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Historical Fire Regime Patterns in the Southwestern United States Since AD 1700

Thomas W. Swetnam and Christopher H. Baisan[1]

Abstract.—Fire-scar chronologies from a network of 63 sites in the Southwestern United States are listed and described. These data characterize the natural range and variability of fire regimes from low elevation pine forests to higher elevation mixed-conifer forests since AD 1700. A general pattern of increasing length of intervals between low intensity surface fires was observed along gradients of low to high elevations, and from the relatively drier pine sites to the wetter mixed-conifer sites. However, large variability in the measures of central tendency and higher moments of the fire interval distributions suggest that elevation and forest type were often weak determinants of fire frequency. Some of the variations in fire interval distributions between similar elevation or forest types were probably due to unique site characteristics, such as landscape connectivity (i.e., ability of fires to spread into the sites), and land-use history. Differences in the sizes of sampled areas and fire-scar collections among the sites also limited our ability to compare and interpret fire interval summary statistics.

Comparison of both the fire-scar network data (1700 to 1900) and documentary records of area burned on all Southwestern Region National Forests (1920 to 1978) with a Palmer Drought Severity Index time series clearly shows the association between severe droughts and large fire years, and wet periods and small fire years. Moreover, important lagging relations between climate and fire occurrence are also revealed. In particular, large fire years in ponderosa pine dominated forests were typically preceded by wet conditions in the prior one to three years. In contrast, large fire years in mixed-conifer forests were associated with extreme drought years, but no consistent lagging relations were observed. We hypothesize that both fuel production (especially grasses and pine needles) and fuel moisture were important climate-linked factors in ponderosa pine fire regimes, while fuel moisture was the primary factor controlling mixed-conifer fire regimes.

These results provide two important types of information for management: (1) Baselines of fire regime ranges and variations are documented across the most economically important and widespread forest types in the Southwest. These data will be useful for guiding, developing, and justifying ecosystem management plans, particularly for the restoration of fire regimes and forest structures to improve forest health and sustainability. (2) The fire-climate relations suggest that a long-range fire hazard forecasting model could be developed that would be a valuable tool for planning and implementing both prescribed fire and fire suppression programs in the Southwest.

INTRODUCTION

On June 2,1900, Gifford Pinchot was riding horseback through park-like stands of ponderosa pine on the Mogollon Rim near Chevlon, Arizona.

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As he rode up onto a ridge he noticed a fire-scarred tree that appeared to have recently died. He dismounted, and taking a hatchet he chopped into one side of the "cat face." On the cut surface he could see the annual tree rings and the successive scars that had formed by the re-burning of the resinous scar boundaries each time a surface fire swept past the tree. He counted the tree rings between the scars, and then he estimated the dates of each fire. In all he counted 14 separate fires, the most recent in 1898 and the earliest in 1785 (photograph and notes on file in Forest Service, Southwestern Region Office, Albuquerque, NM). Pinchot, the future first Chief of the Forest Service, saw for himself the unequivocal evidence that surface fires were an ancient and recurrent forest disturbance, but his interpretation of the role they played was primarily negative. Years later in his book *Breaking New Ground* (1947) he made clear his view of fire in Arizona pine forests: "We looked down and across the plain. And as we looked there rose a line of smokes. An Apache was getting ready to hunt deer. And he was setting the woods on fire because a hunter has a better chance under cover of smoke. It was primeval but not according to the rules."

The scarcity of tree seedlings and the open canopy condition of pine forests convinced Pinchot and most early foresters that the frequent surface fires had kept forests "understocked." They also recognized that many years of abusive grazing practices were partly responsible for the poor tree regeneration. Elimination of fires and control of the grazing situation became the prime directives for the tough, young rangers charged with setting up the National Forest System on the ground.

Now, more than ninety years later we are experiencing a sea change in attitudes and policy towards fire. This change, most recently embodied in the concepts of "ecosystem management," has been driven by accumulated historical and ecological evidence demonstrating that fire is a keystone ecological process in most forest types, and that its exclusion, combined with other factors, has led to significant "forest health" problems. The 1977 La Mesa burn was a wake-up call to perhaps the most pressing forest health problem in Southwestern forests — historically anomalous, catastrophic wildfire in ponderosa pine — created by many decades of fire exclusion.

Prescribed fire has been a part of the fire manager's tool kit since before the La Mesa burn, but even with the greater acceptance and changes in policy over the past two decades the total amount of area treated with prescribed burning (either "natural" or "planned") is minuscule compared to the amount of forest area that would benefit from such treatment. If we are to restore degraded forest ecosystems to conditions of better health and sustainability, and if fire is to be a primary restoration tool, then prescribed burning must be carried out at much larger spatial scales. However, problems of funding, smoke, and the hazards of escaped fires will surely limit the extent to which landscape-scale fire can be reintroduced in the Southwest. The task of researchers and managers is to identify the minimal level of fire re-introduction required for maximal ecological health and sustainability, but also practical and safe given our economic and social limitations.

The paradox of fire management in conifer forests is that, if in the short term we are effective at reducing fire occurrence below a certain level, then sooner or later catastrophically destructive wildfires will occur. Even the most efficient and technologically advanced fire fighting efforts can only forestall this inevitable result. It is clear from many years of study and published works that the thinning action of pre-settlement surface fires maintained open stand conditions and thereby prevented the historically anomalous occurrence of catastrophic crown fires that we are experiencing in today's Southwestern forests (Weaver 1951; Cooper 1960; Swetnam 1990; Covington and Moore 1994; Sackett et al. 1994). The ecosystem management approach explicitly recognizes that these conditions are untenable for the goal of long-term sustainability, and therefore we should strive to reintroduce keystone ecological processes such as fire, or substitute for them with silvicultural treatments such as mechanical thinning (Allen 1994; Kaufmann et al. 1994). The degree to which thinning or other silvicultural treatments can substitute for the fire process is open to debate.

If we are going to re-introduce fire processes we need to learn as much as possible about long-term fire history and fire effects within the forest types to be managed. Ideally, we should have specific knowledge for the particular management units where we are planning the re-introduction. A baseline description of historical conditions provides a view of the "natural range of variability" of the important processes controlling the dynamics and structure of ecosystems (Swanson et al. 1994). This baseline is useful as a reference, but not necessarily as an exact blueprint, for disturbance re-introduction (Morgan et al. In Press). In some cases the natural range and variability define the bounds of the disturbance processes that are most likely to produce a long-term sustainable forest. How do we know that such conditions are sustainable? From a very long temporal perspective of centuries to millennia no forest ecosystem may be considered equilibrial (i.e., sustainable) because climatic, geologic, or anthropogenic fluctuations inevitably lead to ecosystem changes (Botkin 1990; Sprugel 1991; Swetnam 1993). On the other hand, we should remember that the open, park-like stands of ponderosa pine that were both so impressive to our pioneer predecessors, and which have provided the bulk of the timber cut during the settlement era and since, were primarily composed of trees that germinated and survived with such fire regimes for many centuries. Thus, the historical (i.e. "natural) range of variability of pre-settlement forests may be the best, and perhaps the only template we have for long-term sustainability.

The purpose of this paper is to review some of the facts that we have learned from intensive fire history studies in Southwestern ponderosa pine and mixed-conifer forests. After Pinchot's initial fire-scar counting in 1900, Harold Weaver, a forester with the Bureau of Indian Affairs, was apparently the next person to investigate Southwestern fire history patterns in tree rings (Weaver 1951). In the 1970s, Research Scientist John H. Dieterich of the U. S. Forest Service, Rocky Mountain Forest and Range Experiment Station, and Professor Marvin A. Stokes of the Laboratory of Tree-Ring Research, University of Arizona began collecting and dating fire-scarred specimens from throughout the region. In recent years, we (the authors, our students, and collaborators) have greatly expanded these collections. We are currently assembling an even larger fire history network that will encompass the full range of Southwestern woodland and forest types (e.g., pinyon-juniper and oak-pine woodlands up to the spruce-fir zone). We plan to conduct more systematic statistical analyses and modeling using these data. Our goal is to document and understand the natural range of variability of fire regimes across multiple temporal and spatial scales, and to use this knowledge to guide and support ecosystem management programs. We are especially interested in the fundamental causes and mechanisms of fire regime variability, particularly the role of climate and human land-use practices. Here we present a listing of 63 fire history reconstructions in the Southwestern U. S. (mainly Arizona and New Mexico) and some general descriptions of fire regime patterns and associations that we observe in these data.

METHODS

Sampling Considerations

Fire-scarred trees are relatively abundant in forests of the Southwest, but the most informative and useful specimens for fire history reconstructions are somewhat rare. They usually comprise less than about five percent of all standing trees, and a much smaller percentage in stands that have been harvested. Among the few trees with fire-scarred boles an even smaller proportion contain well-preserved, multiple fire scars. We have seen many instances of two fire-scarred trees of approximately the same age growing side-by-side; one of the trees contains a visible record of many fire scars, while the other tree has only one or a few fire scars. Based on these and other observations, it is clear that fire-scarred trees are not all equally consistent and reliable recorders of fires that have burned around their bases. Therefore, it is inefficient and inappropriate to sample fire-scarred trees as if they all belong to the same statistical population.

Many factors are involved in the repeated, consistent scarring of individual trees and the preservation of the fire scars formed on them (e.g., position of the tree on the landscape, bark thickness, lean of the tree, decay of the wood in the fire-scar wound, burning-off of older fire scars by subsequent fires, vigor of the tree and its ability to heal over wounds, production of resin at the wound boundaries, etc.). Historical factors are also important in determining abundance of useful fire-scarred material, such as past timber or fuelwood harvesting. In addition to living fire-scarred trees, snags and logs ("remnants") often contain very long and detailed records of past fires. Remnant specimens can be dendrochronologically dated (i.e., by crossdating, [Stokes and Smiley 1968; Swetnam et al. 1985]) thereby lengthening and replicating the fire-scar record for individual sites (Baisan and Swetnam 1990). Unfortunately, fires in the late twentieth century, including prescribed burns, usually consume the accumulated fire-scar evidence, especially the record preserved in remnants. Salvage of ancient fire-scar records before initiation of prescribed burning programs should therefore be a priority (Van Pelt and Swetnam 1990).

In developing a replicated and complete fire history reconstruction it is necessary to diligently search for and sample many trees with multiple, well-preserved fire scars distributed spatially throughout the sampling unit. Usually 10 to 30 trees or more are sampled within each selected forest stand (hereafter referred to as "sites"). Almost all of our sites range in size from approximately 10 to 100 ha, and a few are up to about 1000 ha. Relatively homogenous sites with little variation in topography or forest type are best. These sites are usually selected as "case studies" of fire history within particular forest types or certain landscape situations. At watershed or mountain range spatial scales, sites may be selected to achieve sufficient spatial dispersion to infer larger fire extent patterns (see discussion below).

The goal of our sampling has been to obtain a fire event "inventory" within sampled sites that is as long and complete as possible; i.e., to identify all or nearly all dates of fires that occurred within the sampled unit for a maximum length of time before the present. Contrary to the views of Johnson and Gutsell (1994) we do not believe that it is necessary, practical, or efficient to randomly sample sites or fire-scarred trees *in all circumstances* in order to obtain complete and un-biased fire history reconstructions. In fact, a random sampling scheme of all fire-scarred trees within sites that sustained high frequency surface fire regimes would not result in a complete or unbiased record *unless the record is preserved in those sites,* and the sampling involved very large numbers of trees; probably hundreds of trees would be required for sites of 100 to 1000 ha.

In many ways, fire-scarred trees are similar to fossils that paleontologists search for to inventory and reconstruct the ancient flora or fauna of an area. In most cases the rarity and the unevenness of the paleorecord, both in quality and quantity, precludes a strict random sampling. There simply are not enough old, well-preserved fossils distributed across the landscape to reasonably assume that a randomly selected set of sites, or of fossils within sites, would provide a clear or complete long-term picture of the past. Moreover, landscapes are often far too heterogeneous to have any hope of sampling, within the lifetime of a researcher, a sufficient number of sites or fossils (trees in our case) to produce a robust statistical description of histories in all landscape types. To reiterate, our objective is not to statistically sample the "population" of landscape types or of fire events that have occurred, but rather to obtain as complete an inventory as possible of all fire events (dates) that have occurred within selected units (i.e., case studies) as far back in time as possible. This is most efficiently accomplished by finding and sampling old living trees and remnants that have recorded and preserved the maximum amount of fire history information at many different points in space.

Fire-scar records are fundamentally a spatial "point record" of fire occurrence. In ponderosa pine forests it is not possible to reconstruct the exact perimeter of low intensity burns that occurred more than a few years before the present. There is no clearly preserved record of the precise extent of the many dozens of individual burns that swept through old-growth ponderosa pine forests in past centuries. This is in sharp contrast to lower fire frequency, stand-replacement fire regimes (such as in chaparral or spruce-fir forests) where the extant stand structure (e.g., ages or heights of trees, or other visible clues) can be used to estimate the perimeters of some past burns, although these methods have serious limitations as well (Heinselman 1973, Tande 1979, Minnich 1983, Johnson and Gutsell 1994). Surface fires in ponderosa pine were of such low intensity that their direct influence on the overstory canopy structure was negligible, or very spatially patchy. Even though surface fires had minimal direct effects on most mature overstory trees, this does not mean they were ecologically unimportant. The individual and cumulative impacts of the frequent, low intensity surface fires had a profound influence on tree seedling dynamics, low and mid-level canopy structures, understory plant species diversity, nutrient cycling and other soil properties, plant growth, and many other ecosystem properties (e.g., diversity of vertebrate and invertebrate fauna).

Localized high intensity burns probably occurred in some places within both ponderosa pine and mixed-conifer forests, such as around recently dead snags with accumulated litter, bark, and branches at their base. The typically longer intervals between fires in mixed-conifer forests, and more extreme drought conditions when fires did occur (see results section), led to a mosaic pattern of variable size patches of high-intensity stand replacement burns within a larger matrix of surface burn (Baisan and Swetnam, In Press).

Although we cannot reconstruct the precise perimeters or prepare detailed maps of past surface fires in Southwestern ponderosa pine and mixed-conifer forests, we can study the *relative* extensiveness of fires at various spatial scales (Figure 1). Patterns of synchrony and asynchrony of fire dates among trees and among sites can be used to infer the relative extent of fire events across these different spatial scales. For example, temporally synchronous fire dates recorded throughout sites by

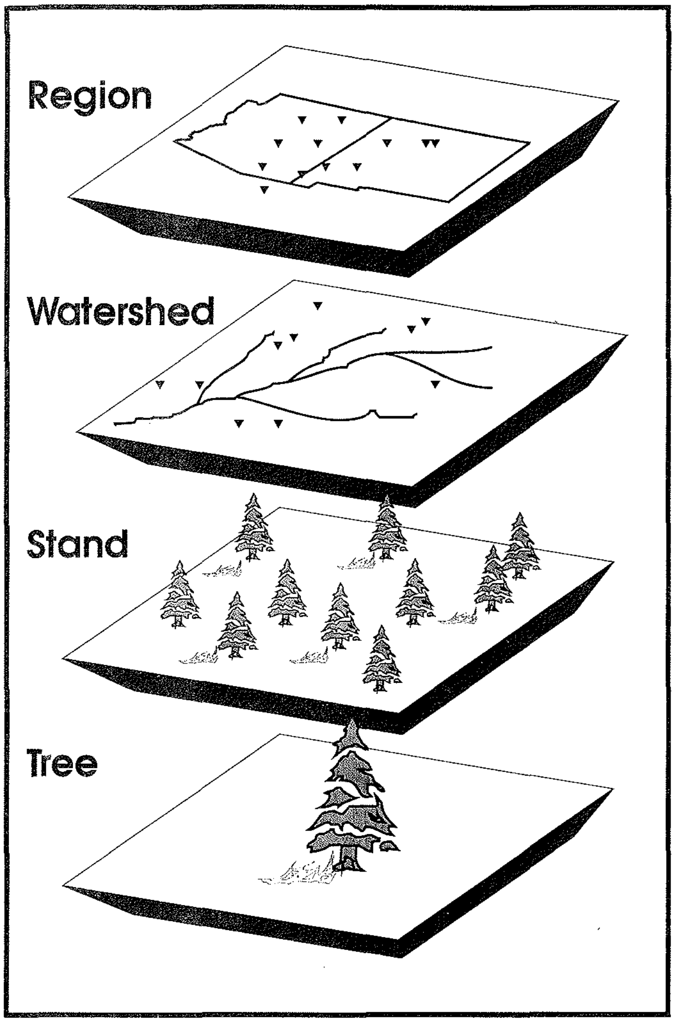

Figure 1.—Spatial scales of fire history analysis. Fire-scar records on individual trees must be carefully selected and sampled in order to maximize the completeness of the fire date inventory within sites. The patterns of synchrony and asynchrony of fire records among spatially dispersed trees within sites, among sites within watersheds (or mountain ranges), and among sites within the region can be evaluated to identify patterns of relative fire size, spread, extensiveness, and associations with climatic variation and land-use history.

many sampled fire-scarred trees can be reasonably inferred to have been burns of larger spatial extent *within the sampled site* than fire dates recorded by only one or a few trees. Similarly, synchronous fire dates recorded in many different sites at watershed or larger spatial scales (Figure 1) probably represent larger areas burned during those years than fire dates recorded in smaller numbers of sites. It is possible that synchronous fire dates recorded on different trees (or in different sites) were not caused by the same contiguous burn. Multiple fire ignitions by lightning or people could have started many different fires during the same year. Nevertheless, the same fire dates recorded at many different points in space would still probably represent larger amounts of area burned during those particular years than fire dates recorded by smaller numbers of trees or sites.

It is also possible that fire intensity is a factor determining synchroneity of the recorded fire dates (i.e., hotter fires may be more likely to scar trees). However, we have observed that even low intensity prescribed burns usually re-scar trees that already have been scarred at least once. In contrast to un-scarred trees, the easily ignited exposed wood and seeping resin on previously scarred trees make them especially "sensitive" to being re-scarred by subsequent fires of any intensity. The vast majority of fire-scar dates in our data sets were recorded on trees that had already incurred one or more scars and had an open wound (i.e., they were already sensitive fire recorders). Hence, with a well-replicated sample set of fire-scarred trees and sites even low intensity, but widespread fires should still be evident as synchronous dates. Moreover, it is probable that during years when fires were likely to spread over large areas they were also likely to be more intense. For example, during drought years fuels are dry and burn intensely and rapidly over large areas. Also, following relatively long periods without fire the fuels accumulate and become more continuous across the landscape, and so when fire occurs it tends to burn intensely and spread over large areas. Thus, the direct association between fire intensity and extensiveness we observe in the present certainly existed in the past, but this relationship does not contradict our interpretation that, within a given area, synchronous fire dates generally represent larger areas burned than asynchronous fire dates.

This idea of assessing patterns of synchrony and asynchrony across different spatial and temporal scales has a direct scientific lineage from the earth sciences, and dendrochronology in particular. Geologists have long used the principle of uniformity ("the present is the key to the past") in reconstructing earth history from matched spatial and temporal patterns of layered records (e.g., sediments). Dendrochronologists rely upon "crossdating" (i.e., synchrony) of annual tree-ring widths among trees and sites to identify the exact chronological placement of tree-rings, as well as for distinguishing the influences of climate on tree growth from the influences of more locally specific factors. The strength of the dendrochronological approach lies in the exactness of the time sequences that are assembled at multiple points in space. This exactness enables us to spatially aggregate the time series and thereby identify patterns of synchrony and asynchrony with high resolution at multiple spatial and temporal scales. Such information on *keystone processes* (*sensu* Holling 1992) spanning seasons to centuries and individual trees to regions is rare in ecology. This approach has proven fruitful in a variety of applications (Fritts and Swetnam 1989), including fire history and fire climatology (Swetnam and Dieterich 1985; Swetnam et al. 1989; 1992; Swetnam and Betancourt 1990; 1992; Swetnam 1993; Baisan and Swetnam 1990; Brown and Swetnam 1994; Grissino-Mayer and Swetnam, In Press; Grissino-Mayer et al. In Press; Touchan et al. In Press; Touchan et al. This Volume), insect outbreak studies (Swetnam and Lynch 1989; 1993; Swetnam et al. In Press) and in tree demography studies (Swetnam and Brown 1993; Betancourt et al. 1993).

Data Compilation and Statistical Description

Master fire-scar chronologies (Dieterich 1980; Dieterich and Swetnam 1984) were developed from more than 1,200 fire-scarred trees sampled in 63 sites located in Arizona, New Mexico, Texas, and Sonora Mexico (Figure 2, Table 1). This is currently the world's largest and longest regional-scale fire history network composed entirely of fire event chronologies accurately dated to annual or seasonal resolution. These tree-ring data were collected and crossdated by many individuals. Some of the detailed fire histories for individual sites are described in published papers (see Swetnam 1990 for a partial list), while others are described in unpublished reports on file at the Laboratory of Tree-Ring Research (LTRR). Other descriptions are contained in papers, theses, and dissertations that are currently in preparation by the authors, our students, and colleagues.

All of the fire dates for each sampled tree in each site were entered in database files. These files were processed through a fire history analysis software package called FHX2, written by Mr. Henri Grissino-Mayer of LTRR. FHX2 computes a variety of descriptive statistics for fire interval and fire frequency data. All of the chronologies compiled for this paper were analyzed for the time period AD 1700 to 1900. Much longer fire-scar data were included in many of the sites, but the post–1700 time period included most of the sampled trees in most sites, and therefore was the best replicated period. Very few fire dates were recorded after about 1900 in most sites due to the advent of intensive livestock grazing, which removed fine fuels (i.e., grasses and herbs) necessary for fire spread, and/or because of organized fire suppression by land management agencies. Thus, the fire-scar analyses concentrate on a two century "pre-settlement period" preceding AD 1900.

The fire interval statistics computed and reported here include (1) measures of central tendency: mean fire interval, median fire interval, Weibull median probability interval (WMPI); and (2) measures of range and variability (or higher moments of the distribution): minimum and maximum intervals, standard deviation, coefficient of variation, skewness, and kurtosis. The WMPI is the estimated fire interval (in years) at which there is a 50 percent probability of longer (or shorter) fire intervals occurring — based on the fitting of a Weibull-type curve (model) to the fire interval distributions (see Johnson and vanWagner [1985] for a description of these models).

The fire interval statistics were computed on three different levels of fire-scar dates. These were: (1) fire dates recorded within each site by any tree; (2) fire dates recorded by 10 percent or more of the fire-scarred trees within each site; and (3) fire-scar dates recorded by 25 percent or more of the fire-scarred trees within each site. An additional criterion for the 10 and 25 percent sortings was that at least two trees within each of the sites recorded the fire dates used to compute the descriptive statistics. This sorting (or filtering) of fire dates recorded by increasing percentages of the trees within each site is a means of assessing patterns of fire frequencies and extent associated with fire events that probably burned progressively greater areas within sites (see discussion in previous section). For example, in some sites many fires were recorded by only one or a few sampled trees, but a few fires were consistently recorded by many or nearly all sampled trees. In these cases the different sortings would show greatly different fire frequencies. In contrast, in some sites most fires were recorded by most sampled trees, and hence fire frequencies varied only slightly among the different sortings. In each type of case a different interpretation may be made regarding the frequencies and extensiveness of fires.

After computing fire interval statistics for all master fire chronologies, the data were sorted by elevation and forest type and plotted to assess patterns that may be related to these two factors. Forest types were broadly categorized as: (1) pine/pinyon-juniper/oak [PINE/PJ/OAK] (2) ponderosa pine [PIPO] (3) ponderosa pine/mixed-conifer [PIPO/MC] (4) mixed-conifer [MC]. The PINE/PJ/OAK category included sites with ponderosa pine, or other pine species (such as Chihuahua pine or

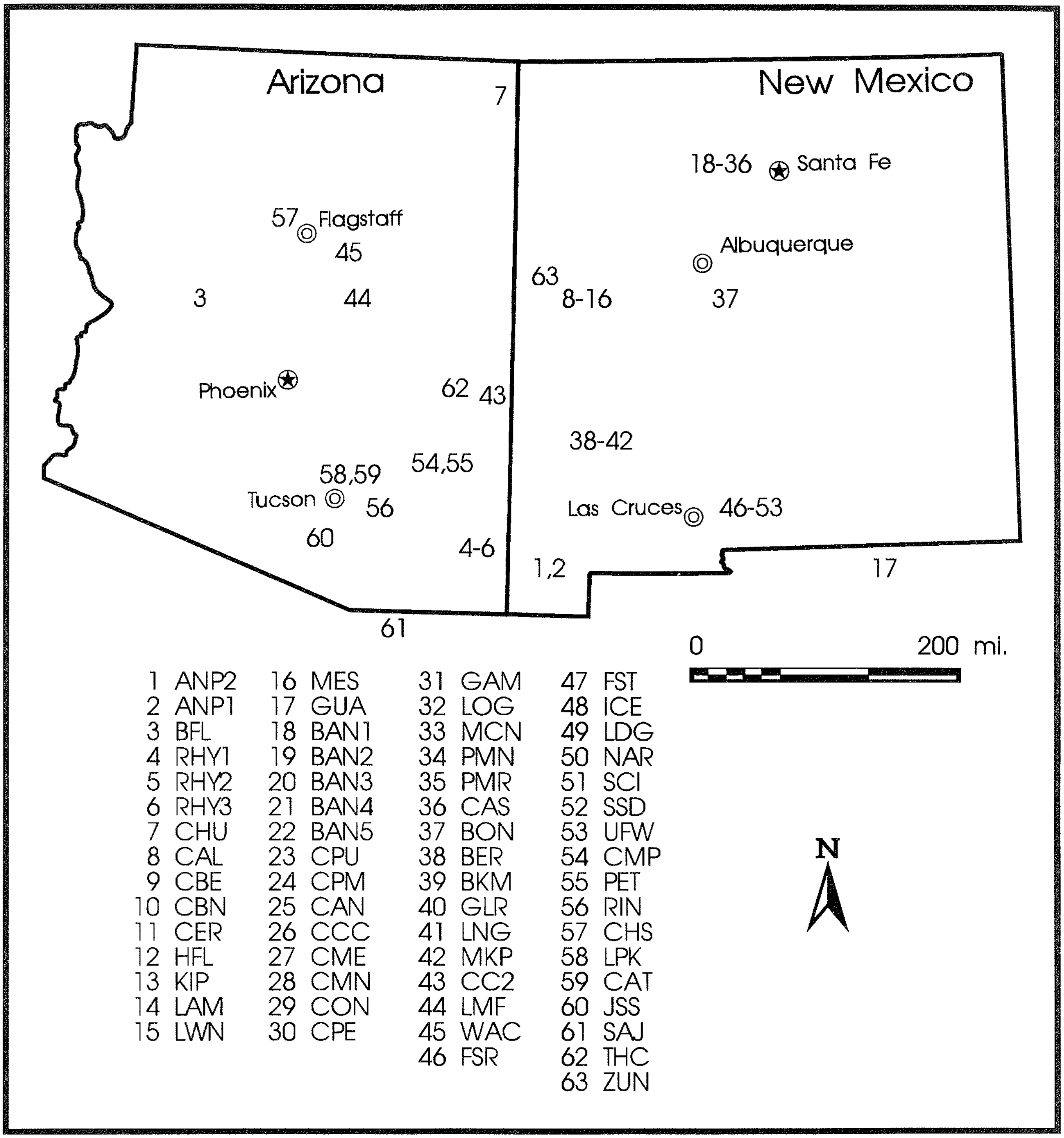

Figure 2.—Map of Arizona and New Mexico showing locations of all fire history sites reported in this paper. The numbers on the map refer to the site codes which are listed below and in Tables 1 to 4. The U.S. Forest Service Southwestern Region [Region 3] is located primarily in these two states.

Apache pine in Southern Arizona) as the major source of fire-scarred samples, but also mixed within the stand were pinyon, juniper, or various oak species. The PIPO category included sites that were pure or nearly pure stands of ponderosa pine.

The PIPO/MC category were sites with ponderosa pine as the primary dominant tree species and some combination of Douglas-fir, or true firs (*Abies*) were also present, but in smaller proportions (density or crown cover) than the ponderosa

Table 1.—Listing of 63 fire-scar sites in Southwestern fire history network. See text for explanation of forest type. Ownership is National Forest (NF), National Park (NP), National Monument (NM), The Nature Conservancy (TNC), or other.

Site Code	Site Name	State	Ownership	Mountain Range of Region	No. of Fire-Scar Samples	Forest Type	Lowest Elevation (Feet)	Highest Elevation (Feet)
ANP2	ANIMAS PEAK-SOUTH	NM	GRAY RANCH (PRIVATE)	AMIMAS	56	PIPO/MC	8000	8100
ANP1	ANIMAS PEAK-NORTH	NM	GRAY RANCH (PRIVATE)	ANIMAS	18	PIPO	8000	8400
BFL	BATTLE FLATS	AZ	PRESCOTT NF	BRADSHAW	7	PIPO/CHAP	5000	5200
RHY3	RHYOLITE CANYON-LOWER	AZ	CHIRICAHUA NM	CHIRICAHUA	12	PINE/OAK	5600	5920
RHY2	RHYOLITE CANYON-MIDDLE	AZ	CHIRICAHUA NM	CHIRICAHUA	30	PIPO/MC	5920	6300
RHY1	RHYOLITE CANYON-UPPER	AZ	CHIRICAHUA NM	CHIRICAHUA	16	PIPO/MC	6800	7000
CHU	CHUSKA	AZ	NAVAJO RESERVATION	CHUSKA	16	PIPO/MC	8800	8900
CBE	CERRO BANDERA EAST	NM	EL MALPAIS NM	EL MALPAIS	32	PIPO	7900	8360
CBN	CERRO BANDERA NORTH	NM	EL MALPAIS NM	EL MALPAIS	35	PIPO	7860	8100
CER	CERRO RENDIJA	NM	EL MALPAIS NM	EL MALPAIS	11	PIPO	7900	8140
CAL	EL CALDERON	NM	EL MALPAIS NM	EL MALPAIS	5	PIPO	7200	7260
KIP	HIDDEN KIPUKA	NM	EL MALPAIS NM	EL MALPAIS	13	PIPO	7375	7440
HFL	HOYA DE CIBOLA LAVA FLOW	NM	EL MALPAIS NM	EL MALPAIS	23	PIPO	7500	7500
LAM	LA MARCHANITA	NM	EL MALPAIS NM	EL MALPAIS	37	PIPO	7700	8000
LWN	LOST WOMAN	NM	EL MALPAIS NM	EL MALPAIS	20	PIPO	7660	7960
MES	MESITA BLANCA	NM	EL MALPAIS NM	EL MALPAIS	26	PIPO/PJ	7370	7420
GUA	GUADALUPE MTNS.-THE BOWL	TX	GUADALUPE MTNS NP	GUADALUPE	26	PIPO/MC	7546	8202
CME	CAMP MAY EAST	NM	SANTA FE NF	JEMEZ	6	PIPO	8900	9080
CMN	CAMP MAY NORTH	NM	SANTA FE NF	JEMEZ	20	MC	9720	10020
CAN	CANADA BONITA NORTH	NM	SANTA FE NF	JEMEZ	28	MC	9720	9840
CAS	CANADA BONITA SOUTH	NM	SANTA FE NF	JEMEZ	31	PIPO	9120	9220
CPM	CAPULIN CANYON MIDDLE	NM	BANDELIER NM	JEMEZ	15	PIPO	6650	6940
CPU	CAPULIN CANYON UPPER	NM	BANDELIER NM	JEMEZ	8	PIPO/MC	8370	8430
CPE	CERRO PEDERNAL	NM	SANTA FE NF	JEMEZ	26	PIPO	8800	9190
CCC	CLEAR CREEK CAMPGROUND	NM	SANTA FE NF	JEMEZ	20	PIPO	8202	8300
CON	CONTINENTAL DIVIDE	NM	SANTA FE NF	JEMEZ	24	PIPO	9350	9400
GAM	GALLINA MESA	NM	SANTA FE NF	JEMEZ	25	PIPO/MC	8520	9180
LOG	LOS GRIEGOS	NM	SANTA FE NF	JEMEZ	15	MC	9250	9500
MCN	MONUMENT CANYON NATURAL AREA	NM	SANTA FE NF	JEMEZ	30	PIPO	8200	8420
PMN	PAJARITO MOUNTAIN NORTH	NM	SANTA FE NF	JEMEZ	28	MC	9340	10080
PMR	PAJARITO MOUNTAIN RIDGE	NM	SANTA FE NF	JEMEZ	23	PIPO	9380	9740
BAN1	RITO DE LOS FRIJOLES-GROUP 1	NM	BANDELIER NM	JEMEZ	9	PIPO/PJ	6660	6750
BAN2	RITO DE LOS FRIJOLES-GROUP 2	NM	BANDELIER NM	JEMEZ	13	PIPO/MC	7100	7700
BAN3	RITO DE LOS FRIJOLES-GROUP 3	NM	BANDELIER NM	JEMEZ	18	PIPO	8235	8640
BAN4	RITO DE LOS FRIJOLES-GROUP 4	NM	BANDELIER NM	JEMEZ	23	PIPO/MC	9154	9620
BAN5	RITO DE LOS FRIJOLES-GROUP 5	NM	BANDELIER NM	JEMEZ	12	PIPO	7267	7430
BON	MANZANO MTNS-NORTH	NM	CIBOLA NF	MANZANO	19	PIPO	7300	7400
BER	"BEARWALLOW, GILA"	NM	GILA NF	MOGOLLON	13	MC	9000	9600
BKM	BLACK MOUNTAIN	NM	GILA NF	MOGOLLON	27	PIPO/ MC	8400	9300
GLR	GILITA RIDGE	NM	GILA NF	MOGOLLON	10	PIPO	8300	8300
LNG	LANGSTROTH MESA	NM	GILA NF	MOGOLLON	18	PIPO/MC	7800	8400
MKP	McKENNA PARK	NM	GILA NF	MOGOLLON	12	PIPO	7640	7800
CCA	CASTLE CREEK	AZ	APACHE NF	MOGOLLON RIM	17	PIPO	8000	8200
LMF	LIMESTONE FLATS	AZ	COCONINO NF	MOGOLLON RIM	13	PIPO	6900	6900
WAC	WALNUT CANYON	AZ	WALNUT CANYON NM	MOGOLLON RIM	18	PIPO/PJ	6660	6800
SCI	FILLMORE SIDE CANYON 1	NM	TNC	ORGAN	7	PIPO	7200	7500
FST	FILLMORE SIDE CANYON 2	NM	TNC	ORGAN	8	PIPO/MC	7200	7700
FSR	FILLMORE SIDE CANYON 3	NM	TNC	ORGAN	10	PIPO	7200	7800
ICE	ICE CANYON	NM	TNC	ORGAN	7	PIPO	7500	7800
LDG	LEDGE SITE	NM	TNC	ORGAN	7	PIPO	7800	7900
NAR	NARROWS	NM	TNC	ORGAN	8	PIPO/PJ/OAK	7000	7300
SSD	SNAG SADDLE	NM	TNC	ORGAN	4	PIPO	7800	8000
UFW	UPPER FILLMORE WEST	NM	TNC	ORGAN	24	PIPO/MC	7800	8200
CMP	CAMP POINT	AZ	CORONADO NF	PINALENO	50	MC	7546	9600
PET	PETER'S FLAT	AZ	CORONADO NF	PINALENO	40	MC	9200	9450
RIN	MICA MOUNTAIN	AZ	SAGUARO NP	RINCON	44	PIPO/MC	6791	8530
CHS	CHIMNEY SPRINGS	AZ	COCONINO NF	SAN FRANCISCO	8	PIPO	7325	7425
LPK	LEMMON PEAK	AZ	CORNOADO NF	SANTA CATALINA	15	MC	8750	8960
CAT	ROSE CANYON + PALISADES	AZ	CORONADO NF	SANTA CATALINA	11	PIPO/MC	7000	7600
JSS	JOSEPHINE SADDLE	AZ	CORONADO NF	SANTA RITA	17	PINE/OAK	6800	7200
SAJ	SIERRA AJOS	—	"SONORA, MEXICO"	SIERRA AJOS	18	PINE/OAK	6890	7218
THC	THOMAS CREEK	AZ	APACHE NF	WHITE	26	MC	8300	9200
ZUN	ZUNI MOUNTAINS	NM	CIBOLA NF	ZUNI	7	PIPO	8000	8400

pine. The MC category were mixed-conifer stands where ponderosa pine or other pines (e.g., Southwestern white pine) were secondary dominants, and generally in much smaller proportions than Douglas-fir, true firs, or spruce.

These forest type categorizations were imperfect for a number of reasons. One problem was that tree species composition and density has changed greatly in many of these stands because of twentieth century fire suppression or harvesting. For example, Douglas-fir and true firs have clearly increased in density in many areas — in some cases converting what were previously pure ponderosa pine stands to mixed-conifer. Generally, we tried to categorize the sites according to the apparent structure of the stands prior to the settlement and fire suppression era (i.e., before ca. 1900). Thus, composition of mature overstory trees that were likely to be older than about 100 years of age were given more weight in the classification. Another problem was that a few sites simply did not fit neatly into these categories because of unique tree species compositions and/or because they were in special locations, such as in riparian canyon bottoms.

Drought—Fire Relations

Temporal patterns of fire occurrence among all sites in the Southwest were compared with regional drought patterns. This analysis was conducted by compiling a set of recent dendroclimatic reconstructions based a large network of climatically sensitive tree-ring chronologies from Arizona and New Mexico (Cook et al., In Press). These reconstructions were arrayed in a spatial grid over the Southwestern Region. Each of the 13 grid points, consisting of reconstructed time series of Palmer Drought Severity Indices (PDSI) for the summer season (June, July, and August), were based on a multiple regression model using PDSI derived from meteorological station data for the period 1928 to 1979 as independent data, and sets of tree-ring width chronologies as dependent data. These models explained between 41 and 72% of the variance (adjusted r^2) in the tree-ring data (calibration period). A regionalized PDSI time series was computed by averaging the 13 grid point time series into a single time series representing annual drought magnitude fluctuations over the whole Southwest from AD 1700 to 1978 (recent decades were not reconstructed because not all tree-ring chronologies extended to the present). PDSI time series were normalized, so that values were expressed in standard deviation units.

A regional compilation of numbers of sites recording individual fire years was computed for the period 1700 to 1900. An additional regional times series of area burned per year for all National Forests in Arizona and New Mexico (Forest Service Region 3) was compiled for the period 1920 to 1978 from U.S. Forest Service documents (Swetnam 1990; Swetnam and Betancourt 1990). The regional time series of (a) numbers of sites recording fire scars and (b) area burned per year were sorted from largest to smallest fire years and sets of the largest and smallest fire years in the fire time series were compared with the regional PDSI time series. The comparisons included plotting the occurrences of the largest and smallest fire years on a line graph of the PDSI time series, and by conducting a "super-posed epoch analysis" (SEA) (Baisan and Swetnam 1990; Swetnam 1993). The SEA involved computing the mean PDSI values during all of the 20 largest and smallest regional fire years in (a) and 10 of the largest and smallest fire years in (b). The mean PDSI values were also computed for each of the five years preceding and two years following the sets of fire years. A Monte Carlo "bootstrapping" simulation was used to estimate confidence intervals on the observed mean values (Mooney and Duvall 1993; Swetnam 1993).

The analysis was run on the largest and smallest fire years based on all sites, and also on a separate sorting of largest and smallest fire years among MC and PIPO/MC sites in one group and PIPO sites in another group. The purpose of this sorting was to determine if different lagging patterns in drought-fire relations might be observed between the wetter and generally more productive MC, PIPO/MC group and the drier and relatively less productive PIPO group. Hypothetically, without regard to forest type, we expected to see that largest fire years were dry and smallest fire years (i.e., years with fewest numbers of sites recording fire events) were relatively wet. We also expected to see some pattern of dry or wet conditions preceding largest or smallest fire years that pre-conditioned Southwestern forests for more or less extensive fires by affecting fuel production. Finally, we did not expect post-fire years to be significantly wet or dry.

RESULTS

Fire Interval Statistics

Fire interval statistics are presented for all fire dates regardless of the number or proportion of sampled trees recording them within sites (Table 2), for fire dates recorded by more than one tree and 10 percent or more of the sampled trees within sites (Table 3), and for fire dates recorded by more than one tree and 25 percent or more of sampled trees within sites (Table 4). Generally, these tables represent measures of central tendency, range and variation of all recorded fires regardless of size (Table 2), and those fires that probably burned over relatively larger proportions (or all) of the sampled sites (Tables 3 and 4). Tables 3 and 4 could be considered more conservative (i.e., longer) estimates of mean fire intervals in that these statistics discount fires that were probably smaller. On the other hand, as previously mentioned, the many apparently smaller fires that are included in Table 2 could have been ecologically very important as well, both cumulatively, and individually. Furthermore, even when including all recorded fires, it is still likely that some of the fire interval estimates were conservative because, despite our efforts to obtain a complete inventory of fire events within sites, we probably still missed sampling some fire dates. This was probably a more important problem in the highest fire frequency sites (i.e., fire intervals less than about 5 years), where fire extent also tended to be very patchy (see a discussion of this pattern in millennia length records in giant sequoia, Swetnam 1993).

The different measures of central tendency (mean, median, WMPI) were usually within one to about three years of each other, and the median was usually closer in value to the WMPI than the mean (Tables 2, 3, and 4). Large differences were observed in only a few cases. Advantages of the WMPI estimate are that it is based on a model that conforms to the typical non-normal shape of most fire interval distributions, and the statistic can be interpreted in terms of probability, which could be useful in simulation modeling or other prediction schemes. The skewness statistic demonstrates that most of the fire interval distributions were moderately positively skewed, i.e., fire dates were often clustered to the "left" with a long tail to the "right" representing many relatively short intervals and fewer unusually long intervals between fires. Thus, because of the skewness of most fire interval distributions the simple mean and median measures of central tendency were usually less statistically robust than the WMPI.

The kurtosis statistic was more variable than the skewness statistic among the sites and among the different sortings by percentage of trees scarred (Tables 2, 3, and 4). Kurtosis measures "peakedness" of the distribution, with positive values indicating relatively highly peaked distributions (i.e., many values clustering near the central tendency) while negative values indicate a relatively flat distribution. Generally, more of the sites showed positive kurtosis in the computations involving all fire dates than the 10 and 25 percent sortings.

Given the large ranges and variability of the fire intervals within and among sites, we believe it would be a mistake to over-emphasize the importance of, or to over-interpret the ecological meaning of statistical summaries. While the fire process can be described with various levels of accuracy and bias by many different statistical summaries, such measurements are only one means of assessing fire regime properties. Other, and perhaps more important temporal characteristics of fire regimes are the historically unique or "time explicit" patterns. By this we mean the chronological and specific occurrence of individual fires, or the unusual short and long intervals between fires; i.e., the historical and contingent aspects of fire regimes. Particular events, and the ordering of these events in relation to other environmental factors and processes (e.g., climate, plant recruitment and mortality, and human-related events), may be more important than any summary statistic for understanding the past dynamics and current structure of ecosystems.

Despite the large intra-site variation in fire intervals, we can still visually detect some patterns in the measures of central tendency when plotted across gradients of elevation (Figure 3) or forest type (Figure 4). There is a general tendency for increasing length of fire intervals from lowest to highest elevations and from PINE/PJ/OAK to MC forest types. However, these patterns appear to be relatively weak in that the ranges of the measures of central tendency among sites at different elevations and forest type broadly overlap. Again, the uniqueness of individual sites and their special histories probably explains some of the overlap in these measures (see Discussion section).

An interesting deviation from the general pattern of increasing length of fire intervals from the drier to wetter forest types is the tendency for somewhat shorter intervals in the PIPO/MC type than in the PIPO type (Figure 4). We speculate that this may be related to higher productivity levels in the relatively mesic PIPO/MC sites. Fuel levels may recover quickly in these types following fire, while the presence of long-needle ponderosa pines assures high flammability of the fuel substrate.

Table 2.—Listing of fire interval statistics for 63 Southwestern fire-scar chronologies. Fire dates were based on fires recorded by any sampled tree within each site, AD 1700 to 1900.

	Fire Intervals (years)—All Fire Scar Dates									
Site Code	No. of Intervals	Mean	Median	WMPI	Minimum	Maximum	Standard Deviation	Coeff. of Variation	Skewness	Kurtosis
ANP2	26	7.42	6	6.61	1	21	5.021	0.676	1.047	0.408
ANP1	37	5.35	4	4.31	1	16	4.392	0.821	0.919	–0.325
BFL	96	2.07	1	1.74	1	17	2.381	1.149	4.013	18.294
RHY3	29	6.17	6	5.41	1	15	3.799	0.616	0.262	–0.800
RHY2	23	8.30	7	6.78	1	33	7.283	0.877	1.727	3.383
RHY1	24	7.96	6	6.66	1	31	6.676	0.839	1.843	3.773
CHU	44	3.93	3	3.14	1	23	4.256	1.082	2.821	8.696
CBE	35	5.63	5	5.22	1	12	3.030	0.538	0.216	–0.956
CBN	36	5.33	5	4.95	1	13	3.089	0.579	0.716	–0.348
CER	19	9.32	9	7.81	1	25	6.840	0.734	0.603	–0.692
CAL	14	13.14	10	11.21	1	30	8.917	0.678	0.464	–0.947
KIP	12	16.50	12	13.27	3	55	15.294	0.927	1.390	0.955
HFL	15	12.00	10	10.83	2	31	8.018	0.668	0.940	0.002
LAM	27	7.30	7	6.79	2	21	4.479	0.614	1.279	1.478
LWN	22	8.96	7	7.70	2	30	7.569	0.845	1.689	1.965
MES	21	9.10	8	8.61	2	22	5.039	0.554	0.842	–0.017
GUA	36	5.11	4	4.36	1	15	3.882	0.760	1.038	0.026
CME	10	17.10	14	13.83	1	46	13.470	0.788	0.860	–0.193
CMN	6	25.17	14	14.35	1	89	32.872	1.306	1.310	–0.054
CAN	8	19.50	16	16.84	4	52	15.712	0.806	1.086	–0.104
CAS	19	10.05	7	8.95	2	29	7.322	0.728	1.313	0.977
CPM	20	9.45	10	8.57	1	21	5.708	0.604	0.565	–0.516
CPU	20	9.45	9	7.92	1	21	6.650	0.704	0.539	–0.878
CPE	11	14.36	11	13.07	4	28	9.102	0.634	0.392	–1.484
CCC	31	5.84	3	4.43	1	24	5.693	0.975	1.463	1.535
CON	25	7.80	4	5.38	1	28	8.588	1.101	1.391	0.534
GAM	43	4.54	4	4.10	1	12	2.922	0.644	0.983	0.300
LOG	12	15.75	13	13.74	1	33	10.217	0.649	0.375	–1.189
MCN	35	5.57	5	5.37	1	12	2.627	0.471	0.509	–0.248
PMN	13	12.00	10	10.45	3	32	8.803	0.734	0.819	–0.313
PMR	28	6.21	5	5.68	1	21	4.149	0.668	1.672	3.559
BAN1	23	8.26	7	7.04	1	25	6.398	0.774	1.190	0.516
BAN2	28	6.79	5	5.72	1	24	5.600	0.825	1.593	2.072
BAN3	34	5.59	5.5	5.01	1	13	3.431	0.612	0.393	–0.961
BAN4	40	4.75	4	4.11	1	17	3.455	0.727	1.297	2.000
BAN5	21	8.00	8	7.26	1	24	4.980	0.622	1.324	2.898
BON	19	9.16	7	7.69	2	38	8.308	0.907	2.206	5.244
BER	29	6.00	5	5.01	1	21	5.007	0.835	1.589	2.341
BKM	66	2.98	3	2.64	1	15	2.557	0.857	3.020	10.526
GLR	43	4.51	4	4.12	1	18	3.232	0.716	2.147	5.482
LNG	7	12.29	13	10.38	1	31	9.358	0.762	0.995	0.043
MKP	55	3.47	3	3.09	1	10	2.218	0.639	0.596	–0.266
CCA	56	3.45	3	3.18	1	11	2.165	0.628	1.298	1.504
LMF	71	2.51	2	2.27	1	12	1.889	0.753	2.596	8.903
WAC	50	3.72	3.5	3.50	1	10	2.080	0.559	0.986	0.703
SCI	34	4.85	3	3.98	1	21	4.900	1.010	2.229	3.973
FST	31	5.90	5	5.23	2	19	4.460	0.755	1.412	1.091
FSR	31	5.52	3	4.65	1	23	4.891	0.887	1.953	3.789
ICE	24	7.38	5	5.89	1	33	7.829	1.062	2.344	4.604
LDG	16	11.25	12	10.64	2	23	5.756	0.512	0.213	–0.722
NAR	30	6.27	3	4.47	1	34	7.465	1.191	2.180	4.571
SSD	24	4.54	4	4.18	1	9	2.484	0.547	0.086	–1.139
UFW	59	2.93	2	2.61	1	15	2.399	0.818	2.801	9.990
CMP	27	6.82	5	5.75	1	23	5.299	0.778	1.335	1.540
PET	31	6.10	4	5.24	1	22	4.686	0.769	1.455	2.175
RIN	65	2.95	3	2.67	1	9	1.940	0.657	1.067	0.673
CHS	71	2.62	2	2.14	1	13	2.669	1.019	2.398	5.523
LPK	28	6.60	6	6.03	1	17	4.080	0.582	0.554	–0.570
CAT	36	5.50	5	5.26	1	15	2.923	0.531	1.315	2.095
JSS	29	6.59	5	6.26	2	18	3.756	0.570	1.254	0.953
SAJ	55	4.04	3	3.79	1	22	3.050	0.464	0.565	0.075
THC	68	2.94	2	2.52	1	9	2.304	0.783	1.235	0.633
ZUN	29	5.86	5	4.84	1	17	4.478	0.764	0.821	–0.232

Table 3.—Listing of fire interval statistics for 63 Southwestern fire–scar chronologies. Fire dates were based on fires recorded by 10% or more of sampled trees within each site, AD 1700 to 1900.

	Fire Intervals (years)—Fire Scar Dates Recorded by 10% or More of Sampled Trees									
Site Code	No. of Intervals	Mean	Median	WMPI	Minimum	Maximum	Standard Deviation	Coeff. of Variation	Skewness	Kurtosis
ANP2	12	14.33	14	12.66	2	32	9.267	0.647	0.343	–1.058
ANP1	14	14.14	9	11.92	3	36	11.114	0.786	0.764	–0.867
BFL	37	4.13	3	3.37	1	22	4.650	1.124	3.097	9.171
RHY3	20	8.75	9	8.03	1	17	4.610	0.527	–0.004	–0.841
RHY2	12	15.25	13	14.20	4	50	11.419	0.749	2.446	4.897
RHY1	14	12.64	12.5	12.21	4	31	6.675	0.528	1.364	1.793
CHU	23	7.22	4	5.30	1	41	8.733	1.210	2.695	7.464
CBE	25	7.08	7	6.87	2	13	3.095	0.437	–0.016	–1.006
CBN	31	6.19	5	5.89	2	13	3.240	0.523	0.603	–0.695
CER	14	12.64	10.5	10.13	3	43	11.256	0.890	1.333	1.339
CAL	7	21.86	17	20.81	8	37	12.116	0.554	0.184	–1.882
KIP	4	36.25	26	33.57	17	76	27.439	0.757	0.815	–1.399
HFL	12	13.58	13	12.14	2	31	8.681	0.639	0.466	–0.786
LAM	19	10.37	9	10.00	4	21	5.134	0.495	0.627	–0.654
LWN	14	14.07	13	13.02	3	30	8.471	0.602	0.669	–0.611
MES	14	13.64	13.5	13.14	4	24	6.404	0.469	–0.041	–1.237
GUA	20	8.75	6.00	7.218	1	26	7.085	0.810	0.987	–0.062
CME	7	24.29	20	23.85	13	46	11.842	0.488	0.808	–0.819
CMN	2	16.00	—	16.00	14	18	2.828	0.177	0.000	–2.500
CAN	4	23.00	23	23.32	14	32	7.528	0.327	0.000	–1.635
CAS	8	23.00	23	23.13	13	33	7.672	0.334	0.000	–1.606
CPM	12	14.00	12.5	13.06	3	29	7.909	0.565	0.404	–0.960
CPU	11	14.27	10	13.90	6	24	6.665	0.467	0.166	–1.790
CPE	7	22.57	21	20.35	4	50	15.054	0.667	0.637	–0.670
CCC	19	8.26	6	6.97	1	24	6.154	0.745	0.891	0.072
CON	16	11.94	6.5	7.74	2	48	15.013	1.258	1.618	1.105
GAM	25	7.80	8	7.36	1	15	3.979	0.510	0.243	–0.980
LOG	7	26.14	25	25.82	10	45	11.379	0.435	0.264	–1.000
MCN	29	6.48	6	6.40	2	12	2.572	0.397	0.291	–0.767
PMN	5	15.60	14	14.93	4	25	8.019	0.514	–0.282	–1.381
PMR	20	8.30	7.5	7.72	1	21	4.846	0.584	0.905	0.417
BAN1	13	14.08	12	12.52	2	25	8.539	0.607	–0.037	–1.665
BAN2	18	10.22	9.5	9.46	1	24	5.897	0.577	0.728	–0.062
BAN3	26	7.31	7.5	6.60	1	23	4.541	0.621	1.330	3.337
BAN4	26	7.31	6	6.28	1	23	5.312	0.727	1.285	1.523
BAN5	12	8.00	8	8.01	4	12	2.730	0.341	–0.080	–1.472
BON	10	17.40	15	15.98	2	38	10.265	0.590	0.565	–0.438
BER	10	16.30	11.5	14.46	2	32	10.904	0.669	0.446	–1.465
BKM	34	5.79	3.5	4.98	1	20	4.471	0.772	1.316	1.336
GLR	19	8.26	5	7.21	3	28	6.822	0.826	1.564	1.519
LNG	37	5.05	4.00	4.483	1	22	3.822	0.756	2.409	8.207
MKP	23	6.30	5	5.52	1	16	4.237	0.672	0.764	–0.167
CCA	26	7.08	7	6.77	1	14	3.346	0.473	0.061	–0.989
LMF	37	4.05	3	3.63	1	13	2.798	0.690	1.276	1.360
WAC	40	4.53	4	4.23	1	12	2.532	0.559	0.900	0.755
SCI	17	9.71	8	8.78	2	23	6.243	0.643	0.630	–0.825
FST	17	10.06	7	8.68	2	23	7.293	0.725	0.585	–1.200
FSR	11	13.73	13	13.55	4	23	5.569	0.406	0.048	–0.942
ICE	7	24.43	27	23.84	7	35	10.768	0.441	–0.469	–1.427
LDG	7	19.43	21	19.68	12	27	5.350	0.275	–0.205	–1.328
NAR	12	10.25	8	9.46	3	21	6.538	0.638	0.733	–1.104
SSD	5	18.80	20	18.66	9	27	8.106	0.431	–0.155	–1.924
UFW	43	4.02	3	3.38	1	23	4.132	1.027	3.022	9.660
CMP	27	8.52	8	7.73	2	23	5.600	0.672	0.818	–0.172
PET	20	9.45	8.5	8.91	3	22	5.296	0.560	0.753	–0.236
RIN	31	6.13	6	6.02	2	13	2.668	0.435	0.873	0.165
CHS	16	7.12	5.5	6.41	1	18	4.674	0.656	0.790	–0.282
LPK	23	8.61	9	7.94	2	17	4.793	0.557	0.061	–1.463
CAT	27	7.33	6	7.01	2	16	3.803	0.519	0.695	–0.451
JSS	21	8.24	7	7.94	3	21	4.242	0.515	1.167	1.593
SAJ	35	5.54	4	5.14	2	22	3.910	0.487	0.553	–0.704
THC	19	9.68	8	8.31	1	24	6.969	0.720	0.703	–0.769
ZUN	5	28.00	21	20.21	1	61	22.847	0.816	0.340	–1.400

Table 4.—Listing of fire interval statistics for 63 Southwestern fire—scar chronologies. Fire dates were based on fires recorded by 25% or more of sampled trees within each site, AD 1700 to 1900.

	Fire Intervals (years)—Fire Scar Dates Recorded by 25% or More of Sampled Trees									
Site Code	No. of Intervals	Mean	Median	WMPI	Minimum	Maximum	Standard Deviation	Coeff. of Variation	Skewness	Kurtosis
ANP2	7	24.57	22	22.82	4	46	13.710	0.558	0.075	-1.080
ANP1	12	16.50	12.5	14.65	4	41	11.767	0.713	0.808	-0.642
BFL	37	4.13	3	3.37	3	28	4.650	1.124	3.097	9.171
RHY3	19	9.21	10	8.77	4	25	4.354	0.473	-0.009	-0.756
RHY2	10	17.90	14.5	17.08	9	50	11.855	0.662	2.125	3.031
RHY1	13	13.08	13	12.67	4	31	6.739	0.515	1.291	1.600
CHU	10	9.30	10	8.31	4	16	6.019	0.647	0.286	-1.269
CBE	22	8.04	8.5	7.76	1	22	3.860	0.480	0.457	-0.529
CBN	28	6.79	6	6.57	4	40	3.178	0.468	0.417	-0.942
CER	14	12.64	10.5	10.13	2	48	11.256	0.890	1.333	1.339
CAL	7	21.86	17	20.81	10	41	12.116	0.554	0.184	-1.882
KIP	4	36.25	26	33.57	14	25	27.439	0.757	0.815	-1.399
HFL	10	16.30	17	15.91	8	37	7.558	0.464	0.422	-0.614
LAM	17	11.59	11	11.04	13	33	5.864	0.506	0.146	-1.444
LWN	10	15.80	15	15.70	2	16	6.443	0.408	0.800	0.182
MES	11	17.36	15	17.01	2	17	8.262	0.476	0.937	-0.189
GUA	5	27.40	22	25.04	2	13	22.018	0.804	1.209	-0.552
CME	7	24.29	20	23.85	10	53	11.842	0.488	0.808	-0.819
CMN	2	16.00	16	—	7	29	2.828	0.177	0.000	-2.500
CAN	3	20.00	21	20.42	3	34	5.568	0.278	-0.261	-2.000
CAS	8	23.00	23	23.13	7	35	7.672	0.334	0.000	-1.606
CPM	11	15.27	13	14.98	14	18	7.058	0.462	0.642	-1.019
CPU	11	14.27	10	13.90	13	46	6.665	0.467	0.166	-1.790
CPE	5	31.60	23	29.82	4	23	18.902	0.598	0.164	-1.911
CCC	11	13.18	13	12.64	2	64	6.954	0.528	0.593	-0.891
CON	9	17.22	9	10.60	6	24	22.543	1.309	1.305	-0.170
GAM	15	11.27	12	11.29	2	23	3.788	0.336	0.148	-0.700
LOG	7	26.14	25	25.82	5	19	11.379	0.435	0.264	-1.000
MCN	20	9.40	8	8.97	3	28	5.103	0.543	0.846	-0.598
PMN	4	19.50	19.5	19.86	12	66	4.655	0.239	0.000	-1.693
PMR	13	12.77	12	12.32	5	31	6.470	0.507	0.682	-0.375
BAN1	9	17.11	20	16.16	3	42	8.623	0.504	-0.263	-1.459
BAN2	16	11.50	10	11.05	5	25	6.240	0.543	1.235	0.916
BAN3	18	10.22	9	8.91	3	43	6.603	0.646	0.561	-0.561
BAN4	15	12.67	11	12.03	1	18	6.715	0.530	0.391	-1.128
BAN5	10	9.60	8.5	9.51	2	20	3.921	0.408	0.278	-1.113
BON	7	19.00	15	16.32	3	30	14.468	0.761	1.027	0.035
BER	7	23.29	19	22.75	17	76	11.280	0.484	0.333	-1.459
BKM	15	13.13	10	12.09	4	21	9.133	0.695	1.691	2.579
GLR	18	8.72	5.5	7.71	12	27	6.841	0.784	1.474	1.285
LNG	21	8.38	7	7.59	1	15	6.029	0.719	1.540	1.646
MKP	21	6.91	6	6.40	2	26	4.024	0.583	0.779	-0.089
CCA	17	10.82	8	9.51	10	45	9.416	0.870	2.257	4.731
LMF	28	5.36	5	5.03	2	24	3.200	0.597	1.418	1.797
WAC	23	7.65	6	6.85	7	30	5.581	0.729	1.547	1.700
SCI	17	9.71	8	8.78	14	25	6.243	0.643	0.630	-0.825
FST	17	10.06	7	8.68	7	35	7.293	0.725	0.585	-1.200
FSR	11	13.73	13	13.55	3	20	5.569	0.406	0.048	-0.942
ICE	7	24.43	27	23.84	1	16	10.768	0.441	-0.469	-1.427
LDG	7	19.43	21	19.68	3	21	5.350	0.275	-0.205	-1.328
NAR	12	10.25	8	9.46	3	22	6.538	0.638	0.733	-1.104
SSD	5	18.80	20	18.66	5	27	8.106	0.431	-0.155	-1.924
UFW	22	7.77	5	7.01	4	31	5.673	0.730	1.368	0.722
CMP	12	12.67	12	11.45	9	50	8.773	0.693	1.164	0.643
PET	15	12.60	12	12.35	3	22	5.248	0.417	0.033	-0.639
RIN	25	7.32	7	7.12	2	13	3.288	0.449	0.307	-1.175
CHS	16	7.12	5.5	6.41	2	22	4.674	0.656	0.790	-0.282
LPK	19	10.42	12	9.65	2	23	5.719	0.549	0.314	-0.303
CAT	27	7.33	6	7.01	2	16	3.803	0.519	0.695	-0.451
JSS	18	9.61	10	9.08	3	30	6.001	0.624	2.079	5.072
SAJ	25	5.88	5	5.47	2	22	4.050	0.582	1.774	3.668
THC	12	14.75	15	13.65	1	24	7.956	0.539	0.099	-0.853
ZUN	5	28.00	21	20.21	1	61	22.847	0.816	0.340	-1.400

Drought—Fire Relations

As we have observed in compilations of smaller sets of fire-scar chronologies from the Southwest (e.g., Swetnam 1990; Swetnam and Betancourt 1990; 1992) there was a remarkable synchrony of fire events across the region during the pre-settlement era (Figure 5). The maximum number of sites recording fires among the 63 sites was 41 in the year 1748. The next largest regional fire year was 1851 with 37 of the sites recording fires during that year (Figure 5). Overall, the regional fire occurrence times series from 1700 to 1900 shows a pattern of about 20 large regional fire years (more than 19 sites) occurring against a background of smaller fire years. An obvious decline in numbers of sites (Figure 5) around 1900 reflects the region-wide onset of intensive livestock grazing beginning in the late 1800s followed by the beginning of organized fire suppression efforts during the first decades of the twentieth century (Swetnam 1990; Touchan et al. This Volume).

The synchrony of large fire years and small fire years, as measured by the largest and smallest numbers of sites recording fires (Figure 5) is probably related to regional-scale year-to-year climatic oscillations. Climate is the only factor operating over such a large area that could produce such a consistent pattern. Obviously, human influences on fire occurrence, such as the fire decline since the late 1800s, were also important, but it is highly unlikely that Native Americans, for example, purposely synchronized the year-to-year timing of their burning practices in dozens of different mountain ranges over the Southwest. We will return to the issue of the importance of fires set by Native Americans versus lightning in the discussion section.

Both the overlay of large and small fire years on the PDSI time series (Figure 6) and the SEA (Figure 7) reveal that important current year and lagging relations existed between fire occurrence and climate. This pattern is fairly consistent in both the

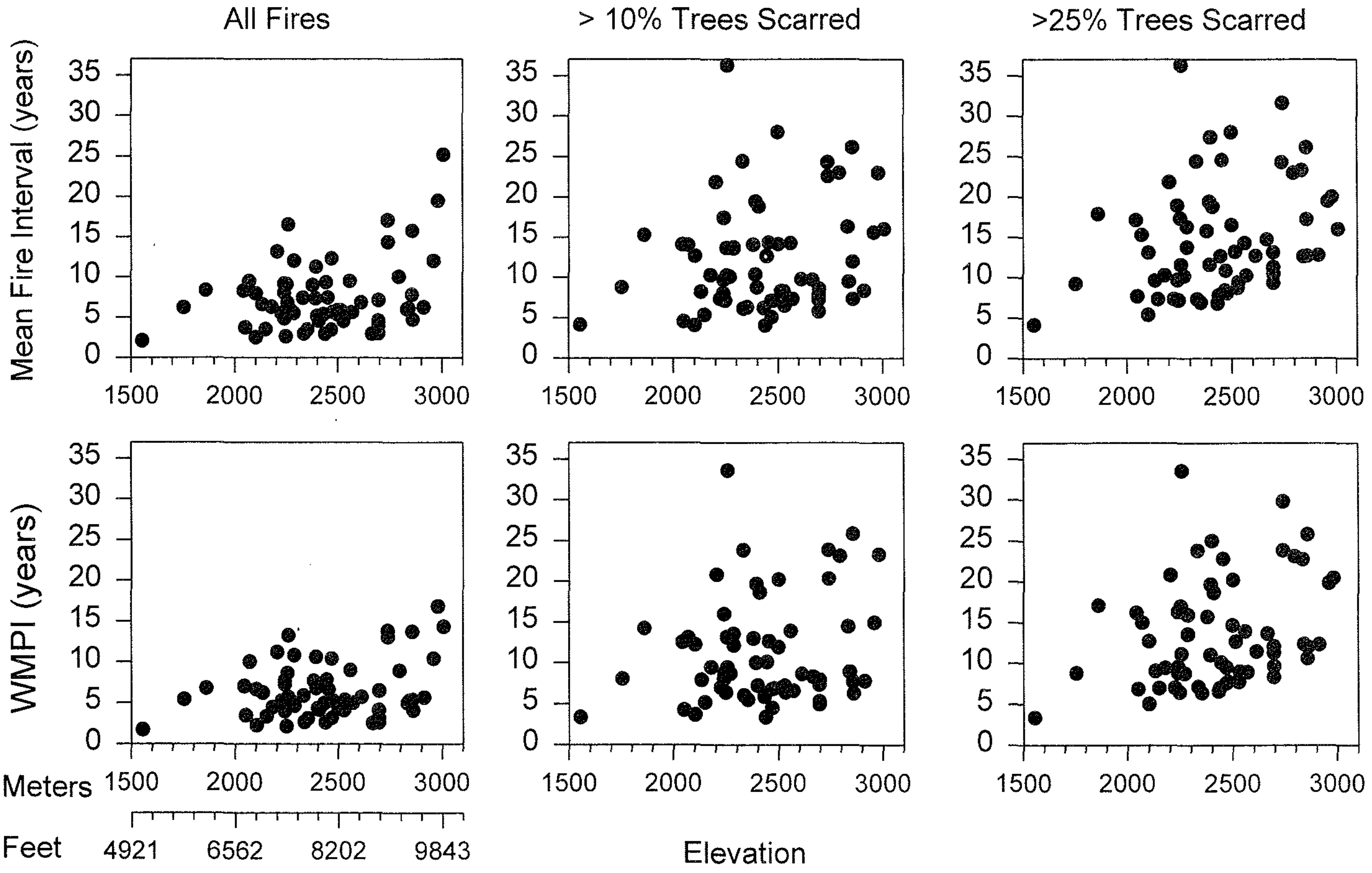

Figure 3.—Measures of central tendency of fire interval distributions - mean fire interval and Weibull median probability interval - versus elevation among the 63 fire history sites. The fire interval estimates were based on three sortings: (1) fires recorded by any number or percentage of trees within sites (All Fires), (2) fires recorded by at least two trees and ten percent or more of the sampled trees within sites, and (3) fires recorded by at least two trees and twenty five percent or more of the trees within the sites.

fire-scar record (pre–1900) and the area burned record from National Forests (post 1920) (Figure 6 and 7). There was a striking correspondence between severe drought years and the largest fire years, especially in the fire-scar record (Figure 6). There was a somewhat less consistent correspondence between the smallest fire years and wet years, particularly before about 1820 (Figure 6). Not all severe drought years were large regional fire years. A visual inspection of Figure 6 suggests that in many instances (particularly in the pre–1900 fire scar record) the largest fire years often followed within one to a few years an unusually wet year (or years) and/or one of the smallest fire years. For example, the largest fire year in the pre–1900 record—1748—was also one of the driest and it followed several very wet years (Figure 6).

The SEA statistically measures the average strength of these lagging relations among the set of largest and smallest fire years (Figure 7). The largest fire years (the 20 years with maximum numbers of sites recording fires) were typically very dry and the second and third years *preceding* these fire years were very wet (upper left plot Figure 7). The sorting of fire years by forest type demonstrates that this pattern was primarily driven by the fire-climate relations in the ponderosa pine sites (middle right plot in Figure 7). In contrast, the largest fire years among the mixed-conifer sites were drier than the largest fire years among ponderosa pine sites, but preceding years had no consistent pattern (middle left plot in Figure 7). The smallest fire years among all sites were typically very wet and the years immediately preceding the smallest fire years were dry (upper right plot in Figure 7). A similar SEA of actual area burned per year on National Forests in the twentieth century shows that largest fire years were on average very dry, the smallest fire years were on average wet, and no significant wet or dry patterns preceded these years (Figures 6 and 7).

DISCUSSION

Fire Interval Variations

The large scatter of data points in the comparison of elevation and forest type versus WMPI or mean fire interval (Figures 3 and 4) suggests that a weak relationship may have existed between fire frequency (or interval distributions) and these fac-

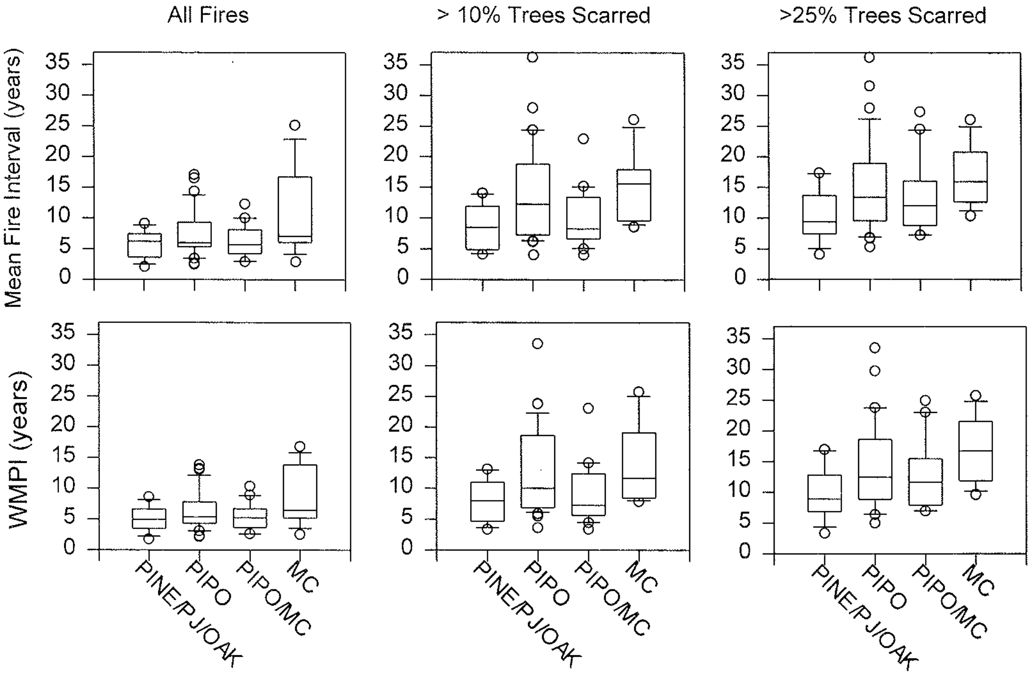

Figure 4.—Measures of central tendency and the variance of these measures sorted by forest type. See text for explanation of the types. The box plots show mean values as horizontal lines within the boxes, the upper and lower sides of the box are the 95% confidence levels, the horizontal lines at the ends of the vertical lines outside of the boxes are the 99% confidence levels, and the small circles above and below are the outliers beyond the 99% confidence levels.

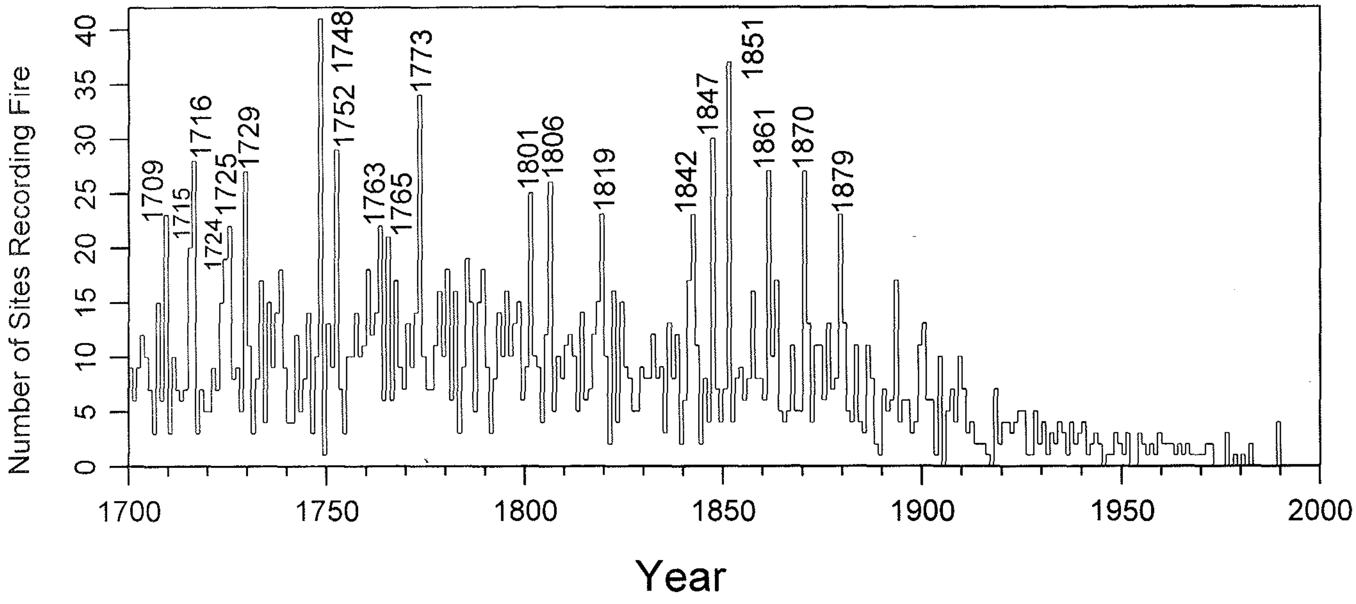

Figure 5. Regional fire occurrence time series from a network of 63 fire history sites in the Southwestern U.S. The largest 20 fire years are listed, based on the maximum numbers of sites recording these years.

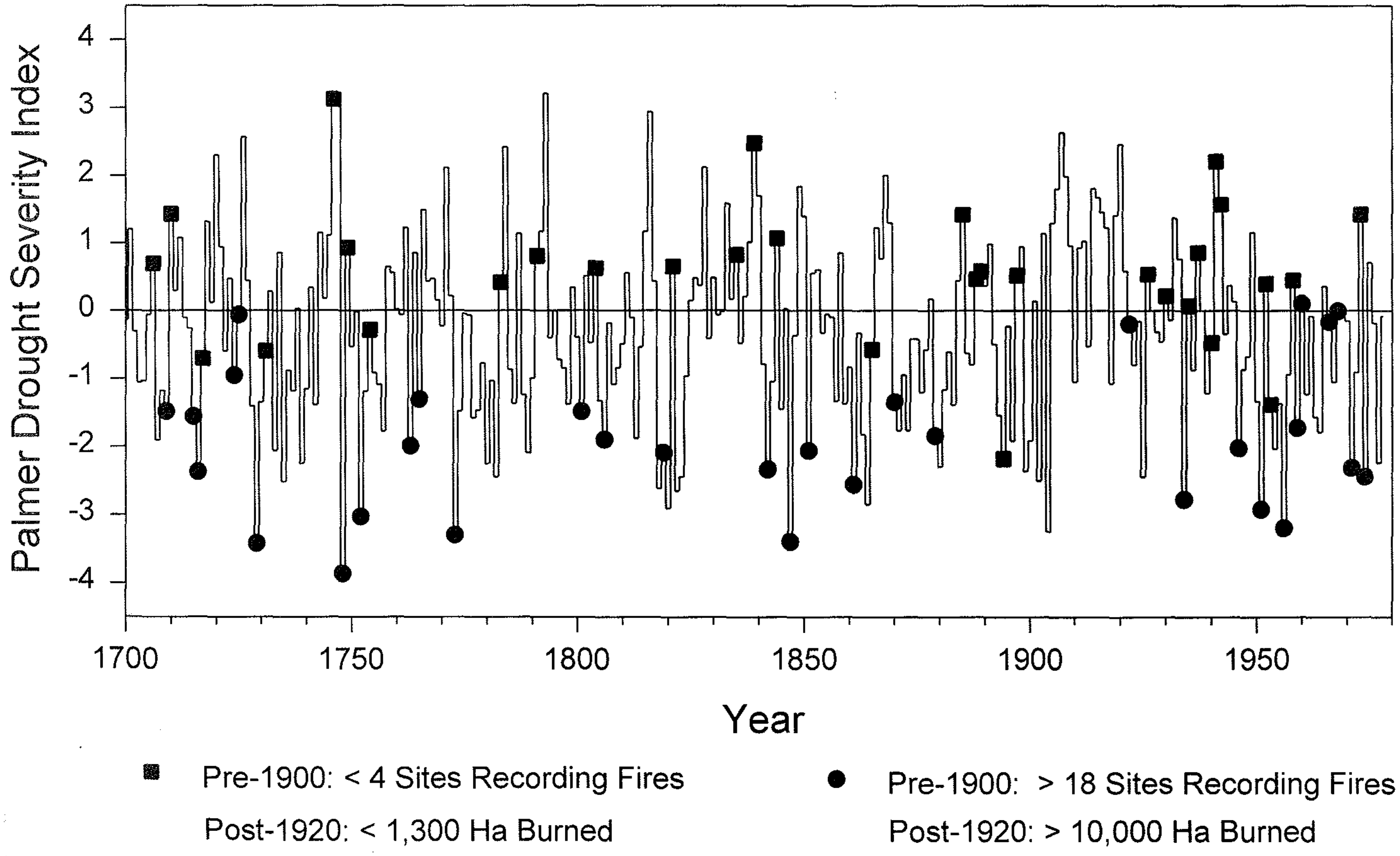

Figure 6. Palmer Drought Severity Index (PDSI) reconstruction (AD 1700 to 1978) for the Southwestern U.S. derived from tree-ring width chronologies (see text for explanation). The circles and squares show the largest and smallest fire years recorded by the regional fire-scar network (1700 to 1900, 20 years each) and the largest and smallest fire years recorded in the area burned per year record from all National Forest lands in the Southwest Region (1920 to 1978, 10 years each).

tors. This general pattern conformed to our initial expectations of longer intervals between fires in the higher, relatively mesic, mixed-conifer sites than in the lower, drier, ponderosa pine sites. However, because of the large scatter of the data points it must be recognized that associations observed here have little or no predictive power for specific sites. We have not yet proceeded with more sophisticated statistical tests and comparisons of these patterns because of various data limitations requiring more study. In particular, a probable cause of some of the variability observed in the fire interval statistics between sites of approximately the same elevation or forest type is the fact that the sampled sites encompassed (and represented) different size areas and included different numbers of sampled trees. The problem is that as study area increases in size the estimated fire frequency for the entire sampled area is also likely to be higher (see Arno and Peterson 1981). Simply stated: larger areas were more likely to have been burned over at least partially by more fires. Number of trees sampled also affects fire frequency estimates if fires were relatively patchy within sites. Hence, some kind of statistical standardization of study area and sample size may be needed for a more rigorous comparison of fire interval distributions.

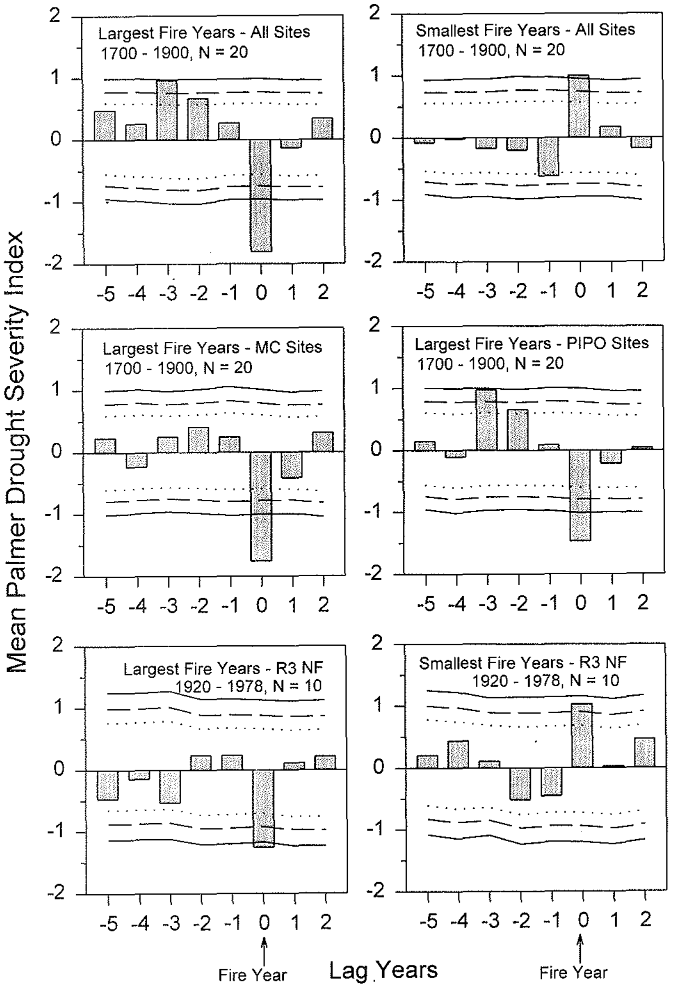

Figure 7. Results of superposed epoch analyses (SEA) using the PDSI reconstruction and sets of largest and smallest fire years recorded in the fire scar network (1700 to 1900) and in Forest Service documents of area burned per year on all National Forests in the Southwestern Region (1920 to 1978). The horizontal lines are confidence intervals (CL) estimated from a bootstrap simulation of 1000 trials of randomly selected sets of the same number of key dates. The dotted line is the 95% CL, the dashed line is the 99% CL and the solid line is the 99.9% CL.

Differences in sampled areas among our sites was actually not very large — usually within an order of magnitude, ranging from about 10 ha to 100 ha (areas defined by a polygon with convex vertices determined by outermost sampled trees within sites, i.e., a "convex hull"). In many of our sites most fires were probably as large or larger than the sampled areas, as indicated by highly synchronous fire dates among sampled trees. In other cases, especially in the higher fire frequency sites, most fire dates were recorded by only one or a few trees. As previously pointed out, in these latter cases, sizes of the areas and numbers of trees sampled can have a more important effect on the estimated fire frequency. However, this effect might be small in terms of absolute values of estimated fire frequency because these values are approaching the limit of possible fire frequency anyway. For example, fire intervals based on all fire dates (Table 2) are about two to three years in the highest fire frequency sites. Expanded area or additional trees sampled in these stands could only increase these frequencies up to the maximum fire frequency we can estimate (and which may be ecologically possible), i.e., one fire each year.

A related problem is the estimation of the size of the area that is represented by a set of spatially dispersed fire-scarred trees. In some cases, very distinct fire barriers, such as cliffs or talus slopes, can help define the probable minimum boundaries of an area that the larger fires burned over. Fire spread simulation models (e.g., Finney 1994) also have potential for defining probable "firesheds" that would be useful in determining areas represented by spatial networks of sampled trees and sites. We are currently experimenting with various spatial statistics models involving tessellations, kriging, and distance measures that estimate *relative* areas that sampled fire-scarred trees might represent. Ultimately, we do not believe that these sampling problems are intractable. In fact, they offer the possibility of learning a great deal more about spatial patterns of past fires, as well as the limitations of paleo-fire reconstruction methods.

In addition to elevation and forest type, other landscape attributes were also important in controlling fire regime characteristics. For example, slope, aspect, and continuity (contiguity) with other landscape units can be very important, even to the extent of over-riding the importance of other factors (Swetnam et al. 1989; Grissino-Mayer and Swetnam, In Press; Grissino-Mayer et al., In Press; Touchan et al. This Volume). Similarly, land-use history can over-ride the importance of other landscape attributes. The onset or decline of intensive livestock grazing, and/or the initiation of organized fire suppression efforts usually resulted in the greatest single temporal change observed in most fire chronologies. These human influences were not all synchronous across the Southwest. For example, certain areas in northeastern Arizona and northern New Mexico were subject to intensive livestock grazing (especially by sheep and goats) at different times in the 18th and 19th centuries, resulting in complex temporal and spatial patterns of interrupted and resumed surface fire regimes. These patterns seem to correlate fairy well with establishments of land grants from the King of Spain to Hispanic colonists, initiation of intensive grazing, and hostilities between the colonists and Native Americans (Savage and Swetnam 1990; Touchan et al. In Press; Touchan et al., This Volume). The associations between patterns of historical livestock grazing, climatic variation, and fire occurrence all point to the importance of the production and moisture content of fine fuels (i.e., grasses, herbs, and tree needles) as key factors driving the pre–1900, surface fire regimes of the Southwest.

Fire Climatology

The patterns of association between drought and fire occurrence observed in the large network of fire histories (Figures 6 and 7) were also observed at smaller spatial scales (e.g., mountain ranges—see Baisan and Swetnam 1990, and Touchan et al. This Volume). Different responses of fire occurrence in pure ponderosa pine versus mixed-conifer, and consistency in these responses at different spatial scales (mountain ranges, and the region) strongly suggests that fuel types, amounts, and condition (e.g., moisture content) were key factors in this system. We hypothesize that the significant lagging relations in ponderosa pine reflects the *initial* importance of fine fuel production tied to moisture levels in previous years (especially one to three years preceding large fire years). This mechanism apparently operated both through the production of higher fuel amounts during preceding wet years (upper left plot Figure 7) and in producing lower amounts of fuels in preceding dry years (upper right plot, Figure 7). This topic has not been studied in ponderosa pine forests, but similar patterns have been documented in lower elevations of southern Arizona (Rogers and Vint 1987). In the pre-settlement era grass production was probably very important to the spread of frequent fires through the open, park-like stands, but the interesting two to three-year lags that consistently show up in our analyses also suggest that tree needle production may also be important. Ponderosa pine typically holds needles on the branches for three to five years before they are abscised and fall to the forest floor. Hence, climatic oscillations on these time scales (e.g., the El Niño-Southern Oscillation) could be important mechanisms that synchronize fuel production, moisture content, and fire occurrence at large spatial scales (Swetnam and Betancourt 1990; 1992).

The lack of significant lagging relations in the mixed-conifer forests further supports the hypothesis that fuels and climate were primary controls of fire regimes. In these relatively high productivity, mesic forests with longer intervals between surface fires, it appears that *fuel amounts* were not limiting. Rather, it seems that *fuel moisture* was most important, as reflected in the very dry conditions that prevailed during the largest fire years (middle left plot Figure 6). Greater canopy cover in mixed-conifer than in ponderosa pine forests, because of greater shade tolerance of the dominant tree species, results in the snow pack persisting longer into the spring. Moreover, the shaded conditions limit the development grass cover, and the short needles of Douglas-fir and true firs tend to compact quickly on the forest floor. This results in a fuel substrate that is less conducive to fire spread than in the grassy understory and loose litter layer of long needles found in ponderosa pine forests. Needle retention is also longer in both Douglas-fir and true firs (five to seven years, or longer). The combination of these micro-environmental and fuel characteristics result in mixed-conifer fire regimes that were unresponsive to previous year's moisture levels and associated fuel productivity, and fires primarily occurred when conditions were very dry.

The twentieth century SEA confirmed the importance of drought conditions during largest fire years in National Forests, but not the importance of preceding years (lower plots, Figure 7). These data, however, combine fire occurrence across a very broad range of forest, woodland, and grassland types in the Southwest and so important lagging relations might be obscured. It is also a fact that fire regimes and fuels across the Southwestern region have greatly changed in the twentieth century. The past one hundred or more years of grazing, fire suppression, logging, road building, recreation uses, etc. have directly altered fuel amounts and composition, ignition sources, and locations. Despite these changes, and the lack of patterns in the SEA documenting lagging patterns, recent fire patterns suggest that prior year's fuel production linked to wet years can be critically important determinants of year-to-year fire loads. The early 1990s are a case in point. An unusual El Niño event persisting for about two and a half years—starting in 1991 and lasting until 1993—resulted in excellent grass production across much of the Southwestern Region. Regional fire occurrence was relatively low during the El Niño years, then dry summer conditions in 1994 led to numerous very large wildfires, especially in southern Arizona and New Mexico.

The Role of Humans in Pre-Settlement Southwestern Fire Regimes

When discussing historical fire regimes it is necessary to point out that fire occurrence patterns were probably influenced to some degree by the intentional and un-intentional burning practices of Native Americans (see the Pinchot quote at the beginning of this paper). The fact that Native Americans did set fire to the Southwestern landscape is well established (Dobyns 1978; Pyne 1982; Bahre 1991). However, we question the implicit or explicit assertion that the use of fire by Native peoples was primarily controlling the dynamics of fire regimes in virtually all parts of North American or the Southwest. This is an over generalization.

In the first place, lightning strikes capable of igniting fires are far more prevalent than most people realize. The installation of lightning detection networks over the whole United States in recent decades clearly documents the fact that *hundreds or even thousands* of lightning strikes occur in single storms passing over mountain ranges. The Southwest has one of the highest incidences of lightning strikes, and the highest rate of lightning ignited fires in the U. S. (Schroeder and Buck 1970:168). The important question is: Were there enough lightning ignitions to account for the fire frequencies that we document in the fire scar record? We believe that in *most cases* there are currently, and there were historically, enough lightning ignitions to produce the fire frequencies we estimate from fire-scar chronologies. This is based on a simple accounting of the rates of successful lightning fire ignitions within our mountain ranges today, as well as the fact that these fires, if not suppressed, would have had the opportunity to burn un-hindered for several months, thus spreading over enormous areas. In fact, the historical record (e.g., newspaper articles) contains many accounts of fires burning millions of acres in the Southwest during particular years (see Bahre 1985).

The data and results we have presented in this paper and elsewhere also support the hypothesis that fuel and climate were primary driving and regulating forces in pre-settlement fire regimes. It is likely that Native Americans set some of the fires that are documented in our fire-scar records, but these fires would not have burned over large areas if the fuels had not been present, and in the condition (e.g., moisture content) necessary for spread. Fundamentally, we argue that ignition sources (or amount of ignitions) were usually not limiting—*fuels and related climatic conditions were.* Hence, it is unnecessary in most cases to invoke human-set fires as an explanation or cause of fire regime patterns in the Southwest. We contend that, even if humans had never crossed the land bridge from Asia to North America, historical fire regimes in most Southwestern forests would still have been similar in most respects to the fire regimes that we have documented.

Now, having made a rather broad generalization of our own, a caveat is in order. We have in a several instances observed unusually high fire frequencies during some time periods in sites that were isolated topographically, so that spread of fires from outside of these areas had a low probability (unpublished data). Infrequent lightning ignitions in the twentieth century within these sites suggest that lightning probably could not account for the frequencies we documented. Furthermore, comparison with climatic data (e.g., SEA) indicated that fire-climate relations were weak or non-existent in these cases. Hence, supplemental fire ignitions by people is a reasonable explanation . The point here is that we do not deny the fact that people strongly influenced fire regimes in *some places and some periods,* but we emphasize that the role and importance of Native Americans in pre-settlement fire regimes of the Southwest were *very site and time specific,* and not ubiquitous.

CONCLUSIONS

Pre-1900 fire regimes of the Southwestern U.S. varied greatly in time and space. Some patterns of fire regime variation were evident across gradients of elevation and forest type, such as a decrease in frequency from low to high elevations and from drier ponderosa pine to wetter mixed-conifer forests. Additional study is needed, however, because fire history reconstructions come from areas of different size and are based on variable sample sizes, which could importantly affect inter-site statistical comparisons. Additional fire history reconstructions are also needed from lower and higher elevation forests and woodlands. For example, we have very little knowledge of fire regime patterns in pinyon-juniper and pine-oak woodlands and their ecotones with grasslands below and pine forests above. Similarly, we have limited fire chronology data from higher elevation mixed-conifer forests, and virtually none from spruce-fir forests. Fire history collections obtained systematically across the full span of the elevation gradient would be useful for evaluating inter-site (type) variations as well as historical fire spread patterns and relative fire extent across the landscape (Caprio and Swetnam, In Press).

Although elevation and forest cover type may ultimately explain more of the variance in fire frequency patterns than is evident in our current data sets, we expect that other landscape attributes (e.g., slope, aspect, landscape connectivity, etc.) will have greater or lesser importance in different instances. We believe this calls for a spatial modeling approach that makes use of historical fire occurrence data to "parameterize" the varying importance of multiple factors. Such a model could be used to map past and potential fire regime patterns across landscapes. Geographic information systems are logical tools to use in such a modeling effort. Even though such models will be very useful in assessing the role and importance of fire in ecosystem dynamics, we must remember that past fire regimes were linked to partially or totally unpredictable climatic patterns and human interventions. Thus, statistics that summarize general fire regime properties (i.e., mean fire interval, WMPI, etc.), or models that attempt to simulate fire regimes and forest structures based on statistics or mechanisms, cannot fully substitute for the historical record in terms of the explanatory power of *knowing what actually happened* within individual sites. This knowledge provides direct explanation and understanding of *how* and *why* past and current forest structures developed.

Finally, our data demonstrate that climatic variations, specifically drought fluctuations, were important in determining temporal and spatial patterns of fire occurrence across time scales of years to centuries and spatial scales from forest stands to the region. Climatic variation (yearly to longer time scales) is extremely complex and therefore difficult to predict. On the other hand, the El Niño-Southern Oscillation (ENSO), which has been called the single strongest control of global inter-annual climate variation, is currently being forecast several seasons in advance with fairly good skill by models and observations (Barnett et al. 1988; Ropelewski 1992). The linkage between ENSO, other climatic variations, and fire is at least partly through the production of fuels *preceding* fire seasons. Thus, the oscillatory and persistent behaviors of both the climate system and the bio-physical system of fire and fuels indicates that development of predictive fire hazard models operating at time scales of seasons to years should be attempted using new knowledge and modeling capabilities that are now available.

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