Forest Ecology and Management 322 (2014) 69–77

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Climatic influences on fire regimes in ponderosa pine forests of the Zuni Mountains, NM, USA

Monica T. Rother *, Henri D. Grissino-Mayer [1]

Laboratory of Tree-Ring Science, Department of Geography, The University of Tennessee – Knoxville, TN 37996, USA

ARTICLE INFO

Article history:
Received 4 November 2013
Received in revised form 27 January 2014
Accepted 25 February 2014
Available online 2 April 2014

Keywords:
Climate–fire interactions
Dendrochronology
Ponderosa pine
Fire history
Palmer Drought Severity Index
El Niño–Southern Oscillation

ABSTRACT

We characterized fire history and examined climate–fire relationships in dry ponderosa pine (*Pinus ponderosa*) forests in the Zuni Mountains of northwestern New Mexico. Our findings indicate that the historical wildfire regime for the study area was typified by high-frequency, low-severity surface fires. Climate–wildfire relationships were assessed using both Superposed Epoch Analysis (SEA) and Bivariate Event Analysis (BEA). SEA revealed that interannual variability of the El Niño–Southern Oscillation (ENSO) and the Palmer Drought Severity Index (PDSI) was a strong driver of widespread wildfires; wetter conditions often occurred one to two years prior to fire and were followed by drought during the fire year. BEA revealed statistically significant relationships only in the case of extreme PDSI events and widespread wildfire in the year of fire ($t = 0$). No relationship was found between either the Pacific Decadal Oscillation (PDO) or the Atlantic Multidecadal Oscillation (AMO) and widespread fire occurrence, signifying that shorter-term (i.e. interannual) oscillations between wet and dry conditions, rather than longer-term climatic variability, were historically most conducive to fire. Contextualizing these findings under ongoing climate and land-use change is challenging. Full restoration to historical conditions may be neither possible nor desired, but targeted efforts to promote a frequent, low-severity wildfire regime are generally consistent with our understanding of historical fire activity in this forest type and may foster ecological, economic, and/or societal goals.

1. Introduction

Wildfire is a prominent disturbance in forested ecosystems and is driven in part by interannual to multidecadal climate variability (Bowman et al., 2009; Flannigan et al., 2009; Kitzberger et al., 2007; Westerling et al., 2003). Further understanding of how climate variability affects wildfire activity is needed to guide managers and policy makers as they face difficult decisions regarding issues such as fuels management, firefighting, and post-fire rehabilitation practices under varying scenarios of climate and land-use change. The relationships between climate variability and current and future fire activity are complex but can be greatly informed by knowledge of past climate–wildfire interactions (Landres et al., 1999; Wiens et al., 2012). In dry ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson) forests of the southwestern USA, human-caused alterations (e.g., grazing, logging, and fire suppression) have led to current forest stand conditions that differ significantly from those of the past (Allen et al., 2002; Covington and Moore, 1994; Covington et al., 1997). However, climate remains an important driver of wildfire activity even in areas where anthropogenic change has been significant (Littell et al., 2009; Westerling and Swetnam, 2003; Westerling et al., 2006). Given the societal, economic, and ecological consequences that can result from fire activity that is outside of the historical range of variability, additional research regarding historical wildfire regimes and climate–wildfire relationships is needed. In this study, we assess historical wildfire regimes in ponderosa pine forests of the Zuni Mountains of northwestern New Mexico and examine how interannual to multidecadal climate variability influenced the occurrence of widespread wildfire.

Typical climate conditions associated with wildfire activity differ markedly from one forest type to another. The spatial heterogeneity in patterns of climate–wildfire interactions at broad scales is related to differences in biomass availability (Krawchuk and Moritz, 2011; Moritz et al., 2012; Pausas and Ribeiro, 2013; Whitlock et al., 2010). In wetter areas characterized by high biomass availability, increased wildfire activity often occurs

* Corresponding author. Present address: Biogeography Lab, Department of Geography, The University of Colorado – Boulder, Campus Box 260, Boulder, CO 80309, USA. Tel.: +1 3034922631.

E-mail addresses: rother@colorado.edu (M.T. Rother), grissino@utk.edu (H.D. Grissino-Mayer).

[1] Tel.: +1 8659746029.

http://dx.doi.org/10.1016/j.foreco.2014.02.034
0378-1127/

following prolonged periods of drought. In contrast, in drier areas where biomass is relatively limited, increased fire activity is often associated with above-average moisture conditions one or more years prior to fire, followed by drought in the fire year. In the latter case, low fuel availability constrains the occurrence of wildfire and antecedent moisture conditions are thus first needed to promote fuel accumulation. In dry ponderosa pine forests of the southwestern USA, relatively biomass-limited, grassy fuels were historically dominant and antecedent moisture conditions were typical before fires (Grissino-Mayer and Swetnam, 2000; Swetnam and Betancourt, 1990, 1998). Wetter conditions likely promoted higher grass fuel amount and continuity, thereby increasing the potential for fire spread.

Research focused on fire–climate interactions in western North America has increasingly included assessment of longer-term, broadscale climate drivers of fire (e.g., Kitzberger et al., 2007; Schoennagel et al., 2007; Trouet et al., 2010; Westerling and Swetnam, 2003). The El Nino–Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO) have been of particular interest. Both ENSO and PDO involve oscillations of Pacific Ocean sea–surface temperatures between warm (positive) and cool (negative) phases. ENSO shifts on a cycle of approximately 2–7 years and is associated with sea–surface temperature anomalies in the equatorial Pacific (Diaz and Markgraf, 2000), while PDO oscillates at periodicities of 20–30 years and is associated with sea–surface temperature anomalies in the northern Pacific (Mantua et al., 1997). The AMO is measured by annual sea–surface temperature anomalies in the North Atlantic Ocean and oscillates between phases approximately every 50–70 years (Kerr, 2000). Because instrumental climate records are relatively short, studies of historical fire–climate relationships frequently rely on climate reconstructions based on proxies such as tree rings. In many cases, multiple reconstructions are available for the same climate pattern (see National Climatic Data Center, 2013). In the case of PDO, the variability between different reconstructions is significant and results of analyses of PDO and wildfire may differ markedly depending on the particular reconstruction used (Kipfmueller et al., 2012).

Climate–wildfire studies commonly employ Superposed Epoch Analysis (SEA) to examine interannual relationships between fire occurrence and a particular climate pattern for relatively short windows of analysis (e.g., Grissino-Mayer and Swetnam, 2000; Swetnam, 1993; Trouet et al., 2010). As interest in longer-term climate oscillations such as PDO and AMO has increased, so has the need for methods suitable for testing relationships spanning longer timescales (Schoennagel et al., 2007). Recent studies have employed Bivariate Event Analysis (BEA) via the K1D software (Gavin, 2010) to examine longer-term interactions between climate variability and wildfire (Gartner et al., 2012; Schoennagel et al., 2007). In the current study, we assessed wildfire–climate relationships in ponderosa pine forests of the Zuni Mountains in northwestern New Mexico at interannual to multidecadal timescales using both SEA and BEA, an approach not previously employed in this forest type (i.e. southwestern ponderosa pine). We also examined the effect of combined phases of ENSO, PDO, and AMO on widespread fire activity. Our research objectives were to: (1) characterize historical wildfire activity in terms of fire frequency and synchrony, and (2) assess the relationship between widespread fire occurrence and interannual to multidecadal climate variability. Based on previous findings in southwestern ponderosa pine systems (e.g., Grissino-Mayer and Swetnam, 2000; Swetnam and Betancourt, 1990, 1998) and our conceptual understanding of typical climate–wildfire relationships in relatively biomass-limited systems with grassy fuels, we hypothesized that fires occurred relatively frequently in our study area and that short-term fluctuations of PDSI and ENSO were important drivers of fire occurrence.

2. Methods

2.1. Study area

The study area is located in the Zuni Mountains of northwestern New Mexico, on the southeastern edge of the Colorado Plateau. The mountain range is situated almost entirely within the Mount Taylor Ranger District of Cibola National Forest. Data from the nearest weather station (El Morro National Monument, 1938–2013) show that the mean maximum January temperature is approximately 6.2 °C, the mean maximum July temperature is approximately 29.4 °C, and total annual precipitation is approximately 351 mm (Western Regional Climate Center, 2013). Precipitation patterns vary over the course of the year, with the largest peak in precipitation typically occurring in the summer along with the North American Monsoon. The study area is also characterized by a high degree of interannual variability of precipitation; a number of annual to multiyear droughts and wet periods are documented in the climate record (Sheppard et al., 2002). Across the study area, ponderosa pine is the dominant tree species, although Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Gambel oak (*Quercus gambelii* Nutt.), piñon (*Pinus edulis* Engelm.) and alligator juniper (*Juniperus deppeana* Steud.) are also common. Grasses such as *Muhlenbergia* spp. and Arizona fescue (*Festuca arizonica* Vasey) generally dominate the understory. In dry ponderosa pine forests of the western USA, the legacy of modern human disturbances has often resulted in present wildfire hazard that many consider to be outside the historical range of variability (Grissino-Mayer, 1999; Moore et al., 1999). However, it remains uncertain if and how different aspects of the fire regime (i.e. frequency, severity, size, etc.) may be changing and whether these changes are a consequence of prior human disturbances. In our study area, fire frequency decreased ca. AD 1880 with the advent of livestock grazing, particularly by sheep (Magnum, 1997). Livestock herbivory can reduce fire frequency and extent by removing fine fuels necessary for fire spread (Grissino-Mayer and Swetnam, 1997; Touchan et al., 1995). Shortly after the advent of sheepherding, forests of the Zuni Mountains were further altered by the timber industry beginning ca. AD 1905. Clear-cutting practices were common, and as a result, large portions of the range are now covered in higher-density, second-growth stands with different fuel conditions. Additionally, the forests of the Zuni Mountains were heavily dissected by rail lines and a road network to support the logging industry, resulting in a fragmented landscape that hindered the ability of fire to spread. Lastly, deliberate fire suppression efforts, especially those undertaken following the end of World War II, further reduced fire activity (Cooper, 1960; Covington and Moore, 1994; Grissino-Mayer and Swetnam, 1997).

2.2. Site selection, field sampling, and sample processing

To characterize historical fire activity in our study area, we relied on fire-scar data obtained from four sites in the Zuni Mountains in northwestern New Mexico (Fig. 1). We sampled in areas that were similar in terms of elevation and vegetation type. The sites ranged in size from approximately 30–100 ha, and elevation varied from 2370 to 2610 m (Table 1). Early 20th century logging activity was evident throughout the study area. At each site, we searched for fire-scarred trees following previously established methods (Arno and Sneck, 1977; McBride, 1983). Targeted sampling is standard in fire-history studies and ensures that the fire record is both long and complete (Fulé et al., 2003; Van Horne and Fulé, 2006). A chainsaw was used to collect full cross sections from dead material (i.e. stumps, logs, remnants) as well as non-lethal partial cross sections from living trees. Nearly all samples we

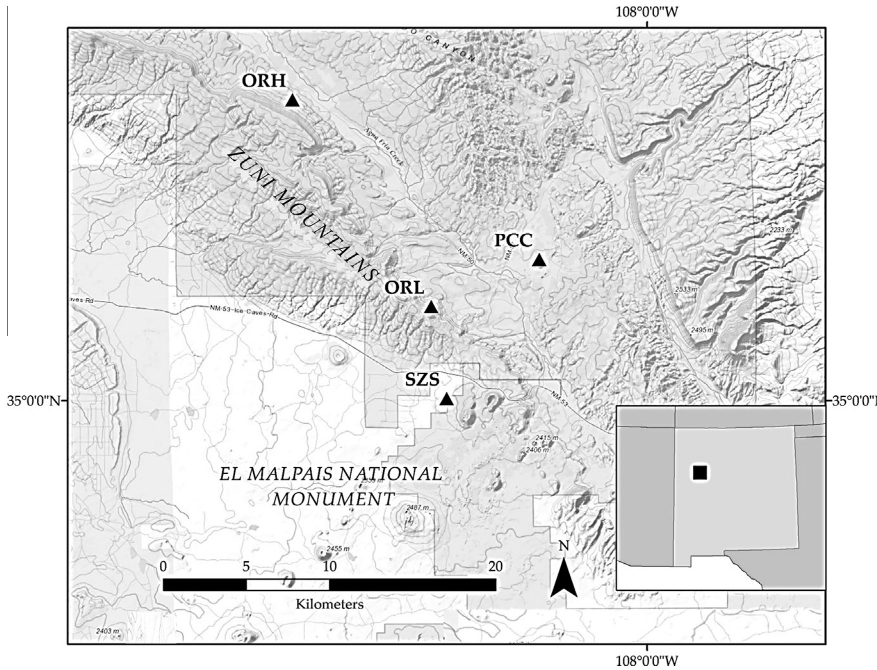

Fig. 1. Study area including the four fire-history sites in the Zuni Mountains of northwestern New Mexico. PCC = Paxton Cinder Cone, ORH = Oso Ridge Head, ORL = Oso Ridge Lookout, and SZS = South Zuni Site.

Table 1
Descriptive information of the fire-history sampling sites included in the study.

Site	Location	Elevation (m)	Area (ha)	Samples (*n*)	Fire scars (*n*)
Paxton Cinder Cone	35° 03′45″N 108° 03′30″W	2380–2460	100	20	201
Oso Ridge Head	35° 08′00″N 108° 11′30″W	2490–2580	50	18	198
Oso Ridge Lookout	35° 02′30″N 108° 07′00″W	2580–2610	50	18	221
South Zuni Site	35° 00′30″N 108° 06′30″W	2370–2400	30	19	186

collected came from living or non-living trees that displayed evidence of repeated scarring. We preferentially sampled less-decayed specimens with solid wood. In the laboratory, standard dendrochronological methods were employed to process and crossdate our samples. Both visual and statistical methods were used to crossdate against a previously developed master chronology (Grissino-Mayer, 2001a; Holmes, 1983). Fire scars were dated based on their occurrence within crossdated annual rings (Dieterich and Swetnam, 1984; Dieterich, 1983; McBride, 1983). Whenever possible, the season of fire-scar formation was identified and assigned a classification of dormant, early-, middle-, or late-earlywood, or latewood based on the position of the fire scar within or between annual rings (Baisan and Swetnam, 1990; Grissino-Mayer et al., 2004).

2.3. Climate datasets

Our analysis of climate–wildfire relationships relied on proxy indices of the Palmer Drought Severity Index (PDSI), ENSO, PDO, and AMO. Proxy data were used because instrumental records do not extend back through the period of analysis (AD 1700–1880). PDSI is an index of variation in moisture availability and for this study we relied on a tree-ring reconstruction of North American summer (June–August) PDSI (Cook et al., 2004, Gridpoint 119). Positive PDSI values correspond with moist conditions while negative PDSI values correspond with drought conditions. We also used a reconstructed index of ENSO. In the southwestern USA, in general, cool, wet conditions occur during El Niño phases (positive departures), while warm, dry conditions occur during La Niña phases (negative departures). Although ENSO is strongly teleconnected with hydrologic conditions in the Southwest, the strength and nature of the teleconnection is both spatially and temporally variable (Diaz et al., 2001). Our ENSO analyses relied on a tree-ring reconstruction of sea–surface temperature anomalies in the Niño 3.4 region of the equatorial Pacific Ocean during December through February (Cook et al., 2008). For PDO, we relied on multiple tree-ring reconstructions (Biondi et al., 2001; D'Arrigo and Wilson, 2006; D'Arrigo et al., 2001; MacDonald and Case, 2005) in our analysis to address problems of poor agreement between reconstructions (Kipfmueller et al., 2012). Finally, for AMO, we used a tree-ring reconstruction of annual North Atlantic sea–surface temperature anomalies (Gray et al., 2004). All the reconstructions used in this study were downloaded from the National Climatic Data Center, USA (see online at http://www.ncdc.noaa.gov/paleo/recons.html).

2.4. Fire history

We developed fire chronologies for each of our four sites and then combined the sites into a single composite chronology for analysis of fire–climate interactions. The software program FHX2 (Grissino-Mayer, 2001b) was used to analyze the fire-history data and aid in the development of individual site chronologies and a composite chronology of all sites. Although fire events were identified as early as the 16th century, we used the period after AD 1700 to ensure adequate sample depth. We excluded fire events after AD 1880 because analysis of climate–wildfire relationships after that time could be confounded by human-caused alterations to fire regimes. Fires of different sizes can result in fire-scar formation, from highly localized spot fires to large fires that occur across a landscape. We aimed to target non-localized, climate-driven fires by examining only fire events that were evident on at least 25% of the samples at each site and scarred a minimum of two trees. We then generated summary statistics for the 25%-scarred record for each site including the Mean Fire Interval (MFI), the standard deviation of the MFI (SD), the Weibull Median Probability Interval (WMPI), and the range between minimum and maximum fire intervals. Next, we compiled all sites into a single composite chronology. Finally, we developed a list of fires ($n = 26$) that were considered to be widespread based on two criteria: (1) the fire occurred on 25% of the samples included in the composite chronology and (2) the fire occurred at a minimum of two of the four study sites. These fires are hereafter referred to as "widespread fires."

2.5. Fire–climate relationships

We relied on both SEA and BEA to evaluate associations between climate variability and widespread fire occurrence. SEA remains a widely-used tool for analyzing past wildfire–climate relationships (e.g., Grissino-Mayer and Swetnam, 2000; Margolis and Swetnam, 2013; Trouet et al., 2010). We used SEA to examine whether the mean value of the climate reconstruction differed significantly before, during, and after years of widespread fire. Our window of analysis ranged from four years prior to fire to two years after. Confidence intervals of 95%, 99%, and 99.9% for assessing statistical significance were determined using bootstrapping methods. Potential drawbacks of SEA for some applications are the temporal autocorrelation present in climate data (Margolis and Swetnam, 2013; Schoennagel et al., 2007) and the relatively short windows of analyses (i.e. approx. 10 years) that are employed.

Next, we used BEA performed in K1D software (Gavin, 2010) to assess all four potential climate drivers (PDSI, ENSO, PDO, and AMO) of wildfire. BEA is based on Ripley's K function (Ripley, 1977) and is a temporal version of spatial point pattern analysis in which one-dimensional time series data can be analyzed (Gavin, 2010). BEA, in contrast to SEA, relies exclusively on select events rather than continuous records and thereby avoids problems with autocorrelation. In our analysis, BEA was used to test for temporal synchrony or asynchrony between extreme climate events and widespread fire events. Extreme climate events were defined as those where the index value was at least one standard deviation from the mean, with positive, extreme events falling at least 1 SD above the mean and negative, extreme events falling at least 1 SD below the mean. Extreme climate events were defined using a threshold based on 1 SD but other definitions of extreme events, such as those that use percentiles, are also possible (e.g., Gartner et al., 2012; Schoennagel et al., 2007). We use standard deviations rather than percentiles because this allowed for the possibility of a differing number of positive or negative extreme events within each analysis. We used a forward selection whereby climate events were assumed to precede fire events and generated 95% confidence intervals based on 1000 Monte Carlo simulations using the random selection option. In K1D software, the K function is computed to $T/2$, where T is the length of the record. In our case, the period of analysis was AD 1700–1880 and thus the K function was computed out to 90 years preceding fire. The bivariate Ripley's K function was transformed into an L function to improve the graphical interpretability of results and to stabilize the mean and variance (Gavin, 2010). When values of the L function fall above the upper confidence interval, results indicate synchrony between fire occurrence and extreme climate events. In contrast, values of the L function that fall below the lower confidence interval indicate asynchrony. When values of the L function fall between confidence intervals, results are statistically insignificant, i.e. fire and climate are independent. For both our SEA and BEA analyses, we assessed only widespread fire events (see Section 2.4 for definition).

Finally, we examined whether certain combinations of phases of ENSO, PDO, and AMO were associated with increased wildfire activity. Specifically, for each two-way combination of the large-scale climate patterns (i.e. ENSO × PDO, ENSO × AMO, and PDO × AMO), we assessed whether the frequency of widespread fire occurring in each of the four possible phase pairs (i.e. + +, – –, + –, or – +) differed significantly from the frequency expected by chance, using chi-square goodness of fit tests ($\alpha = 0.05$). Expected frequencies of widespread fire occurrence were customized based on the distribution of all years ($n = 181$) among the various phase combinations. We used a Yates' correction to address instances where the expected frequency of an outcome fell below five. Three-way combinations were not analyzed because numerous outcomes in each analysis had expected frequencies of less than five.

3. Results

3.1. Fire history

We crossdated 806 fire scars on 75 samples (predominantly ponderosa pine but some Douglas-fir) from our four sites in the Zuni Mountains (Table 1). This effort identified 93 unique fire events, 66 of which fell within the period of analysis (AD 1700–1880). Our findings indicate that the historical wildfire regime for the study area was characterized by high-frequency, low-severity surface fires. Because we did not collect age structure data, we cannot eliminate the possibility of past occurrences of moderate to high-severity wildfires in the Zuni Mountains, although a companion study that analyzed the age structure of over 600 trees just to the south of our study sites showed no such evidence of moderate or high-severity fires (Pilote, 2012). After ca. AD 1880, wildfire activity virtually ceased in the study area, coinciding with the advent of sheepherding and other Euro-American disturbances (Magnum, 1997). The fire-history statistics indicated that the study sites were relatively similar in terms of the frequency of widespread fires. When fire events were filtered to include only those occurring on at least 25% of the samples, MFI values ranged between 6.1 and 7.9 years among sites, with SD values ranging from 2.2 to 4.2 years. WMPI values ranged from 6.0 to 7.4 years (Table 2). The similarity of the WMPI values to the MFI values indicated fire-interval distributions for the 25%-scarred class were normally distributed, i.e. not positively skewed as is common for fire-interval distributions (Grissino-Mayer, 1999). The shortest fire-free interval for

Table 2
Fire-history statistics for each study site. Statistics were calculated using fire dates for the 25%-scarred filter for each site.

Site	MFI (yrs)	SD (yrs)	WMPI (yrs)	Range (yrs)
Paxton Cinder Cone	6.2	2.2	6.2	3–11
Oso Ridge Head	6.1	2.6	6.0	1–10
Oso Ridge Lookout	6.4	2.8	6.2	2–14
South Zuni Site	7.9	4.2	7.4	2–22

MFI = Mean Fire Interval, SD = standard deviation, WMPI = Weibull Median Probability Interval, Range = minimum and maximum fire intervals.

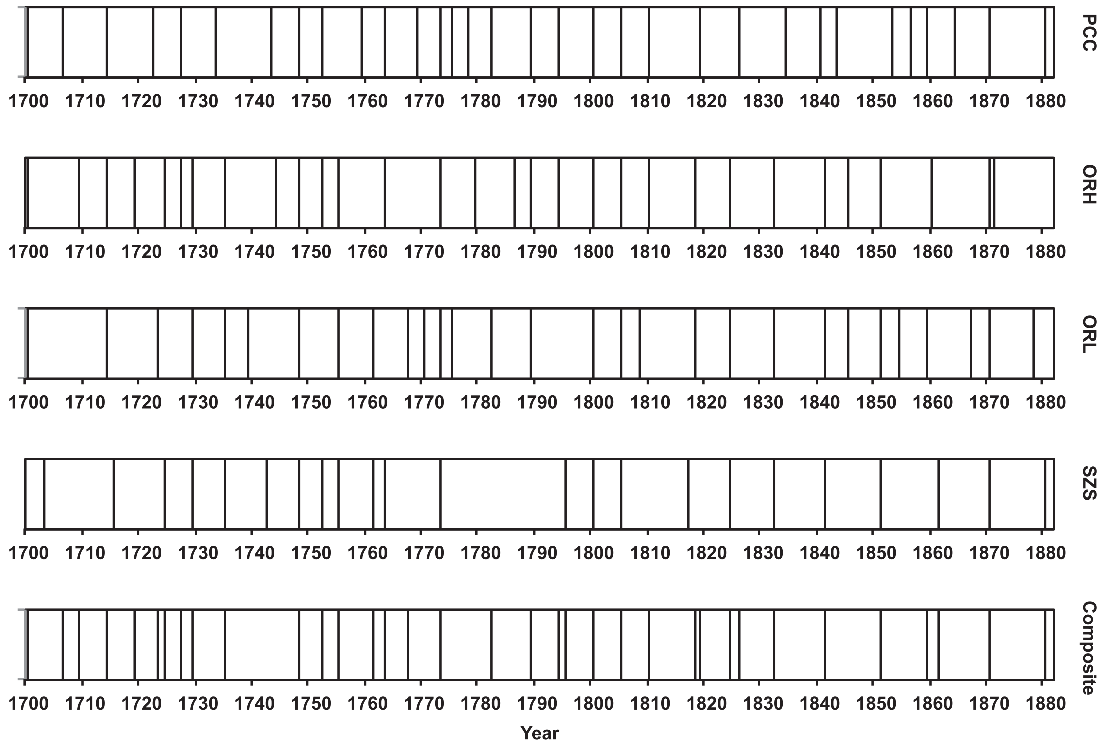

Fig. 2. Fire chronologies of each of the four study sites and of the composite chronology of all four sites combined. In all cases, fires displayed are from the 25%-scarred record. PCC = Paxton Cinder Cone, ORH = Oso Ridge Head, ORL = Oso Ridge Lookout, and SZS = South Zuni Site.

widespread fires that we observed was 1 year (at Oso Ridge Head) and the longest was 22 years (at South Zuni Site) (Table 2, Fig. 2).

When all sites were considered together as one dataset, we found that many of the fires we detected were widespread; more than a third of all fire events during the period of analysis (26 of the 66, 39.4%) were documented by at least 25% of the recording samples and at a minimum of two of the four study sites. Fires that occurred earlier in the season (i.e. fires classified as dormant or early-earlywood) were more common than those that occurred later in the season (i.e. middle- or late-earlywood or latewood);

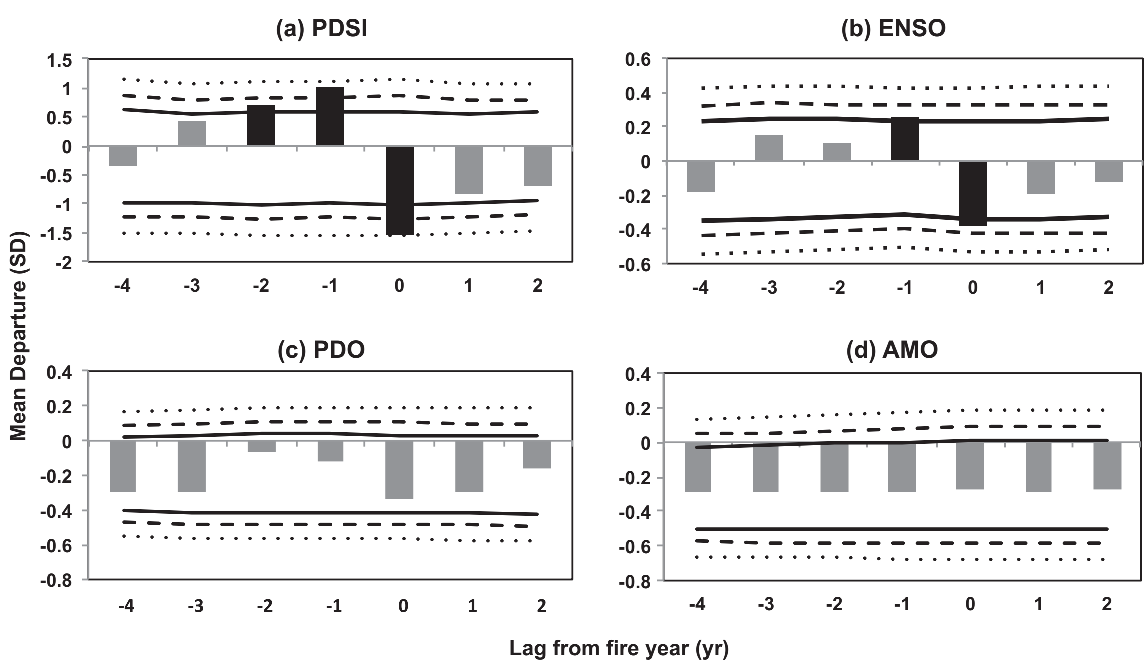

Fig. 3. Results of Superposed Epoch Analyses showing mean departure (SD) from climate indices of (a) the Palmer Drought Severity Index (PDSI; Cook et al., 2004, Gridpoint 119), (b) the El Niño–Southern Oscillation (ENSO; Cook et al., 2008), (c) the Pacific Decadal Oscillation (PDO; D'Arrigo et al., 2001), and (d) the Atlantic Multidecadal Oscillation (AMO; Gray et al., 2004) for years before ($t = -1$ to -4), during ($t = 0$), and after ($t = 1$ to 2) widespread fire for the period of AD 1700–1880. In the case of PDO, three other reconstructions were also examined (Biondi et al., 2001; D'Arrigo and Wilson, 2006; MacDonald and Case, 2005) and results were statistically insignificant. Solid lines, long-dashed lines, and short-dashed lines represent confidence intervals of 95%, 99%, and 99.99%, respectively. Black bars indicate statistically significant departures from the mean ($P < 0.05$).

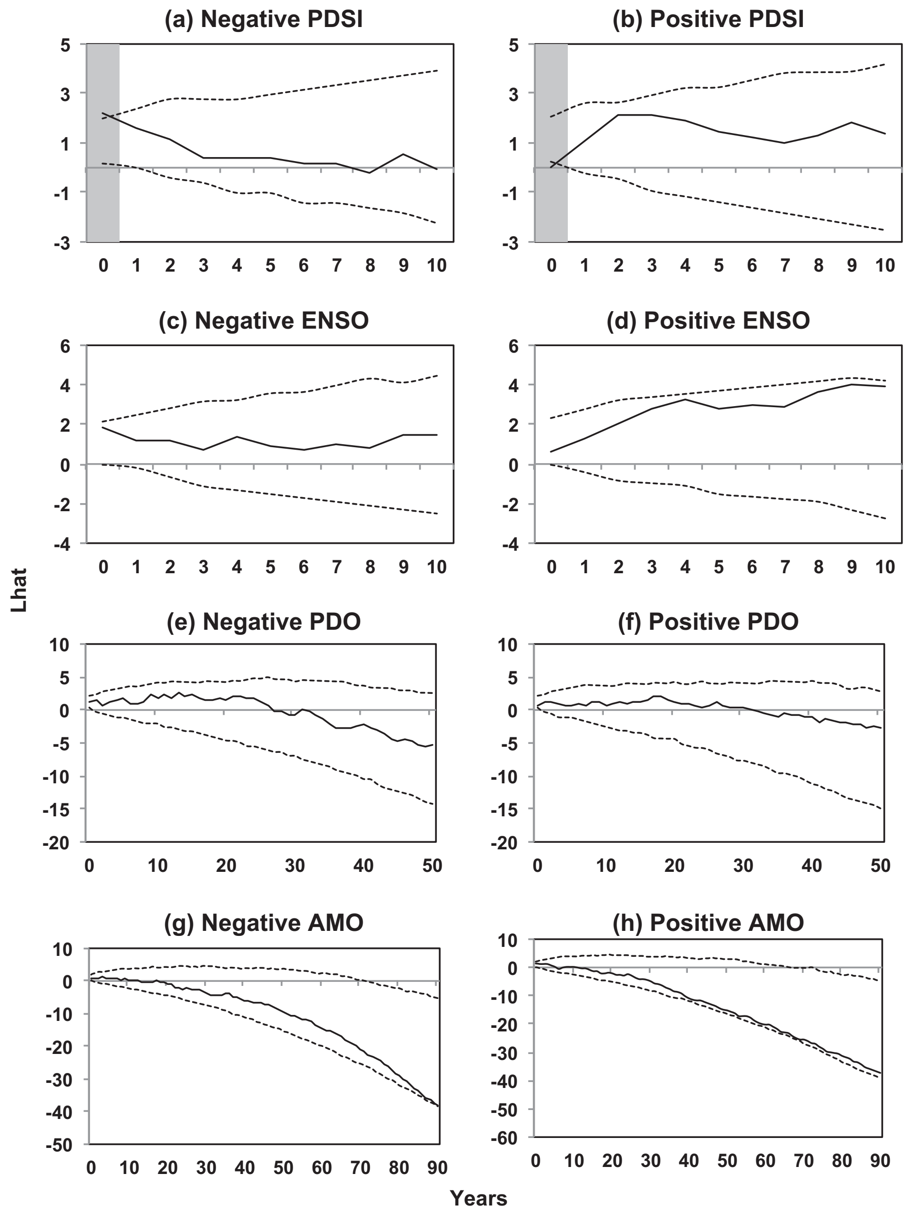

Fig. 4. Results of Bivariate Event Analyses showing temporal association of widespread fire occurrence and extreme years for the (a–b) Palmer Drought Severity Index (PDSI; Cook et al., 2004, Gridpoint 119), the (c–d) El Niño–Southern Oscillation (ENSO; Cook et al., 2008), the (e–f) Pacific Decadal Oscillation (PDO; D'Arrigo et al., 2001), and the (g–h) Atlantic Multidecadal Oscillation (AMO; Gray et al., 2004) during the period AD 1700–1880. In the case of PDO, three other reconstructions were also examined (Biondi et al., 2001; D'Arrigo and Wilson, 2006; MacDonald and Case, 2005) and results were statistically insignificant. The dashed lines on the graph represent confidence intervals of 95% and highlighted portions denote statistical significance ($P < 0.05$). Output from the K1D software allowed us to examine up to 90 years prior to fire, but statistically significant relationships were not found beyond $t = 0$ in all cases. All analyses were run via a forward selection whereby climate events were assumed to precede fire events.

dormant or early-earlywood scars accounted for 55–66.3% of all fire scars, depending on the site. Comparison to a nearby fire-history study in El Malpais National Monument (Grissino-Mayer and Swetnam, 1997; Grissino-Mayer, 1995) indicated that many of the 26 widespread fire years that we observed in our sites in the Zuni Mountains were also widespread fire years in sites in the adjacent El Malpais National Monument (61.5%, $n = 16$).

3.2. Fire–climate relationships

We found statistically significant relationships between widespread fire and PDSI and ENSO using SEA. Fires were significantly associated with dry years that were preceded by one or more years of above-average moisture availability (Fig. 3). In the case of PDSI, years of widespread fire ($t = 0$) were significantly associated with negative mean PDSI ($P < 0.01$) while conditions during the year preceding fire ($t - 1$; $P < 0.01$) and two years preceding fire ($t - 2$; $P < 0.05$) were significantly associated with positive mean PDSI (Fig. 3a). Similarly, SEA of ENSO-wildfire relationships revealed that widespread fire was significantly associated with negative departures from the mean Niño 3.4 index during the year of fire ($t = 0$, $P < 0.05$), while positive departures the year preceding the fire year were statistically significant ($t - 1$, $P < 0.05$) (Fig. 3b).

We also found statistically significant relationships between extreme PDSI events and widespread wildfire occurrence using BEA (Fig. 4). Widespread fire was synchronized with negative, extreme PDSI events (drought conditions) at $t = 0$ ($L_{hat} = 2.2$; $P < 0.05$; Fig. 4a), but was asynchronous with positive, extreme PDSI events (wet conditions) at $t = 0$ ($L_{hat} = 0$, $P < 0.05$; Fig. 4b). Therefore, widespread fires were in-phase with negative, extreme PDSI events but were out-of-phase with positive, extreme PDSI events. Our use of BEA to assess relationships of widespread wildfire and ENSO, PDO, and AMO did not yield statistically significant results at the $P < 0.05$ level. Our BEA results should be interpreted cautiously because relatively few fire events ($n = 26$) were analyzed for a relatively short period ($n = 181$ years).

We found no statistically significant relationships when testing combinations of phases of ENSO, PDO, and AMO (Fig. 5). For each of the two-way combinations of our large-scale climate patterns (i.e. ENSO × PDO, ENSO × AMO, and PDO × AMO) widespread fires that occurred in each of the four possible phase pairs (i.e. + +, – –, + –, or – +) did not differ significantly from the frequencies expected by chance. Although the differences between observed and expected frequencies were not statistically significant, fires occurred most frequently during the following phase pairs: negative ENSO with negative PDO, negative ENSO with positive AMO, and negative PDO with negative AMO.

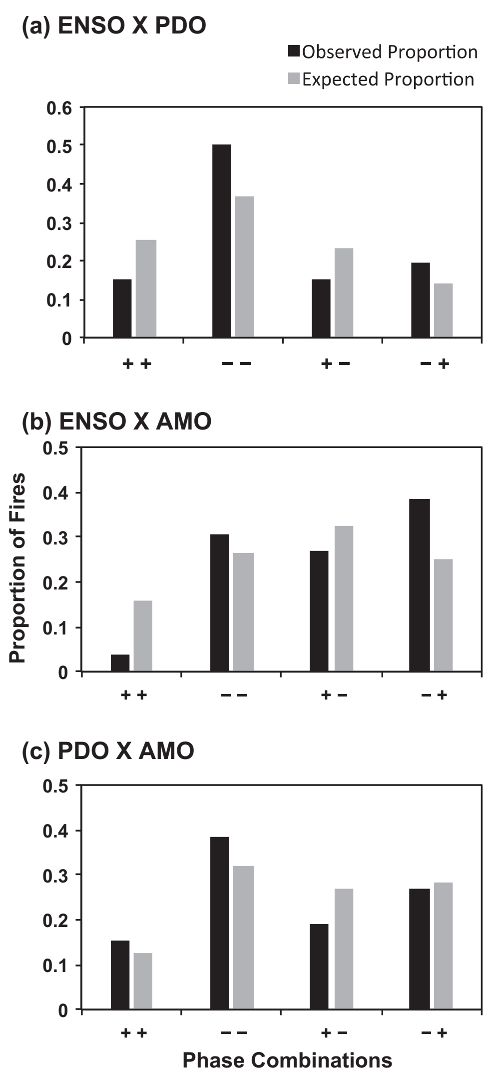

Fig. 5. Observed and expected frequencies of widespread fire occurrence in each two-way combination of the El Niño–Southern Oscillation (ENSO; Cook et al., 2008), the Pacific Decadal Oscillation (PDO; D'Arrigo et al., 2001) and the Atlantic Multidecadal Oscillation (AMO; Gray et al., 2004) during the period AD 1700–1880. In the case of PDO, three other reconstructions were also examined (Biondi et al., 2001; D'Arrigo and Wilson, 2006; MacDonald and Case, 2005). Differences between observed and expected frequencies were statistically insignificant in all cases according to chi-square goodness of fit tests ($\alpha = 0.05$).

4. Discussion

The synchrony of fires across study sites supports the importance of climate as a top-down driver of wildfire in the study area (Gedalof, 2011; Swetnam and Betancourt, 1998; Trouet et al., 2010). Fires may have ignited independently at separate sites but also may have ignited at one or more sites and then spread into the surrounding areas. Our study identified significant interannual relationships between widespread fire occurrence and regional to broadscale climate anomalies during the period AD 1700–1880. Our results from SEA of both PDSI and ENSO indicate that widespread fires tended to occur in dry years that were preceded by one or two wetter years. This finding is consistent with other studies in dry ponderosa pine forests of the southwestern USA (Grissino-Mayer and Swetnam, 2000; Swetnam and Betancourt, 1990, 1998). Our BEA results indicate statistically significant relationships only in the case of PDSI at a temporal window of $t = 0$. Specifically, we found that widespread wildfire was synchronous with negative, extreme PDSI events and asynchronous with positive, extreme PDSI events in the fire year ($t = 0$). This finding suggests that not only did fires occur in years characterized by negative PDSI, but that PDSI values during the fire year were often extreme (>1 SD below the mean).

Our BEA analyses revealed no statistically significant relationships between widespread wildfire and extreme ENSO events. These results should neither be interpreted as contradictory to the known importance of ENSO in driving wildfire in dry ponderosa pine forests (see Gartner et al., 2012; Swetnam and Betancourt, 1990; Veblen et al., 2000), nor as conflicting with the SEA findings we present in the current study. Findings from SEA and BEA are not directly comparable. In this study, SEA was used to evaluate whether the mean value of the Niño 3.4 reconstruction differed significantly before, during, and after years of widespread fire. BEA, on the other hand, was used to evaluate whether years characterized by extreme Niño 3.4 conditions (defined using a 1 SD threshold) and years of widespread fire were synchronous, asynchronous, or independent over a temporal window of 0–90 years. Our BEA findings for ENSO indicate that extreme Niño 3.4 events occurred independently of widespread fire during the period of analysis (AD 1700–1880). These findings should not be overgeneralized to rule out other possible relationships between ENSO and wildfire.

No statistically significant relationships were identified between widespread fire and variability of PDO and AMO through either SEA or BEA. Additionally, no statistically significant relationships were observed between widespread fire occurrence and two-way combinations of ENSO, PDO, and AMO. A recent study found that reconstructions of PDO were highly variable and that the choice of which reconstruction is used can significantly alter the results of PDO-wildfire analyses (Kipfmueller et al., 2012). We included assessment of multiple, widely-used PDO reconstructions and uniformly found no statistically significant relationships with widespread fire occurrence. Our results regarding a lack of relationship between either PDO or AMO and widespread fire are logical given the strong relationships between PDSI and ENSO and fire. In relatively biomass-limited systems where the dominant fuel consists of grasses, it is intuitive that fires would be driven by short interannual shifts between wet and dry conditions rather than by prolonged periods of drought or other prolonged climate conditions.

To our knowledge, this study was the first to use BEA to examine fire-climate relationships for a ponderosa pine study area in the southwestern USA. However, given that our study was limited to four sites in the Zuni Mountains of New Mexico, our findings may not apply more broadly. A regional study that uses BEA to examine fire–climate relationships for a network of southwestern, ponderosa pine fire-history sites will provide better context for our results and will further understanding regarding fire climatology across broad spatial and temporal scales. It may also be useful to consider alternative methods for defining extreme climate events when using BEA. In our study, extreme climate events were defined using a threshold based on 1 SD, but other definitions such as those based on percentiles are also possible (e.g., Gartner et al., 2012; Schoennagel et al., 2007). BEA can be used to ask different questions regarding fire-climate interactions than those associated with SEA. The methodology thus has the potential to expand our understanding of climate as a driver of fire even in systems where previous fire-climate analyses have already been conducted.

5. Conclusion

Contextualizing findings regarding historical climate–wildfire relationships in the face of ongoing climate and land-use change is challenging and requires caution. Some patterns that were prominent historically may no longer apply. For example, in recent years, a number of large, relatively high-severity fires have occurred in dry ponderosa pine forests during periods of prolonged drought without antecedent moisture conditions (e.g. the Rodeo–Chediski fire in the White Mountains of Arizona in 2002). Although historically these systems were relatively fuel-limited, a long legacy of anthropogenic disturbances including livestock grazing, fire suppression, and timber extraction activity have led to forest conditions now frequently characterized by more ample biomass to burn. Large-scale restoration efforts are currently underway in the southwestern USA and elsewhere. Although thus far restoration efforts have been of variable efficacy (see Graham et al., 2012; Roccaforte et al., 2010), targeted efforts to promote a frequent, low-severity wildfire regime in dry ponderosa pine forests are generally consistent with our understanding of historical fire activity in this forest type.

Acknowledgements

We thank I. Feathers, R. Foster, N. Li, A. McGhee, K. Russell, and H. Terrell for assistance with the field work as well as M. Peterson and K. Honeymon who assisted in the laboratory. We also thank S. Jones and N. Garland who assisted with both field and laboratory work and L. Stachowiak for creating the map of our study area. Lastly, we thank D. Gavin for the development of the K1D software used for BEA. This work was supported by the National Science Foundation Graduate Research Fellowship Program, the National Park Service Fire and Aviation Program, the University of Tennessee Graduate Summer Assistantship Program, and a J. Wallace and Kate Dean Graduate Fellowship from the University of Tennessee.

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