Research Article

Spatially and Temporally Variable Fire Regime on Rincon Peak, Arizona, USA

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ABSTRACT

Spatial and temporal patterns of fire history are affected by factors such as topography, vegetation, and climate. It is unclear, however, how these factors influenced fire history patterns in small isolated forests, such as that found on Rincon Peak, a “sky island” mountain range in southern Arizona, USA. We reconstructed the fire history of Rincon Peak to evaluate the influences of broad-scale (i.e., climate) versus local-scale (i.e., topographic) factors on fire occurrence and extent. We evaluated both fire scars and tree demography (natality and mortality) to investigate surface fire and crown fire events. The fire history of a 310 ha study area surrounding the top of Rincon Peak was reconstructed by tree-ring sampling in 21 plots. Between 1648 and 1763, spreading fires on Rincon Peak were controlled primarily by regional climate. Widespread surface fires occurred during drought years, and were generally synchronized with regional fire events known from an extensive network of other fire history studies. After 1763, fire extent was apparently limited by local factors (i.e., fuels) as frequent fires continued to burn, but were limited to the southern part of the study area until a widespread fire occurred in 1819. Landscape fires (i.e., fires that scarred ≥2 plots) were absent from the entire study area between 1819 and 1867 despite continued burning in adjacent mountain ranges. Multiple lines of evidence indicate that the 1867 fire was both a surface and a stand-replacing event that killed most trees within a 60 ha patch. Our findings suggest that past climatic variations had important effects on fire regimes and age structures of small, fragmented ponderosa pine (*Pinus ponderosa*) landscapes like Rincon Peak. Given anticipated climate changes, the rich biodiversity harbored in these steep, isolated landscapes will be critical habitat in the migration of species and should therefore be considered high conservation priority.

Keywords: fuel continuity, landscape fire history, southern Arizona forests

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INTRODUCTION

The fire history at a particular location is controlled by factors that operate at various temporal and spatial scales. Fire occurrence and extent, for example, are often controlled by climate, operating at regional to global spatial scales and at inter-annual to multi-decadal temporal scales (Swetnam and Betancourt 1998, Kitzberger *et al*. 2001). In southwestern forests and elsewhere, associations between drought years and widespread fires have been well established (Swetnam and Betancourt 1990, Swetnam and Baisan 1996, Crimmins and Comrie 2004). Regionally synchronized fires typically occurred during drought years preceded by one to three wet years (Swetnam and Betancourt 1998, Grissino-Mayer and Swetnam 2000, Fulé *et al*. 2003, Kitzberger *et al*. 2001). The combination of wet and dry cycles, sometimes enhanced by the El Niño Southern Oscillation (ENSO), promoted fuel conditions conducive for wildland fires in communities with herbaceous understories (e. g., southwest ponderosa pine [*Pinus ponderosa*] forests) (Swetnam and Baisan 2003). High-elevation mixed conifer stands typically did not exhibit such wet and dry associations between climate and fire but were instead primarily associated only with severe drought. The lack of a lag relationship was probably due to longer intervals between fires and higher fuel production rates that allowed for sufficient fuel buildup (Swetnam and Betancourt 1998, Sibold and Veblen 2006, Margolis *et al*. 2007).

Fire history patterns also were influenced by factors operating at landscape to mountain range scales (Beaty and Taylor 2001, 2008; Heyerdahl *et al*. 2001; Taylor and Skinner 2003; Iniguez 2008). Fire spread patterns, especially during non-drought years, were determined primarily by local factors like topography, local weather patterns, variations in fuels caused by vegetation changes, and people (Rothermel 1983, Agee 1993, Taylor and Skinner 1998, Allen 2002, Mermoz *et al*. 2005). Lightning and human ignition sources were historically abundant in southwest forests. Large fires, however, required both an ignition and continuous flammable fuels. Therefore, fire spread was highly dependent on the continuity of flammable fuels across the landscape. For example, brush fields do not generally carry fires effectively except under relatively extreme conditions (e.g., presence of wind and drought), and thus may have acted as a barrier to the spread of surface fires from adjacent forests. Consequently, forests adjacent to or within a matrix of relatively non-flammable fuels may have experienced fewer fires compared to forests surrounded by flammable fuels (Turner 1989, Taylor 2000, Finney *et al*. 2005).

Fire histories in ponderosa pine and mixed-conifer forests have been well studied, particularly in the southwestern US (Swetnam *et al*. 2001, Fulé *et al*. 2003). Most southwestern studies have been carried out in areas with continuous fuels that provided unimpeded fire spread. These studies have shown that, on average, large surface fires (i.e., fires that scarred >25 % of the samples at a site) occurred every 7 yr to 15 yr (Swetnam *et al*. 2001, Fulé *et al*. 2003). Fire history studies conducted in relatively rugged topography with discontinuous fuels have yielded different results (Baisan and Swetnam 1995, Morino 1996, Touchan *et al*. 1996, Brown *et al*. 2001, Swetnam *et al*. 2001, Grissino-Mayer *et al*. 2004). For example, in the Animas Mountains in southwestern New Mexico, USA, forest stands are dispersed among oak-shrub (*Quercus* spp.) fields, talus slopes, and cliff barriers to fire spread. Consequently, these isolated forests experienced relatively long intervals between some fires (i.e., >15 yr) allowing relatively high fuel loads to accumulate. As a result, a mixture of surface and stand-replacing fires occurred, depending on the location of the stand and time since the last widespread fire (Baisan and Swetnam

1995, Villanueva-Diaz 1996, Swetnam *et al*. 2001). Variable fire regimes also may have occurred on other "sky islands," including parts of the Chiricahua (Barton *et al*. 2001), Huachuca, and Santa Rita mountains (Danzer *et al*. 1996). Because these types of fire regimes often varied both in time (i.e., long and short fire intervals) and severity (i.e., surface and crown fire), we will refer to them as "variable fire regimes."

Additional fire history studies from landscapes with variable fire regimes are needed to better understand their spatial and temporal characteristics. There is currently a lack of knowledge of where and when variable fire regimes occurred, what caused them, at what spatial scales they occurred, and how often surface and stand-replacing fires occurred. In order to set future restoration and management goals that are appropriate and achievable for areas with variable fire regimes, we first need to understand the composition and structure of these landscapes (Swetnam *et al*. 1999). Understanding how variable fire regimes were influenced by local and regional factors in the past may help to forecast future changes (Swetnam *et al*. 1999). Furthermore, such information will be critical for prioritizing management actions, assessing the impacts of contemporary fires, and avoiding one-size-fits-all approaches (Morgan *et al*. 2001, Allen *et al*. 2002, Agee and Skinner 2005).

Objectives

Like forests in the Animas Mountains, forests on Rincon Peak are isolated by talus slopes and extensive shrub fields. Baisan and Swetnam (1990) reported occasional long fire intervals in their Rincon Peak fire chronology and visual evidence of stand-replacing fires; however, the limited samples (six trees) from this area precluded further interpretations. Additional fire history investigations on Rincon Peak were warranted by the lack of information about variable fire regimes and the potential loss of fire history evidence (i.e., fire-scarred trees) to future fires. The goals of this study were to reconstruct the fire history on Rincon Peak, evaluate the influences of broad- (i.e., climate) versus local-scale (i.e., fuel continuity) factors on fire history patterns, and investigate the possibility of a variable fire regime. This study addressed the following four questions. Did previously identified long fire intervals occur across the entire mountain? What was the relationship between climate and fire extent? How did landscape topography and fuel continuity influence fire spread patterns? What was the role of stand-replacing fires in the Rincon Peak area?

METHODS

Study Area

Rincon Peak is the smaller of the two forested areas in the Rincon Mountains; the other being Mica Mountain to the north. The Rincon Mountains are within the Madrean Archipelago in southeastern Arizona and are managed as part of Saguaro National Park. The Rincon Mountains are within a designated wilderness that has not been extensively logged or developed. A more detailed description of land uses in the greater Rincon Mountains is provided elsewhere (Baisan and Swetnam 1990). The geography and vertical relief of the sky islands combine to create a diverse mosaic of vegetation assemblages stratified along elevation and moisture gradients (Whittaker and Niering 1968, Niering and Lowe 1984).

Within the study area, the forests are dominated by ponderosa pine, Douglas-fir (*Pseudotsuga menziesii*), southwestern white pine (*Pinus strobiformis*), Gambel oak (*Quercus gambelii*), silverleaf oak (*Q. hypoleucoides*), Arizona white oak (*Q. arizonica*) and netleaf oak (*Q. rugosa*). Steep slopes contain chaparral communities dominated by similar oak species in addition to pinyon pine (*P. discolor*), juniper species (*Juniperus* spp.) and pointleaf manzanita (*Artostaphylos pungens*).

Field Methods

The boundary of the Rincon Peak study area followed the distribution of pine forests because these were the main source of fire-scarred samples (Figure 1). We delineated the boundary, which encompassed 310 hectares, using a combination of digital elevation maps (DEM), 1:24 000 topographic maps, digital orthophoto quarter quadrangles, and field reconnaissance. We selected the location of each sample point using a random sampling design stratified by aspect and geography. First, to ensure that sample locations were well distributed throughout the study area, we delineated three geographic strata of roughly equal size. Second, we stratified the study area into three aspect classes: north (300º to 360º and 0º to 60º), south-southeast (60º to 180º) and south-southwest (180º to 300º). We then selected six locations at random (two per aspect class) within each of the three geographic strata. We also selected three additional locations to fill gaps between distant points for a total of 21 sample locations.

At each location, we recorded the vegetation and collected fire history samples. We characterized forest vegetation by identifying and measuring the diameter of all trees ≥10 cm diameter at breast height (1.4 m) within a 0.1 ha circular plot. Within each plot we also cored 5 to 7 of the largest trees 15 cm to 20 cm above the ground. On forested plots that exhibited evidence of stand-replacing fires (e.g., snags and a lack of old living trees) we established additional age structure plots. The purpose of these additional plots was to determine the age of the stands, whether previous stand-replacing fires had occurred at those locations, and the dates of those fires. At these plots, we cored all trees within a 10 m × 10 m area, and all trees ≥10 cm diameter at breast height (dbh) within a 10 m × 50 m area.

Each core was sanded and crossdated using dendrochronological techniques to determine pith date (Stokes and Smiley 1968). We estimated missing pith dates by overlaying concentric circle transparencies to match the curvature of the inner most rings (Liu 1986) and only used dates estimated to be within 20 yr of the inner-most ring. For each core, we determined an establishment date (i.e., year of germination) by subtracting, from the pith date, the estimated number of years it took the tree to reach the coring height, based on coring height and growth rate (see Iniguez 2006).

At each of the 21 locations, we also collected fire-scar evidence. We sampled fire scars with the purpose of obtaining as complete and as long an inventory of fire events as possible within a 2 ha plot (Swetnam and Baisan 1996). Because no single tree is a perfect recorder of past fires, obtaining a complete fire record for each plot required sampling multiple trees (Dieterich and Swetnam 1984). To accomplish this, we first located all fire-scarred trees (including live trees, downed logs and snags) within each 2 ha plot and then sampled those with the maximum number of well-preserved, visible scars. We sampled between 2 and 9 fire-scarred trees per 2 ha plot using chain saws, cutting full or partial cross-sections from the lower bole (Arno and Sneck 1977). We polished fire-scarred cross-sections using a belt sander, then crossdated each sample using dendrochronological techniques to determine the calendar year of each fire scar (Stokes and Smiley 1968, Dieterich and Swetnam 1984).

The fire-scar dates from all sampled trees within each plot were composited (Dieterich 1980) for an estimate of plot-level fire frequencies. This approach assumes a uniform fire history within each 2 ha plot (i.e., a fire recorded by any tree probably affected the entire 2 ha area). A plot was therefore “recording” when

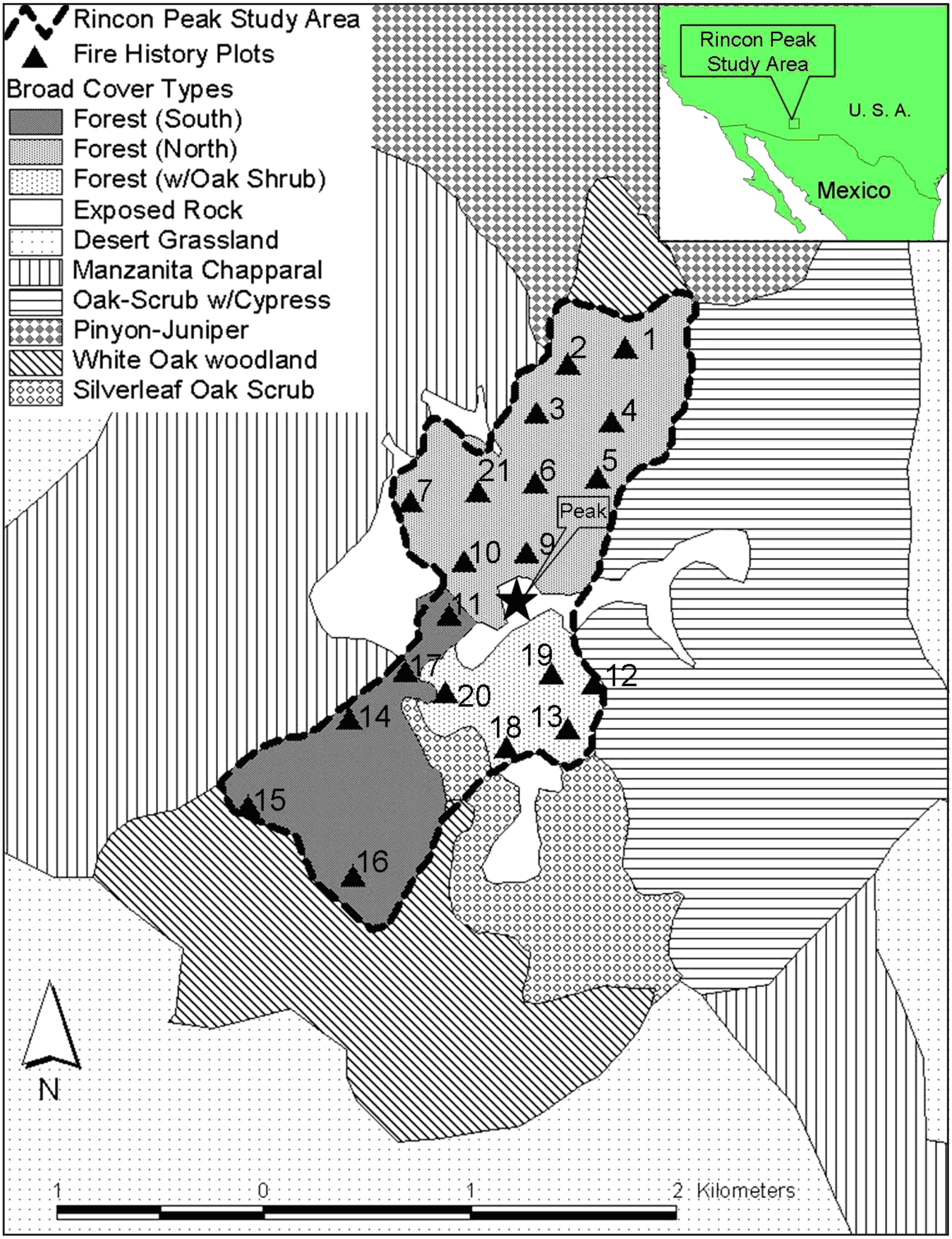

Figure 1. Broad vegetation types and plot locations in the Rincon Peak study area in southeastern Arizona.

at least one sampled tree within that plot had been scarred previously and was still alive (i. e., a ‘fire-scar susceptible tree,” *sensu* Romme 1980). We considered tree samples “not recording” when decay or subsequent fires made it impossible to date the fire-scar year. A visual analysis of the sample depth (i.e., the number of plots “recording” each year) through time revealed that only one plot was recording in the southern part of the study area prior to 1648. Although four plots were recording in the north part of the study area, we felt that the spatial distribution of plots was inadequate to reliably reconstruct fire history spatial pattern (Figure 2). The period of analysis was therefore restricted to the post 1648 period.

Fire History Analysis

Within the period of analysis, we identified a “landscape fire year” when ≥2 plots recorded a fire in the same year. For each landscape fire year, we estimated relative fire extent by calculating the percentage of recording plots scarred. We examined spatial and temporal fire patterns by comparing mean fire interval (MFI) statistics between two areas (north and south) and two time periods (1648 to 1763 and 1763 to 1867). We selected these periods based upon visually obvious changes in the fire-scar record (see Figure 2). Statistical tests between these selected periods, therefore, are tests of the hypothesis that our *a priori* inference of fire frequency differences between time periods, based on visual evidence, was correct.

We compared landscape fire years to climate conditions based on the tree-ring reconstructed summer (June-August) Palmer Drought Severity Index (PDSI) using grid point number 105 in southeastern Arizona (Cook *et al*. 1999). To investigate the relationships between relative fire extent (i.e., widespread vs. local) and inter-annual moisture patterns, we used PDSI in a superposed epoch analysis (SEA) (Baisan and Swetnam 1990). We identified widespread fire years when ≥70 % of recording plots scarred, and local fire years when <70 % of recording plots scarred. The SEA method computed the average climate conditions associated with fire years as well as years before and after the fire event. We then compared the averages to variation in the entire climate record using Monte Carlo simulations that provided an expected average and confidence intervals (Grissino-Mayer 1995).

RESULTS

Temporal and Spatial Patterns of Surface Fires

Fires were recorded at one or more plots in 64 different years between the earliest fire scar in 1502 and the latest in 1988. There were 16 landscape fire years on Rincon Peak between 1648 and 1763 (Figure 2). Seven years were also widespread fire years (i.e., years when ≥70 % of plots recorded fire; Figure 3). During some years, fires were recorded primarily among plots in the southern part of the study area (e.g., 1691, 1708, 1718, and 1738). During other years—1659, 1668, 1670, 1704, and 1715—fires were recorded mostly in the north and central parts of the study area (Figure 3).

Fire spread patterns changed after 1763 (Figure 2). The 1763 and 1819 fires were two of the most widespread events, with at least 95 % of the plots recording fires each of these two years (Figure 3). Between 1763 and 1819, however, there were no widespread fire events (i.e., years when ≥70 % of plots recorded a fire) in the study area (Figures 2 and 3). Fires were recorded, but only among plots in the southern part of the study area such as in 1775, 1786, 1798, and 1806 (Figure 3). Other than the 1775 fire, no other fires were recorded in the nine northern plots between 1763 and 1819 (Figure 2). Fire frequencies declined further

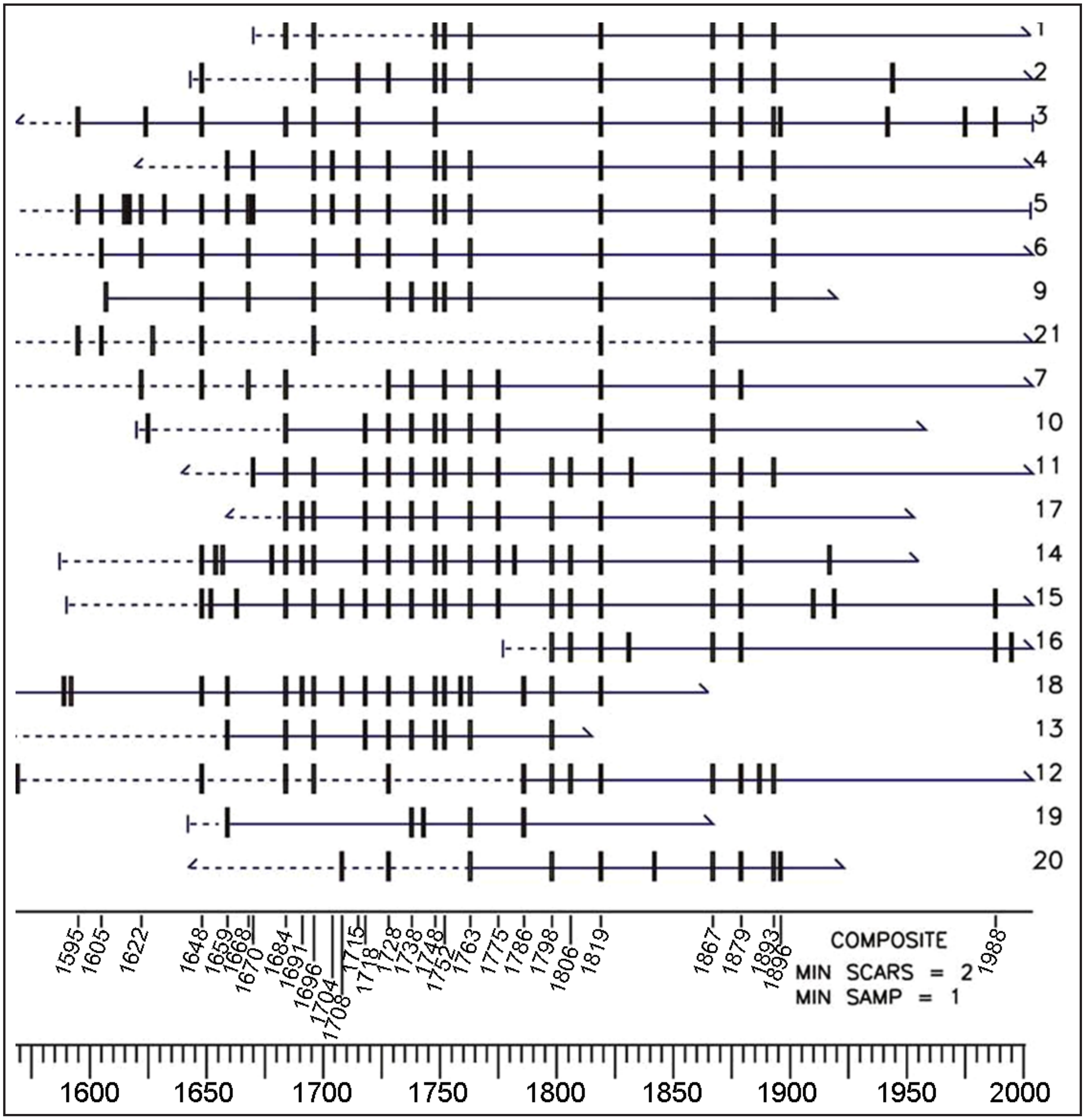

Figure 2. Master fire chronology for the Rincon Peak study area in southeastern Arizona. Horizontal lines represent the composite fire chronology for multiple fire-scarred trees collected over each 2 ha plot (range = 2 to 12 trees). Solid horizontal lines represent recording (i.e., at least one tree was susceptible to fire-scar) and dashed horizontal lines represent non-recording periods (i.e., no trees were susceptible to fire-scar). Small vertical dashes represent fire events in a particular year. Plot numbers on the right correspond to geographic locations (Figure 1), arranged form north (top) to south (bottom). Years labeled along the bottom correspond to landscape fire years (i.e., years when two or more plots were fire-scarred).

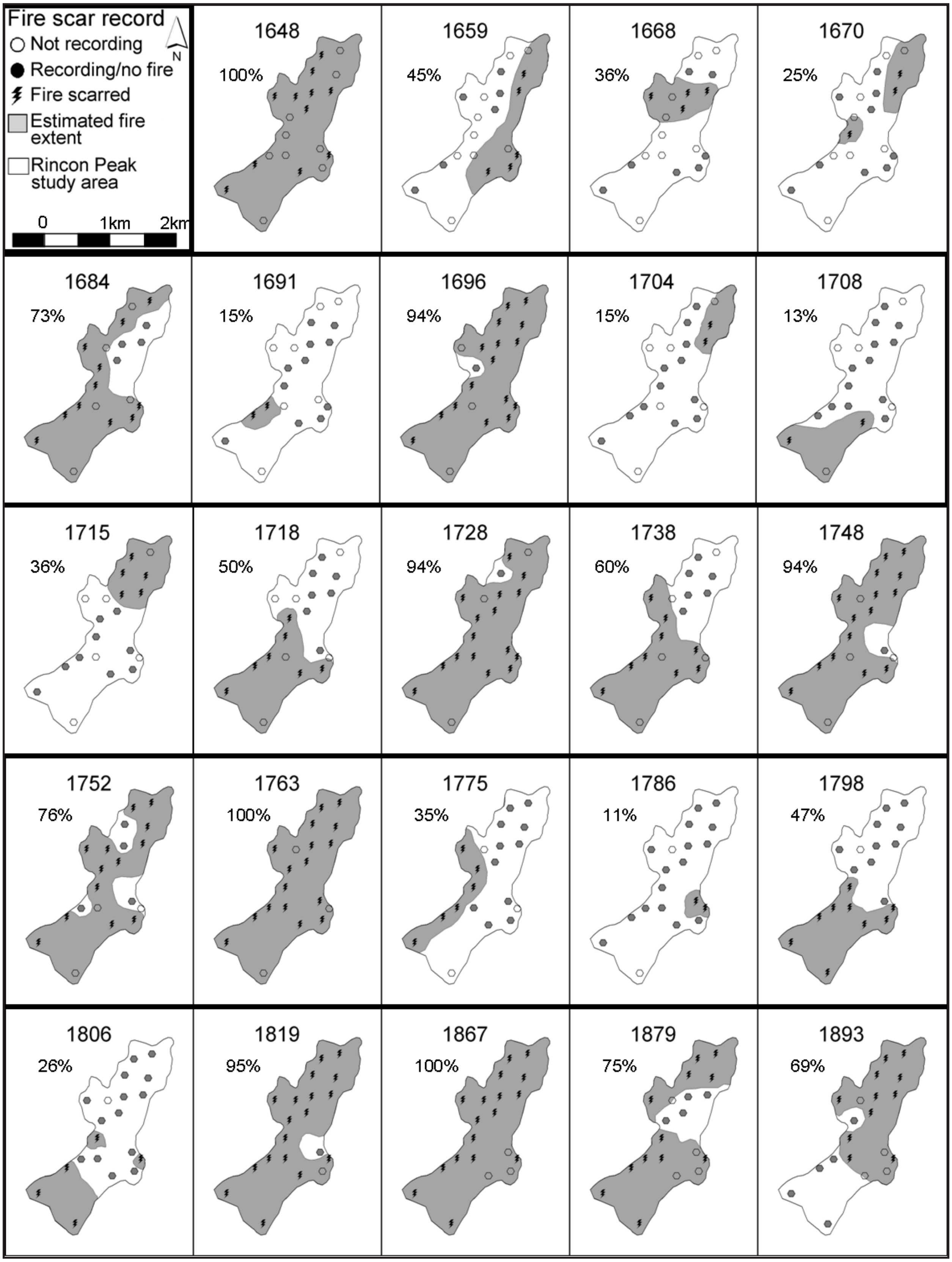

Figure 3. Fire spread patterns for all landscape fire years (i.e., years when at least two plots were scarred) in the Rincon Peak in southeastern Arizona between 1648 and 1893. Estimated percent of total study area (310 ha) burned is indicated below and left of each fire year.

between 1819 and 1867 as no landscape fires were recorded (Figure 2).

Fire intervals in the southern and northern sections of the Rincon Peak study area were highly variable, especially between 1763 and 1867. The MFI for landscape fire years in the northern part of the study area changed significantly from 9.6 yr between 1648 and 1763 to 34.7 yr between 1763 and 1867 ($p < 0.001$, Table 1). The MFI for landscape fire years in the southern part of the study area also lengthened from 10.5 yr to 17.5 yr between these two time periods (a non-significant difference; $p = 0.19$). Across the study area, the 1867 fire marked the end of the 48-year interval between landscape fires (Figure 2). In the 26 years after 1867, fires were recorded in 1879 and 1893. After 1893, 10 fires were recorded in the tree-ring record; however, only the fire in 1988 scarred trees in more than one plot (Figure 2). Across Rincon Peak, widespread fires occurred during drought years ($p < 0.001$) that were typically preceded by 2 to 3 wet years ($p < 0.05$) (Figure 4). Non-widespread fire years (i.e., fires recorded by ≤70% of the plots) were associated with dry conditions ($p < 0.05$), but wet/dry patterns in years prior to the fire did not differ significantly from expected levels (Figure 4).

Evidence for a Variable-Severity Fire

Multiple lines of evidence suggest that a portion of Rincon Peak in at least one fire year experienced both surface and stand-replacing fire behavior. In the area south of the peak we found five plots (12, 13, 18, 19, and 20, in Figure 1) with evidence of both surface and stand-replacing fire events during the 1867 fire. When a fire is recorded by a tree as a fire-scar it suggests that the fire was a relatively low severity event in that location because the tree survived. In the area south of the peak, however, only two of the 22 sampled fire-scarred trees survived after the 1867 fire (Figure 5). Two fire-scarred trees had remnant bark that provided exact death dates of 1867. Three other fire-scarred snags without bark that were probably also killed by severe fire in 1867 had outermost ring dates of 1866, 1865, and 1862 (Figure 5). Of the five plots south of the peak, three were on xeric south aspects and are now oak-shrub fields (Figure 6). Two other plots

Table 1. Spatial and temporal comparison of fire intervals in the Rincon Peak study area in southeastern Arizona. Fire intervals were compared between two time periods (1648-1763 and 1763-1867) and two areas (i.e., forests in the northern and southern parts) within the Rincon Peak study area. Fire history plots are fire chronologies based on multiple fire-scarred trees collected within a 2 hectare area. Fire-interval descriptive statistics are computed using the following filters: All = all fire years when two or more plots recorded a fire and >50 % = fire years when ≥50% of recording plots recorded a fire within the north and south parts of the study area, respectively.

Time period	North[a]	All	>50%	Time period	South[b]	All	>50%
1648-1763	Mean	9.6	14.4	1648-1763	Mean	10.5	12.8
	Median	10.5	14.5		Median	10.0	11.0
	# of Intervals	12	8		# of Intervals	11	9
	St. Dev.	3.5	5.5		St. Dev.	5.5	6.5
1763-1867	Mean	34.7	52.0	1763-1867	Mean	17.3	20.8
	Median	44.0	52.0		Median	12.0	13.0
	# of Intervals	3	2		# of Intervals	6	5
	St. Dev.	19.7	5.7		St. Dev.	15.1	16.2

[a] North includes plots 1-10 and 21.
[b] South includes plots 11-20 in Figure 1.

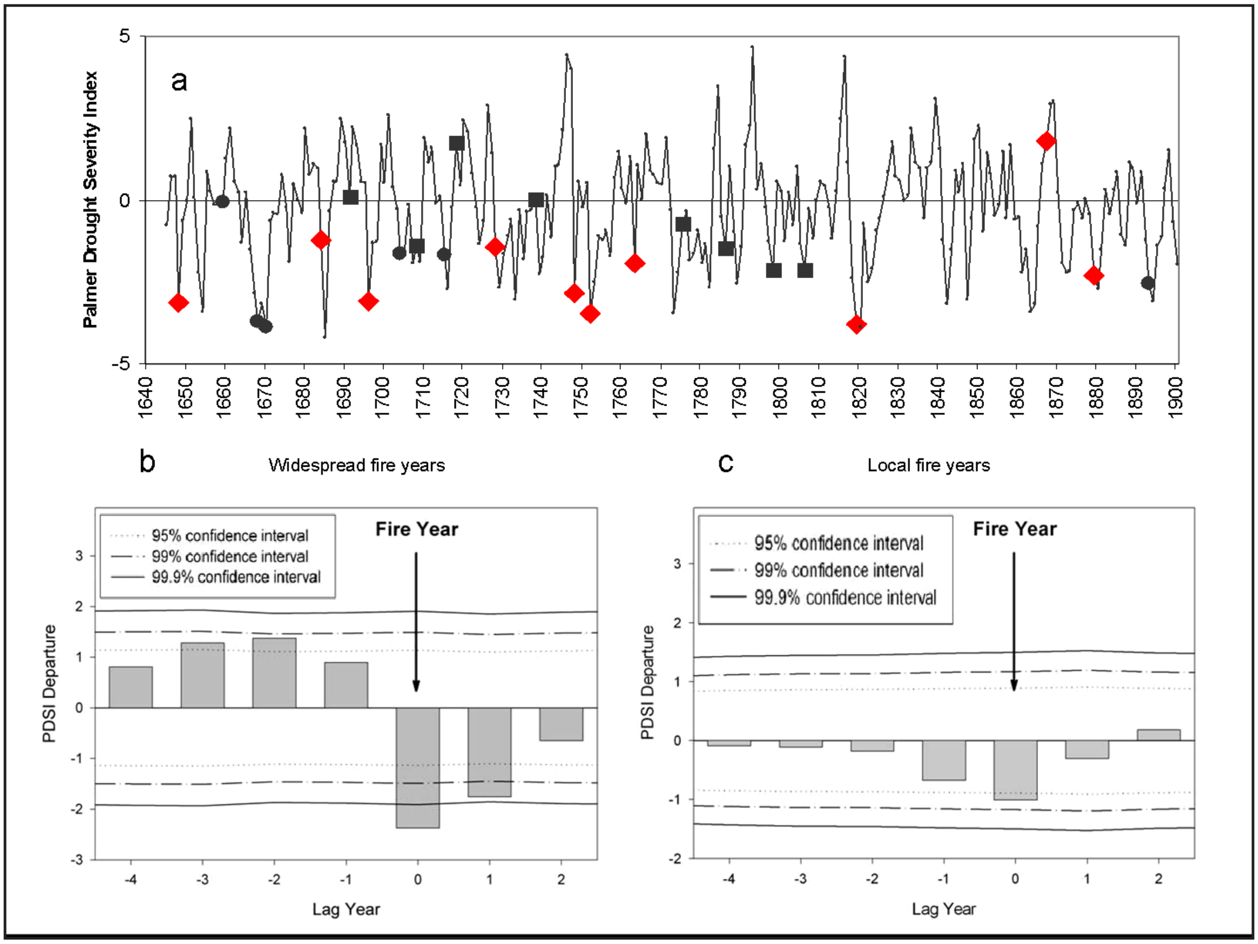

Figure 4. Relationship between summer Palmer Drought Severity Index and relative fire extent between 1648 and 1893 in the Rincon Peak in southeastern Arizona. (a) Diamonds represent widespread fires (i.e., years when ≥70 % of recording plots were scarred), circles represent fire years that scarred plots in the northern part of the study area and squares represent fires years that scarred plots in the southern part. Superposed epoch analysis (SEA) revealed that (b) widespread fire years were significantly drier than normal and preceded by unusually wet conditions 2 yr to 3 yr prior while (c) local fire years were also dry, but were not preceded by wet conditions. Confidence intervals determined from Monte Carlo re-sampling procedure.

(13 and 18) were on more mesic north aspects and are now dominated by ponderosa pine pole stands (Figure 6). Age structure patterns from these two plots show a lack of older trees predating the 1867 fire and indicate a post-1900 even-age regeneration event (Figure 6). Fire-scarred trees indicate a fire event in 1867, but low survivorship, death dates, and regeneration suggest that this fire was mostly stand-replacing in this part of the study area. Further evidence comes from a few scattered older trees outside the age-structure plots that were cored and had either injuries or suppressed growth after 1867 (data not shown). These features may reflect crown scorch or other fire-related damage that provide additional support that 1867 was a severe fire event.

In addition to variable-severity fire behavior in 1867, clustering of outer-most ring dates on several logs prior to fire dates in 1819, 1798, and 1728 suggests that fires on these dates may have also caused overstory mortality (Figure 5). Similarly, a lack of fire-scarred trees predating the 1775 fire on plot 16 may indicate a stand-replacing fire in that area (Figure 2). These age structure and fire history

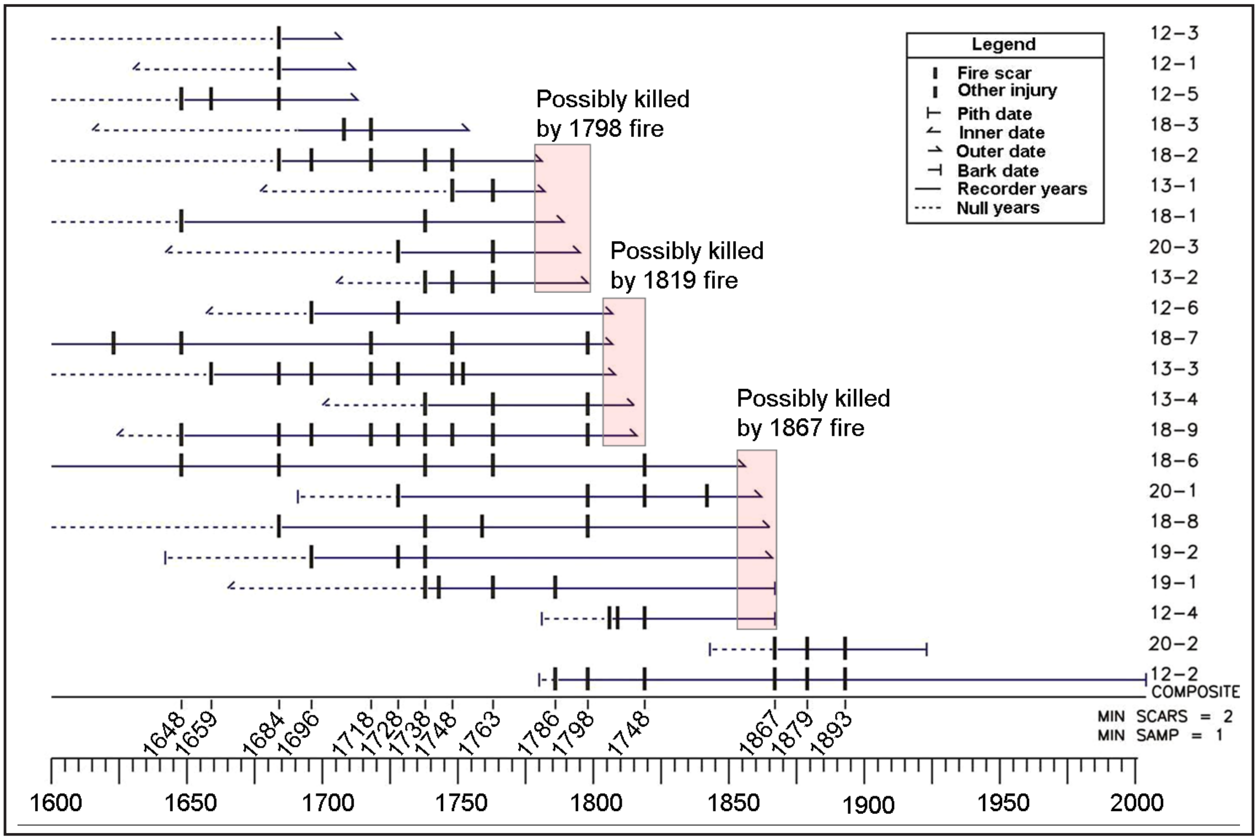

Figure 5. Fire chronology for all fire-scarred trees within six plots south of Rincon Peak. Horizontal lines represent individual trees with corresponding plot-tree identification numbers along right side. Plot locations provided in Figure 1. Bark dates of 1867 on trees 19-1 and 12-4 are exact death dates while other outer-most dates are approximate death dates.

patterns suggest that the southern part of the study area experienced a variable fire regime that consisted of repeated surface fires and infrequent, relatively small (60 ha) stand-replacing fire events.

DISCUSSION

The Influence of Regional Climate Changes on Fire Patterns

Climate has regional influences and, therefore, processes partly controlled by climate, such as forest fires, tend to be synchronized at regional scales (Swetnam and Betancourt 1990). Local fire patterns that are asynchronous with regional fire patterns probably signal an over-riding importance of local controlling factors. Depending on the time period, the fire regime on Rincon Peak was variably influenced by regional climate and local fuel continuity. Between 1648 and 1763, the fire regime on Rincon Peak consisted of frequent surface fires. Within this period, all widespread fire years occurred during drought years (Figure 4) and were synchronous with regional fire years reported by Swetnam and Betancourt (1998). After 1763, fire spread patterns on Rincon Peak became more localized and dissimilar to regional patterns. For example, drought years such as 1798 and 1806 resulted in extensive fires across the southwest (Swetnam and Betancourt 1998), but only small fires on Rincon Peak (Figure 4a). The extensive fire in 1819 (Figure 2 and 3), however, was consistent with other large fires across the region (Swetnam and Betancourt 1998).

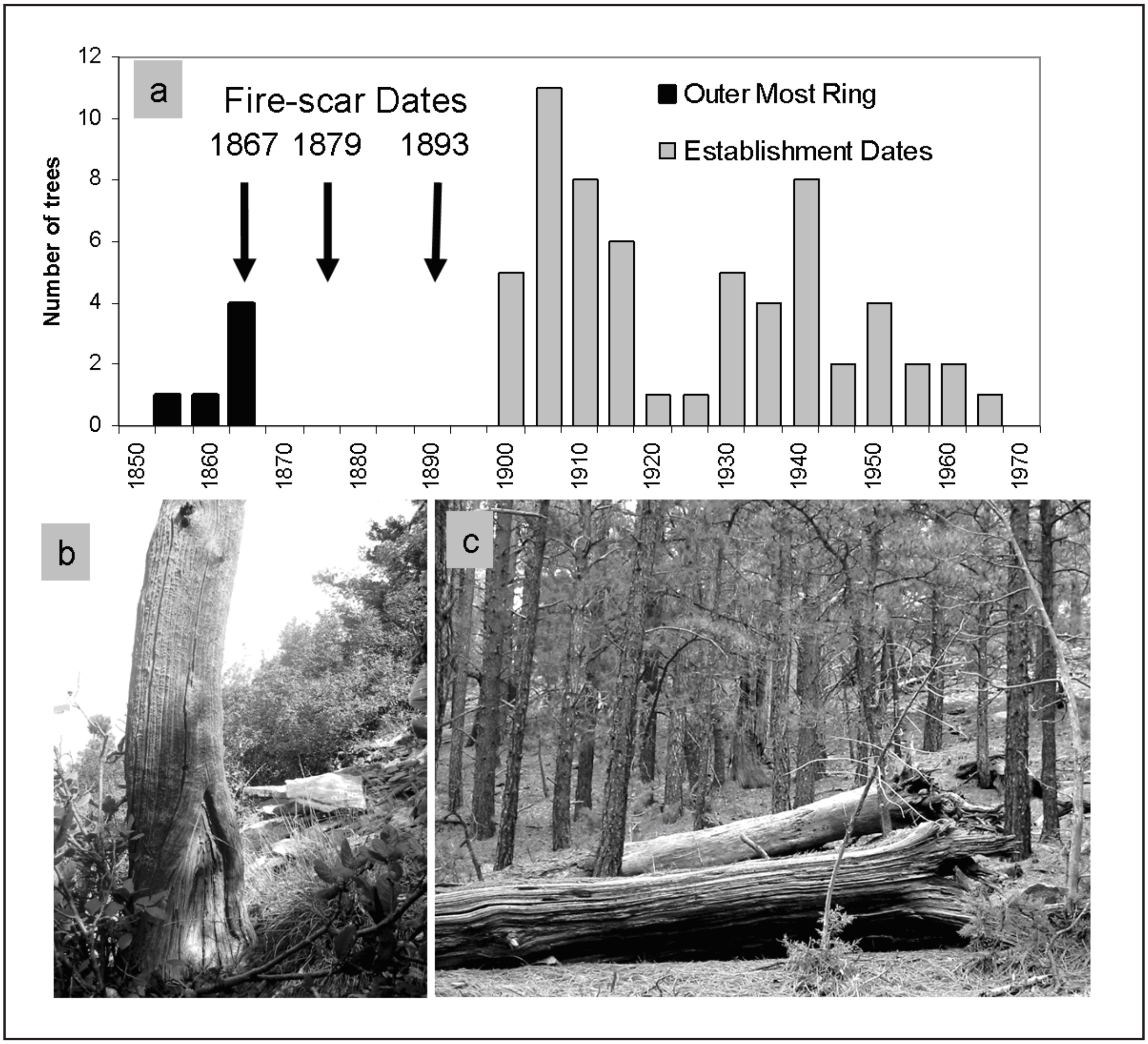

Figure 6. Multiple evidence of a stand-replacing fire in 1867 in stands just south of Rincon Peak in southeastern Arizona. (a) Evidence include (1) fire-scars recorded by two surviving trees, (2) death-dates and outer most rings just prior to 1867, and (3) even-aged ponderosa pine structure following the last fire in 1893. Even-aged forest structure is from two age-structure plots located within fire history plots 13 and 18. After the 1867 crown fire forests in south-facing aspects were converted to oak-shrub fields (b) while north-facing aspects have regenerated with even-aged pine forests (c).

Fire frequency changes observed on Rincon Peak after 1763 are dissimilar to general regional patterns; however, climate still may have played an important role in these fire regime changes. For instance, across large spatial scales a subset of studies have reported distinct fire frequency changes referred to as the late eighteenth early nineteenth transition (LEENT) period (Grissino-Mayer *et al*. 2000). Relatively long fire intervals or "fire gaps" have been documented at regional and hemispheric scales during this time (Veblen *et al*. 2000, Kitzberger *et al*. 2001, Stephens *et al*. 2003, Sibold and Veblen 2006, Skinner *et al* 2008). Kitzberger *et al*. (2001) showed that during the LEENT period, ENSO amplitude was reduced, potentially decreasing the magnitude or frequency of wet and dry oscillations, which would have limited fuel production during wet years and fire ignition and spread during subsequent dry years. Additionally, Grissino-Mayer *et al*. (2004) proposed that a reduction of lightning during the LEENT period might have resulted in limited fire ignitions. Fire frequency patterns on Rincon Peak were highly dependent on lightning ignitions and wet and dry climate cycles. Therefore, global climate changes during LEENT could have been a major contributor to the striking fire frequency changes observed on Rincon Peak after 1763.

The Influence of Local Fuel Continuity on Fire Patterns

Although fire frequency changes on Rincon Peak were probably at least partly climate related, it is also clear that global climate changes during the LEENT period did not cause similar fire frequency changes at all locations. For instance, despite experiencing the same climate changes during the LEENT period, forests on nearby Mica Mountain or in the Santa Catalina Mountains did not experience drastic fire regime changes coeval to those that occurred at Rincon Peak (Iniguez 2008; Calvin Farris, National Park Service, personal communication). Fire histories in neighboring mountains, however, did change from frequent small fires prior to 1819 to less frequent but larger fires afterwards (Swetnam *et al*. 2001, Iniguez 2008). The lack of synchrony in annual to decadal fire patterns between Rincon Peak and nearby mountain ranges suggests that fire regime changes on Rincon Peak were caused at least partly by local factors.

Some of the factors that distinguish the pine forest on Rincon Peak from others are that forests on Rincon Peak are relatively small and isolated by rugged topography. The dissected and highly variable topography of Rincon Peak produces a landscape of fragmented fuel conditions compared to other, more continuous ponderosa pine and dry mixed conifer forests in the southwest. As a result, forests on Rincon Peak often border non-forested areas such as steep talus slopes, rock outcrops, and chaparral (Figure 1). To the east, the study area borders steep (>40º) slopes sparsely vegetated with oak shrubs and stringers of Arizona cypress (*Cupressus arizonica*). To the west, there are steep rock escarpments with sparse vegetation, flanked by dense fields of chaparral (Figure 1). North of the study area, the topography is broken, with areas of dense oak and pinyon-juniper forest as well as some barren rock faces. Some fires probably spread from these areas into the Rincon Peak forests. It is unlikely, however, that this occurred frequently enough to support the history of frequent fires (i.e., every 10 yr to 15 yr) recorded on Rincon Peak prior to 1763. Instead, it is more likely that ignitions came primarily from local lightning strikes and from fires spreading upslope from the grassy woodlands at the southern edge of the study area. South of Rincon Peak the topography is less rugged and fuels transition from grasslands to oak woodlands and into pine forests (Figure 1). These ignition and fuel differences likely contributed to the fire history differences during certain time periods (i.e., 1763-1819).

Fire history differences between the northern and southern parts of Rincon Peak likely were also related to stand-replacing fires that changed landscape fuel continuity over time. The forests in the northern and southern parts of the study area are connected by a narrow strip of forest on a saddle between two areas of exposed rock (Figure 1). We suspect that climate changes during the LEENT period led to longer intervals between fires, greater fuel accumulation, and more severe fires that created shrub fields. This is important because open forest conditions promote grass fuels that serve as an effective carrier of frequent surface fires. In contrast, shrub fields typically lack continuous grass cover, and the shrub layer will usually not carry fire at less than multiple-decadal intervals (Wright and Bailey 1982). Therefore, we interpret that prior to 1763, forests south of the peak were more extensive and surface fires spread unimpeded throughout the study area. The fire corridor between the north and south areas was altered by a stand-replacing fire in either 1763 or 1775 that converted pine forests to shrub fields, which impeded widespread fires in subsequent years.

The Cumulative Influence of Climate and Local Factors on Fire Patterns

Longer fire intervals (i.e., >30 yr) and evidence of stand-replacing fires like those found in the Rincon Peak fire chronology are not typical for southwestern ponderosa pine forests. However, at least two other sites with similar variable fire regimes have been documented in this region. For example, in the Animas Mountains, Swetnam *et al*. (2001) found evidence of stand-replacing fires and fire intervals as long as 32 yr (1825-1857). In Rhyolite Canyon in the Chiricahua Mountains, Barton *et al*. (2001) documented a single 50 yr fire interval (1800-1850). Elsewhere, other studies have found similar results. For example, in a ponderosa pine forest in central Colorado (Brown *et al*. 1999), there was a 128 yr period without widespread fires (1723-1851) although some localized fires were recorded. Similarly, Stephens *et al*. (2003) documented a 40 yr fire interval (1790-1830) in the Sierra San Pedro Martir in Baja California, Mexico.

The four chronologies mentioned above share several characteristics that could explain the patterns observed on Rincon Peak. First, all of these studies documented long fire intervals within approximately the same time period encompassing or within the LEENT. This suggests climate (e.g., ENSO variations) may have been a contributing factor for the lengthening of fire free intervals at this time. Second, these studies are all from sites with rugged topography and complex fuel arrangements, which reflects the importance of landscape fuel continuity and fire spread. In addition, Rincon Peak and the Animas Mountains also share a stand-replacing fire component that probably affected fuel continuity. The physical similarities shared by forests with variable-fire regimes indicate that these landscapes were more susceptible to climatic changes compared to forested landscapes with gentler topography and more continuous fuels.

The striking cessation of landscape fires (i.e., fires that scarred ≥2 plots) between 1819 and 1867 on Rincon Peak likely resulted from a combination of regional and local factors. Climate changes during the LEENT period may have affected lightning occurrence and inter-annual moisture variability, both of which could have resulted in longer fire intervals, a buildup of fuels, and eventually to relatively more severe fires. Subsequent shrub establishment may have disrupted continuous grass fuels and thereby limited fire spread for a period of time. In forested landscapes with limited possibilities for fire spread like Rincon Peak, the consequences of such climatic variations were sufficient to isolate forested areas dependent on fire spread from relatively distant locations. On the other hand, forest landscapes with gentler topography and continuous flammable fuels (e.g., grassy understories in open forests) such as those on other mountain ranges in the area were less affected.

Conclusion and Management Implications

The southwestern ponderosa pine fire regime model is sometimes discussed as if it were a monolithic pattern of 2 yr to 10 yr intervals, low severity surface fires with no high severity component in any place or at any time. This over-generalization should be replaced with a more nuanced and complete understanding that high severity fire is actually an element of all fire regimes, depending on the scale at which one considers the high severity burning. Even prescribed burning can occasionally cause the torching of single tree or small groups of trees. This however does not mean that all surface fire regimes should actually be considered variable fire regimes. In the case of ponderosa pine fire regimes, there is increasing evidence for high severity fires (of some unclear size distribution), particularly in steep isolated landscapes, such as Rincon Peak, and in the northern range of this species where longer (multi-decade) intervals were typical (e.g., Brown *et al*. 1999). It is important, however, that fire historians and managers do not over-generalize ponderosa pine fire regimes (even in the southwest), or jump to conclusions that crown fires were always an important element of these forests everywhere.

Based on the results on Rincon Peak and observations elsewhere in southern Arizona and New Mexico, we hypothesize that under certain climate conditions (e.g., LEENT), ponderosa pine forests in some locations (e.g., landscapes with dissected topography and fragmented fuels) may become vulnerable to longer fire intervals and severe fires occurring over relatively small patches (i.e., <100 ha). Conversely, the same climatic changes produced little or no changes to fire regimes in other continuous ponderosa pine forest landscapes. Therefore it is important to note the fire regime changes observed on Rincon Peak and other similar landscapes were contingent on a combination of regional climate and local landscape factors. As such, the variable fire regime found on Rincon Peak does not contradict the results of studies that have documented surface fire regimes in pine forests elsewhere. In fact, these results show that although variable fire regimes occurred in southwestern ponderosa pine forests, they were restricted to certain locations and times.

Small remote forests with rugged topography like Rincon Peak are common throughout the western USA. The remoteness of these areas creates logistical challenges for both researchers and managers resulting in little knowledge about their ecological importance. Our findings suggest that past climatic changes had a greater impact on small fragmented ponderosa pine forest landscapes compared to larger continuous landscapes. Given the projected climate changes, the rich biodiversity harbored in these steep isolated landscapes will be critical habitat in the migration of species and should therefore be considered high conservation priority. Additionally, a century of fire exclusion is leading to severe fires that are transforming extensive forests into fragmented landscapes with isolated forest patches in a matrix of shrub fields. In this sense, past fire regimes in rugged topographic settings such as Rincon Peak may provide an analog of what could be in store for many forested areas in the semi-arid west.

Managers faced with the challenge of preserving the wilderness character of remote isolated landscapes like Rincon Peak have two alternatives: wildfire or wildland fire use (prescribed fires). Both options will likely include patches of stand-replacing fires; however, the fire use option has a greater chance of limiting the extent of crown-fire patches because managers can, to a greater degree, choose the places and times when such events are allowed. Stand-replacing forest fires occurred historically on Rincon Peak; however, they were limited to less than approximately 60 ha patches. The lack of fire (surface or crown) on this part of the Rincon Mountains for many decades has probably led to a greater connectivity and density of fuels than has existed for many centuries, increasing the likelihood of exceptionally extensive crown fires during future droughts. The threat of losing these pine forests to a large crown fire warrants the use of prescribed fire as a means of conserving natural processes and perpetuating these forests for future generations.

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LITERATURE CITED

Agee, J.K. 1993. Fire ecology of Pacific northwest forests. Island Press, Washington, D.C., USA.

Agee, J.K., and C.N. Skinner. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management 211: 83-96.

Allen, C.D. 2002. Lots of lightning and plenty of people: an ecological history of fire in the upland southwest. Pages 143-193 in: T.R. Vale, editor. Fire, native peoples, and the natural landscape. Island Press, Washington, D.C., USA.

Allen, C.D., M. Savage, D.A. Falk, K.F. Suckling, T.W. Swetnam, T. Schulke, P.B. Stacey, P. Morgan, M. Hoffman and J.T. Klingel. 2002. Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. Ecological Applications 12: 1418-1433.

Arno, S.F., and K.M. Sneck. 1977. A method of determining fire history in coniferous forests of the mountain west. USDA Forest Service General Technical Report INT-GTR-42.

Barton, A.M., T.W. Swetnam, and C.H. Baisan. 2001. Arizona pine (*Pinus arizonica*) stand dynamics: local and regional factors in a fire-prone Madrean gallery forest of southeast Arizona, USA. Landscape Ecology 16: 351-369.

Beaty, R.M., and A.H. Taylor. 2001. Spatial and temporal variation of fire regimes in a mixed conifer forest landscape, southern Cascades, California, USA. Journal of Biogeography 28: 955-966.

Beaty, R.M., and A.H. Taylor. 2008. Fire history and the structure and dynamics of a mixed conifer forest landscape in the northern Sierra Nevada, Lake Tahoe Basin, California, USA. Forest Ecology Management 255: 707-719.

Baisan, C.H., and T.W. Swetnam. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, USA. Canadian Journal of Forest Research 20: 1559-1569.

Baisan, C.H., and T.W. Swetnam. 1995. Management implications of historical fire occurrence pattern in remote mountains of southwest New Mexico and northern Mexico. Pages 153-156 in: J.K. Brown, R.W. Mutch, C.W. Spoon, and R.H. Wakimoto, technical coordinators. Proceedings: symposium on fire in wilderness and park management. USDA Forest Service General Technical Report GTR-INT-320.

Brown, P.M., M.R. Kaufmann, and W.D. Shepperd. 1999. Long-term, landscape pattern of past fire events in a montane ponderosa pine forest of central Colorado. Landscape Ecology 14: 513-532.

Brown, P.M., M.W. Kaye, L.S. Huchaby and C.H. Baisan. 2001. Fire history along environmental gradients in the Sacramento Mountains, New Mexico: influences of local patterns and regional processes. Ecoscience 8: 115-126.

Cook, E.R., D.M. Meko, D.W. Stahle, and M.K. Cleaveland. 1999. Drought reconstruction for the continental United States. Journal of Climate 12: 1145-1162.

Cooper, C.F. 1960. Changes in vegetation, structure and growth of ponderosa pine since white settlement. Ecological Monographs 30: 129-164.

Crimmins, M.A., and A.C. Comrie. 2004. Interactions between antecedent climate and wildfire variability across south-eastern Arizona. International Journal of Wildland Fire 13: 455-466.

Danzer, S.R., C.H. Baisan, and T.W. Swetnam. 1996. The influence of fire and land-use history on stand dynamics in the Huachuca Mountains of southeastern Arizona. Pages 265-270 in: P. F. Ffolliott, L.F. DeBano, M.B. Baker, G.J. Gottfried, G. Solis-Garza, C.B. Edminster, D.G. Neary, S. Allen, and R.H. Hamre, technical coordinators. Effects of fire on Madrean Province ecosystems: a symposium proceeding. USDA Forest Service General Technical Report RM-GTR-289.

Dieterich, J.H., and T.W. Swetnam. 1984. Dendrochronology of a fire scarred ponderosa pine. Forest Science 30: 238-247.

Finney, M.A., C.W. McHugh, and I.C. Grenfell. 2005. Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. Canadian Journal of Forest Research 35: 1714-1722.

Floyd, M.S., W.H. Romme, and D.D. Hanna. 2000. Fire history and vegetation pattern in Mesa Verde National Park, Colorado, USA. Ecological Applications 10: 1666-1680.

Fulé, P.Z., J.E. Crouse, T.A. Heinlein, M.M. Moore, W.W. Covington, and G. Verkamp. 2003. Mixed severity fire regime in a high-elevation forest of Grand Canyon, Arizona, USA. Landscape Ecology 18: 465-486.

Fulé, P.Z., T.A. Heinlein, W.W. Covington, and M.M. Moore. 2003. Assessing fire regimes on the Grand Canyon landscapes with fire-scar and fire record data. International Journal of Wildland Fire 12: 129-145.

Grissino-Mayer, H.D. 1995. Tree-ring reconstructions of climate and fire history at El Malpais National Monument, New Mexico. Dissertation. University of Arizona,Tucson, USA.

Grissino-Mayer, H.D., and T.W. Swetnam. 2000. Century-scale climate forcing of fire in the American southwest. Holocene 10: 213-220.

Grissino-Mayer, H.D., W.H. Romme, M.L. Floyd, and D.D. Hanna. 2004. Climatic and human influences on fire regime of the southern San Juan Mountains, Colorado, USA. Ecology 85: 1708-1724.

Heyerdahl, E., L.B. Brubaker, and J.K. Agee. 2001. Spatial controls of historical fire regimes: a multiscale example from the interior west, USA. Ecology 82: 660-678.

Iniguez, J.M., T.W. Swetnam, and S.R. Yool. 2008. Topography affected landscape fire history patterns in southern Arizona, USA. Forest Ecology and Management 256: 295-303.

Jenkins, S.E. 2007. Fire-related deposition at Kendrick Mountain, Arizona: characterization and implications for fire history reconstructions. Thesis. Northern Arizona University, Flagstaff, USA.

Kitzberger T., T.W. Swetnam, and T.T. Veblen. 2001. Inter-hemispheric synchrony of forest fires and the El Niño-Southern Oscillation. Global Ecology and Biogeography 10: 315-326.

Liu, C.J. 1986. Rectifying radii on off-center increment cores. Forest Science 32: 1058-1061.

Mermoz, M., T. Kitzberger, and T.T. Veblen. 2005. Landscape influences on occurrence and spread of wildfires in Patagonian forests and shrublands. Ecology 86: 2705-2715.

Morgan, P., C. Hardy, T.W. Swetnam, M. G. Rollins, and D.G. Long. 2001. Mapping fire regimes across time and space: understanding coarse and fine-scale patterns. International Journal of Wildland Fire 10: 329-342.

Morino, K.A. 1996. Reconstruction and interpretation of historical patterns of the fire occurrence in the Organ Mountains, New Mexico. Thesis. University of Arizona, Tucson, USA.

Niering, W.A., and C.H. Lowe. 1984. Vegetation of the Santa Catalina Mountains: community types and dynamics. Vegetation 58: 30-58.

Romme, W.H. 1980. Fire history terminology: Report of the ad hoc committee. Pages 135-137 in: M.A. Stokes, and J.H. Dieterich, editors. Proceeding of the fire history workshop. USDA Forest Service, General Technical Report RM-81.

Rothermel, R.C. 1983. How to predict the spread and intensity of wildfires. USDA Forest Service General Technical Report GTR-INT-143.

Sibold, J.S., and T.T. Veblen. 2006. Relationships of subalpine forest fire in the Colorado Front Range with interannual and multidecadal-scale climatic variation. Journal of Biogeography 33: 833-842.

Skinner, C.N., J.H. Burk, M.G. Barbour, E. Franco-Vizcaino, and S.L. Stephens. 2008. Influences of climate on fire regimes in montane forests of north-western Mexico. Journal of Biogeography 35:1436-1451.

Stephens, S.L., C.N. Skinner, and S.J. Gill. 2003. Dendrochronology-based fire history of Jeffrey pine-mixed conifer forests in the Sierra San Pedro Martir, Mexico. Canadian Journal of Forest Research 33: 1090-1101.

Stokes, M.A., and T.L. Smiley. 1968. Introduction to tree-ring dating. University of Chicago Press, Illinois, USA.

Swetnam, T.W., and J.L. Betancourt. 1990. Fire-Southern Oscillation relations in the southwest United States. Science 249: 1017-1020.

Swetnam, T.W., and C.H. Baisan. 1996. Historical fire regimes patterns in the southwest United States since AD 1700. Pages 15-36 in: C.D. Allen, editor. Fire effects in southwest forest. Proceedings of the 2nd La Mesa fire symposium. USDA Forest Service General Technical Report RM-GTR-286.

Swetnam, T.W., and C.H. Baisan. 2003. Tree-ring reconstructions of fire and climate history in the Sierra Nevada and southwestern United States. Pages 158-195 in: T.T. Veblen, W. Baker, G. Montenegro, and T.W. Swetnam, editors. Fire and climatic change in temperate ecosystems of the western Americas. Ecological Studies Volume 160. Springer, New York, USA.

Swetnam, T.W., and J.L. Betancourt. 1998. Mesoscale disturbance and ecological response to decadal climate variability in the American southwest. Journal of Climate 11: 3128-3147.

Swetnam, T.W., C.H. Baisan, and M.J. Kaib. 2001. Forest fire histories of the sky islands of La Frontera. Pages 95-123 in: G.L. Webster, and C.J. Bahre, editors. Changing plant life of La Frontera: observations on vegetation in the United States/Mexico borderlands. University of New Mexico Press, Albuquerque, USA.

Swetnam, T.W., C.D. Allen, and J.L. Betancourt. 1999. Applied historical ecology: using the past to manage for the future. Ecological Applications 9: 1189-1206.

Taylor, A.H. 2000. Fire regime and forest changes in the mid and upper montane forest of the southern Cascades, Lassen Volcanic National Park, USA. Journal of Biogeography 27: 87-104.

Taylor, A.H., and C.N. Skinner. 1998. Fire history and landscape dynamics in a late successional reserve, Klamath Mountains, California, USA. Forest Ecology and Management 111: 285-301.

Taylor, A.H., and C.N. Skinner. 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. Ecological Applications 13: 704-713.

Touchan, R., C.D. Allen, and T.W. Swetnam. 1996. Fire history and climatic patterns in ponderosa pine and mixed conifer forests in the Jemez Mountains, northern New Mexico. Pages 33-46 in: C.D. Allen, editor. Fire effects in southwestern forest: proceeding of the second La Mesa Fire symposium. USDA Forest Service General Technical Report RM-GTR-286.

Turner, M.G. 1989. Landscape ecology: the effects of pattern on scale. Annual Review of Ecological Systems 20: 171-197.

Veblen, T.T., T. Kitzberger, and J. Donnegan. 2000. Climatic and human influence on fire regimes in ponderosa pine forests in the Colorado Front Range. Ecological Applications 10: 1178-1195.

Villanueva-Diaz, J. 1996. Influence of land-use and climate on soils and forest structure in mountains of the southwestern United States and northern Mexico. Dissertation. University of Arizona, Tucson, USA.

Whittaker, R.H., and W.A. Niering. 1968. Vegetation of the Santa Catalina Mountains, Arizona. Journal of Ecology 56: 523-544.

Wright H.A., and A.W. Bailey. 1982. Fire ecology: United States and southern Canada. John Wiley and Sons, New York, New York, USA.