Forest Ecology and Management 325 (2014) 49–59

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Climate and land-use effects on wildfire in northern Mexico, 1650–2010

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ARTICLE INFO

Article history:
Received 23 January 2014
Received in revised form 26 March 2014
Accepted 27 March 2014

Keywords:
Climate
Fire history
Fuels
Interannual climate
Mexico
Palmer Drought Severity Index (PDSI)

ABSTRACT

Characterizing climate controls on fire regimes, and disentangling the effects of human relative to climate influences, has been difficult in forests of the western U.S. due to the nearly ubiquitous legacy of fire exclusion that began in the middle to late 19th century. However, the Sierra San Luis of northern Mexico, just across the border from Arizona and New Mexico, offers an opportunity to examine the influence of climate and land-use on fire history largely without the effects of modern fire exclusion. Pine forests in portions of the Sierra San Luis remain ungrazed and unlogged to this day, while other portions of the Sierra were not logged until ca. 1952–1954 or grazed until the early 1930s. Historical and modern fire regimes closely reflect these differences in land-use through time. Fires were relatively frequent in all sites until 1932, but continued at high frequency only in the sites without grazing or logging. Notably, the influence of drought and antecedent conditions for fires changed over time. From 1650 to 1886 (early period), fires occurred during drought years, with little influence of climate in antecedent years. However, from 1887 to 2003 (modern period), drought in the year of fire became generally unimportant and fires instead occurred following wet years. Above-average precipitation promotes accumulation of fine fuels, which apparently has been the primary constraint on fire ignition and spread in this semi-arid ecosystem during the modern period. Percentage of scarring aligned with multi-year fluctuations in Palmer Drought Severity Index (PDSI), with higher percent scarring in wet periods ($\bar{X} = 19.371$) and lower scarring in dry periods ($\bar{X} = 13.778$). Native American burning was not an important driver of past fire frequency, even though the study area lies within the historical homeland of the Chiricahua Apache people. We found no change in frequency of fires when Apaches were effectively removed in 1886. Climatic controls, rather than Apache wartime and peacetime periods, more easily explain changes in frequency over time. Projected increases in climate variability in the Southwest highlight the need to understand antecedent climate conditions conducive to fire occurrence in fuel-limited systems, including comparisons of historical to current climate–fire relationships. The relict forests of the Sierra San Luis, where fires continue to burn today with only minimal human interference, provide a rare look at these relationships.

1. Introduction

Managing for resilient forests in western North America, particularly with increasingly large, frequent, and destructive wildfires, requires understanding linkages among climate, land-use, and fire occurrence. Understanding such patterns is necessary for both long-range forecasting and assessing forest responses to climate change (Morgan et al., 2001). However, modern land-use changes have been so pervasive in the last 100 years that few montane forests in western North America continue to function under historical influences of climate variations and uninterrupted fire regimes (Stephens and Fulé, 2005). Widespread landscape changes were already prevalent by the early 20th century (Leopold, 1924) following extensive overgrazing, fire suppression, timber harvest, and other impacts that accompanied intensive Euro-American settlement beginning in the middle to late 19th century. Frequent surface fires were generally eliminated by the late 1800s in most lower-elevation conifer forests of western North America, fundamentally altering stand dynamics and fire regimes (Weaver, 1951; Covington and Moore, 1994; Swetnam et al., 2001).

The U.S. Southwest has the longest and most detailed tree-ring records of climate and fire history in the world (Swetnam and Betancourt, 1998). These records have emphasized the importance of interannual moisture variability on fire occurrence in arid regions where wet years may be particularly important for stimulating fine fuel production to carry fires during a subsequent

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http://dx.doi.org/10.1016/j.foreco.2014.03.048
0378-1127/

drought year (Baisan and Swetnam, 1990; Vankat, 2013). The most widespread fire year in the Southwest (1748), for example, followed the greatest amplitude of interannual wet to dry switching (1747–1748) on record (Swetnam and Betancourt, 1998). This pattern of increased fire activity during periods of rapid, high amplitude switching between wet to dry years characterized most of the Southwest for several centuries leading up to the late 19th century (Swetnam and Betancourt, 1998). It is notable however, that tree-ring based fire records generally end in the middle to late 19th century, with the onset of fire exclusion, precluding comparisons of 20th century climate-fire relationships.

Interannual climate-fire relationships for the Southwest in the mid-to-late 20th century have been described using modern data on wildfire area burned each year, recognizing that the patterns are also influenced by the legacy of more than a century of fire exclusion efforts and continued fire suppression. These analyses have demonstrated strong associations with antecedent wet conditions, but reveal little or no importance of drought conditions in the year of fire (Westerling and Swetnam, 2003; Westerling et al., 2003; Crimmins and Comrie, 2004; Littell et al., 2009). These modern interpretations thus differ from historical tree-ring based climate-fire relationships, which emphasize both wet antecedent and dry fire years. Westerling and Swetnam (2003) also used 20th century wildfire area burned data to statistically reconstruct or hind-cast historical area burned during the past three centuries. Interestingly, they found greater correlation to drought (Palmer Drought Severity Index, PDSI) in their statistical reconstructions and with historical tree-ring data than for the modern documentary data used to train the models. All of this suggests caution in assuming a static climate–fire relationship through time.

The importance of Native Americans in modifying pre-Euro-American fire regimes has also been emphasized in the Southwest U.S. – Mexico borderlands region (Pyne, 1982; Swetnam et al., 2001) and elsewhere in the West (e.g., Vale, 2002; Fry and Stephens, 2006; Biondi et al., 2011). Ample debate continues on the relative importance of changes in climate relative to human activities, such as the elimination of Native American burning followed by Euro-American fire exclusion, as drivers of changing fire regimes in modern times (Anderson, 2006; Allen, 2002; Vale, 2002).

Apache wartime periods, in particular, have been proposed as a potential explanation of unusual back-to-back fire years, and overall higher fire frequency periods, unique to several U.S. – Mexico borderland mountains prior to the late 19th century (Morino, 1996; Seklecki et al., 1996; Kaib, 1998; Swetnam et al., 2001), although these events occurred in tandem with variation in climate drivers. Kaib (1998) found that for over 200 fire-related quotations in Spanish, Mexican, and American archival documents relevant to the Southwest, more than 70% were in the context of warfare with the Apache people (Swetnam and Baisan, 2003). These wartime periods include the Apache–Spanish wartime period (WTP1) 1748–1790, and Apache–Mexican/American wartime period (WTP2) 1831–1886 (Seklecki et al., 1996; Kaib, 1998) which correspond to increased fire frequency for several sites in close proximity to our study sites in the Sierra San Luis (Swetnam and Baisan, 2003). Similarly, peacetime periods were often associated with distinct treaties that helped maintain order and correspond to periods of reduced fire frequency (Kaib, 1998). The termination of frequent fires in the Southwest U.S. – Mexico borderlands also coincides with the removal of the Apaches to reservations after 1886 (Seklecki et al., 1996).

To differentiate among these various influences on historical and modern fire regimes, requires examining climate–fire relationships in conjunction with land-use changes for regions having different land-use history but similar climate, environment, and biota (Fulé et al., 2012). In parts of northern Mexico, where intensive livestock grazing did not occur until post-revolutionary land reforms in the mid-20th century and fire suppression remains generally ineffective even today, frequent surface fires continued to occur long after they were eliminated from otherwise similar forests on the U.S. side of the border (Dieterich, 1983; Baisan and Swetnam, 1995; Fulé et al., 2011, 2012). Our research is focused on one such site which includes relict forests that have had little or no grazing, logging, or other intensive modern land-use history. This area is also located in the former Chiricahua Apache territory, the international border serving important purposes in Apache raiding and warfare. The mountains of northern Mexico along the international border within and surrounding our study sites were the last refugia for Apaches decades after others were confined to reservations in the U.S. (Leopold, 1937; Goodwin and Goodwin, 2002). Geronimo and his band of Chiricahua Apaches surrendered to General Nelson Miles in 1886, effectively ending the Indian wars and prompting intensive settlement and land-use changes throughout the U.S. Southwest (Seklecki et al., 1996). However, fear of small bands of Apaches who continued to occupy the mountains of northern Mexico persisted well into the 20th century after Geronimo's surrender, and likely helped keep land-use impacts in Mexico from mirroring those on the U.S. side of the border (Leopold, 1937; Seklecki et al., 1996; Goodwin and Goodwin, 2002; Knight, 2009).

Thus, our research was able to address overlapping influences of both historical and more recent climate and land-use history on fire regimes. We had two primary objectives: (1) to understand climate–fire relationships and changes in these relationships over time, particularly for the post-1886 modern period for which there is paucity of such data; and (2) to investigate the relative influence of climate, Native American burning, and 20th-century land-use activities on fire occurrence and extent. We hypothesized: (1) that large fire years have been closely associated with interannual wet–dry variability whereas small fire years lack a clear climate signal; (2) that these relationships have remained similar throughout both the historical and modern periods; (3) that shorter fire intervals during the historical period consistently overlapped with Apache wartime periods, but not with periods of high interannual wet–dry variability, indicating a primary influence of Native American burning on fire occurrence and extent; and (4) that fire occurrence ended abruptly in those parts of our study area where grazing and logging began in the mid-20th century (similar to what happened north of the international border half a century earlier), but that fires continued to occur frequently in places where these land-use changes did not occur.

2. Methods

2.1. Study area

The Sierra San Luis in northern Mexico encompasses the highland region straddling Chihuahua and Sonora and is comprised of the larger canyons and mountain land features of the northernmost extension of the Sierra Madre Occidental. The Sierra San Luis is part of an array of mountains referred to as the Madrean Sky Island Archipelago, which is the confluence of four biogeographical regions; the Rocky Mountains, the Sierra Madre Occidental, and the Sonoran and Chihuahuan deserts. This convergence results in high biological diversity and species endemism and is part of the two richest floras of mega-Mexico – which ranks as one of the three top mega-diversity centers of the world (Rzedowski, 1991; Felger and Wilson, 1994; Van Devender et al., 2013). It is, however, the divergence in modern land-use history that creates unique opportunities to study ecological differences in Mexico. Aldo Leopold recognized this opportunity in 1937, which he pursued until his death in 1948 (Leopold, 1937). Joe Marshall also recognized the uniqueness of this region two decades later (Marshall, 1957, 1963). In his foundational cross-border comparison work in the mid 20th century, Marshall stated that the high elevation forests in the Sierra San Luis were unlogged with practically no grazing, and with abundant evidence of fires. This was in stark contrast to the U.S. side of the border (Leopold, 1924, 1937; Marshall, 1963). These differences were in part a result of long Apache occupation, followed by the decade-long Mexican revolution (1910–1920, although outbreaks of warfare continued until 1929) and subsequent unstable land policies (Heyerdahl and Alvarado, 2003). The result was delayed modern land-use impacts (e.g., grazing, logging, mining) and in some cases relict forests that have largely escaped these land-uses entirely (Fulé et al., 2012; Cortés Montaño et al., 2012).

Our study took advantage of different land-use histories among sites within the Cajon Bonito watershed (Fig. 1). They included three similar physiographic areas that were (1) never logged and had little grazing pressure (Sierra Pan Duro, SPD), (2) were grazed beginning in the early 1930s and logged from ca. 1952 to 1954 (Pan Duro Arroyo, PDA), and (3) were unlogged but grazed in a similar time period (El Pinito Canyon, EPC). EPC had sharper relief and contained mostly lower elevation (~1800–2000 m) pine-oak forest primarily limited to confines of a major canyon (Junta de los Cajones), plus Douglas-fir (*Pseudotsuga menziesii*) stands at the highest elevations (~2440 m). Douglas-fir stands within EPC may have mostly escaped grazing due to rugged topography and lack of water. Dominant overstory trees in pine-oak forests included Chihuahua pine (*Pinus leiophylla*), Apache pine (*P. engelmannii*), and mixtures of Madrean oaks (*Quercus arizonica, Q. emoryi, Q. oblongifolia*). PDA and SPD had a greater extent of intermediate elevation (~2000–2200 m) ponderosa pine (*P. ponderosa* var. *arizonica*) forest and occasional southwestern white pine (*P. strobiformis*), which is synonymous with Mexican white pine (*P. ayacahuite*). Extensive pinyon-juniper woodlands (mostly *Juniperus deppeana* and *P. cembroides*) were present within all three sites intermixed with manzanita thickets (*Arctostaphylos pungens*) at lower elevations.

Northern Mexico is influenced by mid-latitude (westerly) and tropical (monsoonal) moisture (Metcalfe et al., 1997), producing a strongly bimodal distribution of annual precipitation. Typically, winter precipitation in adjacent southeastern Arizona (December–March) accounts for 30% and summer monsoons (July–September) 50% of annual precipitation respectively (Weltzin and McPherson, 2000). The El Niño-Southern Oscillation (ENSO) accounts for a large source of annual variability in precipitation, with an average interval of 3–4 years between relatively cool wet El Niño winters with intervening warm, dry La Niña winters in the Southwest (Sheppard et al., 2002). These general climate patterns (monsoon, ENSO) are strongly linked to southwestern seasonal and interannual precipitation and fire patterns (Swetnam and Betancourt, 1990; Heyerdahl and Alvarado, 2003; Brown and Wu, 2005).

2.2. Fire history

We reconstructed fire history along a 3.3 km stretch of EPC (~45 ha) and 3.0 km stretch of PDA (~63 ha) in 2008, and for eight stands (2–15 ha in size, 63 ha in total) within SPD in 2010. In PDA, pine forests were less confined to the arroyo than they were in the canyon at EPC; though, aside from SPD, restricting sampling to delineated forested stands (as opposed to an arroyo or canyon) was problematic. We sampled fire scars on trees (both living and dead) exhibiting multiple-scarred (>3) “catfaces” within variable radius plots (Jonsson et al., 1992; Lessard et al., 2002). Plots were either spaced 500 m apart (EPC and PDA) or were selected from a probability based spatially balanced design (Theobald and Norman, 2006; Theobald et al., 2007) for delineable stands (SPD). We also sampled multiple scarred trees opportunistically surrounding our plots. We used non-destructive sampling methods (Heyerdahl and McKay, 2008) to remove partial cross sections from both live and remnant fire-scarred trees.

In the laboratory, samples were sanded until the cellular structure of the xylem was clearly visible under magnification (Grissino-Mayer and Swetnam, 2000). Samples were subsequently crossdated against master reference chronologies from the nearby Animas and Chiricahua mountains. All fire scars were then dated to their year of formation for crossdated samples (Dieterich, 1983; Dieterich and Swetnam, 1984). We assigned ring-boundary scars (dormant season scars) to the year containing earlywood immediately after fire scars. Fire events in the Southwest after cambial growth ends in fall are relatively rare, instead generally burning in the spring prior to monsoons (Baisan and Swetnam, 1990; Fulé and Covington, 1997; Heyerdahl and Alvarado, 2003).

We analyzed fire frequency data with FHX2 software, version 3.2 (Grissino-Mayer, 2001). Analysis at each site was for the period of adequate sample depth, defined as the first fire year recorded by ⩾10% of recording trees, until time of sampling or cessation of fire events was apparent. Recording trees are those with basal injury leaving them susceptible to repeated scarring by fire (Swetnam and Baisan, 1996). We used the same criteria for calculating statistics for the three sites combined (ALL). We calculated fire return intervals for sites (individually and combined) that included all fire years, and for fire years in which ⩾10%, and ⩾25% of recording samples were scarred. Filtering, based on scarring percentage, provides a meaningful relative index of fire size and is generally used to estimate more widespread or relatively large fire years (Swetnam and Baisan, 1996) with 10% and 25% filters commonly reported filtering levels. We report both Weibull median probability intervals (WMPI) and mean fire intervals (MFI) to facilitate comparisons to other studies. WMPI is a less biased estimator of central tendency with skewed data and provides a standard way to compare fire regimes across ecological gradients (Grissino-Mayer, 1999; Yocom et al., 2010).

2.3. Climate, land-use – fire interactions

We used superposed epoch analysis (SEA) in FHX2 version 3.2 (Baisan and Swetnam, 1990; Grissino-Mayer, 2001) to compare relationships of fire occurrence to climate patterns and land-use history. SEA was used to compare independently derived indices of drought (Palmer Drought Severity Index – PDSI) during fire years as well as for five years prior and two years following fire event years. We also used SEA to examine climate conditions associated with years without fire. We used the average of four nearest grid points (105, 106, 120, and 121) surrounding the study area from the North America Drought Atlas PDSI tree-ring reconstructions (Cook et al., 2004). Grid points are every 2.5° across North America and for our sites range from 107.5W to 110W and 30N to 32.5N. We assessed statistical significance using SEA analyses with confidence levels (95% and 99%) calculated from bootstrapped distributions of PDSI data in 1000 iterations. While dates of fire cessation vary among individual sites in the Southwest, 1886 was the last widespread fire year (six or more sites recording an event) in regional fire scar chronologies for 31 sites in ten mountain ranges in the Madrean Archipelago (Swetnam, 2005). Therefore we split the analysis into two periods 1650–1886, and 1887–2003. This split gives our data overlap with tree-ring based interannual climate–fire comparisons but also serves as a bridge to fire atlas data that typically do not begin until the late-20th century. 1886 was also the year Geronimo and his band of Chiricahua Apaches surrendered, prompting intensive land-use changes throughout the U.S.

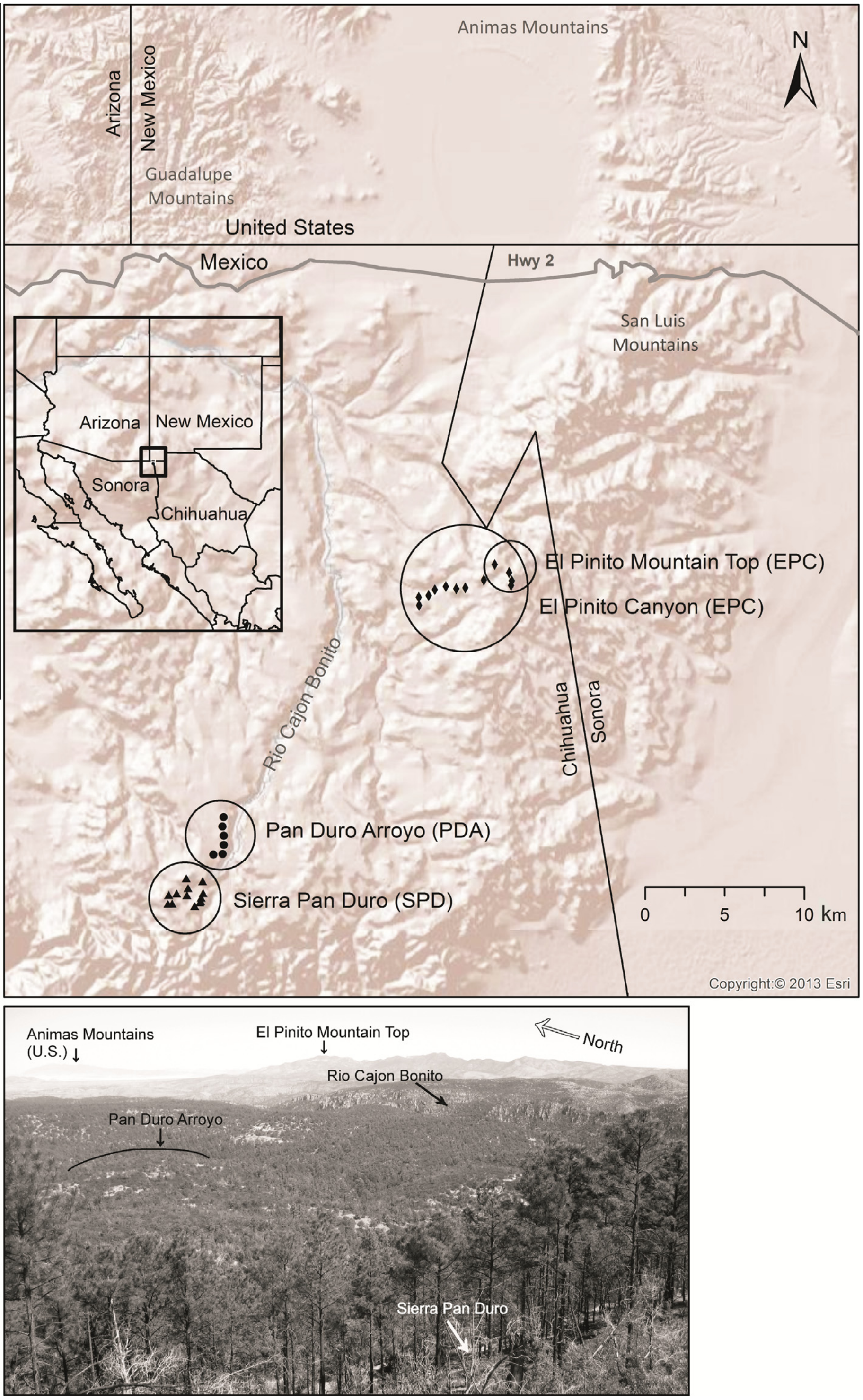

Fig. 1. Study area in the Sierra San Luis, Sonora, Mexico. Symbols represent sampling plots ($n = 30$) within three sites: (1) Sierra Pan Duro (SPD, little to no grazing or logging), (2) Pan Duro Arroyo (PDA, logged and grazed after 1930), and (3) El Pinito Canyon (EPC, grazed after 1930 but not logged). El Pinito Mountain Top consists of high elevation Douglas-fir (*Pseudotsuga menziesii*) stands within the EPC sampling site. *Note:* the orientation of the photo is looking northeast and was taken from a ridge between PDA and SPD.

Southwest (Seklecki et al., 1996). If a reduction of fires in the late 1800s observed elsewhere in Southwest (Seklecki et al., 1996; Kaib, 1998) was attributable to the removal of Apache warfare burning, we would expect a similar reduction in fire frequency in the Sierra San Luis. While a small band of Apaches remained in the Sierra San Luis after Geronimo's surrender, they were subdued, with raiding and warfare effectively ended (Goodwin and Goodwin, 2002).

We also examined climate relationships with fires of different sizes. Generally, filtering to discriminate between large and small fires (Van Horne and Fulé, 2006; Farris et al., 2010) is intended to statistically eliminate the influence of small localized fires on estimates of fire intervals and thereby to identify large events for regional climate–fire associations (Swetnam and Brown, 2011). We compared all fire events (no filter) with larger fires, recorded on $\geqslant$10% of recorder trees. While large fire years may be predominantly controlled by climate, smaller fires may be particularly relevant to periods of frequent, heterogeneous fires attributed to Indian burning (e.g., Fry and Stephens, 2006). We did not restrict our definition or analyses of large fires to fires synchronous across all sites due to the later beginning chronology in EPC (1847) and truncated modern chronologies in EPC and PDA. Synchrony of fires recorded on $\geqslant$10% of recorder trees among sites was fairly high however (~78%). We also examined these same climate relationships during years when fires did not burn.

Finally, we examined changes in fire frequency over time using piecewise regression of cumulative chronological fire dates. Piecewise linear regression procedures (Neter et al., 1989) estimate the number of segments and break points (changes in slope) in fire frequency through time (Brown et al., 1999; Brown and Sieg, 1999). We used Analysis of Covariance (ANCOVA, SAS, 2011) procedures to estimate when there were significant differences in regression slopes between periods. We analyzed climate–fire relationships for high and low slope segment periods and compared resulting segments to human history to examine human relative to climatic explanations for changes in fire frequency.

3. Results

3.1. Fire history

We sampled 194 fire-scarred trees and were able to crossdate 173 (89%) of these, yielding 954 scars in total. Fire-scarred trees were mostly ponderosa pine (55%), and included Chihuahua pine (16%), Apache pine (13%), Douglas-fir (8%), pinyon (7%), and southwestern white pine (1%). About half (54%) of the fire-scarred trees we sampled were living. The earliest fire scar identified in the three sites was 1654 and the most recent fire scars were from 2002 (Fig. 2). Fires burned relatively frequently until 1932 at all three sites, and continued to burn in SPD with the last widespread fire occurring in 2000 (Fig. 2) although with longer fire intervals after 1950.

Weibull median probability intervals (WMPI) for all fires ranged from 6 (PDA, 1745–1932) to 10 (EPC, 1847–1933) years at individual sites. WMPI ranged from 8 (PDA) to 14 (EPC) years when data were filtered to include only fire years in which 25% or more of recording samples were scarred (Table 1). With sites combined, WMPI decreased to 4 years for all fires and 10 years for 25% filtered fire events (1728–2008). While intervals were similar between WMPI and mean fire intervals (MFI), the Weibull model resulted in shorter return intervals and also generally fit the data well (determined with Kolmogorov–Smirnov test for goodness-of-fit).

Temporal changes in fire frequency are evident from slope changes in sequential fire dates for our sites (Fig. 3). With piecewise linear regression we fit multi-line equations for sequential fire dates for each site (Appendix 1), which resulted in four break points (five segments) in both SPD ($R^2 = 0.999$, $SE = 0.578$) and PDA ($R^2 = 0.999$, $SE = 0.590$). EPC was best described with two breakpoints (three segments, $R^2 = 0.997$, $SE = 0.593$). While early fire dates in segment one are subject to the greater influence of a small number of fire years, the "fading record" problem (Swetnam et al., 1999), we found striking similarities among sites. Within our study area, segments were most similar between SPD and PDA (greatest overlap), which were closer in geographic proximity and had larger sample sizes. The greatest differences in these sites were for the most recent period (segment five), where SPD continued to burn frequently but slope declined for PDA after 1911. Continuous slope in EPC for segment five, beginning after 1858, was influenced by recent fires in the high elevation stands, but this site had less frequent fires overall relative to the other sites. Slope segments for data pooled were all significantly different from each other ($P < 0.001$) aside from segments 1 and 3 ($P = 0.088$) and segments 3 and 5 ($P = 0.074$).

3.2. Climate, land-use – fire interactions

SEA analyses indicated that in the early period, 1650–1886, the role of dry years was statistically important (99% confidence level) for fire occurrence whereas antecedent wet conditions were not. However, in the modern period, 1887–2003, antecedent wet conditions were important (years-1, and -2 at 99% confidence levels) with no apparent relationship of drought in fire years (Fig. 4). We identified similar relationships for different levels of filtering and for different climate data (Appendix 2, 3). We also found a similar change in importance of antecedent conditions between periods when considering all years when no fires were recorded in our sites. In years when fires did not occur in any of our sites, conditions were significantly wet (99% confidence level), as would be expected, for the early period 1650–1886 (Fig. 4). In the modern period 1887–2003, non-fire years were also wet (95% confidence level), but the years preceding non-fire years were also significantly dry (99% confidence level).

Piecewise regression fit to sequential fire years for data pooled among our three sites identified five segments (Fig. 3). The resulting segments divide into two periods of high slope/high fire frequency (segments 2 and 4; 1745–1799, and 1848–1947, respectively) and three lower slope/less frequent fire periods (segment 1; 1685–1744, segment 3; 1800–1847; and segment 5; 1948–2002). Hi slope periods had a large amount of overlap with two identified Apache wartime periods; (1) Apache–Spanish wartime period (WTP1) 1748–1790, and (2) Apache–Mexican/American wartime period (WTP2) 1831–1886 (Seklecki et al., 1996; Kaib, 1998, Fig. 3). While the overlap of WTP1 (1748–1790) and segment two (1745–1799) is remarkable, the second high fire frequency period, segment four, continued to burn frequently after 1886, well past the end of the "Indian wars" and WTP2 (Fig. 3).

SEA of PDSI for high and low slope periods split by early and modern time periods reveal a strong but varying climate signal (Fig. 5). Fires burned during drought conditions in low slope, low fire frequency periods (99% confidence level) in both the early and modern periods, and in the early high slope period (95% confidence level) with a change to significantly wet (99% confidence level) antecedent conditions for the modern high slope periods. Mean and distribution of PDSI values were similar across all years within both high and low slope periods. Comparisons of fire occurrence and PDSI indicate that fire frequency (fires per decade) was inversely related to fire size (percent scarred) with percent scarring more closely aligned with PDSI (Fig. 6; both percent scarred and PDSI smoothed with nearest neighbor function).

4. Discussion

4.1. Changes in climate–fire relationships

Although fire frequencies and climate-fire relationships in the Sierra San Luis bore some similarities to other sites in the Southwest, our data reject our hypothesis #1 that large fire years would illustrate interannual climate variability while small fire years would lack such relationships. Most surprising however was a complete lack of support for our hypothesis #2 that these relationships would remain similar over time. Fires in the Sierra San Luis were associated with dry conditions in the year of the fire prior

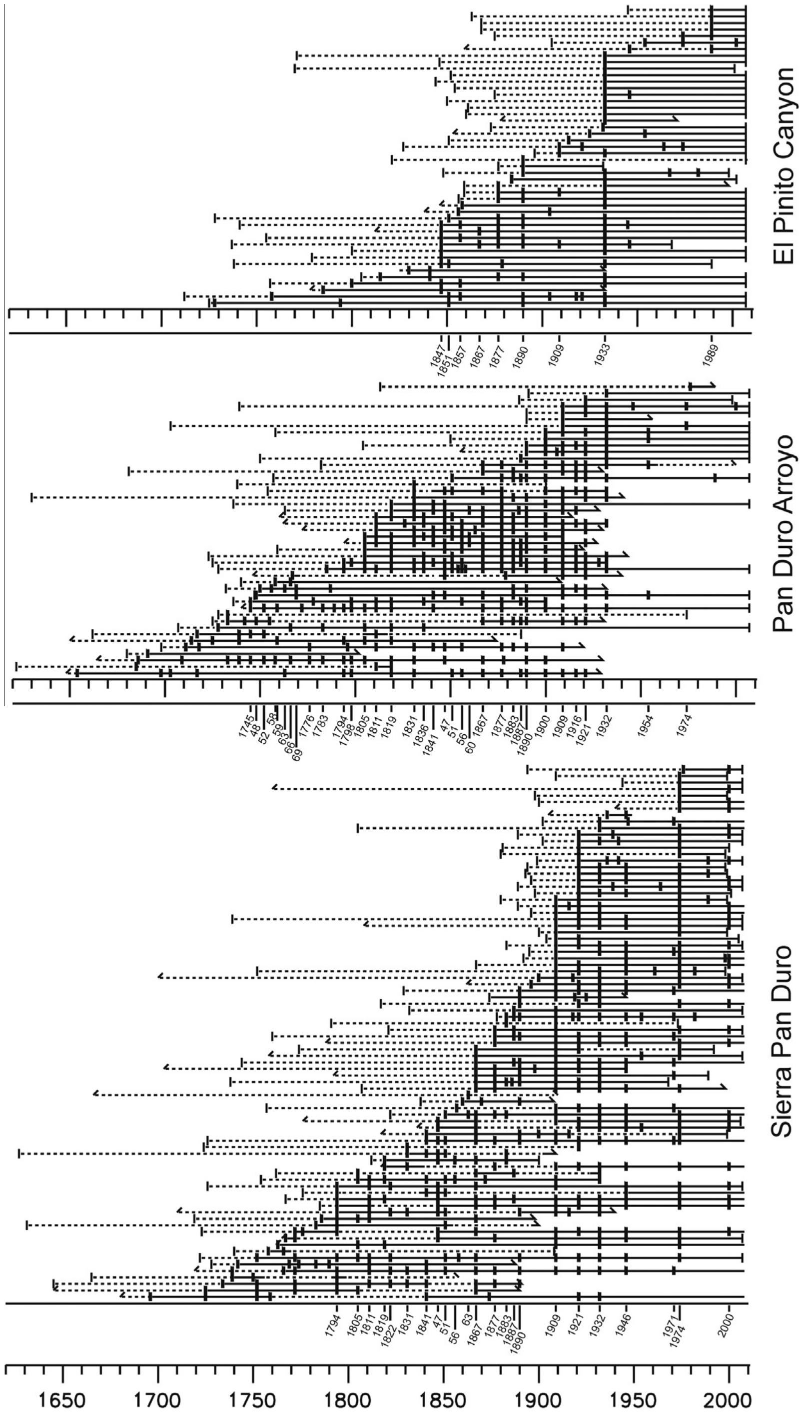

Fig. 2. Fire year chronologies for El Pinito Canyon (EPC, grazed after 1930 but not logged), Pan Duro Arroyo (PDA, logged and grazed after 1930), and Sierra Pan Duro (SPD, little to no grazing or logging) study sites. Bold vertical lines represent fire years, non-bolded vertical lines represent pith and bark dates, vertical spurs are estimates of pith or bark years, dashed horizontal lines are time spans of individual trees before they became recorder trees (prior to first injury), and solid horizontal lines are time spans of individual recorder trees. Dates above *x*-axes are for fires recorded on ⩾10% of recorder trees by site.

to the late 19th century with no association with antecedent wet years. After the late 19th century, the relationship resembled other Southwestern sites, with both antecedent wet years and dry fire years being important – but this was true only when examining all fires regardless of size. For large fire years in the modern period (⩾10% scarred), antecedent moisture was the only significant variable; dry conditions during the year of the fire were not important. This was an almost complete reversal in the role of precipitation between time periods before and after the late 19th century for large fire years (Fig. 4).

Our results differ from most other studies in the Southwest that have emphasized the role of both antecedent wet conditions and drought in the year of fires for large fire years in historical records (Swetnam and Betancourt, 1998). However, additional exceptions to that general pattern have been reported. Morino (1996), for example, found that large fire years in the Organ Mountains in southern New Mexico occurred in drier than average years with little importance of wet antecedent conditions, and offered Apache burning as one potential explanation for this unexpected climate–fire pattern. 20th century fire atlas–climate analyses from

Table 1
Fire interval metrics (years) for the first fire year recorded by ⩾10% of recording trees (minimum of two trees) at each site until time of sampling or disruption of fire events were apparent.

Site, analysis period	Category of analysis	No. intervals	Mean fire interval, MFI	Minimum	Maximum	Weibull median probability interval, WMPI
Sierra Pan Duro	All scars	31	7	2	17	6
1794–2008	10% scars	22	9	3	26	8
	25% scars	17	12	3	28	11
Pan Duro Arroyo	All scars	31	6	1	12	6
1745–1932	10% scars	31	6	1	12	6
	25% scars	24	8	3	17	8
El Pinito Canyon	All scars	9	10	4	14	10
1847–1933	10% scars	7	12	4	24	12
	25% scars	5	17	4	43	14
Sites Combined	All scars	61	5	1	11	4
ALL, 1728–2008	10% scars	41	7	1	28	6
	25% scars	24	11	1	28	10

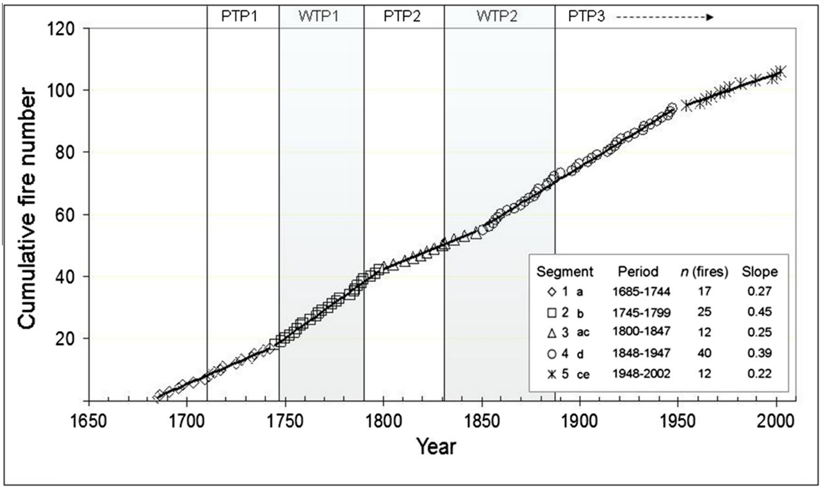

Fig. 3. Fire frequency periods determined by piecewise linear regression slopes fit through cumulative fire dates of best fit segments ($n = 5$) for data pooled among sampling sites (EPC, PDA, and SPD). High and low fire frequency/slope periods are compared to approximate timeline of Apache peacetime (PTP1–3) and wartime (WTP1–2) periods determined by extensive literature review by Kaib (1998). Legend table includes the resulting segments; different letters indicate significant differences ($P \leqslant 0.05$) among segments determined by ANCOVA.

the Southwest have also found strong associations between wildfires and antecedent wet conditions, and little association between moisture conditions during fire seasons (Westerling et al., 2003; Crimmins and Comrie, 2004; Littell et al., 2009). All of this suggests that the 20th century change in climate-fire relationships we identified in northern Mexico (i) may be widespread throughout the Southwest, and (ii) is likely driven primarily by fine fuel abundance, a function of antecedent moisture conditions.

The role of fuel abundance in regulating fire occurrence is well documented, particularly in the arid Southwest (Allen, 2002; Westerling et al., 2003). Surface fires were carried by fine fuels on the forest floor, particularly herbaceous plants but also abundant needle fall (Bradley et al., 1992; Vankat, 2013). However, *changes* in the importance of fuel abundance for fire occurrence over time are less well understood. Swetnam (1993) highlighted the role of fuel limitations in frequent fire regimes of giant sequoia (*Sequiadendron giganteum*) groves in the Sierra Nevada of California where relative size of fires increased as average interval between fires lengthened, apparently because of greater fuel accumulation during longer fire-free periods. In our study, we also found an inverse relationship between the number of fires per decade and percent of trees scarred, though it weakened after the mid-1800s. Percentage of scarring was associated with variation in PDSI – with wet periods corresponding to fewer fires but a higher percent of recorder trees scarring (Fig. 6).

A significant change in the importance of fuel abundance in our study area, occurring around the late 19th century, is supported by several lines of evidence. Non-fire years, years when no fires were recorded in any of our sites, were significantly wet years, which was expected. However, we again found important differences between periods, with antecedent dry conditions further limiting fire occurrence in the modern period but not historically (Fig. 4). This finding points to changes over time in fine fuel abundance and not simply moisture content of fuels in limiting or promoting fire occurrence in a given year. Similarly, fires in low fire frequency periods burned in significantly dry years for both periods while in high slope periods, where we would expect greater fuel limitations from fuel consumption, fires burned in dry years in the early period, but the only association in the modern period was with prior wet conditions (Fig. 5). Limitations of fuel abundance also help explain differences between small and large fire events across periods (1650–2003), with small fires occurring in drier than average conditions without antecedent wet conditions to promote fire spread via fine fuel abundance and continuity. The most widespread fire years in our sites demonstrate opposite relationships, with little evidence of dry conditions in fire years, but two significantly wet antecedent years. We also observed this relationship for fire years that were synchronous across all sites, though sample size was limited ($n = 6$).

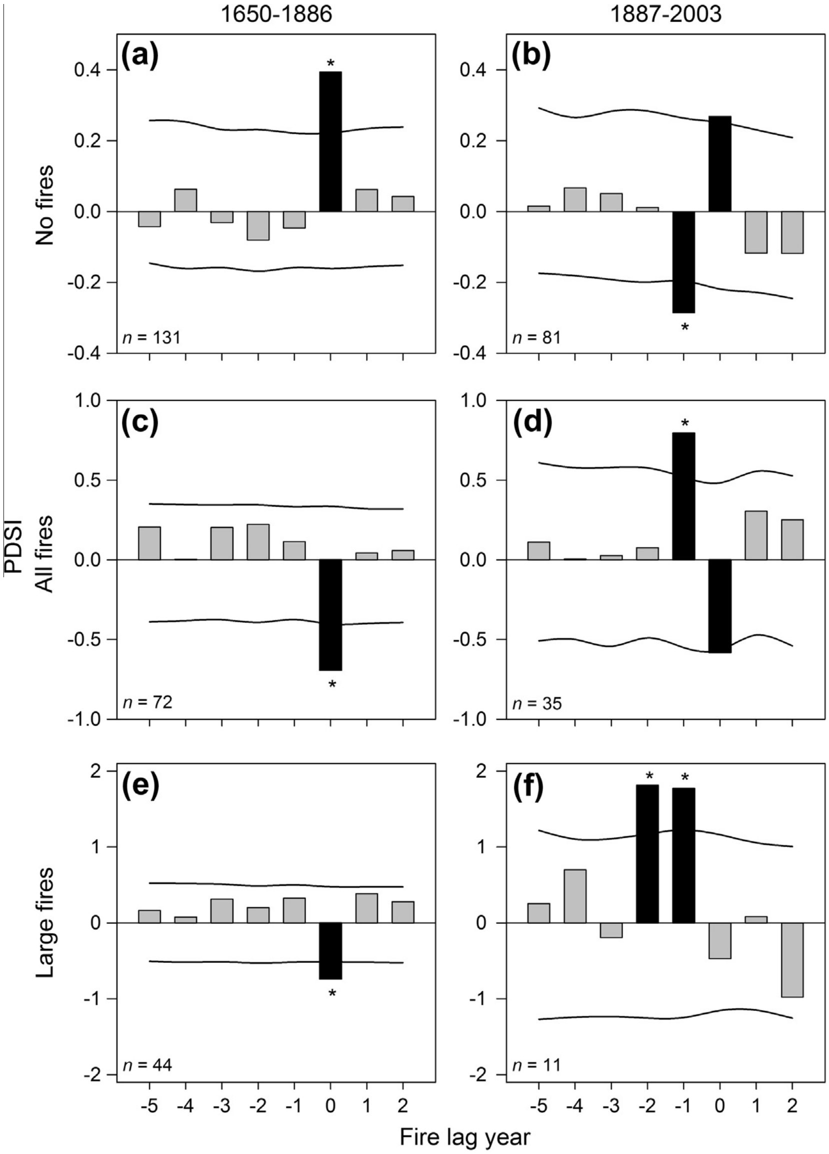

Fig. 4. Results of superposed epoch analysis (SEA) of tree-ring reconstructions of Palmer Drought Severity Index (PDSI, Cook et al., 2004) for years prior and subsequent to fire event years (year 0). Positive PDSI values indicate wet conditions, negative values represent dry conditions. Data shown are for years when no fires were recorded in any of our sites (no fires, a–b), all fire events without filtering (all fires, c–d) and fires recorded on ⩾10% of samples (large fires, e and f) for early (1650–1886) and late (1887–2003) time periods. Solid bars indicate PSDI values outside a 95% confidence interval (depicted by lines); asterisk symbols indicate values outside a 99% CI; All CI's are based on 1000 Monte Carlo simulations of random distributions of annual PDSI. Sample sizes are identified for the number of fire events tested against PDSI data.

These same relationships were also observed when comparing Nino3 sea surface temperature (Appendix 2) and cool season precipitation climate-fire data (Appendix 3). Notably, ENSO, the primary driver of interannual climate in the Southwest, has not remained stationary over time. ENSO fluctuations have included strong amplitude modulation of variability along with an apparent breakdown in interannual variability during the early and mid-19th century toward decadal scale patterns of variability (Mann et al., 2000). This is an active and unresolved area of study, but these changes could have fundamental effects on fire regimes.

4.2. Climate relative to land-use influences on fire regimes

Although the importance of Native Americans in modifying pre-Euro-American fire-regimes is difficult to quantify, our results indicate that interannual climate–fire relationships, rather than Native American burning practices, explain historical fire occurrence. Thus, we reject our hypothesis #3. Apache burning in the Southwest likely had time- and place-specific effects (Swetnam et al., 2001). Such effects may be obscured in a system with the potential to burn in almost any given year and where fire spread and extent are regulated more by fuel limitation than by ignition (Allen, 2002) or by weather at the time of ignition. The Southwest leads the nation in average number of lightning ignited fires in forested areas (Pyne, 2001), and most springs and summers contain periods that are sufficiently dry for fires to burn (Grissino-Mayer and Swetnam, 2000).

The first wartime period (WTP1, 1748–1790) does have remarkable overlap with segment 2, which was our most frequent fire period (1745–1799). However, this period was also a notable period of high amplitude interannual switching from wet to dry (1740–1780), as recorded both in our study area and throughout the Southwest (Swetnam and Betancourt, 1998). A similar regional high amplitude period (1830–1860) also marks the beginning of the second wartime period (WTP2, 1831–1886; Swetnam and Betancourt, 1998). The first part of the 19th century was marked

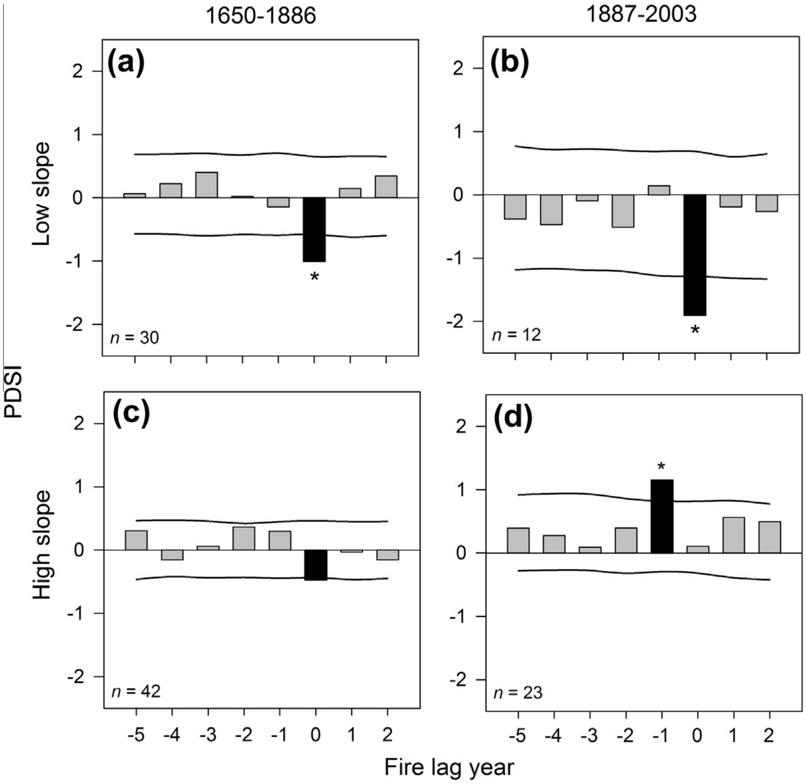

Fig. 5. Results of superposed epoch analysis (SEA) for pooled periods of high and low slope fire events determined by piecewise regression (Fig. 3) and PDSI climate data (PDSI, Cook et al., 2004). Positive PDSI values indicate wet conditions, negative values represent dry conditions. Data shown are for all fire events Solid bars indicate PSDI values outside a 95% confidence interval (depicted by lines); asterisk symbols indicate values outside a 99% CI; All CI's are based on 1000 Monte Carlo simulations of random distributions of annual PDSI. Sample sizes are identified for the number of fire events tested against PDSI data.

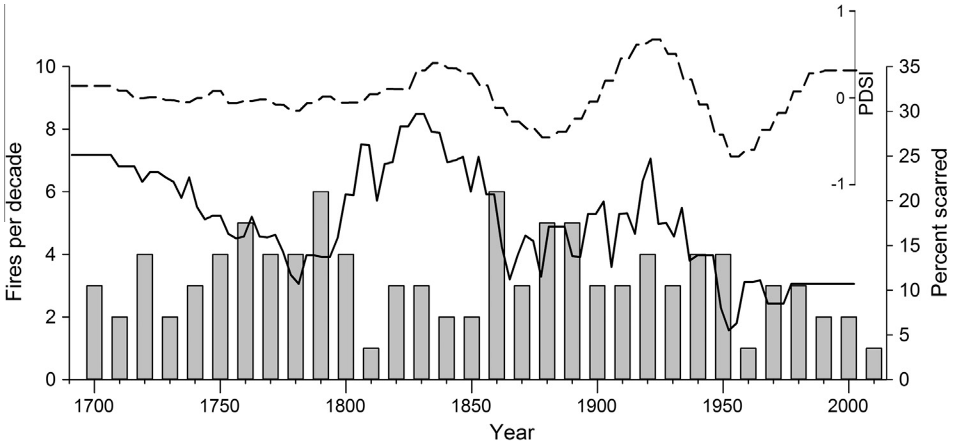

Fig. 6. Timeline depicting changes in fires as a function of climate (Palmer Drought Severity Index, PDSI), fire size (percent scarred), and frequency (fires per decade). Top hashed line illustrates PDSI values from tree ring reconstructions (Cook et al., 2004) with a smoothing function to better depict changes in amplitude. Bar graph illustrates the number of fires per decade. Solid line is the percent of recorder trees scarred in a given year with a smoothing function and a secondary y-axis. Smoothing functions for both lines are nearest neighbor (0.10 sampling proportion) running averages; note that flat lines toward tails are a result of smoothing.

by an Apache peacetime period (PTP2) considered one of the more peaceful periods of the northern frontier (~1787–1831); however, much of this period was also a fire quiescent period throughout much of the western hemisphere (Kitzberger et al., 2001; Swetnam and Brown, 2011). Finally, we did not find a truncated frequency of fire after the end of the Apache wars in 1886, an extended 'peacetime period' that continues to the present day. Rather, fires continued to burn across sites with little change in frequency from 1848 to 1947 (Fig. 3).

The abrupt mid-20th century decrease in fire frequency that we saw in portions of the Sierra San Luis where grazing and logging have occurred (Fig. 3, segment 5: 1948–2002) was strikingly similar to the cessation of frequent fire regimes that occurred north of the international border in the late 19th century when similar land-use changes were implemented, supporting our hypothesis #4. Probably most important in the Sierra San Luis was a grazing-related reduction in fine fuel availability, as direct fire suppression remains generally ineffective in this part of Mexico, and logging did not produce strong density feedbacks in the Sierra San Luis as it did elsewhere in the West (Meunier et al., 2014). The onset of grazing and logging in parts of the Sierra San Luis occurred only when fear of the Apaches had subsided, and it corresponds to documented land-use changes that occurred throughout many parts of Mexico (Heyerdahl and Alvarado, 2003; Cortés Montaño et al., 2012). Notably, however, the mid-20th century change in fire frequency was seen only in places where intensive land-use changes occurred; the remote forests in our SPD site, which were not reached by logging or grazing activities, have continued to frequently burn to the present time. Fire frequency and extent in SPD are still controlled primarily by climate-related drivers, especially by moisture conditions that promote growth of fine fuels as explained above.

Remote forests with largely intact historical fire regimes still persist in the Sierra San Luis, and in some other northern Mexico mountains, but we do not want to imply that these relict forests are extensive or that they are entirely pristine. The relict forests that we studied are restricted to steep topography at high elevations, conditions which may explain why they were never accessed for logging or grazing. In contrast, most of the more accessible parts of the Sierra San Luis have been grazed since the 1930s, and logging has occurred in much of the area as well. Both Aldo Leopold (1937) and Joe Marshall (1957) were careful to limit their descriptions of the unique opportunity of the northern Sierra, with continued frequent fire in the absence of modern land-use changes, to only the high country. The changed fire regimes in surrounding lowlands probably have influenced fire frequency in the remote forests, since some historical fires probably ignited at lower elevations and burned into the higher elevations.

Despite the fact that landscape-scale changes associated with modern settlement and land use may indirectly affect fire regimes even among relict sites that lack those direct influences, the relict forests of the Sierra San Luis are of special conservation significance because of their rarity and the unique insights that they can provide. Climate-dominated and fuel limited controls on fire occurrence and fire size documented in this study imply great uncertainty in future fire regimes to be expected with anticipated increases in southwestern climate variability for the Southwest region as a whole.

4.3. Management implications

Managing for resilient forests requires understanding linkages among climate, land-use, forest structure, and fire occurrence for both pre-1900 and 20th century observations (Grissino-Mayer and Swetnam, 2000). We documented a shift in climate-fire relationships in the late 20th century unlike that seen for >200 years in the Sierra San Luis, suggesting caution in applying these relationships through time. Biondi et al. (2011) using a pyroclimatic model with assumed relationships between past climate and wildfire to project these relationships forward, indicate that a decrease in fire occurrence in the Great Basin after the mid-1800s occurred primarily as a result of climate not modern land-use changes. While our sites may not be directly comparable to the Great Basin, modeling attempts based on climate–fire interactions prior to the mid-1800s would be dubious for our sites given the changes in climate-fire relationships. Understanding temporal changes in climate–fire relationships and recognizing the potential for a self-limiting nature of fire in a fuel limited system is fundamental to ecological management techniques aimed at restoring natural fire ecologies.

The near cessation of fires in EP and PDA in the early 1930s was anomalous for the past 300 years and coincides with recent documented land-use changes, particularly grazing as direct fire suppression remains ineffective in this region. That SPD has continued to burn frequently in the absence of these land-use changes affirms this finding. However, we do not know at landscape scales what the effect of a fragmented fuel matrix has on fire regimes. General heterogeneity of fires suggests that big fire years like 1748, which covered much of the Southwest, would likely have been numerous fires burning in the same year. But what would this same fire year look like in today's landscape with grazing and discontinuous fuels? It could be that extremely wet antecedent conditions like that of 1747 would be of even greater importance today. Maintaining natural fire ecologies in this region with expected increases in climate variability (Gutzler and Robbins, 2010) may require greater landscape scale planning and management.

Acknowledgements

We thank Ruben Ruiz and Valer and Josiah Austin for both permission and assistance in conducting field work in sample sites in Sierra San Luis. Francisco “Cuate” Javier Ramos provided invaluable field assistance and natural history information. Paul White, Bob Sturtevant, Mark Kaib, Mica Keralis, and others provided steadfast labor afield. Many thanks to Chris Baisan who helped with cross-dating samples, Chad Hoffman for logistical support, Dan Binkley and anonymous manuscript reviewers and to Rick Knight who helped motivate and inspire this work. This research was supported by the National Science Foundation (DDR-0926727), and the Ecological Restoration Institute at Northern Arizona University.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2014.03.048.

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