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Century-scale climate forcing of fire regimes in the American Southwest

Henri D. Grissino-Mayer[1] and Thomas W. Swetnam[2]

([1]Department of Physics, Astronomy and Geosciences, Valdosta State University, Valdosta, Georgia 31698-0055, USA; [2]Laboratory of Tree-Ring Research, The University of Arizona, Tucson, Arizona 85721, USA)

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Abstract: Interannual time-scale associations between fire occurrence and drought indices, the Southern Oscillation, and other synoptic patterns demonstrate that large-scale, long-term atmospheric features are precursors to regional fire activity. However, our knowledge of fire-climate relations over longer (century) timescales is fragmentary because of the rarity of comparable climate and fire time-series with sufficient resolution, length and regional extent. In this study, we develop reconstructions of wildfire occurrence from tree-ring data collected from northwestern New Mexico to compare with a millennium-length dendroclimatic reconstruction of precipitation. Reconstructions of both wildfires and climate show simultaneous changes since AD 1700 that indicate climate forcing of wildfire regimes on interannual to century timescales. Following a centuries-long dry period with high fire frequency (*c.* AD 1400–1790), annual precipitation increased, fire frequency decreased, and the season of fire shifted from predominantly midsummer to late spring. We hypothesize that these shifts in fire regimes reflect long-term changes in rainfall patterns associated with changes in synoptic-scale atmospheric circulation patterns and the Southern Oscillation. Our evidence supports century-scale climate forcing of fire regimes in the American Southwest, providing a useful analogue of future wildfire regimes expected under changing global climate conditions.

Key words: Dendrochronology, tree-rings, fire history, climatic change, El Malpais National Monument, Southwestern USA.

Introduction

General circulation models have predicted increases in both mean temperature and precipitation under doubled CO_2 conditions that may significantly impact wildfire regimes (Rind *et al.*, 1989; Ryan, 1991; Balling *et al.*, 1992; Torn and Fried, 1992). Any change in global climate in the coming decades could alter the frequency, severity and areal extent of wildfires, as well as the length and timing of the fire season (Rind, 1988; Balling *et al.*, 1992; Wotton and Flannigan, 1993; Bergeron and Flannigan, 1995; Larsen, 1996). These expected changes further pose a serious challenge for land-management agencies and the development of fire-management policies as ever-increasing human populations continue to encroach on the urban/wildland interface (Gardner *et al.*, 1985; Darlington, 1993). Modelling expected changes in fire regimes has been troublesome, however, because reference conditions necessary for calibration or testing of such models are based largely on twentieth-century observations, a period marked by major human-induced changes to fire regimes (e.g., fire suppression and changes in fuel loadings). The palaeorecord has provided only few insights on high-resolution century-scale climate-wildfire associations, primarily as shifts in the quasi-periodicity of fire activity reconstructed from charcoal in lake sediments (Swain, 1973; Clark, 1988; Millspaugh and Whitlock, 1995; Clark *et al.*, 1996; Long *et al.*, 1998), and by correlations of summer temperature and reconstructions of wildfires based on tree-ring chronologies from California (Swetnam, 1993). The rarity of sufficient proxies that provide both high resolution and time depth over broad areas restricts our ability to hypothesize the nature of wildfire regimes expected under changing global climate conditions.

Interannual timescale associations between fire occurrence and drought indices, the Southern Oscillation and other synoptic-scale climate patterns demonstrate that large-scale, long-term oceanic-atmospheric circulation features are precursors to regional fire activity (Baisan and Swetnam, 1990; Swetnam and Betancourt, 1990; Takle *et al.*, 1994; Bessie and Johnson, 1995). Simple linear associations between climate and fire occurrence, however, should not be assumed because the dynamics of wildfires are driven by a complex of climate-related factors, such as fuel production (with seasonal and annual timelags), fuel moisture levels, lightning ignition frequency, and short-term weather phenomena. While drought often correlates positively with fire occurrence, increased seasonal precipitation could also lead to increased fire activity in some regions through the production of more fine fuels (i.e., grasses and leaf litter) and/or increased rates of lightning ignition (Rogers and Vint, 1987; Baisan and Swetnam, 1990; Price and

Rind, 1994). To better understand the more complex, long-term associations between wildfire and climate, sites should be located and analysed that have high-resolution palaeorecords of past fire regimes and climate with trends preserved on century timescales.

The Southwestern United States is the only region in the world where extensive networks of century-scale climate and fire reconstructions based on tree-rings have been compiled with annual resolution (and seasonal resolution in the case of the fire reconstructions). However, assessing century-scale trends in both types of reconstructions is difficult because evidence of such trends may be diminished due to limitations imposed by the sites where the tree-ring samples were collected. For example, century-scale changes in climate often were not resolvable because the reconstructions developed in previous dendroclimatic studies conducted in the Southwestern US were based on relatively short individual tree-ring series (e.g., <200 years length) found in archaeological contexts (e.g., Rose *et al.*, 1981; Dean *et al.*, 1985; D'Arrigo and Jacoby, 1991; Dean and Funkhouser, 1995). Most century-length, low-frequency variations in these tree-ring series were removed during the process of 'standardization' (Dean, 1988; Cook *et al.*, 1995; Briffa *et al.*, 1996), thus impeding any assessment of past long-term trends in climate. Furthermore, reconstructed fire regimes must have minimal human impact to ensure an accurate assessment of climate/wildfire interactions on century timescales, a difficult requirement because various groups have occupied the Southwest since Spanish settlement began *c.* AD 1540. Southwestern fire chronologies were long enough to detect century-scale changes, but the possible impact of humans on fire regimes during the presettlement period (prior to 1880) was uncertain (Grissino-Mayer *et al.*, 1995; Swetnam and Baisan, 1996; Baisan and Swetnam, 1997).

These limitations were overcome by our discovery of an unusual site in northwestern New Mexico at El Malpais National Monument (Figure 1). This geologically diverse area consists of numerous lava flows that created sheltered enclaves within the interior of the flows. Here, pristine forest stands are composed of ancient Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), pinyon (*Pinus edulis* Engelm.), and various juniper (*Juniperus* spp.) species. The ruggedness of the lava fields, scarcity of water, and lack of herbaceous cover reduced or eliminated effects of human and natural disturbances (i.e., herbivory, fuelwood collecting and wildfire), enhancing conditions favourable for great longevity in the local trees (Grissino-Mayer *et al.*, 1997). Tree-ring chronologies developed from these long-lived trees, some in excess of 1000 years in age, facilitated the study of century-scale trends in past climate (Grissino-Mayer, 1995; 1996). Minimal disturbances by humans on fire regimes during the presettlement period were ensured by the inhospitable nature of the lava flows and distance to the nearest reliable water source, which hindered successful, long-term agricultural, livestock and logging practices. Furthermore, the presence of kipukas – isolated islands of original substrate and vegetation completely surrounded by younger lava flows (Lindsey, 1951) – ensured minimal impact by humans on the local fire regimes. Areas within and surrounding the lava fields are replete with remnant stems and smaller portions of dead trees (i.e., subfossil wood) that persist on the lava surfaces for centuries to millennia, ensuring maximum extensions for both the fire and climate reconstructions.

The purpose of this study was to exploit the uniqueness of this site, which provided an excellent opportunity to investigate climate/wildfire associations across seasonal to century timescales. We had two specific objectives: (1) to develop a multicentury reconstruction of wildfires with annual and seasonal resolution at selected locations within and around the lava flows; (2) to relate observed changes in reconstructed fire regimes with changes in century-scale precipitation patterns previously reconstructed from neighbouring trees (Grissino-Mayer, 1996).

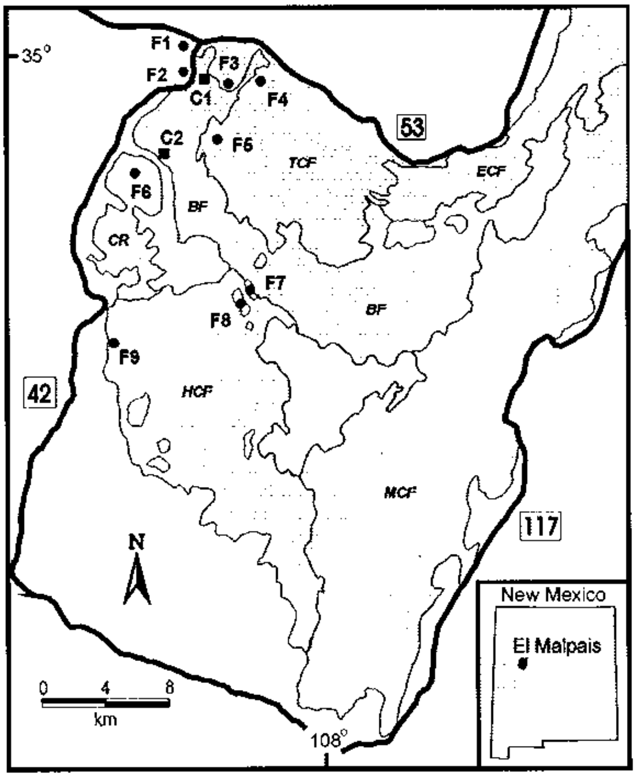

Figure 1 Tree-ring sampling sites at El Malpais National Monument, bounded by highways 53, 42, and 117. C = sites collected for reconstruction of climate, F = sites collected for reconstruction of fire history. C1 = Bandera Ice Cave, C2 = Lindsey, F1 = Cerro Bandera North, F2 = Cerro Bandera East, F3 = Candelaria, F4 = La Marchanita, F5 = Lost Woman, F6 = Cerro Rendija, F7 = Hidden Kipuka, F8 = Mesita Blanca, F9 = Hoya de Cibola. Major lava flows are indicated by TCF = Twin Craters Flow, ECF = El Calderon Flow, BF = Bandera Flow, CR = Cerro Rendija, HCF = Hoya de Cibola Flow, and MCF = McCartys Flow.

Study area

El Malpais National Monument (EMNM) is located in northwestern New Mexico on the southern periphery of the Colorado Plateau (Figure 1), and was established in 1987 to protect a unique environment characterized by geologically recent volcanic activity. Five major lava flows ranging in age from *c.* 3000 years (McCarty's Flow) to *c.* 115 000 years (El Calderon Flow) occur in the monument, as well as classic examples of cinder cones, shield volcanoes, kipukas and other volcanic features (Laughlin *et al.*, 1993). The region is part of the much larger Zuni-Bandera Lava Field in west-central New Mexico, and lies in the central portion of the Jemez lineament, a major fault stretching from central Arizona to northeastern New Mexico (Menzies *et al.*, 1991; Laughlin *et al.*, 1993). Unique features of these lava flows are the numerous kipukas of various ages and sizes that dot the region. Kipukas are ecologically important because they provide isolated communities of vegetation that can potentially serve as control sites for assessing the impact of Euro-American settlement on fire regimes. Most kipukas have had negligible impact from human-related disturbances, such as farming, logging, livestock grazing and fire suppression. In this study, the histories of fire were reconstructed for two kipukas and used to extend the record of fires into the twentieth century, a period that witnessed pervasive human-related impacts on fire regimes in almost all other locations in the Southwestern United States (Swetnam and Baisan, 1996).

The most comprehensive classification of vegetation types for the study area is based on 'biophysical land units', relatively homogeneous areas defined by lithology, surface drainage, soil types, vegetation cover and land use (Carroll and Morain, 1992). Based on this classification, eight vegetation cover types for EMNM were delineated: barren, grass/shrubland, shrub/woodland, mixed conifer, pinyon-juniper, deciduous thickets, ponderosa parkland and pygmy shrub woodlands. Mixed conifer is the dominant cover type, consisting largely of Douglas-fir, ponderosa pine, pinyon and several juniper species. The pygmy forests are second in areal extent, and consist of stunted, contorted conifers rarely 2 m in height, yet which may be many centuries or even millennia in age (Lindsey, 1951). These two cover types were searched to find individual trees for maximum extension of the reconstruction of precipitation previously developed (Grissino-Mayer, 1996). The reconstructions of fire history for the Malpais area were conducted almost exclusively in the ponderosa parkland cover type. Common tree and shrub species found throughout the monument include quaking aspen (*Populus tremuloides* Michx.), mountain-mahogany (*Cercocarpus montanus* Raf. var. *montanus*) and Apache plume (*Fallugia paradoxa* (D.Don.) Endl.), while the grasses are dominated by blue grama (*Bouteloua gracilis* (Willd. ex H.B.K.) Lag. ex Steud.) and mountain muhly (*Muhlenbergia montana* (Nutt.) A.S. Hitch) (Bleakly, 1994).

Analysing the climate/wildfire association

To characterize fire regimes within EMNM, we sampled nine sites that included as many representative habitat types (e.g., cinder cones, ponderosa parklands and older eroded basalt flows) as possible across a north–south gradient. Multiple occurrences of past wildfires were clearly evident on hundreds of trees throughout the monument as basal wounds with characteristic ridges resulting from subsequent overgrowth on previous fire wounds (Schweingruber, 1988; Grissino-Mayer and Swetnam, 1997). Cross-sections were cut using a chainsaw from 217 logs, stumps and snags (standing dead trees) at these nine sites, while partial sections were obtained from a few selected living trees to ensure a complete record of wildfires into the twentieth century. In the laboratory, all sections were reassembled, then sanded using progressively finer grit sandpaper until the cellular structure of the xylem was visible under standard 10× magnification. All tree-ring series from these sections were then cross-dated against the master reference chronologies used to ensure the precise cross-dating of the samples collected for the dendroclimatic reconstruction. All fire scars were then dated to their exact year of formation (Dieterich, 1983; Dieterich and Swetnam, 1984). In addition, the intra-annual positions of the fire scars were recorded (Baisan and Swetnam, 1990) to assess the seasonality of past wildfires, and to help determine whether any long-term changes in fire seasonality have occurred over time.

The years of all past wildfires were entered into a database and statistically analysed using specialized computer software designed for this purpose, called FHX2 (Grissino-Mayer, 1995). Three properties of fire regimes were assessed to determine whether long-term temporal changes in wildfires had occurred: (1) changes in fire frequency; (2) changes in fire seasonality; and (3) changes in the response by fire to annual precipitation. Fire frequency was examined by first transforming the fire interval data for each site to near-symmetric distributions using the method of moments transformations (Box and Cox, 1964; Draper and Cox, 1969), which ensures that extreme values have minimal influence. A Student's t-test was performed to test whether the mean fire interval had changed between periods that had graphically observable changes in fire frequency. Second, changes in fire seasonality were assessed by noting shifts in the dominant mode of seasonal occurrence calculated over 25-year overlapping periods. Finally, superposed epoch analysis (SEA) was performed to compare fire occurrence with reconstructed precipitation to evaluate climate forcing on interannual timescales (Swetnam, 1993). A Monte Carlo simulation of 1000 runs provided bootstrapped confidence intervals to assess the statistical significance of mean climate conditions prior to and during years with fire events.

To examine the probable influence of long-term changes in precipitation patterns on fire regimes, we independently developed a 2129-year tree-ring chronology from living and remnant Douglas-fir and ponderosa pine trees growing within the protected interior of the lava flows. Details of the development and interpretation of the precipitation reconstruction back to 136 BC for the study area are provided by Grissino-Mayer (1996), and only points relevant to this study are summarized here. A central goal in our study was the preservation of long-term trends in the climate reconstruction. To ensure this preservation, we standardized all tree-ring widths using conservative linear or negative exponential growth curves (Fritts, 1976) because more complicated and/or flexible models (e.g., spline curves) would likely have removed portions of the climate signal in the medium to low frequencies. Furthermore, no autoregressive (AR) modelling was performed on the tree-ring series because residual chronologies developed using AR models have stronger relationships with high to medium frequencies in past climate (Briffa *et al.*, 1996), and would not have been useful for analysing the influence of century-scale trends in past rainfall on fire regimes.

Since AD 1000, three major long-term precipitation regimes were distinguished relevant to an appraisal of climate-forcing on fire regimes in the American Southwest: (1) a period of above-average rainfall between *c.* AD 1000 and 1400; (2) an extended period of generally below-average rainfall between *c.* AD 1400 and 1790; and (3) a period of above-average rainfall between *c.* AD 1790 and 1992 (Figure 2A). This reconstruction suggests above-average rainfall prevailed during the 'Medieval Warm Period' (*c.* AD 1000–1400), followed by drier conditions during the 'Little Ice Age' (*c.* AD 1400–1800). This pattern was also suggested by Petersen (1994) who inferred past climate based on high-resolution analyses of pollen from lake sediments in the La Plata Mountains of southwestern Colorado, approximately 250 km to the north. Since *c.* AD 1800, this portion of the Southwest had generally wetter conditions than the long-term average, a finding that has significant consequences for the support of extensive human populations in a region where precipitation could again decrease to levels that occurred prior to AD 1800.

Reconstruction of wildfire occurrence

Although the fire history for some sites at EMNM extended well into the 1300s, we used the period after AD 1700 in our analyses because all sites had an adequate sample depth (> 10 trees) after this date. Clearly noticeable in this reconstruction were four distinct periods marked by differences in fire frequency and synchrony, separated by three discontinuities indicated by near complete absences of fire (Figure 2B). Between *c.* AD 1700 and 1782, fires were relatively frequent, followed by a hiatus of fires between 1783 and 1794. This discontinuity in fires cannot be attributed to human-related factors because Native American and Spanish-Mexican populations were relatively low near the study area throughout the eighteenth century (Mangum, 1990), being concentrated around the Rio Grande to the east where a reliable year-round source of water for agriculture was ensured (Scurlock, 1998). The probable impact of Native American and Spanish-

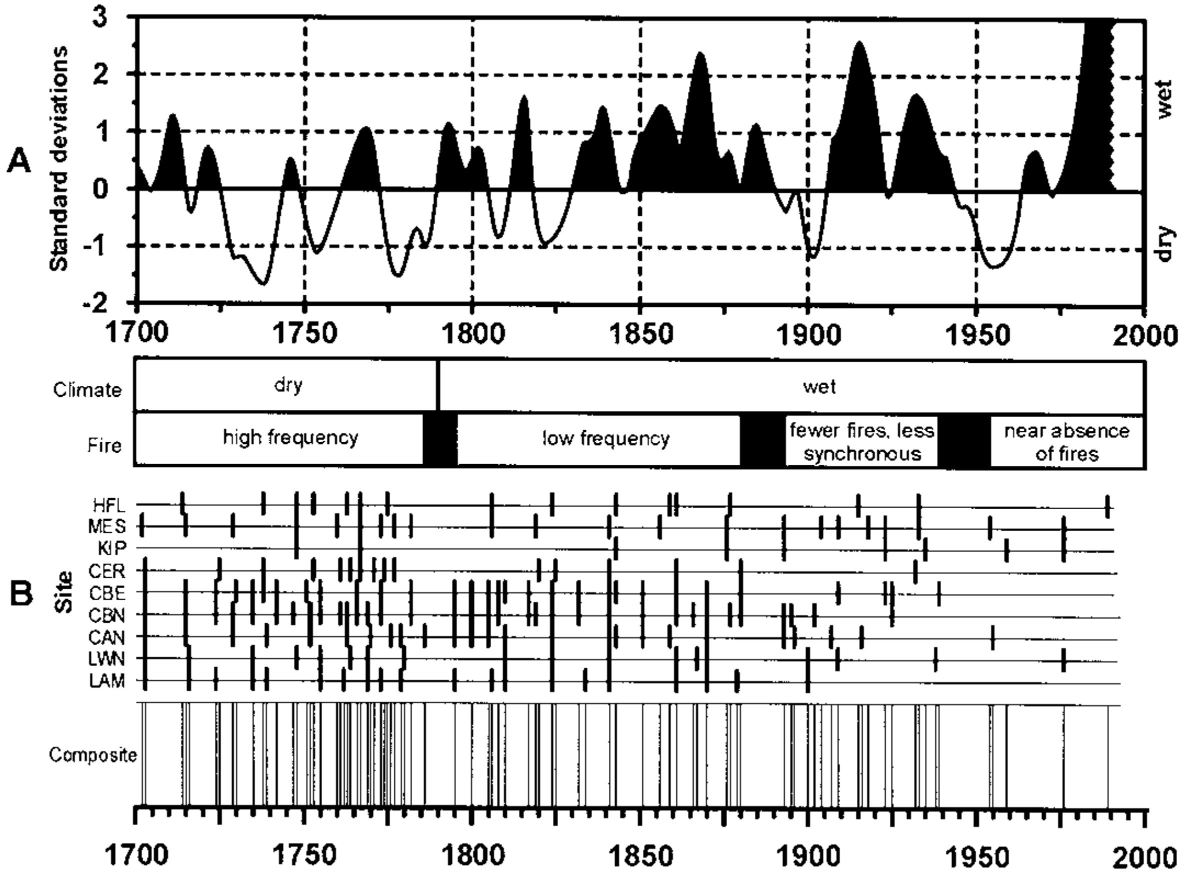

Figure 2 (A) Reconstructed precipitation since AD 1700 depicted as a ten-year spline to accentuate long-term trends, illustrating the shift between below normal to above normal rainfall *c.* AD 1790. (B) Reconstructions of fire history from nine sites at EMNM. Each vertical bar represents a fire event. Site abbreviations: HFL – Hoya Flow; MES – Mesita Blanca; KIP – Hidden Kipuka; CER – Cerro Rendija; CBE – Cerro Bandera East; CBN – Cerro Bandera North; CAN – Candelaria; LWN – Lost Woman; LAM – La Marchanita.

Mexican livestock grazing on fire frequency can also be ruled out because herd numbers during this period were small (usually less than 20 head), never approaching the very high levels reached in the late nineteenth century (Bailey, 1980; Mangum, 1990). Furthermore, reconstructed fire histories for two isolated kipuka sites, where domesticated livestock grazing was highly unlikely, also show a hiatus of fires beginning in the late 1700s. The only other factor that could alter fire regimes on such spatial scales and in such isolated areas is climate (Figure 2A).

Between 1795 and 1880 fires were less frequent, but appeared to be more synchronous between sites. Fire occurrence abruptly terminated between 1881 and1892, reflecting the impact of Euro-American settlement following the relocation of Native Americans to reservations and the penetration of rail lines into the American Southwest. Both factors were instrumental in helping initiate widespread and intensive livestock grazing throughout the American Southwest at this time (Cooper, 1961; Bahre, 1991; Covington and Moore, 1994). The reconstructed fire history, however, is unusual with respect to most Southwestern fire chronologies (Swetnam and Baisan, 1996) because fires re-establish in the mid-1890s and continue well into the twentieth century. Human impact was therefore minimal and of short duration, although the third period (1893–1939) showed a decline in the number and synchrony of fire years between sites. Following an absence of fires between 1940 and 1949, the most recent period (1950 to present) featured a sharp reduction in fire frequency, primarily due to increased fire suppression efficiency using technology developed during the Second World War (e.g., surplus aircraft), and to improved access to backcountry areas.

Seasonal- to century-scale climate-wildfire associations

The hiatus in fire occurrence centred near AD 1790 is our primary concern, because human-related disturbances can be ruled out, leaving only climate change as the likely contributing factor affecting fire regimes in the late 1700s. The most obvious change in fire regimes was a pronounced shift from high fire frequency to low fire frequency (Figure 2B). A Student's t-test confirmed that fire frequency was significantly higher between 1700 and 1782 (one fire every 2.2 years) compared to the period from 1795 to 1880 (one fire every 3.4 years) (Table 1). Another identifiable change in fire regimes around *c.* 1790 concerns the ability of fire

Table 1 Differences in mean fire intervals between the 1700–1782, 1795–1880 and 1893–1993 periods; fire intervals were derived using the composites from all nine sites, using fire dates filtered to remove single-sample fire years (minimum two fire scars per fire year) to emphasize the more widespread fires

Period	No. of intervals	Mean interval	Student's t	$p > t$
1700–1782	36	2.22	2.57	.01
1795–1880	25	3.40		
1795–1880	25	3.40	0.36	.72
1893–1993	22	4.36		

to spread between sites in the study area. Fire spread can be assessed by observing the number of trees that recorded fires within a site, as well as the number of sites at which fire occurred in any given fire year. Between 1700 and 1782, fires were generally less widespread than the more synchronous and widespread fires that occurred between 1795 and 1880 (Figure 2B). After 1880, both fire-frequency and fire-spread patterns were altered considerably (Figure 2B), most likely by increased grazing practices that removed fine fuels necessary for fire spread (Savage and Swetnam, 1990; Grissino-Mayer *et al.*, 1995; Baisan and Swetnam, 1997).

We also observed a significant change in the seasonality of past fires in the late eighteenth and early nineteenth centuries (Figure 3), concurrent with the change in fire frequency. This change in fire seasonality is similar to the change first observed in reconstructions of fire history for northern New Mexico (Allen, 1989). The number of fire scars that occurred in the middle and later portions of the earlywood (most likely fires that occurred in July) decreased until, by the twentieth century, over 70% of all fires were early-season fires (May and June).

The change in fire seasonality suggests a shift in the seasonal distribution of rainfall in the Southwest because the fire season is largely determined by the timing, magnitude and duration of, first, late-winter/early-spring rains; second, the arid foresummer; and, finally, the summer monsoon. Currently, fire frequency is maximal during the arid foresummer (May and June), prior to the onset of the summer monsoon, while the maximum area burned occurs prior to the onset of heavy summer rains (Barrows, 1978; Swetnam, 1990). This fire season corresponds with the dormant and early growing season intra-annual ring position observed in the majority of fire scars formed after the early 1800s. In contrast, if late-winter or early-spring rains are abundant, as often occurs during moderate to strong El Niño events (Douglas and Englehart, 1984; Andrade and Sellers, 1988), fire activity is reduced during the foresummer owing to higher soil and fuel moisture levels persisting into this ordinarily dry season (Swetnam and Betancourt, 1990). However, late-summer rains are typically reduced during El Niño events (Harrington *et al.*, 1992), which may promote above-average fire activity during the latter part of the growing season. Increased growth of cool-season grasses during El Niño winters and springs may also provide additional fuel for late-summer fires, especially at lower elevations (Rogers and Vint, 1987). The late-season dominant fire regime prior to 1800 could have been a consequence of relatively frequent El Niño events and a reduction in summer monsoonal rainfall compared to nineteenth- and twentieth-century patterns.

Results from the SEA also suggest an important change in the interannual response of fuels and fire to precipitation. Between 1700 and1782, fires occurred predominantly during years when precipitation was significantly below average, and were preceded by years when rainfall was above average (Figure 4A). Between 1795 and1880, average precipitation during the fire year was only slightly below average, but rainfall preceding the fire years was significantly above average (Figure 4B). This suggests that an increase in fine fuels due to wetter antecedent conditions in previous years played an important role during both periods, but only between 1700 (and earlier) and 1782 was drought during the year of fire significant. The results of the SEA indicate that fire occurrence during the presettlement period was preconditioned by short-term interannual changes in precipitation patterns, as shown by the significant influence of precipitation prior to and during fire years. However, SEA also indicates the probable influence of longer-term, century-scale changes in precipitation on fire regimes, as shown by a major shift in the response of fire to precipitation between the periods 1700–1782 and 1795–1880. In essence, severe drought was a prerequisite for fire occurrence before *c.* AD 1790, but was no longer a prerequisite for fire occurrence after *c.* AD 1790.

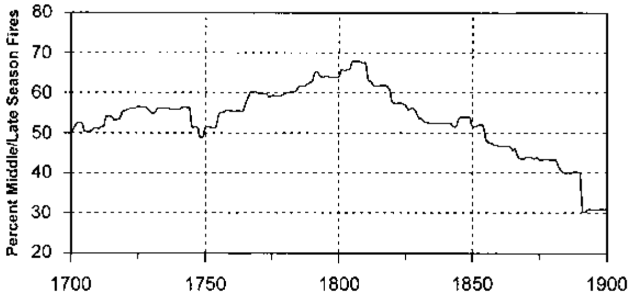

Figure 3 The percentage of middle- and late-season (July) fire scars relative to dormant and early-season scars, showing a shift to a fire regime now characterized by early-season (April to June) fire events.

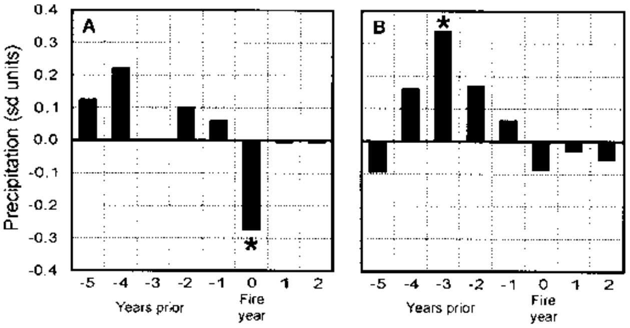

Figure 4 Results from the superposed epoch analysis. Asterisks indicate significant responses. (A) The period from 1700 to 1782 depicts a significant response by fire to severe drought years. (B) The period between 1795 and 1880 no longer depicts a significant response to drought during the year of fire, but rather indicates a significant influence of precipitation prior to the fire year.

A regional-scale assessment of drought and fire records from large networks of tree-ring data from the American Southwest also shows a marked change in climate/wildfire relations beginning in the late 1700s (Swetnam and Betancourt, 1998). Running correlation coefficients between gridded Palmer Drought Severity Indices for the Southwest (Meko *et al.*, 1993) and the number of Southwestern fire-history sites recording fires declined beginning *c.* 1775 (Figure 5). Coefficients were no longer significant ($p > 0.05$) between 1800 and 1830. This degradation in the wildfire/climate relationship was concurrent with long, unprecedented fire-free intervals in many Southwestern fire chronologies generally between 1800 and 1840, although the timing and duration of these intervals were not necessarily synchronous among all chronologies. This breakdown in the wildfire/climate relationship and marked absence of fires for long durations at

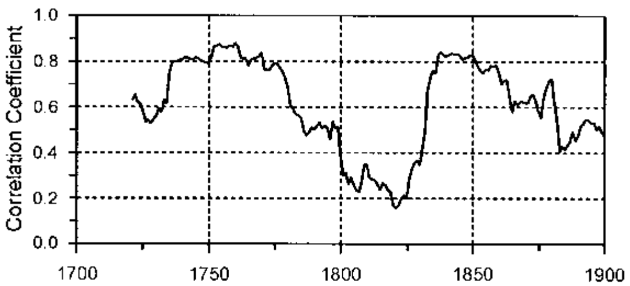

Figure 5 Running correlation coefficients between gridded Palmer Drought Severity Index values and the number of sites recording fires, based on the current network of fire chronologies developed for the Southwest, calculated for 25-year overlapping periods on first-differenced time-series, then inverted to reflect positive values. Coefficients ≥ 0.50 are significant at the 0.01 level.

numerous sites point to a change in climatic factors that regulated fuel dynamics and ignition frequency. We believe this change was related to changes in global-scale atmospheric/oceanic circulation patterns that led to changes in ENSO-driven precipitation patterns. The amplitude and frequency of El Niño events were decreased during the long fire-free period from 1800 to 1840 (Anderson, 1992; Cleaveland *et al.*, 1992), corroborated by other proxies that further demonstrated a change in climate *c.* 1790–1800. Reconstructed $\delta^{18}O$ in tropical corals indicate a rapid change in temperature *c.* 1790 (Dunbar *et al.*, 1994), substantiated by regional-scale dendroclimatic reconstructions of temperature for North America (Jacoby and D'Arrigo, 1989; Luckman *et al.*, 1994).

These changes in fire regimes occurred across multiple temporal (from season to century) and spatial scales (from the stand to regional level), suggesting a probable link between long-term regional-scale changes in precipitation patterns and fire regimes of the Southwestern United States. Our provisional interpretation of the climate/wildfire relationship for the American Southwest therefore begins with changes in atmospheric/oceanic circulation patterns in the late eighteenth century that altered the seasonal distribution of rainfall in the American Southwest. Prior to 1790, winter-spring rains, driven by increased ENSO activity, dominated the distribution of annual precipitation, while summer monsoonal rainfall was reduced relative to amounts during the nineteenth and twentieth centuries. Soil and fuel moisture levels persisted into the early portion of the growing season (April through June), delaying fires until later in the growing season (July and after). The increased late-winter and early-spring rains would have promoted greater grass and litter production. During the intermittent, but relatively frequent, dry years of this period, fires readily ignited and spread in the abundant fine fuels, causing a higher frequency of late-season fires, augmented by diminished summer rainfall. After *c.* 1790, late-winter and early-spring rains diminished and the influence of the summer monsoon increased, causing total annual rainfall to increase as well. Arid foresummers became more typical, and the fire season peaked earlier (May and June) than during previous centuries. Therefore, the current predominant fire season in the American Southwest began *c.* 1790 resulting from arid foresummers that follow relatively moderate to dry winters and springs. In this type of climate regime, unusual drought conditions were no longer the primary limiting factor for fire ignition and spread early in the growing season, as most springs and summers were sufficiently dry for fires to burn. Instead, the importance of adequate moisture in preceding years to produce sufficient fine fuel amounts and to promote fuel continuity across the landscape appear to be more important (Figure 4B).

Our century-scale reconstructions of fire and climate suggest that long-term changes in climate, such as might be expected under doubled CO_2 conditions, are unlikely to produce simple linear responses in global fire regimes, e.g., warmer temperatures may not necessarily lead to increased fire frequency. In northwestern New Mexico, warmer conditions that followed the 'Little Ice Age' (*c.* AD 1400–1800) were accompanied by increased precipitation (Grissino-Mayer, 1996), similar to results from general circulation models that predicted increased mean temperature and precipitation, as well as increased climatic variability, under a world warmed by greenhouse gases (Rind, 1988; Rind *et al.*, 1989). Our empirical-conceptual model for the Southwest proposes that the increase in rainfall that occurred after the 'Little Ice Age' was accompanied by a decrease in wildfire frequency, similar to decreases in frequency observed for fire regimes in the boreal forests of Canada and Sweden (Bergeron, 1991; Bergeron and Archambault, 1993; Engelmark *et al.*, 1994). Furthermore, higher fuel moisture levels that accompanied increased summer rainfall after *c.* 1790 decreased the probability of successful fire ignitions. Our climate scenario for the American Southwest therefore argues for a cool and dry 'Little Ice Age' with higher frequency of wildfires, followed by warmer and wetter conditions since AD 1800 accompanied by lower fire frequency.

Current trends in fire and climate regimes since the mid-1970s further corroborate the probable role of changing rainfall patterns in stimulating regional to continental-scale fire activity. Recent decadal-scale climate changes may be responsible for an apparent increase in annual area burned in both Canada and the western US (Van Wagner, 1988; Sackett *et al.*, 1994) (Figure 6). These recent changes are reflected in anomalously high annual precipitation amounts since *c.* 1976, resulting in a post-1976 growth surge by Southwestern trees that is unprecedented during the last 2000 years (Grissino-Mayer, 1995; Swetnam and Betancourt, 1998). This increased rainfall may be related to the unusual string of El Niño events that began with the 1976–77 shift in oceanic-atmospheric circulation patterns (Ebbesmeyer *et al.*, 1991; Miller *et al.*, 1994; Hayward, 1997). The accumulated fine fuels that resulted from this increased precipitation have now reached levels that induce more widespread fires during years when precipitation amounts are at or near average (e.g., the exceptional fire years in 1993 and 1994 in the American Southwest). Furthermore, low fire activity occurred during summers following extreme El Niño events, while exceptionally large fires occurred during subsequent years, especially during the two La Niña events of 1989 and 1995–96. The late eighteenth-century shift in climate and fire activity may therefore be an analogue of wildfire/climate relations to be expected under a climate regime for the Southwest where precipitation is considerably increased.

The changes in fire regimes that accompanied changes in long-term climate have important implications for fire management in the Southwest. Although we suspect the late twentieth-century surge in area burned in the western US is climatically linked, the relationship is complicated by the simultaneous effects of human-

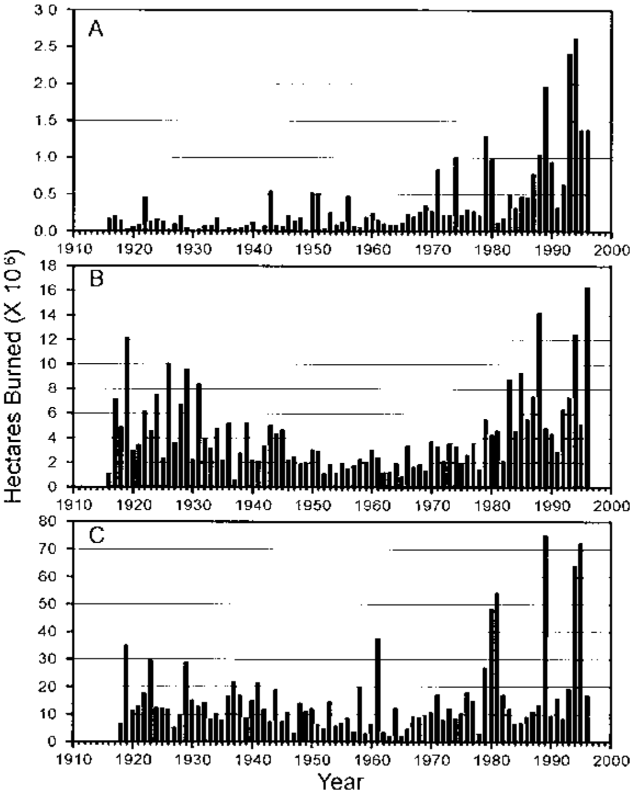

Figure 6 Annual area burned per year has steadily increased since the mid-1970s in (A) Arizona and New Mexico, (B) the 11 states in the western US, and (C) Canada. This increase is probably due to accumulating fuels caused by twentieth-century fire exclusion and suppression and by increased precipitation since 1976.

caused fire exclusion and suppression on accumulating fuels. These unprecedented fuel loadings doubtless have contributed to the occurrence of fires of anomalous size and intensity in recent decades. By the 1960s–70s, fuels may actually have reached sufficient loading and continuity to promote increases in annual area burned. Further clarification and understanding of these climate-fuel-fire interaction patterns will only arise from assessments across a range of temporal and spatial scales, from seasonal to centennial periods and across local to continental areas. Our results emphasize the need to view simplistic assumptions about drought-fire relations cautiously. Finally, the role of increasing fuel loads in stimulating increased fire activity in western US forests should be reassessed in the light of ongoing climate change.

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