Fire History Along Elevational Transects

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Thomas W. Swetnam
Christopher H. Baisan
Kiyomi Morino
Laboratory of Tree-Ring Research
The University of Arizona
Tucson, AZ 85721

Anthony C. Caprio
Sequoia & Kings Canyon National Parks
National Park Service
Three Rivers, CA 93271

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Preface

This report documents research completed by investigators at the Laboratory of Tree-Ring Research with support from the Sierra Nevada Global Change research program for the period 1991 to 1997. The body of this report is prepared as a draft manuscript intended for revision and submission to a peer reviewed journal (probably Ecology or Ecological Monographs). This paper describes the completed work on the reconstruction of fire histories along transects in the Sierra Nevada, an evaluation of fire regime patterns related to elevation, and an investigation of interannual climate-fire patterns. Appendices list and illustrate additional details of the fire history data, and ongoing research using these data. A computer disk with all of the related data files is also delivered with this report. Since this report is considered a draft and is subject to revision following comments from reviewers and additional work by the authors, we ask that it not be distributed beyond the National Parks (Sequoia, Kings Canyon, and Yosemite).

Introduction

A general goal of fire history research is to reconstruct and understand the variability in past fire regimes. The chief factors involved in controlling fire regime variability are climate, topography, vegetation, and humans. To simultaneously evaluate all of these factors requires a sampling and analysis strategy that encompasses a broad range of temporal and spatial scales. Multiple scales of assessment are necessary because the controlling factors operate most strongly within a certain range of scales, but less strongly at others. Climatic controls of past fire regimes, for example, are most clearly identified in regional-scale assessments (Swetnam and Betancourt 1990, 1998, Swetnam 1993, Larsen 1996, 1997, Veblen et al. 1999), whereas human (e.g., Native American) influences tend to be more place and time specific, and therefore are distinguishable from climatic effects in comparative analyses at watershed to stand scales (Barrett and Arno 1982, Anderson and Carpenter 1991, Clark and Royall 1995, Baisan and Swetnam 1997, Veblen et al. 1999).

Temporal assessments of climate-fire relations have commonly focused on long-term, centennial to millennial-scale patterns. This is partly because many of these assessments are based on long (>5,000 years), but relatively low temporal resolution time series from charcoal and pollen in lake and bog sediments (e.g., Anderson and Carpenter 1991, Smith and Anderson 1992, Anderson and Smith 1997, Millspaugh and Whitlock 1996). The highest temporal resolution of most sedimentary studies is multi-decadal, at best, because the temporal control is based on interpolations from carbon 14 dating estimates, approximate ages of volcanic ash deposits, and adjustments for estimated sediment influx rates. Annual and decadal resolution fire regime changes have been detected in fire history reconstructions from rare, layered (varve) sediments (e.g., Swain 1978, Clark 1988), and decadal or better resolutions are claimed for recent studies using fine interval sampling and lead-210 dating methods (e.g., Millspaugh and Whitlock 1996, Larsen and MacDonald 1998).

Tree-ring reconstructions can be used to track both fire and climate changes at resolutions as fine as seasons and years. However, because of the limited life spans of most trees, and progressive loss of the tree-ring record through decay, most of these high resolution records are less than about 300 years in length. Temporal changes in Canadian fire regimes over the past two or three centuries reconstructed with tree rings have commonly been attributed to climatic shifts during and following the Little Ice Age (LIA) (e.g., Johnson and Larsen 1991, Bergeron and Archambault 1993, Larsen 1996). Even in the cases, however, where evidence has been presented supporting climate-induced fire regime changes on time scales of centuries (from either tree rings or charcoal/pollen in sediments), the records have tended to come from single lakes or watersheds, or at best, landscapes of a few hundred thousand hectares. The potential for confounding, local-scale influences (e.g., topography and humans) on fire regimes is magnified in such relatively fine spatial scale assessments.

A regional tree-ring reconstruction from five giant sequoia groves in the Sierra Nevada extends back more than 2,000 years (Swetnam 1993). In linear distance, the two most widely separated of the five groves are about 200 km apart. Annual and decadal-scale changes in independent tree-ring width chronologies developed from foxtail pine and bristlecone pine, and calibrated with summer temperatures and cool season precipitation (Graumlich 1992, Hughes and Graumlich 1998), respectively, correspond with the sequoia fire regime reconstructions (Swetnam 1993). As expected, these millennia-length reconstructions generally show high fire frequencies during a warm and dry Medieval Warm Period (MWP) and lower frequencies during a cool and wet LIA. Independent lake level reconstructions also support the MWP interpretation for the Sierra Nevada (Stine 1994). In combination, these multi-proxy, independent reconstructions constitute the firmest evidence of the existence of a MWP and LIA regional effect on fire regimes in the world. The character and details of these climate-fire patterns are important because the available paleoclimatic evidence indicates that the timing and magnitude of the MWP or LIA were highly variable at all scales, from regional to global (Grove 1988, Hughes and Diaz 1994).

Although extreme centennial to millennial-scale fire and vegetation changes might be most pronounced and detectable in Holocene-length reconstructions from sediments, the effects of climatic change on fire regimes and forest structures were probably manifested across a broader range of temporal scales. Short-term climatic variations occurring over seasons, years, and decades, for example, were probably more immediately influential upon frequent surface fire regimes and forest structures than centennial to millennial trends or changes in climatic means. In these systems, growth and accumulation of the herbaceous and litter layers (i.e., grasses, forbs, tree leaves, cones, small branches, etc.) are critically important in determining fire ignition, spread, and intensity (van Wagtendonk et al. 1996, 1998). Fuel dynamics at these temporal scales are controlled, in part, by seasonal to inter-annual climatic variation (Swetnam and Betancourt 1998, Veblen et al. 1999). Tree recruitment and mortality processes in Sierra Nevada mixed conifer forests are probably also tied to unusual and fire events (or unusual fire-free intervals) (Stephenson et al. 1989).

These multiple temporal scales of climatic influence on fire regimes and forests are superimposed upon the spatial influences of topography. The role of topography in controlling fire regime patterns is fairly well understood at fine spatial scales, but not at broad scales. The effect of slope on fire behavior and spread at time steps of minutes and hours, for example, is effectively modeled with physical equations in quantitative simulations (Finney 1995). In contrast, the broad-scale relations of fire and topography across landscapes and centuries have been studied in only a few instances (e.g., Romme and Knight 1981, Romme 1982, Caprio et al. 1995). Several tree-ring based fire history investigations have been conducted in the southern and central Sierra Nevada, but almost all have been limited to case histories at the stand to small watershed spatial scales, with primary focus on estimating presettlement fire frequencies (e.g., Wagener 1961, Kilgore and Taylor 1979, Pitcher 1987, McLaren and Bartolome 1989, Skinner and Chang 1996).

In this paper we evaluate the assocations between elevation and fire frequency and interannual climatic variability and fire occurrence at the regional scale. We reconstruct fire chronologies in a large set stands over a broad range of elevations. Although we do not specifically evaluate human effects on past fire regimes, we identify and discuss the striking changes that occurred during and following the Euro-American settlement period.

Study Area

Our fire history collections were obtained from 49 sites along four elevational transects on the west slope of the Sierra Nevada (Fig. 1). The northernmost transect is located in Yosemite National Park, and the southernmost is in Mountain Home State Forest. The two middle transects are located in Sequoia and Kings Canyon National Parks. The transects span a broad range of elevations, aspects, slopes, and forest types (Table 1). In general, the transects are located in the middle elevations of the west slope, extending from about 1090 to 2680 m. The transects range in length from 7 to 15 km.

The topography along the length of the transects is relatively steep (up to 100% slopes), although flat areas are also present within and between many of the collection sites. The aspects of the sites are primarily towards the west and south, although a few sites have northern or eastern aspects (Table 1). The transects are situated on continuous topographic features, such as along ridge lines (or close to a ridge line), or along the mid-portions of slopes (Fig. 2). These topographic features extend along the elevational gradient without major fire barriers (e.g., continuous rock escarpments, cliffs, or large rivers) between the collection sites, except for the Giant Forest transect, which is bisected by a major river canyon (Marble Fork of the Kaweah River) (Fig. 2). Because the topography and fuels (at present) are more-or-less continuous between collection sites, fire spread between most sites along the transects is possible. Fire spread between the three southern tansects is possible but unlikely because of distances (i.e., up to 30 km) and major barriers such as deep river canyons and large, continuous rock exposures.

At the lowest end of the transects the dominant over story trees include ponderosa pine (*Pinus ponderosa*) and black oak (*Quercus kelloggii*). Some of these sites are located on the ecotone of pine/oak forest and foothills chaparral types (see xxxxxx for discussion of Sierra Nevada vegetation types). In the middle portions of the transects white fir (*Abies concolor*), ponderosa pine, jeffrey pine (*Pinus jeffreyii*), and giant sequoia (*Sequoiadendron giganteum*) are dominant. This type is commonly referred to as mixed conifer (Rundel et al. 1977). At the highest end of the transects white fir, red fir (*Abies magnifica*), and jeffrey pine are dominant, with western white pine (*Pinus monticola*) and lodgepole (*Pinus contorta*) as occasional dominant trees in some sites.

The fire season extends from April to November in the southern and central Sierra, with a maximum area burned in June, and a maximum in numbers of lightning caused fires in July (Fig 3.).

Methods

Site and Sample Selection

Our previous fire history research in giant sequoia groves (Swetnam 1993) provided a database of fire regime reconstructions for the sequoia-mixed conifer portion of the elevational transects. In our search for suitable collection sites we followed the major topographical features (ridges and slopes) up and down from a set of four groves: Mariposa, Big Stump, Giant Forest, and Mountain Home (Fig. 2). The transects follow elevational gradients, with the sequoia groves in the middle or near the upper end of the transects. We searched for forest stands that were relatively free of major canopy disturbance, such as complete overstory removal from past logging or recent crown fires that would have consumed the fire-scar record preserved in living trees, stumps, logs, and snags. We also searched for forest stands that appeared relatively homogenous (composition and density) and were not dissected by potential fire barriers (e.g., continuous rock outcrops, rivers, etc.).

The selected stands ranged in size from approximately 20 to 50 ha. These areas were defined by topographic features such as ridge tops and drainage bottoms, or obvious changes in the overstory structure (e.g., a change from forest to open meadow). We searched systematically within the stands for fire-scarred trees. Our aim was to thoroughly search the entire area of the stand and to identify a set of broadly distributed specimens that contained a well preserved and long historical record of past surface fires. We examined all potential fire-scarred specimens that we could locate within the selected stands. This searching and examination involved careful inspection of the fire-scarred surfaces of all potential specimens, and identification of those with well preserved wood, datable tree-rings, and maximum numbers of visible scars.

Most of the collected specimens were full cross sections taken with a chainsaw from stumps, logs, and snags. A smaller number of partial sections were taken from living trees (Arno and Sneck 1977) to extend the fire history record to the present. A goal of our sampling strategy was to maximize the temporal completeness and length of the fire event record for each stand. This was not a statistical sampling of the “population” of fire events (or fire intervals), rather, our goal was to obtain an *inventory* of fire events that occurred within the stands that was as complete and as long as possible, given the fragmentary nature of the record and practical limitations in recovering it.

Laboratory Sample Processing and Fire Interval Analyses

Dry cross sections were re-sectioned with a band saw to prepare a smooth surface for sanding. A belt sander was used with progressively finer grits from 150 to 400. All tree-rings were crossdated using variations in ring-width, latewood widths, and false ring patterns to accurately assign calendar years to each growth ring (Stokes and Smiley 1968, Swetnam et al. 1985). Calendar years and seasonal timing were determined for each fire scar by observing under magnification (10X to 30X) the relative position of the scars within the dated annual rings (Dieterich and Swetnam 1984, Baisan and Swetnam 1990, Ortloff 1996).

Scar position was divided into six categories, dormant (D), early-earlywood (E), middle-earlywood (M), late-earlywood (L), latewood (A), and undetermined (U). The early-earlywood, middle-earlywood, and late-earlywood correspond approximately to a division of the earlywood by thirds (Baisan and Swetnam 1990). Based on our knowledge of cambial phenology of conifers (Fritts 1976, Baisan and Swetnam unpublished data, Parsons unpublished data), we estimated the approximate calendrical dates for each of the scars (except U positions) to within 4 to 6 week periods. The undetermined (U) category were scars with too much decay, resin, or suppressed (slow) ring growth in the area of the scar for reliable determination of intra-ring position.

Statistical distributions of historical fire intervals were described for each of the collection sites for the period of analyses. The record becomes progressively more fragmentary and poorly replicated with increasing time before present. Tree mortality, decay, and fire processes continually remove the fire-scar/tree-ring record from the landscape. Since we were interested in comparing fire frequency and fire interval distributions within and between sites that might be related to elevation, rather than sample size effects, we chose a standard period when all sites had an adequate number of trees recording fires (usually more than 5 trees). This period was AD 1700 to 1900. We conducted a "resampling analyses" (or bootstrap, described below) to determine the approximate sample size that was adequate to reconstruct a relatively compete record of surface fires.

Fire frequency estimates from most single fire-scarred tree records (i.e., point fire frequency estimates) provide very incomplete estimates of fire frequency for either the stand or for a point location. Although a few trees may have been consistently scarred by all, or almost all surface fires that actually burned near that particular tree's lower bole, most individual tree records are probably missing fire scars from some of these events. We are more confident that composites of fire-scar records (see Dieterich 1983) from groups of trees at these spatial scales (i.e., 10 to 100 ha.) are relatively complete, at least for the more widespread fires within stands. We base this interpretation on the replication of fire dates among many widely dispersed trees evident in our master fire chronology charts, and on the re-sampling analysis. This analysis is a fairly simple application of re-sampling statistical methods (Mooney and Duvall 1993). We use it to address the question: At what sample size (number of fire-scarred trees) does the fire frequency reach a maximum, given the same approximate sampling area and time period? In other words, as we are compiling our inventory of fire events from multiple fire-scarred trees within a given area, at what sample size (approximately) have we typically detected all or most of the fires that occurred within that stand and time period, and any additional samples (fire-scar dates) are merely replicating previously detected fire dates?

The procedure was accomplished with a computer program (SSIZE, written by R. L. Holmes, Lab. of Tree-Ring Research). Fire frequencies were computed interactively from random selections of the fire-scar tree records from among the full set of records obtained from the stand. For example, a single tree was first randomly selected 1,000 times from the full sample set (sampling with replacement), and the mean fire frequency for a fixed period (1700 to 1900) was computed from these 1,000 re-samples. The mean fire frequency for this single-tree iteration was equivalent to the mean fire frequency per tree in the whole set (i.e., a mean tree, or "point" fire frequency) from that site. (Obviously, the same trees were chosen numerous times during this iteration given that our sample sizes were usually less than 20 trees per site.) Next, the program randomly selected two fire-scarred trees from the set 1,000 times and re-computed the mean fire frequency from the composite records from the two tree sample sets. The same procedure was applied to increasing sample sizes up to the maximum for the full sample set, minus one tree.

Using the re-sampled sets for each reduced sample size, the mean, variance, and confidence intervals around the mean fire frequency were estimated, and plotted as a function of sample size (Fig. 4). If the inventory of fire events is incomplete the mean fire frequency should continuously increase as a function of sample size, i.e., as more fire-scarred tree records are added to the sample set, more fire dates are detected. If the inventory becomes complete or nearly complete before reaching the maximum number of samples, the fire frequency should stabilize around or near a particular mean, i.e., additional fire-scarred trees add few or no new fire dates.

The fire frequency/sample size curves shown in Figure 4 were typical of the range of fire frequency/sample size curves for the 49 sites we studied. Fires recorded by single trees were sufficiently common at the spatial scale of our collections (e.g., 20 to 50 ha) that the sampling density we employed was usually inadequate to obtain a complete inventory of all fires. However, when only fires recorded by 2 or more trees were assessed, the mean fire frequencies always stabilized after about 5 to 10 trees were included in the sample set (Fig. 4), i.e., the fire frequency/sample size function closely approached or reached an asymptote.

It is likely that fires recorded by single trees were usually relatively small fires within the sampled sites. Different fire intensities may also be involved in numbers of trees scarred per event, but we doubt that this was very common because the large majority of fire scar events were recorded by trees that had already been scarred at least once. Trees with existing scars (with exposed wood and seeping resin) are readily re-scarred by fires of any intensity (Dieterich and Swetnam 1984, Swetnam et al. 1992). It is also possible that some single tree fire dates were due to larger burns that only partially burned into the sampled areas. In any case, the stabilized fire frequencies recorded by 2 or more trees with sample sizes greater than about 5 trees indicates that we have sufficient sample sizes to obtain complete inventories of fires of these types within the sampled areas.

Mean fire interval (MFI) and standard deviation, as well as maximum and minimum fire intervals, were determined for the collections using the program FHX2 (Grissino-Mayer 1995, 1997). Median fire intervals and other measures of central tendency were also estimated using Weibull functions fitted to the interval distributions (Grissino-Mayer 1995). MFIs were based on all fires recorded by fire-scarred specimens within the period of analysis (1700-1900). We computed fire interval statistics based on two different fire-scarred tree composites: all fires recorded by two or more trees, and fires recorded by at least 25 percent of fire-scarred trees with a minimum of two trees scarred per fire. The percentage of fire-scarred trees recording a fire date was computed as the number of trees recording the fire date divided by the number of fire-scar susceptible trees (Romme et al. 1980, i.e., trees that already had been fire scarred at least once before) and multiplied by 100..

We consider these categories to be coarse spatial estimates of relative fire extent within the sites. The “all” category probably reflects frequency of most fires larger than “spot fires” (i.e, those recorded by a single tree). The 25 percent category probably reflects relatively larger fires that burned through most or all of a given stand. These estimates of fire extent are relativistic, and undoubtedly subject to various spatial biases. Nevertheless, we consider these to be reasonable and conservative estimates of the frequency of fires that spread beyond single trees within the collection sites.

Comparisons Across Elevational Gradients

Potential fire extent within and between sites, and relations between elevation and fire frequency, were assessed by graphically plotting fire chronologies on charts for each site separately, and then as site composite chronologies on charts for each transect.

These graphical comparisons were useful for identifying patterns of synchrony/asynchrony and the timing of the decline in surface fire regimes during the 1800s (Dieterich 1980, Baisan and Swetnam 1990). The composite site chronologies were arranged on the charts from highest (top of the chart) to lowest (bottom of the chart) elevations. Fire events that were highly synchronous across the elevational transects were labeled on the graphs in a composite event chronology for the entire transect.

Fire frequencies (numbers of fire events/time period) were computed for the 1700 to 1900 period for all sites and were graphed versus the elevation for each site in scatter plots. These elevations were the approximate mid-elevations for the sites, which in some cases extended up and down slope some distance (less than 100 meters). Pearson correlation coefficients and significance levels were computed, and linear regression functions were estimated for the fire frequencies versus elevation. Pooled fire frequency estimates for all sites were also compared with elevations in one scatter plot.

Climate-Fire Analyses

Climate-fire relations at inter-annual scales were evaluated by comparing composited fire records from all sites across the region with reconstructed estimates of summer drought from independent networks of tree-ring width chronologies. The composited fire-scar time series used were the total number and percent of trees scarred each year, and total number and percent of sites recording fires (by any tree within the site) for each year. The drought reconstructions were a set of 3 grid point time series of seasonalized (June, July, and August) Palmer Drought Severity Indices (PDSI) for southern and central California (Meko et al. 1993, Cook et al. 1996, grid points 14, 15, and 23 averaged).

Interannual climate-fire relations were evaluated by conducting superposed epoch analyses (SEA) (Baisan and Swetnam 1990, Swetnam 1993, Veblen et al. 1999). The first step in this analysis was identifying a set of extreme regional fire occurrence years to compare with the tree-ring drought reconstructions. To do this we plotted the time series of numbers of trees and sites recording fires each year from 1700 to 1900. Since there was a century-scale trend in these series that was related to numbers of fire-scarred trees sampled through time (due to decay processes), we identified thresholds above and below certain values (i.e., numbers of trees or sites reecording fires) for identifying the extreme years. This will be explained more thoroughly in the results section.

We used the extreme low and high fire occurrence years in the SEA. The SEA computer program (Holmes and Swetnam, unpublished) computed the mean values from the reconstructions (i.e., PDSI, precipitation, temperature) during the largest and smallest fire occurrence years (year *t*). The program also computed the mean climate values for years *t*-1 to *t*-5 (preceding years) and years *t*+1 and *t*+2 (subsequent years) for all large and small fire events. A Monte Carlo simulation (i.e., re-sampling) was used to estimate confidence intervals around the observed mean values (Mooney and Duvall 1993, Swetnam and Betancourt 1992, Swetnam 1993, Veblen et al. 1999).

Results

Master Fire Chronologies - Stand and Transect Composites

Individual specimens (other than sequoia) contained fire-scar dates extending back to AD 1402. Fire scars in sequoia specimens dated back to 1125 BC (Swetnam et al. 1992). These earliest fire-scar dates indicate that surface fire regimes persisted at least from these times until the late nineteenth century. It is not possible, however, to evaluate the fire frequency (or fire interval distributions) during the earliest centuries of the record because there were too few specimens with fire scars from these times remaining on the landscape. The site fire-scar chronology charts were useful for visually assessing the patterns of synchrony within the sampled stands (Fig. 5).

Fire interval distribution statistics were highly variable among the many site chronologies that were analyzed (Table 2). Most of these distributions were highly skewed to the left, i.e., there were many relatively short fire-free intervals with smaller numbers of long intervals (Fig. 6). Despite this skewness, we find that the different measures of central tendency were not greatly different. The mean, median, and Weibull median intervals for the same extent category and site, for example, usually differed by one year or less, especially for the relatively high fire frequency sites. Differences of one to several years in measures of central tendency were more common in sites with relatively low fire frequencies (Table 2).

The transect fire chronology charts (based on site composites) reveals several general patterns (Fig 7a, b, c, d). First, the decline in frequent, widespread fires generally occurred between circa 1860 and 1880 at most sites. This disruption of the surface fire regime corresponds to the introduction of large numbers of sheep and other livestock into the higher elevation forests of the Sierras during and following the drought of the early 1860s (Vankat 1977). The second general pattern is that some fires were highly synchronous among all or most the sites along the transects. This suggests that during certain years (typically droughts, as will be shown later) multiple fires and/or large fires tended to ignite and spread across elevational gradients independently (more-or-less) of vegetation differences. Third, a general tendency can be discerned in these charts of relatively higher and lower fire frequency along the transects from low to high elevations, respectively.

Seasonal Timing of Fires

The intra-ring positions of fire scars were typically in the latter portion of the growth ring (Fig. 8). Between about 5 and 15 percent of scars occurred in the last one-third of the earlywood, 55 to 60 percent occurred within the latewood, and 20 to 30 percent occurred during the dormant season (i.e., on the boundary between two rings). The intra-ring positions of about 5 to 30 percent of scars could not be determined due to decay, excessive resin, or extremely suppressed ring growth in the areas of the scars.

Our best estimates of the approximate calendrical timing of these events are indicated in Figure 8. Knowledge of cambial phenology of Sierran conifers is limited because so little research has been done on this topic for the relevant species. We do have some unpublished data from increment core samples we have taken at different times of the year from various species, and we have some measurements of sequoia stem expansion/contraction rates during several years from band dendrometers (Parsons unpublished data). Nevertheless, given the potential variations in phenology among different species, different elevations and sites, and different weather conditions for each year, we are only confident in estimating the timing of these events to within time windows of about one month to more than two months for each of the intra-ring position categories. Also note that these estimated time windows overlap among some of the different categories because of the potential sources of variations just mentioned (Fig. 8).

The 20th-century monthly distribution of lightning fires (area burned and numbers of fires, Fig. 3) and the seasonal timing of pre-20th century fire-scar events (Fig. 8) generally correspond, with a dominant period of fire occurrence in the late summer from about July through September. This match appears somewhat better for the monthly numbers of 20th century fires than for the area burned. The 20th-century monthly area burned suggests a peak in June, whereas the dominance of latewood fire-scars suggests a somewhat later peak in fire occurrence, i.e., July or later. This may not be a real difference because we know that the latewood can be formed over a relatively long period during the mid to late summer. In contrast, earlywood tends to form rapidly during the late spring and early summer months, partly as a function of stored nutrient reserves from winter photosynthesis (Fritts 1976). Hence, latewood scars probably represent fires that burned over a relatively longer time period from July into September than most early wood scars forming in June. The combination of the months July to September in the modern record totals to more than 60 percent of all area burned and more than 85 percent of fire numbers (Fig. 3).

Dormant season scars were probably fire events that occurred after tree-ring growth ceased in the late summer or early fall, rather than spring or early summer fires that occurred before cambial growth initiated. We base this assumption on the distribution of 20th century lightning fires, when very few fires were ignited or spread over substantial areas before the cambial growth season (i.e., before early May). Following this reasoning, as a dating convention, we assigned calendar year dates of dormant season scars to the year of formation of the adjacent latewood cells. (Note that dendrochronologists follow a different convention in the Southwestern United States, where early season fires are much more frequent. Here, dormant season fire scars are assigned to the calendar year of formation of the adjacent earlywood cells [Dieterich and Swetnam 1984, Ortloff 1996].)

Elevation/Fire Frequency Relations

Fire frequency tended to be inversely related to elevation. This pattern is discernible in some of the transect composite fire chronologies (Fig. 7), but is more clearly seen in the shape and measures of central tendencies of the fire interval distributions (Fig. 6) and in the scatter plots of fire frequency versus elevation (Figs. 9, 10). The scatter plots show only the relations for the fires recorded by 25 percent or more of fire-scar susceptible trees, however, we found similar inverse relations with the all fires (>1 trees) category (not shown).

Inverse correlations of fire frequency and elevation were quite strong along three of the four transects (i.e., Big Stump, Giant Forest and Mountain Home transects) (Fig. 9). The Mariposa transect had the broadest range of elevations among the four transects, but high fire frequencies were reconstructed along the entire elevation gradient.

The composite scatter plot of fire frequency versus elevation for all sites among the three transects (Fig. 10) shows a flattening of the relations at the lower elevations (< 1700 m), with a steeper curve across the higher end of the gradient (from about 1800 to 2600 m). The flattening at the lower end of the gradient, however, is largely driven by the sites on the Mariposa transect, since these were the lowest elevation sites sampled.

Fire-Climate Relations

The multi-century composite time series of numbers and percentages of trees and sites recording fires each year over the entire study area reveal an emergent property of fire regimes at these scales: regional synchrony of fire occurrence (Fig. 11). The composite record shows some century-scale trends that were largely due to sample depth (numbers of specimens included in the series through time), however, individual fire years stand out as exceptional. Similar patterns of inter-annual synchrony of fire occurrence over centuries and large regions have been shown in the Southwestern United States (Swetnam and Betancourt 1990, 1998) and in Patagonia, Argentina (Veblen et al. 1999). This degree of synchrony among so many widely dispersed sites, despite the high fire frequencies within sites, is much greater than might be expected to occur by chance (Swetnam and Betancourt 1998). Such synchrony is a clear indication of inter-annual climatic influence on fire occurrence, since no other known factor could cause such broad-scale temporal and spatial patterns.

The century-scale trend in numbers of trees and sites recording fires was probably due in part to sample size (Fig. 11). Regionally increased and decreased fire occurrence years (large and small numbers of trees or sites recording fire years) were therefore identified as the largest and smallest years in the time series plots, while considering that sample sizes decreased, especially before 1750 and after 1850 (Fig. 12).

Comparisons of the highly synchronous large and small fire years from the composite record (Fig. 12) with independent, tree-ring based drought reconstructions from California confirm that climate was the most likely cause of regional fire events (Fig. 13). There was a remarkable consistency between large fire years and extreme droughts. Among 38 large fire years between 1700 and 1900, 32 occurred during relatively dry summers (PDSI values below zero). Regional fire years were particularly coincident with extreme drought years. For example, of the 11 years with PDSI values below -3.5, 8 were large fire years. In two of the three exceptions when the extreme drought years did not coincide with large fires, the previous year had a large fire event. This suggests that occasionally, large fire years may remove sufficient amounts of fuel so that subsequent dry years have less effect on synchronizing fire occurrence.

Overall there was less consistency among small fire years (few sites recording fires), with 15 of 22 sites occurring during wet years (PDSI values above zero). The role of both wet and dry years in synchronizing regional fire activity, however, is illustrated in the superposed epoch analyses (Fig. 14). Statistically significant ($p < 0.05$) dry and wet conditions during large and small fire years, respectively, was confirmed, and the importance of prior years conditions (negative lag years in Fig. 13) was also revealed. Wet conditions in the prior one to four years, combined with dry conditions during the fire year, for example, was important to the occurrence of large regional fire events. This pattern was most likely due to the effect of wet conditions on production of fine fuels, especially grasses and tree leaves. The dry prior year (lag -1) conditions for small fire years has a similar and additional interpretation: a dry prior year would result in less fuel production available for fire in a subsequent year, and increased fire occurrence during the dry prior year may remove fuels, so that lack of fire would be further synchronized during subsequent wet years. Very similar lagging and current year climate-fire patterns have been reported in the Southwestern United States (Swetnam and Betancourt 1992, 1998), the Colorado Front Ranges (Veblen et al. 1995), and in Patagonia, Argentina (Veblen et al. 1999).

The large fire years selected by percentages of trees recording fires within sites shows significant ($p < 0.05$) prior year relations (Fig. 14). The large fire years determined by percentage of trees versus sites recording fires are slightly different because some sites had large percentages of trees scarred during certain years. It seems logical that the percentage of trees scarred time series might better reflect the importance of fuel production in prior years than the percentage of sites time series because tree scarring is probably more a function of fire extent and intensity patterns. Since many of the sites are quite distant from each other, especially between transects, fire synchrony in this series is probably less reflective continuity of fuels within and between sites.

Discussion

Elevation-Fire Relations

Strong relations between fire frequency and elevational gradients have been demonstrated or inferred in a number of fire history studies in the western United States (e.g., Habeck and Mutch 1973, Arno 1980, Tande 1979, Allen 1989, Barton 1994, McKelvey and Busse 1996). None of these studies, however, have demonstrated these patterns with systematically collected data sets over multiple, landscape-scale elevation gradients, and over multiple-century time scales. Our 18th and 19th century fire history reconstructions for the west slope of the Sierra Nevada confirm an inverse relation between fire frequency and elevation, at least for the elevational range from about 1,500 to 2,500 m, i.e., from ponderosa pine up through mixed conifer, red fir, and lodgepole pine forests.

The indirect elevational controls on fire regimes most probably operate through the effects of elevation on the water balance. The water balance affects plant species and community type distributions and productivity (Stephenson 1998), which determines fuel types, arrangements, and amounts. The water balance also affects fuel condition (i.e., moisture content), which controls fire ignition probabilities, spread rates, and intensities. Other important topographic and site factors adding complexity to these relations include slope, aspect, soils (especially depth and types), and wind patterns (Agee 1993). Our data are not adequate for testing all of these potential factors because our collection sites do not include enough replicates of different slopes, certain aspects (especially north and east aspects) or soil types, and we lack quantitative measurements of soils, species compositions, densities, etc. on most of these sites. Even if we had these measures there would still exist the problem of potential biases in our selection of fire history study sites along elevational gradients. This has not usually been recognized, however, as a major stumbling block in ecological gradient studies (but see Stohlgren et al. 1995).

Despite these problems, the strong correlations we document between fire frequency and elevation along three out of four transects are supportive of the idea that fire regimes vary in a partially predictable fashion across some large landscapes and long time periods. The lack of any obvious fire frequency-elevation relations along the Mariposa transect, however, is a useful exception; it suggests that other factors can sometimes (and perhaps often) override elevation-related controls on fire regimes. There are a large number of possible reasons for relatively high fire frequencies along the entire extent of the Mariposa transect. These could include non-elevation related lightning or human ignitions, wind, or plant productivity patterns related to soils, etc. It might be impossible to adequately sort out these possible explanations, however, some lines of evidence might be gathered and explored that would support some explanations over others. For example, if humans (i.e., Native Americans) inflated fire frequencies along the gradient by setting many of these fires we would expect that fire occurrence and climate relations might be weaker in these sites, or for the entire transect, compared to other transects. Also, if people were setting fires earlier in the growing season (e.g., April-May) than fires typically ignited by lightning, this might be detectable in the distributions of seasonal timing of fires. These are additional investigations we hope to carry out with our current data sets and to report in future papers.

Further study of fire frequency-elevation relations would be enhanced by extending the fire history collections up and down elevation along the gradients, and by further developing and employing simulation models (e.g., Miller and Urban 1995, Miller 1998). This would be useful for example to test generalized models of fire-elevation relations, such as one proposed by Martin (1982) and discussed at some length by Barton (1994). Martin proposed a bell-shaped fire frequency-elevation function (at continental scales), with low frequencies at the lowest and highest elevations because of lack of sufficient fuels (either too dry, too cold or both), and highest fire frequencies at intermediate elevations where higher productivity would tend to assure adequate and continuous fuels for more frequent fire ignitions and spread. More specific and dynamic models for the Sierras, such as developed by Miller and Urban (1995), might also be modified to predict fire regime patterns across a broader range of elevations, plant physiognomic types, and fire regimes than has been done so far. For example, both model predictions and fire history data to compare with these predictions would be very interesting for the foothills communities (e.g., oak-savannas and chaparral zones) and for subalpine communities (e.g., foxtail pine). It should be possible to reconstruct fire history in the oak types (with fire scars and age structures) and within the chaparral zone using low elevation, fire-scarred pines and oaks that inter-finger into chaparral communities, or exist as islands within the chaparral.

Fire-Climate Relations

It is clear that climatic variations on time scales of less than a decade were very important to fire occurrence in the pre-settlement (i.e., pre-1860) fire regimes of the Sierra Nevada. This particular range of the weather-climate scale had relatively little attention in the published fire climatology literature until recently (e.g., Swetnam and Betancourt 1990, 1998, Veblen et al. 1999). In contrast, the largest body of research, by far, has been conducted on fire weather relations, i.e., time scales of minutes to days and weeks. Likewise most published paleoecological research related to fire climatology has focused on decadal-centennial and longer time scale fire-climate variations evident in sedimentary charcoal and pollen time series. Our research shows, however, that inter-annual fluctuations in moisture are very important to landscape and regional scale fire activity and, therefore, a more complete understanding of how climatic change affects fire regimes must include the seasonal to decadal time scales.

The synchrony of large regional fire years among numerous fire-scarred trees and forest stands across the Sierras, and the remarkable correspondence of these largest fire years with the most extreme drought years, is testimony to the importance of interannual climatic variation. These patterns also demonstrate the usefulness of independently derived tree-ring reconstructions of both fire and climate for illuminating environmental correlates across a broad range of scales. Overall, the drought-fire correlation is not particularly surprising, after all, this is quite logical and would be expected by most knowledgeable fire managers and fire researchers. However, we think these results are quite impressive when considering that we have demonstrated the drought-fire association with a degree of detail and accuracy, and over temporal and spatial scales, never before approached in modern or paleoecological research. More importantly, the details of these relations suggest certain climate-vegetation-fire patterns that could be very useful for prediction. In particular, the lagging relations between regional fire years and prior-year wet conditions coupled with current-year drought, suggest that dynamical models incorporating these relations (or reflecting as an emergent property) could be used in a forecast/prediction mode. We also detect differences in the lagging relations among different forest community types and elevations (Caprio and Swetnam 1995, Swetnam and Betancourt 1998) that suggest a number of important questions that might be addressed with simulation models.

Finally, the regionally synchronous fire years and extreme droughts of the past signal a warning to fire managers and decision makers: these fire regimes and ecosystems can fluctuate very rapidly and at very broad scales in response to extreme wet-dry cycles (i.e., high interannual climatic variability). Regionally extensive fire years have been a characteristic of these landscapes for centuries. In contrast to the regionally synchronized surface fire regimes of the past, changes in the forest (fuels) structures during the 20th century due to fire suppression could mean that regionally synchronized high intensity fires could become the norm.

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Table 1. Fire-scar collection site descriptions.

Transect & Site Code[1]	Number of Samples	Elevation (m)	Dominant Aspects	Dominant Tree Species[2]
<u>Yosemite-Mariposa Transect</u>				
BFH	5	1090	N-NW	PSME, CADE, QUKE, PIPO
POF	12	1150	W	QUKE, PIPO
WCL	7	1200	W/SW,SE	PIPO, QUKE, CADE, PSME
WCU	7	1210	SE,S,SW,W	PIPO, CADE, QUKE, PSME
BBS	6	1305	NE	QUKE, CADE, PIPO
HEL	5	1350	N	PIPO, CADE, QUKE
WWL	7	1365	NE	PIPO, CADE, PILA
WWM	9	1395	NE	PIPO, CADE, PILA
BMD	9	1760	S,SW	PIPO, PILA, CADE, QUsp, ABCO
MP*	19	1916	flat, SW	ABCO, SEGI, PILA
WPS	12	2060	S	ABCO, PILA, PIPO, CADE, QUKE
WPN	10	2060	N	PILA, ABCO, CADE, PIPO, PSME, QUKE
LPS	7	2090	S	CADE, PILA, ABCO, PIPO
RFS	7	2120	NW	PIJE, PILA, ABCO, QUKE
WTH	8	2425	S	ABCO, PIJE, PILA
<u>Big Stump</u>				
GMW	8	1510	S-SE	CADE, PIPO, QUsp
ELP	6	1720	S	QUKE, CADE, PIPO
BS*	21	1894	flat, S, SW	SEGI, ABCO
BSG	13	1930	S-SE	PIJE/PIPO, CADE
ABY	3	1980	SE	ABCO, SEGI, CADE, PIPO/PIJE, PILA
MNZ	3	2220	W-SW	PIJE, ABCO, ABMA
BRF	6	2450	S-SW	PICO
BKR	4	2530	W	ABMA, ABCO, PIJE
<u>Giant Forest</u>				
APR	7	1560	SE, W-NW	PIPO
CMN	6	1685	S	PIPO
CMM	5	1640	S-SE	PILA, PIPO, QUsp
CME	7	1640	SW	PIPO, QUsp, ABCO, ABMA, CADE
CCR	15	1640	SW	PIPO, CADE
CMW	6	1670	S-W	PIPO, CADE, QUsp
MOR	15	1940	W	PIPO, PIJE

BOW	4	1940	S, SE	PIPO, PIJE
BOE	5	1940	S, SW	PIPO, PIJE
CM*	19	2115	flat, W	ABCO, SEGI, PILA
HUK	6	2000	S, SW	PIJE,PIPO, PILA
GFP	9	2133	W-SW, N	PIJE, PIPO, PILA
HSR	20	2180	S-SE	PIJE
HMP/LIR	9	2682	W	ABMA, PIMO, PICO
SPR	5	2273	W, SW	PIJE, PIPO, ABCO, PILA, QUKE

Mountain Home Transect

MOM	13	1600	SE	QUKE, PIPO
LEE	13	1710	E, N, SE	CADE, ABCO,PIPO, PILA, QUKE
LEW	7	1730	N, NW, SW	CADE, ABCO, PIPO PILA, QUKE
DEL	7	1875	SE	PIPO, QUKE
BMK	10	1920	S/SE, W	PIPO, ABCO, CADE
RCP	5	1950	NW	ABCO, PIPO
DEM	20	1970	S/SE	PIPO, ABCO, CADE
MH*	17	2029	all	ABCO, SEGI, PILA
TFP	10	2225	SW	ABCO, PIPO
DEU	12	2042	S	PIPO, ABCO
MMS	9	2560	S	PIJE, ABMA

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[1] Site codes with an asterisk(*) are within giant sequoia groves.

[2] Species codes:
ABCO = Abies concolor; ABMA = Abies magnifica; CADE = Calocedrus decurrens; PICO = Pinus contorta; PILA = Pinus lambertiana; PIJE = Pinus jeffreyi; PIMO = Pinus monticola; PIPO = Pinus ponderosa; QUKE = Quercus kelloggii; QUsp = misc. oak species; SEGI = Sequoiadendron giganteum

Figure Captions

Fig. 1. Map of the central and southern Sierra Nevada showing the National Parks and locations of the fire history elevational transects.

Fig. 2. Maps of the relative locations of the fire history collection sites along the four elevational transects. The large arrows show the approximate direction of increasing elevation. The three-letter site codes (corresponding to Tables 1 and 2) are shown adjacent to symbols for the sites (triangles).

Fig. 3. Monthly distribution of area burned and numbers of fires ignited by lightning in Sequoia National Park from 1922 to 1986.

Fig. 4. Fire frequency as a function of reduced sample size for two sites (CMR from Giant Forest transect and DER from the Mountain Home transect). The two solid curves show the mean fire frequency from 1,000 re-samplings at the indicated sample size (number of fire-scarred trees) from the total sampled set from each site for the period 1700-1900. The dashed curves show the 95% confidence limits estimated from the variance of the 1,000 re-samples (see text for more explanation).

Fig. 5. Examples of master fire chronology charts for two sites (High Sierra Ridge, HSR, on the Giant Forest transect, and Deer Ridge, DEM, on the Mountain Home transect). Each horizontal line represents the fire chronology from a single fire-scarred tree. The tick marks on the horizontal lines represent fire dates recorded by that tree. Extensive fires with the sites are indicated with a long tick mark. Composite dates for the extensive fires are listed at the bottom of each chart.

Fig. 6. Distributions of intervals between fires in each of the sites along the Mountain Home transect for the period 1700-1900. The sites are shown from the highest (top) to the lowest (bottom) elevation. The arrows show the median fire intervals.

Fig. 7. Composite site chronologies arranged from highest (top) to lowest (bottom) elevation sites for each transect (charts A, B, C, and D). The horizontal lines represent the composite chronology of all fire dates recorded by any tree within each of the sites. The composite dates at the bottom of each chart are the fires recorded by 5 or more sites along the transect, except for the Big Stump Grove, where 3 or more site fires are listed.

Fig. 8. Distributions of inter-annual fire-scar positions for three transects. Relative, intra-ring position is shown on the x-axis, and the approximate calendrical timing of tree growth, and inferred fire timing, are shown on the graph.

Fig. 9. Mean fire intervals versus elevations for the four transects. Mean fire intervals were computed for the period 1700-1900.

Fig. 10. Mean fire intervals pooled over all sites (1700-1900) and plotted versus elevation.

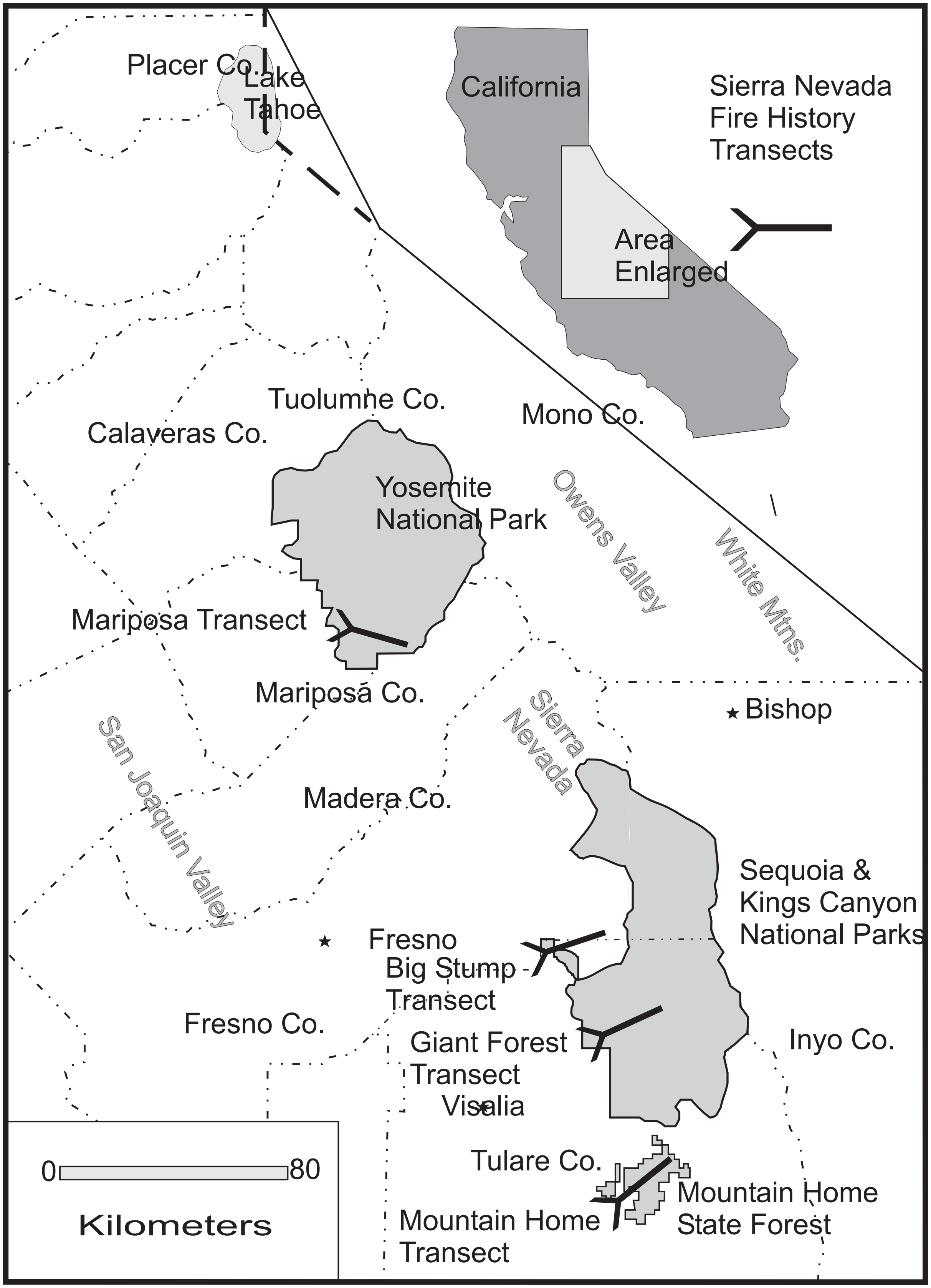
Fig. 11. Time series of the number of trees scarred each year from 1400 to the 1990s. The sample depth curve is the number of fire-scarred trees with datable tree-rings included in the entire data set through time. A 30-year cubic spline, overlaid on the number of tree scarred time series, shows decadal and century-scale variations.

Fig. 12. Time series of the number of sites recording a fire each year from 1700 to 1900. The largest and smallest fire years are labeled.

Fig. 13. Plot of the mean summer Palmer Drought Severity Index reconstructed from tree-rings for the central and southern Sierra Nevada region with the largest and smallest fire years “superposed” on it (1700-1900).

Fig. 14. Mean departures of PDSI values during largest and smallest fire years and lagged years before (negative lags) and after (positive lags) the fire years (1700-1900). Mean departures were calculated as the difference between the mean PDSI value estimated with a random selection of the same numbers of years (1,000 iterations), and the actual mean of the PDSI during the largest and smallest fire years. The confidence intervals were estimated from the variances computed from the 1,000 iterations. Plots are show for analyses using large and small fire years determined from the percentage of sites recording fires (left plots) and percentage of trees recording fire years (right plots).

Figure 1



Placer Co.
Lake Tahoe
California
Sierra Nevada Fire History Transects
Area Enlarged
Tuolumne Co.
Mono Co.
Calaveras Co.
Yosemite National Park
Owens Valley
White Mtns.
Mariposa Transect
Mariposa Co.
Sierra Nevada
Bishop
San Joaquin Valley
Madera Co.
Sequoia & Kings Canyon National Parks
Fresno
Big Stump Transect
Fresno Co.
Giant Forest Transect
Inyo Co.
Visalia
Tulare Co.
0
80
Kilometers
Mountain Home State Forest
Mountain Home Transect

Figure 2

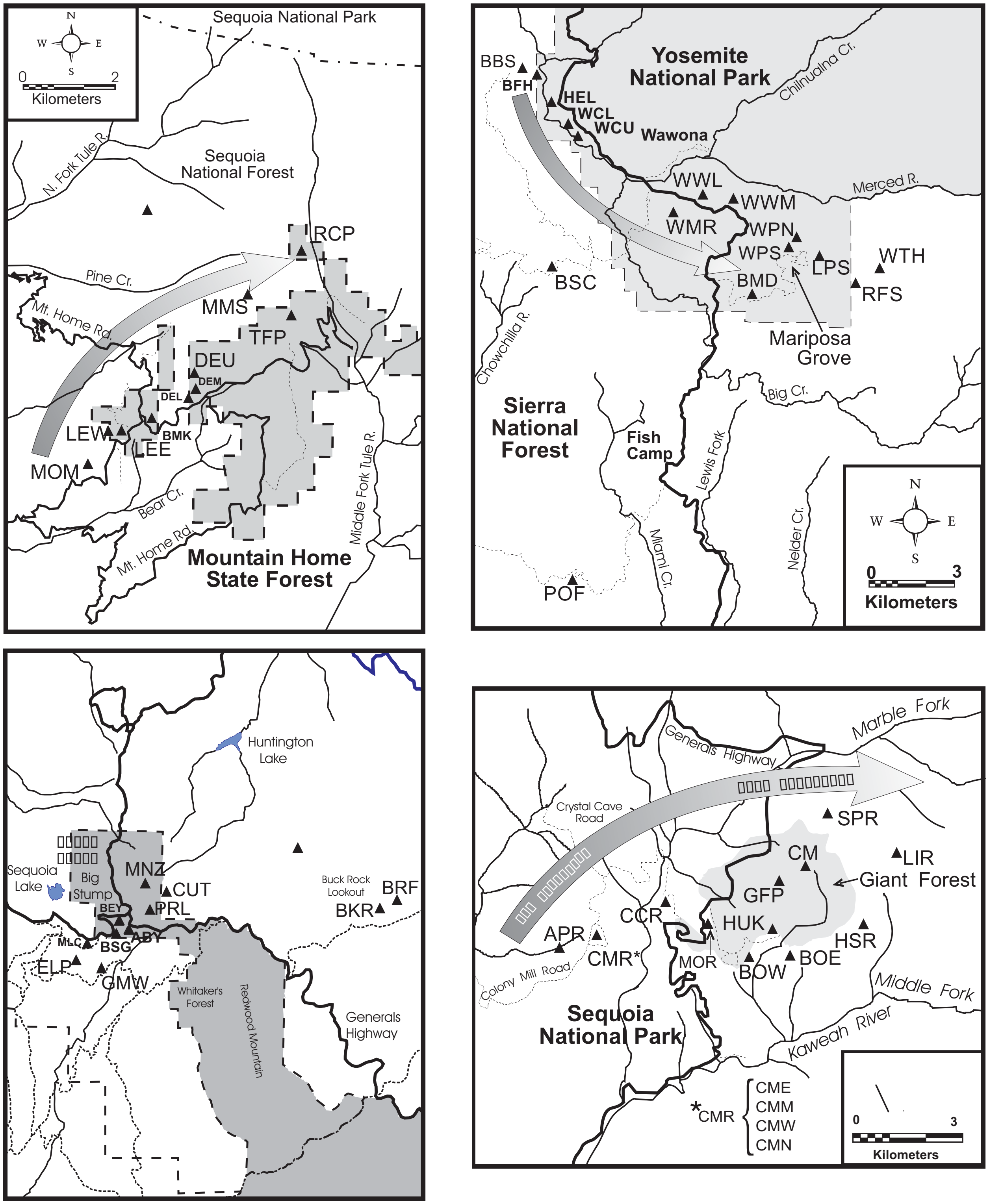
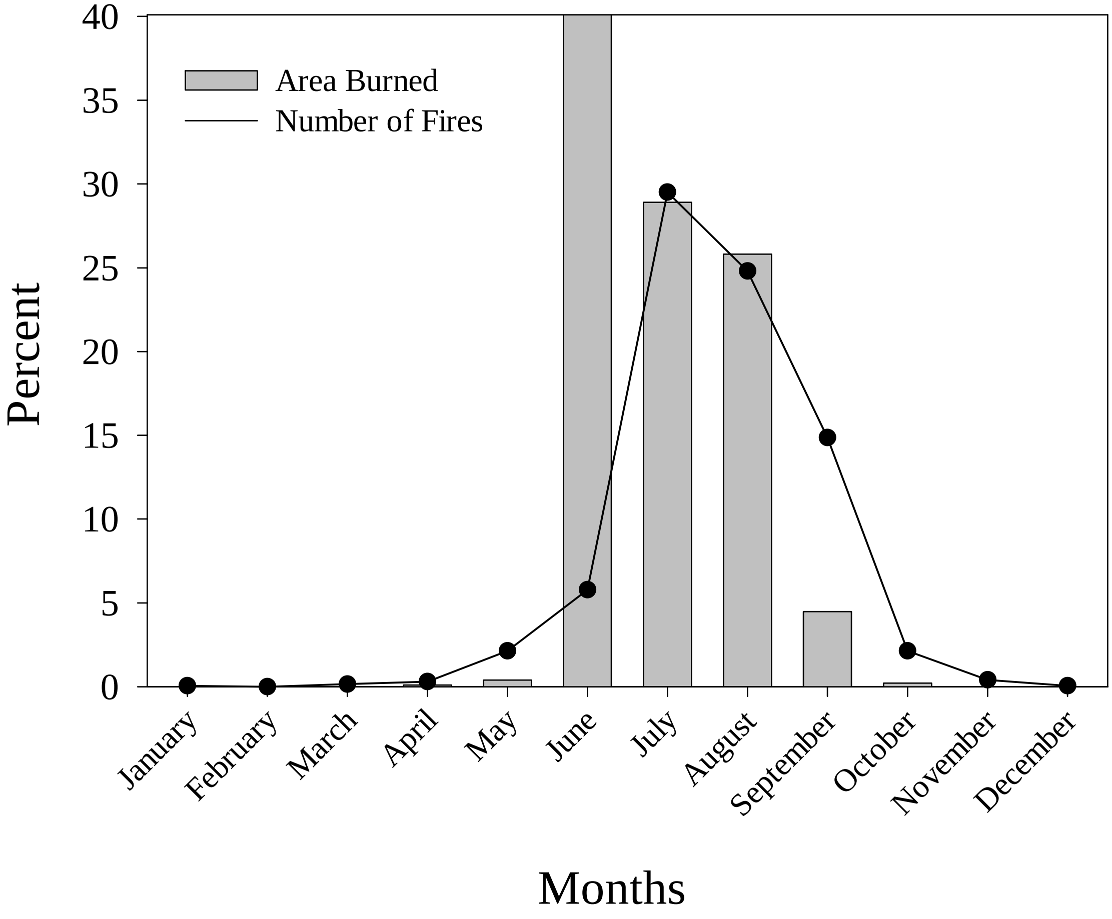
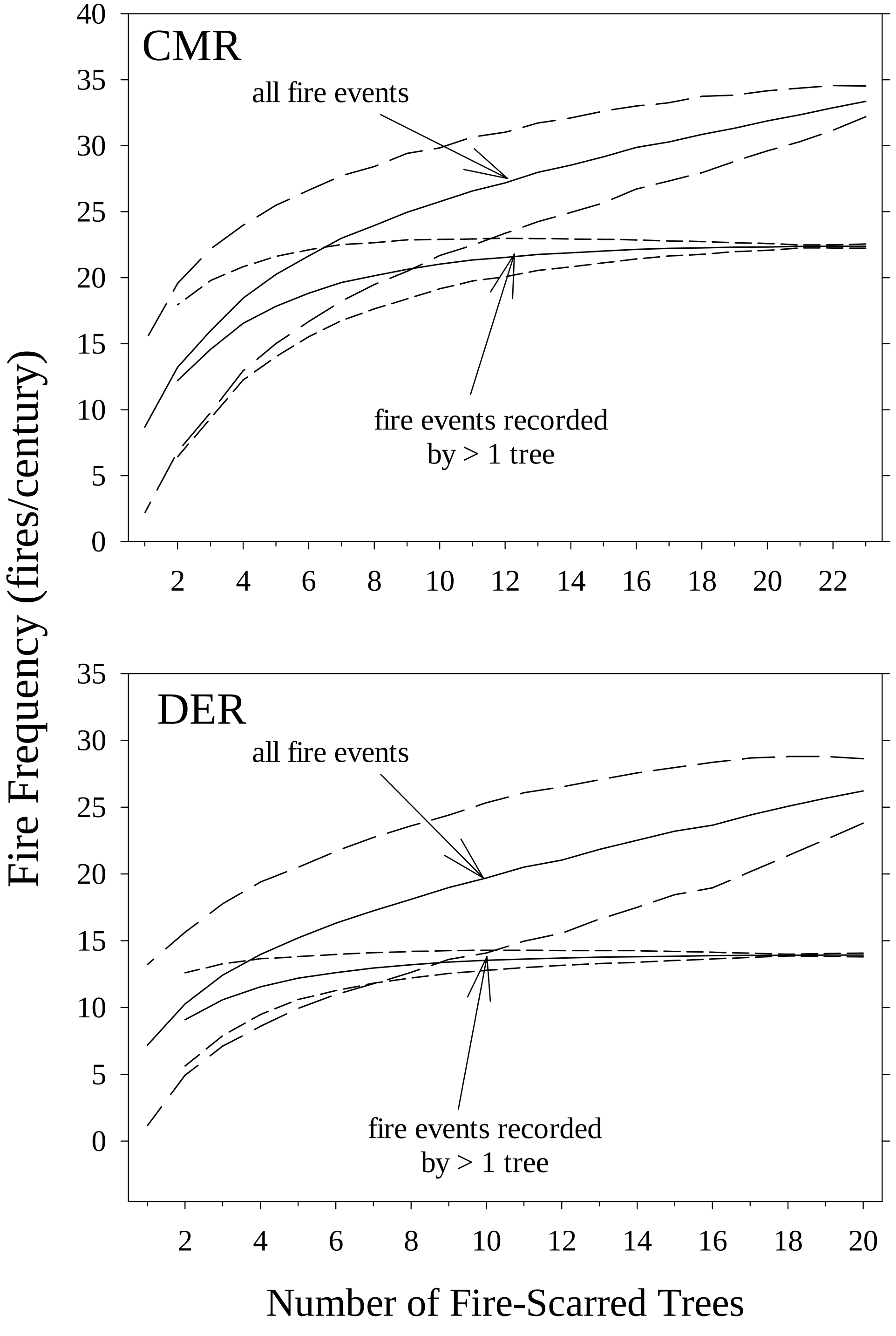

N
W
E
S
0
2
Kilometers
Sequoia National Park
N. Fork Tule R.
Sequoia National Forest
RCP
Pine Cr.
Mt. Home Rd.
MMS
TFP
DEU
DEM
DEL
LEW
BMK
LEE
MOM
Bear Cr.
Mt. Home Rd.
Middle Fork Tule R.
Mountain Home State Forest
BBS
BFH
HEL
WCL
WCU
Yosemite National Park
Chinualna Cr.
Wawona
WWL
WWM
Merced R.
WMR
WPN
WPS
WTH
BSC
LPS
BMD
RFS
Mariposa Grove
Chowchilla R.
Big Cr.
Sierra National Forest
Fish Camp
Lewis Fork
Miami Cr.
Nelder Cr.
POF
N
W
E
S
0
3
Kilometers
Huntington Lake
Sequoia Lake
Big Stump
MNZ
CUT
BEY
PRL
Buck Rock Lookout
BRF
BKR
MLC
ABY
BSG
ELP
GMW
Whitaker's Forest
Redwood Mountain
Generals Highway
Marble Fork
Generals Highway
Crystal Cave Road
SPR
CM
LIR
Giant Forest
GFP
CCR
HUK
APR
HSR
CMR*
MOR
BOW
BOE
Colony Mill Road
Middle Fork
Sequoia National Park
Kaweah River
*CMR
CME
CMM
CMW
CMN
0
3
Kilometers

Figure 3



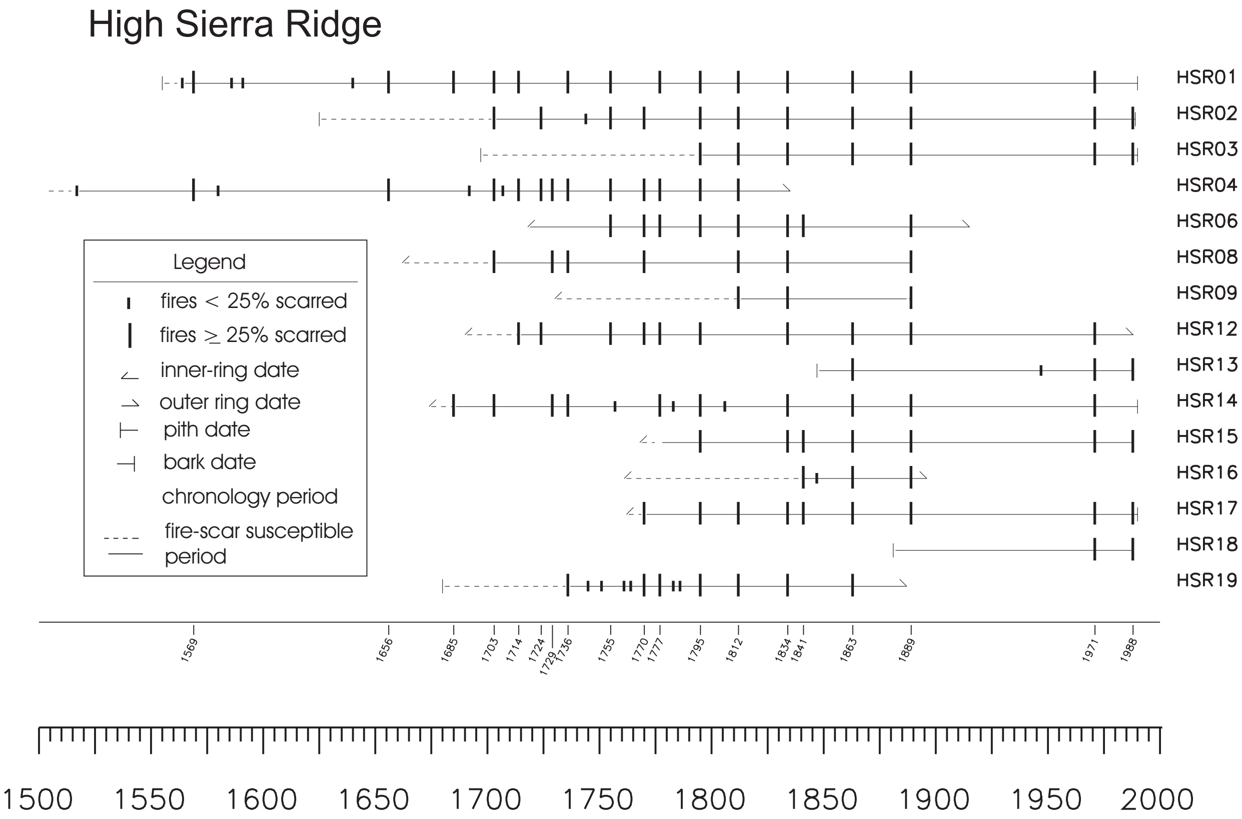
40
35
30
25
20
15
10
5
0
Percent
Area Burned
Number of Fires
January
February
March
April
May
June
July
August
September
October
November
December
Months

Figure 4



CMR
all fire events
fire events recorded by > 1 tree
40
35
30
25
20
15
10
5
0
2
4
6
8
10
12
14
16
18
20
22
DER
all fire events
fire events recorded by > 1 tree
35
30
25
20
15
10
5
0
2
4
6
8
10
12
14
16
18
20
Fire Frequency (fires/century)
Number of Fire-Scarred Trees

Figure 5 A & B


High Sierra Ridge
HSR01
HSR02
HSR03
HSR04
HSR06
HSR08
HSR09
HSR12
HSR13
HSR14
HSR15
HSR16
HSR17
HSR18
HSR19
Legend
fires < 25% scarred
fires ≥ 25% scarred
inner-ring date
outer ring date
pith date
bark date
chronology period
fire-scar susceptible
period
1569
1656
1685
1703
1714
1724
1729
1736
1755
1770
1777
1795
1812
1834
1841
1863
1889
1971
1988
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000

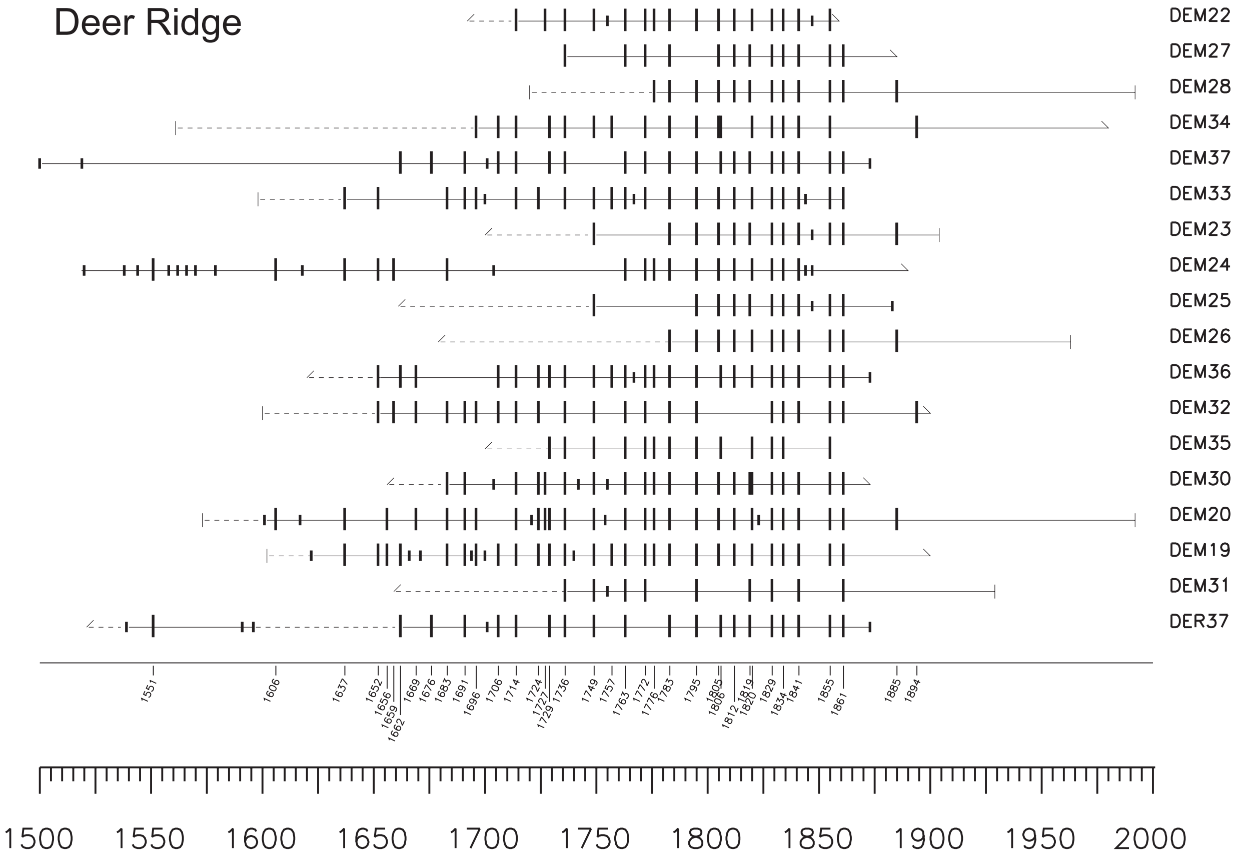

Deer Ridge
DEM22
DEM27
DEM28
DEM34
DEM37
DEM33
DEM23
DEM24
DEM25
DEM26
DEM36
DEM32
DEM35
DEM30
DEM20
DEM19
DEM31
DER37
1551
1606
1637
1652
1656
1659
1662
1669
1676
1683
1691
1696
1706
1714
1724
1727
1729
1736
1749
1757
1763
1772
1776
1783
1795
1805
1806
1812
1819
1820
1829
1834
1841
1855
1861
1885
1894
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000

Figure 6

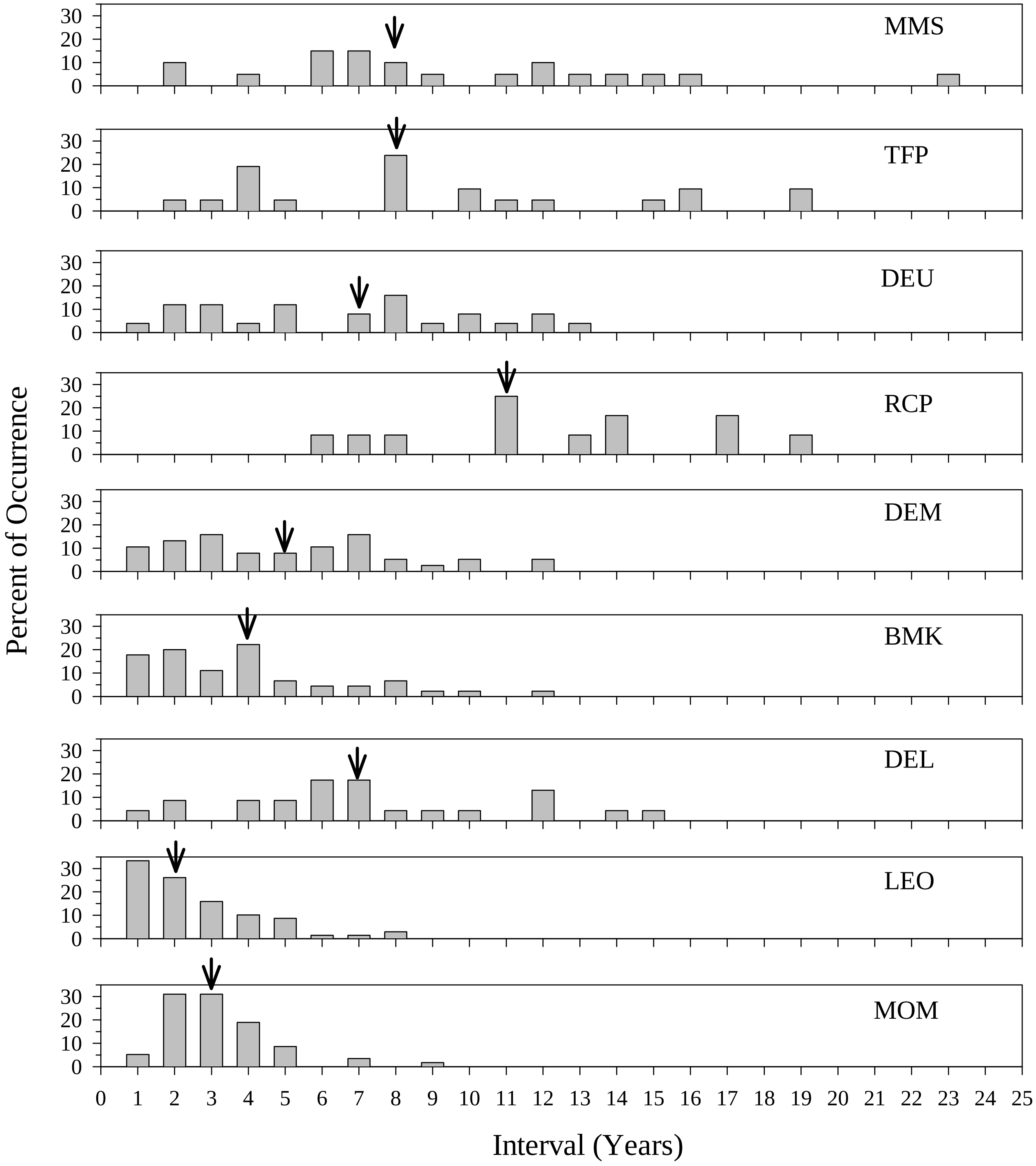
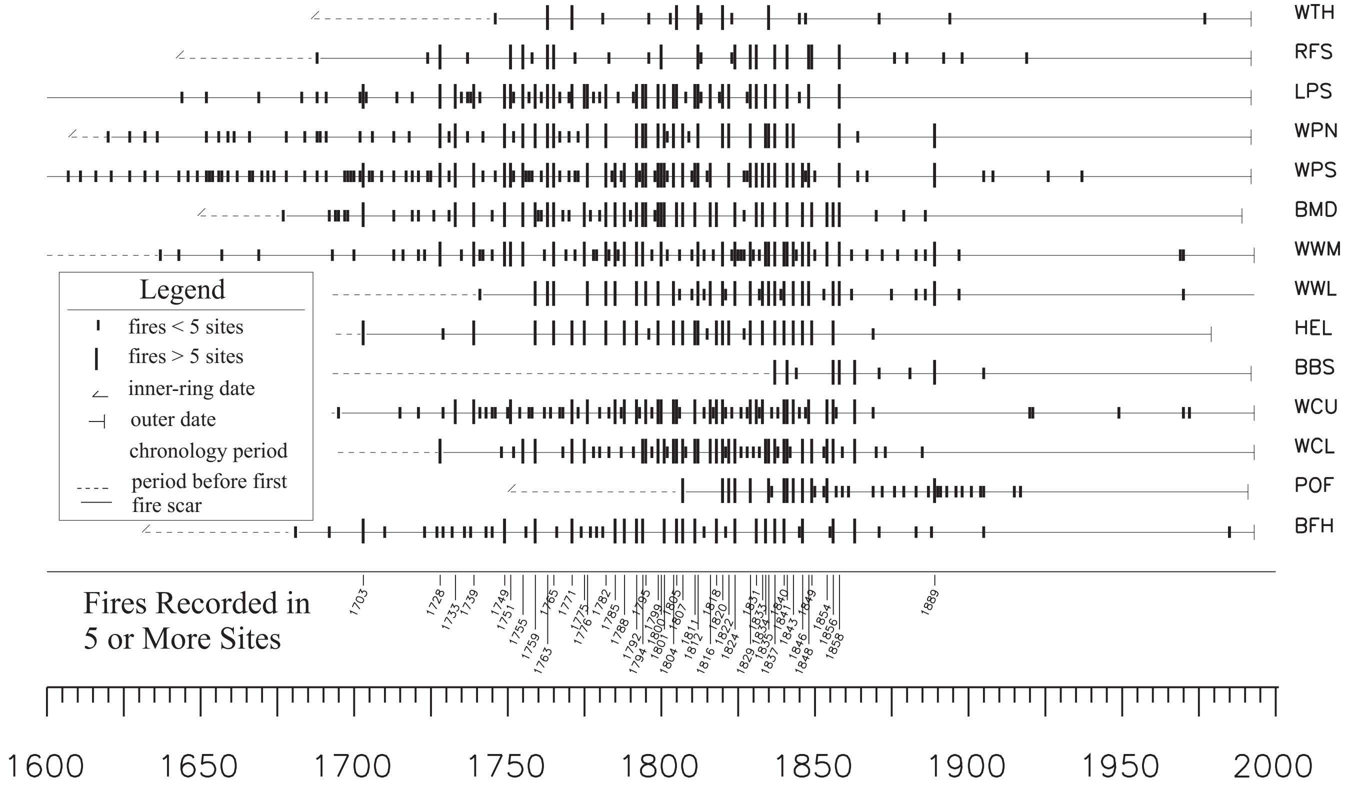

MMS
TFP
DEU
RCP
DEM
BMK
DEL
LEO
MOM
0
10
20
30
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
Percent of Occurrence
Interval (Years)

Figure 7 A & B

A Mariposa-Yosemite Transect



B Big Stump Transect

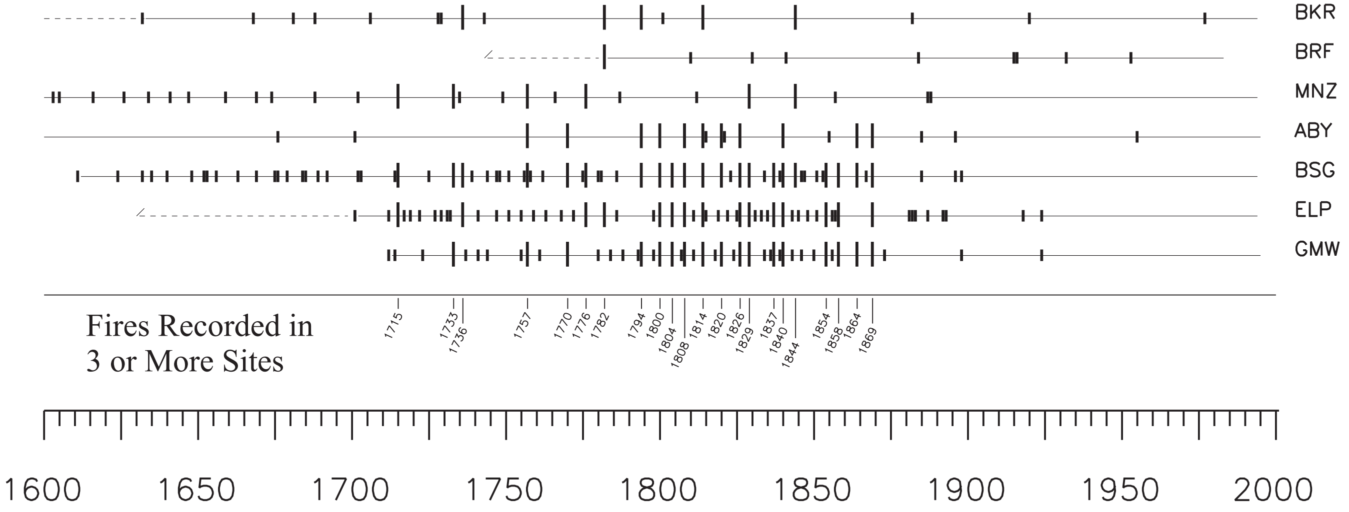
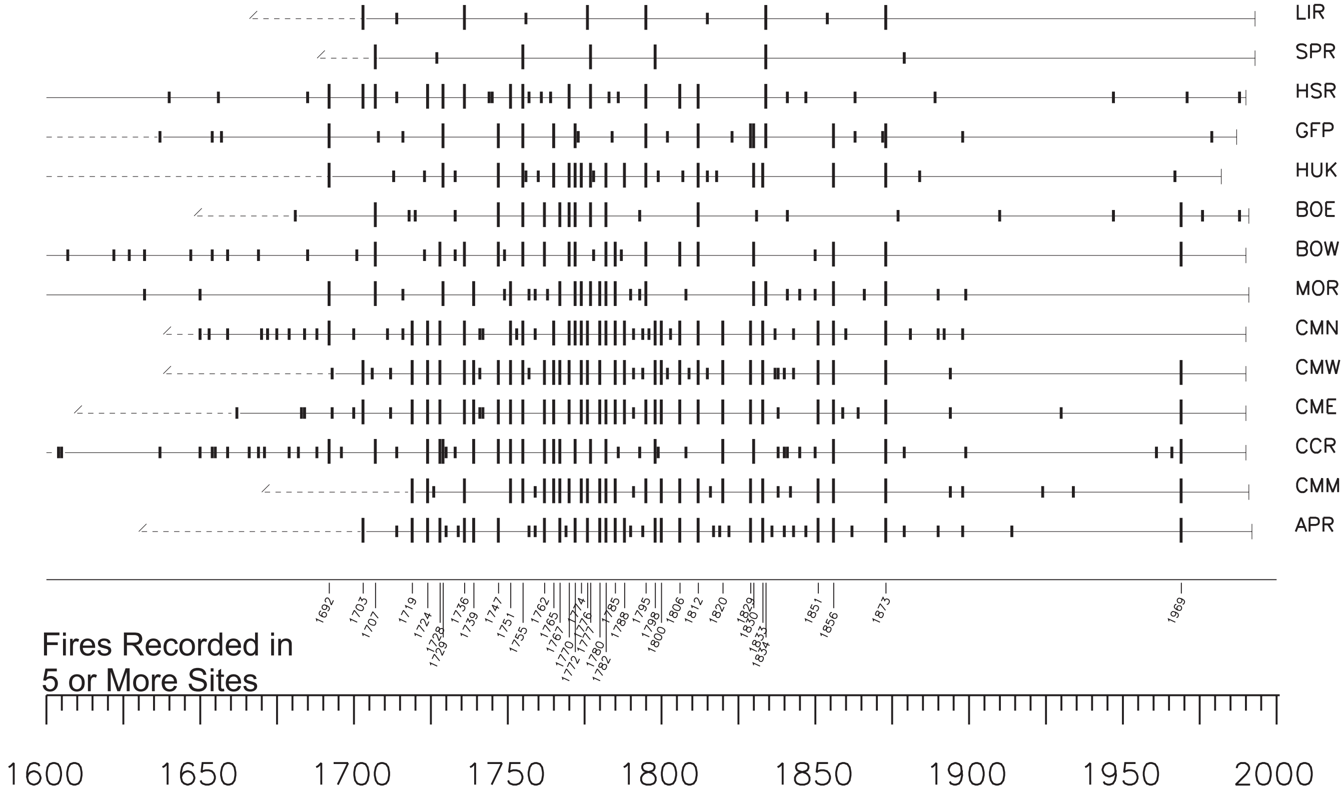


Figure 7 C & D

C **Giant Forest Transect**



D **Mountain Home Transect**

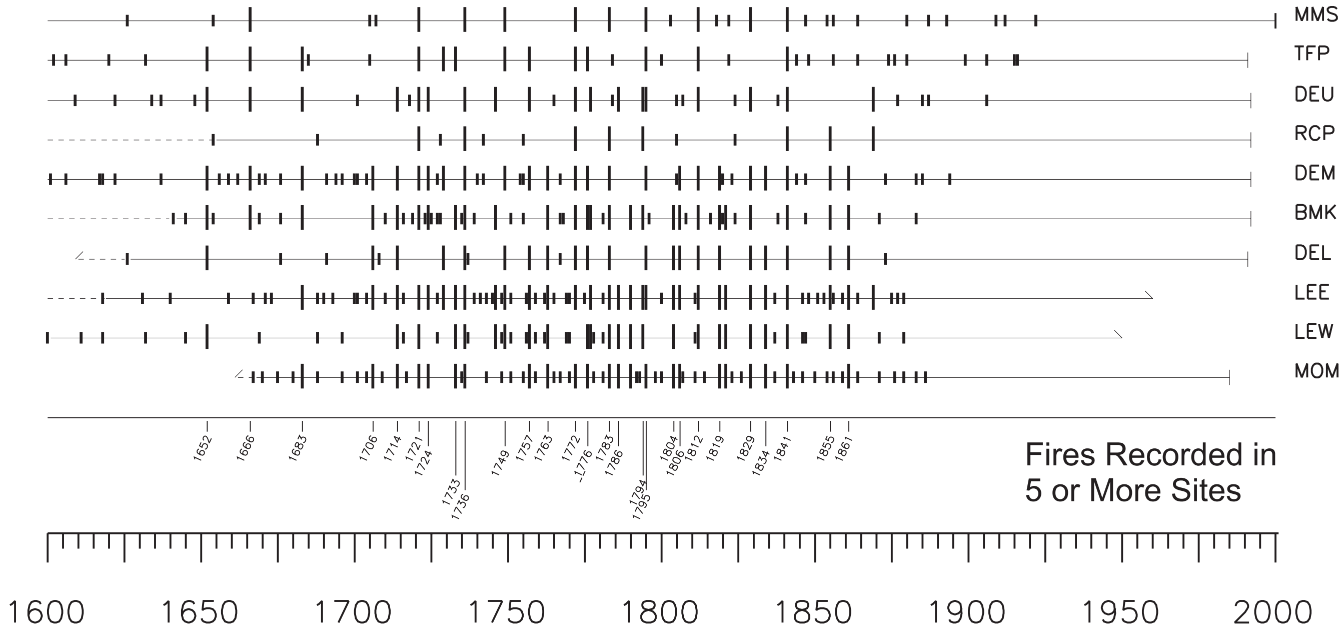
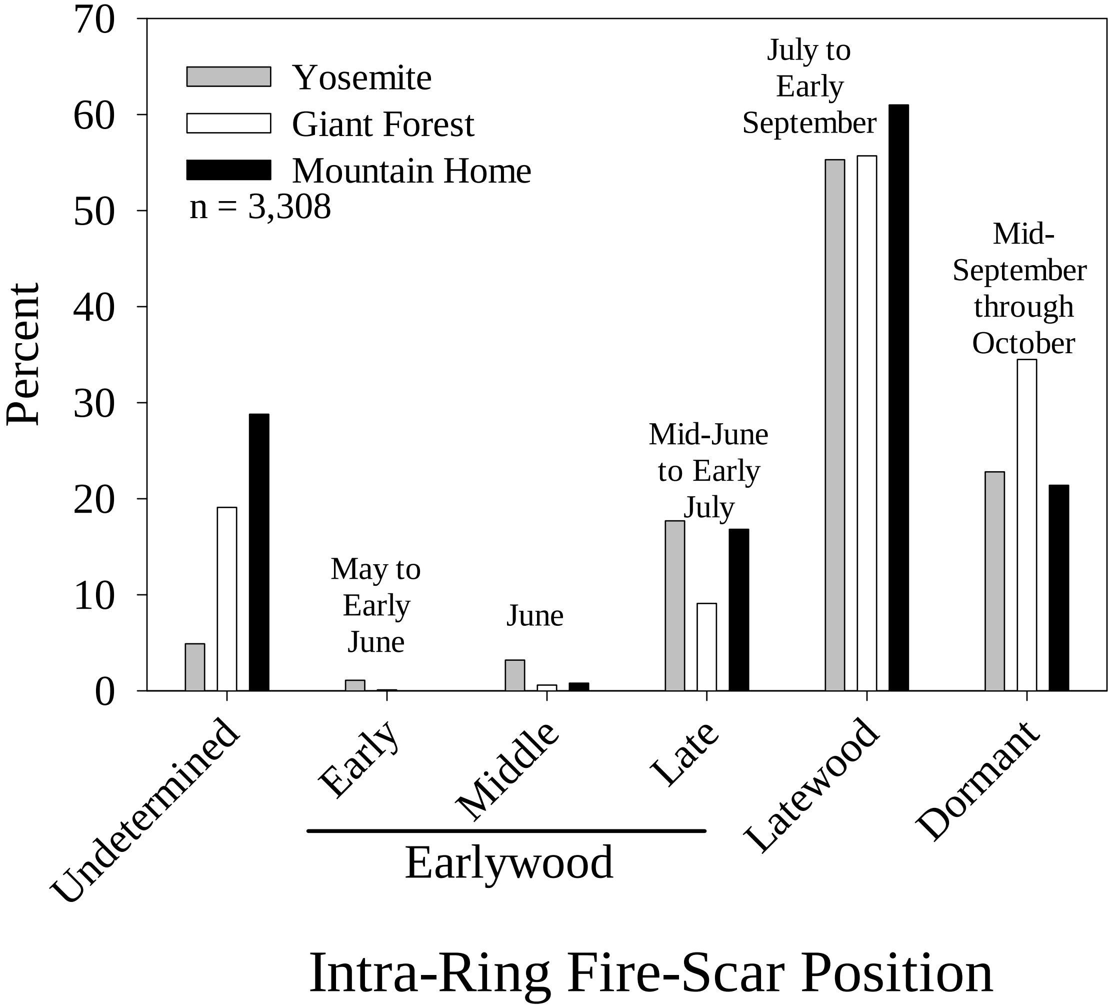


Figure 8



70
60
50
40
30
20
10
0
Percent
Yosemite
Giant Forest
Mountain Home
n = 3,308
May to Early June
June
Mid-June to Early July
July to Early September
Mid-September through October
Undetermined
Early
Middle
Late
Latewood
Dormant
Earlywood
Intra-Ring Fire-Scar Position

Figure 9

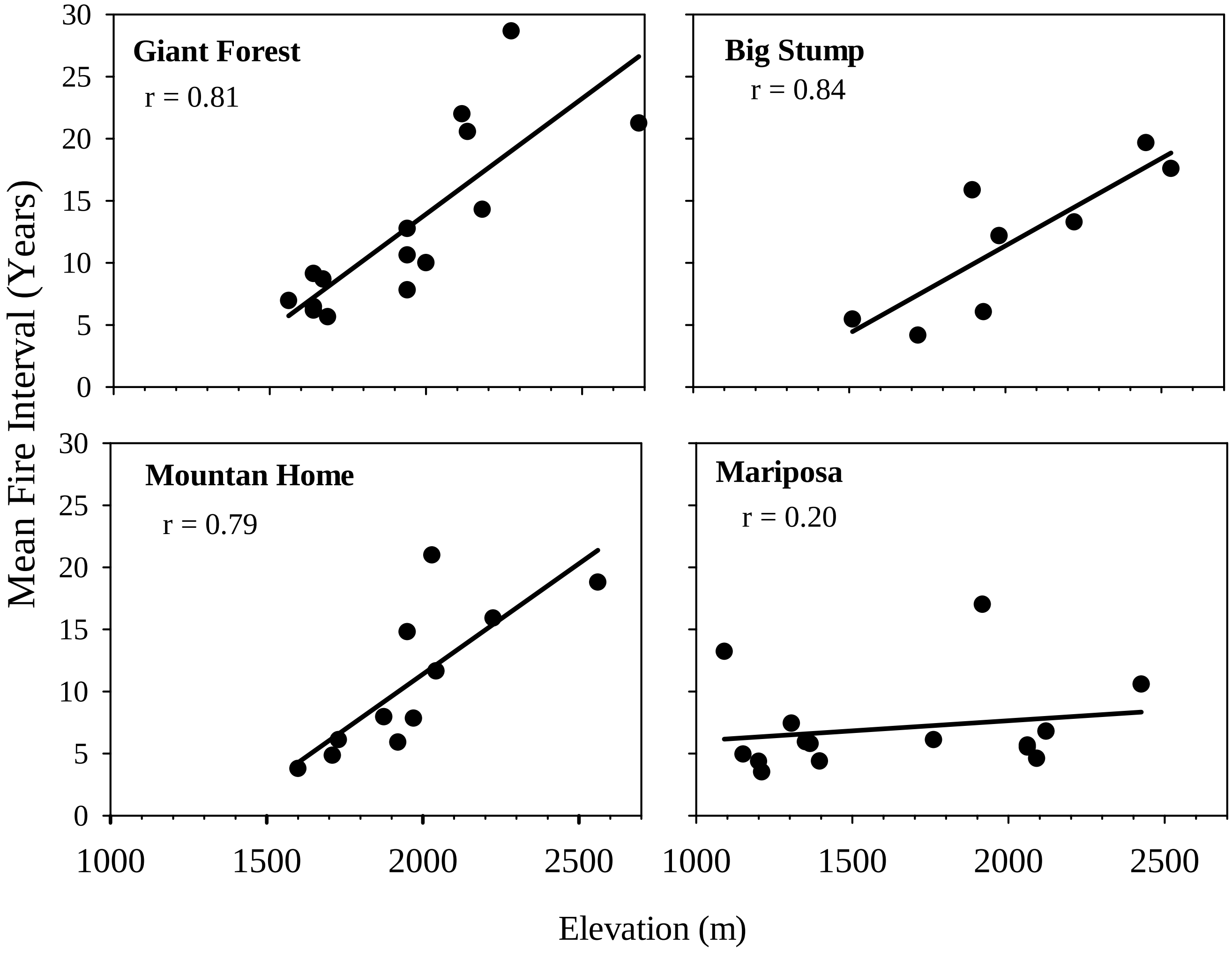

Giant Forest
r = 0.81
Big Stump
r = 0.84
Mountan Home
r = 0.79
Mariposa
r = 0.20
Mean Fire Interval (Years)
0
5
10
15
20
25
30
1000
1500
2000
2500
Elevation (m)

Figure 10

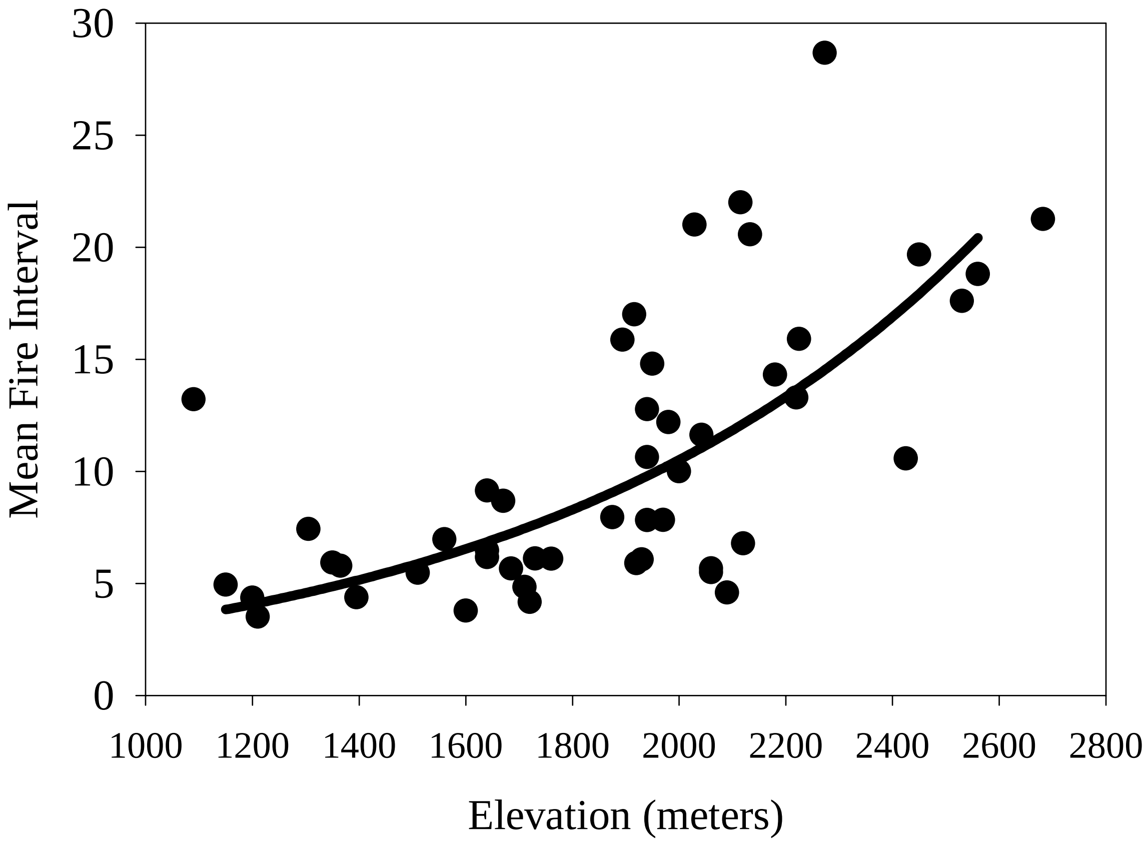
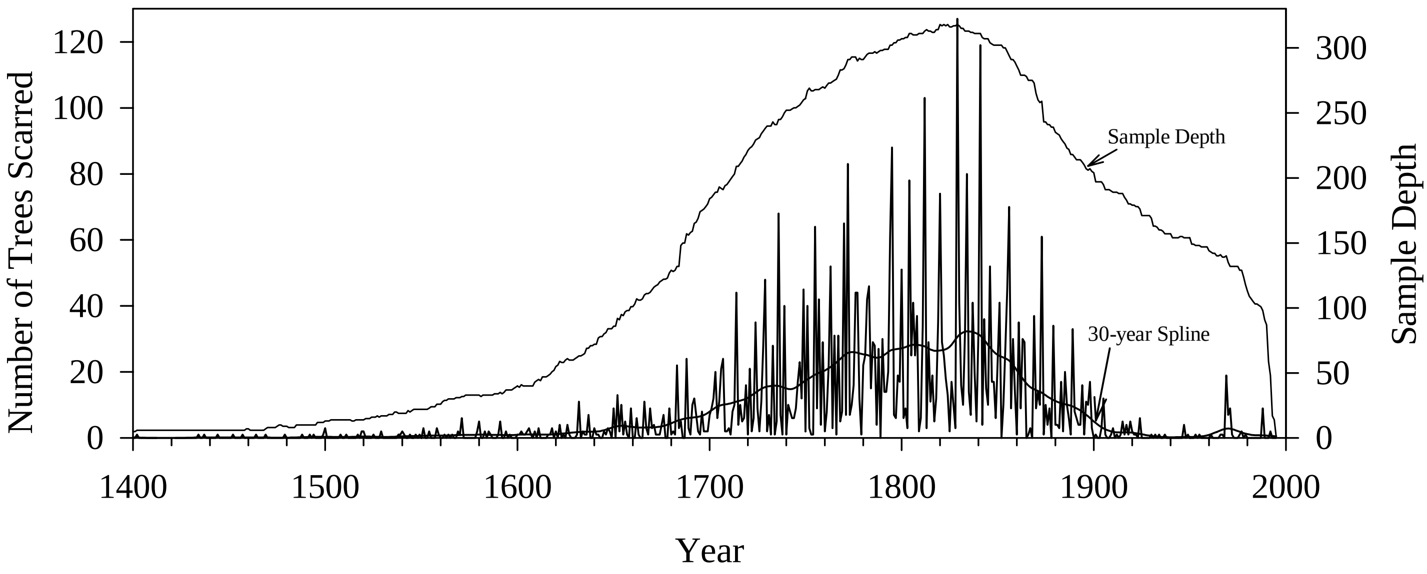

30
25
20
15
10
5
0
Mean Fire Interval
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
Elevation (meters)

Figure 11



Number of Trees Scarred
0
20
40
60
80
100
120
Sample Depth
0
50
100
150
200
250
300
Year
1400
1500
1600
1700
1800
1900
2000
Sample Depth
30-year Spline

Figure 12

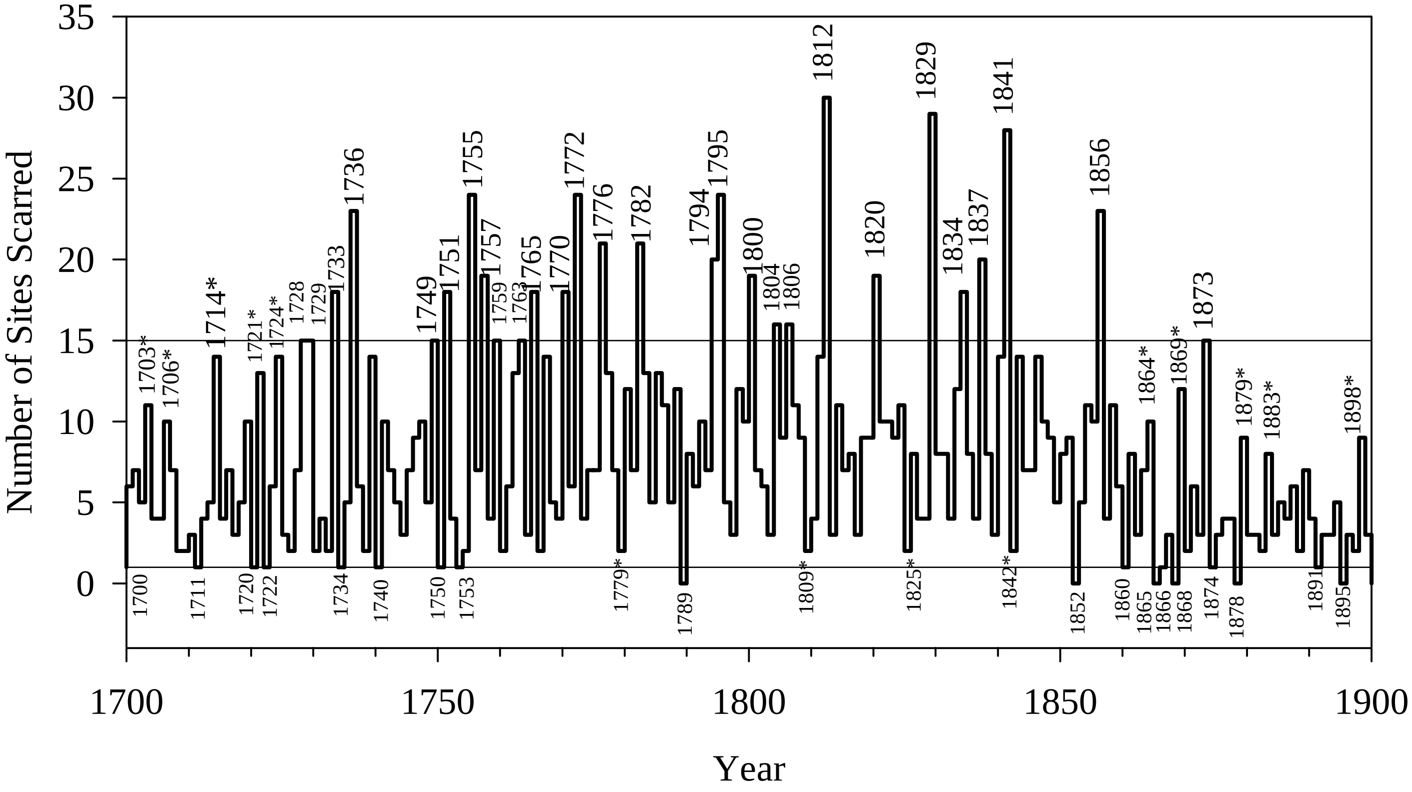
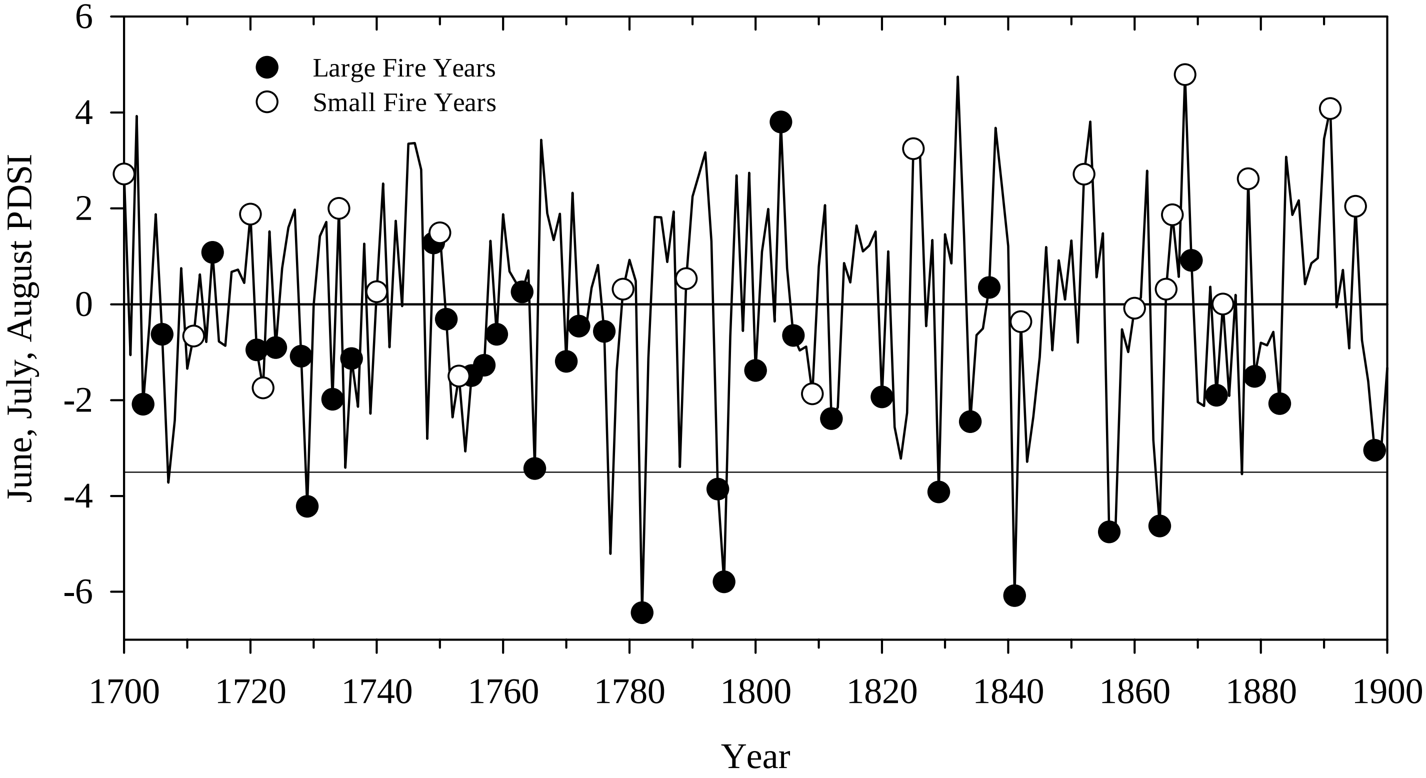
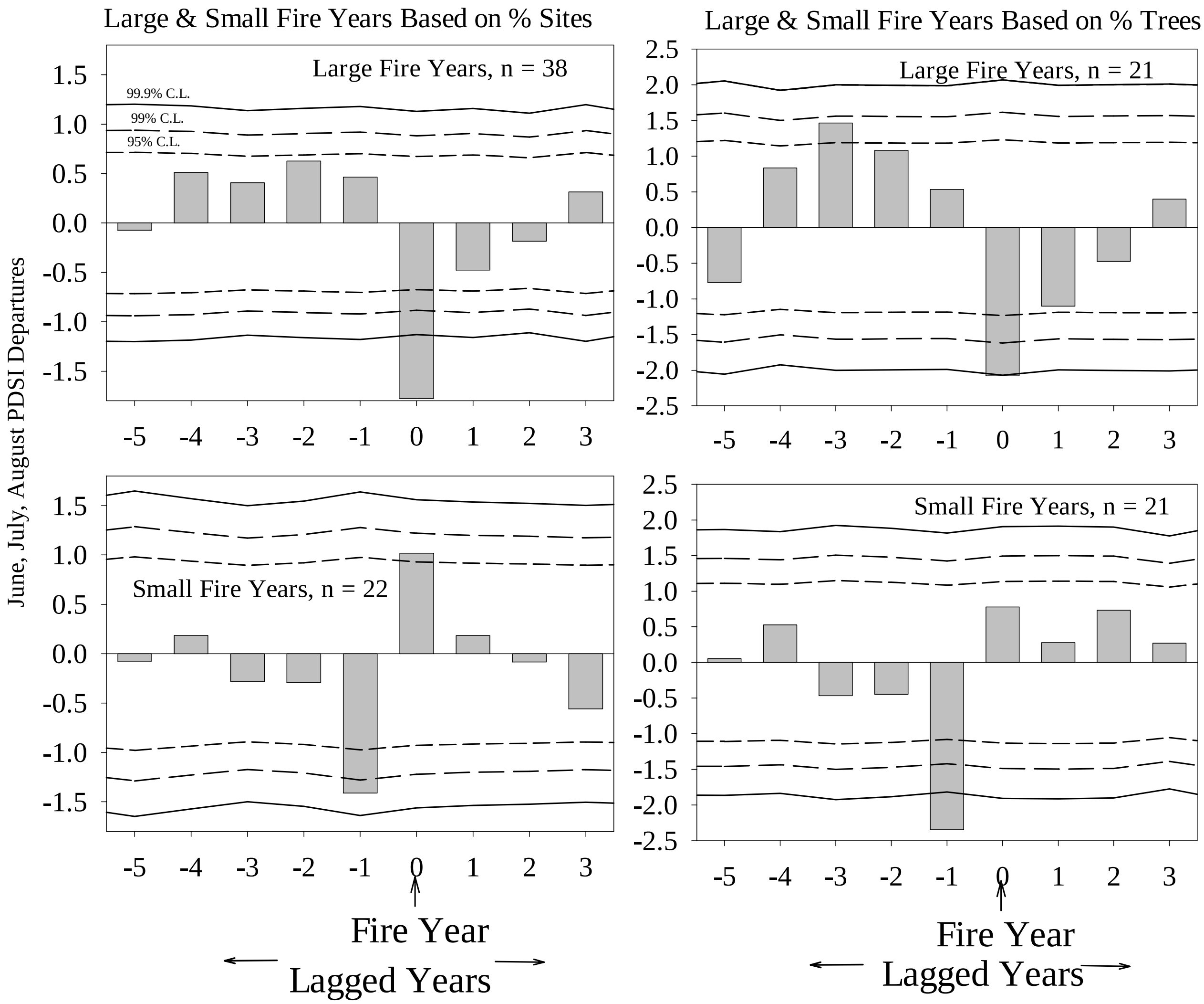

Number of Sites Scarred
Year
35
30
25
20
15
10
5
0
1700
1750
1800
1850
1900
1703*
1706*
1714*
1721*
1724*
1728
1729
1733
1736
1749
1751
1755
1757
1759
1763
1765
1770
1772
1776
1782
1794
1795
1800
1804
1806
1812
1820
1829
1834
1837
1841
1856
1864*
1869*
1873
1879*
1883*
1898*
1700
1711
1720
1722
1734
1740
1750
1753
1779*
1789
1809*
1825*
1842*
1852
1860
1865
1866
1868
1874
1878
1891
1895

Figure 13



Large Fire Years
Small Fire Years
6
4
2
0
-2
-4
-6
June, July, August PDSI
1700
1720
1740
1760
1780
1800
1820
1840
1860
1880
1900
Year

Figure 14


Large & Small Fire Years Based on % Sites
Large & Small Fire Years Based on % Trees
Large Fire Years, n = 38
Large Fire Years, n = 21
Small Fire Years, n = 22
Small Fire Years, n = 21
99.9% C.L.
99% C.L.
95% C.L.
June, July, August PDSI Departures
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
2.5
2.0
-2.0
-2.5
-5
-4
-3
-2
-1
0
1
2
3
Fire Year
Lagged Years