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Widespread fire years in the US–Mexico Sky Islands are contingent on both winter and monsoon precipitation

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Abstract. The climate of the south-western United States and northern Mexico borderlands is marked by a bimodal precipitation regime with the majority of moisture arriving during the cool season via Pacific frontal storm systems, and intense convective storms during the North American Monsoon (NAM). The fire season occurs primarily during the arid foresummer in May and June, before the development of the NAM. Most tree-ring studies of fire climatology in the region have evaluated only the role of winter precipitation. We used tree-ring-width-based reconstructions of both winter and monsoon precipitation, coupled with fire scar reconstructions of fire history from mountain ranges in the US and Mexico, to quantify the historical role and interactions of both seasons of precipitation in modulating widespread fire years. Winter precipitation was the primary driver of widespread fire years in the region, but years with drought in both seasons had the highest fire frequency and most widespread fires. These relationships define a unique monsoon fire regime, in which the timing and amount of monsoon precipitation are important factors in limiting the length of fire season and regulating widespread fire years.

Keywords: climate regulation, monsoon fire regime, North American Monsoon, summer precipitation index, synchrony, winter precipitation index.

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Introduction

Fire is an important ecological process in many terrestrial ecosystems worldwide, influencing vegetation dynamics, carbon exchange and many other key processes (Johnson and Miyanishi 2001; Bowman *et al.* 2009; Hurteau and Brooks 2011; Scott *et al.* 2013). Seasonal and interannual climate is recognised as a primary influence on fire, affecting the timing and size of fires, and intensity of fire behaviour as well as regulating major vegetation types and fuel conditions (Swetnam and Betancourt 1990, 1998; Gavin *et al.* 2007; Abatzoglou *et al.* 2017). The likelihood, behaviour and effects of a given area burning are thus dependent on multiple factors acting at varying temporal and spatial scales (Falk *et al.* 2007; McKenzie *et al.* 2011). Local factors include fuels and forest conditions, localised weather patterns and topography. Regional factors, particularly seasonal to interannual climate variations, can act synchronously over large areas, affecting fire activity at these broadest scales (Grissino-Mayer and Swetnam 2000; Heyerdahl *et al.* 2001; Falk *et al.* 2011). Although local-scale (or 'bottom–up') conditions are important for regulating fire behaviour and post-fire ecological responses, regional scale (or 'top–down') factors can affect the length and activity of fire seasons among mountain ranges (Gill and Taylor 2009; McKenzie *et al.* 2011; Yocom *et al.* 2014; Yocom-Kent *et al.* 2017). Understanding variability in climatic controls is thus key to anticipating large, regional fire years and managing fires in increasingly human-impacted forests, especially in the face of changing global climate (Kitzberger *et al.* 2017).

The largest fires and largest total areas burned in the south-western United States and northern Mexico occur typically in the arid foresummer (April–June) between seasons of relatively high precipitation in the winter and latter parts of the summer (Sheppard *et al.* 2002; Bartlein *et al.* 2008). Foresummer fires typically continue to burn until commencement of the summer rains. Once the monsoon season begins, new fires continue to be ignited by increased frequency of lightning strikes, but these fires tend to be smaller, as has been noted in both palaeoecological (Baisan and Swetnam 1990; Grissino-Mayer and Swetnam 2000) and modern (Barrows 1978; Bartlein *et al.* 2008) fire records, owing to increased relative humidity and fuel moistures. The Palmer Drought Severity Index (PDSI; Palmer 1965) is a common measure of drought often used in studies of fire–climate relations (O'Connor *et al.* 2014; Yocom-Kent *et al.* 2017). However, PDSI reflects conditions for plant growth across multiple seasons, making PDSI less predictive than seasonal indices of large fires and area burned at seasonal scales (St George *et al.* 2010; Riley *et al.* 2013).

Winter (cool season) precipitation in south-western North America is delivered principally as cyclonic Pacific frontal storms, with precipitation falling in the form of rain at lower elevations and snow in forested landscapes at higher elevations (Sheppard *et al.* 2002). Winter storms tend to be fairly widespread, with precipitation falling over large areas over the course of one to several days. Interannual variation in winter precipitation in this region is controlled in large part by teleconnections with the El Niño–Southern Oscillation (ENSO) in the tropical Pacific Ocean (Swetnam and Betancourt 1990; Woodhouse *et al.* 2009; Méndez and Magaña 2010).

Summer precipitation in the US–Mexico borderlands comes primarily from the North American Monsoon (NAM) system, which is responsible for ~50% of annual precipitation in southern Arizona and New Mexico and up to 70% in parts of northern Mexico (Adams and Comrie 1997; Comrie and Glenn 1998; Méndez and Magaña 2010). The onset of the monsoon is earlier at more southerly latitudes (central Mexico) and accounts for a larger share of annual precipitation (Higgins *et al.* 1999). NAM rainfall is characterised by high spatial and temporal heterogeneity as a consequence of the highly variable topography and elevation of the Madrean region, which drives convective storm development (Higgins *et al.* 1999; Liebmann *et al.* 2008). Convective storms increase lightning activity, resulting in increased numbers of lightning-initiated fires (Barrows 1978; Hostetler *et al.* 2006; Holden *et al.* 2007). However, the arrival of the monsoon also brings decreased daily high temperatures and a significant increase in relative humidity (Liebmann *et al.* 2008), resulting in increased live and dead fuel moisture (Yool 2011). These changes are reflected in quantitative measures of fire season potential, such as the Energy Release Component (ERC), a metric that incorporates recent weather and fuel loads to estimate potential energy release at the flaming front of a fire (Schlobohm and Brain 2002). As a consequence, the arrival of the NAM generally marks the end of the most intense fire weather in the region, and generally restricts the extent of landscape-scale spreading fires.

The historical role of winter precipitation in regulating the occurrence of fire seasons in the Madrean region is well established (Swetnam *et al.* 2001; Swetnam and Baisan 2003; O'Connor *et al.* 2014). Cool-season precipitation promotes the growth of fine fuels necessary for fire spread in years preceding fires, as well as regulating live and dead fuel moisture during fire years. The start of the fire season is also determined partially by winter and spring precipitation and temperature, which regulate the depth and persistence of snowpack and drying of fuels (Westerling *et al.* 2006; Bartlein *et al.* 2008; Kitzberger *et al.* 2017). In contrast, the opportunity to examine historical fire–climate relations with summer precipitation is relatively new given the recent reconstruction of summer precipitation from tree rings developed for this region (Griffin *et al.* 2013). This reconstruction utilises the Standardised Precipitation Index (SPI) (McKee *et al.* 1993), which has been shown to correlate highly with fire size and occurrence (Riley *et al.* 2013). Summer precipitation has been implicated in studies examining fire–climate relations during the instrumental period (e.g. Holden *et al.* 2007) but the joint role of winter and summer precipitation over the longer record available in tree-ring studies has only recently been investigated (Margolis *et al.* 2017).

Our objective was to assess the relative roles of cool-season and monsoon precipitation in controlling historical fire regimes in the US–Mexico borderlands (Skinner *et al.* 2008). We examined (1) how winter and summer conditions contribute individually and in combination to regulate the spatial extent of widespread fire years; and (2) how fire frequency and synchrony vary in years with contrasting seasonal climatic signals (e.g. dry winters with wet summers compared with wet winters and dry summers).

Data and methods

Study area

We targeted forested areas in the Sky Island bioregion, a network of mountain ranges spanning south-eastern Arizona, south-western New Mexico and the Mexican states of Sonora and Chihuahua, merging to the south with the Sierra Madre in central Sonora and Chihuahua (Warshall 1995; Gottfried *et al.* 2013) (Fig. 1). The Sky Island mountain ranges are noted for their high intra- and intermountain range biodiversity, with floral and faunal influences from the subtropics to the south, the Rocky Mountains to the north and the Sonoran and Chihuahuan deserts at their base (Brusca and Moore 2013; Van Devender *et al.* 2013). Beginning at elevations of ~2000 m, vegetation transitions with elevation successively into pine–oak, pine, mixed-conifer and subalpine forests. Below the forest zone, most ranges support oak or mixed woodlands and grasslands, surrounded by Sonoran or Chihuahuan desert vegetation at low elevations (Brown *et al.* 1979; Brusca and Moore 2013). The relatively sparse vegetation of the desert lowlands provides a barrier to fire spread due to low and disconnected fuel loads; consequently, fires burning multiple mountain ranges in the same year are generally the result of independent ignitions, not fire spread (Falk *et al.* 2007). All mountain ranges have variable local conditions that can affect suitability for widespread fire, so synchronous fires among mountain ranges tend to indicate the influence of regional and synoptic climate (Brown *et al.* 2004; McKenzie *et al.* 2011; Yocom-Kent *et al.* 2017). Beginning around 1900, a clear break between fire frequency in the US and Mexico is driven by local land-use practices and not by a change in regional climate (Fulé *et al.* 2012).

Fire history

Fire-scarred tree-ring samples provide a record of fire activity for a specific location. If fire intensity (heat output) is high enough to wound the cambium (the location of active cell

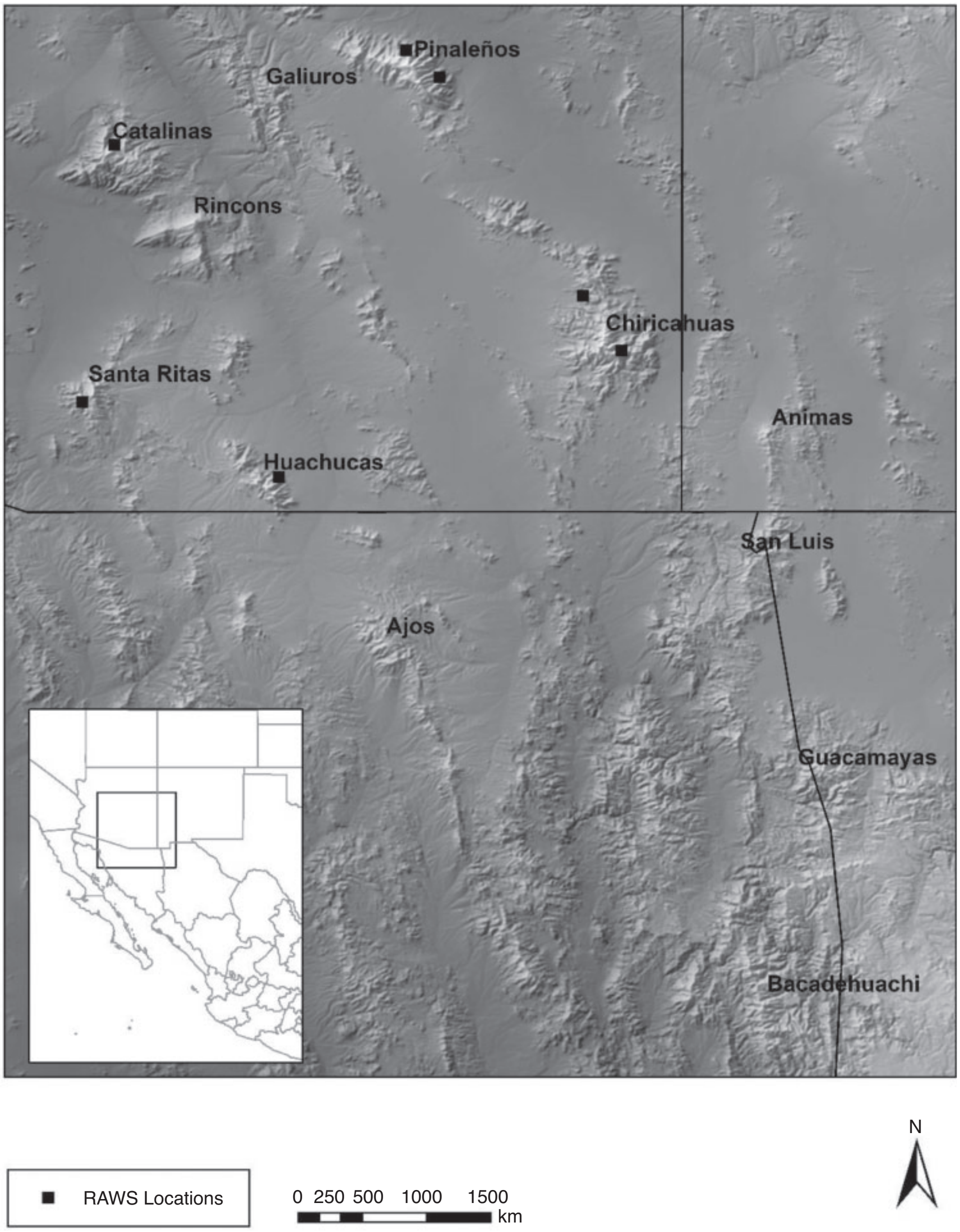

Fig. 1. Mountain ranges with fire history collections used in this study. Black squares show Remote Automatic Weather Station (RAWS) used for Energy Release Component (ERC) analysis. Inset map polygon shows the extent of North American Monsoon (NAM) Region 2 as reconstructed by Griffin *et al.* (2013).

division between the bark and the wood) but not high enough to kill the tree, then a scar is left in a portion of that ring (Dieterich and Swetnam 1984; Gutsell and Johnson 1996; Smith and Sutherland 1999; Smith *et al.* 2016). Large woody fuel build-up at the base of the tree increases heat residence time and contributes to cambial damage and scarring. Tree rings can be cross-dated to determine the calendar date for each ring (Speer 2010), and fire scars in tree-ring samples can thus be assigned exact calendar year dates. Collections of scars from multiple trees provide information on fire years over a spatial domain to determine the spatial extent of fire in that year (Farris *et al.* 2010; Falk *et al.* 2011).

Extensive fire history collections exist for many mountain ranges in the Sky Island bioregion (Swetnam *et al.* 2001; Falk *et al.* 2011). The precision and accuracy of methods for reconstructing fire history have been evaluated by Farris *et al.* (2010, 2013); other studies have used combinations of fire scars, tree age structures and other evidence to develop spatially explicit surface and crown fire histories in some of the studied mountain ranges (e.g. Iniguez *et al.* 2008, 2009; Margolis *et al.* 2011; O'Connor *et al.* 2014). We accessed existing fire history reconstructions for our study area through the International Multi-Proxy Paleofire Database (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/fire-history, accessed 5 December 2013). We obtained additional fire history from other individual researchers (Table 1).

In addition to existing records, we developed new fire history collections by sampling full and partial cross-sections from living and dead trees exhibiting multiple fire scars at three sites in the Galiuro Mountains in Arizona following a targeted sampling design (Farris *et al.* 2013). We included unpublished collections by J. M. Kaib, University of Arizona, from two mountain ranges in Sonora, the Sierra San Luis and the Sierra de Bacadéhuachi, the south-easternmost sky island in the Madrean Archipelago. A total of 67 sites across 12 mountain ranges in our study area were included for initial analysis (Table 1).

Climate reconstructions

We compared fire years recorded within individual study sites, and synchronous fire years across multiple sites, with seasonal precipitation reconstructions from Griffin *et al.* (2013), who derived records of winter (October–April) and summer (June–August) precipitation from tree rings for the North American Monsoon Region 2 (Gochis *et al.* 2009) (Fig. 1). Griffin *et al.* (2013) used chronologies from separate measurements of earlywood widths and latewood widths with their dependence on earlywood removed (Griffin *et al.* 2011) to generate winter and monsoon SPI reconstructions respectively (McKee *et al.* 1993). The winter SPI reconstruction was somewhat more skilful (i.e. explained more variance in seasonal precipitation) than the monsoon SPI (reconstruction variance explained $R^2 = 0.61$ *v.* 0.45 respectively), reflecting in part the greater spatial homogeneity of winter precipitation. NAM Region 2 encompassed all fire history sites with the exception of the Sierra de Bacadéhuachi, which lies just outside the region's boundary.

Fire history chronology development

All individual fire-scarred samples (from trees) for each mountain range were merged into a single master composite chronology of fire events for that range. Composite chronologies of widespread fires within each range were constructed by including only those years in which fires were recorded by a minimum of 25% of active recorder trees within each range. Filtering of fire scar data facilitates comparison of fire history collections with varied sampling methods, including gridded fire history collections with a widespread network of sites and relatively few samples per site (Iniguez *et al.* 2008; Farris *et al.* 2010; O'Connor *et al.* 2014) as well as mountain ranges with widely varying sample depth (Minor 2017). Studies comparing systematic and random landscape-scale sampling of fire-scarred trees have demonstrated that a 25% filter is a robust estimator of the frequency of the most widespread fires within sample areas of ~100 to 2000 ha (Farris *et al.* 2013). Individual tree samples were considered to be in recording condition between the first and last fire scar found on the sample (Kilgore and Taylor 1979; Veblen *et al.* 2000). We calculated percent scarred values as the number of trees scarred in a year divided by the number of samples recording in that year × 100. Site size (area) and number of samples varied by original study designs. Fire data were recorded and analysed in the Fire History Analysis and Exploration System (FHAES; Sutherland *et al.* 2017).

To evaluate regional fire occurrence, we compared records of fire years among mountain ranges to derive a chronology of the most synchronous, widespread fires that burned within and among mountain ranges across the region. These fires are most likely to be associated with regional climate variations at seasonal and interannual time scales, as has been shown in multiple regional- to continental-scale studies (e.g. Swetnam and Betancourt 1990; Swetnam and Betancourt 1998; Kitzberger *et al.* 2007; Falk *et al.* 2011; Yocom-Kent *et al.* 2017). Because our focus was on the interaction of winter and monsoon precipitation signals, we analysed the fire records in all mountain ranges within the NAM Region 2 that also demonstrated a significant relationship between winter precipitation and fire years.

Superposed epoch analysis

We used Superposed Epoch Analysis (SEA) to analyse the influence of seasonal climatic conditions in the fire year and preceding years occurring synchronously in the region. SEA compiles event years and compares the average climatic values of those and antecedent years against bootstrapped simulations of the remainder of the climate series to test significance of departures from average values. SEA has been used to examine climatic conditions in various disturbance processes including fire (Swetnam and Betancourt 1990; Stephens *et al.* 2003; Meunier *et al.* 2014) and insect outbreaks (Flower *et al.* 2014). We used SEA to evaluate the existence of statistically significant ($P < 0.05$) relationships between widespread fire years and winter SPI in each range analysed.

We evaluated the strength of climatic influence on fire occurrence and synchrony by using paired SEAs to assess the role of both seasonal climate indices (winter and monsoon SPI) for each year in the series based on the number of mountain ranges recording fire. Years in the fire record were composited by fire extent over the study area (non-fire years, single mountain range fire years, two-range fire years, and three- or more range fire years). SEA was then applied to each composite to identify the strength and seasonality of climate regulation. We employed the Ljung–Box Q statistic to test for the presence of significant temporal autocorrelation in the SPI series (Ljung and Box 1978).

We organised our data in a contingency table to evaluate the probability that observed patterns in widespread fire years could arise by chance association by comparing expected and observed values (Pagano and Gauvreau 2000). Observed values in our case are the number of fires occurring during years with each combination of seasonal precipitation conditions. Expected values are the number of years that would be expected to have fire if there was no relationship between seasonal precipitation and the number of fires (i.e. random association). This approach has been used elsewhere to examine the relationship between large-scale fire–climate patterns in New Mexico (Rother and Grissino-Mayer 2014) and northern Mexico (Yocom-Kent *et al.* 2017). We applied a chi-squared test to evaluate the significance and magnitude of the difference between the expected and observed values, with a probability level of $P < 0.05$ used to identify significance of association of fire and climate conditions in the tests.

All years in the analysis period were assigned to one of four combinations of winter (winter SPI) and summer (monsoon SPI)

Table 1. Summary of fire-scarred tree collections used in this analysis
DD ≡ decimal degrees. Bold figures in 'No. trees' column indicate total sample size by mountain range

Mountain range and site	Mean Elevation (m)	Latitude (DD)	Longitude (DD)	No. trees	Source
Animas				**57**	
Continental Divide Peak	2470	31.559	−108.782	7	Swetnam *et al.* 2001
Continental Divide Saddle	2410	31.557	−108.775	9	Swetnam *et al.* 2001
Eagle Feather	2440	31.557	−108.78	7	Swetnam *et al.* 2001
Lomas Animas West	2530	31.568	−108.79	3	Swetnam *et al.* 2001
Animas Peak	2575	31.568	−108.788	4	Swetnam *et al.* 2001
Animas Peak East	2515	31.577	−108.788	3	Swetnam *et al.* 2001
Animas Peak North	2560	31.58	−108.784	3	Swetnam *et al.* 2001
Animas Peak West	2530	31.58	−108.787	7	Swetnam *et al.* 2001
Animas West Bench	2530	31.575	−108.79	5	Swetnam *et al.* 2001
BRC	2375	31.565	−108.784	3	Swetnam *et al.* 2001
Turkey Rill	2225	31.56	−108.775	6	Swetnam *et al.* 2001
Bacadéhuachi				**16**	
Bacadéhuachi	2195	29.88	−109.03	16	This study
Catalina				**292**	
Butterfly Peak		Gridded design		103	Iniguez *et al.* 2008
Rose Canyon		Gridded design		138	Iniguez *et al.* 2008
Hitchcock	1965	32.38	−110.68	7	
Palisades	2480	32.42	−110.72	4	Swetnam *et al.* 2001
Mount Lemmon	2743	32.43	−110.78	22	
Rose Canyon East	2210	32.4	−110.7	7	Swetnam *et al.* 2001
Rose Canyon Lower	2190	32.4	−110.7	12	Swetnam *et al.* 2001
Rose Canyon Upper	2370	32.4	−110.68	16	Swetnam *et al.* 2001
Chiricahua				**255**	
Anita Spring	2820	31.851	−109.284	2	Morino *et al.* 2000
Cima Creek Flat	2750	31.861	−109.283	1	Morino *et al.* 2000
Chiricahua Peak	2900	31.843	−109.287	2	Morino *et al.* 2000
Lower Mormon Canyon	2040	31.857	−109.326	5	Morino *et al.* 2000
Mormon Canyon Spring	2070	31.858	−109.323	5	Morino *et al.* 2000
Middle Mormon Canyon	2290	31.853	−109.312	6	Morino *et al.* 2000
Other Rock Outcrop	2540	31.851	−109.303	4	Morino *et al.* 2000
Pine Canyon	1768	31.96	−109.36	27	Kaib *et al.* 1996
Rhyolite Lower	1740	32.006	−109.341	8	Swetnam *et al.* 1989
Rhyolite Middle	1880	32.001	−109.317	30	Swetnam *et al.* 1989
Rhyolite Upper	2088	31.993	−109.311	16	Swetnam *et al.* 1989
Rucker Canyon	2100	31.78	−109.30	21	Kaib 1998
Rustler Park	2560	31.9	−109.27	58	Seklecki *et al.* 1996
Steep and Burnt	2230	31.857	−109.315	5	Morino *et al.* 2000
South of Cima Park	2895	31.853	−109.284	6	Morino *et al.* 2000
Sara Deming Canyon	1950	31.993	−109.325	4	Baisan and Morino 2000
Surprise Canyon	1735	32.012	−109.35	4	Baisan and Morino 2000
Turkey Creek	2100	31.86	−109.36	26	Kaib 1998
Upper Ward Canyon	2650	31.851	−109.296	4	Morino *et al.* 2000
Upper Mormon Canyon1	2580	31.849	−109.299	6	Morino *et al.* 2000
Upper Mormon Canyon2	2460	31.85	−109.308	10	Morino *et al.* 2000
West of Cima Park	2700	31.826	−109.297	5	Morino *et al.* 2000
Galiuro				**16**	
Douglas Canyon	1672	32.62	−110.35	3	Present study
Kennedy Saddle	2074	32.64	−110.31	10	Present study
Rattlesnake Canyon	1438	32.66	−110.36	3	Present study
Huachuca				**70**	
McClure Canyon	2100	31.47	−110.36	18	Kaib 1998
Pat Scott Peak	2370	31.43	−110.35	29	Danzer *et al.* 1996
Saw Mill Canyon	1595	31.45	−110.37	23	Danzer *et al.* 1996
Los Ajos				**37**	
Canyon de Evans Saddle		30.88	−109.91	12	Dieterich 1983
Cerro de Oso		30.98	−109.96	25	Kaib 1998

(*Continued*)

Table 1. (Continued)

Mountain range and site	Mean Elevation (m)	Latitude (DD)	Longitude (DD)	No. trees	Source
Mesa De Las Guacamayas				**153**	
Mesa Prieta	2432	30.52	−108.58	47	Fulé *et al.* 2012
Prieta Sur	2432	30.52	−108.58	29	Fulé *et al.* 2012
El Abeto	2432	30.52	−108.58	33	Fulé *et al.* 2012
Rincon de las Tinajas	2432	30.52	−108.58	44	Fulé *et al.* 2012
Pinaleño				**272**	
Camp Point	2900	32.7	−109.92	50	Grissino-Mayer *et al.* 1994
Peters Flat	2972	32.7	−109.93	40	Grissino-Mayer *et al.* 1994
O'Connor *et al.*		Gridded Collection		182	O'Connor *et al.* 2014
Rincon				**286**	
Mica Mountain	2225	32.2	−110.5	44	Baisan and Swetnam 1990
Rincon Peak	2200	32.12	−110.52	5	Baisan and Swetnam 1990
Mica Mountain		Gridded Collection			Farris *et al.* 2010
Rincon Peak		Gridded Collection			Iniguez *et al.* 2009
Sierra San Luis				**196**	
El Pinito Canyon	2150	31.19	−108.87	46	Meunier *et al.* 2014
Pan Duro Arroyo	2005	31.19	−108.87	45	Meunier *et al.* 2014
Sierra Pan Duro	2100	31.19	−108.87	82	Meunier *et al.* 2014
San Luis Pass	1860	31.31	−108.75	23	Present study
Santa Rita				**16**	
Josephine Saddle	2205	31.7	−110.87	16	Ortloff *et al.* 1995
Total samples				**1596**	

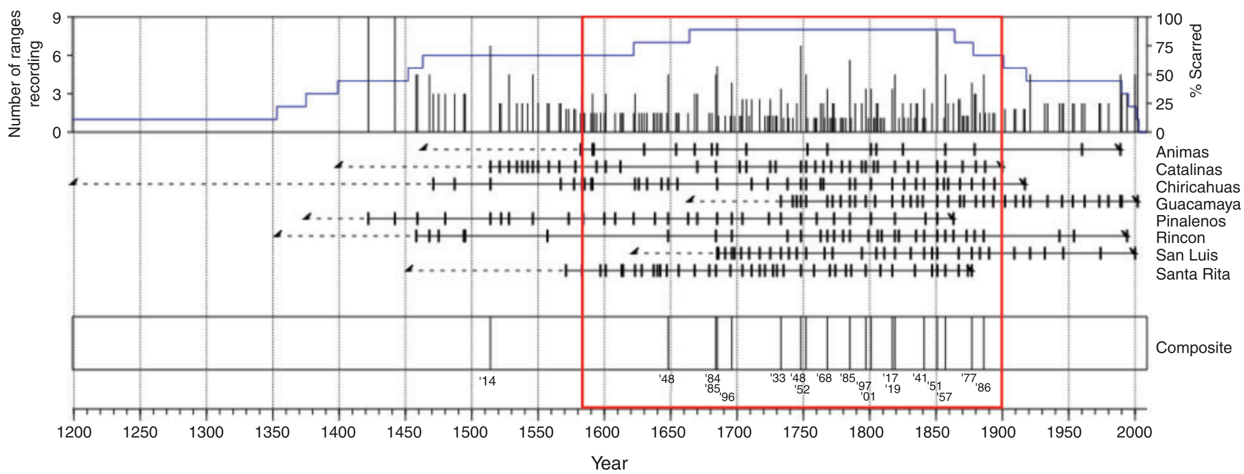

Fig. 2. Fire history chart for the eight mountain ranges used in the final analysis. The top panel shows sample size (blue line, number of ranges in recording status) and percentage of recording trees scarred (histogram bars) through time. Each horizontal line represents a mountain range fire record; vertical tick marks represent fire years found in scars in at least 25% of samples in that mountain range. Composite bar at the bottom shows years with ≥3 ranges recording fires. Red box outlines period of analysis, 1586–1900. Figure generated in FHAES (Sutherland *et al.* 2017).

precipitation, respectively: years with negative SPI in both seasons (Dry/Dry), years with dry winters and wet monsoons (Dry/Wet), years with wet winters and dry monsoon (Wet/Dry) and years with wet winters and summers (Wet/Wet). Dry years were defined by negative SPI values and wet with positive values. We organised two contingency tables to test *a priori* hypotheses concerning the relationship of seasonal climate and fire occurrence (the presence or absence of fire in a year) and synchrony (years in which fires occurred in two or more sites in the same year). We first tested whether climatic conditions in each season affected fire occurrence, with the following hypotheses:

$H1_0$: There is no association between seasonal precipitation and fire occurrence.
$H1_a$: Fires are most common in years with dry conditions in both seasons.

The second analysis tested whether fire synchrony (number of mountain ranges recording fire) was related to biseasonal climate, with the following hypotheses:

$H2_0$: There is no association between seasonal precipitation and fire synchrony.
$H2_a$: Fires are more widespread in years with dry conditions in both seasons.

Results

We analysed 1680 fire history samples from 67 sites across 12 mountain ranges (Table 1). Initial screening indicated significant relationships between fire years and winter SPI in the fire year (SEA, $P < 0.05$) in eight ranges: Animas, Catalina, Chiricahua, Guacamaya, Pinaleño, Rincon, San Luis and Santa Rita (Fig. S1, available as Supplementary material). These mountains provided 1527 fire history samples from 57 sites for analysis. We limited analysis to the period 1586–1900 during which at least six of eight mountain ranges were recording fire; all eight ranges recorded fire between 1733 and 1863 (Fig. 2).

Fire–climate relationships

A bivariate scatter plot (Fig. 3) indicates the relationship of fire extent (number of ranges with fire) to cool-season (winter SPI) and monsoon (monsoon SPI) precipitation for every year during the period of analysis. Non-fire and single-range-fires years were common in all four combinations of wet and dry winter and monsoon seasons. Fire years occurring in two mountain ranges (32) occurred mostly in years with winter drought, but were still present in all four combinations. In contrast, all 18 fire years occurring in three or more mountain ranges coincided with winter drought (winter SPI < 0) and/or low monsoon precipitation (monsoon SPI < 0). No fire years burning in three or more ranges occurred when conditions were wet in both seasons.

Cool season precipitation had a stronger association with widespread fire years than monsoon precipitation (Fig. 4). Monsoon SPI values were significantly different from the series mean only for the most widespread fire years (Fig. 4*h*), whereas dry current-year winters correspond to widespread fire years across all scales (Fig. 4*c*, *e*, *g*). In non-fire years (Fig. 4*a*, *b*), winter SPI was significantly high in the (non)fire year (year 0 on the *x*-axis), exceeding the 99% confidence interval; no other SPI values were significantly different from the series as a whole in the nine-year window of the cool-season SEA for these years. In single-range-fire years (Fig. 4*c*, *d*), fire-year winter SPI values were significantly negative at the 95% confidence interval, whereas no relationship was evident with monsoon SPI. Average cool-season SPI was significantly negative (99% confidence interval) in years when two ranges recorded fire (Fig. 4*e*, *f*), with some indication (non-significant) of wetter antecedent cool seasons, and no significant relationship with monsoon SPI. In years when three or more ranges burned (Fig. 4*g*, *h*), the year of fire was significantly dry in cool season at the 99% confidence interval and the value at year –2 was significantly wet (99% confidence interval). Monsoon SPI values were significantly dry in the fire year in these years. There is no significant low-order autocorrelation in the winter SPI reconstruction. The monsoon SPI reconstruction contains weak but statistically significant negative autocorrelation at lag 1 ($r = -0.145$, Ljung–Box Q stat $P = 0.0098$). However, there was no evidence that this influenced the monsoon SEA results (Fig. 4, right column).

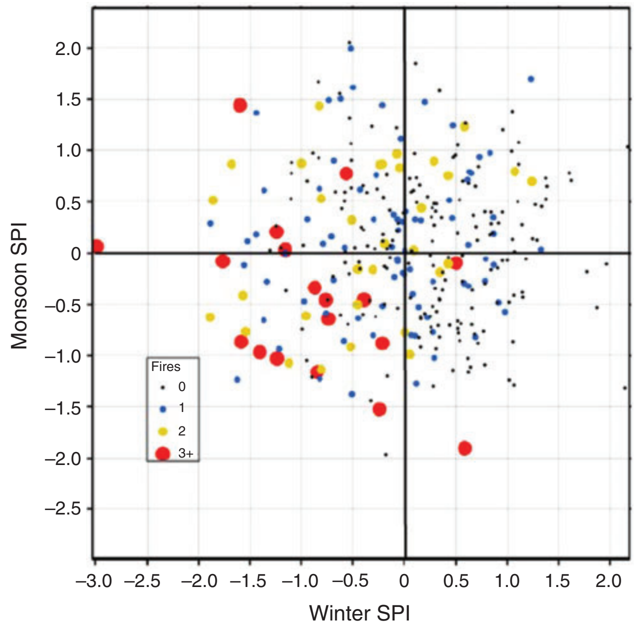

Fig. 3. Bivariate scatter plot of fire extent (number of mountain ranges) against winter (*x*-axis) and monsoon (*y*-axis) Standardised Precipitation Index (SPI) values for each year in the analysis period. Dot colours indicate non-fire years (black), single range fire (blue), two range fires (gold) and three or more range fires (red).

Seasonal precipitation combinations were significantly associated with the number of fires occurring under most combinations of cool and warm season precipitation (winter SPI/monsoon SPI = Dry/Dry, Wet/Dry, Wet/Wet; Table 2). Fires occurred in 131 (41%) of the 318 total years in our study period; these were more common than expected by random occurrence in years with low SPI values in both seasons, and less common in years with wet winters ($\chi^2 = 17.39$, $P = 0.001$); conversely, non-fire years were non-randomly distributed, being less common in years with dry SPI in both seasons, and more common than expected in years with wet winters ($\chi^2 = 12.18$, $P = 0.007$). Fires were most prevalent in years with negative SPI in both seasons (43/68, 63% of years; $\chi^2 = 13.66$, $P > 0.000$) and least common in years with positive SPI in both seasons (22/78 years, 28% of years; $\chi^2 = 5.40$, $P = 0.020$) and years with positive cool season SPI and dry monsoons (24/89, 27%; $\chi^2 = 7.48$, $P = 0.006$) compared with expected values. Thus, we rejected $H1_0$ of no association between seasonal precipitation and fire occurrence, and concluded that fires are most common in years with dry conditions in both seasons, and least common following wet winters, consistent with $H1_a$.

Multi-mountain-range fires were more common than expected in years with shared drought in both seasons (11/68 *v.* 3.9/68 year), and less common than expected for years with matched wet seasons (0/78 year; $\chi^2 = 19.57$, $P < 0.000$) (Table 3 and Fig. 5*b*). Conversely, non-fire years (25) were significantly less common than expected (40.0 year) in years with shared drought in both seasons, and significantly more common (56 year) than expected (45.9 year) for years with matched wet seasons ($\chi^2 = 12.18$, $P = 0.007$) (Table 3 and Fig. 5*b*). Years with single- and two-range fires were not

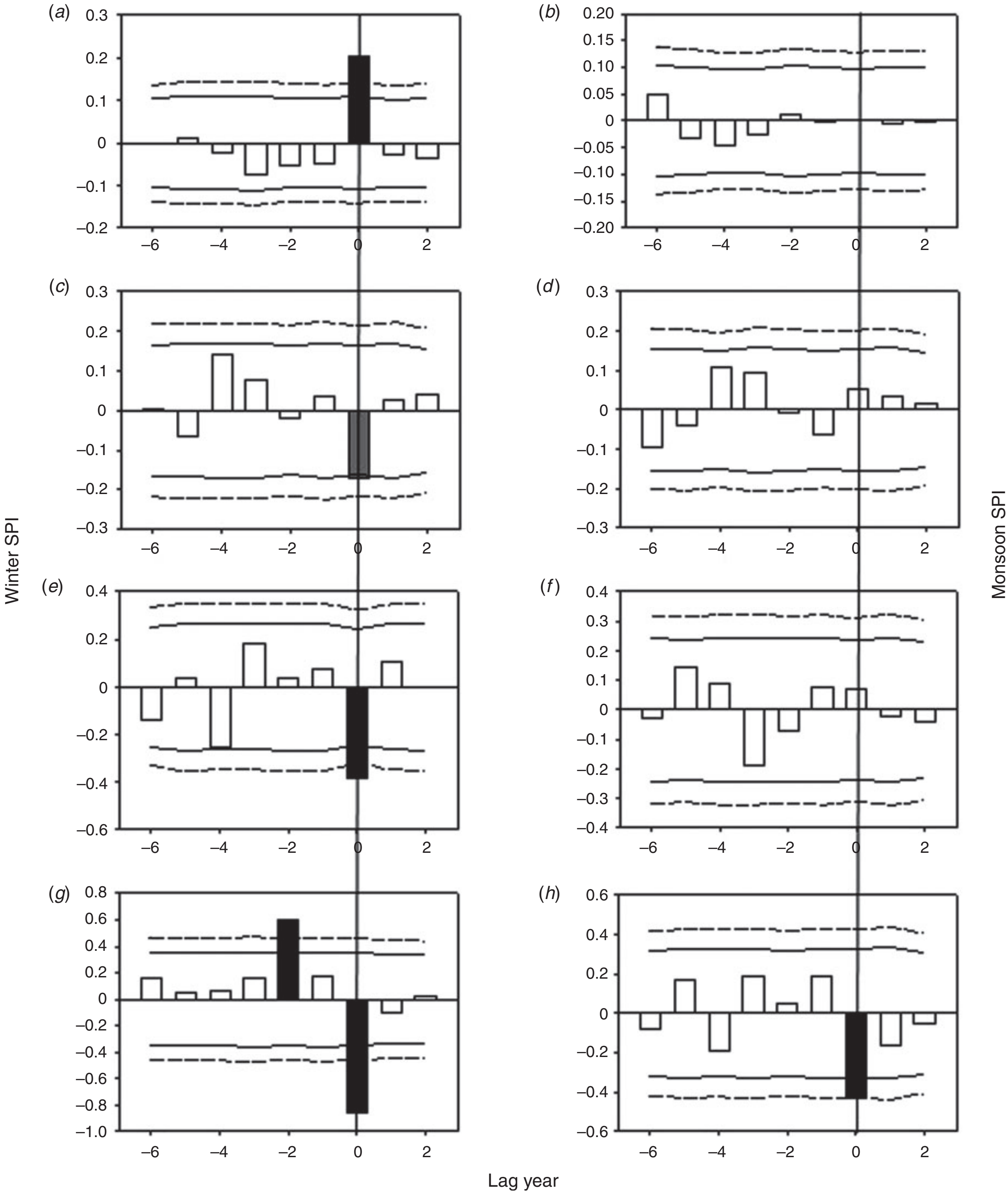

Fig. 4. Superposed Epoch Analyses of winter (left column), and monsoon (right column) seasonal precipitation indices (SPIs) in relation to fire years 1586–1900. In each panel, 0 indicates the fire year (vertical line); years to the left of 0 are prior years. Panels (*a*) and (*b*) are non-fire years; (*c*) and (*d*) are years with single mountain ranges recording fire; (*e*) and (*f*) are years with two mountain ranges recording fire; (*g*) and (*h*) are years with three or more mountain ranges recording fire. Lines above and below the bars represent the 95% (solid) and 99% (dashed) confidence intervals. Grey bars indicate results significant at the 95% confidence interval; black bars significant at the 99% confidence interval.

significantly different from expected values. Years with both winter and summer drought had more fires (22 years) in two or more ranges than expected by random occurrence (10.7 year; $\chi^2 = 22.06$, $P < 0.000$). Years of wet winters and summer drought had significantly fewer observed multirange fire years (6) than expected (14.0 year; $\chi^2 = 8.64$, $P = 0.035$), as did years with both wet winters and summers ($\chi^2 = 7.81$, $P = 0.050$). Based on these results, we rejected $H2_0$ of no association

Table 2. Contingency analysis testing independence of seasonal precipitation (winter and monsoon Standardised Precipitation Index (SPI) respectively) in the presence or absence of fire

Column totals may not add exactly due to rounding. χ^2 statistic and P values are shown for each combination of seasonal climate and each extent of regional fire. Statistically significant relationships are shown in bold

	Non-fire years		Fire years			χ^2 statistic	P
	Observed	Expected	Observed	Expected	Total observed		
Dry Dry	25	39.99	43	28.01	68	13.661	**0.000**
Dry Wet	41	48.81	42	34.19	83	3.026	0.082
Wet Dry	65	52.34	24	36.66	89	7.479	**0.006**
Wet Wet	56	45.87	22	32.13	78	5.400	**0.020**
Total	187	187.01	131	130.99	318		
χ^2 statistic	12.178		17.387				
P	**0.007**		**0.001**				

Table 3. Contingency analysis testing independence of seasonal precipitation (winter and monsoon Standardised Precipitation Index (SPI) respectively) in the number of mountain ranges recording fire

Column totals may not add exactly due to rounding. χ^2 statistic and P values are shown for each combination of seasonal climate and each extent of regional fire. Statistically significant relationships are shown in bold

	No. of mountain ranges recording fire										
	0		1		2		≥3				
	Observed	Expected	Observed	Expected	Observed	Expected	Observed	Expected	Total Observed	χ^2 statistic	P
Dry Dry	25	39.99	21	17.32	11	6.84	11	3.85	68	22.606	**<0.0001**
Dry Wet	41	48.81	26	21.14	11	8.35	5	4.70	83	3.173	0.366
Wet Dry	65	52.34	18	22.67	4	8.96	2	5.04	89	8.635	**0.035**
Wet Wet	56	45.87	16	19.80	6	7.85	0	4.42	78	7.809	**0.050**
Total	187	187.0	81	81.0	32	32.0	18	18.0	318		
χ^2 statistic	12.178		3.582		6.553		19.571				
P	**0.007**		0.310		0.088		**0.000**				

between seasonal precipitation and fire synchrony, and concluded that fires were more widespread in years with dry conditions in both seasons, and less common in years with wet winters, consistent with $H2_a$.

Discussion: the monsoon fire regime

Examining seasons of precipitation separately provides important insights into the role of seasonal climate in conditioning fire regimes (Arizpe 2016). Winter and monsoon precipitation play different roles in the fire season. Winter precipitation prepares the fire season in years preceding the fire by promoting fine fuel growth in wet years, as well as affecting the start of the fire season via mechanisms of snowmelt and fuel moistures. The arrival of the NAM marks the end of the large-fire season. Lightning activity peaks with the arrival of the monsoon, but as the monsoon season progresses, fires tend to be smaller in most years. Conversely, when monsoon precipitation is weak, the summer lightning pattern can contribute to extended widespread summer fire seasons. Our results suggest that areas characterised by a significant proportion of annual precipitation during the NAM, such as the Madrean Sky Islands and northern Sierra Madre, have a distinctive monsoon fire regime, in much the same way that Mediterranean fire regimes are characterised by distinctive patterns of seasonal rainfall and fuel moisture (Keeley *et al.* 2011).

Studies using instrumental records have identified antecedent moisture and fire-season precipitation as two major factors in fire occurrence. Crimmins and Comrie (2004) found antecedent climate conditions to be the primary driver of fire variability across multiple seasons spanning one or more years in southeastern Arizona. Holden *et al.* (2007) found the number of days without rain combined with the maximum days without rain during the fire season to be the primary drivers of fire variability in western New Mexico. Numerous fire history reconstructions have identified combinations of fire-year and prior-year drought conditions as crucial for fire (Swetnam and Betancourt 1998; Skinner *et al.* 2008; Iniguez *et al.* 2009; O'Connor *et al.* 2014). Our study examines all three of these climatic components: precipitation in prior years, winter precipitation in the fire year and monsoon precipitation; we found that the most widespread fire years occur consistently when all three climatic conditions are met. These findings are consistent with Margolis *et al.* (2017) who found that winter precipitation was an important component of all fire years whereas monsoon precipitation was significant only in years when fires burned later in the season.

The NAM Region 2 SPI reconstructions by Griffin *et al.* (2013) explicitly separate summer and winter precipitation.

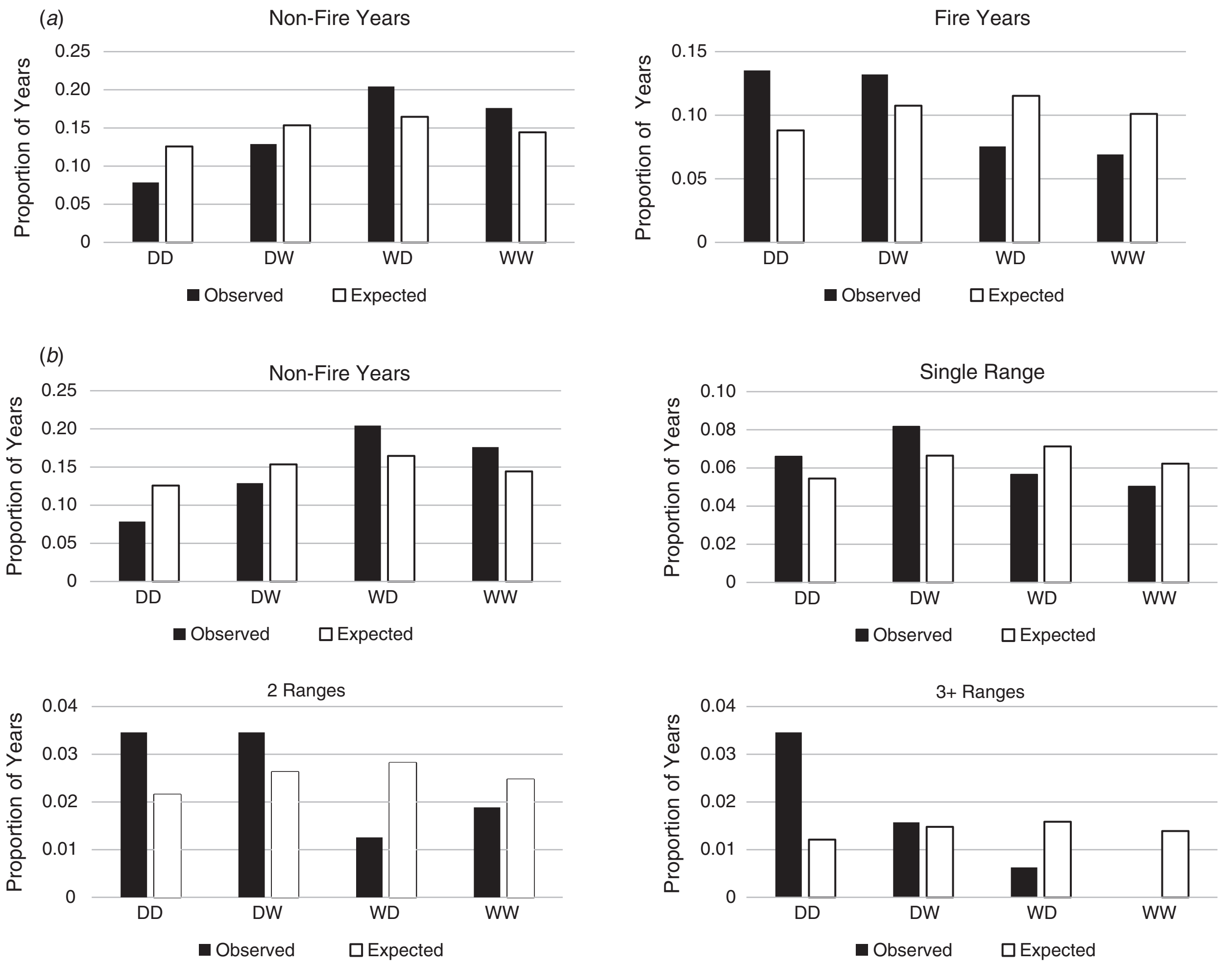

Fig. 5. Observed and expected frequencies of (*a*) fire occurrence; and (*b*) fire synchrony with combinations of winter and monsoon precipitation. See Tables 2 and 3 for contingency data and statistical analysis. Letters beneath each pair of bars represent winter and summer respectively (W, Wet; D, Dry); *y*-axes are the proportion of years meeting each criterion for observed (black) and expected (white) values respectively.

Comparing fire years with the seasonal SPI reconstruction allows a more detailed examination of how seasonal precipitation conditions interact. Until recently, tree-ring reconstructions have been used primarily for cool-season precipitation and drought reconstructions for the south-western US, where winter precipitation plays a key role in growth of conifer species (Fritts 1974; St George *et al.* 2010). This includes the summer (June–August) PDSI reconstruction (Cook and Krusic 2004; Stahle *et al.* 2016) used in many fire histories in the region (e.g. O'Connor *et al.* 2014; Meunier *et al.* 2014), which largely reflect cool-season moisture conditions in the study region.

Both winter (cool-season) and summer (monsoon) precipitation regulate regional fire occurrence across scales in northern Mexico and the south-western United States. Non-fire years tended to be wetter in both seasons, while fire years reflected the influence of dry conditions, especially in winter (Fig. 4*a*), supporting H1a. Fire years occurring in one, two and three or more mountain ranges were significantly dry during the winter (anomalously low winter SPI). Monsoon SPI appears to exert an influence primarily in the most widespread fire years, i.e. those with a minimum of three mountain ranges burning ($P < 0.01$; Fig. 4*h*). This result reinforces the strongest expression of monsoon precipitation in the most widespread fire years, which is its role in regulating length of the fire season.

The NAM is noted for both temporal and spatial heterogeneity (Liebmann *et al.* 2008). The onset date of the monsoon is highly variable across the region: Higgins *et al.* (1999) note a mean start date of 7 July for the Arizona–New Mexico region, but start dates varied by more than 1 month (18 June to 21 July) over the period 1963–88. In northern Mexico (Sonora and Chihuahua), monsoon rains can start as early as 22 May. Liebmann *et al.* (2008) notes that 35% of total monsoon precipitation variability in the northern part of the range relates to the length of monsoon season; years with shorter seasons also tend to have lower overall monsoon SPI in the northern extent of the monsoon. Later start dates are consistent with deficient monsoons (Higgins *et al.* 1999). This spatial and temporal variation in the NAM introduces substantial variability into when the fire season winds down.

The mechanisms by which the monsoon regulates fire season are captured in the instrumental record by values of ERC, a widely used measure of potential energy released from fuel per

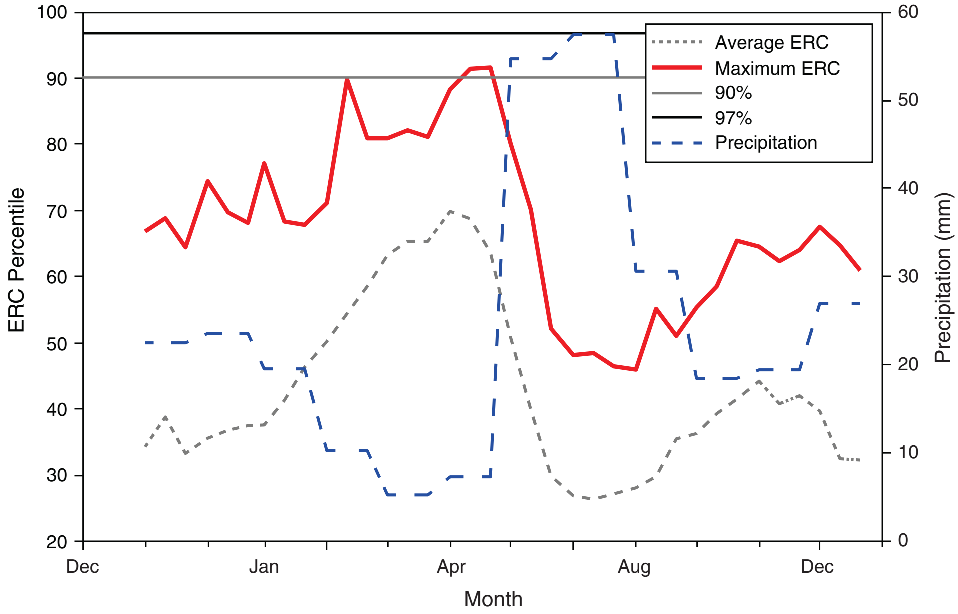

Fig. 6. Energy Release Component (ERC) for a composite of seven south-western US weather stations (RAWS; see Fig. 1) 2000–15. Short-dashed (grey) line shows the average conditions for all stations across all years; red line shows the maximum conditions for all stations across all years. Average 15-day precipitation values (mm) are graphed in long-dashes (blue). The 90th and 97th percentile lines (grey and black lines respectively) indicate high and extreme ERC values. Data compiled in *FireFamily Plus 4.0* (Bradshaw and McCormick 2000).

unit area. ERC is based on variation in temperature and live and dead fuel moistures (Schlobohm and Brain 2002); values change daily but incorporate an ~40-day lag in large (1000-h timelag) fuels, which track atmospheric humidity more slowly. ERC values correlate strongly with fire spread and fire occurrence in modern fires in the western United States (Andrews *et al.* 2003; Riley *et al.* 2013; Littell *et al.* 2016). We graphed average and maximum daily values of ERC for all sites across all months from 2000 to 2015 (Fig. 6). ERC values exhibit a peak in the summer months of May and June, indicating the period of highest fire potential; ERC values decline sharply in early July, reflecting reduced flammability caused by increased relative humidity and fuel moisture, and decreased air temperature associated with the onset of the monsoon.

Fires igniting immediately before or during the build-up phase of the NAM, when ERC values are lower, develop under fire weather less favourable to growth and spread (Fig. 6). Although numerous fire ignitions occur after the onset of the monsoon, area burned by wildfire peaks in June whereas lightning ignitions peak in July, suggesting smaller fires associated with monsoon-related lightning (Barrows 1978; Swetnam and Betancourt 1998). Because monsoon season fires tend to be smaller in size, our record of summer fires in the region may underestimate the number of these events. Although larger synchronous fires account for the great majority of area burned at landscape scales, smaller events can be locally significant ecologically and merit further investigation. It is also possible that winter and monsoon climate interact in ways not tested here, such as a carryover in fuel production from a wet monsoon to the fire season in the subsequent year following a dry winter.

Human impacts on fire regime

Pre-European peoples have had an important impact on fire regimes in ecosystems of north-west Mexico and south-western US. Indeed, given the length of human occupation in this region, it would be surprising if humans had not influenced fire regimes to some degree and scale. Several studies have identified areas where people and climate jointly influenced the local fire regime. Kaye and Swetnam (1999) found a signal of Mescalero Apache occupancy and land-use in fire regimes (fire frequency and seasonality) of the Sacramento Mountains in the western New Mexico borderlands, which have known human occupation for at least the past 12 000 years. Human–fire interactions varied widely based on time and levels of intertribal and European hostility (Kaib 1998). Resident peoples including the Acaxee, Xixime and Tepehuán peoples in the Michiliá region and elsewhere in Durango (Fulé and Covington 1997, 1999) probably contributed ignitions during years that were climatically favourable for fire initiation (Román-Cuesta *et al.* 2003). Further north, in the Jemez Mountains in northern New Mexico, Puebloan peoples (Jemez) contributed to high-frequency, low-severity fire regimes until European contact; forest fires became less frequent but more regionally synchronous following European contact and forced relocation of native peoples (Liebmann *et al.* 2016; Swetnam *et al.* 2016).

In some areas of Mexico managed locally by *ejido* collectives established since the 1930s, reductions in fire frequency were associated with land uses such as grazing, logging and agriculture (Heyerdahl and Alvarado 2003; Fulé *et al.* 2005; Yocom *et al.* 2010). However, in other areas under *ejido* management, historical fire regimes have persisted into the present (Cortés Montaño *et al.* 2012; Cerano-Paredes *et al.* 2016). In a study area in Chihuahua, Fulé *et al.* (2011) documented a continuous frequent-fire regime that has operated without interruption for more than two centuries in an area occupied by the Rarámuri (Tarahumara) people. In the present study area, the impacts of native populations on fire frequency in the region tend towards more frequent and less synchronous fire; while resident peoples likely contributed ignitions within the local mountains where they lived and worked (our single-range-fire years), there is no evidence to suggest that groups travelled the tens of thousands of square kilometres igniting fires simultaneously in distant mountain ranges. Regional climate remains the most parsimonious explanation for widespread synchronous fires in multiple mountain ranges over this large area (Fulé *et al.* 2012).

Management implications

Fire history provides a window into historical landscape dynamics and climate relationships (Swetnam *et al.* 1999; Falk *et al.* 2011). Reference conditions provide valuable baseline estimates for land managers seeking to reintroduce fire in a manner that resembles (or at least reflects) the historical fire regime (Fulé 2008).

As climate changes, fires are expected to increase in size, frequency, severity and aggregate area burned, reflecting deep changes in fire regimes, not just individual events. Elevated winter and spring temperatures are already causing earlier onset of fire season by triggering earlier snow melt and drying of the fine fuel growth from winter moisture (Westerling *et al.* 2006; Kitzberger *et al.* 2017). The Southwest is expected to become more arid under average conditions of likely climate change scenarios (Williams *et al.* 2013), accentuated during the La Niña phase of ENSO, during which years winters are already drier than average (Seager *et al.* 2007). Projected changes to relative humidity and ERC suggest an extension of the fire season by three weeks (Brown *et al.* 2004). Forecast changes to monsoon precipitation are less certain but some models suggest a decrease in monsoon precipitation (Cayan *et al.* 2013; Pascale *et al.* 2017). Understanding how winter and summer precipitation jointly condition years for fire combined with these forecasts suggests that fire seasons are likely to expand and that fire size is likely to increase in the region, creating an important research opportunity (Williams *et al.* 2014). Weak or delayed monsoons could play a particularly important role in extending the fire season in the south-western US.

Fire in the Sky Island region is a largely fuel-driven process dependent on precipitation across multiple seasons or years. Consequently, fuel reductions, including thinning and burning as well as managing natural ignitions will be an increasingly important component of ecosystem restoration and improving resilience. Mechanical fuel treatments are among the most expensive treatment options available, whereas fire as a treatment has potential to treat a much larger area at a lower cost per area (North *et al.* 2012; Stephens *et al.* 2013). Thus, identifying periods when climatic conditions are favourable to promote fire spread, but moderate enough that desired fire behaviour and effects result instead of uncharacteristically high severity, can be a valuable criterion for using fire as a management tool as well as an opportunity for management-relevant research. Understanding the role of seasonal precipitation in the monsoon region is an important aspect of determining when fires could be permitted to burn in an effort to achieve management objectives.

Although using fire as a means to manage fuels and fire behaviour is essential, fire suppression will remain an important aspect of land management for the foreseeable future, especially near inhabited areas (North *et al.* 2012). Understanding the role of both winter and summer precipitation in conditioning fire seasons may give land managers additional tools with which to anticipate fire seasons that are likely to include larger and more widespread fires, and prepare accordingly by mobilising suppression resources. Conversely, understanding the key role of the monsoon in regulating the fire season may allow managers to permit some natural ignitions to progress, as a means of restoring the historical dynamics of these complex ecosystems.

Conflict of interest

The authors declare no conflicts of interest.

Acknowledgements

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