**CSIRO** PUBLISHING

*International Journal of Wildland Fire* **2014**, *23*, 686–697
http://dx.doi.org/10.1071/WF13089

# Modern fire regime resembles historical fire regime in a ponderosa pine forest on Native American lands

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**Abstract.** Forests on tribal lands in the western United States have seen the return of low-intensity surface fires for several decades longer than forests on non-tribal lands. We examined the surface fire regime in a ponderosa pine-dominated (*Pinus ponderosa*) forest on the Hualapai tribal lands in the south-western United States. Using fire-scarred trees, we inferred temporal (frequency and seasonality) and spatial (synchrony) attributes and regulators of the fire regime over three land-use periods (historical, suppression, modern) between 1702 and 2007. Patterns of fire frequency and synchrony were similar, but fire seasonality was dissimilar, between the historical and modern periods. Logistic regression and generalised linear mixed models identified a suite of variables representing fuels, climate and human land uses that were associated with the probability of a site burning. Combined, these results allow for valuable insights regarding past fire spread and variability in fire frequency throughout our study area. In some respects, the current distinct fire regime in our study area, which predominately consists of prescribed fires implemented since the 1960s, resembles the past frequent surface fire regime that occurred here and in similar forest types on non-tribal lands in the south-western United States. Our results will be useful for informing adaptive management throughout the region as climate warms.

**Additional keywords:** climate, dendrochronology, fire scars, fuels, generalised linear mixed models, Hualapai Tribe, logistic regression models, *Pinus ponderosa*, prescribed fire, south-western United States.

Received 30 May 2013, accepted 14 January 2014, published online 22 May 2014

## Introduction

In the western United States, forests on tribal lands have a different recent management history than those on non-tribal lands. Prescribed burning was first implemented in ponderosa pine (*Pinus ponderosa*) forests on tribal lands in the western United States in 1942 to mitigate wildfire behaviour and effects and, since then, has been applied as a management tool more often and more broadly to forests on tribal *v*. public lands (Biswell *et al.* 1973). Prescribed burning in ponderosa pine forests aims to mimic the low-intensity surface fires that frequently occurred in this forest type before Euro-American settlement (Weaver 1943; Brown *et al.* 1999; Heyerdahl *et al.* 2001; Swetnam and Baisan 2003). Although fire use in forests on public lands in the western United States began in the late 1960s, until recent decades both prescribed fires and resource benefit fires (wildfires managed for resource benefits) on public lands were generally limited in scope (Pyne 1982; Stephens and Ruth 2005).

Because forests on tribal lands have seen the return of fire for several decades longer than many forests on public lands, forests on tribal lands may be useful for gauging our current success at restoring temporal and spatial characteristics of this disturbance process. For ponderosa pine forests, emulating patterns of past surface fire and forest structure is consistent with increasing their resistance to severe burning and reducing their vulnerability to catastrophic loss under a warming climate (Fulé 2008; Stephens *et al.* 2012). Therefore, knowing the status of our present burning practices in ponderosa pine forests relative to those of the past can help elucidate potential future conditions and resiliency of other such forests that are currently being managed in similar ways.

Beginning *c*. 1960, prescribed burning and thinning treatments aimed at reducing wildfire hazards were first implemented in the ponderosa pine forest on the Hualapai (pronounced Wal-lah-pie, meaning 'People of the Tall Pines') tribal lands (Arizona) in the south-western United States (Truesdell 1969; US Bureau of Indian Affairs 1989) and have continued to the present (US Bureau of Indian Affairs, unpubl. data). Given its long history of recent fire, this forest affords a unique opportunity to compare modern and historical fire regimes. Furthermore, its location in a region where a large percentage of forests and woodlands occur on tribal lands, yet a limited amount of forest fire-history research has been conducted on these lands, makes it a valuable study site for addressing gaps in knowledge. Approximately 24% of all forests and woodlands in Arizona and New Mexico are on tribal lands (US Geological Survey 2011). However, only 3% (6 of 246) of the numerous crossdated fire-scarred tree chronologies from Arizona and New Mexico are from forests and woodlands on tribal lands (Falk *et al.* 2010).

Fire regimes in forests on tribal and non-tribal lands in the south-western United States are likely regulated by similar mechanisms of climate, topography, vegetation and human land uses that vary and interact along a gradient from coarse to fine temporal and spatial scales (Heyerdahl *et al.* 2001; Falk *et al.* 2007). At coarser scales, fire activity in ponderosa pine and mixed-conifer forests on non-tribal lands has been shown to be strongly influenced by interannual moisture patterns, which play a primary role in synchronising fires among sites across the region by creating fuel conditions conducive to burning over broad, distant areas (Swetnam and Baisan 2003; Crimmins and Comrie 2004). At finer scales, fire activity in these forests is largely influenced by local variability in topography as well as temporal and spatial patterns of vegetation type, moisture and connectivity, which affect fire spread and synchrony among nearby sites (Swetnam and Baisan 2003; Iniguez *et al.* 2008; Ireland *et al.* 2012). In light of the distinct recent management history of forests on tribal lands, it is necessary to investigate factors that have regulated fire regimes here over time. Doing so will provide essential information to help develop appropriate restoration and fuels reduction plans for these forests. Considering the warmer and drier conditions that are predicted for the south-western United States in the coming decades (Seager and Vecchi 2010), the associated effects of these conditions on potential fire activity (Westerling *et al.* 2006), and the great cultural, economic and spiritual value of forests on tribal lands (Alcoze 2003), this information is of increasing importance.

We used tree rings to study the history and drivers of low-intensity surface fires in a ponderosa pine forest on the Hualapai tribal lands. We asked the following questions. (1) Does the modern fire regime introduced into the forest resemble the historical fire regime? (2) What were the regulators of fire across this forest and over time? We combined commonly used techniques for studying fire regimes (e.g. superposed epoch analysis, $\chi^2$ tests) with those less commonly used in fire-history studies (e.g. binomial logistic regression models). Together, these approaches allowed us to derive more comprehensive inferences about the fire regime over time and space.

## Study area

The area surrounding the Hualapai tribal lands has a semi-arid, continental climate. Precipitation follows a bimodal pattern, with a primary maximum resulting from summer convective activity (July–September) and a secondary maximum resulting from winter cyclonic-frontal activity (November–March) (Sheppard *et al.* 2002). Within the 27 500-ha ponderosa pine forest, mean annual temperature is 12°C, with a mean of 23°C in July (warmest month) and a mean of 2°C in January (coldest month), and mean annual precipitation is 400 mm, with means of 60 and 50 mm in August and March (two wettest months) and a mean of 10 mm in June (driest month) (1971–2000 Normals, Parameter-elevation Regressions on Independent Slopes Model [PRISM] Climate Group, Oregon State University, http://www.prismclimate.org, accessed March 2013).

Besides ponderosa pine, Gambel oak (*Quercus gambelii*), pinyon pine (*Pinus edulis*) and juniper (*Juniperus* spp.) occur throughout the forest, with the latter two trees becoming more prevalent near the forest-woodland ecotone. Understorey plants include shrubs such as New Mexico locust (*Robinia neomexicana*) and wax currant (*Ribes cereum*), forbs such as buckwheat (*Eriogonum* spp.) and grasses such as blue grama (*Bouteloua gracilis*) and bottlebrush squirreltail (*Elymus elymoides*). Soils are mostly well-drained Ustalfs that formed in residuum or alluvium largely derived from sandstone and limestone (Prevost and Lindsay 1999).

## Methods

### *Field and laboratory procedures*

We sampled five 25-ha sites (Fig. 1) to reconstruct surface fire history. We selected sites to reflect the gradient of ponderosa pine forest on the landscape, with three sites located across the centre of the forest (Youth Camp, Manzanita High and Manzanita Low) and two sites located to the north and south at ecotones where ponderosa pine forest meets pinyon–juniper woodland (Turkey Tank and Twenty Pines). At the ecotonal sites, ponderosa pine dominates in low-lying areas, where moister and cooler conditions occur, with pinyon and juniper more prevalent on adjacent higher ground. Sites lie between 1940 and 2220 m above sea level. At each of the five sites, we systematically searched for fire-scarred trees along transects that comprehensively covered the sites and used chainsaws to collect partial cross sections from living trees, stumps, snags and logs of any species with a high number of visible, well preserved fire scars (Van Horne and Fulé 2006; Farris *et al.* 2010). Although individual living trees did not always contain a high number of fire scars, collecting them ensured that the fire history included the most recent period.

We mounted the cross sections and sanded them until the cell structure of each was visible with a microscope. All tree rings were crossdated with the aid of a ponderosa pine ring-width chronology from the nearby Mt. Trumbull area (A.E. Waltz, unpubl. data) and measured to the nearest 0.001 mm using a stereozoom microscope and a sliding-stage micrometer interfaced with MeasureJ2X software (VoorTech Consulting, Holderness, NH, USA) to statistically verify the accuracy of our crossdating (program COFECHA version 6.06P, Holmes 1983). Where possible, we identified the tree ring, thus calendar year, in which each fire scar formed and recorded its inter- or intra-ring position to estimate the approximate season the fire occurred. Fire scars were noted as having occurred in one of six positions: dormant (i.e. between two rings), early earlywood, middle earlywood, late earlywood, latewood or undetermined (Dieterich and Swetnam 1984). Dormant scars that occurred before the onset of prescribed burning were assigned to the following calendar year, because modern records indicate that lightning-ignited fires in our study area have mostly taken place between May and August (US Bureau of Indian Affairs, unpubl. data). Dormant scars that occurred after the onset of prescribed burning were assigned to the previous calendar year, because prescribed fires in our study area have mostly taken place

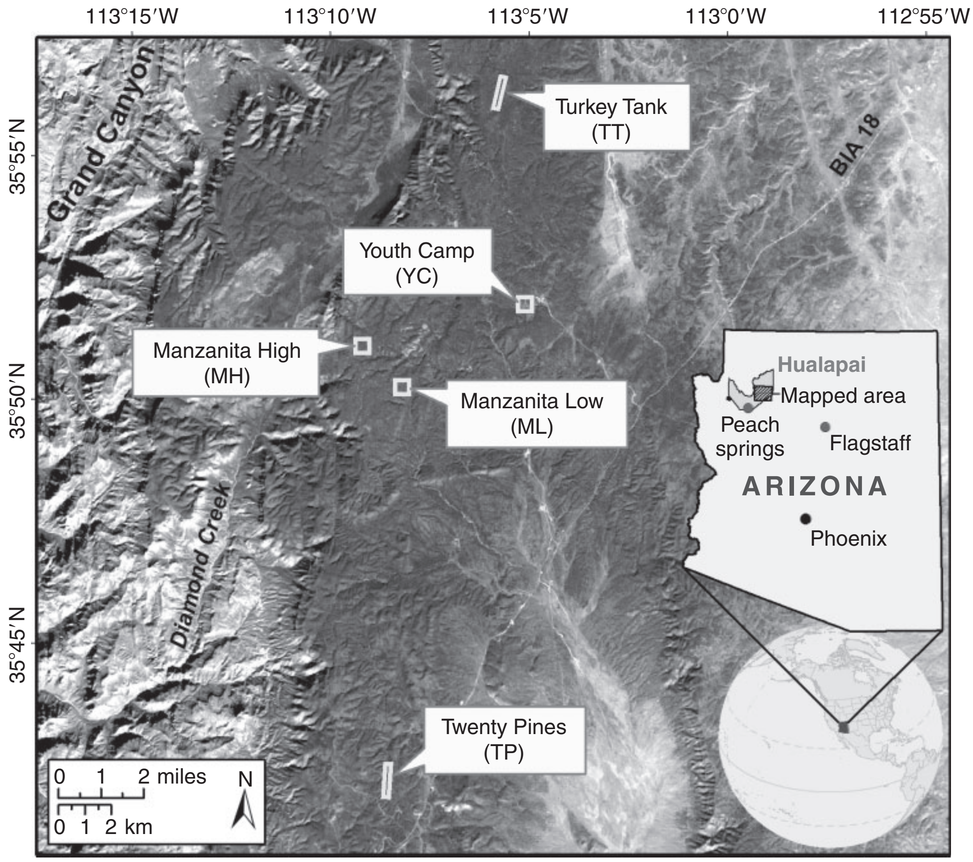


**Fig. 1.** Map of the five study sites located in ponderosa pine-dominated forest on the Hualapai tribal lands in the south-western United States. Background imagery is from the Landsat 7 Enhanced Thematic Mapper (ETM+) sensor: 4,3,2 RGB colour composite.

between October and December (US Bureau of Indian Affairs, unpubl. data).

### *Data analyses*

To assess attributes of the fire regime over time, we combined the fire-scar data from all trees into site composites and identified three land-use periods (historical, suppression, and modern) in which fire activity varied consistently over the entire study area. We identified the periods using historical records but framed each period using a fire-scar date we identified in our tree-ring samples. As a first step, we truncated the earliest portion of the fire chronology for each site so that each began in the first fire year when at least 10% of the total trees sampled were recording. A tree is considered 'recording' after an initial injury by fire or another agent (e.g. lightning) leaves an open wound, making the tree more susceptible to further injury by fire (*sensu* Romme 1980). A tree is considered 'not recording' if it has never been wounded or during periods when rings, and any potential fire scars, close to a wound have eroded, decayed or burnt off or after a wound has healed shut. The historical period began the first year that all five sites were recording (1702) and ended the last year among all sites in the late 1800s that ≥2 trees were scarred by fire within at least one site (1886). The end of the historical period coincided closely with the timing of Euro-American settlement of northern Arizona (Altschul and Fairley 1989; Friederici 2003) and the establishment of the Hualapai Reservation in 1883. The modern period began the first year among all sites that ≥2 trees were once again scarred by fire within at least one site (1958) and ended the last year of our tree-ring record (2007). The start of the modern period coincided closely with the onset of prescribed burning in our study area (Truesdell 1969). The suppression period occurred in between these two periods (1887–1957) and comprised years in which <2 trees were scarred by fire within any site.

We assessed temporal attributes of the fire regime, including fire interval, the percentage of years with fire and fire seasonality. We calculated composite fire interval statistics (program FHX2 version 3.2, Grissino-Mayer 2001) for each site for the historical and modern periods using (1) all fire years, including those in which a single tree was scarred and (2) years in which a minimum of two trees and ≥25% of the recording trees were scarred (i.e. 'widespread' fire years). We applied this filtering approach to contrast our results with those of other studies, as similar approaches have been used to infer the relative extent of fires within a site, with fires recorded by a higher proportion of trees assumed to be more extensive than those recorded by a lower proportion of trees (Swetnam and Baisan 2003;

Farris *et al.* 2010). Because fire-interval distributions are often skewed, we used Kolmogorov–Smirnov goodness-of-fit tests to check if a normal or a Weibull distribution adequately modelled the data and estimated both the mean fire interval (MFI) and the Weibull median probability interval (WMPI). In addition, we calculated the mean fire interval per tree (i.e. point fire interval, PFI) during the historical and modern periods and averaged these intervals by site. PFIs provide a useful, but conservative, estimate of fire frequency at any point on the landscape, because not all trees that experience a fire will form a scar (Van Horne and Fulé 2006). Calculating fire interval statistics for the suppression period as well seemed tenuous on account of the low number, or absence, of intervals at individual sites during this period. Therefore, to compare fire occurrence among all three periods and to provide a complementary approach to our fire interval analyses, we also calculated the percentage of years with fire for each site for each of the three periods using all fire years and widespread fire years. Lastly, to examine fire seasonality, we summarised the data on ring position of fire scars for the five sites combined for each of the three periods.

To assess spatial attributes of the fire regime and to infer whether or not fire was spreading, we examined the degree of synchrony (or asynchrony) of fires among and between sites. Using all fire years, we summarised the percentage of fire years that one, two, three, four or five site(s) burned during each of the three periods. In addition, we statistically examined the degree of synchrony between pairs of individual sites during the historical period using all fire years and contingency tables together with Chi-Square tests of independence. In the contingency tables, we included only those years in which fire occurred in at least one of the two sites ($2 \times 1$ contingency tables; program FHX2 version 3.2, Grissino-Mayer 2001). This approach is considered appropriate when topographic or vegetative conditions imply that fires could have spread between sites (Grissino-Mayer 1995), which was a reasonable assumption in this study. We used the false discovery rate method (Benjamini and Hochberg 1995; Pike 2011) to adjust the $P$-values from the 10 Chi-Square tests for multiple comparisons (R Development Core Team 2012). Because of the low number of fire years at individual sites during the suppression and modern periods, it was not appropriate to examine the degree of synchrony during these periods using Chi-Square tests.

To infer the role of drought in synchronising fires, we used superposed epoch analysis (SEA) (program FHX2 version 3.2, Grissino-Mayer 2001). Summer Palmer Drought Severity Index (PDSI) is often correlated with historical and modern fire occurrence in the south-western United States (Swetnam and Baisan 2003; Crimmins and Comrie 2004). Therefore, we used a gridded tree-ring reconstruction of summer (July–August) PDSI (Cook *et al.* 2004) in the SEAs. We selected the four grid points nearest to our study area (72, 73, 87 and 88) and used bilinear interpolation to estimate PDSI. Because the PDSI reconstruction was temporally autocorrelated (autocorrelation test with six lags: $P < 0.0001$, SAS Proc Arima), we selected autoregressive (AR) moving-average models based on lowest Akaike's information criterion (AIC, Burnham and Anderson 2002) and significant but uncorrelated parameters (SAS Institute 2010) to meet the assumptions of SEA. We used the white noise residuals from an AR(1) model (white noise test: $P = 0.49$) in the SEAs. Because of the low number of fire years during the suppression and modern periods, particularly years in which more than one site burned, SEAs were done using data from the historical period only. Using all fire years, we assessed whether or not PDSI in years that zero, one, two and three or more sites burned exclusively differed significantly from average conditions in the year of fire or in the years preceding or following the year of fire.

We developed binomial logistic regression models to assess the probability of a site burning ($P$) in a particular year and period as a function of site characteristics and drought conditions. We used *a priori* knowledge to create a set of ecologically relevant variables that might explain the probability of burning between 1702 and 2007, including *site*, *period*, standardised year (*year_st*), standardised time since fire at each site (*tsf_st*), which we used as a proxy for the relative amount of fuel present at a site, the number of other sites burning in a particular year (*osb*), which we used to represent synchrony patterns across sites and PDSI in the year of fire (*pdsi*) and 1 and 2 years before the year of fire (*pdsi_1* and *pdsi_2*). For PDSI, we used the same white noise residuals as applied in the SEAs. Variables *year* and *tsf* were standardised (mean = 0, s.d. = 1) to place them on a scale similar to that of the other variables included in our models. In addition, we incorporated interactions of both *site* and *period* with standardised time since fire, the number of other sites burning, and all three PDSI variables. Using all fire years and this set of 18 terms, we used the R package glmulti (Calcagno and de Mazancourt 2010; R Development Core Team 2012) to (1) perform automated model selection using AIC corrected for small sample size ($AIC_c$, Burnham and Anderson 2002), (2) estimate the importance (i.e. relative weight) of each term, computed as the sum of the relative weights of all models in which the term appeared and (3) compute model-averaged parameter estimates and their unconditional variances from the top 100 models.

Because the residuals from the top model identified using glmulti were temporally autocorrelated (acf plot and Durbin-Watson two-sided test statistic = 2.12; $P = 0.03$) (R Development Core Team 2012), we applied a second modelling approach that allowed us to incorporate error correlation components using random effects. In this approach, we modelled the probability of burning as a generalised linear mixed model using a binomial response distribution and included an AR(1) error correlation structure on the residuals indexed by *year* within *site*. We also included *site* as a random effect, as sites are theoretically drawn at random from a population of sites. We started with the full model that included all 18 terms, removed all non-significant interactions, and then removed non-significant main effects one at a time. We used Moran's $I$ to test the residuals from the final mixed model for spatial autocorrelation (R Development Core Team 2012).

## Results

We collected cross sections from 114 trees across all five study sites, many of which were dead when sampled (73%). Most of the sampled trees were ponderosa pine (97%), although a few were Gambel oak (3%). We successfully crossdated the tree rings on cross sections from all but one tree. From the 113 dated

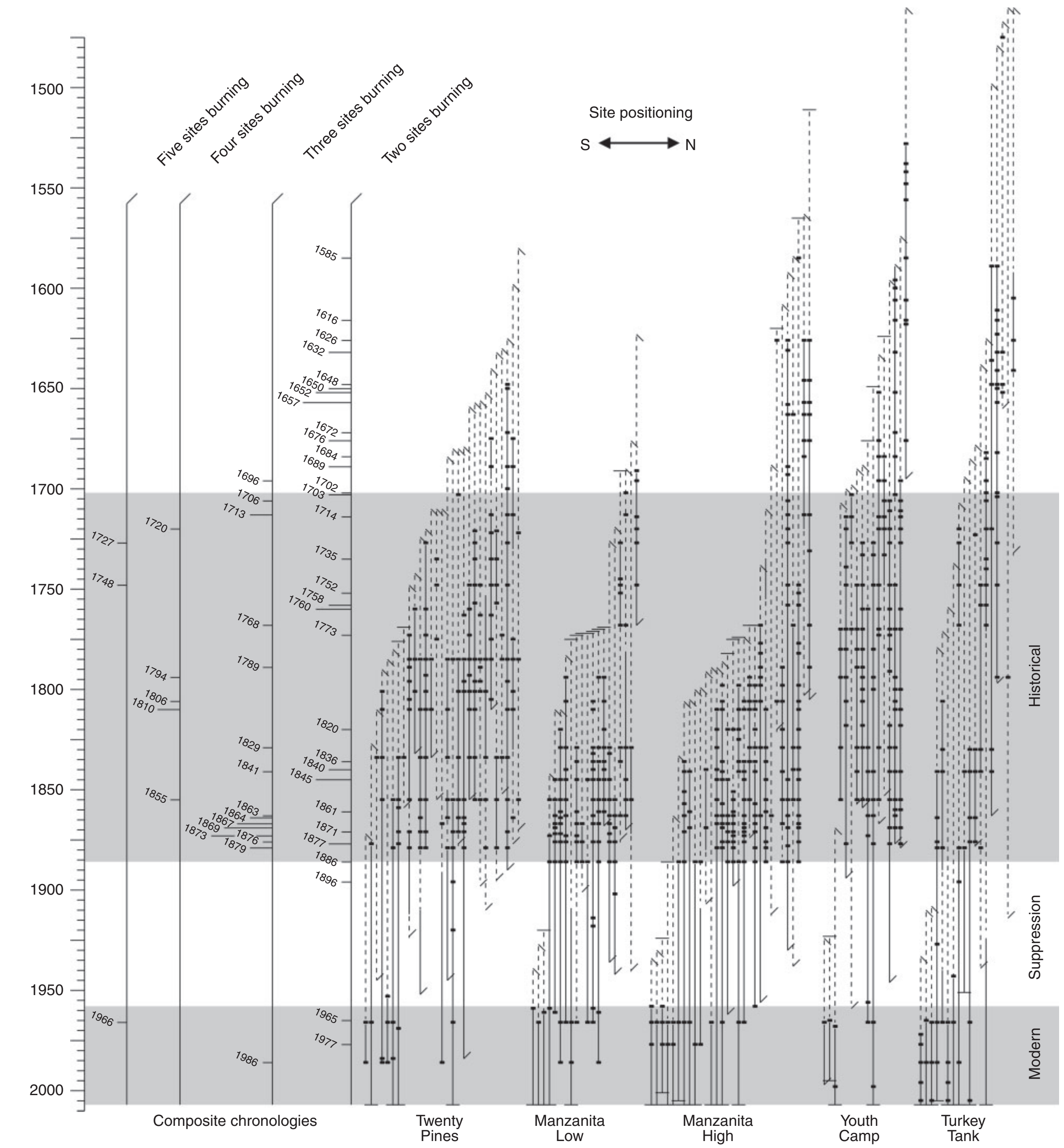


**Fig. 2.** Fire chronologies for each of the five study sites on the Hualapai tribal lands. Sites are arranged from south (Twenty Pines) to north (Turkey Tank). Vertical lines represent the time span of individual trees, with solid and dashed lines representing years when a tree was 'recording' and 'not recording' (see Methods) respectively. Horizontal bars represent dated fire scars. The composite chronologies depict years when two, three, four or five sites burned exclusively based on all fire years.

trees, we dated 738 fire scars, which comprised 134 unique fire years, between 1475 and 2005 (Fig. 2).

Depending on how the data were filtered (i.e. all *v.* widespread fire years), MFIs at individual sites during the modern period were 4 years shorter to 24 years longer (only 5 years longer if we were to exclude widespread fires at Youth Camp) than they had been during the historical period. WMPIs were similar to MFIs during the historical period; the same was true in instances where WMPIs could be calculated during the modern period (Table 1). PFIs ranged from 10–24 years and from 10–31 years during the historical and modern periods respectively (Table 1). Considering the low number of intervals at individual sites during the

**Table 1. Fire interval (years) statistics for each of the five study sites on the Hualapai tribal lands during the historical period (1702–1886) and the modern period (1958–2007)**

Incomplete intervals at the start or end of a period were not included in any analyses. Dashes indicate values that could not be calculated. Categories: All, all fire years including those in which a single tree was scarred; Widespread, years in which a minimum of two trees and ≥25% of the recording trees (see Methods) were scarred. Average tree mean interval was calculated using only those trees that had a minimum of 1 interval. Sample sizes (Historical, Modern) were the following: Turkey Tank (9, 6), Youth Camp (12, 2), Manzanita High (18, 4), Manzanita Low (15, 4) and Twenty Pines (19, 4)

| Site | Period | Category | Number of intervals | Mean interval | Range of intervals | Weibull median prob. interval | Average tree mean interval |
|---|---|---|---|---|---|---|---|
| Turkey Tank | Historical | All | 17 | 10.4 | 2–26 | 8.9 | 23.6 |
| | | Widespread | 11 | 16.1 | 3–36 | 14.8 | |
| | Modern | All | 6 | 6.7 | 1–10 | 6.3 | 20.1 |
| | | Widespread | 2 | 19.5 | 19–20 | – | |
| Youth Camp | Historical | All | 27 | 6.4 | 2–14 | 6.2 | 15.2 |
| | | Widespread | 21 | 8.3 | 3–15 | 8.1 | |
| | Modern | All | 3 | 11.0 | 1–30 | 5.0 | 31.0 |
| | | Widespread | 1 | 32.0 | – | – | |
| Manzanita High | Historical | All | 35 | 5.1 | 1–17 | 4.7[A] | 12.2 |
| | | Widespread | 24 | 7.2 | 1–35 | 6.1[A] | |
| | Modern | All | 2 | 9.5 | 8–11 | – | 10.3 |
| | | Widespread | 1 | 11.0 | – | – | |
| Manzanita Low | Historical | All | 27 | 6.8 | 1–26 | 5.5[A] | 9.9 |
| | | Widespread | 17 | 9.4 | 1–26 | 7.9 | |
| | Modern | All | 3 | 9.0 | 2–20 | 6.9 | 18.0 |
| | | Widespread | 3 | 9.0 | 2–20 | 6.9 | |
| Twenty Pines | Historical | All | 26 | 6.8 | 1–24 | 5.8[A] | 16.5 |
| | | Widespread | 19 | 8.7 | 1–24 | 7.8[A] | |
| | Modern | All | 3 | 6.7 | 2–15 | 5.2 | 15.0 |
| | | Widespread | 2 | 10.0 | 2–18 | – | |

[A]Only a Weibull distribution adequately modelled the fire-interval data (Kolmogorov–Smirnov test, $\alpha = 0.05$).

modern period, particularly with greater filtering, fire intervals during this period must be interpreted cautiously.

Except for at the Turkey Tank site, the historical period had the highest percentage of years with fire, followed by the modern period; there was almost no fire during the suppression period (Fig. 3). Depending on how the data were filtered, the percentages of years with fire at individual sites during the modern period were 30 to 144% of what they had been during the historical period.

Fire seasonality varied over time, as estimated from the 392 of 659 (59%) fire scars from all five sites for which ring position could be determined across all three periods (Fig. 4). Fire scars mostly occurred in the middle earlywood (39%) and late earlywood (42%) positions during the historical period and in the dormant (90%) position during the modern period.

Fires were predominantly asynchronous among the sites over time (Fig. 2). Of the 72 years with fire during the historical period, 50, 22, 18, 7 or 3% had one, two, three, four or five site(s) burning. Of the 14 years with fire during the modern period, 72, 14, 7, 0 or 7% had one, two, three, four or five site(s) burning. Pairwise comparisons using Chi-Square tests supported a pattern of more asynchrony than synchrony between sites during the historical period (Fig. 5). Of our 10 comparisons, three showed a significantly greater number of asynchronous *v.* synchronous fire years ($P = 0.030$), six showed a trend towards a greater number of asynchronous *v.* synchronous fire years, and the remaining one showed a significantly greater number of synchronous *v.* asynchronous fire years ($P = 0.030$). In general, sites that were further away from one another had more asynchronous than synchronous fire years (Fig. 5).

The most synchronous fire years during the historical period were most strongly related to PDSI (Fig. 6). In years in which three or more sites burned, departures from average PDSI were pronounced, with significantly ($P < 0.05$) drier conditions (negative departures) during fire years and significantly ($P < 0.01$) wetter conditions (positive departures) during the 2 years before fire years. An opposite pattern occurred in years in which zero sites burned, with significantly ($P < 0.001$) wetter conditions during non-fire years and significantly ($P < 0.01$) drier conditions during the 2 years before non-fire years.

We had 7286 logistic regression models within our candidate model set that described the probability of a site burning in a particular year and period. Based on the top 100 models, four terms had relative weights of 1.0 (*site*, *tsf_st*, *osb*, *site* × *osb*), two terms had relative weights above 0.95 (*period*, *pdsi*), two terms had relative weights above 0.6 (*pdsi_1*, *period* × *tsf_st*), eight terms had relative weights below 0.4, and two terms were not present in the suite of models (Fig. 7). Delta $AIC_c$ for the 100th model was 6.78. Model-averaged parameter estimates of the eight most important terms, defined by their relative weights, are

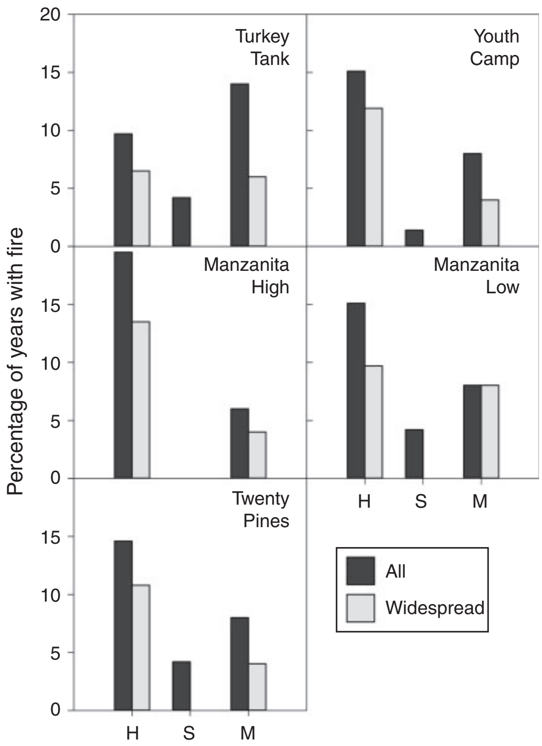


**Fig. 3.** Percentage of years with fire during the historical (H; 1702–1886; 185 years), suppression (S; 1887–1957; 71 years) and modern (M; 1958–2007; 50 years) periods for each of the five study sites on the Hualapai tribal lands for all fire years and widespread (i.e. minimum two trees and ≥25% of the recording trees scarred) fire years.

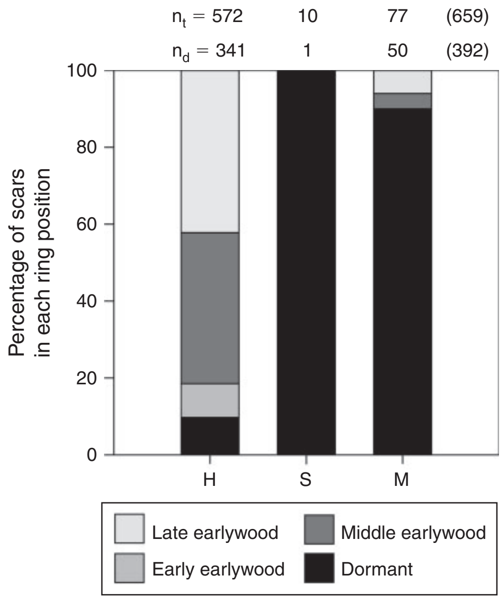


**Fig. 4.** Percentage of fire scars, by ring position, for the historical (H; 1702–1886), suppression (S; 1887–1957) and modern (M; 1958–2007) periods for the five study sites combined on the Hualapai tribal lands. There were no scars in the latewood position during any of the three periods. $n_t$ is the total number of dated fire scars in each period and $n_d$ is the number of dated fire scars in each period for which ring position could be determined.

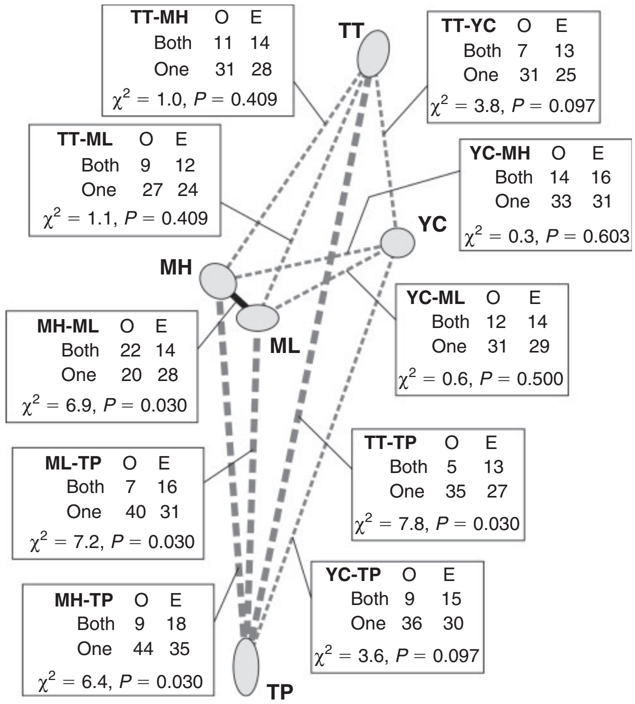


**Fig. 5.** Chi-Square tests illustrating spatial patterns of synchrony or asynchrony of fires during the historical period between each of the five study sites (TT, Turkey Tank; YC, Youth Camp; MH, Manzanita High; ML, Manzanita Low; TP, Twenty Pines) on the Hualapai tribal lands based on all fire years. The solid black line represents a significantly greater number of synchronous *v.* asynchronous fire years (i.e. observed(O) > expected (E) for both sites burning and a significant $\chi^2$), thicker dashed grey lines represent a significantly greater number of asynchronous *v.* synchronous fire years (i.e. observed (O) > expected (E) for one site burning and a significant $\chi^2$), and thinner dashed grey lines represent a trend towards a greater number of asynchronous *v.* synchronous fire years (i.e. observed (O) > expected (E) for one site burning and a non-significant $\chi^2$). *P*-values were adjusted for multiple comparisons using the false discovery rate method (Benjamini and Hochberg 1995; Pike 2011).

presented in Table 2. Models indicated a lower probability of burning in the suppression and modern periods compared to the historical period (suppression ≪ modern < historical). Drier conditions in the year of fire and wetter conditions 1 year before the year of fire were associated with increased probability of burning. The effect of other sites burning varied by site, as indicated by the *site* × *osb* term. Specifically, as the number of other sites burning increased, the probability of burning increased for all sites. However, the magnitudes of the coefficients varied according to the spatial arrangement of the sites, i.e. the effect of other sites burning was greater for the grouped sites (Manzanita High, Manzanita Low and Youth Camp) compared to the isolated sites (Turkey Tank and Twenty Pines). The effect of time since fire varied by period, as indicated by the *period* × *tsf_st* term. Specifically, as time since fire increased, the probability of burning increased for all periods. However, the effect of time since fire was greatest during the modern period, intermediate during the historical period and least during the suppression period.

The mixed modelling gave similar results as the logistic regression modelling. Except for *site*, which was included as a

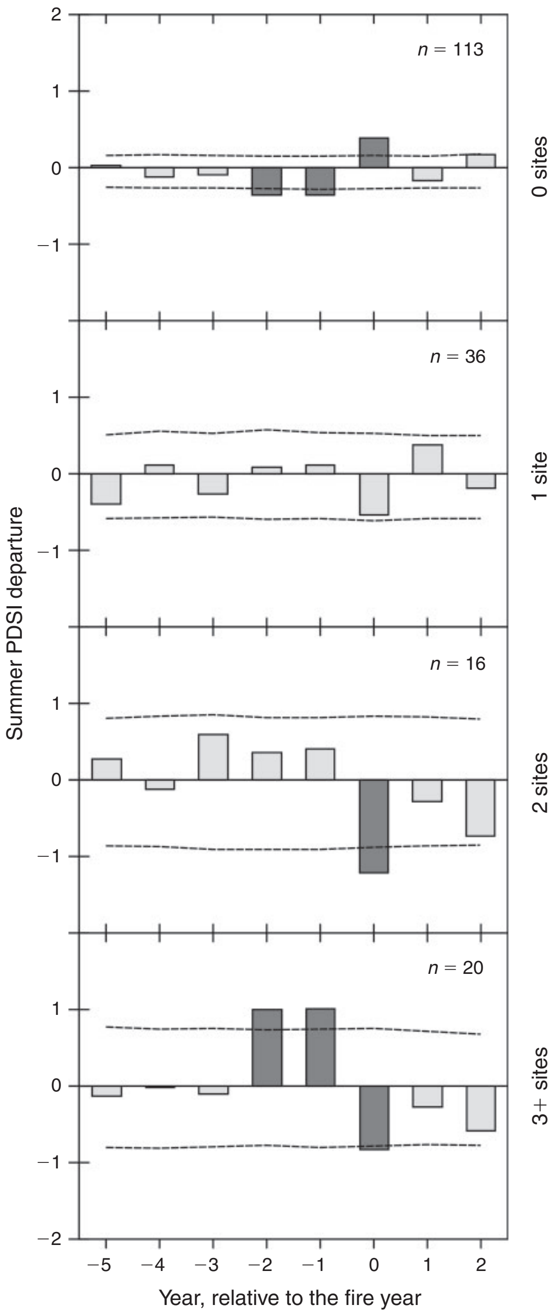


**Fig. 6.** Superposed epoch analysis illustrating departures from the mean value of reconstructed summer (July–August) Palmer Drought Severity Index (PDSI) for years during the historical period when fires burned zero, one, two and three or more study site(s) on the Hualapai tribal lands based on all fire years. Year 0 is the year of fire. Dashed lines represent 95% confidence intervals derived from 1000 Monte Carlo simulations. Darker shaded bars are those that exceed the 95% confidence interval.

random effect, and its interaction with *osb*, the final mixed model included all the same terms as the top logistic regression model identified using glmulti: *osb*, *tsf_st*, *pdsi*, *period*, *pdsi_1*, *period* × *tsf_st* (Tables S1, S2). Moran's $I$ indicated no spatial autocorrelation (Moran's $I = -0.0004$; $P = 0.63$) among the residuals of the final mixed model.

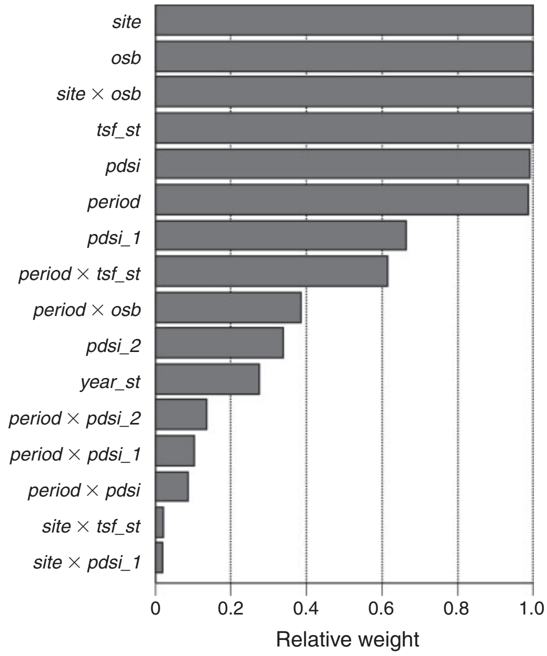


**Fig. 7.** Relative weights (importance) of the 16 terms included in the top 100 logistic regression models from an exhaustive screening of 7286 candidate models describing the probability of a site burning in a particular year and period on the Hualapai tribal lands. The 16 terms shown include *site*, the number of other sites burning in a particular year (*osb*), standardised time since fire at each site (*tsf_st*), Palmer Drought Severity Index (PDSI) in the year of fire (*pdsi*), *period*, PDSI 1 and 2 year(s) before the year of fire (*pdsi_1* and *pdsi_2*), standardised year (*year_st*), the interactions of *site* and *period* with *tsf_st*, *osb*, and PDSI variables (*pdsi*, *pdsi_1*, and *pdsi_2*). Two terms, *site* × *pdsi* and *site* × *pdsi_2*, were not in any of the top 100 models and are not shown.

## Discussion

### *Modern fire regime resembles historical fire regime*

Our findings suggest that the current prescribed burning program in the ponderosa pine forest on the Hualapai tribal lands is effectively mimicking some of the temporal and spatial attributes of the past surface fire regime. Fire frequency and asynchrony patterns are qualitatively similar between the modern and historical periods. In addition, nearby ponderosa pine forests on non-tribal lands exhibit patterns of historical fire frequency (Fulé *et al.* 2003*a*, 2003*b*; Biondi *et al.* 2011; Ireland *et al.* 2012) and asynchrony (Ireland *et al.* 2012) comparable to those that once existed in our study area. A few larger, remote landscapes in the western United States (Rollins *et al.* 2001; Collins and Stephens 2007; Farris *et al.* 2010) and isolated parts of northern Mexico (Stephens *et al.* 2003; Fulé *et al.* 2011) have pine-dominated forests where fire has been maintained or reintroduced over the 20th century. To our knowledge, this is the first study in the south-western United States to document regaining some features that resemble those of a near-historical fire regime using prescribed fire.

Burning season is one attribute of the fire regime that differs substantially between the modern and historical periods. As found in other studies of nearby forests (Fulé *et al.* 2003*a*, 2003*b*; Ireland *et al.* 2012), a large number of fire scars occurred

**Table 2. Model-averaged parameter estimates of the eight most important terms in the top 100 models describing the probability of a site burning in a particular year and period on the Hualapai tribal lands**

The eight terms, which are listed in order of their importance in the models, are *site*, the number of other sites burning in a particular year (*osb*), *site* × *osb*, standardised time since fire at each site (*tsf_st*), Palmer Drought Severity Index (PDSI) in the year of fire (*pdsi*), *period*, PDSI 1 year before the year of fire (*pdsi_1*) and *period* × *tsf_st*. Estimates for each level of categorical variables *site* and *period* and their interaction with quantitative variable *osb* or *tsf_st,* are shown. Intercept is the historical period and the Manzanita High site

| Term | Estimate | Unconditional variance |
|---|---|---|
| Intercept | −2.978 | 0.136 |
| *site* (Manzanita Low) | −0.080 | 0.214 |
| *site* (Turkey Tank) | −0.054 | 0.215 |
| *site* (Twenty Pines) | 0.669 | 0.168 |
| *site* (Youth Camp) | 0.183 | 0.185 |
| *osb* | 2.797 | 0.204 |
| *site* (Manzanita Low) × *osb* | −0.584 | 0.312 |
| *site* (Turkey Tank) × *osb* | −1.409 | 0.261 |
| *site* (Twenty Pines) × *osb* | −1.818 | 0.242 |
| *site* (Youth Camp) × *osb* | −1.216 | 0.262 |
| *tsf_st* | 0.359 | 0.076 |
| *pdsi* | −0.157 | 0.004 |
| *period* (modern) | −0.262 | 0.194 |
| *period* (suppression) | −1.131 | 0.305 |
| *pdsi_1* | 0.070 | 0.006 |
| *period* (modern) × *tsf_st* | 0.346 | 0.210 |
| *period* (suppression) × *tsf_st* | −0.181 | 0.113 |

in the middle earlywood and late earlywood positions during the historical period. The shift to scars in the dormant position during the modern period is consistent with the onset of prescribed burning between October and December *c*. 1960 (Truesdell 1969). In the south-western United States, prescribed burning is generally conducted during autumn and early winter, when fire crews are most available to assist with the process and cooler, less windy conditions help to moderate fire behaviour (Hunter *et al.* 2007).

Studies looking at the effects of prescribed fires conducted outside the historical fire season have produced mixed results. For ponderosa pines trees with similar crown damage, Harrington (1993) observed 2.5 times greater mortality in trees burned during the late spring and mid-summer growing season *v.* those burned during autumn dormancy. Peters and Sala (2008) found that season of fire influenced reproductive output of ponderosa pine, with spring burning resulting in smaller seeds and seedlings and autumn burning resulting in larger seedlings. Other studies that looked at tree mortality (McHugh and Kolb 2003; Schwilk *et al.* 2006; Fettig *et al.* 2010), tree growth and physiological performance (Sala *et al.* 2005), native perennial forb cover or richness (Knapp *et al.* 2007; Kerns *et al.* 2011) and wildlife habitat (Monroe and Converse 2006) in ponderosa or Jeffrey pine (*Pinus jeffreyi*) forests found that damage factors (e.g. crown scorch, bark beetle attack) or degree of environmental change associated with fire intensity explained more variation than season of fire (i.e. plant phenology) (Knapp *et al.* 2009). Given these results, it seems important that managers understand the intensity of out-of-season fires relative to those that occurred historically, monitor fire effects over time and adapt management activities according to local findings and desired outcomes when conducting prescribed fires in any season.

## *Regulators of the fire regime*

The logistic regression and mixed modelling approaches allowed us to simultaneously assess the relative influence of predictor variables on the probability of a site burning in a particular year and period. Variables representing fuels-related, climatic and human controls of fire are present in the top models of our candidate model set, suggesting that all provide important information regarding the likelihood of fire. These results combined with those from our other analyses lead to valuable ecological insights regarding past fire spread across the landscape and variability in fire frequency over time.

The interaction of the synchrony term with site (*site* × *osb*) in the logistic regression models allows us to speculate on past fire spread across our study area, especially given the fine spatial scale of our analysis and the presence of PDSI terms in the models. The results of the Chi-Square tests also support our inferences, as they imply a spatial association with synchrony during the historical period. Because fire spread is influenced by the amount, type, and condition of fuels, our findings suggest that fuels conducive to fire spread were discontinuous between some sites, particularly those that were further away from one another. For example, the distant location of Turkey Tank and Twenty Pines from one another and their position at the ecotone where ponderosa pine forest meets pinyon–juniper woodland might have limited fire spread between these sites. This would make sense, particularly if similar conditions that exist today also existed in the past. Higher amounts of pinyon and juniper trees currently occur at these sites compared to those more centrally located in the forest, and patches of pinyon and juniper woodland occupy areas in between them. Historically, fires in ponderosa pine forest did not appear to spread into adjacent pinyon-juniper woodland (Huffman *et al.* 2008), perhaps because of differences in fine fuels between these vegetation types. Fine fuels in pinyon–juniper woodlands tend to be sparse and discontinuous and fires typically spread over large areas only during instances of extreme drought and sustained high winds, which allow fires to move through tree crowns (Floyd *et al.* 2000; Romme *et al.* 2009). Therefore, except in very dry years, pinyon–juniper woodland might have served as a barrier to past fire spread. In contrast, sites that are closer together and more centrally located in the forest, such as Manzanita High and Manzanita Low, might have had more abundant and continuous fine fuels, which were common in ponderosa pine forests in the past. As our results suggest, these fuels may have built up in antecedent wet years and permitted fires to spread more easily between nearby sites in subsequent dry years. This close coupling between wet or dry conditions and fire is well documented for ponderosa pine forests in the south-western United States (Swetnam and Baisan 2003; Crimmins and Comrie 2004). Interestingly, the most synchronous fire years in the past were most strongly related to PDSI, supporting our inference that past fires may have spread across a larger part of the landscape, to more distant sites, only when fuel conditions were appropriate. Taken together, this information can be used to improve prescribed burning strategies in this landscape and similar landscapes across the region, with closer sites potentially being burned in the same years most often.

Our finding of increasing fire risk with increasing time since last fire fits well with the notion of fire as a self-limiting process, where a certain amount of time must pass before fuels in a burned area can recover enough for that area to burn again (Miller and Urban 2000; Collins *et al.* 2009). Further support for this process comes from our finding that fires were spatially discrete in our study area, with no instances of back-to-back fire years at the same point (i.e. tree) (data not shown). The amount of time needed for burned areas to regain enough fuels should scale with the historical fire-return intervals of a particular forest type and its topographic and climatic setting. Using logistic regression, Collins *et al.* (2009) found time since fire to be an important predictor in explaining whether or not a fire burned over a previously burned area in mixed conifer forests of the Sierra Nevada. Those authors also found that previously burned areas took at least 9 years to burn again, a finding that matched historical fire intervals in their study area (Collins and Stephens 2007).

Modern and historical fire intervals are very similar in our study area, implying that burns today resemble those of the past and perhaps are conducted following similar levels of climate-driven fuel recovery. However, our models show that the effect of time since fire on fire risk is greatest during the modern period, suggesting a stricter schedule of burning than existed in the past. Given this finding, managers might try incorporating more variability into their burning schedules to better emulate past fire frequency and the shifting mosaic of burn patches that likely composed the historic landscape.

## Conclusions

Owing to the early use of prescribed burning and thinning, forests on tribal lands may be in an advantageous position relative to others in the western United States, potentially having characteristics that support greater resistance to severe burning and thus, increased resilience to the effects of climate change (Millar *et al.* 2007; Fulé 2008). Carrying out additional studies in other forests on tribal lands with a history of recent burning will provide information to help managers anticipate short- and long-term effects of prescribed fires, improving their ability to implement and adapt burning programs. For our study area, we are currently conducting follow-up research that examines forest structure and composition and uses simulation modelling to assess potential fire behaviour and vegetation change under a suite of climate change and management scenarios. This information will help us gauge potential future conditions of this forest and similar forests in the south-western United States that are experiencing comparable but, at present, shorter-lived burning and thinning programs. In addition, because our study area is at the lower elevational limit of ponderosa pine in the south-western United States, it is particularly useful for exploring how forests in the region that are being managed for conditions analogous to the past might perform in the warmer and drier climate of the coming decades. Perhaps we will find that the historical range of variation documented in the centuries-long fire-scar record is the most appropriate approach to managing ponderosa pine forests in the south-western United States in the decades to come (Roos and Swetnam 2012). Or, perhaps we will find that future disturbance regimes are so different from the recent past that ecosystems that appear to be in the best condition today based on history will no longer be viable in their current form as the climate warms (Millar *et al.* 2007). Either outcome highlights the need to continuously identify and monitor relevant ecological, climatic and social variables for effective adaptive management under rapid and uncertain change.

The results of the logistic regression, mixed modelling and other analyses allow us to derive more comprehensive inferences about the fire regime over time and space. Although our analyses provide valuable insight into what regulated past and current surface fires, they undoubtedly tell an incomplete story. Evaluating additional climatic and non-climatic variables, over longer time scales, across tribal and non-tribal lands, can help improve our understanding of the processes that have influenced, and continue to influence, fire regimes in the south-western United States.

## Acknowledgements

We are grateful to the Hualapai Tribe for granting us permission to work on their lands. Special thanks to Melvin Hunter Jr, Charles Murphy and Richard Powskey for providing support throughout this project. We thank Melvin Hunter Jr, Matt Tuten and Larissa Yocom for assisting in the field and Don Normandin, Melvin Hunter Jr and student members of the Ecological Restoration Institute (ERI) at Northern Arizona University (NAU) for assisting in the laboratory. Erik Schiefer provided valuable assistance with analyses. We thank Emily Heyerdahl, Larissa Yocom and two anonymous reviewers for their thoughtful comments on earlier versions of the manuscript. We thank L. Scott Baggett for his statistical review of the manuscript and for his assistance with the modelling approaches. Thanks to Tom Swetnam and Don Falk for providing data on fire-scar sites in the south-western United States. This project was funded by Agriculture and Food Research Initiative Competitive Grant number 2011–67012–30665 from the USDA's National Institute of Food and Agriculture, the Mission Research Program (McIntyre-Stennis) of the School of Forestry at NAU, and the ERI. The National Fire Plan provided salary funding for Jamie Sanderlin.

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