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Climate drives fire synchrony but local factors control fire regime change in northern Mexico

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Abstract. The occurrence of wildfire is influenced by a suite of factors ranging from "top-down" influences (e.g., climate) to "bottom-up" localized influences (e.g., ignitions, fuels, and land use). We carried out the first broad-scale assessment of wildland fire patterns in northern Mexico to assess the relative influence of top-down and bottom-up drivers of fire in a region where frequent fire regimes continued well into the 20th century. Using a network of 67 sites, we assessed (1) fire synchrony and the scales at which synchrony is evident, (2) climate drivers of fire, and (3) asynchrony in fire regime changes. We found high fire synchrony across northern Mexico between 1750 and 2008, with synchrony highest at distances <400 km. Climate oscillations, especially El Niño-Southern Oscillation, were important drivers of fire synchrony. However, bottom-up factors modified fire occurrence at smaller spatial scales, with variable local influence on the timing of abrupt, unusually long fire-free periods starting between 1887 and 1979 CE. Thirty sites lacked these fire-free periods. In contrast to the neighboring southwestern United States, many ecosystems in northern Mexico maintain frequent fire regimes and intact fire–climate relationships that are useful in understanding climate influences on disturbance across scales of space and time.

Key words: Atlantic Multidecadal Oscillation; climate; dendrochronology; El Niño-Southern Oscillation; fire history; fire regime; fire scars; Mexico; Pacific Decadal Oscillation; synchrony.

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INTRODUCTION

The occurrence of wildfire in a given ecosystem is influenced by a suite of factors ranging from "top-down" influences such as climatic oscillations and regional drought, to "bottom-up" localized influences such as ignitions, fuel availability, land use, and topography (Falk et al. 2007, Gill and Taylor 2009, McKenzie et al. 2011). Top-down and bottom-up drivers also interact; for example, climate patterns influence vegetation type and fuel availability, and local soil and topography can affect how strongly regional drought is expressed. Strong top-down control over fire at a regional scale is evidenced by synchronous fire occurrence at widely separated sites, whereas bottom-up drivers influence fire spread and local behavior, leading to more asynchronous fire occurrence among sites (Heyerdahl et al. 2001, Falk et al. 2011). Abrupt and persistent shifts in fire regimes that are not related to climatic conditions could also indicate the influence of bottom-up drivers. A large spatial network is needed for evaluating top-down/bottom-up influences because of the linkages between top-down influences and fire synchrony at widely separated sites and between bottom-up influences and asynchrony. Understanding cross-scale drivers of fire and climate–fire relationships is important for explaining tree recruitment patterns (Meunier et al. 2014*a*), carbon cycling (Mouillot and Field 2005), the relative importance of human vs. climate drivers of fire (Taylor et al. 2016), and for understanding how fire-adapted forests may respond to climate change (Flannigan et al. 2009).

Climate is the dominant time-varying top-down process regulating fire regimes. Using centuries-long records of fire from fire scars in tree rings and reconstructed climate indices, climate has been shown to influence fire occurrence in North American regions such as the southwestern United States (e.g., Swetnam 1990, Swetnam and Betancourt 1990, Swetnam and Baisan 1996, Grissino-Mayer and Swetnam 2000), the Pacific Northwest and southwestern Canada (e.g., Hessl et al. 2004, Heyerdahl et al. 2008*a*), the northern Rocky Mountains (e.g., Heyerdahl et al. 2008*b*), and Utah (Brown et al. 2008). Climate drives synchronous fire even at the scale of the North and South American continents (e.g., Kitzberger et al. 2001, 2007, Trouet et al. 2010, Falk et al. 2011). Collectively, these studies comprise a major archive of a key ecological process, as well as how climate influences that process, representing hundreds of study sites and tens of thousands of trees (Falk et al. 2010, 2011). Fire regime reconstructions from fire-scarred trees typically represent ecosystems with relatively frequent surface fires that most dominant trees survive, albeit sometimes with scars. Evidence from systems with infrequent, stand-replacing fire regimes in North America suggests that similar fire–climate relationships exist, although at longer time scales (Schoennagel et al. 2005, Sibold and Veblen 2006).

These networks of fire history sites have shown that large-scale spatial and temporal patterns of fire occurrence are highly correlated with the occurrence of regional drought (Falk et al. 2010). Droughts and pluvials are in turn driven by teleconnections with major coupled ocean–atmosphere oscillatory modes in the climate system (Diaz et al. 2001, Gray et al. 2003, McCabe et al. 2004, Woodhouse et al. 2009). The El Niño-Southern Oscillation (ENSO) affects fire occurrence throughout western North and South America, particularly the occurrence of widespread fire years across thousands of kilometers (e.g., Swetnam and Betancourt 1990, Kitzberger et al. 2001). Longer-phase climate oscillations, including the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO), interact with ENSO to reinforce or dampen regional drought conditions, which in turn influence historical fire occurrence patterns (Hessl et al. 2004, Schoennagel et al. 2005, Taylor and Beaty 2005, Sibold and Veblen 2006). However, most previous studies are limited to analyzing climate–fire relationships before the 20th century, because in much of North America north of Mexico, fire regimes were interrupted in the late nineteenth century by human influence, including livestock grazing and other land-use changes (Belsky and Blumenthal 1997, Heyerdahl et al. 2001, Swetnam et al. 2001).

Potentially facilitating our understanding of the historical and current relationships between climate and fire in North America, some areas in northern Mexico maintain relatively intact fire–climate dynamics. Human impacts in the mountains of northern Mexico have followed a different history than the United States, with large-scale livestock introduction largely deferred until post-revolutionary land reforms in the mid- to late-twentieth century. Comprehensive fire suppression was never achieved in some areas, despite management policies requiring it (e.g., Leopold 1937, Rodríguez-Trejo and Fulé 2003, Skinner et al. 2008, Fulé et al. 2012). Heyerdahl and Alvarado (2003) suggested that fire exclusion, where it did occur, was closely associated with the formation of *ejidos*, which are communally held and managed lands. When *ejidos* were granted as part of an agrarian land reform in the early to mid-twentieth century, fire regimes may have changed due to increased livestock grazing, road building, logging, and changing the traditional role of fire (Heyerdahl and Alvarado 2003). A documented example of livestock grazing expansion associated with fire regime interruption was described by Fulé and Covington (1999). Although some sites were interrupted around the time of *ejido* formation (e.g., Heyerdahl and Alvarado 2003, Poulos et al. 2013), a few sites experienced fire regime interruption in the late 1800s or early 1900s, long before the formation of *ejidos* (e.g., Yocom et al. 2010), and fire regimes at other sites have fires continuing to the present (e.g., Fulé et al. 2011).

A network of fire history sites has been developed in northern Mexico over the past several decades. Many of these sites have been used to explore fire–climate relationships as well as historical fire regimes, although climate linkages to fire occurrence have been studied only at the scale of individual sites or within mountain ranges. Only in the last few years are new data sets being completed that expand the network to eastern Mexico (Yocom et al. 2010, 2014, Poulos et al. 2013) and northern Chihuahua (Fulé et al. 2011, Meunier et al. 2014*b*). Until the establishment of a large fire history network, a broad-scale analysis of top-down and bottom-up drivers of fire has not been possible for this part of North America.

Our goal was to assess the patterns and drivers of fire regimes across northern Mexico. Our first objective was to quantify synchrony of fire across spatial scales. Our second objective was to evaluate the influence of climate on fire occurrence across the region. Synchrony of fires (and nonfire years) at broad scales among distant sites, and relationships between fire dates and climatic oscillations such as ENSO, are evidence of top-down climatic influences. Our last objective was to assess asynchrony in dates of abrupt changes in fire regimes, which would reflect bottom-up, local influence on the timing of these changes.

Methods

We included 67 fire history sites in northern Mexico, originally sampled as individual research projects (Fulé and Covington 1997, 1999, Heyerdahl and Alvarado 2003, Fulé et al. 2005, 2011, 2012, Drury and Veblen 2008, Skinner et al. 2008, Cerano Paredes et al. 2010, Yocom et al. 2010, 2014, Poulos et al. 2013, Meunier et al. 2014*b*, P. Z. Fulé, *unpublished data*; Appendix S1: Table S1). The sites extend geographically from northern Baja California in the west, east to the Sierra Madre Oriental, north in the Sierra Madre Occidental to close to the U.S.–Mexico border, and south in the Sierra Madre Occidental to southern Durango (Fig. 1). All sites are at 1500 m above sea level or higher and are dominated by conifer species. Eighteen tree species were sampled across all sites, including 14 species of pine (Appendix S1: Table S2). Fire chronologies were assembled from the International Multiproxy Paleofire Database or contributed by the original investigators. At each site, fire-scar data were sampled in an area ranging from 2 to 353 ha (mean 29, SD 49), and the number of crossdated fire-scarred tree samples from each site ranged from 6 to 104 (mean 29, SD 16; Appendix S1: Table S1). Although the area sampled and the number of samples collected varied widely between sites, we used all sites in this analysis because we did not calculate statistics such as the mean fire interval, where widely variable site size or the number of samples could be problematic for comparison between sites (van Horne and Fulé 2006). We identified fire years at each site as those years when scars occurred on ≥2 trees (to eliminate lightning scars or very small fires that scarred only one tree), and these dates were compiled into site chronologies.

We grouped the 67 sites into five geographic regions, designated Baja, Occidental North, Occidental Central, Occidental South, and Oriental (Fig. 1). We identified "within-region" synchronous fire years as those in which multiple sites in a region recorded fire, to evaluate climate impacts on fires separately for each region. To do this, we identified the years of highest fire synchrony among sites within each region (range 23–31 yr identified per region). We also identified

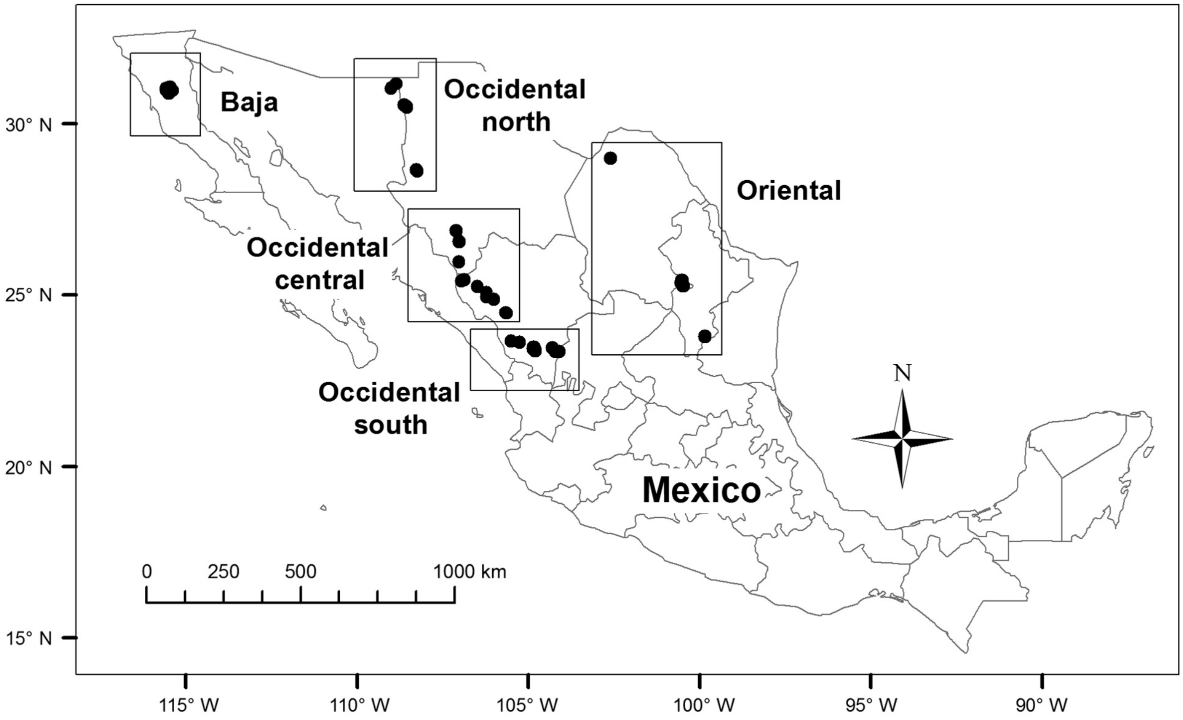

Fig. 1. Map of 67 fire history sites within five regions in Mexico. Sites follow major mountain ranges. From west to east, Sierra San Pedro Mártir, Sierra Madre Occidental, Sierra Madre Oriental.

"across-region" synchronous fire years as those when ≥4 regions recorded fire synchronously. We identified no-fire years as those when 0 regions recorded a fire, and we also identified years when one, two, or three regions recorded a fire.

To assess fire synchrony across scales, we first calculated Jaccard distance in fire dates for every pair of sites. We then analyzed Jaccard distance as a function of geographic distance between each pair of sites using a Mantel test (Mantel 1967) and a Mantel correlogram (Oden and Sokal 1986, Borcard and Legendre 2012). A Mantel test analyzes the correlation between two distance matrices (in this case, Jaccard distance and geographic distance), while a Mantel correlogram tests for correlation at different distance classes (Legendre and Legendre 1998). We used the functions "mantel" and "mantel.correlog," each with 1000 permutations, in the R package "vegan" for these tests (Oksanen et al. 2016), and we set breakpoints in the Mantel correlogram for every 100 km.

We compared fire chronologies (from 1750 to 2005) to an independently derived tree-ring reconstruction of ENSO to assess potential climate forcing, using a winter NINO3 (December through February) SST anomaly index (Cook et al. 2008). Negative (positive) NINO3 index values are associated with La Niña (El Niño) conditions. To address temporal autocorrelation in the NINO3 index, we fit autoregressive integrated moving average models and used the resulting white noise residuals in our analyses. To evaluate the influence of ENSO on fire occurrence, we used superposed epoch analysis (SEA) in FHX2 (Grissino-Mayer 1995) to compare fire occurrence with NINO3 climate index values during fire years, five years prior to fire years, and two years after fire years. To assess statistical significance of the SEA results, we calculated 95% confidence intervals using bootstrapped distributions of climate data in 1000 trials.

We evaluated the influence of two-way and three-way combinations of the phases of AMO, PDO, and ENSO on fire occurrence in northern Mexico, from 1750 to 1990 (D'Arrigo et al. 2001, Gray et al. 2004, Cook et al. 2008). Although Kipfmueller et al. (2012) suggested that linking PDO with historical fires is problematic because different reconstructions yield different results, PDO has been identified as a potentially important driver of regional fire across a range of forested ecosystems (Schoennagel et al. 2005, Kitzberger et al. 2007, Margolis and Swetnam 2013). We used the D'Arrigo et al. (2001) reconstruction because it is based on a wide geographic range of trees, including trees from northern Mexico (see Margolis and Swetnam 2013). Expected values of fire occurrence in each phase combination were calculated from the proportion of years from 1750 to 1990 in each of the combinations, and observed values were the number of across-region fire years in each phase combination. We used χ^2 goodness-of-fit tests to compare the expected fire occurrence with observed fire occurrence to determine whether fires occurred disproportionately during particular phase combinations of large-scale climate oscillations (positive and negative phases of AMO, PDO, and ENSO). *P*-values were calculated using a Monte Carlo simulation, randomly sampling from the expected fire occurrence distribution, with 1000 replicates. Statistics were calculated using the "Stats" package in R (R Core Team 2015).

To determine dates of fire regime interruption, for each site we identified the last fire date before an unusually long fire-free interval, defined as greater than the mean fire interval for that site plus two standard deviations of the mean, and greater than 12 yr, representing half of the interval commonly used to designate "frequent" fire regimes (Heinselman 1973).

RESULTS

Between 1750 and 2005, there were 13 yr when all five regions in northern Mexico recorded fire: 1798, 1820, 1838, 1851, 1860, 1874, 1877, 1894, 1899, 1902, 1909, 1916, and 1917. There were an additional 55 yr when four regions recorded fire; we designated the 68 yr when ≥4 regions recorded fire as across-region synchronous fire years (Appendix S1: Fig. S1). There were 48 yr in which only one region recorded a fire, 63 yr in which two regions recorded a fire, and 52 yr in which three regions recorded a fire. There were 25 yr in which no fires were recorded in any of the regions.

Jaccard distance in fire dates was significantly related to geographic distance between sites based on results of the Mantel test ($r = 0.31$, $P < 0.001$).

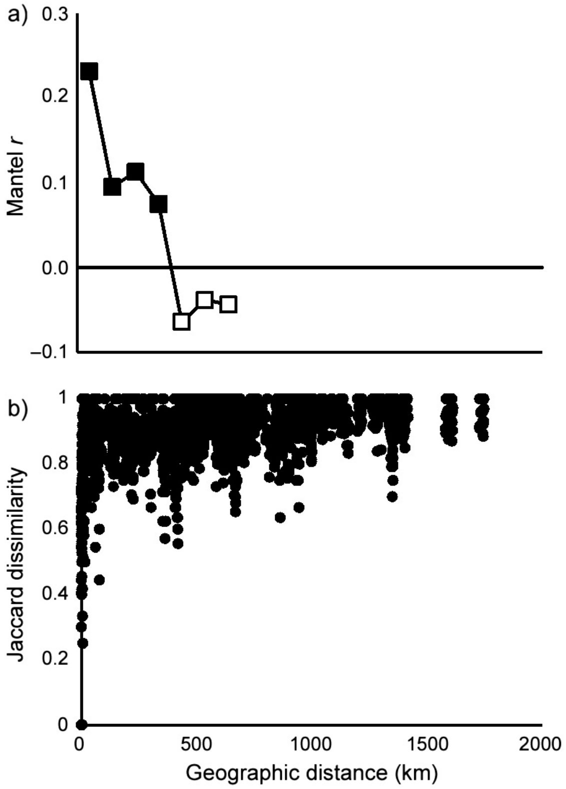

Fig. 2. Jaccard dissimilarity among fire dates by geographic distance between sites. (a) Mantel correlogram of Jaccard dissimilarity among fire dates in six distance classes (each class = 100 km). A black square indicates a significant correlation between Jaccard dissimilarity and geographic distance for that distance class. (b) For each pair of sites, Jaccard dissimilarity plotted by geographic distance (km).

Plotting the Mantel correlogram results (Fig. 2a), as well as the Jaccard distance index as a function of geographic distance between each pair of sites (Fig. 2b), revealed that fire dates were more similar at closer geographic distances. Jaccard distance was positively and significantly associated with geographic distance for the first four distance classes, under 400 km (Fig. 2a).

El Niño-Southern Oscillation by itself was a significant driver of synchronous fire years. Average NINO3 values were significantly low (La Niña-type conditions) in years when ≥4 regions recorded fire, and significantly high (El Niño-type conditions) in years when 0 regions recorded fire (Fig. 3). Average NINO3 values

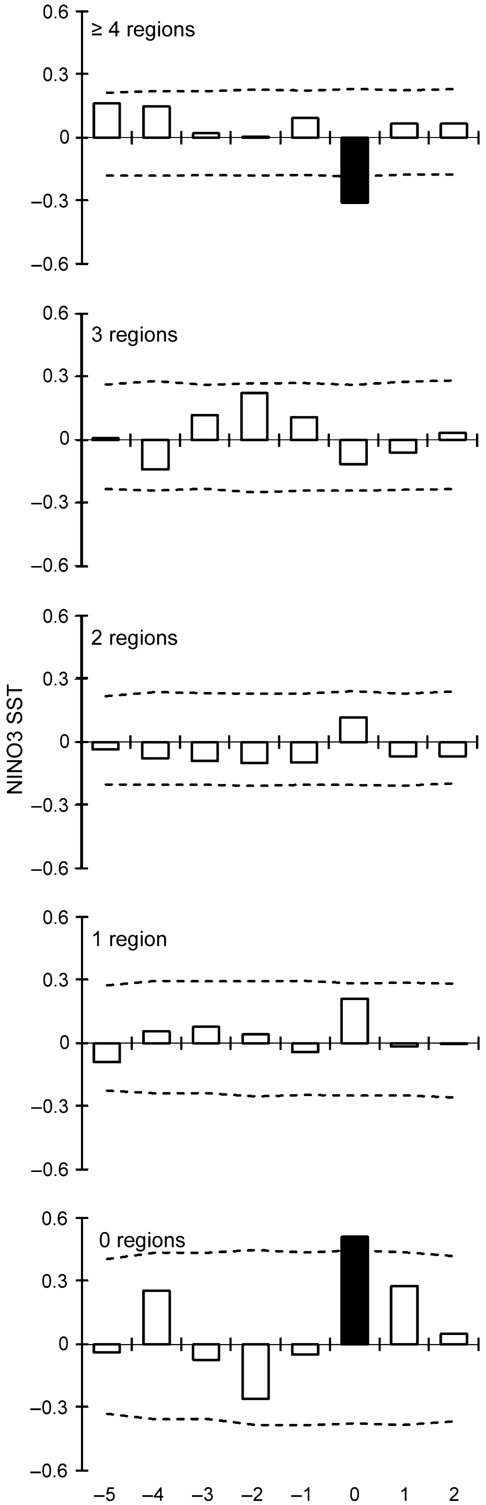

Fig. 3. Superposed epoch analysis showing average departure from the mean value of NINO3 SST (Cook et al. 2008) for years when ≥4, 3, 2, 1, and 0 regions recorded fire. Fire years are indicated by 0 on the *x*-axis, and values are also given for 5 yr prior to fire years (negative values on *x*-axis) and 2 yr after fire years. Dashed lines represent the 99% confidence interval.

were significantly low in within-region fire years in Baja, Occidental North, Occidental Central, and Oriental, but not in Occidental South (Appendix S1: Fig. S2). ENSO in antecedent years was important in some regions as well: NINO3 values were significantly above-average one year prior to fire years in Occidental North and one and two years prior to fire in Occidental South (Appendix S1: Fig. S2).

In the three-way combinations of climate oscillation phases, there were more fires than expected in the combinations where PDO and ENSO were both negative, especially when AMO was positive (Fig. 4). The chi-square test for the three-way combinations was significant ($\chi^2 = 17.1$, $P = 0.02$). In two-way combinations, fires occurred more often than expected when both the PDO and ENSO were in negative phases ($\chi^2 = 14.2$, $P = 0.003$), and when AMO was positive and ENSO was negative ($\chi^2 = 12.7$, $P = 0.007$). Expected vs. observed number of fires were not significantly different in AMO × PDO two-way combinations.

Fire interruption dates ranged from 1887 to 1979; 30 (45%) sites never experienced fire interruption (Fig. 5). The Sierra Madre Oriental experienced fire regime interruption earliest of the five regions (several sites prior to 1920), although there was variation within the region, with fire interruption dates ranging from 1887 to 1952. Three sites in that region had uninterrupted fire regimes according to our definition. Fire regime interruption in Baja California occurred between 1932 and 1955, with five sites not experiencing fire interruption. In Occidental North, most sites had a fire regime interruption between 1932 and 1955, with four sites recording uninterrupted frequent fire. In Occidental Central, seven sites maintained uninterrupted

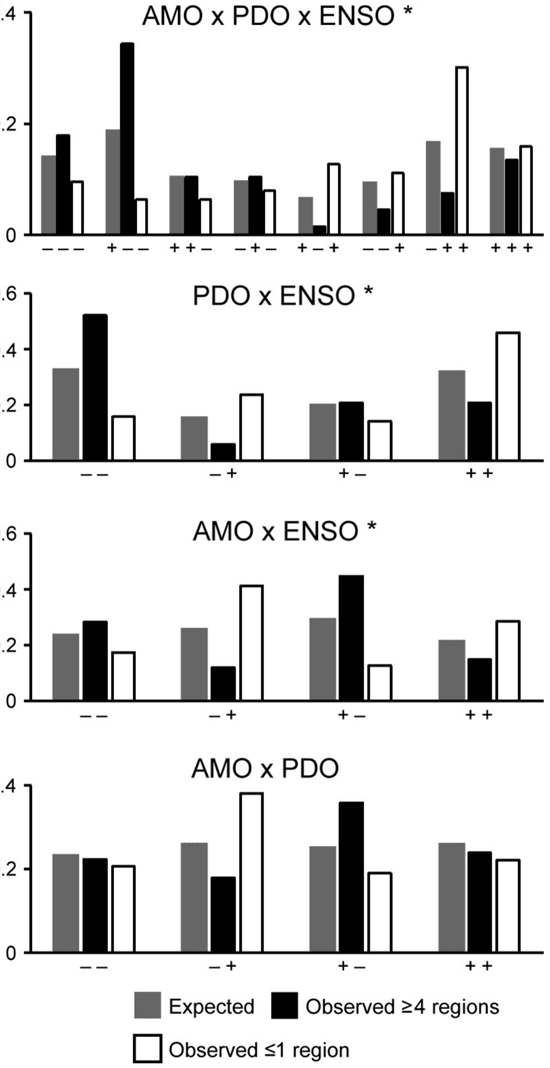

Fig. 4. Expected and observed frequencies of fire in two-way and three-way combinations of AMO, PDO, and ENSO. Warm (positive) phases of these oscillations are represented by + symbols, and cool (negative) phases are represented by − symbols. Significant differences between expected and observed proportions of fire occurrence (represented by *) were evaluated using chi-square tests.

fire regimes; other sites had a change in fire regime as early as 1935 and four experienced a change in the 1950s. In Occidental South, fire regime interruption dates were again scattered, ranging from 1930 through the subsequent decades. Eleven sites in this region had a continuous record of fire.

DISCUSSION

Top-down and bottom-up drivers of fire are evident in the patterns of fire seen across northern Mexico. The influence of top-down (climatic) factors can be seen in the synchrony of fires over time and space, with 68 yr (27%) of high fire synchrony during the period of analysis, and an additional 25 synchronous years (10%) in which none of the regions recorded fire. Although synchrony was noted across the entire study area of northern Mexico, spatial autocorrelation is present in fire dates, and as would be expected, synchrony of fires appears to be stronger at shorter geographic distances, up to about 400 km.

Climate was a significant driver of the synchrony seen in northern Mexico. We found an association between La Niña conditions (negative phase of ENSO) and across-region synchronous fire years (≥4 regions), as well as a significant association between La Niña conditions and within-region synchronous fire years in four of the five regions. The ENSO–fire association is founded on the connection between ENSO and precipitation; modern Mexican precipitation records show a clear link to ENSO phases (Caso et al. 2007). Modern fire atlas records are temporally and spatially limited, but our results are also corroborated by Návar Cháidez (2011), who found that an index of ENSO explained over 30% of variation in area burned in the state of Durango in recent years. It is notable, however, that within-region synchronous years in Occidental South were not significantly related to La Niña years in our study; this is the same result that Drury and Veblen (2008) found in this region. Drury and Veblen (2008) suggested that in the southern Sierra Madre Occidental, other climatic drivers were more important; it is close to the transition zone north of which La Niña events are associated with dry conditions and south of which El Niño conditions are associated with dry conditions (Stahle et al. 2012, also see climate maps in Caso et al. 2007 and Yocom and Fulé 2012).

The PDO and AMO were also influential in driving across-regional fire occurrence, with greater than expected numbers of synchronous fires occurring when PDO was negative and AMO was positive, in combination with negative ENSO. The PDO has also been shown to be a significant driver of fire in western North America

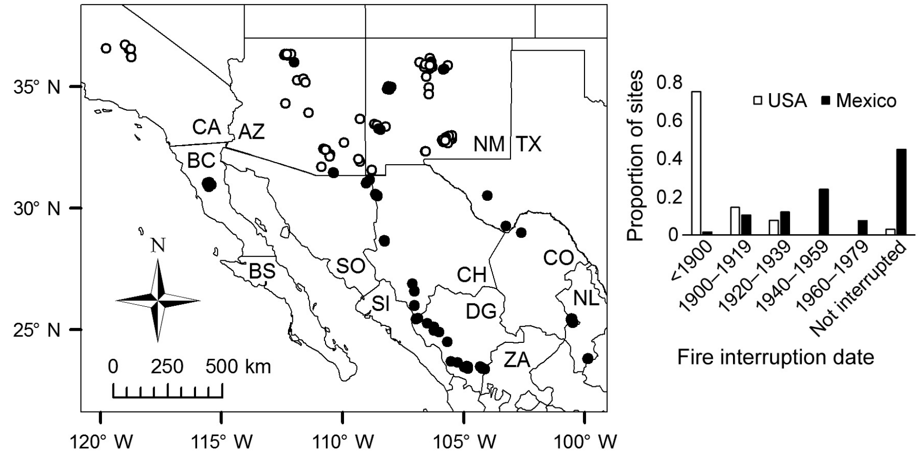

Fig. 5. Left: map showing fire interruption dates in the southwestern United States and northern Mexico. Unfilled circles represent a fire interruption date prior to 1900, and filled circles represent a fire interruption date later than 1900. Right: number of sites in each country that experienced fire interruption by 20-yr category.

(Kitzberger et al. 2007) and in regional studies in the Pacific Northwest (Hessl et al. 2004, Heyerdahl et al. 2008*a*), western Colorado (Schoennagel et al. 2007), and Utah (Brown et al. 2008). The AMO has been shown to drive fire synchrony at a continental scale (Kitzberger et al. 2007). Although top-down influences are important, their strength in synchronizing fire varies among regions in northern Mexico. For example, in Baja California, a maximum of 50% of sites (5/10) ever recorded fire in the same year, but there were two instances when 100% of the 11 sites in Occidental North recorded fire in the same year.

Fire regime interruption dates were highly variable across sites, spreading over nearly 100 yr. Almost half of the sites were classified as having an uninterrupted fire regime. It should be noted, however, that although we calculated fire interruption using a mathematical definition to avoid bias, several sites that were categorized as having continuous fire (e.g., MA in Oriental, CA in Occidental South, and TM in Occidental North) seemed to shift toward longer fire intervals during the 20th century (Appendix S1: Fig. S1). This means that even in "uninterrupted" sites, fire may not be occurring at the same frequency as it did historically. We did not find evidence across northern Mexico of the "hiatus" in fire in the transition from the late 18th to the early 19th century that has been pointed out in sites in the western United States and in Baja California (e.g., Swetnam 1990, Swetnam and Betancourt 1998, Stephens et al. 2003), although in some regions the fire record may not be long enough to detect such a hiatus (Appendix S1: Fig. S1). Stephens et al. (2003) suggested three potential reasons for the change in fire that was noted in the late 18th century in Baja California: grazing, a decline in native populations, and changes in regional climate. The first two reasons were related to the establishment of the San Pedro Martir Mission, which is a special circumstance not applicable to other sites in northern Mexico.

The variability in fire regime interruption dates and the presence of only one site in northern Mexico (out of 67) with a fire regime interruption date before 1900 are in striking contrast to the adjacent southwestern United States, where fire regimes were typically interrupted in a period between about 1870 and 1900 (Fig. 5; Swetnam and Baisan 2003, although see Grissino-Mayer and Swetnam 2000, Sakulich and Taylor 2007, and Poulos et al. 2013 for examples of locations where frequent fires continued into the 1920s or later). This interruption has been attributed to the removal of Native Americans, introduction of sheep and other livestock, other land-use changes, and subsequent fire suppression policies (Savage and Swetnam 1990, Belsky and Blumenthal 1997, O'Connor et al. 2014, Taylor et al. 2016). The variability in fire regime interruption dates across northern Mexico is consistent with the mechanism of human land use as the driving force behind changing fire regimes over the 19th and 20th centuries in western North America. In a direct cross-border comparison between mountain ranges separated by only 150 km in Arizona, United States, and Chihuahua, Mexico, Fulé et al. (2012) found that fire regimes in both ranges were indistinguishable and synchronized by climate before 1892, after which fires were abruptly and completely excluded from the Arizona sites. Fire regimes in the four Chihuahua study sites continued uninterrupted until the 1950s with one site burning frequently up to the present (Fulé et al. 2012). Forests where modern fires continue in historical patterns in synchrony with contemporary climate, such as many sites in northern Mexico, provide a rare opportunity to examine climate–fire relationships without major human-caused alteration.

In northern Mexico, variable local land-use history is the likely reason for the variability in fire interruption dates. For example, the three sites at Pino Gordo, which have an uninterrupted fire regime, are difficult to access, and internal political struggles have kept logging from occurring there (Fulé et al. 2011). In other sites, fire interruption was coincident with the formation of *ejidos* (Heyerdahl and Alvarado 2003, Drury and Veblen 2008, Poulos et al. 2013) or reduction in Native American populations that used fire (Evett et al. 2007). In contrast to the western United States, where a wave of settlers, livestock, and railways washed across much of the territory before 1900 and changed the fire regime of widespread areas within a short time (Swetnam and Baisan 2003, Taylor et al. 2016), many sites in Mexico have individual stories of land use, human interaction, and fire regime change.

The climate in the southwest and northern Mexico is projected to become more arid in the near future, with this transition already underway (Seager et al. 2007, 2009). Drier conditions are conducive to fire spread, and longer, warmer summers have been linked to greater area burned in the western United States (Westerling et al. 2006). On the other hand, fine fuel production may be limited with drier conditions, resulting in less frequent fires. As climate change projections and our understanding of how climate change will impact Mexico improve (Sáenz-Romero et al. 2010), explorations of historical climate–fire relationships will provide insight into future fire regimes.

Information from the Mexican network is being applied to align national fire policy more closely with quantitative data on the fire ecology of specific forest types (Rodríguez-Trejo 2008, Jardel et al. 2014). Sites with continuing fire regimes have provided insights into forest structure (Fulé and Covington 1997), fuel biomass (Stephens et al. 2007), fire behavior (Rivera-Huerta et al. 2016), and wildlife habitat (*unpublished manuscript*) that are unavailable for study elsewhere. In addition, many sites in Mexico that have maintained an active disturbance regime may be more resilient in the future as climate continues to change, providing a valuable model for other North American forests considered vulnerable to climate change (Stephens et al. 2010, Hurteau et al. 2014).

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