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A 1416-year reconstruction of annual, multidecadal, and centennial variability in area burned for ponderosa pine forests of the southern Colorado Plateau region, Southwest USA

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Abstract

Fire history reconstructions from fire scars in tree rings have been valuable for assessing fire regime changes and their climatic controls. It has been asserted, however, that these two- to four-century long records from the western USA are unrepresentative of longer periods of the Holocene and are of limited use for understanding current or future fire regimes. The Medieval Climate Anomaly (800–1300 CE) is often suggested as a better analog for future Southwestern US climates but is beyond the chronological range of most fire-scar studies in this region. To evaluate fire regime changes over the past millennium, we build on centennial-length fire–climate studies to generate a 1416 year long reconstruction of fire activity in ponderosa pine forests of the Southern Colorado Plateau region of Arizona and New Mexico. We used a split-period calibration and verification protocol to test the reliability of a multiple regression model using annual and antecedent precipitation (reconstructed from tree-ring width chronologies) to predict the percentage of fire-scar localities (i.e. sites, N=45) that recorded extensive fires within those sites (>25% of recorder trees scarred) each year between 1700 and 1899 CE. The model explains approximately 50% of the variation in annual fire activity. Applying the model to the entire precipitation reconstruction provides a proxy for annual area burned since 572 CE. There are no statistically significant differences between the period available for fire-scar study (1600 CE–present) and the Medieval Climate Anomaly (800–1300 CE) in terms of predicted annual area burned or the frequencies of regional fire years. Multidecadal and centennial variation in the frequencies of regional fire years, however, does indicate reduced surface fire frequencies from approximately 700–800 CE and 1360–1455CE. We hypothesize that these were periods when some forests were vulnerable to altered canopy structure, accumulated fuels, and increased fire severity.

Keywords

climate-predicted fire activity, fire history, 'Little Ice Age', Medieval Climate Anomaly, multiple regression, ponderosa pine

Introduction

Wildland fire activity has been increasing in the American West, due to changing climate in the context of altered stand structures and fuel loads (Westerling et al., 2006). Fire history reconstructions have been particularly useful for determining pre-Euroamerican settlement fire regimes to gauge postsettlement changes in fire activity and the relative role of historic land use, active fire suppression, and climate change (Swetnam and Baisan, 2003). In middle elevation forests of the American Southwest, such as those dominated by ponderosa pine (*Pinus ponderosa*), fire activity over the past century has been outside of the historical range of variability described from studies of fire-scarred trees (Allen et al., 2002, 2008). For at least 200 years prior to Euroamerican settlement, extensive fires occurred frequently in these forests (e.g. every 3–15 years), consuming fine surface fuels and maintaining an open, park-like structure of mixed age forests (Fulé et al., 1997). Although internal fuel characteristics, disturbance history, and ignitions were all important, regional fire activity appears to have been significantly governed by interannual moisture patterns (Swetnam and Baisan, 2003). These middle elevation forests experience lightning regularly (Allen, 2002) and are probably fuel, rather than ignition limited. Antecedent moist years were apparently necessary to produce abundant and continuous fine surface fuels (e.g. needles, grasses and herbaceous understory plants) that subsequently cured during dry years, promoting fire ignitions and spread (Crimmins and Comrie, 2004; Swetnam and Baisan, 2003).

In this scenario, interannual moisture variability drives the timing of climate-driven, fuels-limited fire regimes characterized by frequent, low severity surface fires. Modern fire behavior, characterized by large, high severity crown fire patches in ponderosa pine-dominant forests is thought to be 'unnatural' relative to the reconstructed pre-settlement fire regime (Allen et al., 2002;

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Covington and Moore, 1994). Indeed, adaptive traits of ponderosa pines, such as thick bark, self-pruning branches, regularly dehisced needles creating an easily combusted fuel bed, and high crown scorch tolerance, suggest that frequent, low severity fires were likely a part of the evolutionary environment for this species (Covington, 2003).

Recent fire history studies in some central and northern Rocky Mountain ponderosa pine forests (Baker et al., 2007; Ehle and Baker, 2003; Sherriff and Veblen, 2008) have found longer mean fire intervals than in Southwestern forests, and they have argued that high severity crown fires played a more important role than previously recognized in those regions (cf. Brown, 2006). Stand age structure, fire-scar analyses, and fire behavior modeling in the ponderosa pine forests of Mount Rushmore (part of the Black Hills), however, indicates that 'passive' crown fires occurred only in small patches (<100 ha), accounting for less than 4% of forest area burned during the past 400 years (Brown et al., 2008). In some northern ponderosa pine or mixed conifer forests, where fuels were less limiting and fire return intervals were longer, fire-related debris flows were common during the middle Holocene and Medieval Climate Anomaly, presumably indicative of an increase in high severity fire activity (Meyer and Pierce, 2003; Pierce and Meyer, 2008).

These studies, from less fuels-limited environments, evoke increased temperature associated with long-term drought as climatic mechanisms driving changes in fire regimes (Pierce and Meyer, 2008; Pierce et al., 2004). In fuels-limited Southwestern forests, recruitment, which occurs during periods of reduced surface fire frequency coupled with wet conditions (Brown and Wu, 2005), and resultant changes in canopy connectivity and ladder fuels contribute to the initiation and propagation of crown fires. Although these changes occurred in twentieth-century forests because of extensive grazing and fire suppression (see also Collins and Stephens, 2007), it is not clear if forest structural and fuels changes could have occurred in the past at scales necessary to promote large crown fires (i.e. high severity burn patches exceeding 100 ha). Recent findings indicate that finer-scale crown fire events (<100 ha) did occur prior to the twentieth century in some relatively isolated southern Arizona ponderosa pine forests where barriers (cliffs, talus slopes and exposed rock surfaces) may have inhibited surface fire spread from adjacent areas, allowing these stands to accumulate fuels over multidecadal periods (Iniguez et al., 2009).

An additional challenge that has emerged from the suggestion that large high severity crown fires may have been a part of the 'natural' range of variability in ponderosa pine forests, particularly at millennial timescales, is that fire regimes recorded in fire-scar records may be unrepresentative of Holocene fire regimes (Whitlock et al., 2008). Although the 'Little Ice Age' (LIA; defined as *c*. 1400–1850 CE) was not a spatially or temporally uniform climate anomaly across the western US (e.g. see Salzer and Kipfmueller, 2005), it is assumed that attendant cool and moist conditions during this period would have favored relatively low intensity and perhaps less frequent fires that were not characteristic of longer timescales and periods of warmer temperatures and more pronounced drought. Although not necessarily globally homogenous (Hughes and Diaz, 1994), the so-called 'Medieval Warm Period' or Medieval Climate Anomaly (MCA; *c*. 800–1300 CE) was indeed drier across large swaths of the Western USA relative to other periods over the last two millennia (Cook et al., 2004). Global sedimentary records do indicate differences in the accumulation of charcoal between the MCA and LIA but these records are predominantly from fuel-rich areas where fire intervals are much longer than Southwestern ponderosa pine forests and where fire behavior is typically characterized by high severity crown fires (Marlon et al., 2008).

Moreover, it is pointed out that most projections of future climate change for the Southwestern USA (e.g. Hoerling and Eischeid, 2007; Seager et al., 2007) indicate that warmer and drier conditions than those experienced during the twentieth century are expected in coming decades. If true, does this mean that Southwestern ponderosa pine fire regimes of the recent half-millennium, characterized by frequent, low severity surface fires, are no longer an appropriate analog for managers and restoration ecologists trying to cope with global climate change (Millar et al., 2007)? Would the MCA be a more appropriate analog for anticipated future climate and fire regime changes (Swetnam et al., 2009)?

We hypothesize that for widespread crown fires to have been an important feature of Southwestern ponderosa pine fire regimes in the past, (1) relatively *long intervals between surface fires* (multidecadal) and (2) *prolonged wet periods* would have been necessary to produce sufficient fuel, canopy recruitment and connectivity (Brown, 2006; Brown and Wu, 2005). Surface fire frequency relies, in part, upon abundant and continuous fine fuels driven by interannual moisture patterns (Crimmins and Comrie, 2004; Swetnam and Baisan, 2003; Westerling et al., 2002). If the climatic conditions of the MCA were a better analog than the LIA for contemporary and predicted future climates and fire regimes, then it would be necessary to demonstrate that interannual moisture and fire occurrence patterns similar to the last 400 years did not occur during the MCA (or vice versa). Conversely, reconstructed fluctuations in climate-driven surface fire frequency coupled with records of multiyear wet and dry periods, will allow us to predict periods when Southwestern ponderosa pine forests may have been vulnerable to altered fire regimes.

Here we expand and modify a paleohistorical-modeling approach used by Westerling and Swetnam (2003) and Girardin and colleagues (Girardin, 2007; Girardin and Sauchyn, 2008; Girardin et al., 2006). In these studies, modern area burned time series from documentary records (after 1900) were used in combination with ring-width based climate reconstructions of drought indices to calibrate a transfer function during the recent period, and then the transfer function was applied to the tree-ring width reconstructions to 'retrodict' past fire activity over longer time periods. In the case of the Westerling and Swetnam (2003) study, the retrodicted area burned during the pre-1900 period based on ring-width indices was then tested against the completely independent fire-scar record from 1700 to 1900. In the present study we use a fire-scar chronology network of 45 sites in the Southwest to provide a 200 year long calibration to develop a 1416 year long model of predicted regional fire activity based on tree-ring reconstructed interannual moisture patterns. The extensive and well-replicated Southwestern ponderosa pine fire-scar record provides a unique opportunity to test centennial length subperiods for calibration and verification of the model prior to its use.

Data and methods

The southern Colorado Plateau is home to a variety of ecosystems but is unique in the Southwest USA for its large, continuous stands of conifer-dominated middle elevation forests, including the largest continuous stand of Southwestern ponderosa pine

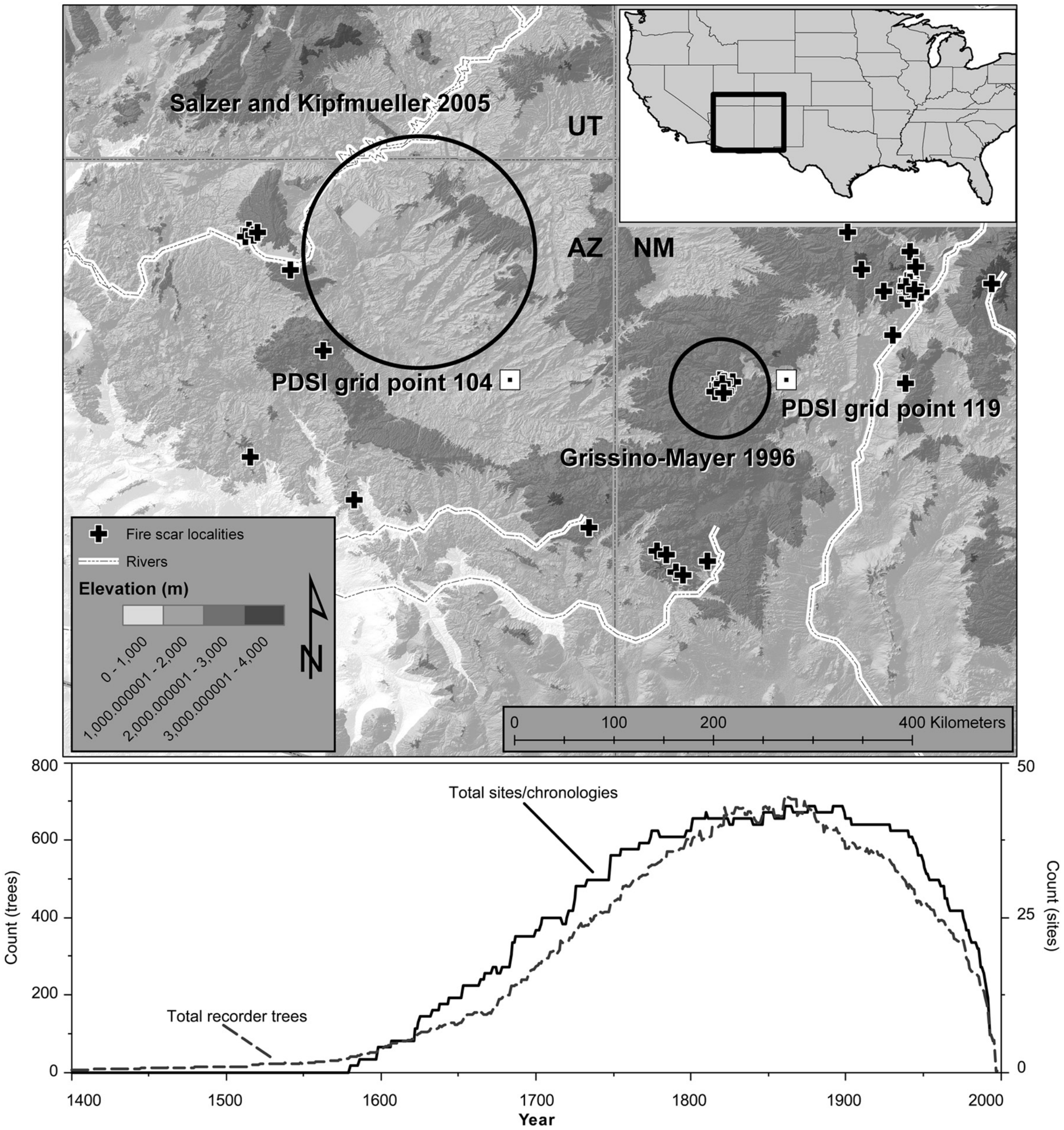

Figure 1. Map of fire-scar localities and climate reconstructions used in the regression model (top) and sample depth for both recorder trees and fire-scar localities (bottom)

(*Pinus ponderosa* Laws.) forest along the Mogollon Rim stretching from Flagstaff, Arizona to western New Mexico. We use 714 fire-scarred trees from 45 fire history localities from ponderosa pine forests across the margins of the southern Colorado Plateau (Figure 1) to characterize regional fire activity (all chronologies are available on the International Multi-Proxy Paleofire Database, http://www.ncdc.noaa.gov/paleo/impd/paleofire.html). Specifically, we chose 45 fire-scar study localities (i.e. fire-scar chronologies) from ponderosa pine sites on or near the margins of the Colorado Plateau between 33° and 36.5°N latitude. These study sites typically encompassed areas of 10 to 100 ha, and 10 to 30 fire-scarred trees were sampled (Swetnam and Baisan, 2003). We limited ourselves to this subset of the existing, larger Southwestern fire-scar chronology network (see Kitzberger et al., 2007) to avoid confounding climate signals resulting from variable zonal circulation and its relationship to seasonal and annual moisture patterns over the last 2000 years (Peterson, 1988). We also excluded data sets that document a decline in fire activity decades before 1900 because of local land-use histories, such as livestock grazing (e.g. Savage and Swetnam, 1990), which we suspect would have introduced inhomogeneities in the data set and into the climate–fire associations.

The earliest dated fire scar from the 45 chronologies was in 1230 CE, but sample depth is greatest (>25 sites and >270 trees) for the period 1700–1976 CE (see Figure 1). Composite fire chronologies were used for each study locality that had a minimum of five recorder trees, and we considered only widespread fires within sites, defined as fire dates recorded by at least 25% of the recording trees within the site. Recent intensive fire-scar sampling and corroboration studies in Southwestern ponderosa pine suggest that the 25% criterion is generally representative of the subset of surface fires that burned the majority of the area within study sites at these spatial scales (Farris et al., 2010). Prior to calibration of the regression model, the percentage of localities burned was transformed using the natural logarithm to normalize the data. A Komolgorov-Smirnov test comparing the natural log

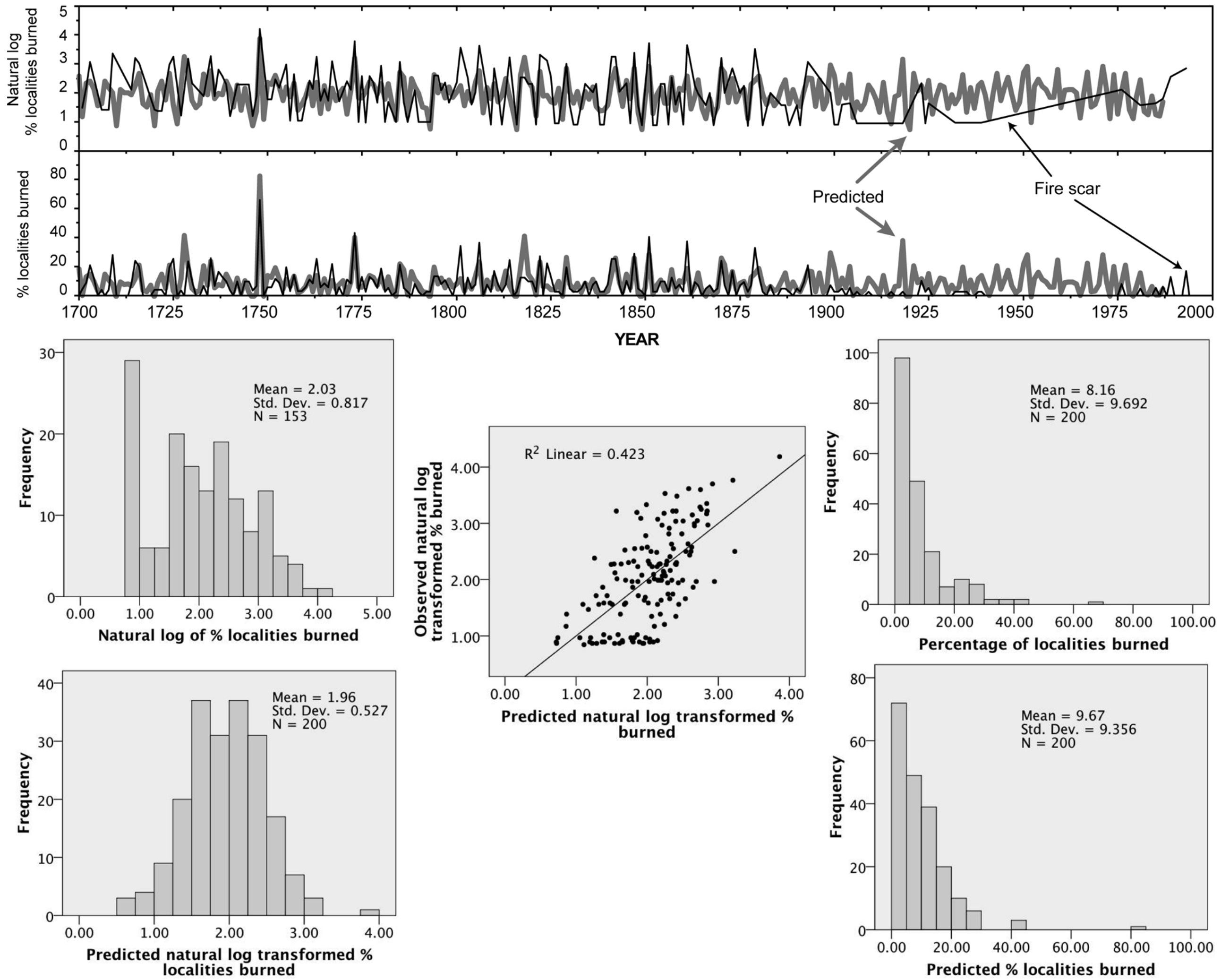

Figure 2. Natural log-transformed fire-scar data and predicted fire-scar data (top) with the original tree-ring data and the corrected, rescaled, and back-transformed predicted data (second from top). Histograms on the left plot the distribution of natural-log transformed fire-scar data (top) and predictions (bottom), whereas histograms on the right plot the original fire-scar data (top) and the corrected, rescaled, and back-transformed predictions (bottom) in percentage of localities burned

of the percentage of localities burned to a normal distribution indicate that the transformed data is normally distributed with 90% confidence (Z=1.243, p=0.091; Figure 2).

For regional, interannual moisture variability, we used two independent long-term reconstructions of precipitation. We combined the 1418 year reconstruction of annual precipitation for the southwestern Colorado Plateau reported by Salzer and Kipfmueller (2005) with the 2129 year reconstruction of precipitation from the southeastern Colorado Plateau reported by Grissino-Mayer (1996) using Principal Components Analysis. The first principal component (PPT PC1) explains 79.9% of the shared variability in these independent chronologies (eigenvalue=1.598, p<0.001) for the 1418 years of their overlap from 570 to 1987 CE.

We used a split calibration and verification protocol to develop a transfer function with which to use the 1418 year reconstruction of regional moisture variability to predict regional surface fire activity. Superposed Epoch Analysis of regional fire years indicate that typically two or more significantly wet years precede dry fire years in the Southwest (Swetnam and Baisan, 2003). Annual (time t) and three years of antecedent (t-1, t-2, t-3) precipitation (from PPT PC1) were used as predictors and the natural log transformed annual percentage of localities burned (from the fire-scar records) served as predictand for stepwise multiple linear regression models calibrated for 100 year intervals from 1700 to 1799 and 1800 to 1899 CE (N=153 fire years for the combined 200 year period). Transfer functions for each calibration period were tested (verified) against the alternative period for quality of fit using standard statistical tests used in dendroclimatic studies, such as the coefficient of determination (r^2), the sign test, reduction of error (RE) and coefficient of efficiency (CE) statistic (Cook et al., 1999; Fritts, 1976, 1991). Finally, we maximized the representativeness of the calibration period by calibrating the regression model against the full 200 year period 1700–1899 CE.

Other variables were explored in the development of this model, including reconstructed proxies that have significant associations with modern fire history or fire-scar data in this or other regions, such as annual temperature (Westerling et al., 2006), El Niño Southern Oscillation (Swetnam and Betancourt, 1990, 1998), Atlantic Multidecadal Oscillation, and Pacific Decadal Oscillation (Kitzberger et al., 2007). The annual temperature reconstruction for northern Arizona/southern Colorado Plateau (Salzer and Kipfmueller, 2005), the Niño 3 reconstruction (a proxy of ENSO, D'Arrigo et al., 2005), reconstructed Atlantic Multidecadal Oscilation (Gray et al., 2004), and reconstructed Pacific Decadal Oscillation (MacDonald and Case, 2005) were not statistically significant

Table 1. Regression statistics for split calibration-verification model of climate predicted fire activity using reconstructed precipitation. (A) Contains the statistics for the model calibrated with 1700–1799 CE and verified against 1800–1899 CE. (B) Contains the statistics for the model calibrated with 1800–1899 CE and verified with 1700–1799 CE. (C) Contains the statistics for the model calibrated against the full fire-scar record 1700–1899 CE with verification statistics

		p	*F*
(A) Calibration, 1700–1799			
r^2	0.378	<0.001	14.182
precipitation	β	*p*	*t*
Constant	2.022	<0.001	27.342
t	−0.431	<0.001	−6. 245
t-1	0.158	0.021	2.357
t-2	0.203	0.032	2.823
Verification, 1800–1899		*p*	*F*
r^2	0.460	<0.001	65.561
RE	0.378	CE	0.430
(B) Calibration, 1800–1899		*p*	*F*
r^2	0.474	<0.001	22.572
precipitation	β	*p*	*t*
Constant	1.905	0.001	25.526
t	−0.552	<0.001	−7.976
t-1	0.234	0.003	3.046
t-3	0.156	0.028	2.241
Verification, 1700–1799		*p*	*F*
r^2	0.366	<0.001	41.531
RE	0.484	CE	0.336
(C) Calibration, 1700–1899		*p*	*F*
r^2	0.423	<0.001	36.380
precipitation	β	*p*	*t*
Constant	1.958	<0.001	38.092
t	−0.492	<0.001	−10.135
t-1	0.185	<0.001	3.695
t-2	0.179	<0.001	3.616
Verification statistics			
Sign test	69.9% (107/153)	RE	0.425

predictors of variability in annual percentage burned ($p > 0.1$) for all calibration periods, and so no further analyses were carried out with these variables. A model reconstruction using annual and antecedent Palmer Drought Severity Indices (PDSI) from the North American Drought Network (Cook et al., 2004) was also attempted. The PDSI reconstruction performed as adequately as the precipitation model ($r^2 = 0.426$; $p<0.001$) but only used one year of antecedent climate. Because the precipitation model better approximated previous fire–climate studies in its use of two antecedent climate years (Crimmins and Comrie, 2004; Kitzberger et al., 2007; Swetnam and Baisan, 2003), we chose to focus exclusively on the precipitation reconstruction. Predicted percentage of localities burned were transformed from natural log scale using a power transformation that included correction for skewness bias (Baskerville, 1972). The predicted values were then rescaled to the mean and standard deviation of the 153 fire years in the fire-scar data set between 1700 and 1899.

Most of the area burned in surface fires occurs during locally extensive and regionally synchronous fire years (Farris et al., 2010; Westerling and Swetnam, 2003). Moderate and large regional fire events were identified in the predicted and fire-scar time series based on years that were more than one (moderate regional fire years) or two standard deviations above the mean values (large regional fire years) for the entire record (572–1987 CE) for the predictions and 1700–1899 CE for the fire-scar data. The frequencies of moderate or large regional fire years were calculated using 25 year centered sums in order to characterize long-term, low-frequency variation in the occurrence of regionally synchronous moderate and large fire years. Intervals between moderate or large regional fire years were also calculated to evaluate long-term changes in fire-free periods over the course of the record.

To determine if the climatic drivers of surface fires during the period amenable to fire-scar investigation were unusual relative to other parts of the late Holocene and the Medieval Climate Anomaly in particular, we used Mann-Whitney U tests to compare the mean ranks of (1) predicted annual area burned and (2) fire-free intervals for the period amenable to fire-scar investigation (*c*. 1600–1987 CE) against the entire remaining record (572–1599 CE) and against the Medieval Climate Anomaly (800–1300 CE). Chi-squared tests were used to evaluate whether moderate or large regional fire years occurred more or less frequently than expected in either period. Further, to identify statistically significant changes in mean values or in variance over the entire record, predicted annual area burned was analyzed using sequential t-tests and F-tests in the Regime Shift program (Rodonov, 2004, 2005).

Results

An arid year *t* and a wet *t*-1and *t*-2 or *t*-3 were consistently significant predictors in the two 100 year modeling periods ($p<0.05$). R^2 values for each calibration period were greater than 0.37 and explained at least 36% of the variation in the percentage of localities burned in each verification period (Table 1). The final transfer function using *t*, *t*-1, and *t*-2 explained more than 42% of the variability in natural log area burned ($p<0.001$) between 1700 and 1899 CE. A sign test indicated that the model of predicted fire activity significantly tracked interannual changes in the percentage of localities burned with 70% success ($\chi^2=12.67$; $p<0.001$). Positive RE and CE values indicated that the reconstruction had substantial improvement over calibration and verification period mean values (Cook et al., 1999; Fritts, 1976). Once the predicted values were transformed with a correction for skewness bias and rescaled to the variance of the fire-scar data, the reconstruction explains slightly more than 50% of the variation in fire years (N=153) from the original, untransformed fire-scar data (R = 0.711; $r^2 = 0.506$; $F = 154.537$; $p<0.001$; Figure 2).

The entire reconstruction predicts the proportion of ponderosa pine localities that would be expected to burn in a given year, a proxy for annual area burned, based on annual and two years antecedent moisture (Figure 3). Although there is interesting annual, decadal, and multidecadal variability visible in the predicted values, climate-predicted area burned during the period amenable to fire-scar investigation (1600–present) is not significantly different than the entire remaining record (Mann-Whitney U = 194,432; $Z = -0.729$; $p = 0.466$) or the Medieval Climate Anomaly (Mann-Whitney U = 95,043; $Z = -0.567$; $p = 0.571$). The MCA is predicted to have had one year (1067 CE) comparable with the well-known fire year of 1748 CE, when more than 65% of fire-scar localities burned (Swetnam and Baisan, 1996) and when crown fires have been inferred for some high-elevation mixed conifer forests in the Southwest (Margolis, 2007).

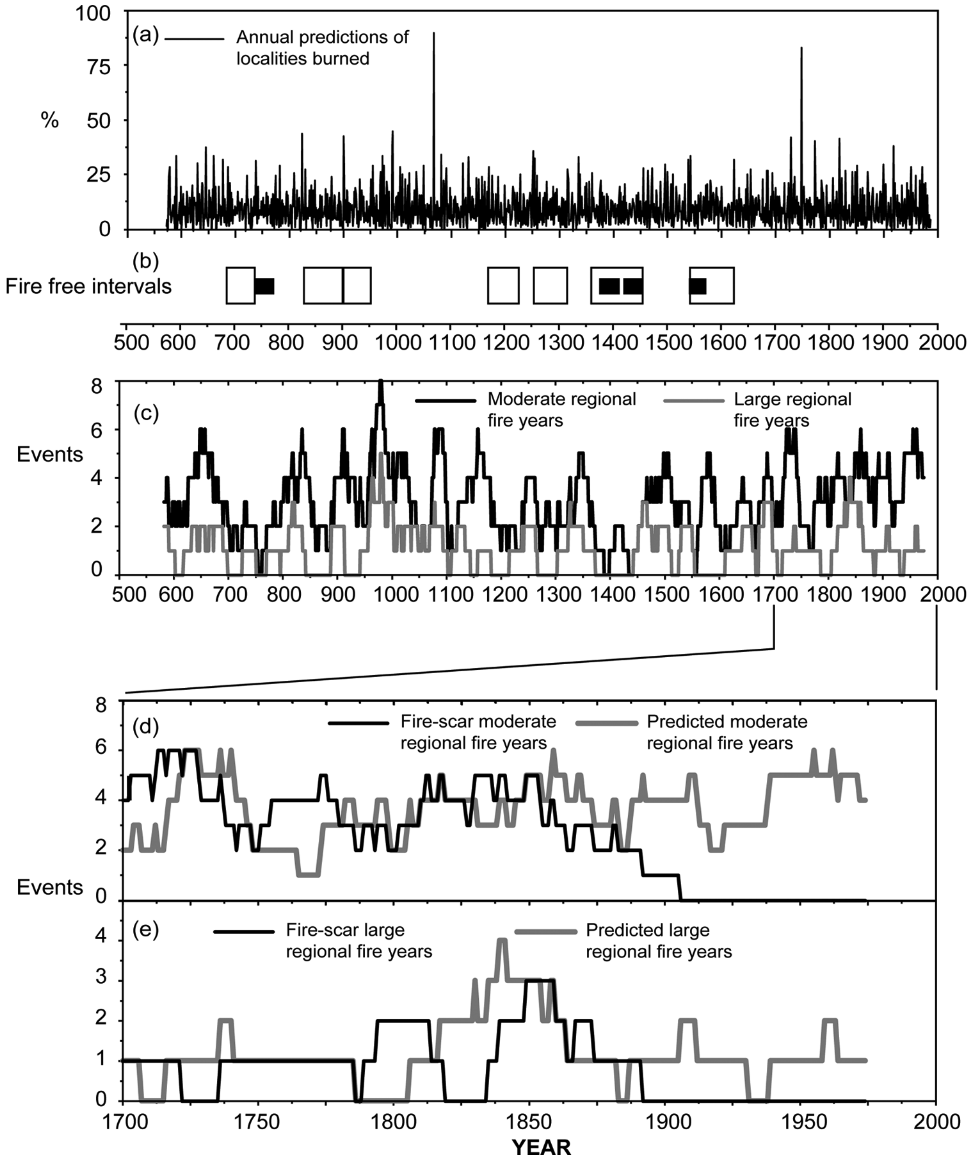

Figure 3. Annual predictions of the percentage of localities burned (a); intervals longer than 24 years between moderate regional fire events (solid bars in (b)) and intervals longer than 49 years between large regional fire events (boxes in (b)); the frequencies of moderate and large regional fire years within 25 year centered moving windows (c); and comparisons between the 25 year frequencies of moderate (d) and large regional fire years (e) predicted by the climate model and in the original fire-scar data

The regression model predicts a similar number of moderate (28) and large regional fire years (10) for the calibration period as are recorded in the fire-scar record (29 moderate events, 9 large). Figure 3 plots the number of moderate and large regional fire events over 25 year moving windows for the entire reconstruction as well as a comparison of reconstructed and fire-scar based event frequencies since 1700 CE. Highest frequencies of both moderate and large regional fire years were reached in the late tenth century, whereas nadirs in both types of regional fire years occurred during the eighth and fourteenth to fifteenth centuries. There is no statistically significant difference in the occurrence of moderate or large regional fire years as predicted for the period amenable for fire-scar investigation and the MCA (Table 2).

No statistically significant shifts in mean predicted annual area burned were detected throughout the entire 1416 year record. However, several multidecadal changes in the variance of predicted annual area burned were identified at the 95% confidence interval (Figure 4). The vast majority of the record has variance between 40% and 65% but 968–991 and 1724–1748 CE have variance greater than 180, whereas variance is unusually low (σ^2=22) between 1381 and 1454 CE.

Discussion

The results of the regression model suggest that the annual area burned and the frequencies of climate-driven surface fires during the Medieval Climate Anomaly were statistically indistinguishable from those of the period typically encompassed by fire-scar investigation (i.e. post 1600). Therefore, the historical range of variation documented by the Southwestern US fire scar record from *c*. 1600 to 1900 CE may still be a relevant analog for reference dynamics (*sensu* Falk, 2006) for restoration and management purposes, even if warm and dry conditions of the MCA are a good analog for near-term future climate scenarios, as some models predict (e.g. Hoerling and Eischeid, 2007; Seager et al., 2007).

Although long-term variation in predicted fire activity and regional fire frequency does not consistently correspond with hemispheric or global climate episodes as they have been

Table 2. Results of Chi-Squared and Mann-Whitney U tests to compare the frequency of regional fire events and the duration of intervals between regional fire events between the period commonly available for fire-scar study (*c.* 1600 CE–present) and the Medieval Climate Anomaly (800–1300 CE)

	Non-fire years Observed (expected)	Fire years Observed (expected)	Total *N*
Moderate regional fire years			
Fire-scar period	352 (351.3)	52 (52.7)	404
MCA	435 (435.7)	66 (65.3)	501
	$\chi^2 = 0.18$	d.f. = 1	$p = 0.921$
Large regional fire years			
Fire-scar period	385 (384.8)	19 (19.2)	404
MCA	477 (477.2)	24 (23.8)	501
	$\chi^2 = 0.04$	d.f. = 1	$p = 0.951$
	Years[a]	Mean Rank	*N*
Intervals between moderate regional fire years			
Fire-scar period	1623–1977	59.47	51
MCA	807–1295	58.64	66
	Mann-Whitney U = 1659	$Z = -0.132$	$p = 0.895$
Intervals between large regional fire years			
Fire-scar period	1648–1971	22.67	18
MCA	809–1315	20.63	24
	Mann-Whitney U = 195	$Z = -0.534$	$p = 0.593$

[a]Intervals were only included if the majority of their duration occurred during the Medieval Climate Anomaly (800–1300 CE) or the fire-scar period (1600 CE–present) and if both the beginning and end dates were marked with predicted fire years and not the beginning or end of the record.

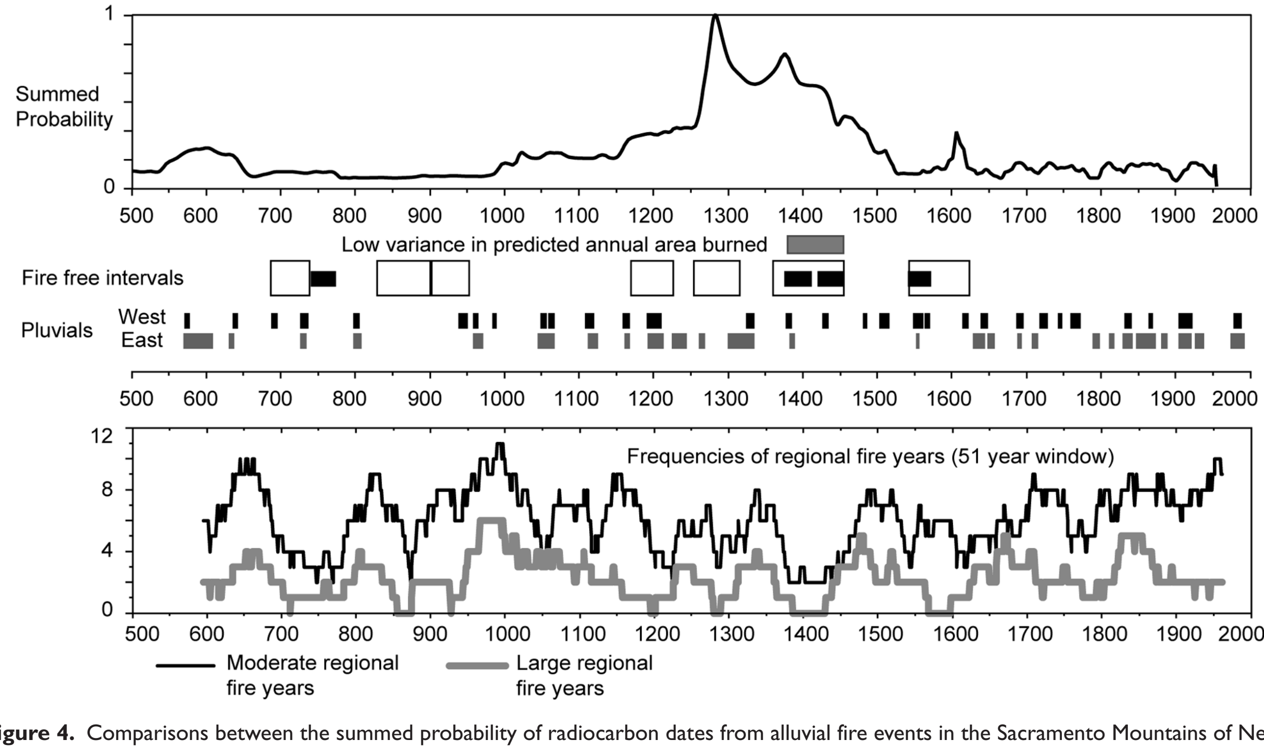

Figure 4. Comparisons between the summed probability of radiocarbon dates from alluvial fire events in the Sacramento Mountains of New Mexico (Frechette and Meyer, 2009), the period of low variance in annual area burned, long fire-free intervals, unusually long wet periods from the southwestern (Salzer and Kipfmueller, 2005) and southeastern (Grissino-Mayer, 1996) Colorado Plateau, and the frequency of moderate and large regional fire years within 51 year centered moving windows

monolithically defined, such as a warm and dry MCA (800–1300 CE) or a cool and moist LIA (1400–1850 CE), frequencies of regional fire years correspond well with the only published millennial length fire-scar chronologies from the west. In this case, Giant Sequoia fire frequencies were elevated between 1000 and 1300 CE prior to a substantial reduction after 1300 CE, and an increase again during the 1600s and 1700s (Swetnam, 1993; Swetnam et al., 2009). This is a meaningful comparison because, prior to active fire suppression, Giant Sequoia fire regimes were characterized by frequent, low severity surface fires analogous to those that characterized Southwestern ponderosa pine forests. Furthermore, most of the western USA including parts of the Sierra Nevada and the greater Southwest, were exceptionally dry during the MCA (Cook et al., 2004).

Although there are no clear differences between the fire-scar record and the MCA, there are unusually long, multidecadal periods between regional fire years that are not represented in the fire-scar period. In particular, unusually low regional fire frequencies that correspond with nearly a century between large regional fire years and a period that includes only three moderate regional fire years separated by the two longest intervals of the record occurred between 1360 and 1455 CE. These long intervals between regional fire years coincide with the period of significantly low variance in annual percentage of localities burned, suggesting that many Southwestern forests may have been essentially fire free during this interval. One or two unusually wet periods or 'pluvials' occur during this period of reduced fire activity (Grissino-Mayer, 1996; Salzer and Kipfmueller, 2005) prior to one of the identified hemispheric mega-droughts of the last millennium during the fifteenth century (Stahle et al., 2007). Pluvials in the context of reduced fire frequencies would have been likely to encourage canopy recruitment (Brown, 2006; Brown and Wu, 2005) thus creating the fuel and canopy structural conditions necessary for large crown fires. We suspect that the late fourteenth and fifteenth centuries were periods in which some Southwestern ponderosa pine forests were more vulnerable to altered fire behavior, including large crown fires. Some of the limited evidence used to support inferences of high-severity crown fires during the Medieval Climate Anomaly may actually date to the late fourteenth or fifteenth centuries. For example, in the relatively low-temporal resolution sedimentary records from the Sacramento Mountains of New Mexico south of the southern Colorado Plateau, cumulative radiocarbon probabilities of fire-related alluvial fan deposits reach their late-Holocene peak between cal. 1300 and 1500 CE (Figure 4), implicating an increase in moderate or high severity fire activity in these watersheds at that time (Frechette and Meyer, 2009; New, 2007). Rather than being attributable to severe Medieval droughts alone, we suspect that the long intervals between regional fire years in our high-resolution reconstruction, coupled with likely enhanced tree recruitment and fuel accumulation during pluvials, heightened the vulnerability of these forests to elevated fire severity.

This is also an important observation for understanding altered fire behavior over the last century. At present, many Southwestern forests have not experience fire in more than a century. Only one interval between large regional fire years (1360–1455 CE) approaches that length and the longest period between moderate regional fire events is 35 years (1376–1411 CE). If interannual climate had continued to drive production and curing of surface fuels during the twentieth century, the surface fire patterns of the eighteenth and nineteenth centuries would have continued unabated (Figure 3). By 1950, the beginning of the modern period of large forest fires in the Southwest (>20 000 ha), with many crown fire patches exceeding 1000 ha (Savage and Mast, 2005), the duration of time with little to no local or regional fire activity was truly anomalous in the entirety of the 1416 year record. In the absence of fire suppression, our model indicates that Southwestern ponderosa pine forests would have burned frequently throughout the twentieth century. This fact, coupled with abundant evidence of dense forests, accumulated fuels, and increasingly severe drought and warming in many areas of the Southwest today (and elsewhere in the west) points to truly 'no-analog' conditions in recent decades in terms of fire hazard and fire behavior (Allen et al., 2002).

Conclusion

To evaluate the hypothesis that the fire-scar record of Southwestern ponderosa pine fire regimes is unrepresentative of the last 2000 years and, by extension, is no longer appropriate for guiding management and restoration, we generated a reconstruction of climate-predicted area burned since 572 CE. Our regression model explains slightly more than 50% of the variation in the percentage of 45 fire scar localities burned during 153 fire years between 1700 and 1899 CE, prior to inadvertent and active fire suppression. Like recent fire–climate studies of middle elevation forests in the Southwest (Crimmins and Comrie, 2004; Kitzberger et al., 2007; Swetnam and Baisan, 2003), our model incorporates two years of antecedent climate as well as annual climate in predicting annual fire activity.

According to our model, climate-predicted frequencies of moderate and large regional fire years did vary at multidecadal to centennial scales. Our model suggests an anomalous reduction in fire frequencies between *c*. 1360 and 1455 CE, with less pronounced reductions in fire frequencies in the eighth, ninth, and sixteenth centuries. Rather than crown fires being restricted to the MCA, these may have occurred primarily following periods when local fuel accumulations and canopy recruitment driven by pluvials and reduced surface fires led to altered forest structures that were more vulnerable to increased fire severity.

It is important to note, however, that our model has distinctive limitations. Our regression model is linear and focuses exclusively on one process, albeit an important one (Swetnam and Baisan, 2003), that is known to affect fine fuels and surface fire activity. Although they are not represented in our linear model, other non-linear fire–climate relationships and non-climatic processes may have been important at long timescales. For example, human activities interrupted the interannual climate–surface fire relationship over the last 100+ years and it is possible that other processes, including the use of fire by ancient people (Kaye and Swetnam, 1999; Roos et al., 2010), may have maintained surface fires in occupied or regularly used areas even as unoccupied areas experienced declining fire frequencies (Fulé et al., 2011; Roos, 2008). Indeed, we regard our interpretations of vulnerability to fire regime shifts as chronologically specific working hypotheses that should be evaluated in the future with additional fire history data (both sedimentary and tree-ring based) and non-linear modeling approaches, including both statistical and process models for fire, climate, and forest (fuel) dynamics.

Although the Medieval Climate Anomaly (*c*. 800–1300 CE) has been suggested as a better analog than the fire-scar record (*c*. 1600 CE–present) for near-term climate conditions in the Southwest, we found no statistically significant differences in the average annual area burned or the frequencies of regional fire years for the two periods in our model predictions. We suggest that if the MCA is a useful analog for comparison with contemporary and near-term climate conditions, then the eighteenth and nineteenth century fire-scar record also remains an appropriate source of reference dynamics for fire and forest management. It is worth noting in this context that drought persistence and magnitude during the MCA was apparently much greater than has yet been experienced in the modern era (i.e. twentieth and twenty-first centuries, Cook et al., 2004). Therefore, improved understanding of fire and forest dynamics during both the MCA and the 1700s and 1800s will be useful as we develop and test models of future changes under anticipated warming and increasing droughts in coming decades. In support of other Southwestern fire history studies, our model highlights the last 120 years as truly anomalous over the last 1400 years for the absence of surface fires.

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