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Climate and human influences on historical fire regimes (AD 1400–1900) in the eastern Great Basin (USA)

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Abstract

High fire activity in western North America is associated with drought. Drought and fire prevail under negative El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) phases in the Southwest and with positive phases in the Northwest. Here, I infer climate effects on historic fire patterns in the geographically intermediate, eastern Great Basin and seek out evidence of human influence on reconstructed fire regimes. Surface fire chronologies were constructed for 10 sites using tree-ring-based fire scars. Regional (67) and local (247) fire years and no-fire (187) years were identified from 1400 to 1900 CE. I compared fire chronologies with indices of the Palmer Drought Severity Index (PDSI), ENSO, and PDO. Regionally, fires were significantly more common during drought and were associated with negative ENSO and positive-to-negative PDO transitions while no-fire years were associated with positive ENSO and negative-to-positive PDO transitions. Conditions were significantly wetter 2 years prior to regional fire years and drier 4 years prior to no-fire years, providing evidence that fires were historically fuel limited. Local fire years occurred under a broad range of climate conditions. Most sites showed either persistent late or bimodal (early and late) fire seasonality patterns. These patterns are distinct from the mid-season peak observed for modern lightning-caused fires, suggesting a human influence on historical ignition patterns. Results demonstrate that climate was an important synchronizer of fire at the regional scale and that locally fire regimes were the product of climate-regulated fuels and some combination of human and lightning ignition patterns.

Keywords

anthropogenic fire, El Niño Southern Oscillation, fire history, fire seasonality, Pacific Decadal Oscillation, Palmer Drought Severity Index

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Introduction

Climate influences fire probability and pattern through its effect on the accumulation and conditioning of fuels. Analysis of multi-century tree-ring-based fire chronologies from the North American Southwest (Brown and Wu, 2005; Margolis and Balmat, 2009; Swetnam and Betancourt, 1990, 1998), Central Rockies (Donnegan et al., 2001; Grissino-Mayer et al., 2004; Schoennagel et al., 2005; Sherriff and Veblen, 2008), Northern Rockies (Brown, 2006; Heyerdahl et al., 2008a), Northwest (Hessl et al., 2004; Heyerdahl et al., 2002, 2008b; Taylor et al., 2008), Pacific Southwest (Skinner et al., 2008; Stevens and Collins, 2004; Swetnam, 1993; Taylor and Beaty, 2005), and Intermountain highlands (Brown et al., 2008) and written records of modern fire patterns (Abatzoglou and Kolden, 2013; Littell et al., 2009; Morgan et al., 2008; Westerling et al., 2006) provide consistent documentation of the link between drought and increased fire occurrence in western North America. In dry forests, antecedent wet conditions may increase the probability for major fire years by increasing the production and continuity of fine fuels needed for surface fire spread (Brown et al., 2008; Margolis and Balmat, 2009; Sherriff and Veblen, 2008). Historically, wet–dry cycles synchronized fire activity at regional scales (Grissino-Mayer et al., 2004; Heyerdahl et al., 2008a, 2008b; Kitzberger et al., 2007; Morgan et al., 2008; Skinner et al., 2008; Taylor et al., 2008).

Climate variability in western North America and associated patterns of fire occurrence have been coupled to fluctuations in Pacific Ocean surface temperatures (SST) including the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO; Kitzberger et al., 2007; Westerling and Swetnam, 2003). In the Southwest, negative phases of ENSO and PDO result in relatively dry conditions and high fire occurrence and positive phases result in wet conditions and low fire occurrence (Margolis and Balmat, 2009; Swetnam and Betancourt, 1990, 1998). The effects of one or both of these climate patterns appear to extend into the Central Rockies (Donnegan et al., 2001; Sherriff and Veblen, 2008), Colorado Plateau (Brown et al., 2008), and as far south as Baja California (Skinner et al., 2008). ENSO and PDO effects on precipitation and fire activity in the Northwest tend to be opposite those of the Southwest; negative phases are wet and positive phases are dry, which in turn favor higher than average fire activity (Heyerdahl et al., 2002, 2008b). When ENSO and PDO phases are in sync (+/+ or −/−) their effects on climate and fire activity

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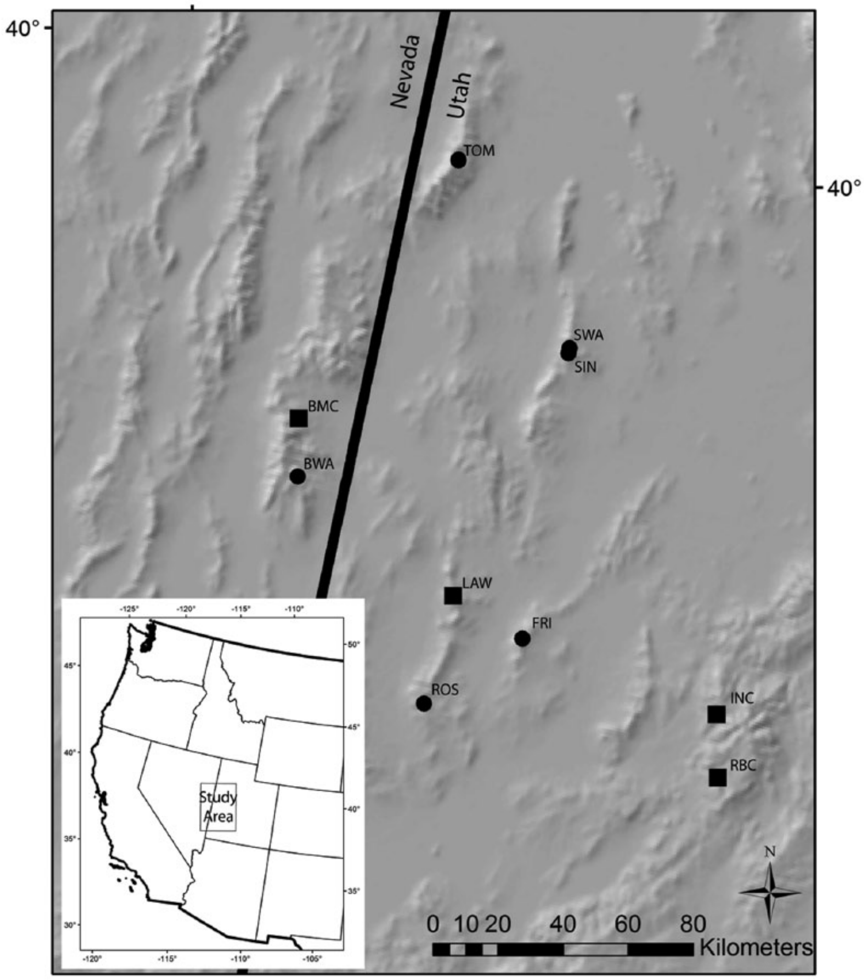

Figure 1. Map showing eastern Great Basin mountain ranges with the locations of 10 fire history sites. Study sites include the Right Fork of Beaver Creek (RBC) and Indian Creek Canyon (INC) on the Tushar Mountains, Frisco Peak (FRI) on San Francisco Mountain, Lawson Cove (LAW) and Rose Spring Canyon (ROS) on the Wah Wah Range, Burnt Mill Canyon (BMC) and Big Wash (BWA) on the South Snake Range, Sinbad Springs (SIN) and Swasey Mountain (SWA) on the House Range, and Tom's Creek Canyon (TOM) on the Deep Creek Range. Squares indicate sites with a gridded sampling design and circles designate locations where targeted sampling strategies were employed.

are magnified (Brown et al., 2008; Gershunov et al., 1999; Heyerdahl et al., 2008b; McCabe and Dettinger, 1999; Skinner et al., 2008). It has been suggested that the geographic fulcrum that separates these opposing climate–fire modes lies near ~40° N latitude (Brown and Comrie, 2004; Dettinger et al., 1998; Mock, 1996; Schoennagel et al., 2005). An understanding of the nature of past and present climate–fire relationships on landscapes proximal to this alleged transition zone is lacking and may be critical for assessing geo-spatial variation in fire patterns under changing climate conditions and whether this fulcrum has changed location through time.

Fire is also regulated by the frequency and timing of ignitions, either as the result of dry lightning storms or human activities. Teasing out the relative importance of each in historic fire chronologies can be difficult, especially where the probability of ignition is high from both sources (Allen, 2002; Griffin, 2002). Allen (2002) proposed that indirect evidence of human influence on historic fire regimes might come in the form of unexpected patterns in fire frequency or seasonality, or in decreased climate–fire correlations.

My objectives were to (1) analyze the effects of climate drivers on historic surface fire variability for eastern Great Basin forests located in close proximity to 40° N latitude and (2) assess variability in fire seasonality as indirect evidence of a possible human footprint on past fire regimes. I explore relationships among multi-century, tree-ring-derived fire chronologies and existing, tree-ring-based indices of regional climate that capture annual variability in summer temperature and drought as well as large-scale climate patterns that have been shown to fluctuate over longer time periods (ENSO and PDO). I propose that differences observed between fire seasonality patterns manifest prior to Euro-American settlement (~1860) and those of modern fire records, or predicted from climate and biogeographic settings, constitute indirect evidence for indigenous human influence on fire ignitions and thus fire regimes (Allen, 2002; Williams, 2004).

Study area

Biogeographic setting

The Great Basin encompasses the northern, elevated section of the Basin and Range Province of western North America. The region is characterized by over 100 separate mountain ranges with a generally north/south orientation. The climate is generally dry due to rain shadow effects of the Sierra Nevada and Cascade Ranges to the west and Rocky Mountains to the east (Peterson, 1994). Represented in this study are the Tushar Mountains on the eastern rim of the Great Basin and San Francisco, Wah Wah, Snake, House, and Deep Creek Ranges located progressively to the north and west (Figure 1). The study area covers approximately 1.7° latitude and 1.9° longitude and is immediately south of 40° N (Table 1), the proposed approximate pivot point for the dipole pattern of droughts and pluvials associated with ENSO and PDO variability.

Table 1. Fire chronology sites from the eastern Great Basin arranged from north to south.

Site (code)	Mountain range	Location (LAT/LON)	Elevation range (m)	Area (ha)	Trees sampled	Fire years	Recording years
Tom's Creek Canyon (TOM)	Deep Creek	39°52′ N/113°52′ W	2475–2480	5	6	16	294
Swasey Mountain (SWA)	House	39°24′ N/113°19′ W	2370–2620	30	14	15	443
Sinbad Springs (SIN)	House	39°23′ N/113°19′ W	2375–2395	1	4	20	439
Burnt Mill Canyon (BMC)*	Snake	39°02′ N/114°16′ W	2365–3230	455	110	99	734
Big Wash (BWA)	Snake	38°52′ N/114°14′ W	2480–2560	20	28	40	307
Lawson Cove (LAW)*	Wah Wah	38°37′ N/113°34′ W	2195–2685	430	137	124	707
Frisco Peak (FRI)	San Francisco	38°32′ N/113°17′ W	2580–2770	60	27	59	796
Indian Creek Canyon (INC)*	Tushar	38°23′ N/112°23′ W	2365–2550	130	32	57	754
Rose Spring Canyon (ROS)	Wah Wah	38°17′ N/113°36′ W	2240–2330	120	30	116	661
Right Fork, Beaver Creek Canyon (RBC)*	Tushar	38°12′ N/112°27′ W	2360–3080	910	167	105	501

Names with asterisk were gridded sites.

Human occupation

The Great Basin has been inhabited by humans for at least 13,000 years (Grayson, 2011; Simms, 2008). The study area encompasses a region where, immediately prior to Euro-American settlement, Western Shoshone, Ute, and Southern Paiute cultures converged in what is now western Utah (Simms, 2008). The mobile, hunter-gatherer economies practiced by these inhabitants contrast with the more sedentary, semi-agricultural model of the Fremont that appears to have dominated the area from 900 to 1300 CE. For millennia before the Fremont, Archaic foraging strategies included the desert-mountain settlement pattern with wide-ranging seasonal migrations, and the less-mobile wetland settlement pattern in which economies benefited from resource-rich environments such as those found at lake margins and marshes (Janetski and Madsen, 1990; Simms, 2008). Throughout this long pre-history, fire undoubtedly had many useful applications and was an essential tool for manipulating natural environments (Williams, 2004) as well as an accidental consequence of occupation (Kay, 2007). However, knowledge regarding specific practices used in this region and how they might have varied through space and time is lacking. Griffin (2002) generalized practical purposes for setting fire into three categories typical of hunter-forager societies namely: (1) to increase the quantity and quality of useful vegetation, (2) to improve or maintain habitat for important animals, and (3) to drive game in hunting. In addition to utilitarian applications, aboriginals may have conducted pyro-modification of Great Basin landscapes to fulfill perceived stewardship responsibilities born from prevailing belief systems (Spoon et al., 2015). Numerous, allegedly human-set fires were observed and recorded in the fall of 1776 by the Dominguez–Escalante expedition while passing through the eastern margins of the Great Basin (Chavez and Warner, 1976). In spite of these and other records (see Griffin, 2002; McAdoo et al., 2013), the relative importance of human-set fires on historic fire regimes of western North America is not well understood and remains a point of scientific disagreement.

As with other parts of the continent, the first impacts of European colonization in the Great Basin were likely from diseases to which indigenous peoples had little resistance. Elsewhere, repeated epidemics in the 1500s to 1700s reduced Native American populations by 70% or more (Butzer, 1992; Reff, 1991; Thornton, 1987). Evidence for a disruption in human fire ignition patterns associated with drastic depopulation might be anticipated.

Euro-American settlement within the study area began in the 1850s (Young et al., 1979). Settlements were small and widely dispersed, especially west of the better-watered valleys located adjacent to mountains forming the eastern rim of the Great Basin. Farming and ranching with horses, cattle, and sheep were the principal economic activities of early settlers. Regionally, stocking rates were generally low until the 1880s when the number of sheep trailed to the area for winter–spring grazing increased dramatically and remained high for 50+ years (Murdock and Welsh, 1971). Large numbers of domestic livestock impacted surface fire regimes throughout the western United States by reducing the quantity and continuity of fine fuels (Covington and Moore, 1994; Mandany and West, 1983; Pyne, 1982). The timing and intensity of livestock-induced impacts on fire regimes within the study area likely varied in response to such factors as drinking water availability, ruggedness of terrain, and trailing distance.

The need for fire suppression was a point of debate in the United States until 1910 when the federal government adopted an aggressive policy to suppress fire on all public lands (Keane et al., 2002; Pyne, 1982). Similar to the effects of livestock, the application of this policy within the sparsely inhabited and undervalued study area must have varied considerably and may have been essentially non-existent on remote mountain ranges before post-World War II mechanization extended agency capacity to fight fire on most landscapes.

Methods

Historical surface fire chronology reconstructions

Fire-scar-based fire histories were reconstructed for 10 sites with a combined range in elevation of 1035 m (Figure 1; Table 1). A systematic sampling strategy (see Brown et al., 2008) was used to sample small watersheds at four sites. Data from these sites were used in a 270-year climate–fire analysis for Utah and eastern Nevada (Brown et al., 2008). Basic fire regime and forest demographic data for the same set of sites are presented in Heyerdahl et al. (2011). An analysis of fine-scale fire regime and vegetation variability is available for two sites (Kitchen, 2012). I employed a targeted sampling approach (Van Horne and Fulé, 2006) for the remaining six sites in which sample tree number and sample area varied (Table 1). One or more partial cross-sections were removed from scarred surfaces (cat-faces) of fire-scarred trees using chainsaws and standard methods (Arno and Sneck, 1977). Although trees with multiple scars were selected preferentially, numerous trees with one to three scars were also sampled. Because sites differed in sample strategy, effort, and area, intra-site comparisons regarding fire frequency were not attempted.

Sample pieces were stabilized and sanded until cell structure was discernible using a binocular microscope. Samples for 4 to 167 trees per site were cross-dated using combinations of locally and regionally developed ring-width chronologies (skeleton plots) and lists of marker (narrow) years (Stokes and Smiley, 1968). Specimens that could not be clearly cross-dated and fire scars that could not be dated with annual accuracy were excluded from the analysis. Although datable scars were sampled from 11 tree species, most were taken from ponderosa pine (*Pinus ponderosa*; 58%), Douglas-fir (*Pseudotsuga menziesii*; 15%), or limber pine (*Pinus flexilis*; 9%). These same species typically had the most scars per tree, with one ponderosa pine stump recording 35 fire dates. Dead trees (snags, logs, and stumps) made up 64% of cross-dated samples.

I determined a calendar year for 2173 fire scars of which I assigned an intra-ring (i.e. early (EE), middle (ME), late early-wood (LE), or late-wood (LW)) or inter-ring (ring boundary (RB) or sometimes designated as dormant) position to 1691 scars (Dieterich and Swetnam, 1984). Seasonality of fire scars associated with very narrow rings or eroded scar-ring structure was classified as unknown (UNK). In temperate North America, RB scars are caused by either late-season fires that occur after ring growth is complete or by early-season fires that burn in the following year before growth is initiated. Typically, these inter-ring scars are assigned to the following year in the Southwest and to the preceding year at more northern latitudes based upon the seasonality of modern fires and the relative abundance of early-wood and late-wood scars in tree-ring-based studies (Heyerdahl et al., 2007; Schmidt et al., 2002). The intermediate geographic position of these Great Basin study sites suggests caution is warranted before adopting either convention as a rule. I assigned RB scars to preceding years when evidence of a late-season fire (LE or LW scar) in that same year was found in at least one tree from the study area, and similarly to post-boundary years when evidence of an early-season fire (EE or ME scar) was collected from the study area for the same year. Fire year was assigned to the post-boundary year (Southwest convention) when fire year could not be conclusively determined using these criteria (Kitchen and McArthur, 2003).

Climate effects on fire occurrence

All years with at least one assigned fire scar were composited into a single surface fire chronology for each site using program FHX2 (Grissino-Mayer, 2001). A site was considered to be a recording site when a least one tree from the site was in recording status. A tree was in recording status when it had experienced at least one fire, the post-fire scar surface was open and sufficiently intact to detect subsequent fire scars. A regional fire chronology was created from the individual site chronologies representing those years in which surface fires were recorded on at least 33% of recording sites. Local fire years (fire recorded on <33% of recording sites) and no-fire years (no fire scars for any of the 10 sites) were also tabulated.

I compared individual site and regional fire chronologies with four indices of climate variability derived from independent, tree-ring reconstructions of climate variables to assess fire–climate relationships. These indices include (1) warm-season temperature (April–September) near the study area (grid point 17; Briffa et al., 1992); (2) Palmer Drought Severity Index (PDSI), a measure of June through August drought, averaged from four grid points closely associated with the study area (grid points 71, 72, 86, and 87; Cook et al., 2004); (3) winter (December through February) NINO3, an index of ENSO variability that fluctuates on a sub-decadal (3–8 year) scale (D'Arrigo et al., 2005); and (4) PDO, an index of annual north Pacific temperature patterns that vary at decadal scales (McDonald and Case, 2005). I used superposed epoch analysis (SEA) to compare average annual climate conditions with climate conditions associated with fire and non-fire years in the regional and individual site fire–climate analyses, and with conditions prior to (5 years) and following (2 years) the event year (Swetnam, 1993). I identified significance of departures at two levels based upon 95% and 99% confidence intervals determined by bootstrapping techniques (1000 trials; Grissino-Mayer, 2001).

Fire seasonality analysis

Generalizations about fire seasonality can be inferred based upon the position of scars within annual growth rings (Dieterich and Swetnam, 1984). Because initiation and termination of active ring growth vary by species and topographic setting (Heyerdahl et al., 2007), care must be given to account for these sources of variation when elucidating fire seasonality. To eliminate intra-specific sources of seasonality variation, I limited fire seasonality analysis to the 1797 cross-dated fire scars secured from ponderosa pine samples. The elevational distribution of this species was also relatively narrow (≈300 m) in comparison to that of full gridded sites that spanned multiple vegetation zones, reducing the effects of variation attributable to topographic position.

Within sites, I assigned fire seasonality to six classes: unknown, dormant, early, middle, late, or multi-season, using predetermined classification criteria that assess, as a group, the ring positions of the complete list of fire scars associated with each fire (Table 2). Multi-season fires always included EE (early early-wood) and LE (late early-wood) or LW (late-wood) fire scars and generally also included ME (middle early-wood) and RB fire scars (Baisan and Swetnam, 1990; Grissino-Mayer et al., 2004). Sites were grouped based upon the dominant season(s) of fire occurrence. I assessed within-group temporal variability in fire seasonality by comparing relative abundance of fires in each seasonality class partitioned into 100-year segments (1400–1900).

Results

Earliest and latest fire dates across all 10 sites were 1205 and 1960, respectively. I selected the year 1400 as the fire–climate analysis starting point for five sites that were in recording status and for the regional analysis (Figure 2). More recent dates were selected as starting points for the other individual sites (1500–1700) corresponding to initiation of fire records for each site. The end year for all fire–climate analyses was 1900 corresponding to a drop-off in fire occurrence at most sites. Between 1400 and 1900, I identified a total of 342 fire years with 67 regional fire years with a mean regional fire interval of 9 (range: 1–33) years (Figure 2; Supplemental Table 1, available online). There were 247 local fire years and 187 no-fire years.

Climate effects on fire occurrence

Departures in reconstructed summer temperature for fire (or no-fire) years were not significant in individual site or regional analyses and will not be considered further here. PDSI was negative for 50 of 67 regional fire years (Figure 3a). Departures in PDSI were significantly negative (indicating drought) during regional fire years (Figure 4a) and for four sites (Supplemental Figure 1, available online). The first year after fire was also significantly negative for regional fire years. PDSI departures 2 years before regional fire years were significantly positive, resulting in a pattern of wetter than average conditions before and dry conditions during and immediately after regional fire years (Figure 4a). Conditions during at least 1 year before fire were significantly PDSI-positive (indicating wet conditions) for four sites (Supplemental Figure 1, available online). I observed no significant departures in PDSI associated with local fire years (Figure 4d). Although PDSI values during and after no-fire years were not different than average, departures for the four preceding years were significantly negative, suggesting that fire was least common after extended periods of drought (Figure 4g).

Departures in NINO3 were significantly negative for regional fire years (Figure 4b) and for fire years on three sites (Supplemental Figure 1, available online). No significant departures in NINO3 were observed for local fire years and associated lag years (Figure 4e), but the positive departure for no-fire years was significant (Figure 4h). PDO departures during regional fire years and for 2 years after were significantly negative (Figure 4c) suggesting that regional fire years were most likely to occur at or just

Table 2. Criteria for assigning fire event seasonality based upon fire-scar ring positions (UNK = unknown; RB = ring boundary; EE = early, early wood; ME = middle, early wood; LE = late, early wood; LW = late wood).

Presence (Y) or absence (N) of each class of inter- or intra-ring fire scar among those assigned to each fire event					Assigned season
UNK	RB	EE	ME	LE + LW	
Y	N	N	N	N	Unknown
Y or N	Y	N	Y	N	
Y or N	Y	N	N	N	Dormant
Y or N	Y	Y	Y or N	N	Early
Y or N	N	Y/EE > ME	Y	N	
Y or N	N	Y or N	Y/ME ⩾ EE ME ⩾ LE + LW	Y or N	Middle
Y or N	Y	N	Y	Y	Late
Y or N	N	N	Y or N	Y/LE + LW > ME	
Y or N	Y or N	Y	Y or N	Y	Multi-season

Yes (Y) indicates a minimum of one fire scar of that class is listed for the fire year at a given site.

after positive-to-negative phase changes in PDO. This pattern is supported by significant departures for four individual sites (Supplemental Figure 1, available online). Conversely, departures in PDO for no-fire years and 2 years after are significantly positive (Figure 4i), suggesting that surface fire was least likely to occur during a negative-to-positive PDO phase change.

Fire seasonality

I assigned a ring position to 80% of all ponderosa pine fire scars (Supplemental Table 2, available online). RB scars were the dominant classification for eight sites (range: 32–63%) and accounted for 16% of scars for the other two sites (INC and RBC). Seasonality was assigned to 88% of fires (Supplemental Table 3, available online). Of these, 35% were represented by RB scars only and were classified as dormant-season fires. RB scars were also associated with a large percentage of early-season (59%) and late-season fires (38%) across all sites, inferring that substantial numbers of dormant-season fires occurred both before initiation (early season) and after completion (late season) of cambial growth. Among sites, the proportion of dormant-season fires ranged from 8% to 62%.

BMC, FRI, RBC, SIN, TOM were classified as predominantly late-season fire sites based upon a low (<0.7) early/late-season fire ratio (Figure 5). For these sites, mid-season fires were represented at low to moderate levels (Supplemental Table 3, available online) but never as numerous as late-season fires. Fire seasonality was classified as bimodal for three sites (BWA, LAW, ROS) in which the numbers of early- and late-season fires were approximately equal (early/late-season fires ≈1.0) and notably greater than mid-season fires (mean of early- and late-season fires/mid-season fires >1.7; Figure 5). These sites also had high numbers of dormant-season fires which, if distributed between early- and late-season classifications, would magnify the bimodal pattern already apparent. Seasonal distribution of fire for two sites was relatively even suggesting no dominant-season (INC) or insufficient fires (SWA) to reveal a consistent pattern.

Within-groups, relative abundance of early-, mid-, and late-season fires remained relatively constant from 1600 to 1900 (Figure 6). Before 1600, seasonal proportions differed from subsequent centuries but were based upon relatively few fires suggesting differences may be an artifact of small sample size. Climatic differences associated with the onset of the 'Little Ice Age' (1450–1850) might also have affected fire seasonality during this earlier period; however, there are insufficient data to address that possibility here. Dormant-season fires increased gradually after 1600 for both groups. Late-season fires peaked in the 1600s and maintained their importance relative to early- and mid-season fires for 300 years (1600–1900).

Discussion

Fire chronologies for the 10 sites in this study reveal a general pattern of frequent surface fires that was sustained over multiple centuries (Figure 2). This was particularly so on larger sites with greater numbers of sample trees and broader sample tree dispersal, suggesting the importance of the contribution of small fires to the site-level composite fire records. Visual examination of these composite chronologies would seem to suggest that site-level fire return intervals were longer before ~1500. However, it is difficult to tease out the effects of this fading record from any real differences in fire frequency through time because early portions of the record were constructed from fewer trees. Conversely, variation in fire seasonality should not be impacted by the fading record.

Climate effects on fire occurrence

Antecedent wet years increase fire probability, and hence regional fire synchrony, through greater production of fine fuels (e.g. grasses and pine needles) which burn in subsequent dry years (Baisan and Swetnam, 1990; Swetnam and Betancourt, 1998). Strong correlations between regional fire years and drought coupled to wet conditions (positive PDSI) during pre-fire years have been observed in dry forests of the Southwest (Brown et al., 2001; Fulé et al., 2003; Grissino-Mayer and Swetnam, 2000; Iniguez et al., 2009; Margolis and Balmat, 2009), Colorado (Donnegan et al., 2001; Grissino-Mayer et al., 2004; Veblen et al., 2000), Utah (Brown et al., 2008), and northwestern Mexico (Skinner et al., 2008). Conditions two or more years prior to major fire years are commonly wetter than the year that immediately precedes fire (Brown et al., 2008; Iniguez et al., 2009; Margolis and Balmat, 2009; Sherriff and Veblen, 2008; Skinner et al., 2008) as was the case in this study (Figure 3a). Also notable, drought persisted after regional fire years; a pattern documented in the Southwest (Iniguez et al., 2009; Margolis and Balmat, 2009) and in northwestern Mexico (Skinner et al., 2008). This suggests that years of widespread surface fire were not merely a product of 1-year droughts but that fire was synchronized by multi-year wet–dry oscillations in many locations. Hence, the probability of fire was highest during the first year of strong drought following one or more wet years. The lack of significant departure for the year immediately before regional fire years could portray years climatically transitional in the multi-year oscillation. An increased probability for synchronized fire associated with a multi-year positive-to-negative shift in PDSI has been documented elsewhere in western North America including the Tahoe Basin of eastern California (Beaty and Taylor, 2008), Rincon Mountains in southeastern Arizona (Iniguez et al., 2009), Sacramento Mountains, southeastern New Mexico

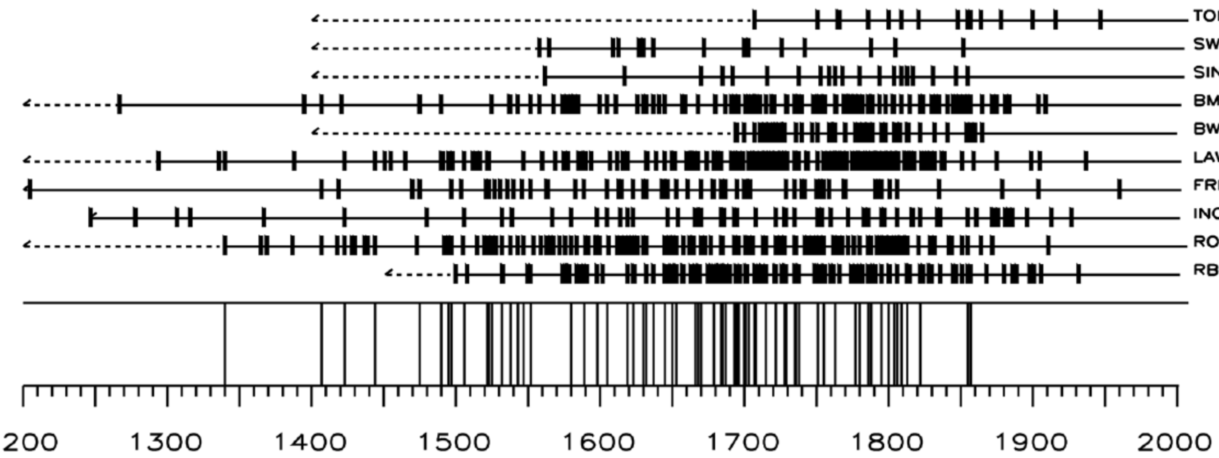

Figure 2. Fire chronologies for 10 eastern Great Basin sites arranged from north (top) to south. Horizontal lines are composite records of fire for each site. Solid lines indicate at least one tree is in recording status. Short vertical lines mark fire dates. Long vertical lines indicate timing of regional fire years in which ⩾33% of recording sites recorded fire.

(Brown et al., 2001), and Archuleta Mesa in southwestern Colorado (Brown and Wu, 2005). A reverse pattern of multiple years of drought resulting in subsequent low fire probability (no-fire years; Figure 4g) is a logical extension and represents a separate segment of the oscillation (Figure 4g). Years in which fire occurred on few sites (local fire years) do not follow this pattern and in fact appear not to be linked to climate variation in any way (Figure 4d–f).

The observed relationship between regional fire years and ENSO was clearly Southwestern in nature (Swetnam and Betancourt, 1990, 1998) with fire years correlated with significantly negative and no-fire years correlated with significantly positive NINO3 departures (Figure 4b and h). PDO values for regional fire years and 2 years thereafter were significantly negative (Figure 4c), while values for no-fire years and 2 years after were significantly positive relative to average (Figure 4i). This multi-year pattern is similar to that observed for the PDSI analysis in that the probability of regional fire was greatest as PDO was shifting from warm to cold phases (positive to negative values), an indication of the onset of drought in the Southwest. The multi-year positive departure in PDO during and following no-fire years is also consistent with the idea that regional fire years were synchronized by multi-year drivers of climate and that surface fires were least likely as the climate shifted from dry or average to wetter conditions. Skinner et al. (2008) reported similar patterns for regional and no-fire years in relation to drought and PDO for northwestern Mexican forests using McDonald and Case (2005) and Biondi et al. (2001) PDO indices. A third index (D'Arrigo et al., 2001) failed to reveal this pattern there or for the Colorado Front Range (Sherriff and Veblen, 2008). These differences in PDO–fire relationships reflect differences in the climate proxies themselves and suggest one or more are substantially influenced by additional factors. Although clarification of the PDO–fire relationship will require refinements in proxy records, the patterns observed here and in northwestern Mexico using the McDonald and Case (2005) PDO proxy suggest a broad regional fire synchronization in response to multi-year oscillations in precipitation that are, at least to some degree, responsive to variation in PDO.

Regional fire-year frequency was somewhat stable from the late 1400s to 1822 with periods of high frequency from 1619 to 1738 and from 1777 to 1822 (Figure 2; Supplemental Table 1, available online). An anomalously long gap in regional fire years occurred between 1553 and 1579 (Figure 2), a period devoid of major drought (average to high PDSI), muted inter-annual differences in ENSO, and high PDO (Figure 3a–c), conditions favorable for reduced fire activity (Kitzberger et al., 2001). Regional fire frequency remained relatively low from 1579 to 1619. During this period of below average fire synchronization, drought gave way to wetter conditions (negative to positive PDSI), ENSO oscillations were average (Figure 3b), and PDO was mostly positive (indicating wet) and stable (Figure 3c). Between 1620 and 1738, fire frequency was high, droughts were frequent and severe, ENSO oscillations were about average, and PDO was mostly negative. Average PDO became slightly positive but was highly variable from 1739 to 1777, a period of somewhat reduced frequency in regional fire frequency. This period of reduced regional fire was synchronous with a distinct hiatus in local and regional fires documented for southwestern Colorado (Grissino-Mayer et al., 2004). In this study, local fire frequency remained high during this period, inferring that drivers of the phenomenon might have been weaker in the eastern Great Basin. A second long hiatus in regional fire years occurred from 1822 to 1855 and is more or less synchronous with a lengthening of fire intervals at five sites (SIN, BWA, LAW, FRI, ROS; Figure 2). During this 33-year period, years of severe drought were few, ENSO oscillations were muted, and PDO was mostly positive or trending positive (Figure 3a–c), conditions similar to those of the mid 1500s hiatus already noted. A decrease in surface fire activity during the early 19th century has been documented for sites in the interior Northwest (Heyerdahl et al., 2001, 2002), Colorado Plateau (Brown and Wu, 2005; Brown et al., 2008), Central Rockies (Donnegan et al., 2001), Southwest (Iniguez et al., 2009; Swetnam and Betancourt, 1998), northwestern Mexico (Skinner et al., 2008), and Argentina (Kitzberger et al., 2001). This study supports the conclusions of these earlier studies – that this widespread period of reduced fire occurrence was caused by reduced variability in ENSO oscillations – but also identifies the lack of severe drought and positive PDO as possible contributing factors.

The last regional fire year was in 1857, roughly synchronous with the last fire recorded for three sites (SWA, SIN, BWA). All of the remaining sites continued to record fires into the 20th century (although at mostly lower frequencies) with the last local fire year recorded in 1960. A late 1800s loss or reduction in fire-scar-based records is a common feature of fire regime reconstructions in the western United States and is generally attributed to the impacts of domestic livestock on fine fuels and changes in human burning practices. The persistence of fire well into the 20th century on about half of the sites suggests that the timing and intensity of livestock impacts varied within this study area. Post-1900 ignitions may also have been less frequent though both natural and human sources were probable. Disruptions of Native American ignition patterns may have contributed to longer fire intervals as

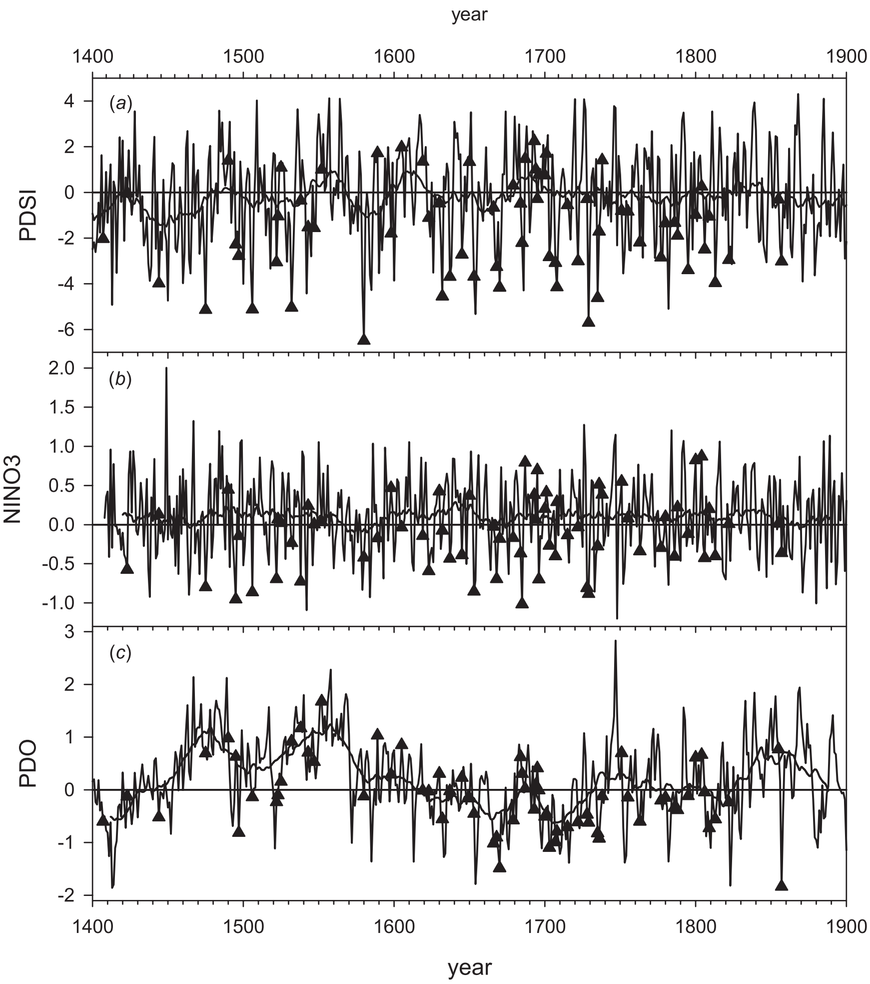

Figure 3. Variation in tree-ring-based proxies for Palmer Drought Severity Index (PDSI), El Niño Southern Oscillation (NINO3), and Pacific Decadal Oscillation (PDO) plotted against regional fire years (triangles) for 10 eastern Great Basin sites (1400–1900). Plot lines show annual variation and variation smoothed with cubic splines that retain 50% of variation over segments of 25 years.

early as ~1800 for some sites (see FRI, ROS, and LAW; Figure 2), more than 60 years before Euro-American settlement and the introduction of domestic livestock to this region. Similarly, reduced human-caused ignitions on a subset of sites might also have contributed to the 1822–1855 regional fire hiatus already noted. Potential explanatory causes for pre-settlement changes in Native American burning could include local depopulation because of the spread of new diseases (Reff, 1991; Thornton, 1987). The deployment of modern fire suppression techniques and equipment after World War II improved suppression efforts on these remote ranges and was more or less synchronous with the last fire years recorded in the study.

Fire seasonality

Fire seasonality varied among sites and was relatively consistent over time allowing grouping of eight sites based upon seasonal dominance patterns in the fire regime (Figure 5). Emergent patterns included dominance by late-season fires and comparable, bimodal dominance by early- and late-season fires. The presence of RB scars in substantial proportions of both early- and late-season fires, and the high proportion of dormant-season fires for most sites, reinforce these seasonal patterns. Results demonstrate that the historic fire season in the eastern Great Basin was potentially long, beginning before and ending after the period of annual ring growth. This would be expected given the generally dry climate in the region expressed by both early spring snowmelt and a weak or absent summer monsoon. The observed seasonal variability in fire regimes was not expected among sites sharing a common climatic pattern and constitutes indirect evidence of human influence on the fire regimes for at least some of the sites (Allen, 2002).

Similar to this study, among-site seasonal variation and bimodal seasonal timing were identified in a study in the San Juan Mountains (Grissino-Mayer et al., 2004), an area located on the Colorado Plateau roughly 500 km east of these eastern Great Basin sites. Authors suggested that wet conditions during the summer monsoon reduced fire occurrence during mid-summer causing the bimodal pattern but offered no explanation for among-site differences. Among-site variability in surface fire seasonality has been reported for site clusters elsewhere in western North American studies including the Blue Mountains in Oregon (Heyerdahl et al., 2001) and the Sierra San Pedro Mártir in northwestern Mexico (Skinner et al., 2008). Topographic variability expressed at fine spatial scales could explain some differences in fire seasonality due to the effects of aspect, slope, and elevation on the rate of fuel desiccation and timing of tree-ring growth. Conversely, if we allow for a human element in fire ignitions, the variability in patterns of human occupation or burning strategies could explain major among-site differences in early- and late-season fire dominance.

Long-term climate variability has been used to explain temporal variability in surface fire seasonality through the interaction of temperature and precipitation (timing and abundance) on the production and desiccation of fine fuels (Grissino-Mayer and Swetnam, 2000). In this study, seasonal patterns were stable across multiple centuries (Figure 6) while fire synchronization varied at the regional scale (Figure 2). A peak in late-season fire during the

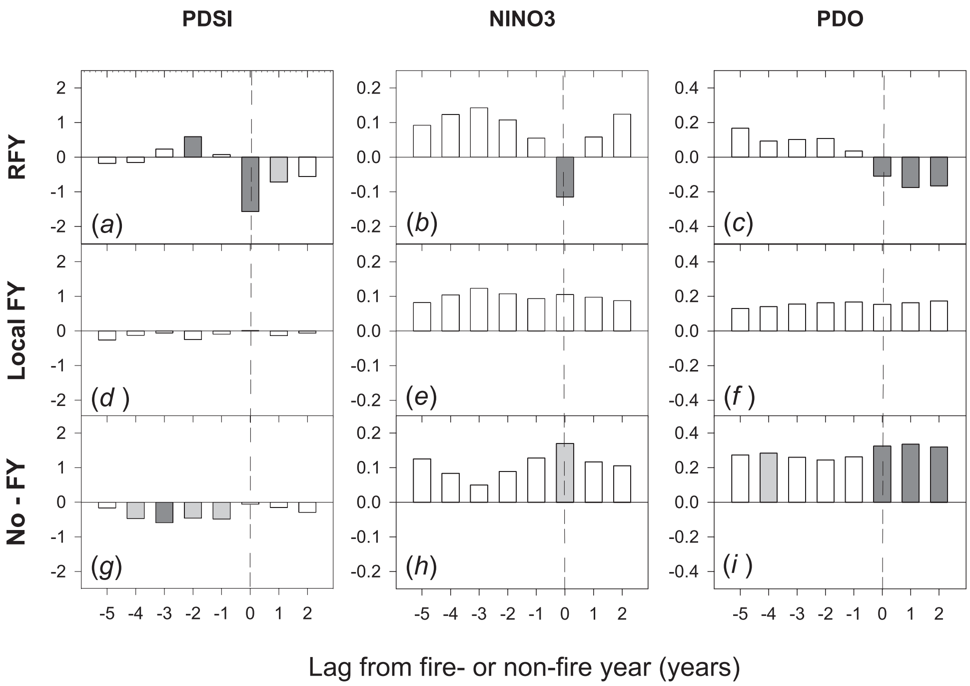

Figure 4. Superposed epoch analysis (SEA) of average departures for Palmer Drought Severity Index (PDSI), El Niño Southern Oscillation (NINO3), and Pacific Decadal Oscillation (PDO) during regional and local fire years (RFY, Local FY) and no-fire years (No-FY). Analysis is for 5 years before and 2 years following fire years (dashed vertical line). Light and dark bar shading indicate departures exceeding 95% and 99% confidence intervals, respectively.

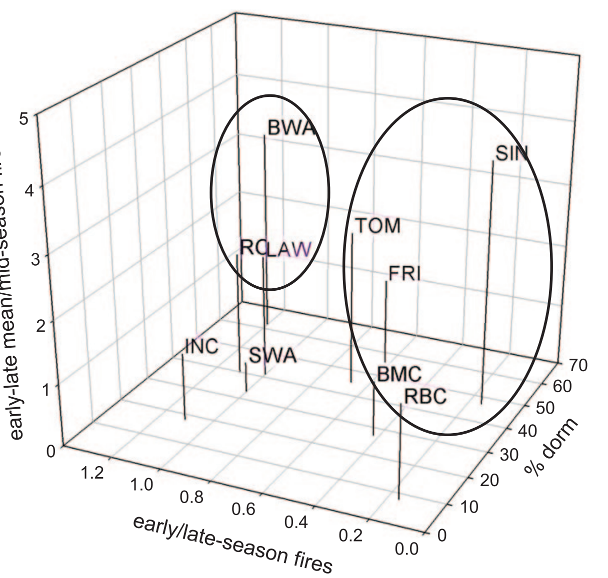

Figure 5. Distribution of 10 eastern Great Basin sites in three-dimensional space based upon measures of fire seasonality: (1) percent dormant-season fires (% dorm) and (2) ratio of early- to late-season fires (E/L), and ratio of the mean of early- and late-season fires to mid-season fires ((E + L)/2/M). Groupings (ovals) include late-season dominant (E/L < 0.7) and bimodal-season dominant (E/L ≈ 1.0, (E + L)/2/M > 1.8) sites.

early 17th century may have been influenced by a cool-wet period that dominated the early 1600s; however, relative abundances of early-, mid-, and late-season fires were similar to those of later periods for both groups.

In addition to among-site variability, unexpected seasonality patterns may also indicate human influence on fire regimes (Allen, 2002; Williams, 2004). Modern (post 1980) fire seasonality distribution for the eastern Great Basin, measured either in number of fires or area burned, has a middle- to late-season (July and August) peak (Griffin, 2002; Schmidt et al., 2002; Westerling et al., 2003). A narrower peak from mid-July to mid-August is suggested for lightning-caused fires based upon a 42-year record of fire from the Snake Range (Nevada) and surrounding area (data on file at the US Forest Service, Shrub Sciences Laboratory, Provo, Utah). Predicted effect of the warming trend that began in the mid-1800s would be to lengthen the fire season resulting in more early- and late-season fires. This prediction is confirmed by a lengthening of the fire season in the western United States associated with the accelerated warming trend during the last three decades (Westerling et al., 2006). However, the modern, lightning-caused seasonal distribution of fire lacks the strong late- or bimodal seasonal patterns apparent for eight of our study sites suggesting that regulation of historic fire seasonality likely involved one or more non-climatic factors.

In this study, the case for an anthropogenic source of ignitions is perhaps strongest for the Sinbad Springs (SIN) site. The site is defined by a small cluster of mature ponderosa pine trees occupying ~1 ha near a perennial spring. Beyond the influence of the spring, the vegetation changes sharply to old growth pinyon–juniper and mountain mahogany woodland, vegetation poorly adapted for frequent burning. Consequently, the ignitions that sustained the high frequency fire (mean fire interval: 15.4 years) documented for this site almost certainly originated from within the site. Given the small size and recessed nature of the study site relative to the surrounding landscape, the likelihood of lightning being a primary source of ignitions is remote. The presence of a reliable water source in this dry landscape would have been an attraction to both humans and animals that would constitute important food sources. The best explanation for the frequent-fire regime found at this site is that it represents, perhaps exclusively, a pattern of intentional (and possibly accidental) ignitions by Native Americans dating back to late 16th century. Late- and dormant-season fires are approximately equal in number and together they account for nearly 90% of the fires at this site indicating that burning occurred primarily in late summer or fall. This may have been the only time that the spring-fed vegetation was sufficiently cured to burn most years

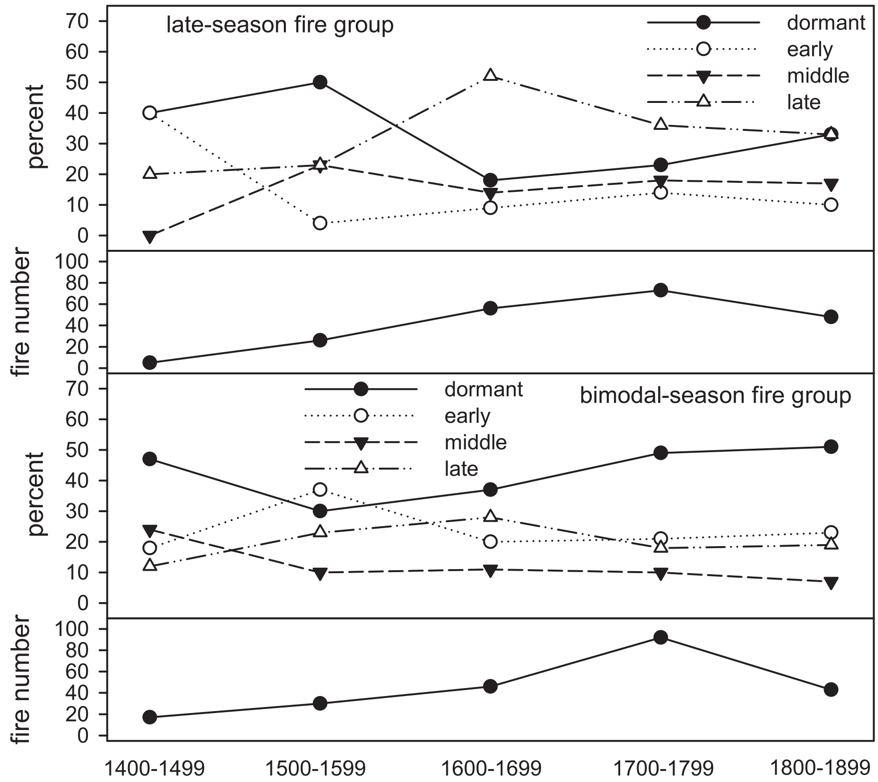

Figure 6. Distribution of dormant-, early-, middle-, and late-season fires for eastern Great Basin (a) late-season dominant and (b) bimodal-season sites across five centuries (1400–1900). Individual site fires were pooled in 100-year bins for each group/season combination.

and is in agreement with historical accounts that indicate that fall was a preferred time for Native American burning in this part of the West (Chavez and Warner, 1976; Griffin, 2002). Fall is also a time of reduced lightning, strengthening the argument for human ignitions at this site. Practical reasons for intentional burning are potentially numerous (Williams, 2004) and include clearing vegetation to improve visibility for ambush hunting, 'greening' of vegetation to attract large herbivores, or improving growth characteristics of useful vegetation. Although the unique biophysical setting of this site is useful for deducing a probable source of ignitions there, fire frequency and seasonality are similar to other less unique sites in the late-season fire group. This could be interpreted as an indication of the difficulty of teasing out the human fire 'footprint' from a background fire regime dictated by lightning ignitions. Alternatively, the relative 'normality' of the fire regime for this site argues that the impact of human ignitions, though locally variable, was likely widespread (McAdoo et al., 2013). Fine-scale spatial variation in fire frequency within the BMC site was previously interpreted as evidence of differential human ignition activity (Kitchen, 2012) and provides additional support for an interpretation of anthropogenic regulation of fire regimes in this region.

Conclusion

Multi-year, wet–dry cycles synchronized fire at a regional scale with greatest fire activity corresponding to wet-to-dry transitions and least fire activity associated with dry-to-wet transitions. Responses to Pacific-driven oscillations in climate followed a Southwest mode supporting the notion that the pivot point in the precipitation dipole lies north of the study area. Fire seasonality patterns were primarily late-season dominated or bimodal with early- and late-season peaks. The most reasonable interpretation for these patterns of fire seasonality requires human ignitions and constitutes credible evidence that Native American peoples consistently impacted fire regimes in the region. Taken together, results support an interpretation that fire regimes were the product of dynamic interactions between a variable climate and human fire use. The relative importance of each of these factors likely varied through time and across the study landscape.

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