6. Tree-Ring Reconstructions of Fire and Climate History in the Sierra Nevada and Southwestern United States

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Most of the fire history research conducted in the past century has focused on case studies and local-scale assessments of pattern and process, with an emphasis on describing typical fire frequencies in forest stands and watersheds. Dominant research themes have included the characterization and analyses of fire frequencies across ranges of topographic settings and habitats. In general, these "histories" have been more about describing time-averaged processes, than elucidating the events, narratives, and contingencies of "history." Now that many crossdated fire chronologies have been developed from tree-ring analyses of fire-scarred trees, it is possible to assemble regional to global-scale networks of fire occurrence time series. These networks and time series can be used in quantitative, historical analyses that identify and separate broad-scale climate-driven patterns of fire occurrence from local, nonclimatic features of individual sites. The seasonal to annual resolution of tree rings facilitates historical fire climatology because the high temporal resolution of these data allows us to connect multiple events in space and time. The importance of climatic influence is reflected in the degree of synchrony in specific fire events and decadal to centennial trends among widely distributed sites (Swetnam and Betancourt 1990, 1998; Swetnam 1993; Veblen et al. 1999; Veblen, Kitzberger, and Donnegan 2000; Grissino-Mayer and Swetnam 1997, 2000; Heyerdahl, Brubaker, and Agee 2001, in press; Kitzberger and Veblen 1998; Kitzberger, Veblen, and Villalba 1997; Kitzberger, Swetnam, and Veblen 2001; Brown, Kaufmann, and Shepperd 1999; Brown et al. 2001; Allen 2002).

Synchrony of events across space is a fundamental principle of dendrochronology and is the basis of tree-ring dating and the identification of broad-scale environmental patterns in tree rings (Douglass 1941; Fritts and Swetnam 1989). Patterns of wide and narrow rings, for example, are highly correlated among precipitation-sensitive trees growing in arid and semi-arid regions. Significant correlations ($p < 0.05$) of standardized ring-width series extend up to 1100 km between trees and sites in the western United States (Cropper and Fritts 1982; Meko et al. 1993). The reason for these positive correlations is that broad-scale drought and wet years have acted to synchronize the relative changes in tree-ring growth of moisture-limited conifers over large geographic areas (LaMarche and Fritts 1971; Fritts 1976, 1991). Local weather and nonclimatic variations result in unique variations in tree growth at individual sites. However, by combining numerous ring-width chronologies from broad areas, the site-specific variations are averaged out, while the common climatic signals are concentrated in mean value functions, or amplitude series from principal components analysis (Fritts 1976). It is from these composite, regional tree-ring networks that climatic history is most effectively reconstructed (e.g., Fritts 1976, 1991; Meko et al. 1993; Cook et al. 1999).

The short- and long-term climatic fluctuations that have importantly affected tree growth at local to global scales have also affected fire regimes. The common link of climatic influence on tree-ring growth and forest fuels (quantity and moisture content) provides the basis for fire-climate research in dendrochronology. In this chapter we illustrate our key findings regarding climatic controls of past fire regimes in the southwestern United States and Sierra Nevada of California. Following a description of tree-ring sampling strategies and methods of fire chronology development, we illustrate with a set of examples how fire-scar networks can be used to identity fire-climate associations across a broad range of spatial scales. Of particular importance is the finding that annual resolution fire-scar networks can provide an independent indicator of changing temporal patterns of globally important climatic processes, such as of the El Niño–Southern Oscillation.

Fire-Scar Chronologies

Fire-scar chronologies were reconstructed in forest stands throughout Arizona and New Mexico, and on the west slope of the Sierra Nevada (hereafter, these regions are referred to as the "Southwest" and the "Sierras," respectively). Many of these chronologies were developed through cooperative studies with land management agencies in national forest and national park wilderness and protected areas. Presence of living or dead fire-scarred trees was obviously necessary for reconstructing fire-scar based fire history, but sample areas included a broad range of abundance of fire-scarred trees. Concerns over impacts and aesthetics, and limited access sometimes required opportunistic sampling near roads or trails. Study areas and stands to be sampled were often located in areas where prescribed fire and forest restoration efforts were underway or planned. Some collection sites were selected as areas that were judged to have vegetation and topographic characteristics that were representative of broader areas within the management units. Other collections were obtained along natural fire spread corridors, such as along coniferous canyon bottoms linking grasslands to uplands, with the explicit purpose of evaluating landscape-scale linkages and processes (e.g., Kaib et al. 1996; Kaib 1998; Barton, Swetnam, and Baisan 2001).

Given the constraints listed above, the selection of study areas and trees was necessarily nonrandom and largely subjective, so the fire frequency estimates and other aspects of the reconstructed fire regimes may not be fully representative of larger surrounding areas. Potential biases due to nonrandom sampling and problems with fire frequency analysis methods have been highlighted in recent critiques of tree-ring based fire histories (e.g., Johnson and Gutsell 1994; Baker and Ehle 2001). The scope and context of this chapter does not allow a detailed and direct response to these critiques. In general, most of the critiques involve problems in estimating fire interval distributions (i.e., fire frequency analyses) and are only indirectly relevant to our focus on the historical aspects of past fire regimes. In subsequent sections we will show that notwithstanding possible biases and limitations of the fire-scar record, well-replicated fire-scar chronologies can provide complete inventories of widespread fire events within sites, and useful indices of local to regional fire activity.

Fire-Scarred Tree Selection

Our sampling strategy was to maximize the completeness of an inventory of fire dates within study sites over as a long a time period as possible, while also collecting samples that were spatially dispersed throughout the sites. We located fire-scar specimens within sites by systematically searching throughout forest stands. Site (or forest stand) boundaries were usually delineated by cliffs, rock outcrops, scree slopes, canyon bottoms, and ridgelines. During searches we carefully examined every living tree, log, and snag with a fire scar that was observed along walking traverses throughout the site. We sampled trees with maximum numbers of well-preserved fire scars that were broadly distributed throughout the sites.

We have often collected multiple clusters of fire-scarred trees (2–5 trees) in relatively small areas (i.e., 1–5 ha) within stands. These clusters can sometimes be useful for estimating small area (point) fire frequencies by compositing the fire dates from the cluster (e.g., Kilgore and Taylor 1979; Baisan and Swetnam 1990; Brown and Swetnam 1994). Site (or stand) chronologies typically include a minimum of 10 fire-scarred trees, and encompass areas of about 10 to 100 ha. Some of our collections were from many clusters of trees along elevational transects and/or within medium to large watersheds (1000–10,000 ha). In a few cases our collections included 50 to 100 (or more) fire-scarred trees widely dispersed across entire mountain ranges or large landscapes (20,000–>50,000 ha) (e.g., see Baisan and Swetnam 1990, 1997; Caprio and Swetnam 1995; Grissino-Mayer and Swetnam 1997). More details about our collections and study sites, including summaries of fire interval statistics, can be found in Swetnam and Baisan (1996), Swetnam, Baisan, and Kaib (2001), and the many fire history papers in the Reference section.

Composite Chronologies, Filtering and Sample Size Effects

Fire chronologies were composited (sensu Dieterich 1980, 1983) at different spatial scales to evaluate fire regime changes (e.g., Baisan and Swetnam 1990; Grissino-Mayer and Swetnam 1997; Brown and Sieg 1996, 1999; Brown, Kaufmann, and Shepperd 1999; Brown et al. 2001) (Fig. 6.1). One of the ways we have assessed fire regime variations is by "filtering" methods, whereby minimum numbers or percentages of trees scarred are used to sort and describe fire event and interval data (e.g., Swetnam and Baisan 1996; Swetnam, Baisan, and Kaib 2001). These filters helped identify fires that were probably more or less extensive within sites in a relative sense. Filtering also helped identify fire frequency estimates that were less affected by sample size (described below). Fire-scar data compilation, sorting, statistical analyses, and graphical presentation were greatly facilitated by Henri Grissino-Mayer's development of the FHX2 software (Grissino-Mayer 1995, 1999, 2001, and see *http://web.utk.edu/~grissino/fhx2.htm*). Using the FHX2 program, different minimum numbers and/or percentages of trees scarred per fire can be defined and used as a coarse filter for computing fire interval statistics for fires of different relative spatial extent within or between stands.

In using filtering approaches, our aim was to reasonably identify and classify fire events that were probably more or less widespread, while recognizing that fire-scar data analyzed in this manner provide relative (versus absolute) estimates of fire frequency and extent. In assessments of the degree and pattern of synchrony of fire events within sites, we commonly used filters of a minimum of two trees scarred per fire, and/or 10% and 25% of trees recording fires per year. Although particular fire event filters (e.g., 10% or 25%) may be arbitrary, such a priori selection of threshold quantities for testing, classifying, and sorting data is a widely accepted statistical practice (e.g., the use of specific confidence intervals, or percentile thresholds in statistical description and hypothesis testing). Use of a priori filtering thresholds also facilitates comparisons among sites because filtered fire frequencies are less affected by sample size (see below).

One of the concerns in fire history sampling is the effect of study area size, and number of fire-scarred trees sampled, on fire frequency estimates (Arno and Peterson 1983; Swetnam and Baisan 1996; Baker and Ehle 2001). As study areas increase in size the chances of encompassing additional past fire perimeters increases. Likewise, as more fire-scarred trees are sampled and included in composites, there is an increased chance of detecting additional fires that burned in previously unsampled areas, or only in small areas. The effects of changing sample size and the completeness of the inventory of fire dates within sites or study areas can be assessed in a manner that is similar to the use of species–area

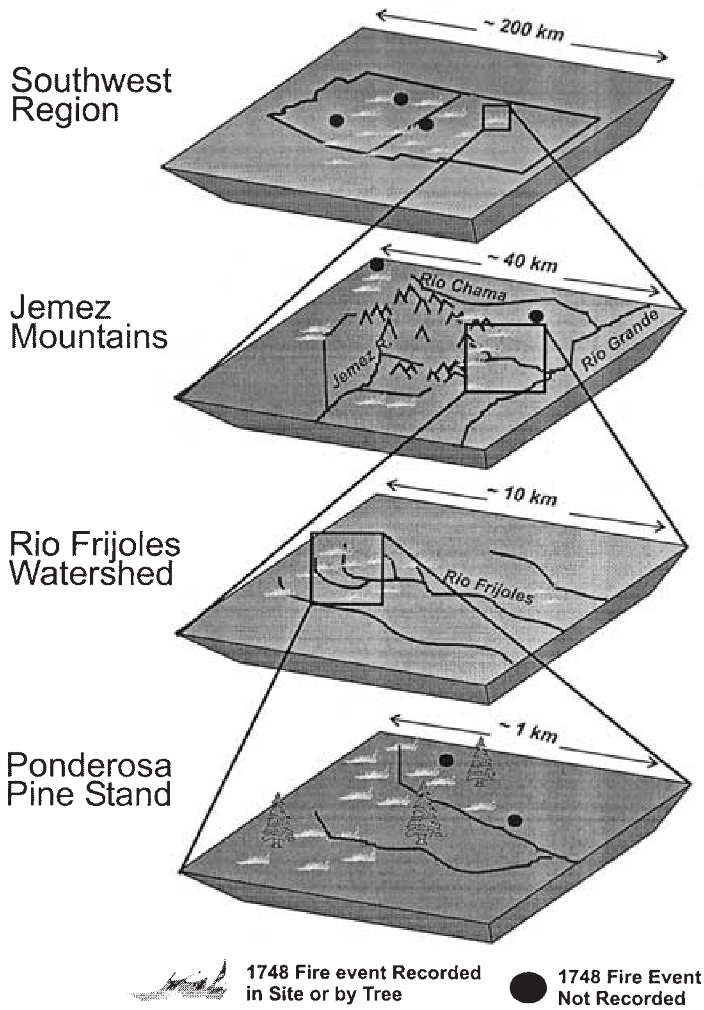

Figure 6.1. Different spatial scales of analyses in fire histories are illustrated in this hierarchical set of maps. The fire year 1748 was the most synchronous fire year in the southwestern fire-scar network, and is shown schematically as an example of cross-scale synchrony. Synchrony of fire dates between trees and nearby stands can be reasonably inferred to indicate fires that spread between sample points, although unburned areas between points, and separate fire ignitions are acknowledged possibilities. Synchrony of fire dates among stands, watersheds, and mountain ranges separated by great distances or barriers to fire spread is most probably caused by climatic entrainment of fire occurrence.

curves by botanists for assessing the completeness of inventories of plant species diversity (e.g., Colwell and Coddington 1994; Rosenzweig 1995).

We address here the issue of completeness of our fire-scar chronologies because this is relevant to our interpretations that we were able to detect widespread fires within and between sites, and that these relatively extensive fire events were associated with climatic variations. In our example, fire frequencies (fires/century) at different sample sizes were re-computed for a fixed time period and study site using randomly selected sub-sets of the sampled trees (Fig. 6.2). Re-sampling (bootstrap) methods were used to estimate the confidence intervals of the mean fire intervals recomputed at different sample sizes (Mooney and Duval 1993).

As expected, a general pattern that we commonly observed in these assessments was that fire frequencies tended to increase as more trees were added to the collection. However, when we applied the least restrictive filter of fire dates—namely the inclusion of only those fire dates recorded by two or more trees—the fire frequency estimates were typically asymptotic as a function of sample size (Fig. 6.2). This result suggests that single-tree fire-scar dates were probably representing relatively localized, small fires that occurred around those single trees. As sample size increased more of these small fires were detected, and so fire frequency continuously increased.

Presumably, with additional samples from an area of fixed size the fire frequency should eventually stabilize. If the area was large enough, as more samples were collected fire frequency would eventually reach the maximum possible frequency of one fire a year (i.e., all years with fire-scar dates). However, at the spatial scale of most of our sample areas (10–1000 ha), surface fires recorded by two or more fire-scarred trees probably represented relatively widespread fires that exposed many trees to re-scarring. Hence, when only these fire events were included, the fire frequencies tended to stabilize after a certain number of trees were sampled. In application of this kind of assessment to many of our fire-scar chronologies, we have found that in sites of less than approximately 100 ha, 10 to 15 trees were usually sufficient to reach fire frequency asymptotes using the 2-tree minimum filter. In large sample areas (1000–10 000+ ha) asymptotes were usually not achieved with the 2-tree minimum filter but often were achieved with more restrictive filters (e.g., 25% or more trees scarred per fire, unpublished data).

The main interpretation from these analyses was that most of our fire-scar chronologies were complete, or nearly complete, inventories of relatively widespread fires that occurred within the sampled areas. Frequencies of fires of any size, occurring anywhere within the study sites, however, were probably underestimated because many small fires were probably not picked up by fire-scar sample sets of these sizes.

An important point to bear in mind is that mean fire intervals (i.e., the inverse of fire frequency) estimated from composite fire-scar chronologies should not be interpreted to indicate that every square meter burned within the study area, on average, at those intervals. Even in the case of mean fire intervals computed using

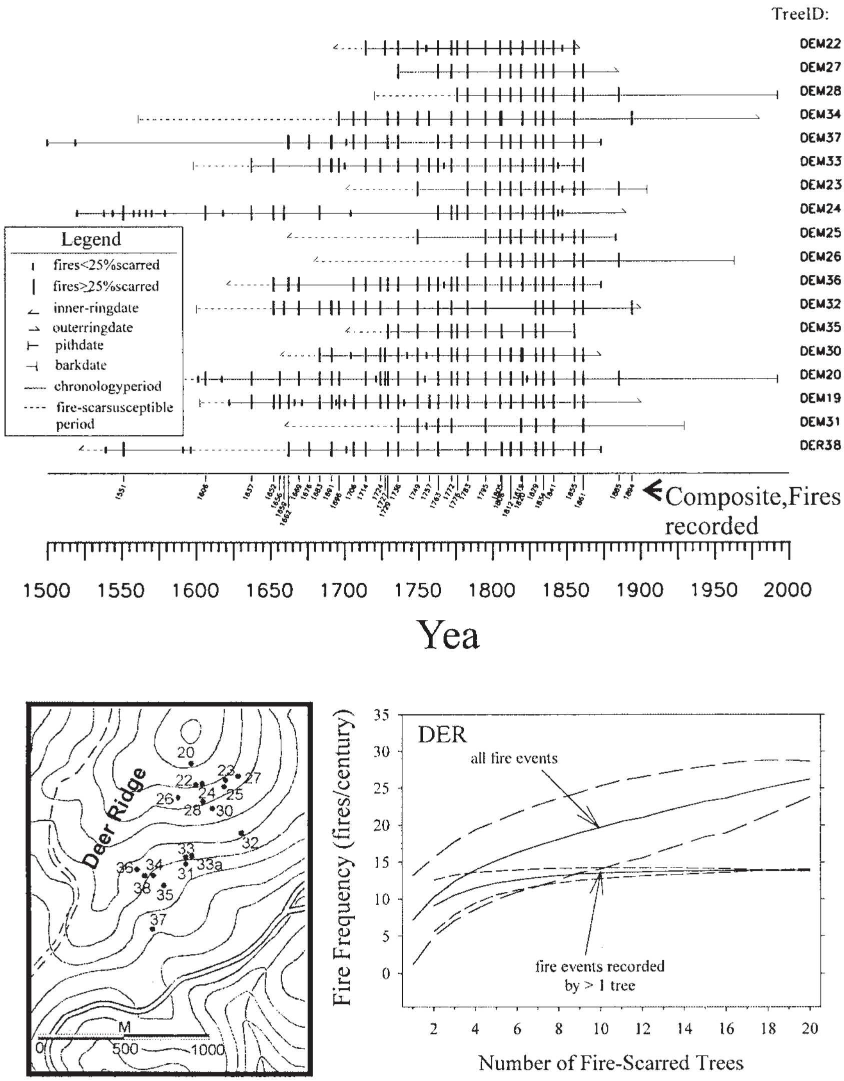

Figure 6.2. Example of a fire-scar chronology from a forest stand in the Sierra Nevada, California (Deer Ridge, Mountain Home State Forest, upper graph). Time spans of specimens from individual fire-scarred trees are shown by the horizontal lines, and the fire dates are indicated by vertical tick marks. The map (*lower left*) shows the spatial distribution and extent of this site (note that only the specimens from the central clusters of this site are included in the master fire chronology chart). The graph on the lower right illustrates the fire frequency in this stand computed as a function of sample size. The mean fire frequencies (*solid lines*) were computed from random inclusion (1000 re-samplings) of subsets of the 18 fire-scarred trees for each sample size. The time period used was 1700 to 1900 because most trees were recording fires during this period. The 95% confidence limits (*dashed lines*) of the computed fire frequencies were estimated from the mean and variance of the re-sampled sets at each sample size.

the more restrictive filters (e.g., 10% or 25%), and thereby inferring that these were intervals between relatively widespread fires, this does not imply that no areas were unburned within the sampled areas during those fire events.

In general, it is our view that fire historians have tended to overemphasize fire frequency analyses (i.e., description and testing of different fire interval distributions) as the primary goal of fire history research. Statistical descriptions and tests of fire interval distributions are inherently limited in objectivity, resolution, and reliability. One reason for this is that selection of an appropriate study area extent or time period to analyze, which very importantly affect interval distributions, will always be subjective or arbitrary at some level (Millar and Woolfenden 1999). Improved sampling methods can only go so far in estimating or correcting for biases and peculiarities in the paleorecord, which by its nature is fragmentary and preserved by only partially understood biological and physical processes (Swetnam, Allen, and Betancourt 1999).

Rather than focusing so exclusively on statistical analysis of fire interval distributions, we think that historical approaches are likely to be equally or more reliable and informative about the drivers of past fire patterns and processes, such as humans and climatic variations. Powerful explanations and understanding can be derived from the discovery of specific historical events, trends, contingencies, and patterns. These historical processes are often obscured in time-averaged summaries, statistically fitted models, and estimates of central tendency. Reasonable and convincing explanations often derive from relatively straightforward graphical assessments of the temporal-spatial patterns of event synchrony. Such patterns are often evident in fire-scar chronology composites, especially when compared with independent historical records of climate and land-use history. Statistical detection and testing of visually evident historical changes and linkages are also possible using methods such as contingency, correlation, and superposed epoch analyses. These kinds of graphical and statistical analyses emphasize the unique, historical nature of fire regimes, rather than just the time and space averaged view emphasized in fire frequency (fire interval) analyses.

Examples of Mountain Range-Scale Fire Chronologies and Historical Interpretations

Master fire chronologies from two mountain ranges in the southwestern United States illustrate the value of examining historical patterns, rather than just the time and space-averaged aspects of fire regimes (Figs. 6.3 and 6.4). The two mountain ranges are the Mogollon Mountains in the Gila Wilderness, New Mexico, and the Santa Catalina Mountains near Tucson, Arizona. Stands were sampled along elevational transects in both mountain ranges. The tree rings and fire scars in these samples were dated and composited using techniques described in detail elsewhere (Dieterich 1980; Dieterich and Swetnam 1984; Swetnam and Dieterich 1985; Baisan and Swetnam 1990; Swetnam and Baisan 1996; Abolt 1997; Swetnam, Baisan, and Kaib 2001).

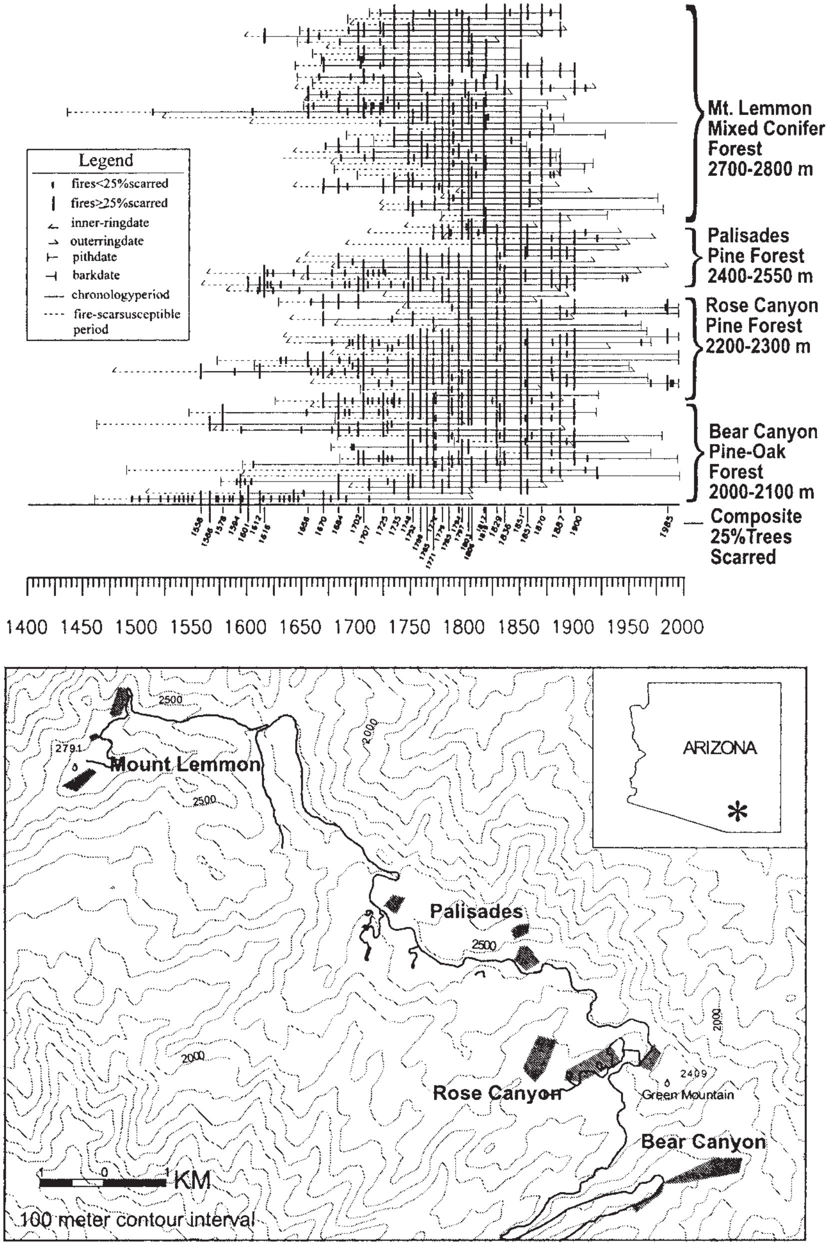

Figure 6.3. Master fire chronology from an elevational transect in the Santa Catalina Mountains (near Tucson, AZ) extending from mixed conifer forest near the summit of Mount Lemmon down to pine-oak forests at Bear Canyon. The transect spans elevations of approximately 2000 to 3000 m over a linear distance of about 20 km. Groups of fire-scarred trees sampled in sites (stands) are indicated by brackets and site names on the right. Note the high degree of synchrony of a subset of the fire dates across the elevational gradient; this is compelling evidence that widespread fires occurred during those synchronous fire years.

Composite stand and transect chronologies show several common patterns in fire histories of pine and mixed-conifer forests in the Southwest and Sierras. One of the most obvious patterns is a striking change in fire frequency in the late nineteenth or early twentieth centuries (Figs. 6.3 and 6.4). This reduction in fire occurrence coincides in almost all cases to within a few years of the first documented introduction of large numbers of domestic livestock (sheep, goats, cattle, or horses). The great ranching boom of the late nineteenth century, for example,

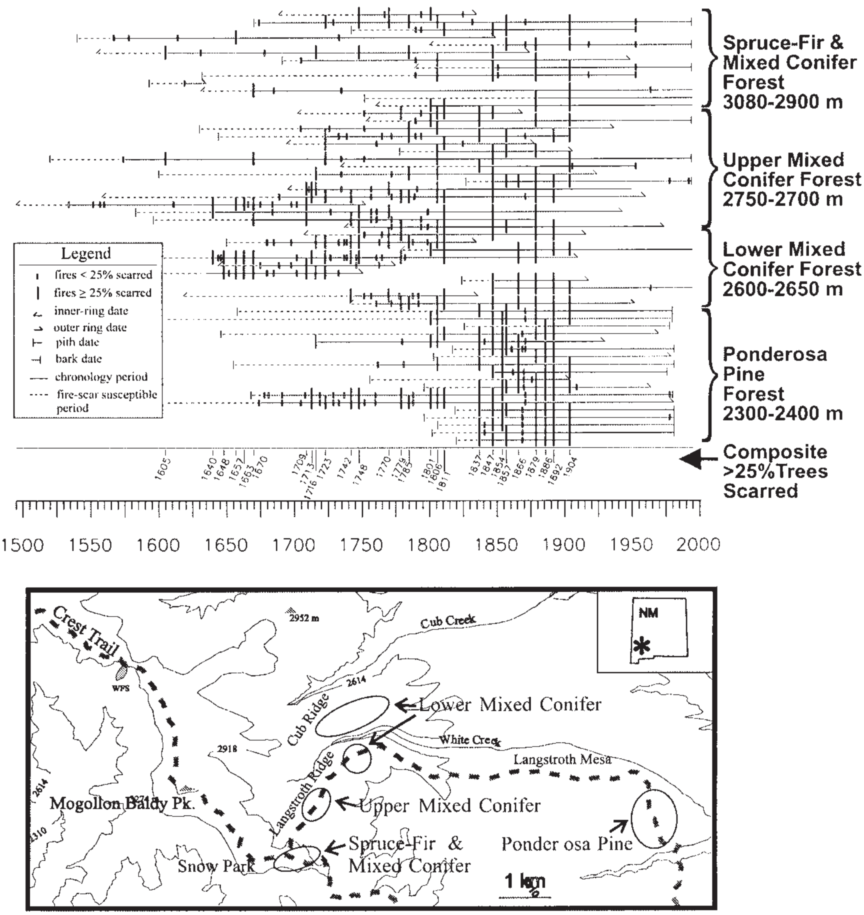

Figure 6.4. Master fire chronology from an elevational transect in the Mogollon Mountains (Gila Wilderness, NM) extending from spruce fir forest near the summit of Mogollon Baldy and down to ponderosa pine forests on Langstroth Mesa (see map at bottom). The transect spans elevations of approximately 2300 to 3080 m over a linear distance of about 15 km. Groups of fire-scarred trees sampled in sites (stands) are indicated by brackets and site names on the right. Note the apparent change in fire frequency and synchrony ca. 1800, and also in Figure 6.3.

led to sheep or cattle introduction to some mountain areas as early as the 1870s, and was delayed in other more remote mountain ranges until after around 1900. The timing of the decline of frequent fires as recorded by the fire scars closely reflects these historic land use differences (see Swetnam, Baisan, and Kaib 2001 for specific examples). In general, the livestock introduction and coincident reduction in fire occurrence preceded by a decade or more the advent of organized and systematic fire suppression by government agencies. In most places limited fire fighting by a few government agents began about 1905 to 1910. Organized fire fighting was probably not very effective in many areas until increased numbers of fire fighters, lookout towers, and equipment (e.g., aircraft) became available after the 1930s or 1940s (Pyne 1982; Swetnam, Baisan, and Kaib 2001; Rollins, Swetnam, and Morgan 2001).

In the southwest, frequent fires were typically interrupted between about 1870 and 1900. Figures 3 and 4 show examples of disrupted fire regimes around 1900; see Swetnam, Baisan, and Kaib (2001) for examples of variable fire regime disruption dates from the 1870s to 1900s in southern Arizona and New Mexico. Exceptions were places where earlier introduction of livestock (especially sheep) by Hispanic or Navajo herders occurred (i.e., early nineteenth, eighteenth, or seventeenth centuries, depending on location), as documented with independent archival records (Savage and Swetnam 1990; Touchan, Allen, and Swetnam 1996; Baisan and Swetnam 1997). Other exceptions were uninterrupted fire regimes in locations where intensive livestock grazing did not occur because of topographic barriers, such as impassable lava flows (Grissino-Mayer and Swetnam 1997).

Fire regimes were not disrupted until the midtwentieth century (i.e., 1940s and 1950s) in the remote, rugged mountains of northern Mexico where permanent water or roads needed for intensive livestock and human uses were lacking. These late disruptions coincide with the "ejido reforms" of the 1940s, after which there was an increase in numbers of roads, water tank development, livestock grazing, and logging in some areas (Fulé and Covington 1997, 1999; Fulé, Covington, and Moore 1997; Kaib 1998; Swetnam, Baisan, and Kaib 2001; Heyerdahl and Alvarado, Chapter 7, this volume). These exceptions essentially prove the rule: intensive livestock grazing and associated human land uses were the initial causes of fire regime disruption in most areas of the greater Southwest. Continued absence of widespread, frequent surface fire in the mid to late twentieth century (at least on the U.S. side of the border) was probably due to a combination of livestock grazing and organized, increasingly effective fire suppression efforts by government agencies.

Climate change is an unlikely explanation for the late nineteenth- to early twentieth-century fire regime disruptions. This is because (1) the disruptions were typically asynchronous between mountain ranges that shared similar regional climate patterns, (2) droughts and wet periods during this era (i.e., 1870s–1910s) do not consistently coincide with the disruptions, whereas the dates of livestock introductions generally do coincide, (3) portions of some remote mountains in Sonora, Mexico, that were not heavily grazed continued to burn throughout the twentieth century, despite having very similar climate as nearby mountain ranges on the U.S. side where grazing occurred and frequent fire regimes were disrupted (Swetnam, Baisan, and Kaib 2001).

The frequent surface fire regimes of mid-elevation forests (2000 to 3000 m) in the Sierras were typically disrupted earlier than in most southwestern sites. The last widespread fire in our sites on the west slope of the Sierras occurred between about 1850 and 1870 (Fig. 6.2, and see Caprio and Swetnam 1995). This corresponds with movement of large sheep herds into the Sierras during and following a severe drought in the early 1860s, which forced sheepherders in the Central Valley to seek forage in the high mountain meadows (Vankat 1977). This intensive grazing led to denudation of large tracts of formerly grassy areas in the high Sierras by the 1870s, as decried by John Muir; he called these sheep herds "hooved locusts" (Muir 1911).

Native Americans and High-Frequency Fire Regimes

The decline of frequent fire regimes in the Southwest and elsewhere has sometimes been attributed to the forced removal of Native Americans from these landscapes during the nineteenth century and earlier (Pyne 1982, 1985). Drawing primarily from written historical documents, and interviews of Native Americans during the twentieth century, some cultural and environmental historians argue that human manipulation of vegetation with fire was ubiquitous for many millennia before the arrival of Europeans (e.g., Dobyns 1978; Pyne 1982, 1985; Denevan 1992; Anderson 1996). A general conclusion is that humans were the dominant and overriding influence on fire regimes. "Natural" (nonhuman) factors, such as climate and lightning variability, are also acknowledged as important drivers of past fire regimes but are typically considered to be of secondary importance, or as merely complementary to the human drivers.

Although the written histories that the cultural historians depend on is extensive, alternative views on the universality of human dominance of past fire regimes, particularly for the western United States, have been presented (e.g., Vale 1998; Vale 2002). One of the chief points made in recent papers is that lightning was a more frequent and dominant cause of fires in western U.S. landscapes than was appreciated by almost all nineteenth- and early twentieth-century observers (e.g., Allen 2002; Baker 2002). It is only in the past couple of decades that with the new lightning detection technologies, comprehensive maps have become available showing millions of lightning strikes per year over regions the size of individual western states (e.g., Gosz et al. 1995). In a recent study of detected lightning fires during the twentieth century, we have found rates of ignition in southern Arizona mountains as high as two fires per km^2/y (unpublished data). A lack of knowledge of the very high rates of fire ignitions by lightning in some western forests, combined with anti-Indian biases in the nineteenth century and earlier, probably led to erroneous attribution of some fires to Native Americans, while under estimates of the importance of lightning as causes of forest fires (Allen 2002; Baker 2002).

Based on our research in the Southwest and Sierras, we conclude that Native American control of past fire regimes was very time and place specific, and cannot be broadly generalized as ubiquitous or dominant in all places and times. Fire regimes in large portions of these regions would probably have had similar characteristics (fire frequency, seasonality, extent, etc.) if people had never entered the Americas. It is clear, however, that people profoundly affected fire regimes in particular places and times. For example, in a study of more than 200 fire-related quotations in Spanish, Mexican, and American archival documents (relevant to the Southwest) extending back to the seventeenth century, Kaib (1998) found that more than 70% were in the context of warfare with the Apache people of southern Arizona and New Mexico. Intentional burning of large areas was very rare, except during times of warfare. The use of fire against enemies was a common practice used by all sides—Apache, Spaniard, Mexican, and American soldiers. Combatants burned particular places (campsites, livestock watering and grazing areas, etc.) during conflicts, but intentional burning of broader areas was only rarely mentioned in the documentary sources. The general picture was one of great temporal and spatial variability and specificity in the firing of landscapes during warfare.

This emphasis on the time and place specific influence of Native Americans on past regimes in the Southwest is supported by tree-ring studies. For example, a tree-ring study of eighteenth- and nineteenth-century fire history in several mountain ranges of southern Arizona and northern Mexico revealed that fire frequency generally tracked the occurrences of peacetime and wartime (Kaib et al. 1996; Kaib 1998). Based on place name references in archival documents, it was evident that some of the sampled stands were located near historic campsites or travel routes. Highest fire frequencies occurred during periods of maximal conflict among all sides, while reduced fire frequencies occurred when truces with Apaches were in effect. Other fire-scar studies in the Chiricahua Mountains of Arizona (Seklecki et al. 1996) and the Organ Mountains of New Mexico (Morino 1996) also found evidence of changing fire frequencies and seasonal timing that were speculated to be related to presence or absence of Apaches. Again, these study sites were located in specific areas where independent documentary sources indicate historical usage by Apaches.

In a detailed case study in the Sacramento Mountains, Kaye and Swetnam (1999) used independent documentary records and tree-ring dates of "culturally modified trees" to pinpoint the presence of Apaches in both time and place. In this study the culturally modified trees were "peeled" ponderosa pines that the Apaches had used as a food source by peeling the bark and cambium layer from a section of the lower bole (Swetnam 1984). The soft cambium provided carbohydrate and other nutrients (Martorano 1981) and was probably used primarily as an emergency food source (Swetnam 1984). Tree-ring dates from the peelings, and documented dates of skirmishes between Apaches and soldiers within and near the study area, were used to assess frequency and season of fires during known occupation periods versus other times. We also assessed regional climatic associations with fire dates and fire frequency trends.

We found that Apaches may have increased fire frequencies during some periods, and altered the seasonal timing of a few fires. Overall, however, the results were equivocal. Even in this unique case study, where detailed independent sources of temporal and spatial evidence were available to assess possible Native American influence on past fire regimes, it was not possible to strongly conclude that they significantly altered the character of fire regimes from what would have prevailed with lightning alone as an ignition source.

A broader-scale study of fire histories within the Sacramento Mountains, including the chronologies used by Kaye and Swetnam (1999), confirmed that climatic variations (drought/wet years) were dominant controls of past fire regime variations at the landscape scale (Brown et al. 2001). Again, the most significant and demonstrable effect of humans on past fire regimes was the disruption of frequent, widespread surface fires in the late nineteenth and early twentieth centuries when large numbers of livestock were introduced, and organized fire suppression began.

Twentieth-Century Verification of Fire Events

A common observation in fire chronologies from the Southwest and Sierras are a few scattered fire-scar dates in the twentieth century (Figs. 6.3, 6.4, and 6.5). There is usually a good correspondence of these dates with known twentieth-century fires in these areas. For example, almost all fires greater than 10 acres (4 ha) documented in fire atlases maintained by the U.S. Forest Service for the portion of our elevation transect in Gila Wilderness (Rollins, Swetnam, and Morgan 2001) were confirmed by the fire-scar dates from these areas (Fig. 6.4). In fact the particular trees that recorded fires corresponded well with the mapped perimeters of these fires. For example, a 1953 wildfire is know to have burned only within the area in the uppermost site, whereas a 1978 "prescribed natural fire" burned only with the areas of the lowermost site (Fig. 6.4) (Abolt 1997). The widespread 1904 fire in this chronology was referred to in both old Forest Service records and the local newspaper, with very specific place names that locates this fire within our study sites (Abolt 1997).

In the Santa Catalina Mountains of Arizona the last widespread fire in 1900 along our sampled transect was described and photographed by government surveyors who fought this low-intensity surface fire (Swetnam, Baisan, and Kaib 2001). This fire was clearly recorded as an extensive fire-scar event along the 20-km transect (Fig. 6.3). The 1985 fire was also documented in this network of site chronologies as occurring only within the Rose Canyon site (Fig. 6.3). Verification of dozens of other fire-scar dates, through references in documents or mapped fire perimeters in fire atlases, provides a high degree of confidence to our interpretation that fire-scar collections were generally complete and accurate recorders of past fires (for additional examples, see Dieterich and Swetnam 1984; Swetnam and Dieterich 1985; Baisan and Swetnam 1990; Caprio and Swetnam 1995; Swetnam, Baisan, and Kaib 2001).

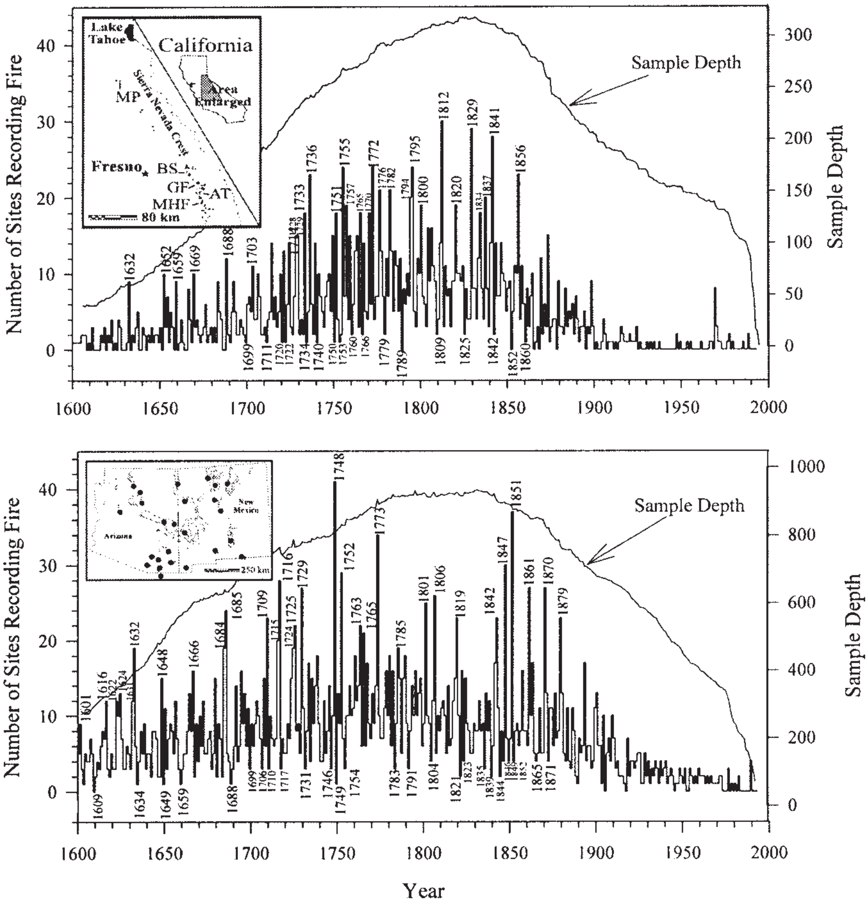

Figure 6.5. Composite time series of fire events in the Sierra Nevada (upper graph) and Southwest (lower graph) from regional networks of fire-scar chronologies. Number of sites recording fire each year are shown (AD 1600–1995). The number of fire-scarred trees included in the data sets during each year (sample depth) are also shown. The map insert of the Sierras shows locations of the five giant sequoia groves (letter codes). Small irregular dots show approximate range of sequoia groves. The 49 sites from the Sierras included in the composite are from four elevational transects adjacent to the Mariposa Grove (MP), the Big Stump Grove (BS), Giant Forest (GF), and Mountain Home State Forest (MHF). The map insert of the Southwest shows 26 mountain ranges (as dots) where the 63 sites included in the composite are located. The irregular outline on this map is the approximate range of ponderosa pine in Arizona and New Mexico.

Synchrony within Stands, Watersheds, and Mountain Ranges

An outstanding feature of many fire-scar chronologies in the Southwest and Sierras is a high degree of synchrony of fire-scar dates among trees across a broad range of spatial scales, from stands to regions. The high degree of synchrony of some fires over linear distances of more than 10 km and elevation gradients of 1000 to 2000 m (Figs. 6.3 and 6.4) leads to a simple and logical interpretation: relatively large areas burned within these study areas during these synchronous years.

It is likely that some of these synchronous events represent separately ignited fires that did not coalesce into contiguous burned areas. It is also very likely that some unburned areas existed between sampled trees and sites along these transects and within the surrounding areas. Despite these considerations our basic interpretation is still reasonable, that relatively greater areas probably burned during the highly synchronous years than during less synchronous years (i.e., fire years recorded by a single tree or a few trees; Figs. 6.2, 6.3, and 6.4). It is also very likely that many pre-1900 fires burned over very large areas because lightning ignitions occur as early as April in some years in the Southwest, and fires are known to have burned for weeks to months. Nineteenth-century newspapers, for example, reported that wildfires burned for long periods of time and achieved enormous sizes; some fires exceeded 500,000 ha (Bahre 1985).

The synchrony of multiple tree and site fire events is often statistically significant ($p < 0.05$) across a range of spatial scales. For example, contingency analysis of the fire dates common to 3, 4, or 5 sampled giant sequoia groves over the past 1300 years showed that the odds of obtaining this observed degree of synchrony of events by chance was less than 1 in 1000 (Swetnam 1993). In general, we have interpreted significant synchrony of fire dates among trees within stands to be indicative of widespread fire at this scale. Synchrony among widely scattered sites—especially where effective fire barriers or distance separate the sites (as in the giant sequoia example)—is indicative of regional climatic influence on fire occurrence (e.g., Swetnam and Betancourt 1990, 1992, 1998; Grissino-Mayer and Swetnam 2000; Swetnam and Baisan 1996; Kaib et al. 1996).

Fire Drought Patterns in the Southwest and Sierras

Regional Composites and Synchronous Fire Years

The regional networks of fire-scar chronolgies we have assembled are from 63 sites in 26 mountain ranges in the Southwest, and 49 sites from four elevational transects on the west slope of the Sierras. Our Sierran collections include five giant sequoia fire-scar chronologies, which will be described separately. The influence of interannual climatic variation is evident as years when many sites (and trees) have recorded fires during particular years, and as years when no, or few sites (and trees) have recorded fire events (Fig. 6.5). The interpretation of climate as the primary driver of this synchrony is reasonable because there is no other known factor that operates at these spatial and temporal scales that could result in such a high degree of year-to-year synchrony. Also, as will be demonstrated below, these synchronous dates are statistically associated with independent records of interannual wet and dry conditions.

The synchrony is visually obvious (Figs. 6.3, 6.4, and 6.5), but it is reasonable to ask: Is the degree of observed synchrony statistically significant? Specifically, if this number of independent, random time series were combined could the observed synchrony among the series have occurred purely by chance? The statistical strength of the observed synchrony is illustrated by a contingency calculation. Fire frequency within 63 individual sites in the Southwest averaged about one fire per 7.5 years from 1700 to 1900. Using this average fire frequency and simple binomial joint probability calculations, strictly by chance we would expect about one coincidence of the same fire date in 21 of the 63 sites (one-third) in about a 35,000-year period. Yet 15 different years met or exceeded this criterion in the 201-year period (Fig. 6.5). The probability of 41 of 63 sites recording the same fire date by chance, as in 1748, is vanishingly small. These probability calculations oversimplify the contingency of fire events among multiple sites because the fire interval distributions and probabilities are not necessarily binomial; they are different from site to site, and they change through time. Nevertheless, these probability estimates indicate that it is highly likely that our general conclusion is robust: the degree of synchrony observed is much greater than one would expect to occur by chance.

The relative, year-to-year strength of the synchrony is difficult to assess directly because the regional time series contains trends that are in part due to the sample depth (number of fire-scarred trees that were alive and recording fire-scar dates each year). Some of these trends, however, are probably related to climatic variability. An example of a decade-scale variation in regional fire occurrence and climate will be described in the next section, but first we focus on the extreme year-to-year (interannual) variations and their associations with climate variability.

The years of highest synchrony are labeled in Fig. 5 and were identified as years that exceeded the 95th percentile of smallest or largest values in a ranking of the fire years based on the number of sites recording fires per year in 20-year moving periods. By using a moving period for the percentile rankings we adjusted for the changing sampling depth. The year-by-year values of the 95th percentile threshold were variable (i.e., the values produced a somewhat jagged curve, not shown) because the moving period included or excluded the particularly large or small values as it was shifted along the time series. The result was that some "extreme" years exceeding the 95th percentile were included or excluded in a somewhat arbitrary fashion. Therefore we used the 95th percentile curves (upper and lower) as a general guide for selecting the years to include or exclude in the analyses. Overall, this approach led to the inclusion or exclusion of only a few additional years (either large or small), and in a separate analyses we found that the basic results were not changed relative to use of only years strictly defined by the moving period.

Although the ranking in moving periods provided some adjustment for sample size, we decided it was best to exclude the pre-1700 and post-1860 periods of the Sierra regional chronology, and the post-1880 period of the Southwest regional chronology. The sample depth in the earliest period (before ca. 1700) in the

Sierras drops below approximately 100 trees and 10 sites, and therefore it is doubtful that we are accurately identifying all regional extremes with this reduced sample size, especially small fire years. Some regional large fire events were evident in the 1600s (Fig. 6.5, upper graph) and these were included in the analyses. The many apparent low fire activity years during the 1600s, however, were probably due to the small sample size, and so the extreme small events in this century were not included in the analysis. In general, as more sites and trees enter the data sets in later years, the number of zero value years decline, and the regional small years tend to become more apparent (Fig. 6.5). The Southwest network included more than 200 trees and 20 sites back to 1600, so regional large and small events were included in the analysis back through the 1600s.

The post-livestock-grazing eras were evident in both regional chronologies as declines in numbers of sites recording fires in the late 1800s. Several large event years (e.g., 1871, 1898, and 1970 in the Sierras, and 1891 and 1899 in the Southwest) and many small event years appear after the onset of intensive grazing in the two regions. We chose to exclude these post-livestock-grazing periods in the fire-climate analysis because of the known change in fuels in these periods relative to the preceding periods, and the obvious change in the nature of the fire-scar record at these times (e.g., Figs. 6.2, 6.3, 6.4, and 6.5; see also discussion and literature cited in previous sections). Interestingly the 1970 large event in the Sierras is traceable to extensive prescribed burning along one of the four elevation transects—in Sequoia National Park. These fires were set by the National Park Service in an ambitious prescribed burning effort during this particular year (unpublished Sequoia and Kings Canyon national parks fire history database).

The decline in sample depth through the twentieth century was due to our selective sampling of primarily dead fire-scarred trees (i.e., stumps, snags, and logs) to maximize chronology length and minimize impacts on living trees. The outer ring dates of these dead specimens were often in the early or midtwentieth century (e.g., Figs. 6.2, 6.3, and 6.4). Although this decline in sample depth probably affected our ability to detect some fires during the late twentieth century, we doubt that this effect was very pronounced. Support for this interpretation is the fact that the twentieth-century fire-scar records were commonly confirmed by the independent documentary record (e.g., 1970 example, and other examples mentioned previously). Also in most sites, where it was permissible and possible, we also sampled a few living trees with fire scars for the purpose of obtaining the full record of twentieth-century fire dates. Most of the time, these living fire-scarred trees had frequent fire scars extending up to the disruption period near the turn of the century, then no fire scars, or only one or two fire scars recorded during the twentieth century (e.g., Figs. 6.2, 6.3, and 6.4).

Interannual Fire Associations with Dry/Wet Patterns

We used superposed epoch analyses (SEA) to evaluate the interannual relations between extreme fire years (large and small) as identified in the two regional fire chronologies (Fig. 6.5). This method involved computing the average (or departure from average) climate condition during, before and after the extreme years. Monte Carlo techniques were used to estimate the confidence intervals of the observed averages (or departures) (Mooney and Duvall 1993). A similar technique was first used in studies of the potential effect of volcanic eruptions on global climate patterns, and was adapted by Baisan and Swetnam (1990), Swetnam and Betancourt (1992), Swetnam (1993), and Grissino-Mayer (1995) for use in fire history studies.

The FHX2 software includes a subroutine written by Richard Holmes to carry out the SEA computations (Grissino-Mayer 2001). The program requires the input of a list of key dates and a continuous time series of an environmental variable, such as a precipitation or drought index. In the present case, for the key years we used the extreme large and small fire years in the regional chronologies (years labeled in Fig. 6.5). The environmental time series we used were two recently developed tree-ring reconstructions of summer (June–August) Palmer Drought Severity Index (PDSI) from the Southwest and the Sierras (Meko et al. 1993; Cook et al. 1999). These PDSI reconstructions are based on large networks of drought-sensitive tree-ring-width chronologies, and they were derived via calibration and validation using linear regression techniques. Details of the calibration and validation statistics of these reconstructions are described on the worldwide web (at *http://www.ngdc.noaa.gov/paleo/pdsi.html*; see also Meko et al. 1993 and Cook et al. 1994, 1999). The reconstructed values were summer (June–August) PDSI, but in general also reflect persistent moisture conditions during the preceding month (i.e., May) because the PDSI algorithm includes lagging water balance effects of preceding periods.

The SEA results (Fig. 6.6) were similar to patterns observed in the other SEA studies of fire associations with interannual precipitation or drought variables (e.g., Veblen et al. 1999; Veblen, Kitzberger, and Donnegan 2000; Donnegan, Veblen, and Sibold 2001). In particular, large fire years (on average) tended to be significantly dry ($p < 0.001$, Fig. 6.6, upper and lower left graphs). Small fire years tended to be significantly wet in the Southwest ($p < 0.05$). The association of fire and drought was not surprising, but more interesting results were the findings of lagging relationships in fire–PDSI comparisons. For example, summer PDSI in the year before small fire years was consistently low (dry) in both the Southwest and Sierras ($p < 0.001$, Fig. 6.6, upper and lower right graphs). Summer conditions in years preceding large fire years tended to be wet, but this was consistent and statistically significant only in the Southwest regional composite. We interpret the importance of lagging patterns in the Southwest to be due to a high importance of fine fuel accumulation during wet years in these relatively dry sites. The widespread fires within and among sites throughout the region were largely a function of the accumulation of a continuous fuel layer of grass and tree needles. A series of one to three years of wet conditions was often important for the development of a continuous fuel layer that carried the spreading surface fires. Understory fuel accumulation and dynamics were also important because the frequently occurring fires consumed these fine fuel layers. In

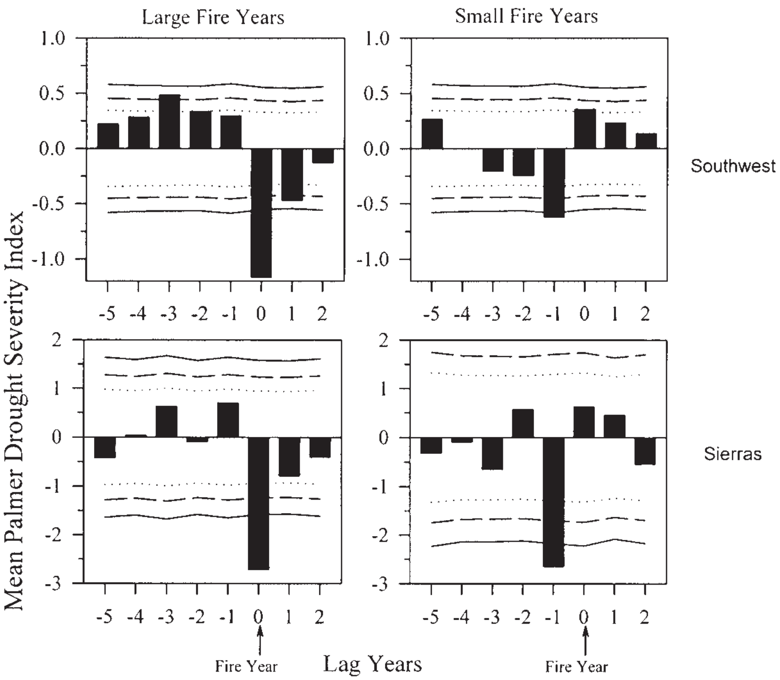

Figure 6.6. Results of superposed epoch analysis (SEA) comparing summer Palmer Drought Severity Indexes (PDSI) during relatively large (extensive) and small (less extensive) fire years in the Southwest (*top row*) and Sierras (*bottom row*). (See text for explanation of how "extensive" and "less extensive" were defined and time periods analyzed.)

semi-arid conditions, it probably required one to several years of relatively wet conditions (and lack of fire) to rebuild continuous surface fuels. The importance of dry years preceding the smallest regional fire years was probably due, in part, to the occurrence of extensive fires during these preceding dry years, thus limiting the ignition and spread of fires during the next year. Dry preceding years also limited fuel production necessary for fire ignition and spread in the subsequent year, especially if the subsequent year was wet (i.e., in the Southwest comparison, Fig. 6.6 upper right).

The different fire–PDSI lagging patterns in the Southwest and Sierras were probably due to the different mixtures of tree species and understory conditions in the two regions. In other studies we have sorted study sites into those with significant ponderosa pine or Jeffrey pine components, versus somewhat higher elevation, mixed conifer sites where these pine species were relatively minor components or were absent (Swetnam and Baisan 1996; Caprio and Swetnam 1995; Swetnam and Betancourt 1998). We found that the lagged wet conditions preceding large fire years was restricted to the pine-dominant sites. Mixed conifer sites tended to show no significant previous years wet patterns, but drier conditions occurred during large fire years than in the ponderosa pine sites. As just described, we think this difference was due to the high importance of understory fuel amounts in the relatively xeric, pine-dominated forests. In contrast, low fuel moisture was probably more important for successful fire ignition and spread in the relatively mesic, and productive mixed conifer forests (i.e., fuels were generally not limiting). Hence the lack of significantly wet years preceding regional large fire years in the Sierras could be because most of these sites were in relatively productive mixed conifer stands, whereas the majority of the southwestern sites were in dry ponderosa pine stands.

This interpretation is supported by similar SEA results in Oregon and Washington (Heyerdahl, Brubaker, and Agee, in press) where precipitation is greater and mixed conifer forests are more productive than in the southwestern pine-dominant stands. Also the relatively dry pine forests sampled in Colorado (Veblen, Kitzberger, and Donnegan 2000; Donnegan, Veblen, and Sibold 2001), Mexico (Heyerdahl and Alvarado, Chapter 7, this volume), and *Austrocedrus chilensis* woodlands in Argentina (Kitzberger, Veblen, and Villalba 1997; Kitzberger and Veblen 1998; Veblen et al. 1999) had similar wet years preceding large fire years.

El Niño–Southern Oscillation and Fire Relationships

The importance of wet/dry sequences to synchronized fire activity in some regions is at least partly explainable by El Niño–Southern Oscillation (ENSO) teleconnections to regional rainfall patterns. ENSO events are known to affect seasonal rainfall amounts through changes in atmospheric circulation (e.g., position, strength, and sinuosity of the jet stream) and frequency of tropical and subtropical storms (Aceituno 1988; Andrade and Sellers 1988; Nicholls 1992; Diaz and Markgraf 2000; Harrington, Cerveny, and Balling 1992). Weak to moderate correlations have been identified between modern fire occurrence and fire-scar records and various indexes of the Southern Oscillation in the Southwest, Colorado Front Range, Oregon, Washington, Mexico, and in Patagonia (Swetnam and Betancourt 1990, 1992; Kitzberger, Veblen, and Villalba 1997; Kitzberger and Veblen 1998; Fulé and Covington 1999; Veblen, Kitzberger, and Donnegan 2000; Donnegan, Veblen, and Sibold 2001; Heyerdahl, Brubaker, and Agee, in press; Heyerdahl and Alvarado, Chapter 7, this volume).

A key finding of these studies was that synchronized, regional fire events tended to occur during dry years that were often associated with La Niña events (in the Southwest, Colorado, and Patagonia). These dry, regional fire years tended to follow one to several wet years that were often associated with El Niño events. Wet/dry patterns and regionally synchronized fire events were not entirely consistent within regions or through time, but were sufficiently strong as to be detectable in both twentieth-century and paleo-fire and climate comparisons (Fig. 6.7). Moreover, as expected, reverse correlations were noted in the Pacific Northwest, where El Niños tended to produce drier conditions and increased fire activity (Morgan et al. 2001; Heyerdahl, Brubaker, and Agee, in press). As

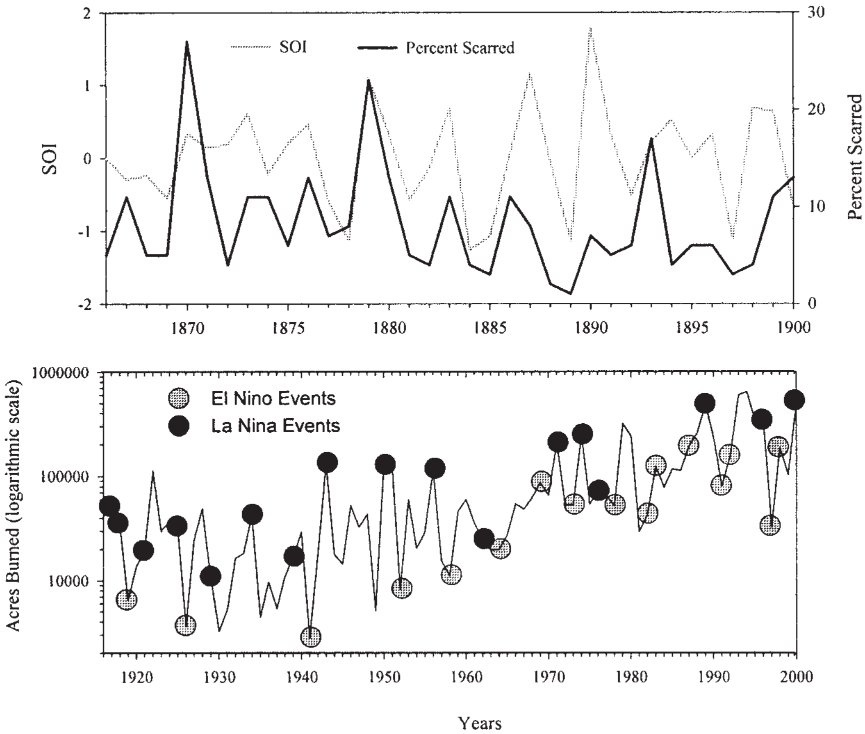

Figure 6.7. Time series of the percentage of trees scarred per year in a network of 15 sites in Arizona and New Mexico compared with the estimated Darwin-Tahiti Southern Oscillation Index (upper graph). The Spearman rank correlation from 1866 to 1905 is 0.46, $p = 0.002$ (Swetnam and Betancourt 1990). In the lower graph the annual area burned in all federal, state, and private lands in the Arizona and New Mexico (1905–1994) is compared with El Niño and La Niña events.

remarkable as these regional fire-climate relationships were, an even more interesting pattern recently emerged at the global scale. We discovered that fire occurrence time series from the Southwest and Patagonia shared similar interannual to decadal scale variations (discussed below) (Kitzberger, Swetnam, and Veblen 2001). Given that ENSO climate teleconnections are similar in the two regions, perhaps it should not be surprising that ENSO might act as a pacemaker, synchronizing fire activity at interhemispheric (i.e., global) scales.

Decadal-Scale Changes in Fire Frequency and Climate

In addition to interannual fire-climate variations and correlations we have also detected decadal-scale fire-climate patterns. One of the most interesting decadal-scale changes occurred in the Southwest from about 1780 to 1840. (Other examples of decadal-scale fire-climate changes will be described in the next section on giant sequoia fire history.) In recent years the evidence for this change in the

Southwest and other regions, and its association with global-scale climate patterns, has continued to build (Swetnam and Betancourt 1998; Grissino-Mayer and Swetnam 2000; Kitzberger, Swetnam, and Veblen 2001; Heyerdahl, Brubaker, and Agee, in press). At present, there are five lines of evidence pointing to a major climate-driven fire regime change in the late eighteenth and early nineteenth centuries: (1) unusually long intervals between fires during this period, (2) a shift from higher to lower fire frequency (and a related shift from less synchronous to more synchronous fire events), (3) a shift in seasonality of fires, (4) a striking decrease in the interannual correlation of fire events and climate indexes, and (5) the existence of a similar secular change in northern Patagonia, Argentina.

The first indication of a late eighteenth to early nineteenth century fire regime shift that we noticed was an unusually long interval between surface fires in the Gila Wilderness, New Mexico (Swetnam and Dieterich 1985). Since then, we have identified unusually long fire-free intervals around this time in many other (but not all) chronologies in the Southwest (Fig. 6.8). In some areas a long interval begins as early as the 1780s, and in others the interval does not begin until the early 1800s (e.g., Figs. 6.4 and 6.8). In some sites a few small fires (i.e., recorded by one or a few trees) occurred during the long interval, but there was a notable lack of widespread (highly synchronous) fires (Figs. 6.4, 6.8, and note also the slight dip in the number of sites recording fire in the Southwest during the early 1800s in Fig. 6.5).

The second indication of an important fire regime shift was a decrease in fire frequency after ca. 1800, and a notable increase in synchrony of fire events between trees (Figs. 6.3 and 6.4). This kind of change in frequency and synchrony was also noted in our giant sequoia studies during another time period (i.e., a change around AD 1300). Such frequency/synchrony (extent) shifts may reflect the natural feedbacks between fire frequency, fuel amounts, types, and spatial arrangements (Swetnam 1993). During relatively high frequency periods, fuels become more of a limiting factor to fire ignition and spread because the lags between fire events are too short for fuel continuity (amounts and spatial connectedness) to build to the point where fires will spread extensively through stands. This feedback between fires and fuels leads to spatially heterogeneous fuel layers and fire extent patterns. During relatively low fire frequency periods, fuels are less limiting because the longer lags enable fuel continuity to increase. When fires do occur, they tend to spread through the relatively abundant, spatially continuous fuels. Recent dynamic simulation models, incorporating climate and fuels components, generally support these interpretations with direct comparisons between simulated spatial and temporal patterns of fire frequency and extent and actual fire history data (Miller and Urban 1999, 2000).

A third line of evidence pointing to fire-regime and climate changes at the turn of eighteenth to nineteenth centuries is an apparent shift in seasonality of fire in a set of fire-scar chronologies from west central New Mexico (Grissino-Mayer and Swetnam 2000). Allen (1989) noted a similar seasonality change in a fire-scar data set from the Jemez Mountains in northern New Mexico. By examining the intraannual position of fire scars, we were able to infer the relative timing of past

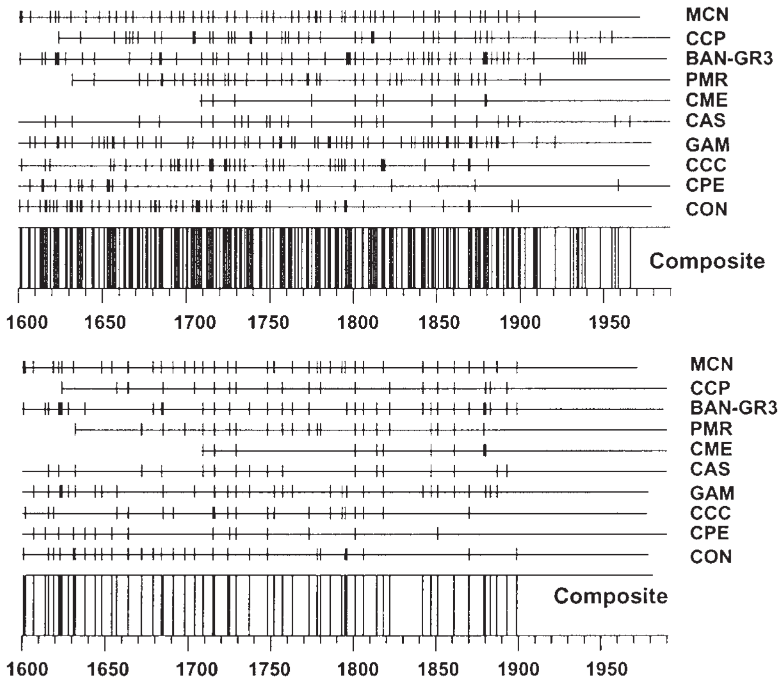

Figure 6.8. Composite fire-scar chronologies from the Jemez Mountains, New Mexico. These 10 stands are very broadly distributed around the mountain range, over an area of about 50,000 ha (see schematic map in Fig. 1). The horizontal lines and tick marks in the upper graph show time spans and fire dates, respectively, of fires recorded by any sampled fire-scarred tree within the stand. The bottom graph shows the same chronologies, but only fire dates recorded by 25% or more of the trees within each of the stands. The long vertical lines at the bottom show the composite of all dates for each graph. Note that the 25% filter emphasizes fires that were probably relatively widespread, both within and among stands. The fire regime disruption at around 1900 is evident in both graphs. Early and persistent fire regime disruption is evident in the three lowermost stands (CCC, CPE, and CON), and this has been attributed to early livestock grazing by Hispanic ranchers in these specific sites (Touchan, Allen, and Swetnam 1996). An early 1800s gap in fire occurrence in all chronologies is most apparent in the 25% filtered chronologies (bottom graph).

fires in relation to the cambial growth and dormant seasons (Dieterich and Swetnam 1984; Ortloff 1996). In a compilation of several hundred intraannual ring position observations, it was apparent that a secular change in fire seasonality began in the early 1800s (Fig. 6.9). Moreover the composite chronologies from this subregion of the Southwest show a pattern of reduced fire frequency ca. 1780, and more synchronous fire events after this time (Grissino-Mayer and Swetnam 2000).

SEA analysis of the periods before and after the shift reveals changes in the responses of fire occurrence to interannual climate patterns (Fig. 6.10). Our

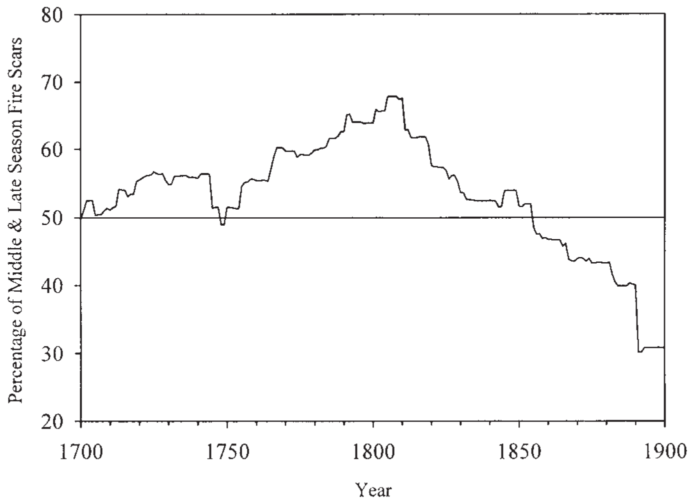

Figure 6.9. The relative position of fire scars within tree rings at El Malpais, New Mexico, changed through time, with a decreasing percentage of middle to late season scars (probably July–September) after ca. 1800 (from Grissino-Mayer and Swetnam 2000).

general conclusions from these analyses were that fire seasonality changes were probably related to a shift in seasonality of rainfall patterns (Grissino-Mayer and Swetnam 2000). In particular, the shift from a late-season dominant fire regime prior to 1800 to more early season fires after 1800 (Fig. 6.9) could have been a consequence of fewer El Niño events after circa 1800 than before. El Niño events

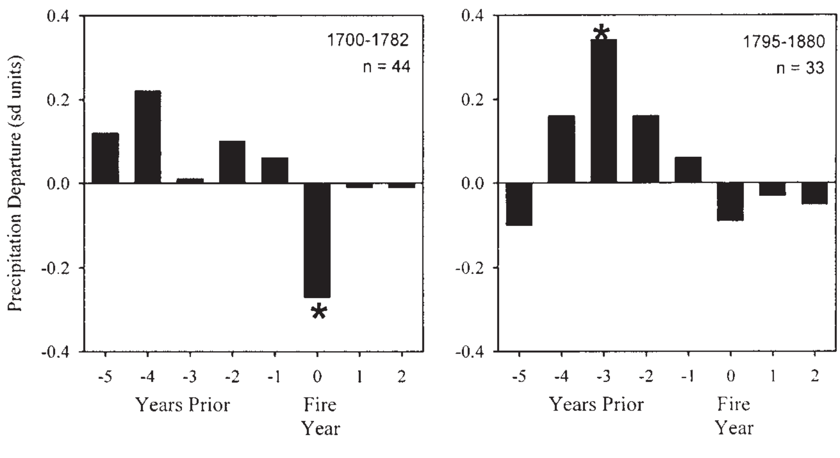

Figure 6.10. Superposed epoch analysis of the fire events before (*left*) and after (*right*) ca. 1800 at El Malpais, NM, suggests a change in the lagging relations between fires and climate in the two periods (from Grissino-Mayer and Swetnam 2000).

tend to result in relatively wet winters and early springs (Andrade and Sellers 1988), and a reduction in summer monsoonal rainfall (Harrington, Cerveny, and Balling 1992; Gutzler and Preston 1997). Hence, with more frequent El Niño events before circa 1800, the peak dry conditions and fire season in the Southwest would have often been relatively late, that is, from July to September. Higher fire frequencies in the pre-1800 period than in the post-1800 period could also have been partly related to more frequent El Niños, which would lead to increased fuel production in the relatively dry Southwest forests.

The SEA (Fig. 6.10) suggests that moist conditions in prior years were generally important both before and after 1800 (but this pattern was not statistically significant before 1800). Drought conditions were strongly associated with extensive fire events before but not after 1800. This pattern may have developed because the post-1800 period had an increasing frequency of dry, late springs/early summers (and increasing numbers of fire events occurring during this season, e.g., Fig. 6.9). In a climatic situation when dry springs were the norm, drier than average conditions (relative to the whole period) could not have been very important for fire ignitions and extensive fire spread.

The fourth line of evidence for a change in fire-climate relations ca. 1780 to 1840 was a large drop in correlation between regional drought indexes and fire occurrence over the entire Southwest during this period (Fig. 6.11). For this analysis, first differences were computed (see equation in the caption to Fig. 6.11) for both the regional drought and fire-scar series, so only the year-to-year variations were retained in the series and all long-term variations (e.g., decadal to centennial) were removed. Remarkably high interannual correlations were evident in the periods preceding and following ca. 1780 to 1840, with Pearson *r*-values exceeding 0.8 during the 1730s to 1780s and 1840s. Again, the importance of extreme switching between relatively wet and dry years (e.g., see especially the mid-1700s in Fig. 6.11) appears to be a key to regional fire and climate synchrony. Decreased climate and fire variance and correlation during the 1780s to 1840s period points to a weakening of the interannual switching of wet to dry conditions.

The fifth line of evidence offers a plausible climatic explanation for the decadal-scale change. A very similar reduction in fire occurrence during ca. 1780 to 1840 occurred in Patagonia, Argentina (Kitzberger, Swetnam, and Veblen 2001). Cross-spectral analyses of the Southwest and Patagonia regional fire time series showed moderate coherence in the 2- to 10-year portion of the spectrum, with clear changes in coherence during the 1780 to 1840 period. We also noted that this period had the lowest frequency of El Niño and La Niña events in the past two to three hundred years, as determined from a broad range of paleoclimatic reconstructions (ice cores, tree-rings, coral layers, and archival documents) (Kitzberger, Swetnam, and Veblen 2001). The early 1800s (i.e., ca. 1810s–1830s) was notable as a pronounced cold period throughout the Northern Hemisphere (Mann, Bradley, and Hughes 1998), and some extremely cold years occurred during these decades that were probably related to major volcanic eruptions (e.g., the cold year of 1816 which followed the eruption of Tambora in 1815). Finally,

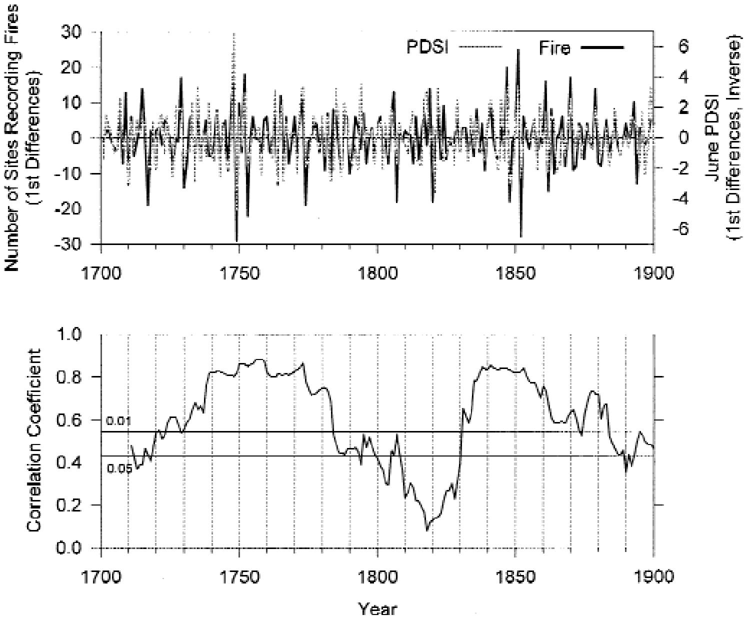

Figure 6.11. A composite time series of fire events in the Southwest (number of sites recording fires each year) is compared with a composite of Palmer Drought severity grid point reconstructions for June to August (from Cook et al. 1999) (upper graph). The interannual variations in the two time series are emphasized in this comparison by transforming (filtering) them by computing the first differences (i.e., first difference = value (year t) − value (year $t-1$)). Note that PDSI values were multiplied by −1 so that dry years (negative values) would be positive and correspond with large fire years (positive values). The lower graph shows a 20-year running correlation (plotted on the eleventh year of the period) between the two time series (from Swetnam and Baisan 1996 and Swetnam Betancourt 1998).

Heyerdahl's study in the Pacific Northwest shows a very similar decline in fire frequency during the early 1800s (Heyerdahl, Brubaker, and Agee, in press). Although the precise climatic mechanisms for reduced fire activity in such broadly scattered regions as the Pacific Northwest, the Southwest, and Patagonia are unclear, the evidence would suggest that wet/dry oscillations associated with ENSO, and/or anomalous global-scale cold conditions were probably involved.

Giant Sequoia Fire History and Climate

Giant sequoias are remarkable recorders of past surface fires. By sampling dozens of fire-scarred sequoia stumps, logs, and snags in five sequoia groves on the western slope of the Sierras, we reconstructed a network of fire histories that span the past 2000 to 3000 years (Stephenson, Parsons, and Swetnam 1989; Swetnam et al. 1991, 1992; Swetnam 1993). The composite record of fire dates from five groves shows that fire regimes varied across a range of temporal scales, from interannual to decadal, to centennial (Fig. 6.12).

The fire history work in giant sequoia groves provides an example of extreme sampling constraints and difficulties that fire historians face in reconstructing long and well-replicated fire-scar chronologies. Fire-scar cavities are common on ancient sequoias, but there are aesthetic, ethical, and regulatory constraints in obtaining cross-sectional samples from these magnificent living trees. These constraints required that we obtain our specimens entirely from dead trees. The sampling involved very arduous cutting with large chain saws (1–2-m length bars).

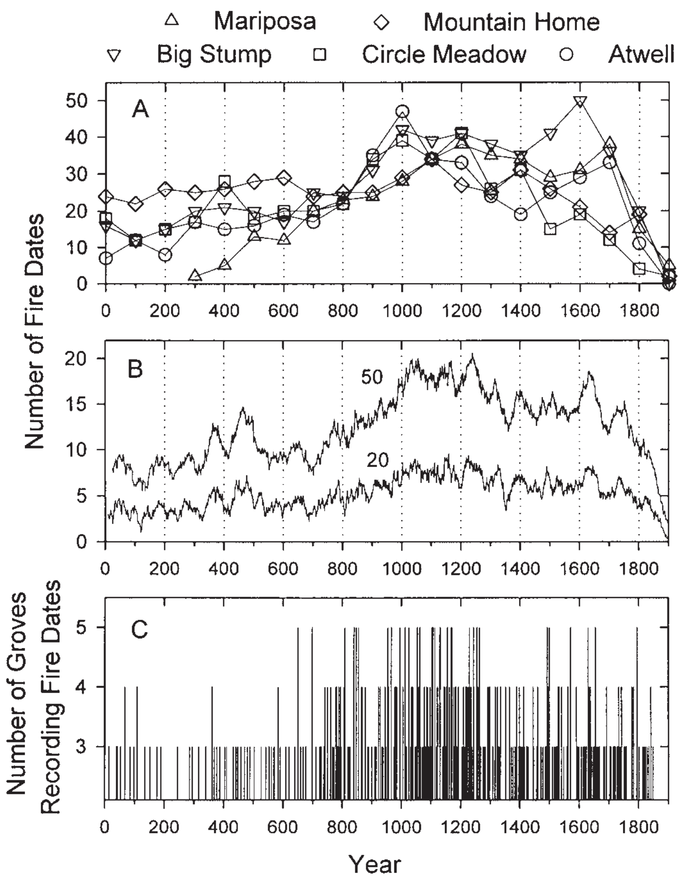

Figure 6.12. Fire occurrence in 5 sequoia groves since 1 BC. The upper graph shows centennial fire frequencies (number of fires/century) computed in each of the 5 groves, plotted on the first year of the century. The middle graph shows moving-period fire frequencies among all groves (sum of all years with fires in any of the 5 groves) for 50- and 20-year periods, plotted on the 25th and 10th years, respectively. The lower graph shows synchronous fire years in 3, 4, or 5 groves for each year (from Swetnam 1993).

Each sampled tree had several deep fire-scar cavities and a dozen or more cross sections were typically removed per tree. Careful judgment and selection of the "best" trees for sampling (and the best locations of those trees) was imperative because most dead trees with fire-scar cavities clearly did not have well-preserved, long records of past fires. In addition to loss of fire-scar evidence because of decay, and burning off of old fire scars, there were practical limitations in obtaining specimens from some trees because the fire-scar cavities were too deep to use conventional chain saws, or were at angles and heights that were unsafe for cutting. In sum, random or rigidly systematic sampling designs (e.g., grids) were thoroughly impractical in this forest type.

Despite the sampling difficulties and potential biases in selection of particular sequoia trees, we were able to obtain very long, well-replicated records and to detect substantial common variation in fire events and trends among the groves (Fig. 6.12). A variety of evidence indicate that these temporal and spatial changes in fire regimes were largely associated with past climatic variability. As previously mentioned, contingency analyses confirmed that synchrony of fires among the five groves (and synchrony of years without fires) was much greater than would be expected to occur by chance ($p < 0.01$) during most centuries. A SEA, using independent tree-ring chronologies and precipitation reconstructions from drought sensitive trees (Hughes and Graumlich 1996; Graybill and Funkhouser 1999), also confirmed that fire event synchrony was associated with drought, and lack of fire events was associated with wet years (Fig. 6.13). The drought-fire association was strongest during the most extensive fire event years (i.e., the more groves recording a fire event per year, the drier the average conditions) (Fig. 6.13).

A composite time series of fire occurrence in all groves showed substantial decadal to century-scale variability, and this series was significantly correlated ($p < 0.02$) with growing season temperatures estimated from independent foxtail pine (Graumlich 1993) and bristlecone pine tree-ring chronologies from the region (LaMarche 1974) (Fig. 6.14). An interesting result of this analysis was that at these time scales of decades and centuries, no significant correlations with the precipitation time series were identified ($p > 0.05$). But, as noted in the SEA, precipitation was associated with the occurrence of synchronous (widespread) fire events (Fig. 6.13). In contrast, SEA revealed no association between synchronous fire events and the growing season temperature estimates from foxtail and bristlecone pine tree-ring widths (results not shown).

Hence there appears to be a frequency-dependent response of giant sequoia fire regimes to precipitation and temperature. High-frequency (interannual) variations in precipitation, but not temperature, were associated with regionally synchronous fire events (Fig. 6.13). Low-frequency (decadal to centennial) variations in temperature, but not precipitation, were associated with variations and trends in fire frequency (Fig. 6.14). A plausible interpretation of these results is that interannual variations in fire activity were largely driven by moisture content of fuels. The interannual variance of growing season temperature is typically lower than the interannual variance of precipitation. Conversely, there is typically more

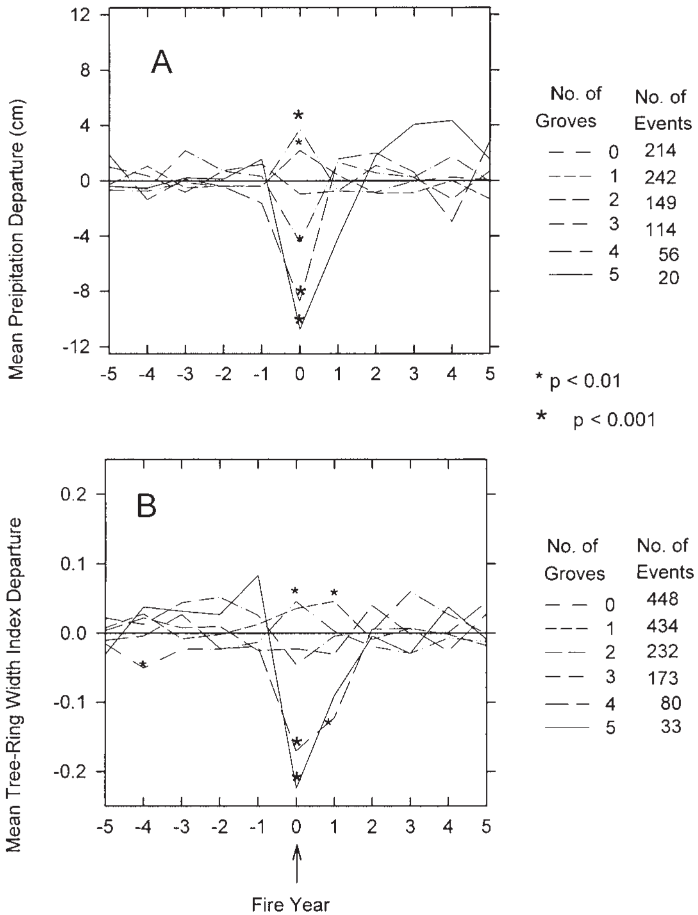

Figure 6.13. Superposed epoch analysis (SEA) of sequoia fire events versus precipitation time series. The upper graph shows the SEA using a reconstruction of winter precipitation in the Sierra from AD 1060 to 1850 (Graybill and Funkhouser 1999), and the lower graph shows the SEA using a drought-sensitive bristlecone pine chronology from the lower forest border in the White Mountains, CA, from AD 500 to 1850 (LaMarche 1974; Hughes and Graumlich 1996). Note that the more extensive fire events (i.e., synchronous fire events in 4 or 5 groves) had the strongest drought-fire signal (from Swetnam 1993).

decadal- to centennial-scale variance in reconstructed temperatures than in reconstructed precipitation time series (Graumlich 1993; Hughes and Graumlich 1996). It may be that the decadal- to centennial-scale responses of fire regimes to similar time-scale temperature regimes (Fig. 6.14) are a natural consequence of the concentration of climatic variability in this part of the spectrum. Moreover we suspect that the highest fire frequencies in sequoia groves occurred when decadal-scale warm temperatures coincided with high interannual variability in precipitation.

These conditions would be conducive to production of copious fuels during warm and wet years, and abundant fire ignitions and extensive fire spread during the warm and dry years.

Examples of such situations may have occurred during some decades of the so-called Medieval Warm Period, which appears to have been strongly expressed in the Sierra Nevada region from ca. AD 900 to 1300 (LaMarche 1974;

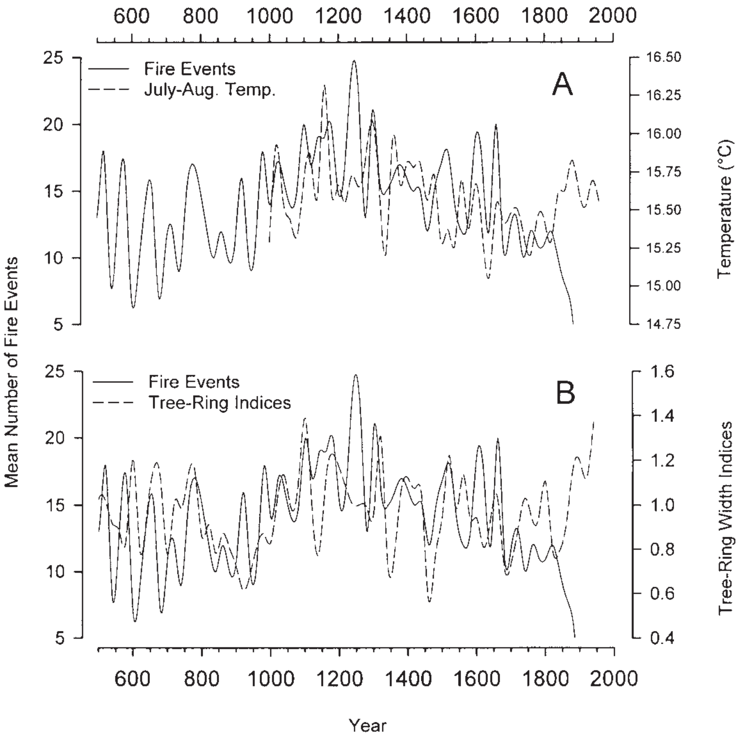

Figure 6.14. Decadal and centennial variations in estimated temperatures and fire occurrence in the Sierras are compared. The fire occurrence time series was computed from a weighted sum of fire events in the five sequoia groves in 20-year nonoverlapping periods (i.e., each year had a value of 0 to 5 depending on number of groves recording fire). The temperature series were 20-year, nonoverlapping means, and both the temperature and fire occurrence series were slightly smoothed with a cubic spline (for graphical purposes, but not for the statistical analyses). The upper graph shows a comparison of fire activity with reconstructed summer temperature from foxtail pine in the Sierras (Graumlich 1993), and the lower graph shows a comparison with a temperature responsive, upper treeline bristlecone pine chronology from the White Mountains, CA (LaMarche 1974). The Pearson correlation between the foxtail reconstructed temperature and fire series was $r = 0.41$, $p = 0.006$, and the correlation between bristlecone ring-width chronology and fire series was 0.30, $p = 0.012$ (unsmoothed values used in correlation analysis; from Swetnam 1993).

Graumlich 1993; Stine 1994). The highest fire frequencies in the past 2000 years occurred during this period (Fig. 6.14). This period, and the subsequent Little Ice Age (ca. AD 1400–1840, Grove 1988) have often been overextrapolated by various researchers, with unwarranted assumptions that these were monolithic periods of temporally consistent climate in virtually all regions of the Northern Hemisphere (see a critique of these assumptions regarding the Medieval Warm Period by Hughes and Diaz 1994). We agree that there is a high degree of regional variability in climate, and a lack of strong evidence for anything like a Medieval Warm Period or Little Ice Age in many parts of the world. Nevertheless, the climate history of the Sierras apparently coincided with the approximate timing and climatic conditions usually ascribed to these two periods (warm and cold, respectively).

In addition to the tree-ring width evidence (LaMarche 1974; Graumlich 1993) and lake level evidence (Stine 1994), now fire history may be added as another line of independent evidence in support of the occurrence of a generally warm period ca. 900 to 1300 and a subsequent cool period in the Sierra Nevada (regardless of whether they are given the appellation "Medieval Warm Period" or "Little Ice Age"). As noted above, fire frequencies were highest during the late Middle Ages (especially ca. 1100–1300) and decreased fire frequencies occurred after 1300s, especially during the major cold episodes of the mid 1400s and late 1600s. Although fire can only be considered an indirect proxy for past climatic variations, it is arguably not any less directly related to climate than, for example, lake levels.

Conclusion

Regional synchrony of ecological process is the hallmark of climatic influence and is an emergent property evident in fire occurrence time series aggregated over regions to continents (e.g., Swetnam and Betancourt 1998; Kitzberger, Swetnam, and Veblen 2001). Although fire history is often a function of site-specific environmental and cultural variables, it is clear that with network approaches, involving massive replication of high-resolution fire-scar time series across multiple points in space, it is possible to reconstruct very useful proxies of ecologically effective climatic change. The synchrony of fire regime variations in different regions can be compared and contrasted to elucidate historical climatic and cultural events and variations.

Disentangling climatic and human effects on past fire regimes is very challenging but not impossible. Multiple case studies and comparisons across networks of fire history sites is a key to identifying and distinguishing the effects of humans and climate on past forest fire regimes. More comparisons are needed of fire-scar chronologies with independent reconstructions and records of both climate and human history (e.g., from documentary sources or culturally modified trees). So far we have identified a few cases in the Southwest where Native American effects on fire frequency and seasonality before 1900 may be discernable. The most striking and clearly identified effect of humans on nineteenth- and early twentieth-century fire regimes in the Southwest and Sierras was the disruption of fire regimes by the introduction of intensive livestock grazing.

Interesting time periods showing coherent and significant fire and climate changes, such as the early 1800s and transition from Medieval Warm Period to Little Ice Age (1300–1400), offer unique opportunities for fire historians and paleoclimatologists to target specific regions and mechanisms for testing. For example, as we learn more about regionally consistent and specific terrestrial teleconnections to ocean-atmosphere patterns (El Niño–Southern Oscillation, Pacific Decadal–Oscillation, North Atlantic Oscillation, etc.), we could target key "sensitive" regions for new fire history collections and reconstructions. We have learned that climatic teleconnections in some regions are opposite in response relative to other regions. The Pacific Northwest, and northern U.S. Rockies, for example, tend to have opposite drought and fire responses to ENSO relative to the Southwest. The changing and variable nature of these inverse patterns should be thoroughly assessed using combinations of twentieth-century climate and fire occurrence data (fire atlases) and tree-ring based fire histories (Morgan et al. 2001). Direct comparisons between existing fire atlases and broad-scale networks of fire histories will be one way to do this, but development of more extensive networks is needed, especially in regions where relatively few crossdated fire-scar chronologies have been developed, such as in southwest Canada and the Pacific Northwest, northern Rockies, Great Basin, and northern Mexico.

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