophylla</i>	FRC	Not enough information			
Mesa-top pine–oak (all fire years) ^a	LFA, LFA2	1900–1950	4	10 ± 3	Yes
		1951–2001	9	5 ± 1	
Xeric hillslope pine–oak (all fire years)	ECA, ESO, ESO3	1750–1874	12	6.9 ± 2.8	No
		1875–2001	45	2.8 ± 0.3	
Xeric hillslope pine–oak (all fire years)		1900–1950	22	2.3 ± 0.3	Yes
		1950–2001	13	4.0 ± 0.9	
Mesic hillslope pine–oak (all fire years)		1750–1874	31	3.5 ± 0.4	No
		1875–2001	34	3.7 ± 0.5	
Mesic hillslope pine–oak (all fire years)	AEP, ECF, ESO2, LGA	1900–1950	22	2.4 ± 0.3	Yes
		1951–2001	7	6.3 ± 1.9	

^a Not enough information due to small sample size to analyze the entire 1750–2001 study interval. Data are for all fire years with a minimum of two scarred trees per fire per sample site

Severe fires

A minimum of one fire year was identified as a potentially severe fire year in all sample sites from the late 1920s to early 1940s based on multiple, intersecting lines of evidence discussed earlier (Table 5). Potentially severe fires also occurred at earlier dates within the Reserve, with a common period of severe fire occurrence from 1860 to 1890 (Table 5). Although cohort establishment dates were used in conjunction with number of trees recording an individual fire, the death dates of possibly fire killed trees, and the amount of tree bole killed by the fire, no fires identified as potentially severe fires occurred independently of post-fire tree cohort establishment (Table 5). About 5 years of widespread, potentially severe fires were identified: 1871, 1890, 1928, 1832, 1938, and 1945. Four of these severe fire years were previously identified as widespread fire years associated with years of below average moisture

availability (Fig. 5a, b). Moreover, potentially severe fire years tend to be associated with multi-year periods of extremely low moisture availability or drought (Figs. 3 and 5c).

Discussion

How does variation in climate influence fire occurrence and fire severity in the Las Bayas region?

Regional variations in annual climate appear to be influencing fire occurrence, particularly widespread fire occurrence in the Las Bayas Reserve (Fig. 5). This is in agreement with earlier studies in the Sierra Madre Occidental where years with high incidence of fire occurred during years with below average moisture availability that followed years when moisture was abundant (Fulé and Covington 1997, 1999;

Table 5 Percentage of conifers that established in the 20 years following each severe fire year, based on the total number of establishment dates in 40-year windows centered on the fire year

Exposed oak–pine communities	<i>Pinus leiophylla</i> Community	Mesa-top pine–oak communities	Xeric hillslope pine–oak communities	Mesic hillslope pine–oak communities
Los Alisos (ALI)	Frenton Colorado (FRC)	La Fortuna (LFA)	El Solitario (ESO)	Arroyo El Pescador (AEP)
1875 (75%)	1938 (83%)	1940 (93%)	1866 (86%)	1871 (88%)
1951 (67%)			1885 (50%)	1945 (93%)
			1906 (60%)	
			1950 (69%)	
Cordon de Burro (CDB)		La Fortuna #2 (LFA2)	El Cerro Alto (ECA)	El Cerro Fuera (ECF)
1874 (75%)		1890 (70%)	1802 (67%)	1938 (92%)
1932 (86%)		1938 (95%)	1890 (57%)	
			1932 (82%)	
1945 (33%)				
1977 (44%)			El Solitario #3 (ESO3)	La Grulla (LGA)
			1840 (75%)	1928 (89%)
			1855 (50%)	
			1871 (69%)	
			1928 (87%)	
			1960 (74%)	
				El Solitario #2 (ESO2)
				1879 (71%)
				1928 (89%)

Other criteria (number of fire scars, extent of damage to tree boles, and presence of dead trees) were also used in designating a year as a severe fire event

Heyerdahl and Alvarado 2003). An important result from this study was the lack of significance between fire occurrence and the positive phase (La Niña) of the SO (Fig. 5). Heyerdahl and Alvarado (2003) in their regional study on the drivers of fire regime variability found that widespread fire years were significantly related to fluctuations of the SOI. In their study, widespread fires were synchronized during drier La Niña years (positive SOI) that followed wetter El Niño years (negative SOI). In the Las Bayas Forestry Reserve, widespread fire years tended to occur more frequently one year following the negative phase of the SO (Fig. 5). The El Niño years tend to be wetter and cooler especially in winter in northern Mexico (Ropelewski and Halpert 1986; Kiladis and Diaz 1989; Cavazos and Hastenrath 1990). The higher moisture availability associated with El Niño events enhances the growth of forbs and grasses. In the following drier years, these herbaceous plants remain on the landscape as fine fuels. The increased quantities and continuity of fine fuels in the landscape increase the probability that fire will spread throughout the area.

It is unclear at this time why the positive phase of the SO did not significantly synchronize fire within the Las Bayas Forestry Reserve (Fig. 5) as has been shown for other areas in Durango (Heyerdahl and Alvarado 2003). However, our results suggest that in the southern Sierra Madre Occidental, widespread fire years may be driven by other climatic events such as fluctuations in the Mexican Monsoon (Douglas et al. 1993). Based on the intra-ring scar position identified in this study, most fires in the Reserve occurred in early spring. These early spring ignitions appear to be strongly influenced by the strength and onset of spring and summer monsoon precipitation. The timing of the arrival of the Mexican Monsoon varies year to year depending on the latitudinal movements of the intertropical convergence zone (Douglas et al. 1993). It is possible that fluctuations in the Mexican Monsoon may lessen the influence of SOI on fire occurrence. A later arriving, or weak monsoon season would tend to decrease fuel moistures and increase fire ignition probabilities, even during negative SOI event years. Further study on the relationship between the SO and the onset of monsoon precipitation needs to be done to clarify the climatic drivers influencing this region of the Sierra Madre Occidental.

Is the occurrence and severity of fires more influenced by the top down influence of regional climate or more a consequence of the bottom up influence of topography on microclimate?

The topographic differences in fire regimes noted in the Las Bayas Forestry Reserve (Table 2) contrasted with Heyerdahl and Alvarado's (2003) more regionally oriented study. In more northerly latitudes, it has been shown that topographic differences in solar insolation may influence microclimate and fuel moisture conditions and may influence the probability of fire occurrence (Taylor and Skinner 1998; Heyerdahl et al. 2002). Moreover, Fulé and Covington (1999) noted spatial differences in their La Michilia study which they attributed to locational differences in fire ignition and fire spread. However, Heyerdahl and Alvarado (2003) found no evidence that topography was a major driver of fire regimes in the Sierra Madre Occidental. Our results were more in agreement with the arguments put forth in Fulé and Covington (1999). For example, fires were more common in hill slope habitat types than in the flatter or more exposed communities (Table 2). Part of this difference may be a reflection of methodological problems; more evidence of historical fire occurrence was present in the hill slope habitat types than in the other habitat types which allowed the creation of longer, more complete fire records (Fig. 4). Nevertheless, fires tended to occur more frequently in hillslope communities than in the other habitat types (Table 2), which may be a result of more variable microclimate conditions in the hillslope communities. The more exposed oak–pine communities and the flatter, mesa-top communities are more xeric and may have microclimate conditions conducive to burning every year—however, fine fuel production may be limited by these dry conditions. Lower fuel production would limit the amount of fuel available for fire ignition and fire spread. The more variable conditions on hillslopes may allow for substantial biomass production during wetter years (when fuel moistures are high), which would dry and cure during low precipitation years. These dried and cured fuels would then carry the fire throughout the area when ignition sources were present.

Fire ignition potentials may also vary spatially. Although there was little elevational difference between sample sites, the hillslope communities

may have a greater chance of lightning strikes and subsequent fire ignition than the flatter mesa-top communities. Also many of the hillslope communities were located near roads, enhancing the potential for human caused fires.

Species compositions and prior fire severity may also result in variable fire regimes. For example, the longest intervals between successive fires and the largest quantities of evidence to suggest that these sample sites burned more severely over time were found in the exposed oak–pine communities (Fig. 3). Many historic fires within this habitat type resulted in tree death, especially in the pines. These exposed oak–pine communities were comprised predominately of an evergreen oak, *Quercus arizonica*. The tough sclerophyllous litter from these trees may require hotter, drier conditions characteristic of multi-year droughts to reach the fuel moisture conditions necessary for fuel ignition. Also, this oak species vigorously resprouts after fire, particularly severe fires. The dense cohort of resulting *Quercus arizonica* sprouts would shade the forest floor leading to higher fuel moistures and longer intervals between successive fires. Fuel quantities would increase during the long time intervals between successive droughts and associated fires. Once ignited, the fires that occur would potentially be more intense favoring continued *Quercus arizonica* dominance and a more severe fire regime.

Is there a link between changes in land-use practices and temporal and spatial patterns of fire occurrence?

Temporal variation in fire occurrence has been linked to land use change in many xeric conifer ecosystems. For example, the sharp decline in fire frequency in the late 1800s throughout the southwestern United States has been attributed to the introduction of grazing animals in the 19th century (Swetnam and Baisan 1996). In northern Mexico, Fulé and Covington (1997, 1999) and Heyerdahl and Alvarado (2003) also concluded that the temporal changes in fire frequency they observed were related to changes in human land use. In their studies, fires abruptly ceased in some areas and fire frequency decreased in many other areas during the early to mid-20th century (Fulé and Covington 1997, 1999; Heyerdahl and Alvarado

2003). These authors concluded that the temporal changes in fire frequency coincided with increased human manipulation of the landscape due to the post-Mexican revolution establishment of the *ejido* system of cooperative land ownership. They argued that the *ejido* system effectively granted more people greater access to the land. In their view, fuels would have been more contiguous prior to the arrival of *ejidos*. The *ejidos* would have created greater fuel discontinuity due to the construction of roads, tree harvesting, increased but limited fire suppression, and other land management activities. Most fires would have continued to be ignited by lightning, but these fires would not have spread into adjacent areas. Subsequently, the number of fires within an area would have decreased while the interval between subsequent fires would greatly increase.

We observed similar, but less dramatic, changes in the temporal distribution of fire occurrence for the Las Bayas Forestry Reserve (Fig. 4). Fires have not occurred in many areas within the Reserve since the mid-1960s to late 1970s, but this 25–35 years break in fire occurrence is not outside the historic range of fire free periods for individual sample sites within the Reserve (Fig. 4). However at the Reserve scale, the frequency of all fires (i.e., including small fires) was lower pre-1950 than post-1950, whereas the incidence of years of widespread fires was the same pre- and post-1950 (Tables 3 and 4; Fig. 4).

The lack of change in occurrence of years of widespread fires during the 20th century in conjunction with a reduction in the number and/or spread of small fires after 1950 (Table 3) implies that indigenous people may have been a more significant cause of fires prior to 1950. It is likely that fuels became more discontinuous due to more intensive land use since 1950 as also noted by Fulé and Covington (1999) and Heyerdahl and Alvarado (2003) which would reduce fire spread potentials. We suggest that if fuel discontinuity alone was the limiting factor to the number of fire scars encountered in the post-1950 fire record, then the number of years of widespread fire post-1950 should have declined also. An alternative explanation to the fuel discontinuity argument is an explanation based on a change in the number of fires set by the indigenous people. Many of the small patchy fires we see in the pre-1950 fire record (Fig. 4) were possibly ignited by indigenous peoples, but in years that were not climatically extreme, these fires

did not spread to large areas due to topographically controlled differences in fuel conditions. These anthropogenic ignitions, both intentional and accidental, probably declined 1950 as the free movement of people across the landscape became more limited when land tenure changed. Thus, we suggest that in addition to lightning-ignitions there was a small but significant contribution of human-set fires to fire frequency in the pre-1950 period which subsequently declined following *ejido* establishment in the Las Bayas vicinity.

The interpretation that indigenous people contributed significantly to the number of fires recorded in the tree-ring fire record at Las Bayas is consistent with ethnographic and historical knowledge of this region. Prior to the introduction of Spanish rule in the mid 1500s the dominant cultural group in the Las Bayas area (Municipio de Pueblo Nuevo) of the Sierra Madre Occidental were the Tepehuanes who sporadically located homes across the landscape in single to multi-family homesteads Pennington (1969). While the Tepehuan population may have never reached great numbers, Pennington (1969) discusses how the Tepehuan regularly used fire for cooking, heating homes, and as a tool for clearing and maintaining agricultural fields. The dispersed, semi-nomadic lifestyle of the Tepehuanes and their everyday use of fire suggests that even a small population could have significantly influenced the number of fire ignitions (by accident or with intent) across a broad landscape and may have left long-term legacies reflected in vegetation patterns.

Conclusions

Years of widespread fire in the Las Bayas Forestry Reserve coincide with dry years that follow wet years. The predominance of spring fires appears to be influenced by the onset of the Mexican monsoon. In the Las Bayas Forestry Reserve, widespread fire years were not strongly synchronized by fluctuations in the strength of the SO as found in nearby fire history studies (Heyerdahl and Alvarado 2003). In agreement with earlier studies, widespread fire years tended to occur more frequently following El Niño years. However, our results contrast with earlier conclusions that widespread fires occurred during La Niña years.

Although widespread fire years were drier, they were not significantly synchronized with La Niña events.

In the Las Bayas Forestry Reserve, stand structural evidence is cautiously interpreted as indicating that severe fires (i.e., fires that kill large percentages of the canopy trees) occurred at long time intervals but played a significant role in all community types. Severe fires, as identified in this study, are significantly associated with multi-year episodes of below average moisture availability. Moreover, severe fires are followed by episodes of abundant tree establishment and appear to play an important role in the dynamics of Madrean pine–oak forests (Drury 2006). The idea that severe fires are not outside the historic range of variability for fire regimes in the region is consistent with historical photographs of forests taken at the end of the 19th century (Lumholtz 1902). A total of 12 forest photos in Lumholtz (1902) can be interpreted as representing young, even-aged pine cohorts that presumably regenerated after a severe disturbance, most likely fire, in the latter part of the 19th century.

In addition to climatic variation, human activities also appear to have influenced fire regimes in the Madrean pine–oak of the Las Bayas Forestry Reserve. Fire occurrence has decreased within the Reserve since the 1950s, a decrease that corresponds with the establishment of the *ejido* system of land management in the region. The decreased presence of fire on the landscape since the 1950s may be a result of more attention to fire suppression as the timber resource is better protected. However, while there are fewer total years recording fires (i.e., including small fires) in the Reserve, the frequency of widespread fire years has not been significantly altered since the 1950s. From this we infer that the observed decrease in the number of fires and the subsequent increase in the time between successive fires may be an artifact of the removal of the indigenous groups from this area as the land changed hands. Before the 1950s, indigenous groups may have moved throughout the area igniting fires, accidentally or intentionally, and most of these fires would have been local in nature. During most years only the more exposed sites with drier microclimate conditions would be conducive to fire ignition and spread. A much more heterogeneous and patchy fire regime such as we see within the Reserve prior to 1950 would result.

In conclusion, both climate and humans have influenced the fire regime within the Las Bayas Forestry Reserve over the time frame of this study. Regional climate and topographical climate differences influence the potential for fires to ignite and spread. Human activities and lightning strikes served, and continue to serve, as ignition sources within the Reserve. As humans continue to manage these forest ecosystems it is likely that small fires will continue to be suppressed whenever possible. The suppression of small fires may lead to increased intensity and severity of fires on some sites that historically burned more frequently. However, intense, biologically severe fires do not appear to have been outside the historic range of variability within the Reserve. Moreover, these biologically severe fires appear to have been ecologically important drivers of tree regeneration and community composition within the Las Bayas Forestry Reserve.

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