Climatic Change (2017) 142:433–446
DOI 10.1007/s10584-017-1958-4

Drought, multi-seasonal climate, and wildfire in northern New Mexico

E. Q. Margolis[1] · C. A. Woodhouse[2,3] · T. W. Swetnam[3]

Received: 22 August 2016 / Accepted: 21 March 2017 / Published online: 25 April 2017

Abstract Wildfire is increasingly a concern in the USA, where 10 million acres burned in 2015. Climate is a primary driver of wildfire, and understanding fire-climate relationships is crucial for informing fire management and modeling the effects of climate change on fire. In the southwestern USA, fire-climate relationships have been informed by tree-ring data that extend centuries prior to the onset of fire exclusion in the late 1800s. Variability in cool-season precipitation has been linked to fire occurrence, but the effects of the summer North American monsoon on fire are less understood, as are the effects of climate on fire seasonality. We use a new set of reconstructions for cool-season (October–April) and monsoon-season (July–August) moisture conditions along with a large new fire scar dataset to examine relationships between multi-seasonal climate variability, fire extent, and fire seasonality in the Jemez Mountains, New Mexico (1599–1899 CE). Results suggest that large fires burning in all seasons are strongly influenced by the current year cool-season moisture, but fires burning mid-summer to fall are also influenced by monsoon moisture. Wet conditions several years prior to the fire year during the cool season, and to a lesser extent during the monsoon season, are also important for spring through late-summer fires. Persistent cool-season drought longer than 3 years may inhibit fires due to the lack of moisture to replenish surface fuels. This suggests that fuels may become increasingly limiting for fire occurrence in semi-arid regions that are projected to become drier with climate change.

Electronic supplementary material The online version of this article (doi:10.1007/s10584-017-1958-4) contains supplementary material, which is available to authorized users.

✉ E. Q. Margolis
emargolis@usgs.gov

1 US Geological Survey, Fort Collins Science Center, New Mexico Landscapes Field Station, 301 Dinosaur Trail, Santa Fe, NM 87508, USA

2 School of Geography and Development, University of Arizona, 1064 E. Lowell St, Tucson, AZ 85721-0137, USA

3 Laboratory of Tree-Ring Research, University of Arizona, 1215 E. Lowell Street, Box 210045, Tucson, AZ 85721-0137, USA

Keywords Tree ring · North American monsoon · Fire-climate relationships · Fire season

1 Introduction

Over the past decade, wildfires have made headlines due to their increasing size, severity, and cost. Warming temperatures, drought, and earlier snowmelt—all consistent with projected future climate in the southwestern USA—have been linked to an increasing number of large fires (Dennison et al. 2014; Westerling 2016). The legacy of late nineteenth and twentieth century land use and forest management has also played an important role by increasing fuels that have led to recent megafires (10,000 ha to >100,000 ha), particularly in dry conifer forests (Stephens et al. 2014). Natural climate variability, in addition to human influences, has long been a primary driver of variability in wildfire occurrence, severity, and seasonality (Littell et al. 2016; Swetnam et al. 2016). Climate change will likely alter fire regimes globally, but the mechanisms and the directions of the effects are complex and will vary geographically (Moritz et al. 2012).

Understanding the relationships between climate variability and wildfire by analyzing instrumental and paleoecological data (e.g., tree rings or sediment charcoal) is increasingly valuable for fire management and modeling future fire regimes. Robust relationships have been established in North America between variability in instrumental period (twentieth and twenty-first century) and paleo (pre-twentieth century) fire records and a suite of climate variables, climate patterns, and ocean-atmosphere oscillations (Swetnam and Betancourt 1990; Westerling et al. 2006; Kitzberger et al. 2007; Marlon et al. 2012; Williams et al. 2015). However, fire-climate relationships are spatially and temporally complex, with significant variability within and among regions in fire and moisture seasonality, and lagging relationships that drive fire (Swetnam and Betancourt 1998; Littell et al. 2009; Keeley and Syphard 2016). To date, there is limited understanding of the impacts of the seasonality of moisture and persistent drought on wildfire size and seasonality.

The relationships between cool-season moisture and fire over past centuries (circa 1600–1900 CE) have long been established in the southwestern USA using data from fire-scarred trees (for background on fire scars, see Text S1). A pattern of one or two wet cool seasons followed by cool-season drought is consistently associated with fire occurrence in dry conifer forests of the region (Swetnam and Betancourt 1990; Swetnam and Betancourt 1998). In contrast, the role of summer moisture, delivered through the North American monsoon (NAM) and accounting for up to 50% of the annual precipitation in the southwestern USA, has not been well investigated. Limited research indicates a potential influence of the NAM on fire through increased fine fuels from prior wet monsoons (Crimmins and Comrie 2004; Text S2), or the possibility of monsoon drought leading to more monsoon-season fires (Grissino-Mayer and Swetnam 2000). Until recently, there have been no tree-ring proxies of summer moisture, but a large new network of partial ring-width chronologies now enables the reconstruction of both cool- and monsoon-season moisture in the southwestern USA (Griffin et al. 2013; Text S3).

In this study, we compile the largest known collection of fire scar data for a single mountain range and develop new reconstructions of cool- and monsoon-season moisture to investigate relationships between historical fire regimes and multi-seasonal climate in northern New Mexico. Our main research questions are (1) How do monsoon- and cool-season moisture variability affect fire occurrence, extent, and seasonality? and (2) What is the relationship between fire and prolonged drought? Our goal is to improve the understanding of fire-climate relationships in the past to help inform how climate change may impact fire regimes in the future.

2 Study area and data

The Jemez Mountains are located in northern New Mexico within NAM region 3 (Gochis et al. 2009; Fig. 1). Approximately 44% of the annual precipitation falls in the cool season (October–April) and 43% in the monsoon season (July–September). The warmest and driest months of the year are May and June, when the largest fires occur. Multiple large fires have burned in the Jemez Mountains in recent years, including the 2011 Las Conchas fire (63,400 ha). Vegetation in the Jemez Mountains ranges from grasslands at the lower forest border (~2000 m a.s.l.), to ponderosa pine and mixed conifer forests, to montane meadows and spruce forests at the highest elevations (~3000 m a.s.l.). The majority of the landscape was historically dry conifer forest that included ponderosa pine. The region has extensive networks of fire-scarred and climatically sensitive trees, making it an ideal location for tree-ring fire-climate analyses (Swetnam et al. 2016).

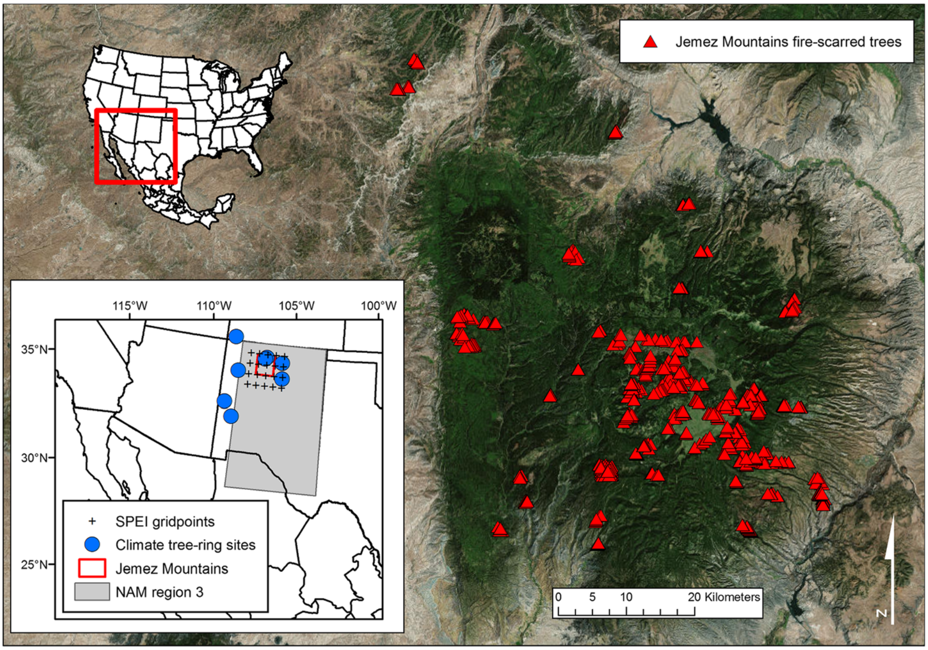

Fig. 1 Study area in southwestern North America focused on the North American monsoon (NAM) region 3. Inset map indicates the location of the climate-sensitive tree-ring sites, the standardized precipitation-evapotranspiration index (SPEI) gridpoints used in the climate reconstructions, the Jemez Mountains, and NAM region 3. The aerial photo is of the Jemez Mountains in New Mexico, which contain a network of 1343 fire-scarred trees

2.1 Tree-ring climate reconstructions

To reconstruct cool- and monsoon-season moisture, we used existing earlywood and adjusted latewood chronologies from 23 sites in New Mexico and southern Colorado located within and adjacent to the Jemez Mountains and NAM region 3 (Text S3). Adjusted latewood chronologies have the dependence of latewood growth on earlywood removed statistically (Griffin et al. 2011). We reconstructed the standardized precipitation-evapotranspiration index (SPEI), because fire is influenced by the combined effects of temperature and moisture that are integrated into SPEI (Williams et al. 2015). SPEI data were obtained from the Global SPEI Database, which uses monthly precipitation and potential evapotranspiration at a 0.5 degree spatial resolution. A regional time series was generated based on the average of 20 grid points centered on the Jemez study area (Text S3, Fig. 1). Monthly SPEI was averaged for the cool (October–April) and monsoon (July–August) seasons.

Reconstruction models were developed by calibrating earlywood chronologies with October–April SPEI and adjusted latewood chronologies with July–August SPEI separately, using stepwise regression (1896–2007). Models explained 67 and 52% of the total variance for October–April and July–August SPEI, respectively. Models met the assumptions of linear regression, and cross-validation statistics indicate reasonable skill. Details of regression results are in supplemental materials (Text S3, Table S1, Fig. S1). The October–April SPEI reconstruction extends 1594–2007 and July–August SPEI, 1599–2008. The relationship between the seasonal SPEI variables is preserved, for the most part, in the reconstructions. There is no relationship between the instrumental cool- and monsoon-season SPEI ($r = -0.09$, $p > 0.05$), but there is a weak correlation between the reconstructed cool- and monsoon-season SPEI in the instrumental period ($r = 0.23$, $p < 0.05$). Over the full common reconstruction period, 1599–2007, the cool and monsoon-season SPEI are uncorrelated ($r = 0.09$, $p > 0.05$).

2.2 Tree-ring fire history reconstructions

The tree-ring fire scar data were compiled from existing collections in the Jemez Mountains. The data cover approximately 300,000 ha of historically dry conifer forests that used to burn predominantly with low-severity fire. This network, the largest in North America for a single mountain range, is a compilation of 19 studies conducted over 40 years (Text S4). A total of 8588 fire scars from 1295 trees were dated to the year (1599—1899). Fire seasonality was determined for 77% of the scars ($n = 6581$) from the position of the scar within the annual ring. Categories for scar positions and their seasonal timing include: dormant (D—early spring); early, mid, and late earlywood (E, M, L—late spring through mid-summer); and latewood (A—late summer and fall). Most fire years historically had scars in multiple fire seasons (Fig. 2 and S2). Details of the fire scar seasonality methods are described in the supplementary materials (Text S1).

Fire scar data were compiled and analyzed with the "burnr" fire history package in R (Malevich et al. 2015; R Core Team 2015). Percent of recording trees scarred was used as a proxy for relative fire size (e.g., Farris et al. 2010). Fires recorded by a single tree were not included in the analysis. After 1899, the number of fires in the Jemez Mountains declines precipitously due to increased human land use, so the common period for the fire and climate data is 1599–1899. Native Americans influenced fire regimes through the mid-1600s in the southwest Jemez Mountains (Swetnam et al. 2016), which could affect fire-climate relationships in the early part of the record.

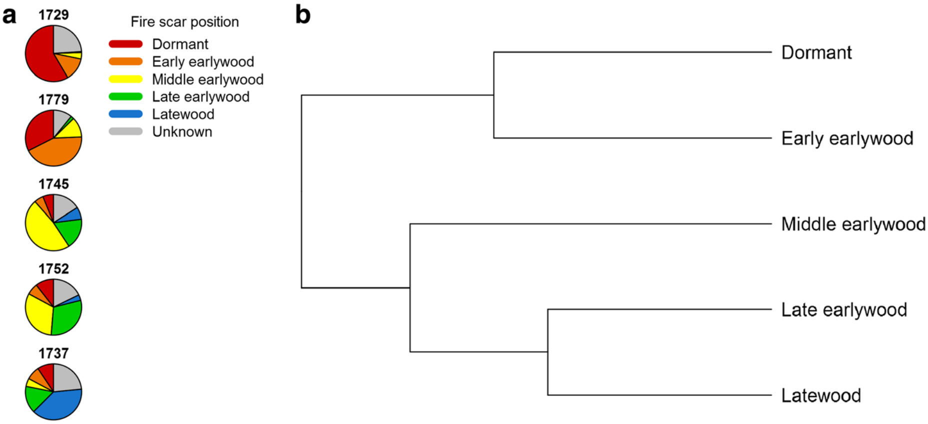

Fig. 2 **a** The proportion of trees scarred by fire in the Jemez Mountains in each fire scar position, or season, for five large fire years. The selected years have the largest number of fire scars in the spring dormant (1729) through late summer/fall latewood (1737) fire seasons in the 1700s. Note the inter- and intra-annual variability in the distribution of fire seasonality. **b** Cluster dendrogram of large, 95th percentile fire years by fire-scar position (n = 16 years for each scar position). Note the grouping of dormant and early earlywood (DE) fire years and middle earlywood, late earlywood and latewood fire years (MLA)

Analyses focused on the extreme fire years. Extreme large and small fire years were determined by the 95th and 5th percentile rank of the percent of recording trees scarred in a year (Table S2). Extreme fire years were first determined for all fires (combining all fire seasons, including unknown seasonality), and then for each of the five individual fire scar seasonalities (spring through fall). A total of 16 fire years fell within the 95th percentile (Fig. S2). The 5th percentile years were all years when no fires occurred.

3 Analysis methods

3.1 Multi-seasonal fire-climate analysis

We used superposed epoch analysis (SEA) to test whether fire occurrence and fire seasonality were associated with cool- and monsoon-season SPEI anomalies (Swetnam 1993). SEA is a compositing approach that uses block re-sampling and bootstrap simulations to evaluate the significance of the concurrence between fire event years and wet or dry conditions in the event year or lagged years. We examined 7-year blocks of cool- or monsoon-season SPEI spanning 4 years before, and 2 years after the fire year (year zero). We first used SEA to test whether cool- and monsoon-season SPEI anomalies were associated with all extreme large fire years and no fire years, and then for SPEI associations with the separate individual fire seasons.

To determine associations among the different fire scar positions, as well as relationships between fire-scar positions and seasonal climate, we used hierarchical cluster analysis of extreme large fire years for all five individual fire scar positions (hclust; R Core Team 2015). The analysis includes all possible combinations, not just adjacent scar positions. The groups that resulted from the cluster analysis were used as a framework for combining multiple fire scar positions for analyzing the relationships between sequences of cool- and monsoon-season moisture and the related fire scar positions, as well as the drought-fire analysis.

3.2 Drought-fire analysis

Reconstructed cool- and monsoon-season SPEI series were first analyzed to investigate characteristics of seasonal drought. This included the number and length of droughts (single and consecutive years with negative SPEI values) and comparisons of these metrics between cool- and monsoon-season droughts. The relationships between droughts and large fire years in the early (D and E) and mid-to-late (M, L, and A) fire seasons—as grouped by the cluster analysis—were then examined to determine (1) the length of droughts in which the large fires occurred and (2) the year in the drought that large fires occurred. On the basis of the SEA results, early-season fires were evaluated with cool-season droughts, and mid- to late-season fires were evaluated with both cool- and monsoon-season droughts.

We also assessed whether the driest decades of the cool- and monsoon-season SPEI reconstructions were associated with increased fire. Here, we relax the threshold for fires to include those with at least 2.5% of trees scarred (74th percentile, $n = 79$ fire years for early-season fires and 85th percentile, $n = 46$ fire years for mid- to late-season fires). Decadal dry periods were identified as the five driest non-overlapping decades for each climate season. Decades with the highest fire activity for early and mid- to late-season fires were defined as the five non-overlapping decades with the largest sum of the percent of recording trees scarred. These decadal measures of climate and fire were compared visually to assess the correspondence between the most active fire periods and the driest periods.

4 Results

4.1 Cool-season climate associated with large fire years

The SEA analysis for the largest fire years, regardless of fire season, highlights the importance of cool-season drought during the fire year (Fig. 3a, top row). The largest fire years were also associated with wet cool seasons 2 and 3 years prior to the fire year. No significant associations were found between all large fires and monsoon-season moisture, although a similar pattern of dry conditions during the fire year preceded by wet years is suggested (Fig. 3b, top row). Years without fire were associated with wet cool seasons in the fire year, but not with monsoon moisture.

When the largest fire years for each fire season are analyzed, several different fire-climate relationships are revealed. The SEA results indicate that early season (D and E) fires are most strongly associated with cool-season drought during the fire year, with the strength of the association decreasing by mid-summer through fall (Fig. 3a). Similarly, the importance of prior wet cool seasons associated with large fire occurrence decreases through the fire season; spring (D) fires are associated with two prior wet cool seasons 2 and 3 years before the fire year; early- to mid-summer fires (E, M, and L) are associated with one wet cool season 2 or 3 years prior to the fire year; and late-summer and fall (A) fires have no significant relationship with prior wet cool seasons.

4.2 Monsoon-season climate associated with large fire years

Monsoon-season drought during the fire year is significantly associated with large late season (L and A) fire occurrence (Fig. 3b). There is a suggestion of a similar relationship with the

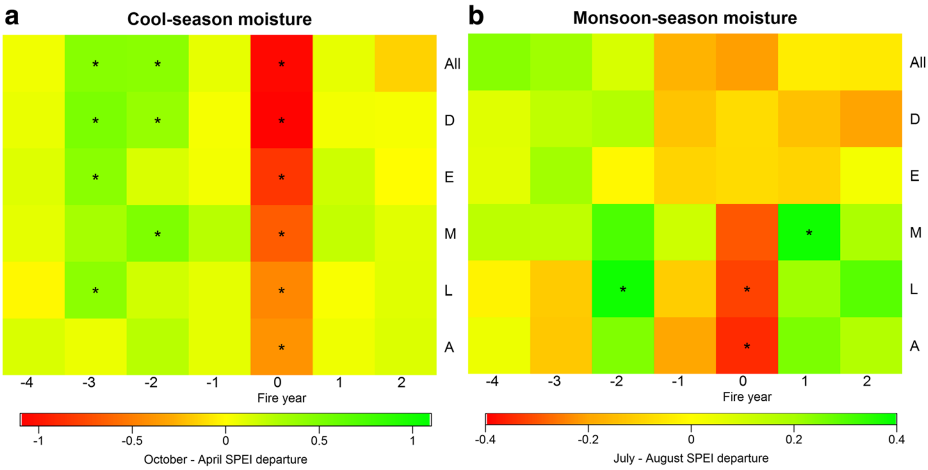

Fig. 3 Superposed epoch analysis of **a** cool-season moisture and **b** monsoon-season moisture by fire-scar position for large, 95th percentile fire years in the Jemez Mountains ($n = 16$ fire years for each seasonality, 1599–1899). All = all fire scar positions, D = dormant, E = early earlywood, M = middle earlywood, L = late earlywood, and A = latewood. SPEI = standardized precipitation-evapotranspiration index. *Asterisks* in cells denote significant departures from mean SPEI based on bootstrap simulations ($p < 0.05$)

monsoon and mid-season (M) fires. Since late-season fires are also associated with cool-season drought during the fire year, joint drought in the cool and monsoon seasons appears important for widespread late-season fires. Wet conditions in the cool and monsoon seasons 2 or 3 years prior to the fire year also appear to be important in this sequence favoring late-season fires. There is no significant association between monsoon moisture and D or E fires.

4.3 Fire seasonality patterns

The cluster analysis of the fire-scar seasonality of large fire years supports results from the SEA. There were two main groups of fire scar positions: (1) dormant and early earlywood (DE) and (2) middle earlywood, late earlywood, and latewood (MLA) (Fig. 2b). The patterns of fire-climate relationships from the SEA suggest a similar grouping of M, L, and A fires, particularly in association with monsoon moisture (Fig. 3b). This implies different climatic controls on spring and early summer (DE) fires compared with the mid-summer to fall (MLA) fires. Large early-season fires, by virtue of their timing, are strongly linked to cool-season drought, and they rarely continue to burn throughout the summer (Fig. 2 and S2). Whereas the largest MLA fires burn through the summer under dry monsoon conditions and consequently are associated with drought in both the cool and monsoon seasons. Mid-summer (M) fires are most likely to continue burning through the late summer and fall (L or A scars), but only during dry monsoons (e.g., differing fire-scar position distributions of the 1729 dormant fire year compared to the 1745 middle earlywood fire year, Fig. 2 and S2).

4.4 Relationships between persistent drought and fire

Results from the SEA and cluster analysis suggest that a sequence of both wet and dry years in the cool and monsoon seasons lead to large fires. Thus, a short-term drought might be most favorable for fire, while persistent (multi-year) droughts that do not include intervening wet

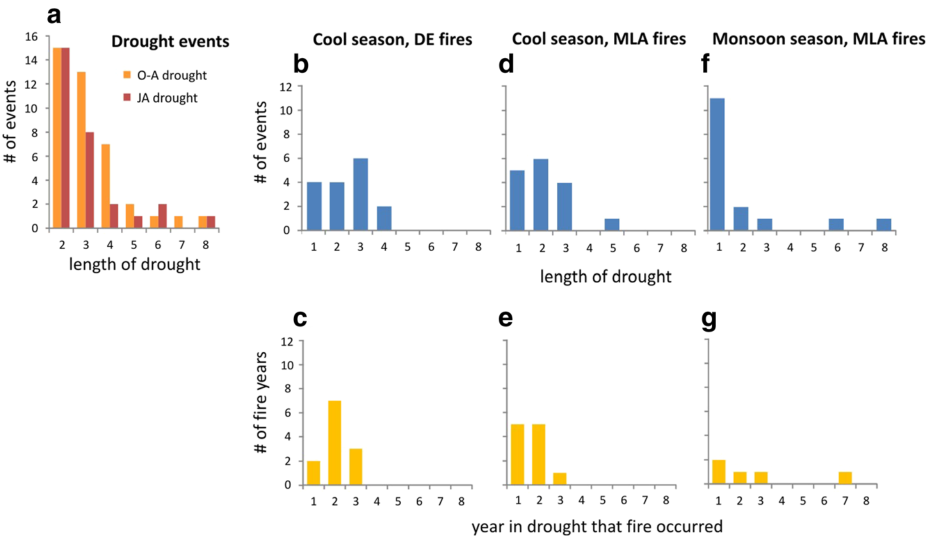

Fig. 4 **a** Numbers and length of droughts (consecutive years of negative SPEI) for October–April (*orange*) and July–August (*brown*) SPEI, 1599–1899. **b**, **d**, and **f** Lengths of the droughts in which the largest fire years occurred, and numbers of fire years corresponding to each drought length for cool season DE fires, cool season MLA fires, and monsoon season MLA fires. **c**, **e**, and **g** The year within the drought in which the fire occurred

conditions could inhibit large fires. The SPEI drought analysis revealed differences in the distributions of drought lengths between the cool and monsoon seasons (Fig. 4a). Single dry years are more common in the monsoon and multi-year droughts occur more frequently in the cool season. There were 25 cool-season droughts of 3 years or more, compared to 14 for the monsoon (Table S3). The longest cool-season droughts lasted up to 8 years. In order to explore the relationship between fire occurrence and drought length, we examined when large fires occurred relative to multi-year cool- and monsoon-season droughts.

Although there are cool-season droughts lasting 5 to 8 years, none of the largest early-season (DE) fires occur during these persistent droughts (Fig. 4). Of the 16 largest early season fire years, ten occurred within a 2- to 3-year cool-season drought, and two within a 4-year cool-season drought (Fig. 4b). The remaining four large early season fire years occurred during single-year cool-season droughts. Within a multi-year cool-season drought, fires only occurred in the first 3 years and primarily in the second year of the drought (Fig. 4c). This result generally supports the SEA, which indicates that conditions most strongly linked to large early-season fires include a wet year 2 or 3 years prior to the fire year, but not the year prior to the fire year.

Relationships between persistent cool-season droughts and the largest mid- to late-season fires (MLA) are similar to the early-season fires. Most of the mid- to late-season fires occur during droughts of 2 or 3 years (Fig. 4d). Almost all large mid- to late-season fires occur in the first 2 years of a cool-season drought (Fig. 4e).

Similarly, persistent monsoon-season drought was not related to large fire occurrence. Only 31% (5 of 16) of the large mid- to late-season fire years occurred during persistent monsoon droughts (Fig. 4f). These monsoon droughts lasted 2 to 8 years. All but one of these large fires occurred within the first 3 years of the persistent drought (Fig. 4g). Results for the monsoon droughts may reflect the fact that, compared to the cool season, monsoon droughts are more likely to occur as single years (Fig. 4a).

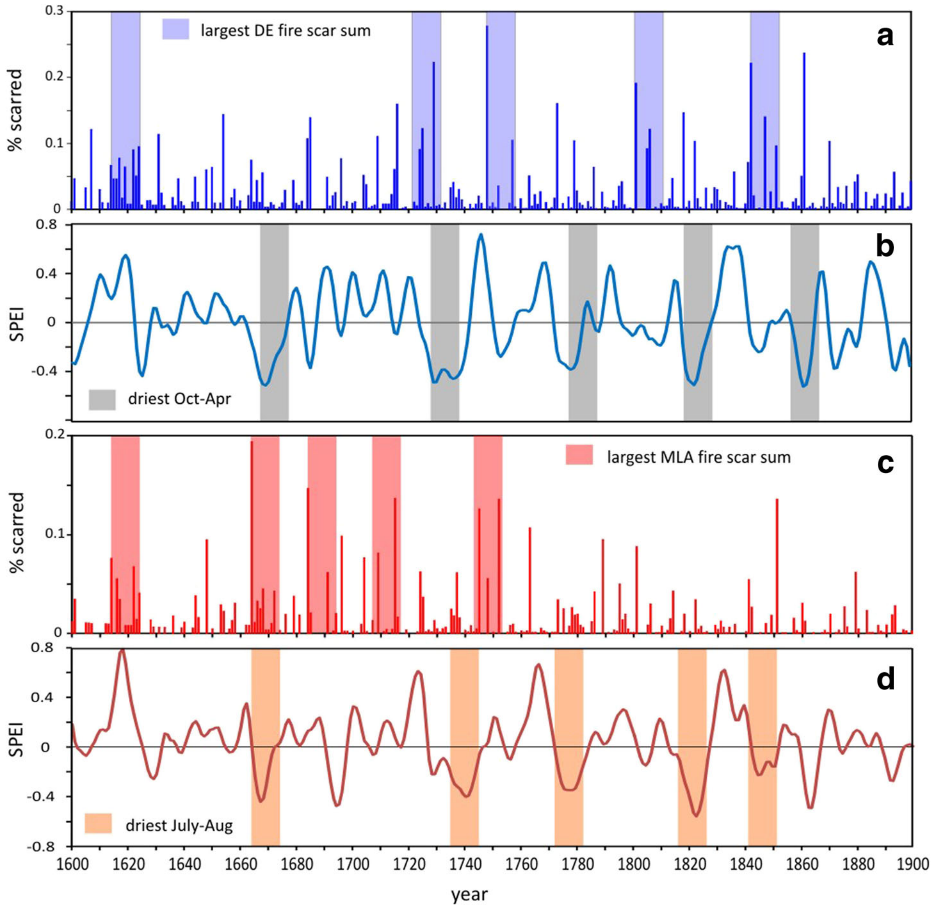

Fig. 5 **a** Percent of recording trees scarred by early-season (DE) fires in *dark blue bars*. *Light blue vertical bars* are the five non-overlapping decades with the largest sums of percent DE scarred trees. **b** October–April SPEI smoothed with a 10-year spline; *vertical bars* are the five non-overlapping decades with the lowest SPEI values. **c** Percent of recording trees scarred by mid- to late-season (MLA) fires in *dark red bars*. *Light red vertical bars* are the five non-overlapping decades with the largest sums of percent MLA scarred trees. **d** July–August SPEI smoothed with a 10-year spline; *vertical bars* are the five non-overlapping decades with the lowest SPEI values

When the driest decades of both SPEI seasons were assessed, they were not consistently related to decades of high fire occurrence. For early season (DE) fires, the five decades with the largest sum of percent trees scarred—periods of widespread fire—had little correspondence with the driest decades of cool-season moisture (Fig. 5a, b). Since both cool- and monsoon-season drought appear to influence mid- to late-season fires (Fig. 3), we compared dry decades for both seasons with high MLA fire decades. These dry periods are distributed across three centuries (Fig. 5b, d), whereas the decades with the largest MLA fire scar sums are concentrated in the first half of the record (Fig. 5c). As with DE fires, there is little correspondence between the decades with the most widespread MLA fires and the driest decades of cool-season SPEI. The one exception is the mid-1660s to mid-1670s (Fig. 5b, c). However, when looking at monsoon moisture, two of the five driest decades do overlap with high mid- to late-season fire scar sums. The mid-1660s is unique, with widespread mid- to late-season fires coinciding with some of the driest decades in both seasons. This period includes the year with the highest percent of trees scarred in the mid-to-late fire season, 1664.

5 Discussion

5.1 Multi-seasonal climate associated with large fire years

The largest early-season fires tend to occur when wet cool seasons are followed by cool-season drought. Years without fires occur after wet cool seasons, with no influence from climate in prior years. These results emphasize the historical importance of cool-season moisture for promoting conditions conducive to large fires in the dry conifer forests of the Jemez (Touchan et al. 1996), the southwestern USA (Swetnam and Betancourt 1998), and the western USA (Swetnam et al. 2016). Modern studies confirm the importance of cool-season wet-dry oscillations in the cool season for fire occurrence across the western USA, but highlight regional differences. Cool-season drought is an important predictor of twentieth century area burned in northern or mountainous ecoprovinces across the western USA, whereas wet cool seasons in prior years are also important in drier ecoprovinces (Westerling et al. 2003; Littell et al. 2009).

Our results are the first documented effects of the NAM on fire occurrence prior to the twentieth century. Monsoon moisture has the greatest effect on mid- to late-season (M, L, and A) fires. The monsoon must be dry for these mid- to late-summer and fall fires to be widespread, as hypothesized by Grissino-Mayer and Swetnam (2000). Large late-season fires may also depend on cool-season conditions, such that dual-season drought preceded by dual-season wet conditions are important for large late-season fire occurrence. Modern studies indicate that prior-year NAM moisture was associated with fires in Arizona and the Great Basin (Westerling et al. 2003; Crimmins and Comrie 2004; Littell et al. 2009). In these studies, wet summers 1 and 2 years prior to the fire likely increased fine fuels, such as grasses, that were important for fire spread.

The intra-annual distribution of fire seasonality derived from tree-ring fire scars provides additional insights into the effects of the monsoon on fire seasonality. The largest early-season fires appear to burn until the onset of the monsoon (Fig. 2 and S2). This is consistent with modern fires in the region, many of which are extinguished by monsoon moisture. Historically, many of the largest late summer and fall fires appear to have occurred when dry monsoons allowed relatively small early-season fires to continue to burn into the summer and fall. This is indicated by all of the largest late summer and fall fires having some proportion of trees scarred in the early (DE) fire seasons (see distribution of fire scar positions for large latewood fires in Fig. 2 and S2). It is also possible that some large late-season fires may have ignited during a dry monsoon season. Multiple ignitions over the fire season could confound these interpretations.

5.2 Persistent drought and fire

Analysis of cool- and monsoon-season droughts and fire occurrence indicates that, overall, fires most often occur during the first or second year of multi-year droughts. Long droughts do not appear to promote large fires in the later years of the drought. The occurrence of all but one large fire in the first 3 years of a drought is not surprising (Fig. 4c, e, and g), but reinforces the importance of short droughts for fires in the region. This is further supported by the sequence of climate conditions leading to fires, which include a wet cool season several years prior to the fire. Because of the key role of wet cool seasons 2 and 3 years prior to a large fire year, and to a lesser degree in the monsoon season, prolonged drought may actually limit the occurrence of large fires in dry conifer forests. Once these dry forests burn, they need moisture to replenish surface fuels before the area can burn again.

The decades with the driest cool seasons were not consistently related to periods of high fire occurrence. These dry decades do not provide the necessary periodic wet conditions that precede the biggest fire years. Fitch and Meyer (2016) also found that extended dry periods in the Jemez Mountains, going back multiple millennia, did not necessarily correspond with increased fire activity, likely due to fuel limitations. While extremely dry winters are a necessary component for the most widespread fires, regardless of fire seasonality, if dry conditions persist beyond several years, the chances of widespread fire likely diminish. This result of persistent drought reducing fire occurrence in a fuel-limited ecosystem supports observations of the importance of biomass variability for modeling fire regimes globally and their response to climate change (Krawchuk et al. 2009).

Overall, these results suggest that the strongest climatic controls over fire regimes in the Jemez Mountains were seasonal and inter-annual to sub-decadal in scale. Decadal fire-climate relations were generally weak. This suggests that fine fuel biomass production (grasses, tree needles, and cones), which can respond to these short time-scale variations in climate, was likely the most important mechanism of climatic influence. It is probably not coincidental that the El Niño-Southern Oscillation (the key synoptic climate control over wet-dry oscillations in the southwestern USA), the phenological cycle of ponderosa pine (*Pinus ponderosa*) needle and cone production, and the frequency of surface fires, all typically occur over time scales of about 2 to 7 years (Maguire 1956; Swetnam and Betancourt 1990). That is, natural wet-dry oscillations might readily entrain inherent (and evolved) vegetative and reproductive cycles of flammable fuel production, which in turn promote synchronized, extensive surface fires.

5.3 Insights from the past for future fire regimes

Projecting fire response to climate change in semi-arid, biomass-limited regions is challenging, and future fire regimes will likely vary temporally in accordance with biomass availability. Climate-driven changes in vegetation will further confound forecasts of future fire regimes. Williams et al. (2015) suggest that future increased drought and moisture stress will increase fire occurrence in the southwestern USA, until fuel becomes limiting. Our results suggest that in the semi-arid southwestern USA, fuel was historically limiting in dry conifer forests and that persistent cool-season drought actually reduced fire occurrence. This differs from wetter, more productive mixed-conifer, aspen, and spruce-fir forests that are not fuel limited and where prior wet years are not associated with fire occurrence, only severe drought during the fire year (Swetnam and Betancourt 1998; Margolis and Swetnam 2013). Fine and heavy fuel loads in dry conifer forests have increased significantly over the last century due to fire exclusion (Fulé et al. 1997), although mega-fires in recent decades are beginning to reduce these overabundant fuels in portions of the landscape (Stephens et al. 2014). As warming continues to increase drought stress and increase large fire occurrence, some of the drier ecosystems in the region may move back toward being fuel-limited, with consequences for forecasting future fire regimes.

A major uncertainty for future fire regimes in fuel-limited systems is future moisture variability. Forecasting future precipitation is particularly complex in the southwestern USA, because of the two seasons of moisture. Projected extended drying in the region, due to reduced cool-season moisture (e.g., Seager and Vecchi 2010) would likely continue to increase fire occurrence in coming decades. However, as biomass becomes limiting, fire occurrence could ultimately decrease in dry forests and woodlands where fine-fuels are important for fire spread. A transition to a shortened or a weak NAM (e.g., Cook and Seager 2013) could extend the fire season in the southwestern USA through the summer and into the fall, which is currently rare, but consistent with the tree-ring record. Failed monsoons could represent the scenario with the greatest fire occurrence in the near term, before moisture stress from increased temperature supersedes any potential increases in precipitation (e.g., Williams et al. 2013), and biomass becomes increasingly limiting to fire occurrence.

6 Conclusions

We present the first in-depth, landscape-scale analysis of historical multi-seasonal climatic controls of fire size and seasonality using tree rings. Our findings suggest different seasonal climate controls on early season and mid- to late-season fires, but in both cases, sequences of wet and dry conditions are critical for preconditioning forests to burn. Dry conditions in the year of the fire—dry in the cool season for early-season fires, and dry in the monsoon season for late-season fires—are critical. Equally important are wet conditions, particularly in the cool season, 2 to 3 years preceding the fire year. The importance of this sequence of wet and dry years has key implications for relationships between fire activity and drought, and our results indicate persistent drought is not associated with the largest fires or periods of high fire activity in this region.

Our results suggest that as moisture stress increases in the southwestern USA due to warming (Seager et al. 2007; Williams et al. 2013), large fire occurrence may decrease in some fuel-limited ecosystems. Many model projections of global fire response to climate change use multi-decadal climate “normals” and lack inter-annual or intra-annual climate variability (e.g., Krawchuk et al. 2009; Moritz et al. 2012). We demonstrate that inter- and intra-annual climate variability is an important control for large fire occurrence and fire seasonality in a semi-arid, monsoon-affected region of southwestern North America. Accurate projections of inter- and intra-annual moisture variability will likely be important to accurately model future fire in the southwestern USA, particularly due to the bimodal precipitation regime and a likely future increase in biomass limitations on fire occurrence (i.e., requiring wet conditions to produce fuels to burn). In the future, in semi-arid regions such as the southwestern USA, prolonged droughts driven by warming could decrease fire activity due to biomass limitations.

Acknowledgements This work was supported by the National Science Foundation Macrosystems award number 1065790. K. Miller, B. Olimpio, L.B. Johnson, C.H. Guiterman, E. Bigio, D.A. Falk, C.H. Baisan, and S.B. Malevich provided comments and assistance with data collection and data management. G. Meyer and two anonymous reviewers provided useful comments. We thank the researchers who developed the fire history data used in this study, particularly D.A. Falk, C.H. Baisan, and C.D. Allen. This work is a contribution of the Western Mountain Initiative, a USGS global change research project. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

References

Cook BI, Seager R (2013) The response of the North American monsoon to increased greenhouse gas forcing. J Geophys Res 118:1690–1699. doi:10.1002/jgrd.50111
Crimmins MA, Comrie AC (2004) Interactions between antecedent climate and wildfire variability across south-eastern Arizona. Int J Wildl Fire 13:455–466
Dennison PE, Brewer SC, Arnold JD, Moritz MA (2014) Large wildfire trends in the western United States, 1984–2011. Geophys Res Lett 41:2928–2933. doi:10.1002/2014GL061184
Farris CA, Baisan CH, Falk DA et al (2010) Spatial and temporal corroboration of a fire-scar-based fire history in a frequently burned ponderosa pine forest. Ecol Appl 20:1598–1614
Fitch EP, Meyer GA (2016) Temporal and spatial climatic controls on Holocene fire-related erosion and sedimentation, Jemez Mountains, New Mexico. Quat Res 85:75–86. doi:10.1016/j.yqres.2015.11.008
Fulé PZ, Covington WW, Moore MM (1997) Determining reference conditions for ecosystem management of southwestern ponderosa pine forests. Ecol Appl 7:895–908
Gochis D, Schemm J, Shi W et al (2009) A forum for evaluating forecasts of the North American monsoon. Eos (Washington DC) 90:249–250. doi:10.1130/GES00147.1.Oberlies
Griffin D, Meko DM, Touchan R et al (2011) Latewood chronology development for summer-moisture reconstruction in the US southwest. Tree-Ring Res 67:87–101
Griffin D, Woodhouse CA, Meko DM et al (2013) North American monsoon precipitation reconstructed from tree-ring latewood. Geophys Res Lett 40:954–958
Grissino-Mayer HD, Swetnam TW (2000) Century-scale climate forcing of fire regimes in the American southwest. The Holocene 10:213–220
Keeley JE, Syphard AD (2016) Climate change and future fire regimes: examples from California. Geosciences 6:1–14. doi:10.3390/geosciences6030037
Kitzberger T, Brown PM, Heyerdahl EK et al (2007) Contingent Pacific-Atlantic Ocean influence on multicentury wildfire synchrony over western North America. Proc Natl Acad Sci U S A 104:543–548
Krawchuk MA, Moritz MA, Parisien MA et al (2009) Global pyrogeography: the current and future distribution of wildfire. PLoS One 4:e5102. doi:10.1371/journal.pone.0005102
Littell JS, McKenzie D, Peterson DL, Westerling AL (2009) Climate and wildfire area burned in western U. S. ecoprovinces, 1916-2003. Ecol Appl 19:1003–1021
Littell JS, Peterson DL, Riley KL et al (2016) A review of the relationships between drought and forest fire in the United States. Glob Chang Biol 22:2353–2369. doi:10.1111/gcb.13275
Maguire WP (1956) Are ponderosa pine crops predictable? J For 54:778–779
Malevich SB, Margolis EQ, Guiterman CH (2015) Burnr: fire history analysis in R. https://github.com/ltrr-arizona-edu/burnr
Margolis EQ, Swetnam TW (2013) Historical fire-climate relationships of upper elevation fire regimes in the south-western United States. Int J Wildl Fire 22:588–598
Marlon JR, Bartlein PJ, Gavin DG et al (2012) Long-term perspective on wildfires in the western USA. Proc Natl Acad Sci U S A 109:E535–E543
Moritz MA, Parisien M-A, Batllori E et al (2012) Climate change and disruptions to global fire activity. Ecosphere 3:art49. doi:10.1890/ES11-00345.1
R Core Team (2015) R: A language and environment for statistical computing. Version 3.1.1
Seager R, Vecchi GA (2010) Greenhouse warming and the 21st century hydroclimate of southwestern North America. Proc Natl Acad Sci 107:21277–21282. doi:10.1073/pnas.0910856107
Seager R, Ting MF, Held I et al (2007) Model projections of an imminent transition to a more arid climate in southwestern North America. Science 316:1181–1184
Stephens SL, Burrows N, Buyantuyev A et al (2014) Temperate and boreal forest mega-fires: characteristics and challenges. Front Ecol Environ 12:115–122. doi:10.1890/120332
Swetnam TW (1993) Fire history and climate change in giant sequoia groves. Science 262:885–889
Swetnam TW, Betancourt JL (1990) Fire-southern oscillation relations in the southwestern United States. Science 249:1017–1020
Swetnam TW, Betancourt JL (1998) Mesoscale disturbance and ecological response to decadal climatic variability in the American southwest. J Clim 11:3128–3147
Swetnam TW, Farella J, Roos CI et al (2016) Multi-scale perspectives of fire, climate and humans in western North America and the Jemez Mountains, USA. Proc R Soc London Ser B-Biological Sci 371:20150168. doi:10.1098/rstb.2015.0168
Touchan R, Allen CD, Swetnam TW (1996) Fire history and climatic patterns in ponderosa pine and mixed-conifer forests of the Jemez Mountains, northern New Mexico. USDA For. Serv. RM-GTR-286:33–46
Westerling AL (2016) Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. Philos Trans R Soc London Ser B 371:20150178. doi:10.1098/rstb.2015.0178

Westerling AL, Gershunov A, Brown TJ et al (2003) Climate and wildfire in the western United States. Bull Am Meteorol Soc 84:595–604
Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase western US forest wildfire activity. Science 313:940–943
Williams A, Allen CD, Macalady AK et al (2013) Temperature as a potent driver of regional forest drought stress and tree mortality. Nat Clim Chang 3:292–297
Williams AP, Seager R, Macalady AK et al (2015) Correlations between components of the water balance and burned area reveal new insights for predicting forest fire area in the southwest United States. Int J Wildl Fire 24:14–26