

Fire Histories From Pine-Dominant Forest in the Madrean Archipelago

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Abstract—The pine-dominated woodlands and forests of the Sky Islands typically sustained surface burns about once per decade until the turn of the 19th to the 20th centuries, when livestock grazing and organized fire suppression effectively ended this centuries-long pattern. Fire scar chronologies from 31 sites in 10 mountain ranges illustrate this history. By combining elevational transects of fire scar chronologies in three of the mountain ranges it is possible to visualize the temporal changes in widespread fire occurrence. Combining all 31 chronologies for the region, it is evident that there was a high degree of synchrony in fire occurrence that must have been related to broad-scale climate variations. Comparisons of synchronous fire years with a regional tree-ring reconstruction of precipitation confirm the importance of wet/dry seasonal and inter-annual climate patterns in promoting widespread burning.

Introduction

For many centuries fire and smoke were as regular in the Sky Islands as the Southwest monsoon. Indeed, fiery columns of smoke rising from the mountains were as normal a sight in May and early June as watery cumulous clouds in late June and July. Then in the late nineteenth century, large numbers of American settlers arrived with their enormous herds of livestock. Thousands of sheep, goats, cows, and horses clipped the bunch grasses and pounded trails and driveways across the landscape. This disruption of surface fuels effectively ended the centuries-long pattern of free spreading surface fires (Leopold 1924). Tree-ring studies from dozens of forests and woodland sites in the Sky Islands clearly show these patterns of change. The timing of the last widespread fire in any given mountain range closely coincides with the first arrival of large livestock herds in that particular range (Swetnam et al. 2001; Swetnam and Baisan 2003). At about the same time that livestock numbers decreased in the early 20th century, government foresters adopted fire suppression as a primary mission (Pyne 1982).

Although the human-caused changes to fire regimes in the late 19th century—from frequent, widespread surface fires to nearly total fire exclusion—is very obvious in tree-ring and documentary records, we are less certain about the causes and controls of fire regime changes before circa 1880. Undoubtedly, both climatic variability and human uses of fire were responsible for fire frequency changes, but what were their relative roles and importance? The answer depends upon the time and the place. In some places and times, American Indians greatly modified ecosystems, and in other places and times the role of humans in controlling past fire regimes was probably non-existent or negligible (Swetnam et al. 2001; Allen 2002). Even in those places and times where people were using fire frequently and extensively, it still is likely that climatic variations were important in controlling, to some degree, the variations in local

to regional fire regimes. In fact, the fire scar record from the broader Southwest, as well as the Sky Islands, confirms this interpretation.

In this paper I illustrate three tree-ring based fire histories from elevational transects in ponderosa pine and mixed conifer forests of the Madrean Archipelago. These case studies exemplify the kinds of variations and changes that occurred in surface fire regimes over the past 300 to 500 years. I also summarize fire history patterns in a total of 31 sites in 10 Sky Island Mountain Ranges (figure 1), and the linkages of wet and drought years to fire occurrence from 1640 to 1900. Both human and climatic influences are evident in these fire chronologies.

Three Examples of Surface Fire Histories Along Elevational Transects

Over the past 20 years we have sampled hundreds of fire scarred trees in dozens of sites across the Sky Islands region. “Sites” in these cases are forest stands where fire scarred trees were collected over areas typically ranging from about 10 to 100 hectares. In some cases the fire scar records from multiple sites were combined at broader scales (100 to 2,000+ ha) to form a single, composite fire scar chronology for a watershed or for the forested area at the top of a Sky Island. Sites typically included 10 to 50 fire scarred trees. Broad composites of multiple sites distributed over large areas typically included 50 to 100+ fire scarred trees. The composite fire chronologies are useful for studying fires that occurred anywhere within the sampled area, as well as widespread fires. The period of time that is well represented by the fire scarred trees usually extends between about AD 1600 and the present, although some sampled trees extend back to AD 1400 or earlier.

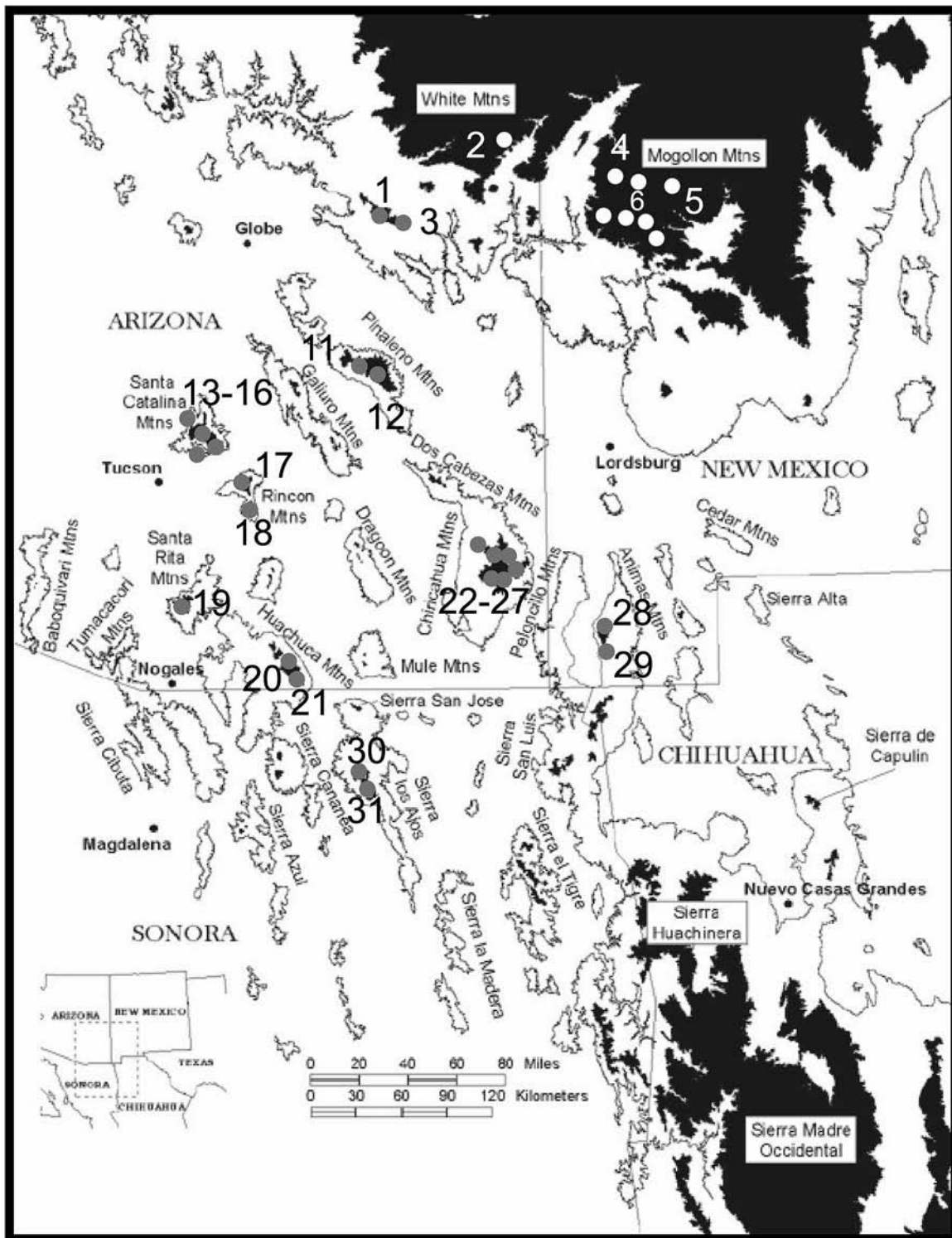


Figure 1—Map of the Madrean Archipelago region, with numbered locations of fire scar collection sites and chronologies.

The collection sites are generally within pine-dominated forests and woodlands. These include pine-oak mixtures at the lowest elevations, pure ponderosa pine stands at middle elevations, and mixed conifer at the highest elevation stands. Ponderosa pine (*Pinus ponderosa*) or Arizona pine (*Pinus arizonica*) was the most common, dominant over story species in these stands, and the most common fire scarred tree sample. Other pine species included Southwestern white pine (*Pinus strobiformis*), Chihuahua pine (*Pinus leiophylla*), and Apache

pine (*Pinus engelmannii*). The mixed conifer stands sometimes contained pine species only as a minor component (Douglas-fir, [*Pseudotsuga menziesii*], and white fir, [*Abies concolor*], were typically dominant in these cases). In a few cases the uppermost elevation sites (e.g., the Gila [or Mogollon], and Piñaleno Mountains) were adjacent to spruce-fir stands.

The collection sites were selected based upon a broad range of considerations. Of course, the presence of fire scarred trees was a primary factor, which naturally limits these

reconstructions to conifer forests. Evergreen oaks in the borderlands area are generally not suitable for tree-ring analyses because the rings are not annual, or are very difficult to identify. In general, the mountain ranges and watersheds where we sampled fire scarred trees were selected because they were of interest to fire management programs in Federal agencies and conservation organizations, and we had financial and logistical support from these agencies to carry out studies in these areas. Accessibility, travel routes, and permission to sample with chain saws or handsaws also partly determined our sampling strategies. Within the study areas we attempted to collect samples from spatially dispersed locations, and often from a range of elevations, aspects, and forest conditions. Although the sites and trees sampled were not randomly located, they were often systematically placed so that some general representation of the areas and conditions were likely to be captured (see Swetnam and Baisan [1996] for additional discussion of sampling strategies and rationale). One of the systematic sampling approaches we used was to collect fire scarred trees along elevational transects (figure 2).

Graphical depictions of the composite fire scar chronologies are very useful for visualizing the temporal and spatial changes in surface fire regimes (figure 2). When the individual tree records, and sites are arranged along an elevational transect on the y-axis, it is sometimes possible to discern fire frequency differences and similarities among sites. The three elevation transects illustrate several common patterns seen elsewhere in the Sky Islands and other pine-dominant forests of the Southwest (see also Barton et al. 2001 for another example of an elevational transect of fire scar chronologies in the Chiricahua Mountains).

The most obvious pattern is the disruption of the fire regime around the turn of the 19th to the 20th century. Note that the timing differs between the areas, with the last widespread fire in 1904 along the Gila transect, 1917 along the Chiricahua transect (but with a long interval preceding this back to 1894), and 1900 along the Santa Catalina transect (figure 2). As previously mentioned, the timing of the surface fire regime disruptions tends to correspond very well (usually to within a few years) with the first introduction of large numbers of sheep, goats, cows, and/or horses in these specific areas. The last widespread fires, as recorded by the fire scars, was confirmed in all three of these cases by independent documentary sources mentioning the fires (e.g., newspaper accounts and government documents; see Swetnam et al. 2001 for detailed historical references and examples).

The other most obvious pattern evident in these broad fire chronology comparisons is the high fire frequency before circa 1900, but highly variable intervals between fire events. In general, at the scales of these transects (see caption in figure 2), there was typically a fire burning somewhere within the general area about once every 2 to 4 years. However, it is important to bear in mind that this does not mean that all of these fires were widespread. In fact, many fires were not widespread. Between 1650 and 1900, 22% of fires were recorded as fire scars only on single trees on the Gila, 43% on the Chiricahua transect, and 36% on the Santa Catalina transect. This pattern is not surprising because lightning ignition rates within these

mountain ranges can be quite high, but most fires typically do not spread beyond the tree that was struck, or a few hectares. A recent examination of lightning fire ignition rates over the 20th century in the Rincon Mountains, for example, indicates that the frequency of any fire occurring *anywhere* in the conifer forests on the mountain was at least 1 fire per year (Farris and others, unpublished manuscript).

Of greater interest, and perhaps greater ecological importance, are the relatively widespread fire events. These are visible along the fire scar/elevational transects as broadly synchronous events between trees and sites (figure 2). The actual extent of these events is unknown because many of these fires probably burned far beyond the areas we sampled, and they probably did not burn all areas between the sampled trees. Moreover, the spatial distribution of the trees we sampled was non-random and non-uniformly distributed. Likewise, the time coverage varied from location to location because of different spans of time, and quality (completeness) of the fire record as represented by the sampled trees. Hence, these records have various spatial and temporal biases that limit their direct interpretation or extrapolation to quantitative amounts of area burned, or for detailed mapping of the spatial patterns of fire events within sites. These limitations and uncertainties of fire scar records have been highlighted in recent papers (Minnich et al. 2000; Baker and Ehle 2001), but Fulé et al. (2003) and Stephens et al. (2003) present some countering evidence and perspectives. Falk (2004; Falk and Swetnam 2003) also evaluates the dependencies of fire frequency estimates upon sampled area and sample size (numbers of fire scarred trees included in chronologies).

Despite the uncertainties that exist in fire scar chronologies (whether sampled systematically or randomly), there is increasing evidence that relatively widespread fire events can be completely inventoried by fire scar collections (Fulé et al. 2003; Swetnam and Baisan 2003; Falk 2004; Farris and others, unpublished manuscript). In particular, "filtered" fire events, which are identified as those events recorded on a minimum number and/or percentage of fire scarred trees, can provide complete, or nearly complete, chronologies of relatively widespread fires within sampled areas. We have confirmed this interpretation in numerous instances where documented 20th century fires were well represented in the fire scar record. For example, the cases previously mentioned of the last widespread fires in the Gila, Chiricahua, and Santa Catalina Mountains (figure 2) correspond well with the historic records, including a few recent, large fires (and see examples described in Swetnam et al. 2001, the papers cited therein; and Farris and others, unpublished manuscript).

As mentioned above, even widespread fire events, as interpreted from broadly synchronous fire scar dates within sites, should not be interpreted to have burned all areas between fire-scarred trees. Fire intensity, severity, and completeness of burning of fuels tend to be highly variable at all spatial scales. Even in the most widespread, low intensity surface fire, or in the most widespread and high severity crown fire, there is almost always some degree of "patchiness," where fuels are left unburned or only partially burned. Furthermore, it should be recognized that fire histories of all kinds have some degree of bias and inaccuracy, including those based on mapped

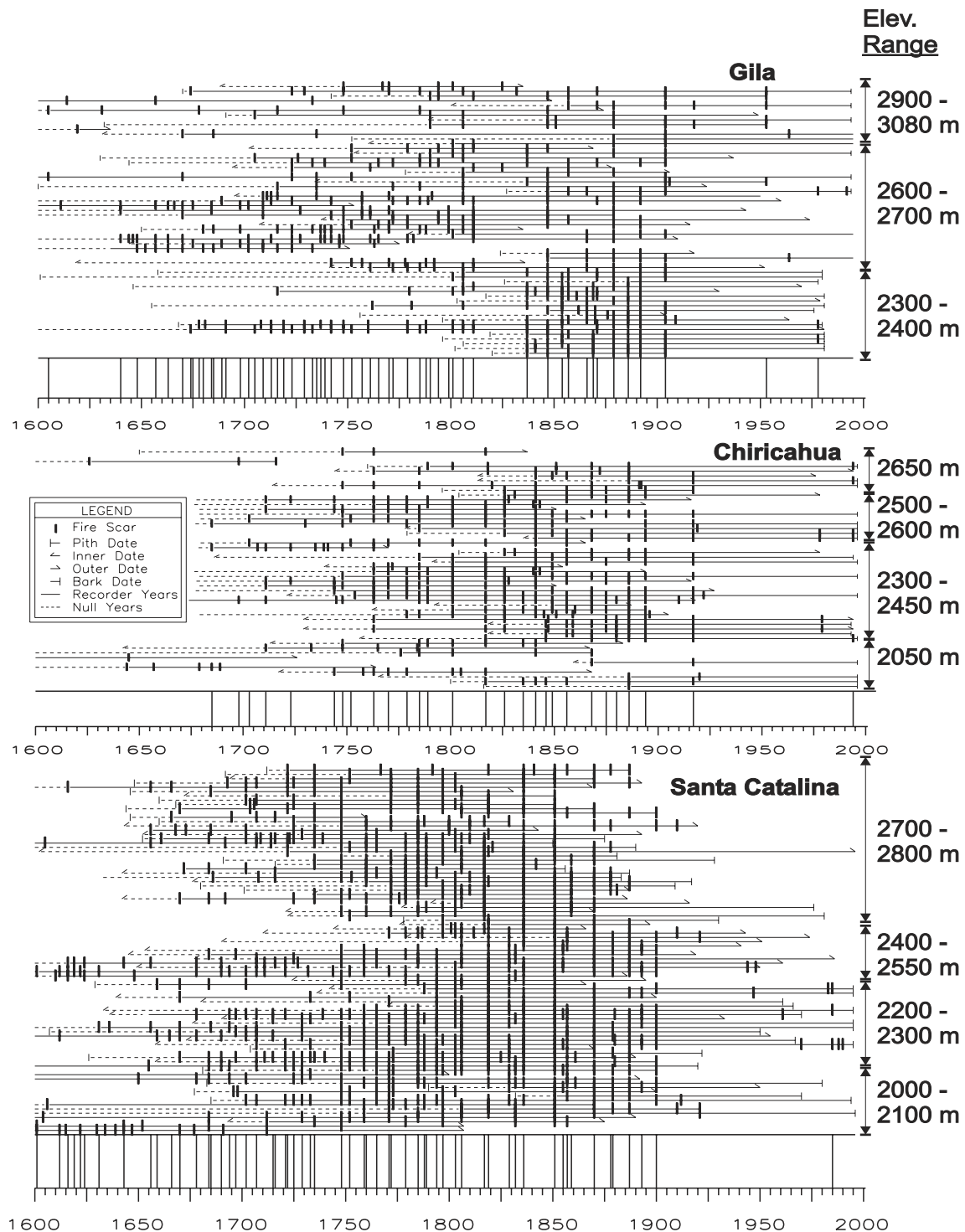


Figure 2—Fire scar chronologies from elevational transects in the Gila Wilderness, New Mexico (sites 7-10 in figure 1), the Chiricahua Mountains, Arizona (sites 24-27), and the Santa Catalina Mountains, Arizona (sites 13-16). The Gila transect sites are near the headwaters of the West Fork, extending from Langstroth Mesa to Snow Park. The Chiricahua transect sites are within the Mormon Canyon watershed, extending up to Anita Park. The Santa Catalina transect sites extend along the Mt. Lemmon Highway, from Bear Canyon to Mt. Lemmon. The Gila transect spans an elevation range of approximately 2,300 m to 3,080 meters and a linear distance of about 9 km. The Chiricahua transect spans an elevation range of approximately 2,050 m to 2,650 meters and a linear distance of about 5 km. The Santa Catalina transect spans an elevation range of approximately 2,100 m to 2,800 meters and a linear distance of about 13 km. The horizontal lines in each transect graph are the records represented by individual fire scarred trees, and the vertical tick marks are the fire dates recorded in those sites.

perimeters of fires from direct observations and documents (e.g., fire atlases, aerial photos, or satellites) or stand age structure evidence (Finney 1995; Rollins et al. 2001; Morgan et al. 2001). It is also likely that fire scar-based estimates of location and timing of past fires are, in some cases, more accurate than estimates based on other methods of fire history.

Synchronous fire scar dates on trees distributed across the elevational transects probably represent widespread fires, although it is possible that some of these events were multiple, separate fires that ignited (e.g., by lightning) and spread during the same year. The repeated occurrence of many different fire dates through time that are synchronous on the same trees (e.g., figure 2), however, logically argues that most of these dates were likely widespread fires, rather than separate ignitions.

In general, the widespread fire events along the fire scar transects can be estimated as those that were recorded by 25% or more of the trees (see the vertical lines at the bottom of each chronology chart). This particular percentage (25%) is somewhat arbitrary, but useful at this stage of our understanding and analyses to identify events that were probably widespread along the transects. The means of all intervals between the 25% filtered fire events (from 1650 to 1900) were 10.7 years along the Gila transect, 9.9 years along the Chiricahua transect, and 9.0 years along the Santa Catalina transect.

Regional Fire History and Climate

In contrast to the elevational gradients, synchrony of fire events at the regional (or sub-regional) scale, such as the Madrean Archipelago (figure 1), most likely relates to broad-scale climate variability. This is confirmed in a comparison of the 30 most synchronous fire years between 1640 and 1900 (labeled years in figure 3) and an independently developed tree-ring width reconstruction of November to April precipitation for Arizona Climate Division 7 (figure 4) (Ni et al. 2002). This climate division encompasses the entire Arizona portion of the study area. Note that 23 of the 30 most synchronous fire events fall on dry years (below the mean line), while only 7 fire events fell on wet years (above the mean line). The November to April period compared here is the season proceeding the typical fire season, which usually extends from about April to August, and is the period when most fire scars were formed.

A superposed epoch analysis (SEA) (inset graph in figure 4) also confirms this pattern of the most synchronous fire years among the Sky Islands corresponding with dry preceding winters/springs. The SEA involves computing the mean seasonal (November to April) precipitation amounts during all 30 regional fire years (0 year lag in figure 4), and the mean precipitation during 5 years prior to and 5 years following the regional fire years. The SEA reveals a pattern commonly seen in these types of comparisons of fire occurrence time series and precipitation or drought indices—a correspondence of 1 to 3 wet prior years combined with dry current years is a typical wet/dry cycle that promotes fire synchrony (Baisan and Swetnam 1990; Swetnam and Betancourt 1998). This pattern probably reflects the role of prior year's moisture in promoting

the growth of fine fuels (grasses and tree leaves) and appears to be particularly important in drier, lower elevation woodlands and forests where grass cover was an important factor in fire ignition and spread.

The importance of wet/dry patterns in fire occurrence has been common wisdom among knowledgeable fire managers in the Southwest for some time, but it seems to have been first identified systematically and statistically in our tree-ring fire history work (Baisan and Swetnam 1990; Swetnam and Betancourt 1992). Subsequently, a number of other tree-ring studies found similar patterns in the Southwest (e.g., Grissino-Mayer and Swetnam 2000; Brown et al. 2001; Fulé et al. 2003), and in Colorado (e.g., Veblen et al. 2000; Donnegan et al. 2001). Again, the wet/dry pattern seems to predominate in semi-arid forests and woodlands where grass cover was an important fuel. At higher elevations (e.g., mixed conifer) or higher latitudes the current year drought signal is often stronger, but the lagged, prior year wet conditions typically become unimportant (statistically insignificant) (e.g., Swetnam and Baisan 2003; Veblen et al. 2001; Heyerdahl et al. 2002).

Recent statistical studies of 20th century fire occurrence data (numbers of fires and areas burned) from the whole Western United States have confirmed the existence and statistical importance of lagged, prior year wet conditions to subsequent years increased fire occurrence in the modern period, especially in parts of the Southwest (Westerling et al. 2002, 2003; Westerling and Swetnam 2003; Crimmins and Comrie, in press). These lagged patterns offer useful opportunities for forecasting because statistical models can make use of prior seasons conditions for “predicting” the relative hazard of the up-coming fire season (Westerling et al. 2002; Kitzberger 2002). In fact, such models and forecasts are being used now as one of the tools for long-range fire management planning at regional and continental scales (e.g., see Seasonal Outlook Web pages of the Southwest Greater Area Coordination Center (GACC) at: <http://www.fs.fed.us/r3/fire/swapredictive/swaoutlooks/swaoutlooks.htm> and the Predictive Services group at the National Interagency Fire Center (NIFC) at: http://www.nifc.gov/news/intell_predserv_forms/season_outlook.html).

An important aspect of these wet/dry and synchronous fire occurrence patterns across the Southwest (widespread fire) is that they are fairly robust from the 17th through the 20th centuries, despite the major changes that have occurred in fire regimes, forest conditions and fuels. Westerling and Swetnam (2003) recently applied these wet/dry lagging relationships in a linear regression model, where 20th century area burned statistics (1916-1978) from all lands in the Southwest were “calibrated” with a time series of Palmer Drought Severity Indices (PDSI) for the Southwest over the same time period. The regression model was then applied to a 300 year long tree-ring reconstruction of PDSI (from hundreds of drought sensitive tree-ring width chronologies) for the entire Southwest (Cook et al. 1999) to estimate area burned (using PDSI as the predictor variable) back to AD 1700. The resulting estimates from the modeled area burned correlates well with a composite time series from 63 fire scarred tree chronologies from the Southwest (Spearman's $r = 0.61$, $p < 0.05$, 1700-1900 period).

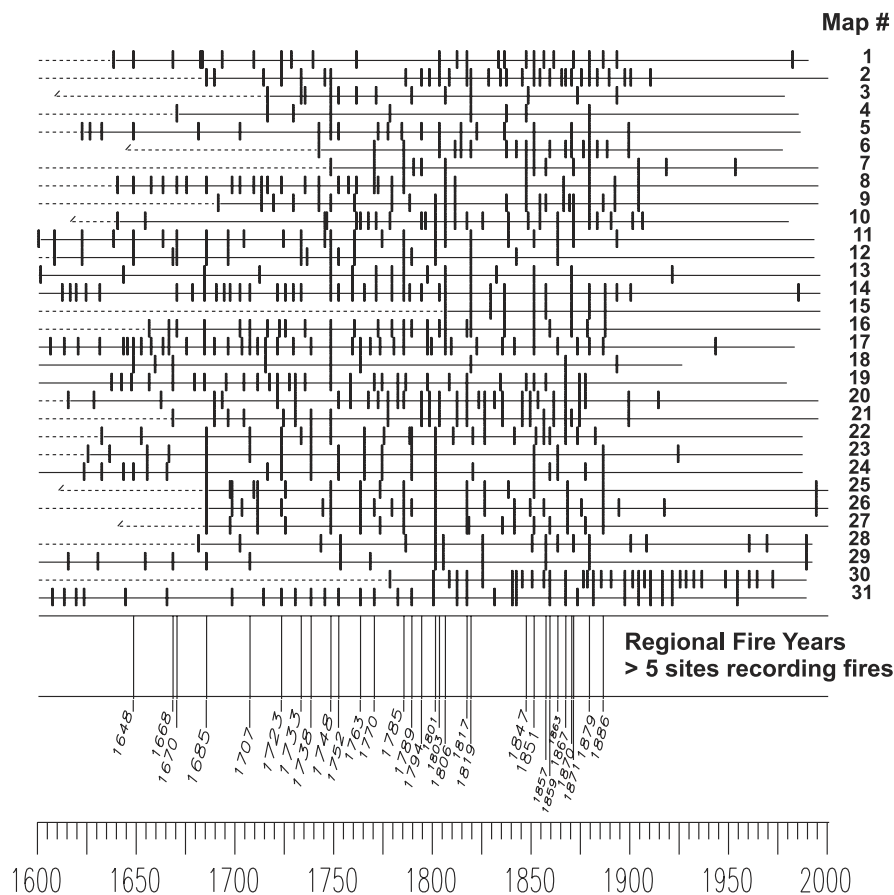


Figure 3—Regional composite fire scar chronology from 31 sites in the Madrean Archipelago (see numbered locations on map in figure 1). The horizontal lines are time spans represented by all fire scarred trees sampled within each site, and the vertical tick marks are fire events recorded by 25% or more of sampled trees (in that year) within each site. The composite vertical lines and dates at the bottom of the graph show the 30 most synchronous fire years among the 31 sites (6 or more sites recording an event).

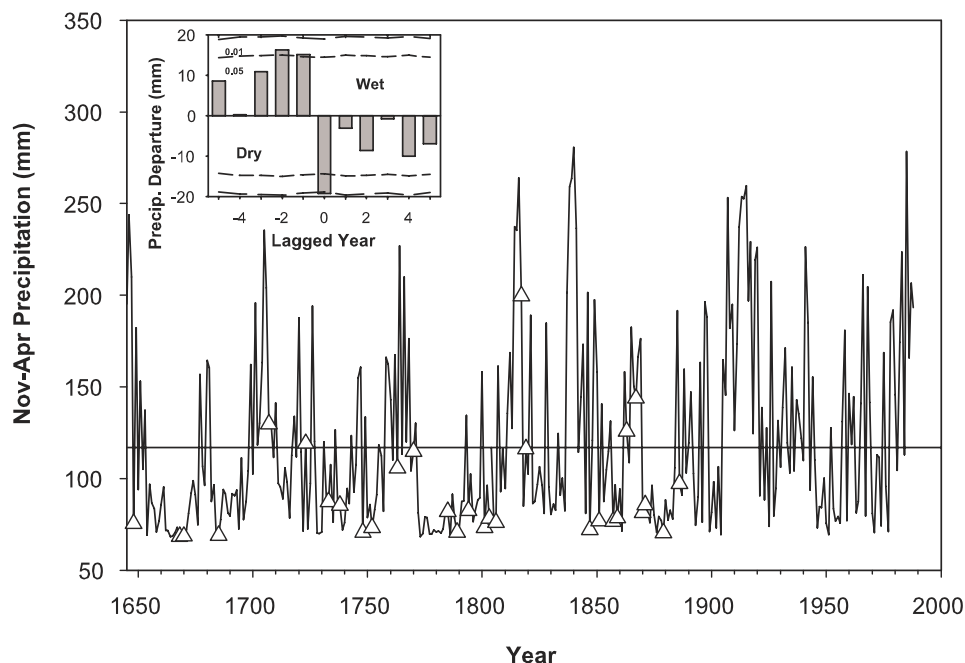


Figure 4—November to April precipitation (1650 to 1989) and the 30 most synchronous fire years among the Sky Islands (labeled dates from 1650 to 1900 in figure 3). The inset graph in upper left corner shows the results of the superposed epoch analysis, with average conditions significantly dry ($p < 0.01$) during the 30 synchronous fire years, and the previous two years significantly wet ($p < 0.05$) (see text for explanation).

These results indicate that inter-annual variations in climate, especially wet and dry patterns, have been important to fire activity in the Southwest and Sky Islands sub-region for hundreds of years. Moreover, expanded studies on these lagging patterns using modern fire occurrence data may provide useful fire hazard forecasting tools. Examples of the use of

these kinds of tools are the Southwest GACC and NIFC Web sites listed above. Another example is the Wildfire Alternatives (WALTER) Web site at: <http://walter.arizona.edu/>

The WALTER model provides a set of spatial analytical tools, combining physical, ecological, and social factors, for assessment of relative fire hazard. The model also includes a

sophisticated climate input that derives in part from and assessment of season to season lags in climate and fire responses (Crimmins and Comrie, in press).

One additional kind of climate-fire pattern that has occurred in the Southwest Sky Islands is worth pointing out. As shown in the SEA (figure 4) and the statistical modeling results (i.e., Westerling and Swetnam 2003) inter-annual climate-fire relations are important, but it is also evident that decadal scale patterns of climate and fire synchrony (and asynchrony) are also important. For example, it is possible to visually detect a change in fire frequency and synchrony during the 1700s and 1800s (figures 2 and 3). Notice that fires tended to be more frequent along the elevational transects during the 1700s, and then there is a change to decreased fire occurrence around 1800. This change is most obvious in the Gila and Santa Catalina transects. A “gap” in fire occurrence—i.e., a long interval between fires—appears in many of the sampled sites along the transects (and elsewhere in the Southwest) during the early 1800s. Note the long interval between synchronous events (>5 sites) in the Sky Islands composite between 1819 and 1847 (figure 3).

This hiatus, or gap in fire occurrence was first noted in fire scar chronologies developed in the Gila Wilderness (Swetnam and Dieterich 1985). Since that time, it has been found in numerous other fire scar chronologies in the Southwest (but not a majority of sites), and interestingly, in very far flung locations, such as Baja California (Stephens et al. 2003) and the Blue Mountains of Oregon (Heyerdahl et al. 2002). A marked decrease in correlation between fire occurrence and drought indices in the Southwest also occurs during this period (circa 1780-1840) (Swetnam and Betancourt 1998). Most remarkably, a decrease in fire frequency during this period also appears in fire scar chronologies from semi-arid *Austrocedrus chilensis* woodlands and forests in Patagonia, Argentina (Kitzberger et al. 2001). Based on comparisons between the Southwest and Patagonia fire scar chronologies, and climatic records, we hypothesized that these inter-hemispheric fire regime correlations must be driven by very broad-scale ocean-atmosphere patterns, such as decadal-scale changes in the frequency and amplitude of the El Niño-Southern Oscillation (ENSO) (Kitzberger et al. 2001). (Barton et al. [2001] also detect a gap in fire occurrence during the early 1800s within the Rhyolite Canyon watershed in Chiricahua National Monument. However, this long interval is restricted to only part of the Canyon, and appears to be a local-scale event, possibly related to a flood that disrupted fuel continuity within the Canyon for a period of time.)

Much more study is needed of both inter-annual and decadal scale patterns of climate and fire. In addition to ENSO, a variety of oscillatory, hemispheric to global scale ocean-atmosphere patterns that affect climate in the Western United States have been identified in recent years (e.g., Pacific Decadal Oscillation, Atlantic Multi-decadal Oscillation, others). Comparisons of fire occurrence time series (modern and paleo) with these ocean-atmosphere time series can reveal important insights on regional to continental fire climatology (e.g., Swetnam and Betancourt 1990, 1992; Veblen et al. 2000; Heyerdahl et al. 2002; Norman and Taylor 2003; Westerling and Swetnam 2003).

Conclusions

Fire climatology has the potential to provide new understanding of how climate variability and change affects fire regimes and ecosystems over long time scales and broad spatial scales. This understanding will be needed as we enter an increasingly warm and variable climatic period, which will likely result from increasing greenhouse gases. Recent assessments of possible climate change impacts on fire regimes indicate that the Southwestern United States is particularly vulnerable, with probable increases in areas burned (McKenzie et al. 2004; Brown et al. 2004). As the example of inter-annual lagging relations between climate and fire in semi-arid forests (wet/dry cycle) shows, the paleo-ecological record of fire and climate can be very useful in uncovering relationships, which can then be further tested and evaluated with modern data and modeling. Some of these relationships can lead to development of forecasting tools that will be an aid to fire management planning.

The fire scar record in the Sky Islands has been very useful in clearly documenting the fact that surface fires were once very frequent and widespread in the pine dominant forests, but that rather drastic changes took place when livestock grazing and organized fire suppression began. In addition to fire-climate studies, the existing chronologies are most useful for coarse-scale assessment of fire frequency within sampled areas, but are limited in their usefulness for examining more detailed spatial patterns within and between sites. Increased sampling intensity and extent in spatial grid designs or random sampling (e.g., Heyerdahl et al. 2001; Fulé et al. 2003; Falk and Swetnam 2003; Farris and others, unpublished manuscript) will undoubtedly improve our estimates of the spatial pattern of past fires, and also provide fire frequency estimates that are less biased by sampled area and sample size. These kinds of assessments will be particularly useful in wilderness areas and parks, as fire managers eventually move beyond the current phase of surface fire regime re-introduction, and into a phase of fire regime maintenance. In this latter phase of fire use and management at landscape scales, the importance of knowing and understanding spatially explicit fire regime patterns will be of increasing importance.

Acknowledgments

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