International Journal of Wildland Fire 9 (1): 37-50, 1999. ©IAWF. Printed in Canada

Modeling Fire Interval Data from the American Southwest with the Weibull Distribution

Henri D. Grissino-Mayer
Department of Physics, Astronomy and Geosciences
Valdosta State University
Valdosta, Georgia 31698-0055 USA
Phone: (912) 333-5757; Fax: (912) 219-1201; e-mail: grissino@valdosta.edu

Abstract

In this study, the Weibull distribution is tested as a possible model for fire interval data derived from dendrochronologically-dated fire scars from four sites in the American Southwest. Two- and three-parameter Weibull distributions were fit to fire interval data sets, and additional statistical descriptors based on the Weibull were derived to improve our understanding of the range of variability in presettlement fire regimes. The three-parameter models failed to provide improved fits versus the more parsimonious two-parameter models, indicating the Weibull shift parameter may be superfluous for Southwestern fire regimes. The Weibull Modal Interval (MOI) was a superior overall measure of central tendency, and appears to identify a common underlying structure in Southwestern fire regimes independent of habitat type and environmental gradients. Unusually short and long fire intervals were identified by the lower and upper exceedance intervals (LEI and UEI) and the Maximum Hazard Interval (MHI) based on the Weibull hazard function. Model statistics were nearly identical between two pairs of sites that were 260 kilometers distant that differed in topography, vegetation, and land-use history. However, differences were observed between sites only 10 kilometers apart, suggesting the influence of local factors (e.g., topography and substrate) over regional influences (e.g., climate). Although the Weibull models helped quantify the historical range of variability in presettlement fire regimes, ecological interpretations of the Weibull parameters proved difficult.

Keywords:

Weibull distribution
fire intervals
fire regimes
fire history
disturbance history
Southwestern United States
Pinus ponderosa

Introduction

The fitting of distributions as models to real and simulated data is a powerful statistical tool in the social, econometric, and physical sciences, often used to model the behavior of stochastic processes over time (Schribner 1987). In many ecological data sets, frequency distributions do not exhibit a distinct shape, which otherwise would aid the identification of a particular class of models to which the data set belongs. Specification of a particular model based on the fitting of distributions would have great utility in studies that use fire interval data to better understand characteristics of fire regimes, because interval data provide insights on both direct (i.e., the time elapsed since the last fire) and indirect (i.e., the temporal properties of forest fuels) properties of fire regimes useful to land management agencies. For example, the parameters of these distributions may help reveal important links between ecological factors that operate on local and regional scales (e.g., climate and topography) with characteristics of fire regimes, such as fire frequency, fuel accumulation rates, and the seasonality of fires (Johnson 1979, Johnson and Van Wagner 1985).

The fitting of distributions to fire interval data could become a more widely used and valuable tool for forest managers and land management agencies interested in quantifying the range of "natural" or historical variability in fire regimes (Morgan et al. 1994, Swanson et al. 1994, Allen 1994) prior to widespread and pervasive human disturbances. Knowledge of this historical range of variability is vital because a central goal of ecosystem management is to sustain the viability of ecosystems by maintaining or restoring past ecological processes that created or shaped these ecosystems (Kaufmann et al. 1994). The reconstruction of wildfire regimes during the presettlement period provides information on certain ecosystem processes that functioned in the past, but provides few quantifiable statistical measures that delimit those processes. The Weibull distribution can be used to model the data that help define these fire regimes by providing statistical descriptors that "bracket" this historical range of variability. Such an analysis could then help assess the hazard of future wildfires. For example, global warming, whether natural or human-induced, could alter the frequency, severity, seasonality, and areal extent of wildfires (see e.g., Overpeck et al. 1990, Ryan 1991, Bergeron and Flannigan 1995), as well as the length of the fire season (Wotton and Flannigan 1993). Environmental data from historical wildfires, coupled with the calculated parameters of a distribution fit to fire interval data, could be used to model changes in fire regimes expected with increased temperatures due to increasing atmospheric carbon dioxide.

In fire history studies, the Weibull distribution (Weibull 1951) is desirable as a model because it is highly flexible, able to model a variety of positively skewed distributions, and often provides a superior fit to fire history data than most other distributions (Clark 1989, Johnson 1992, Baker 1992). The distribution has been applied primarily to data collected in the North American boreal forests, which are characterized by stand-replacing fires that create an uneven-aged mosaic across the forest landscape (Johnson 1979, Baker 1989, Clark 1989). However, the distribution is gaining considerable attention from researchers in the American Southwest (Grissino-Mayer et al. 1995; Fulé and Covington 1997; Wolf and Mast 1998). Unlike the fire regimes in the boreal forests, Southwestern fire regimes were more typically characterized by low-intensity, high-frequency surface fires prior to widespread Euro-American settlement that began ca. 1880 (Swetnam 1990, Covington and Moore 1994, Swetnam and Baisan 1996). The Weibull distribution could furnish a new means for characterizing these surface fire regimes by providing the necessary probabilistic framework for deriving an additional suite of descriptive statistics to help define the historical range of variability. These new descriptors are not meant to replace those derived from the actual data, but instead provide additional information on temporal properties of the fire regime not found (or perhaps masked) in the actual data.

Furthermore, the use of a single distribution type applied to fire interval data from multiple sites provides a standard system for comparing fire regimes between habitat types along environmental gradients. Such comparisons are especially desirable for the Southwestern U.S. where temporal and spatial patterns of fire result from complex interactions of both human and natural factors. Eventually, these comparisons could help distinguish between and identify local and regional factors that maintain and/or alter fire regimes. This is significant because Southwestern fire regimes exhibit a broad spectrum of fire interval distributions across both time and space (Swetnam and Dieterich 1985, Grissino-Mayer 1995, Swetnam and Baisan 1996). The flexibility of the Weibull distribution is, therefore, especially suitable. In this paper, I demonstrate the use of the Weibull distribution as a model for fire interval data derived from fire-scar data collected from four sites in the American Southwest. Specific goals include: (1) providing an improved description of the range of variability in presettlement fire regimes by developing and applying an additional suite of statistics derived from the Weibull distribution; (2) the derivation and estimation of measures of central tendency in fire interval distributions based on the fitted Weibull models rather than the actual data; and (3) defining statistical descriptors based on the Weibull distribution that further delimit critical threshold fire intervals for evaluating fire hazard.

The Weibull distribution

The cumulative distribution function (cdf) for the two-parameter Weibull distribution (a = 0) is defined as:

$$F(t) = 1 - \exp[-(t/b)^c],\ t > 0,\ b > 0 \qquad [1]$$

(Johnson and Kotz 1970, Hallinan 1993), where *t* represents the fire interval data (i.e., the time between two successive fire years), *b* is the scale parameter, and *c* is the shape parameter. For the three-parameter model, the shift parameter, *a*, is subtracted from *t*. Data used in fire interval analyses are usually obtained from crossdated tree-ring sequences that contain multiple fire scars (Dieterich and Swetnam 1984, Baisan and Swetnam 1990, Grissino-Mayer 1995) or from time-since-fire data using age classes of forest patches (or in combination with fire intervals from fire-scarred samples) across a landscape (Heinselman 1973, Johnson and Van Wagner 1985, Baker 1989). The Weibull has been almost exclusively applied to data from this latter category.

The *cdf* is synonymous with the cumulative mortality function (Somers et al. 1980, Johnson 1979, 1992), i.e., the probability that an organism will not survive to time *t*. In fire interval studies, substituting a specific value for *t* provides the cumulative probability that a fire interval will be less than *t* (i.e., the level of non-exceedance). For fire interval data, the complement of the *cdf, A(t)*, is perhaps more useful, defined as:

$$A(t) = 1 - F(t) = \exp[-(t/b)^c] \qquad [2]$$

This function is synonymous with the survivorship function (i.e., 1 - mortality) (Pinder et al. 1978). In fire interval studies, substituting specific values for t represents the probability of obtaining fire intervals greater than *t* (i.e., the exceedance probability).

The Weibull hazard function, *h(t)*, is stated as

$$h(t) = (ct^{c-1}) / b^c \quad [3]$$

and interpreted as the instantaneous burning interval, similar to the instantaneous death rate used in time-since-fire studies (Clark 1989, Johnson 1992). Note that for $c = 1$ (a negative exponential distribution), $h(t) = 1/b$, indicating a constant hazard. Because $h(t)$ can exceed 1, $h(t)$ is not considered a probability, but a rate.

The probability density function (*pdf*) of the Weibull distribution, $f(t)$, is defined as:

$$f(t) = h(t)A(t) = [(ct^{c-1}) / b^c] \exp[-(t/b)^c] \quad [4]$$

and provides the density form for the fire interval data being modeled. The *pdf* reflects the direct relationship between hazard of burning, $h(t)$, and survivorship, $A(t)$, i.e. as the hazard of fire increases ($c > 1$), the chance of survivorship must decrease. $f(t)$ approximates the shape of the frequency distribution for the actual data, although the fitting of the Weibull distribution uses the cumulative form $F(t)$.

In some distributions with only positive random variables, the shift parameter (a) can be set to zero, greatly simplifying the estimation of the remaining two parameters (Hallinan 1993). Because all fire interval distributions have the theoretical lower limit of one year (even though in some fire regimes, such as the boreal forest, this lower limit is ecologically unlikely), setting the shift parameter to zero would enable direct comparisons of fire interval distributions between sites because all distributions would be "anchored" along the abscissa with a common endpoint. By definition, the scale parameter (b) approximates the 63rd percentile of the distribution (Bailey and Dell 1973, Johnson and Kotz 1970), and physically locates the distribution across the axis containing the interval classes. This parameter is also sensitive to the range of fire interval values. The Weibull shape parameter (c) is used to characterize the overall shape of the fire interval distributions. For $c = 1.0$, the Weibull reduces to a negative exponential distribution (Johnson and Kotz 1970), characteristic of time-since-fire distributions in the boreal forests of Canada (Johnson and Van Wagner 1985, Johnson 1992). If $1 < c < 3$, the distribution is skewed and usually peaked. If $3.25 < c < 3.61$, the Weibull approximates the normal distribution (Dubey 1967, Johnson and Kotz 1970).

Methods

Study sites

I selected four sites in the Four Corners area of the Southwestern U.S. (Table I) to demonstrate the fitting of the Weibull distribution to fire interval data sets. Each site comprises a contiguous stand of ponderosa pine (*Pinus ponderosa*) trees that represent the majority of forests within the immediate region regarding stand composition, density, and structure. The Plateau (PLT) and Turkey Springs (TKS) sites are located in the southern portion of the San Juan National Forest in southwestern Colorado (Figure 1). Both sites have little topographic relief, consist of open ponderosa pine forests with a well-developed grass and herbaceous understory, and were impacted by both Native American and Euro-American land-use practices. The Cerro Bandera East (CBE) and Hoya de Cibola (HDC) sites are located in the western portion of El Malpais National Monument, south of Grants, New Mexico (Figure 1). Both have relatively open ponderosa pine forests with a history of past logging and livestock grazing that began ca. 1880. The CBE site occupies the east-facing slope of a steep-sided cinder cone, while the

Table 1. Physical characteristics of sites discussed in this study

Site Name	Elevation (m)	Slope (%)	Area (ha)	Substrate	Vegetation
Plateau	2423	0-3	200	Dakota sandstone, shale and loess	pure ponderosa, few shrubs, extensive grass cover
Turkey Springs	2457	0-1	200	Dakota sandstone, shale and loess	pure ponderosa, few shrubs, extensive grass cover
Cerro Bandera East	2435	25-35	12	mid-Quaternary, volcanic cinder	mostly open ponderosa, some mixed conifer, few shrubs, grassy cover
Hoya de Cibola	2285	3-5	13	late Quaternary basaltic lava	open ponderosa, few shrubs, grassy cover, but much bare surface

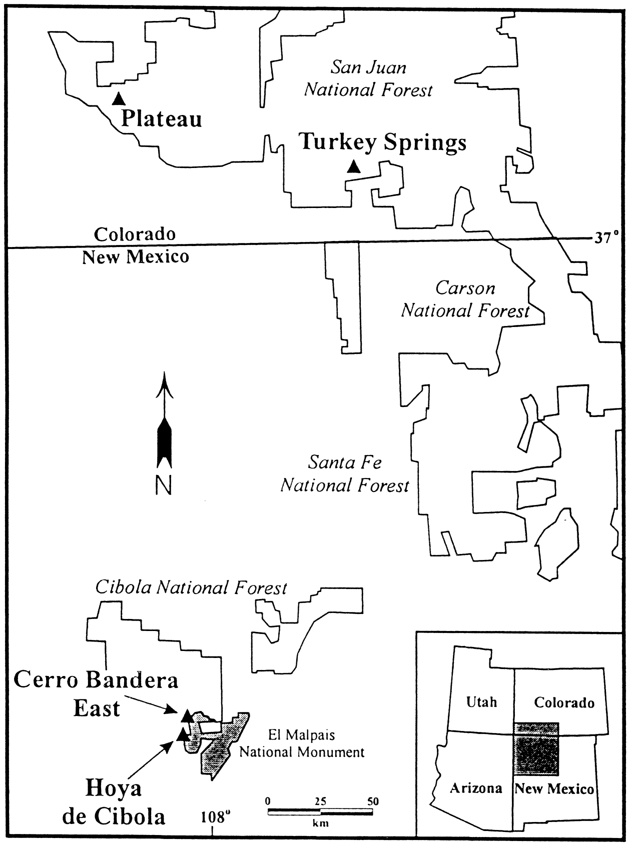

Figure 1. Locations of the four study sites within the Southwestern United States (inset) used in this study.

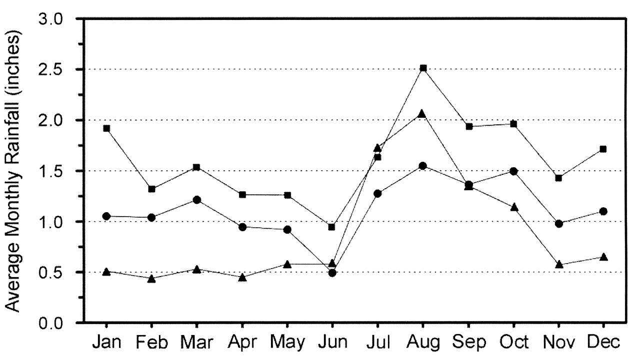

Figure 2. Average monthly precipitation for (1) Pagosa Springs, Colorado (boxes), representing rainfall patterns found near the Turkey Springs site (1939-1997), (2) Cortez, Colorado (circles), representing rainfall patterns found near the Plateau site (1911-1997), and (3) Grants, New Mexico (triangles), representing rainfall amounts at the two El Malpais sites (1953-1998). Data for Cortez and Pagosa Springs obtained from the Colorado Climate Center, Colorado State University, while data for Grants obtained from the New Mexico Climate Center, New Mexico State University.

HDC site occupies a rugged lava flow with little topographic relief (Grissino-Mayer 1995). The two El Malpais sites are located approximately 260 kilometers south of the two San Juan sites.

These sites were selected for pairwise comparisons of fire regimes between sites and regions for analyzing local and regional factors that affect fire regimes. The first comparison matches the TKS and PLT sites in the San Juan National Forest, two sites with similar topography, vegetation, and land-use history, but separated by ca. 120 kilometers. The Plateau site is located in a generally drier portion of the National Forest compared to the wetter conditions found near the Turkey Springs site (Figure 2), suggesting possible differences in fire regimes may arise due to differences in fuel moisture properties. The second comparison matches the CBE and HDC sites at El Malpais, sites that are essentially contiguous, but separated by ca. 10 km of grasslands, ponderosa pine forests, and pinyon-juniper forests. The close proximity of these sites suggests their fire regimes should be similar due to a common intra-regional climatic influence. Furthermore, fire spread between these two sites is possible; however, the two have very different substrates and topographic relief that may cause differences in fire regimes. The third comparison matches the two sites from El Malpais with the two sites from the San Juan National Forest. Differences in fire regimes between such widely separated areas may occur because the two southerly El Malpais sites experience a very dry winter/spring season compared to the generally wetter winter/spring season seen at the two San Juan sites (Figure 2). However, all four sites experience a dry foresummer (May and June) that precedes the onset of summer monsoonal rainfall in July.

Dendrochronology

In the American Southwest, individual ponderosa pine stands sampled for reconstructions of fire history most often are delineated by topographic or other environmental barriers (e.g. hillslopes, streams, meadows and grasslands, and cliffs). Fire-scarred trees often are numerous, displaying multiple (5-30) fire scars on any one individual tree. To ensure a complete inventory of fires was obtained for each site in this study, fire-scarred stumps, logs, and snags with the most numerous scars were systematically identified within the stand and sampled with a chain saw (Arno and Sneck 1977). Partial cross sections from a few selected living trees were also obtained to provide information on fire occurrence during the 20th century. In the laboratory, all sections were sanded with progressively finer sandpaper to increase the visibility and cellular structure of the xylem under 10X magnification (Baisan and Swetnam 1990).

Tree rings were crossdated using master chronologies (Stokes and Smiley 1968) developed previously from nearby sites (Grissino-Mayer 1995). Yearly dates were assigned to all fire scars and entered into a database using FHX2 fire history software, designed specifically for graphing and statistically analyzing fire interval data from tree rings (Grissino-Mayer 1995). Composite fire interval graphs (Dieterich 1980) were then created that displayed the spatial and temporal characteristics of the four fire regimes (Figures 3 and 4). All analyses were conducted on the composite fire interval information for each site rather than on intervals from individual samples to prevent effects of temporal and spatial correlation. To facilitate the comparisons, the statistical analyses were conducted over the common period 1700 to 1880. These endpoints are reasonable choices because all four sites have well replicated fire events that extend back to 1700, while most areas of the Southwestern U.S. witnessed extensive anthropogenic disturbances beginning ca. 1880, thereby disrupting fire regimes both temporally and spatially.

Fitting the Weibull distribution

In this study maximum likelihood methods (Harter and Moore 1965, Johnson and Kotz 1970, Rockette et al. 1974) were used to estimate Weibull parameters for all four fire interval data sets, using Weibull-fitting routines developed and supplied by the USDA Forest Service. I fit both two- and three-parameter Weibull distributions to these data sets to compare the effectiveness of one type of distribution over the other. Goodness-of-fit was tested using the one-sample Kolmogorov-Smirnov (K-S) test (Law and Kelton 1991). This test uses the d-statistic, which measures the maximum distance between the cumulative frequency distribution of the actual data and the fit of the Weibull distribution, $F(t)$. Small values of d are desirable, as are large probabilities of obtaining a higher d by chance. In addition to the suite of commonly-used univariate descriptive statistics derived from the actual data, I introduce others derived from the Weibull distribution that demonstrate the advantage for using this distribution as a model for fire interval data:

(1) *Weibull Median Interval (MEI):* the fire interval associated with the 50th percentile of the fitted distribution. Because the MEI represents the quantile midpoint of the theoretical distribution fit to the actual data, it represents a measure of central tendency that is resistant to large values in the actual fire interval data. The MEI is identical to the Weibull Median Probability Interval (WMPI) used in previous studies (e.g., Grissino-Mayer et al. 1995, Swetnam and Baisan 1996, Fulé et al. 1997).

(2) *Weibull Modal Interval (MOI):* the fire interval that contributes the greatest amount of area under the pdf, calculated as:

$$b[(c\text{-}1)/c]^{1/c} \qquad [5]$$

This interval represents the theoretical mode in a frequency distribution where the mode may not otherwise be discernible in the actual data.

(3) *Lower Exceedance Interval (LEI) and Upper Exceedance Interval (UEI):* the theoretical fire intervals associated with the 87.5 and 12.5 percentiles, respectively. These levels were chosen because they delimit the 25% of all intervals (12.5% at each tail) that may be considered extremes. More commonly-used percentiles (e.g., 97.5 and 2.5) would perhaps be too stringent for ecological and managerial purposes, but any user-defined values can be substituted in the FHX2 software. The LEI delimits the interval in the shorter range of the distribution exceeded by 87.5% of all intervals, while the UEI delimits the interval in the longer range of the distribution exceeded by only 12.5% of all intervals.

(4) *Maximum Hazard Interval (MHI):* obtained by substituting .875 for h(t) (Equation 3) and solving for t using the Weibull-derived parameters. The MHI represents the fire interval t associated with the theoretical maximum fire-free period an ecosystem can sustain before burning is highly probable (i.e., the instantaneous burning interval) based on all previous intervals during the presettlement period. Again, .875 was chosen because higher levels may be too stringent for ecological purposes, but the user can supply any value in the FHX2 software.

Results

Fitting the Weibull distribution

The frequency distributions demonstrated the various forms fire interval data sets for sites in the American Southwest can assume (Figure 5). The PLT and CBE distributions showed a greater clustering of intervals (range between 1-10 years) compared to the TKS and HDC sites, which showed greater variability in the lengths of intervals (range between 2-31 years). Assessing central tendency would be difficult, especially in the skewed distributions for TKS and HDC. Furthermore, no one interval assumes a modal value in three of the four distributions, a common feature of fire interval distributions for Southwestern sites. Based on these distributions, the statistical characteristics normally used to delimit the historical range of variability

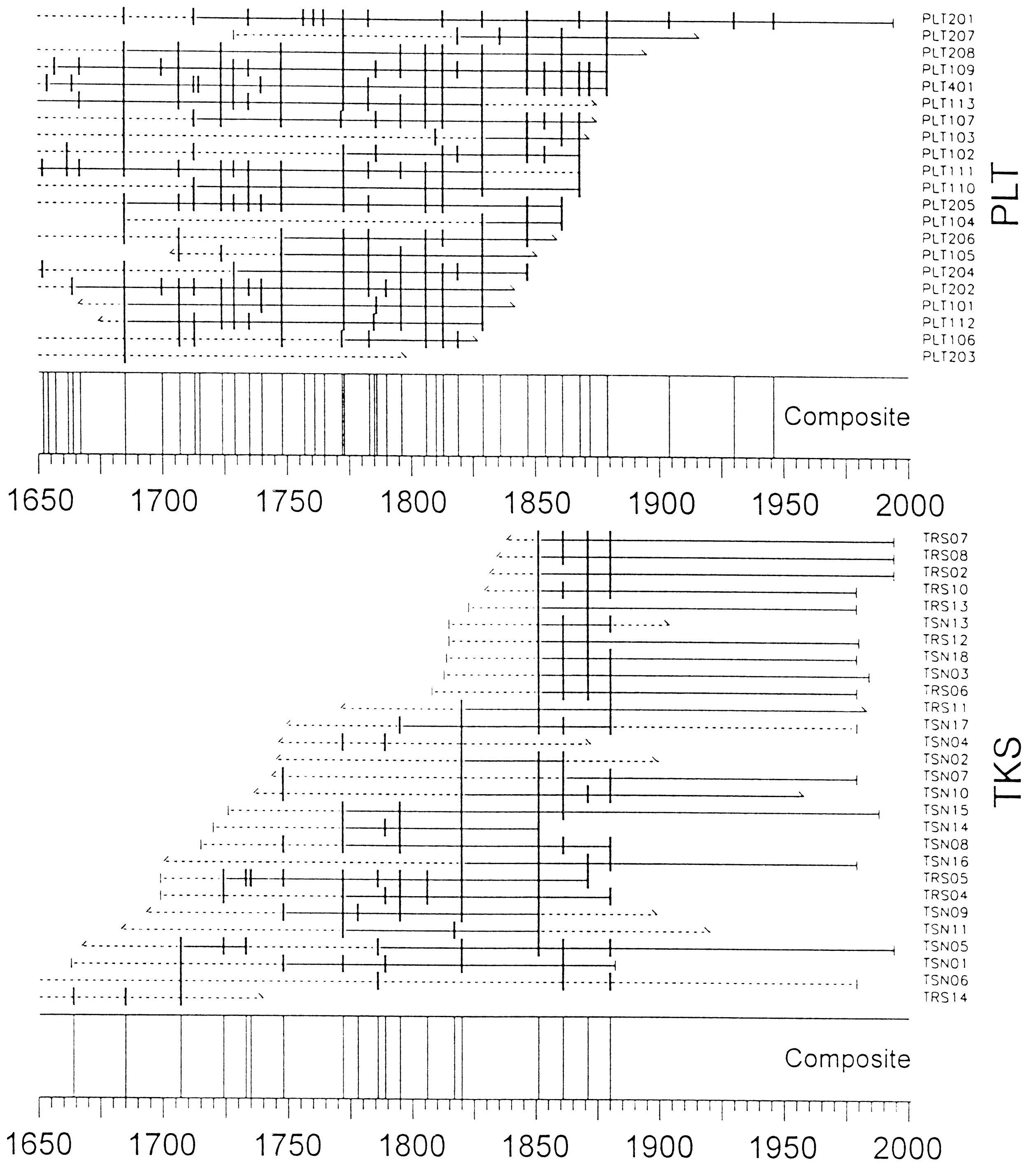

Figure 3. The composite fire chronologies for the Plateau (PLT) and Turkey Springs (TKS) sites. Horizontal lines represent individual fire-scarred trees (with tree identification numbers to the right), while small vertical bars represent crossdated fire scars. Dotted lines indicate years when information on fire history was not available for the sample (i.e., the tree had not yet initially been scarred, or the wood was badly decayed or burned away). Pith and bark years are indicated by small vertical bars at each end of the sample, while inner (pith not present) and outer (bark not present) years are indicated by arrows.

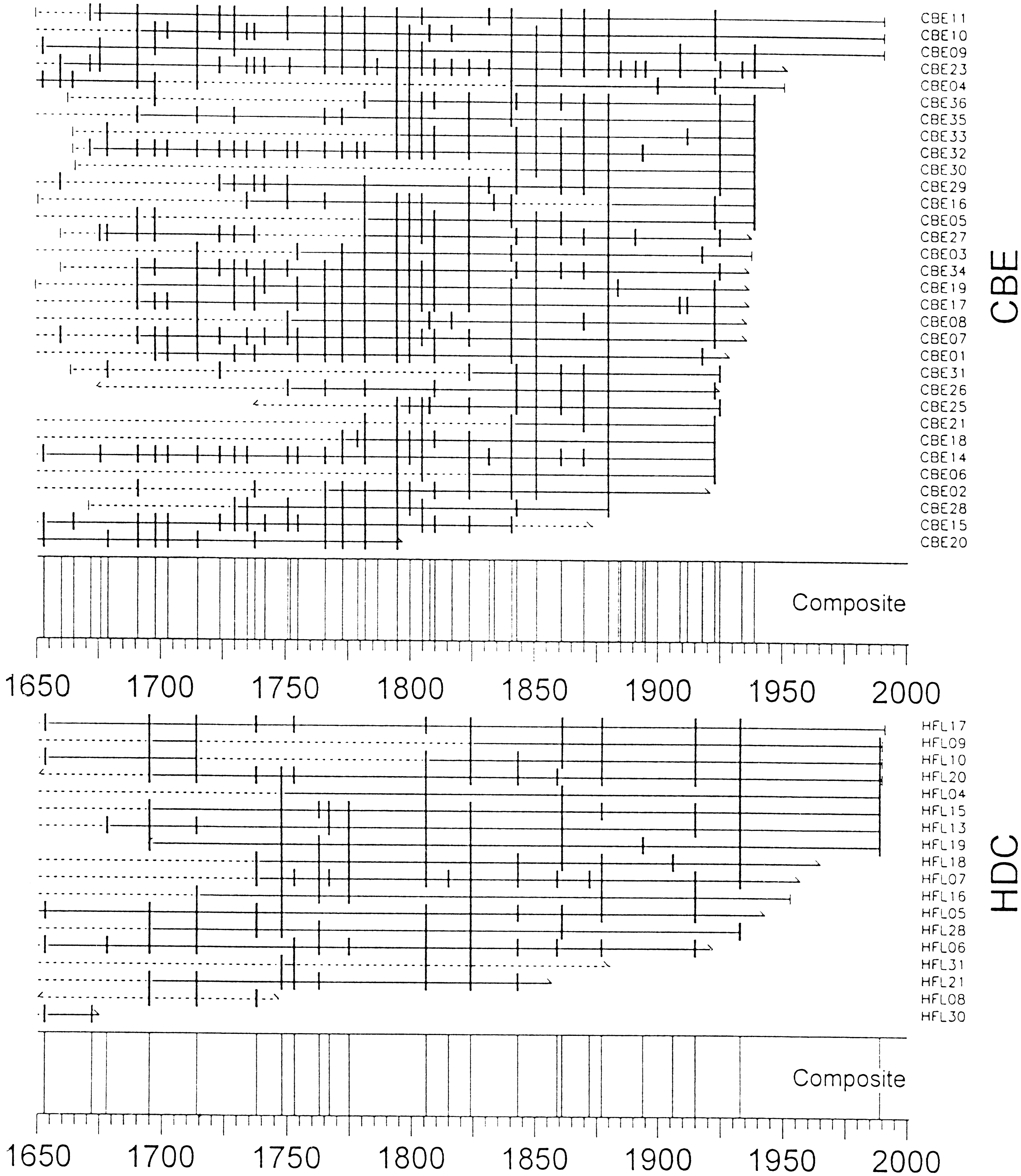

Figure 4. The composite fire chronologies for the Cerro Bandera East (CBE) and Hoya de Cibola (HDC) sites. See Figure 3 for explanation of symbols.

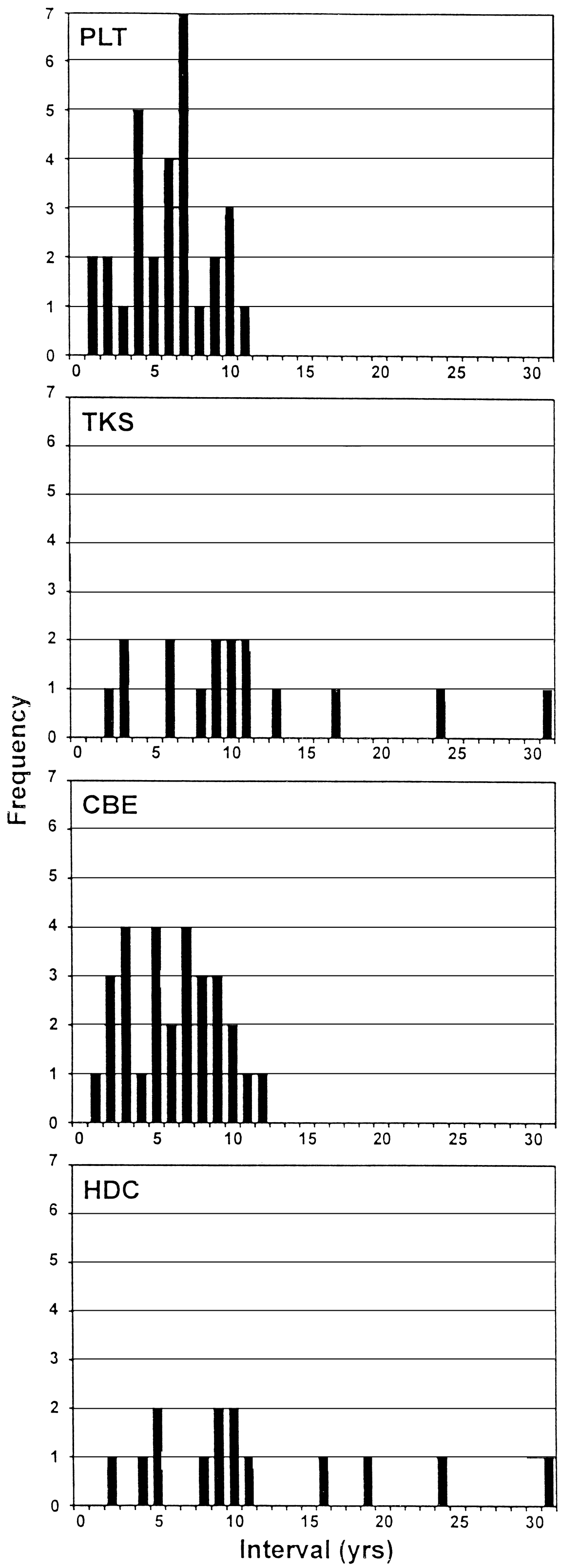

Figure 5. Frequency distributions of fire intervals for all four sites.

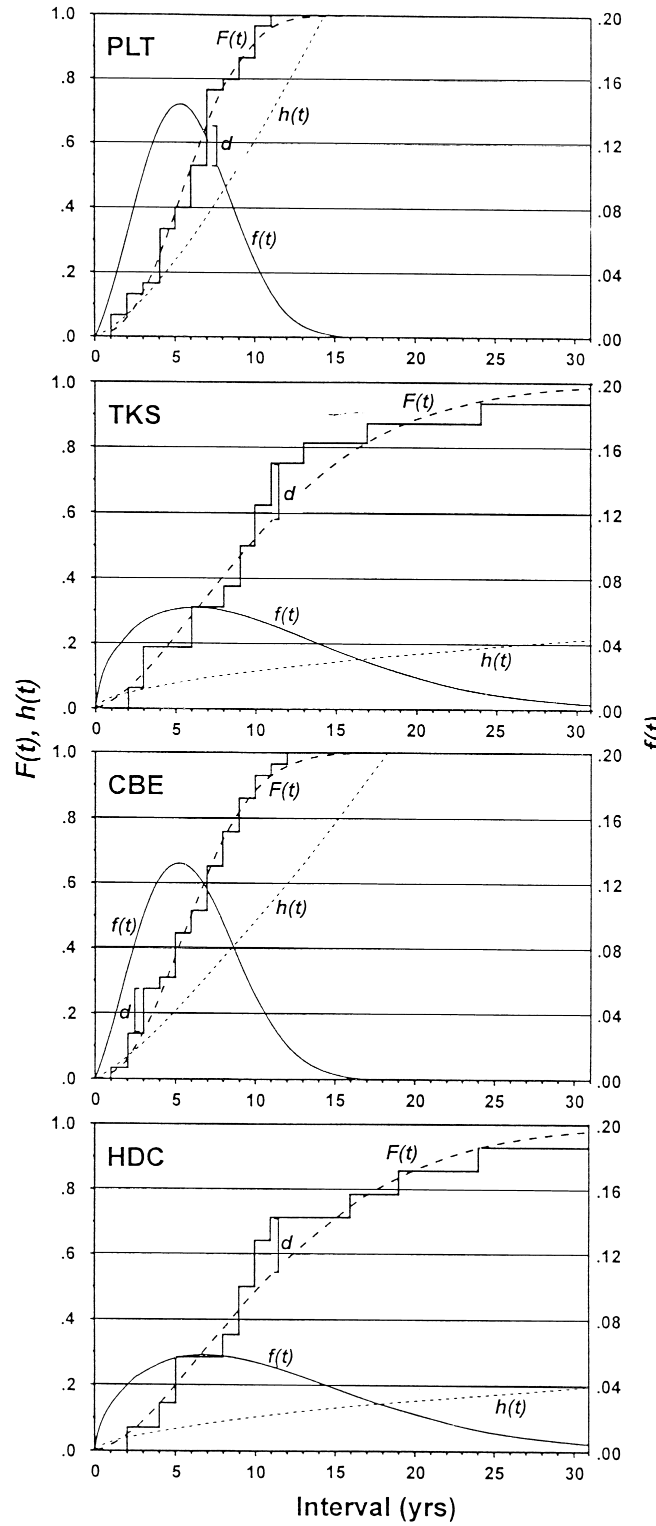

Figure 6. The Weibull cdf, F(t), fit to the cdf for the actual interval data (solid, stepped line), hazard function h(t), probability density function f(t), and K-S d-statistic (the greatest difference between the two cumulative distribution functions).

in presettlement fire regimes could be inaccurate, emphasizing the need for theoretical distributions, such as the Weibull, to serve as models. The curves of *F(t)* fit to the cumulative distributions for the original fire interval data sets illustrate the ability of the Weibull to accurately model various fire interval frequency distributions (Figure 6). However, high values for the *d*-statistic for the TKS, CBE, and HDC sites (Table 2) arise because of poor fits between the actual and modeled cumulative frequency distributions in only *one* frequency class. For example, the high *d*-statistic for the CBE site arises from the *lack* of fire intervals in the 4-year class. Despite this limitation, the Weibull models provide an accurate depiction of the actual fire interval distributions (Figure 6).

The location parameter of the three-parameter Weibull models for both the PLT and CBE sites converged to 0, thus reverting to two-parameter models (Table 2). The three-parameter models for the TKS and HDC sites indicated models with poorer fits than those provided by the two-parameter models, as indicated by the higher *d*-statistics. In general, the three-parameter models failed to provide better fits of the Weibull distribution to the actual data, suggesting the more parsimonious two-parameter models were adequate. At the TKS and HDC sites, the non-zero shift parameters could indicate a minimum time required in the ecosystem before fire can occur, perhaps related to fuel accumulation rates and flammability as Johnson (1979) suggested. However, the actual minimum fire intervals (2.0 years) and theoretical LEI values (ca. 3.0 years) (Tables 3 and 4) are better indicators of this lag effect, making the shift parameters superfluous.

The scale parameters (*b*) for all six models were directly related to the range of years and the maximum intervals in the distributions: the greater the maximum interval, the greater the scale parameter. The shape parameters for the TKS (1.55) and HDC (1.57) sites indicated peaked distributions clustered in the smaller intervals, as well as being highly skewed due to the few longer intervals (Figure 5). The three-parameter model for the TKS site reverted to a negative exponential (c = 1.0), yet this was the worst fit of all six models (d = 0.25).

Descriptive statistics

The PLT and CBE sites had a comparable number of fires between 1700 and 1880, as did the TKS and HDC sites (Figures 3 and 4). The similar values of the three measures of central tendency (mean, median, and MEI) for the PLT and CBE sites (5.8 to 6.1) (Table 3) suggest that these distributions were near symmetrical (Figure 5), verified by (1) the LEI and UEI values, which were near equivalent distances on either side of the central tendency measures, and (2) the near-zero values for the skewness coefficients. The lack of coincidence of central measures for the TKS and HDC sites suggests asymmetric distributions (Figure 5), especially for the HDC site where the mean and median were over 2.0 years apart. This asymmetry was confirmed by both the high skewness values and the disparate distances between the LEI and UEI statistics and measures of centrality. In symmetric distributions, the MEI may be redundant (e.g., MEI of 5.8 years ≈ Mean Fire Interval of 6.0 years for the PLT site). Although symmetry was apparent for the PLT and CBE sites, normality was not apparent as the distribution for PLT was slightly leptokurtic, while the distribution for CBE was slightly platykurtic (Figure 5).

LEI values for all four sites suggest a fire interval of ca. 3.0 years delimits unusually short intervals (Table 4), based on the overall shape of the distribution and the percentile level chosen (87.5). The near coincidence of these four values may indicate the minimum time required for fuel accumulation in Southwestern ponderosa pine forests to reach levels that would accommodate fire ignition and spread. Intervals shorter than these theoretical limits are uncommon in fire history analyses, but can occur because fuels may be only partially burned during any given fire year, and because climatic patterns conducive to consecutive-year fires may persist from year to year (Swetnam and Dieterich 1985, Grissino-Mayer et al. 1995, Grissino-Mayer 1995).

The UEI values reflected the higher ranges and variabilities of intervals at the TKS and HDC sites. Actual fire-free periods that approached or exceeded 19 (TKS) and 21 (HDC) years indicate unusually long fire intervals. In contrast, the UEI values for the PLT and CBE sites indicate that presettlement intervals of only 9-10 years were unusually long. These values mark the *initial* levels at which a fire-free period may be considered approaching a critical length, because intervals of these lengths were rare during the presettlement period. The Maximum Hazard Intervals demarcate the *maximum* fire-free period these areas can sustain before burning is highly probable. At all four sites the actual maximum intervals did not exceed these theoretical maximum intervals during the presettlement period (Table 4). Values for MHI calculated for the TKS and HDC sites, however, were extremely high. Plots for *h(t)* confirmed a near constant hazard for increasing intervals, indicated by relatively flat curves (Figure 6). Hence, highly skewed, amodal distributions appear to cause ecologically unreasonable estimates of the longest fire-free period that an ecosystem can sustain. Greater confidence can therefore be placed in MHI values calculated for distributions that are less skewed or near symmetric, such as those for the PLT and CBE sites.

Table 2. Results from the fitting of two and three parameter Weibull distributions to the fire interval data for all four sites. a = location, b = scale, and c = shape parameters. K-S d is the d-statistic reported in the Kolmogorov-Smirnov goodness-of-fit test. Low values (and therefore high probabilities) are desirable.

	2-parameter				3-parameter				
Site	*b*	*c*	K-S *d*	*p>d*	*a*	*b*	*c*	K-S *d*	*p>d*
PLT	6.71	2.37	0.10	0.93	0.00	6.71	2.37	0.10	0.93
TKS	12.10	1.55	0.17	0.73	2.00	8.81	1.00	0.25	0.29
CBE	6.89	2.20	0.13	0.73	0.00	6.89	2.20	0.13	0.73
HDC	13.04	1.57	0.18	0.76	1.86	10.26	1.16	0.19	0.70

Table 3. Descriptive statistics for fire interval data from all four sites. num samp = number of sampled trees, num fi = number of fire intervals between 1700-1880, mean = mean fire interval, med = median fire interval, MEI = Weibull median interval, MOI = Weibull modal interval, skew = skewness, kurt = kurtosis, CV = coefficient of variation.

Site	num samp	num fi	mean	med	MEI	MOI	skew	kurt	CV
PLT	21	30	6.0	6.0	5.8	5.3	-.07	0.81	.46
TKS	28	16	10.8	9.5	9.6	6.2	1.30	1.06	.71
CBE	32	29	6.1	6.0	5.8	5.2	.08	-1.06	.49
HDC	23	14	11.6	9.5	10.3	6.8	1.06	.12	.70

Table 4. Critical threshold fire intervals for the four sites used in this study. Min = minimum fire interval, max = maximum fire interval, LEI = lower exceedance interval, UEI = upper exceedance interval, and MHI = maximum hazard interval.

Site	min	max	LEI	UEI	MHI
PLT	1.0	11.0	2.9	9.1	13.0
TKS	2.0	31.0	3.3	19.4	85.9
CBE	1.0	12.0	2.8	9.6	16.0
HDC	2.0	31.0	3.6	20.8	432.1

Discussion

Paired-site analyses

The paired-site analyses illustrate the complexity involved when investigating possible underlying climatic and ecological factors that affect Southwestern fire regimes. The two San Juan sites, PLT and TKS, are nearly identical in vegetation composition, stand structure, topography, and land-use history, yet the fire regimes for these sites are very dissimilar. Only eight fire years (20%) were common to both sites. However, the Plateau site receives considerably less annual precipitation (13.4 inches) in the southwestern portion of the San Juan National Forest compared to the Turkey Springs site (19.4 inches) in the south-central portion of the forest (Figure 2). The lower amount of rainfall at the Plateau site would suggest generally drier fuel moisture conditions, and therefore an increased probability of successful fire ignition and a greater frequency of fires.

The CBE and HDC sites are located only 10 kilometers apart, yet also represent very disparate fire regimes, suggesting local factors may predominate to mask regional factors. Although both sites consist of open ponderosa pine forests, the topography of each is unique. The Hoya de Cibola site is a fissured, slightly eroded lava flow, with some grass cover, but with large areas of bare lava surface and little topographic relief. The Cerro Bandera site is located on the east-facing, drier slope of a steep-sided cinder cone, well above the surrounding lava plains, with a well-developed herbaceous cover. Conditions at Cerro Bandera are therefore more conducive to a higher number of successful ignitions, a greater probability of trees being scarred, and an increased ability for fire spread. While the close proximity of these two sites to each other suggested similar fire dates should be evident, the descriptive statistics and model parameters indicated otherwise. A chi-squared test confirmed the statistical independence between the two fire regimes - only four fire dates were common to both sites (9.7%).

Similar values for the scale and shape parameters were found between the PLT and CBE sites and between the TKS and HDC sites, although the two San Juan sites are separated from the two El Malpais sites by nearly 260 kilometers. These similarities arise despite the fact that no synchroneity of fire dates was evident between the two pairs of sites. Only six fire years (10.9%) were common to the PLT and CBE sites, while only three fire years (10.3%) were common to the TKS and HDC sites. Results from chi-squared tests of association confirmed that patterns of fire at these two pairs of sites were statistically independent. Therefore, regional climate appears to exert a limited influence on Southwestern fire regimes, although the regional signal may be masked by local factors.

In general, it was difficult to generalize the ecological meaning of the Weibull parameters based on the distributions for these four sites. However, the Weibull Modal Intervals (MOI) for the four sites may provide information critical to understanding the influence of local versus regional factors on fire regimes. MOI values ranged between 5.3 and 6.8 years, and were less variable than either the mean, median, and MEI values. This finding suggests that a common underlying structure in fire interval data may exist in Southwestern fire regimes that cuts across both local and regional factors, and may be independent of habitat type. Because the mode of the distribution represents that value that occurs with greatest frequency, the MOI may be a superior *overall* indicator of fire frequency in Southwestern forests. The MOI values strongly suggest a regional factor, such as climate, may be imparting considerable influence on Southwestern fire regimes. While climate has long been considered the dominant factor, the strength of its influence has been elusive, often masked by local factors. By statistically evaluating the entire network of 90+ fire-scar chronologies in the Southwest (see e.g., Swetnam and Baisan 1996), the degree to which local factors influenced fire regimes may be assessed by first deriving a regionally-calculated average MOI along with its standard deviation, then by calculating the MOI for an individual site to determine where the local MOI falls within the regional distribution. Sites where the MOI falls above the 12.5 or below the 87.5 percentiles may perhaps suggest sites where the effects of local factors on fire regimes were considerable relative to regional factors.

Assessing 20th century fire hazard

Information concerning the hazard of fire in the 20th century is particularly useful for management purposes. In this study, I found that the UEI, the maximum interval, and the MHI provided an ordered sequence (UEI-MAX-MHI) for evaluating actual and theoretical critical threshold intervals for the upper limits of the historical range of variation in presettlement fire regimes. For example, the sequence (rounded to the nearest integer) for the CBE site was 10-12-16 (Tables 3 and 4). Since the last widespread (i.e., fire scars recorded on more than three trees) presettlement fire in 1880, major fires were recorded only in 1923 1925, and 1939 (Figure 4), creating fire intervals of 43, 2, and 14 years, respectively. The 43 year interval greatly exceeded the MHI, suggesting the fire in 1923 may have been more intense than previous presettlement fires. The short two-year interval that followed was below the LEI for the site (2.8 years), indicating that only a portion of the Cerro Bandera site burned during the 1923 fire (Figure 4). More importantly, no fire was recorded on any of the living trees sampled since 1939, creating a (minimum) fire interval of 55 years, nearly four times the presettlement MHI.

At the Turkey Springs site, the sequence can be reported as 20-31-385. While 17 fire-scarred samples were collected that extended past 1950, no fire was recorded on any sample since the widespread fire of 1880. This 114 year fire-free period is likely due to a combination of livestock grazing and changes in land-use and vegetative cover, followed by fire suppression (Floyd-Hanna et al. 1996). Hence, this fire-free period is nearly four times the maximum interval recorded during the presettlement period. Even if the fire record was somehow extended well prior to 1700 with excellent sample depth, it is doubtful such a long fire-free period would have occurred naturally. These situations emphasize that wildfires no longer function within their presettlement period range of variability, and that silviculturally-based remediation efforts, such as fuel reduction, may be beneficial to these forests. With many decades of fuel accumulation, high intensity, catastrophic fires are now more likely to occur rather than the low intensity surface fires that were once characteristic of Southwestern forests (Swetnam 1990, Covington and Moore 1994, Swetnam and Baisan 1996).

In summary, the Weibull distribution shows promise as a model for fire interval data from the American Southwest, providing a theoretical framework for assessing the range of historical variation in presettlement fire regimes. Its application in a systematic study on the network of 90+ fire-scar chronologies for the Southwestern U.S. may help reveal the existence of spatio-temporal patterns in fire regimes that cuts across different habitat types along various topographic and climatic gradients. If patterns exist, such an analysis could improve our understanding of the relationship between fire occurrence and regional climate. Sites could be stratified into habitat types to help determine whether a common underlying structure exists that is dependent on (or independent of) vegetation and fuel characteristics (see e.g., Swetnam and Baisan 1996). An important extension of this exercise would be fitting the Weibull distribution to fire interval data from two separate, independent periods (e.g. 1700-1800 and 1801-1900, provided each period has an adequate number of intervals to analyze) for each individual site and for data sets grouped from several sites in a smaller subregion (see e.g. Reed et al. 1998). Any substantial differences in the Weibull parameters or descriptive statistics for the two distributions could indicate mixed distributions (Johnson 1992), and help identify temporal changes in fire occurrence in Southwestern sites, possibly related to climate change.

Acknowledgments

The National Park Service, El Malpais National Monument in Grants, New Mexico, graciously provided funds and field support for the collections of fire history sites throughout the monument. I thank Bill Romme, Lisa Floyd-Hanna, and Dave Hanna, who helped develop the fire-scar chronologies used in this study through funding supplied by the USDA Forest Service, San Juan National Forest. Routines for fitting the Weibull distribution were kindly supplied by Bernie Parresol of the USDA Forest Service, Southern Forest Experiment Station, while Sofia Vasina helped incorporate the routines for use with the FHX2 system. Tom Swetnam and Kiyomi Morino read early drafts of this manuscript and provided helpful critiques for improving the statistical treatment of fire interval data. I am particularly grateful to Bill J. Reed of the Department of Mathematics & Statistics at the University of Victoria, and David R. Gibson of the Department of Mathematics and Computer Science at Valdosta State University for meticulously checking the statistical treatments discussed in this study.

References

Allen, C.D. 1994. Ecological perspective: linking ecology, GIS, and remote sensing to ecosystem management. In V.A. Sample (Editor), Remote Sensing and GIS in Ecosystem Management. Island Press, Covelo:111-139.

Arno, S.F. and K.M. Sneck 1977. A method for determining fire history in coniferous forests of the mountain west. U.S. Department of Agriculture Forest Service, General Technical Report INT-42. 28 pp.

Bailey, R.L. and T.R. Dell 1973. Quantifying diameter distributions with the Weibull function. Forest Science 19:97-104.

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

Baker, W.L. 1989. Effect of scale and spatial heterogeneity on fire-interval distributions. Canadian Journal of Forest Research 19:700-706.

Baker, W.L. 1992. The landscape ecology of large disturbances in the design and management of nature reserves. Landscape Ecology 7:181-194.

Bergeron, Y. and M.D. Flannigan 1995. Predicting the effects of climate change on fire frequency in the southeastern Canadian boreal forest. Water, Air and Soil Pollution 82:437-444.

Clark, J.S. 1989. Ecological disturbance as a renewal process: theory and application to fire history. Oikos 56:17-30.

Covington, W.W. and M.M. Moore 1994. Southwestern ponderosa forest structure: Changes since Euro-American settlement. Journal of Forestry 92:39-47.

Dieterich, J.H. 1980. The composite fire interval - a tool for more accurate interpretation of fire history. In M.A. Stokes and J.H. Dieterich (Editors), Proceedings of the Fire History Workshop, October 20-24 1980, Tucson, Arizona. U.S. Department of Agriculture Forest Service, General Technical Report RM-81:8-12.

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

Dubey, S.D. 1967. Normal and Weibull distributions. Naval Research Logistics Quarterly 14:69-79.

Floyd-Hanna, L., A.W. Spencer, and W.H. Romme 1996. Biotic communities of the semiarid foothills and valleys. In R. Blair, T.A. Casey, W.H. Romme, and R.N. Ellis (Editors), The Western San Juan Mountains: Their Geology, Ecology, and Human History. University Press of Colorado, Niwot, Colorado: 143-158.

Fulé, P.Z. and W.W. Covington 1997. Fire regimes and forest structure in the Sierra Madre Occidental, Durango, Mexico. Acta Botanica Mexicana 41:43-79.

Fulé, P.Z., W.W. Covington, and M.M. Moore 1997. Determining reference conditions for ecosystem management of Southwestern ponderosa pine forests. Ecological Applications 7: 895-908.

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

Grissino-Mayer, H.D., C.H. Baisan and T.W. Swetnam 1995. Fire history in the Pinaleño Mountains of southern Arizona: effects of human-related disturbances. In L.F. Debano, G.J. Gottfried, R.H. Hamre, C.B. Edminster, P.F. Ffolliott, P.F., A. Ortega-Rubio (Editors), Biodiversity and Management of the Madrean Archipelago: The Sky Islands of Southwestern United States and Northwestern Mexico. U.S. Department of Agriculture Forest Service, General Technical Report RM-GTR-264:399-407.

Hallinan, Jr., A.J. 1993. A review of the Weibull distribution. Journal of Quality Technology 25:85-93.

Harter, H.L. and A.H. Moore 1965. Maximum-likelihood estimation of the parameters of gamma and Weibull populations from complete and from censored samples. Technometrics 7:639-643.

Heinselman, M.L. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. Quaternary Research 3:329-382.

Johnson, E.A. 1979. Fire recurrence in the subarctic and its implications for vegetation composition. Canadian Journal of Botany 57:1374-1379.

Johnson, E.A. 1992. Fire and Vegetation Dynamics: Studies from the North American Boreal Forest. Cambridge University Press, New York.

Johnson, E.A. and C.E. Van Wagner 1985. The theory and use of two fire history models. Canadian Journal of Forest Research 15:214-220.

Johnson, N.L. and S. Kotz 1970. Continuous Univariate Distributions. Houghlin Mifflin Company, Boston.

Kaufmann, M.R., R.T. Graham, D.A. Boyce, Jr., W.H. Moir, L. Perry, R.T. Reynolds, R.L. Bassett, P. Mehlhop, C.B. Edminster, W.M. Block, and P.S. Corn 1994. An ecological basis for ecosystem management. U.S. Department of Agriculture Forest Service, General Technical Report RM-246.

Law, A.M. and W.D. Kelton 1991. Simulation Modeling and Analysis. McGraw Hill Inc., New York.

Morgan, P., G.H. Aplet, J.B. Haufler, H.C. Humphries, M.M. Moore, and W.D. Wilson 1994. Historical range of variability: a useful tool for evaluating ecosystem change. Journal of Sustainable Forestry 2:87-111.

Overpeck, J.T., D. Rind, and R. Goldberg 1990. Climate-induced changes in forest disturbance and vegetation. Nature 343:51-53.

Pinder, III, J.E., J.G. Wiener and M.H. Smith 1978. The Weibull distribution: a new method of summarizing survivorship data. Ecology 59:175-179.

Reed, W.J., C.P.S. Larsen, E.A. Johnson, and G.M. MacDonald 1998. Estimation of temporal variations in historical fire frequency from time-since-fire map data. Forest Science 44:465-475.

Rockette, H., C. Antle, and L.A. Klimko 1974. Maximum likelihood estimation with the Weibull model. Journal of the American Statistical Association 69:246-249.

Ryan, K.C. 1991. Vegetation and wildland fire: implications of global climate change. Environment International 17:169-178.

Schribner, T.J. 1987. The nature and role of simulation in the design of manufacturing systems. In J. Retti and K.E. Wichmann (Editors), Simulation in CIM and Artificial Intelligence Techniques. Society for Computer Simulation, San Diego:5-18.

Somers, G.L., R.G. Oderwald, W.R. Harms, and O.G. Langdon 1980. Predicting mortality with a Weibull distribution. Forest Science 26:291-300.

Stokes, M.A. and T.L. Smiley 1968. An Introduction to Tree-Ring Dating. The University of Chicago Press, Chicago.

Swanson, F.A., J.A. Jones, D.O. Wallin, and J.H. Cissel 1994. Natural variability - implications for ecosystem management. In M.E. Jensen and P.S. Bourgeron (Editors), Volume II: Ecosystem Management: Principles and Applications. U.S. Department of Agriculture Forest Service, General Technical Report PNW-GTR-318:80-94.

Swetnam, T.W. 1990. Fire history and climate in the Southwestern United States. In J.S. Krammes (Technical Coordinator), Effects of Fire Management of Southwestern Natural Resources, Proceedings of the Symposium. U.S. Department of Agriculture Forest Service, General Technical Report RM-GTR-191:6-17.

Swetnam, T.W. and C.H. Baisan 1996. Historical fire regime patterns in the Southwestern United States since AD 1700. In C.D. Allen (Editor), Fire Effects in Southwestern Forests: Proceedings of the Second La Mesa Fire Symposium. U.S. Department of Agriculture Forest Service, General Technical Report RM-GTR-286:11-32.

Swetnam, T.W. and J. Dieterich 1985. Fire history of ponderosa pine forests in the Gila Wilderness, New Mexico. In J.E. Lotan, B.M. Kilgore, W.C. Fischer, and R.W. Mutch (Editors), Proceedings - Symposium and Workshop on Wilderness Fire. U.S. Department of Agriculture Forest Service, General Technical Report INT-182:390-397.

Weibull, W. 1951. A statistical distribution function of wide applicability. Journal of Applied Mechanics 18:293-297.

Wolf, J.J. and J.N. Mast 1998. Fire history of mixed-conifer forests on the North Rim, Grand Canyon National Park, Arizona. Physical Geography 19:1-14.

Wotton, B.M. and M.D. Flannigan 1993. Length of the fire season in a changing climate. The Forestry Chronicle 69:187-192.