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RESEARCH REPORT

FHX2—SOFTWARE FOR ANALYZING TEMPORAL AND SPATIAL PATTERNS IN FIRE REGIMES FROM TREE RINGS

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ABSTRACT

Many studies use the temporal record of dendrochronologically-dated fire scars to document properties of fire regimes before human interference (*e.g.* fire suppression, logging, and agriculture) became pervasive. Such reconstructions provide vital information that can be used by land management agencies when designing and implementing fire management policies, and are especially useful for justifying the reintroduction of fire to areas where fire has long been excluded by humans. Tree-ring based fire history studies produce large quantities of data that require efficient tools for compilation, organization, and analysis. In this paper, I describe the development and use of FHX2, software comprised of individual modules designed specifically for (1) entering and archiving of fire history data, (2) creating graphs that display both temporal and spatial features of the site fire history, (3) conducting statistical analyses on fire intervals and seasonality, and (4) performing superposed epoch analysis to analyze climate/wildfire interactions. Although designed to analyze fire history, the software can be used to analyze any set of events recorded in the tree-ring record, such as growth suppressions and releases, floods, and insect outbreaks.

INTRODUCTION

Reconstructions of fire history based on tree-ring data provide valuable information on reference conditions of fire regimes prior to widespread Euro-American settlement and its associated disturbances. Analyses of these reconstructions allow assessments concerning the changing structure of forests due to (1) possible human-induced disturbances on fire occurrence, such as grazing, fire suppression, and land use (Cooper 1960; Covington and Moore 1994), and (2) natural factors that operate over both local and regional scales, such as climate change (Johnson and Miyanishi 1991; Swetnam 1993; Grissino-Mayer 1995). Many studies have used dendrochronologically-dated fire scars found within the growth-ring record to establish temporal and spatial patterns of past fires (*e.g.* Weaver 1951; Zackrisson 1977; Kilgore and Taylor 1979; Baisan and Swetnam 1990; Swetnam 1993; Grissino-Mayer 1995; Veblen *et al.* 2000). The escalating number of studies that use fire-scar data underscored a need for software to systematically process and analyze the large volumes of data generated. The FHX2 system was developed to meet this need.

FHX2 is DOS-based software that facilitates the analysis of past fire history from fire scars and other fire-related injuries found in the annual growth rings of trees. Four modules comprise the FHX2 system (Figure 1). The Data Entry Module allows one to enter, edit, and archive fire history information. The Graphics Module creates and prints graphs that display the temporal and spatial patterning of past fire within a site. The Statistics Module provides a wide array of statistical analyses, including the modeling of fire interval data using the Weibull distribution, tests for analyzing fire seasonality, and tests for detecting changes or differences in fire regimes over time and space. Finally, the Superposed Epoch Analysis Module assesses the preconditioning of fire occurrence due to climate. The maximum number of samples FHX2 can analyze is 255 up to 800 years in

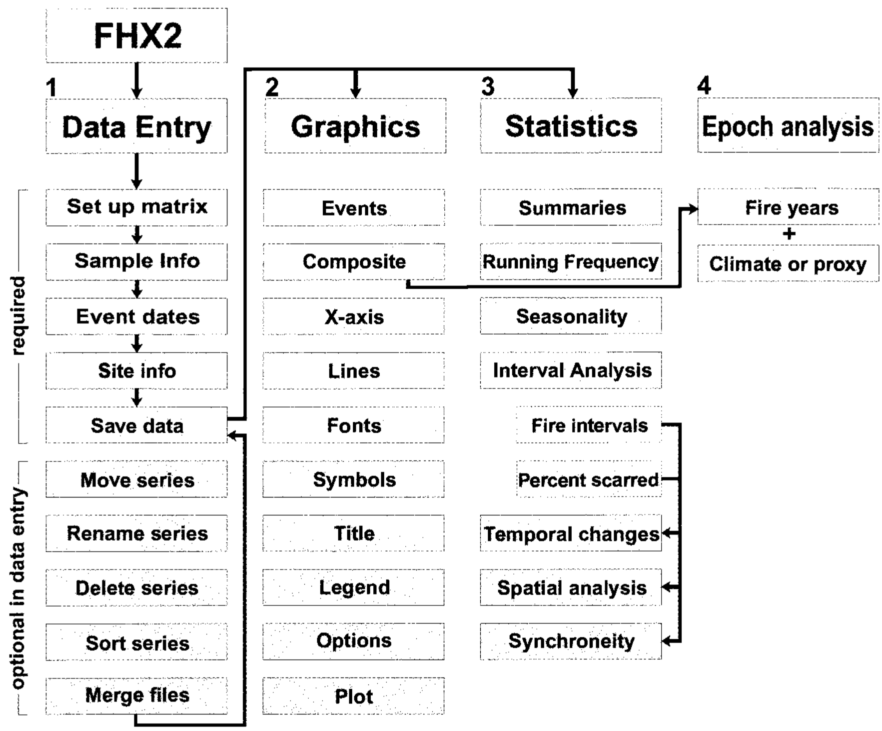

Figure 1. The FHX2 system contains four primary modules: (1) Data Entry, (2) Graphics, (3) Statistics, and (4) Superposed Epoch Analysis (SEA). The FHX2 data files are used directly in the Graphics and Statistics modules, while the SEA module uses a list of fire years generated from the composite information for an individual site, along with a climate proxy (*e.g.* a tree-ring chronology) or tree-ring based climate reconstruction.

length, or 99 up to 2,500 years in length. The software is menu driven using dialog boxes, and guides users through intuitively-designed pop-up windows that enhance ease of use. A 110 page User's Manual is supplied with the software.

The FHX2 system has been used primarily to analyze fire regimes in the American Southwest dominated by ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws.) forests (*e.g.* Grissino-Mayer 1995; Ortloff *et al.* 1995; Morino 1996; Swetnam and Baisan 1996; Fulé *et al.* 1997; Baisan and Swetnam 1997; Grissino-Mayer and Swetnam 2000). However, the software has been used to analyze a variety of fire regimes where tree rings can provide annually resolved dates for past wildfires. Such fire regimes include the ponderosa pine forests of the central Rocky Mountains (Veblen *et al.* 2000; Brown *et al.* 2000) and Black Hills region (Brown and Sieg 1999), the mixed-oak forests of the central United States (Sutherland 1997), the boreal forests of Fennoscandia (Lehtonen *et al.* 1996; Lehtonen and Huttunen 1997), the conifer forests of southern Canada (Guyette and Dey 1995; Dey and Guyette 2000), the mixed-conifer forests of the American Southwest (Grissino-Mayer *et al.* 1995; Wolf and Mast 1998) and the mixed-conifer forests of the Pacific Northwest (Wright 1996; Everett *et al.* 2000). Although designed to analyze fire history, the software can be used to study any event recorded in the tree-ring record, such as flood scars (McCord 1996) and stand dynamics effects (*e.g.* growth releases or suppressions).

THE FHX2 FORMAT

The FHX2 system uses a character-based data format designed to (1) speed data entry, (2) provide an intuitive format for fire history data, (3) create a standard for tree-ring based fire history

Table 1. Symbols used in the FHX2 data format and their explanations.

Symbols	Explanation
[	left square bracket: pith date, the very inside date possible on the tree
]	right square bracket: bark date, the very outside date possible on the tree
{	left curly bracket: the innermost date possible on the tree—pith is not present
}	right curly bracket: the outermost date possible on the tree—bark is not present
.	a period: a "null" year—a dated tree ring for which no information on fire history is available, *e.g.* the ring formed prior to the initial scarring event
|	a vertical line (or "pipe" symbol): a "recorder" year—a dated tree ring that formed after the initial scarring event, but contains no scar
D, d	a fire scar (uppercase) or injury (lowercase) situated in the dormant position, between the previous year's latewood and the current year's earlywood
E, e	a fire scar (uppercase) or injury (lowercase) situated in the early (one-third) portion of the earlywood
M, m	a fire scar (uppercase) or injury (lowercase) situated in the middle (one-third) portion of the earlywood
L, l	a fire scar (uppercase) or injury (lowercase) situated in the latter (one-third) portion of the earlywood
A, a	a fire scar (uppercase) or injury (lowercase) situated in the latewood
U, u	a fire scar or injury for which the position could not be determined

data, and (4) provide flexibility for new data types in the future. In this format, characters indicate a particular property (Table 1), such as a scar in the early portion of the earlywood ("E") or a scar in the dormant season portion of the ring ("D"). Fire scars are always denoted by capital letters based on the position of the scar within the annual ring, while any other injury, whether or not related to fire, is denoted by a lowercase letter. Table 2 lists a file in FHX2 format.

The format considers whether a tree was a potential "recorder" of fire during any particular year or series of years (Romme 1980) because this information is crucial for more accurate statistical analyses (*e.g.* calculating the percentage of trees scarred in any given fire year). "Recorder" rings are those tree rings that formed after the tree had been initially scarred by fire, as this initial wound increases the tree's chances of recording subsequent fires. "Null" rings are the exact opposite. These tree rings provide no information on fire history because they (1) formed prior to the initial scarring event, (2) formed after the tree has completely healed over the initial fire wounds and is no longer a recorder of fire events, or (3) were damaged due to decay or burning by subsequent fires, thus masking whether the tree was a recorder of fire or not. Researchers should maintain meticulous notes that record which portions of the fire-scarred samples were "recorder" years and which were "null" years.

DATA ENTRY

Data entry is menu-driven using steps to guide the user through the process. In Step 1, the user can either (1) set up a new data file (called a matrix), (2) import an old data file for further data entry, or (3) change the settings of a current data file already loaded. In Steps 2, 3, and 4, the user specifies a file name for the matrix, the ID for the sample being entered, and the beginning year of that sample. In Step 5, the actual data are entered. In Step 6, the user documents the data file by entering all site information, which is saved in the same file as the fire-scar data. Comments can be added to the data file. The Data Entry module also provides utilities to (1) merge one or more data files, (2) move or rename individual series, (3) delete individual or entire sets of series, and (4) sort the data file using nine different sort options (*e.g.* sorting by the first year of each series, or by the first year that recorded a fire scar). Sorting is a valuable tool because temporal and spatial patterns of past fires may be indistinguishable if samples are simply analyzed in the order in which they were originally collected in the field.

GRAPHICS

The production of high-quality graphics showing the temporal and spatial characteristics of a site's fire history is an important function of the FHX2 system (Figure 2). Dieterich (1980) first de-

Table 2. A simulated data file in FHX2 format. The second line contains the beginning year, number of samples (columns), and the length of characters in the sample ID. Each sample is represented by a column, while each row contains the fire history information for the year.

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FHX2 FORMAT
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scribed the use of graphical "composite fire intervals." These graphs consist of horizontal lines representing individual sampled trees on which symbols are overlain that denote the years that contain the dendrochronologically-dated fire scars. The sample ID of each tree is displayed to the right of each line, while the x-axis is the time line ranging from the earliest year of information to the latest. In FHX2, a "composite" axis is also drawn that represents the composite fire information from all individual series (or a subset) over the entire range (or a subset) of years. The program also has options for adding a title, legend, custom lines (to help delineate certain fire years), seasonal designations (if available), and tic marks and labels, and the user can choose to graph a subset number of years or a subset number of series. Several font and symbol types are available.

The composite information is important for assessing changes in fire frequency over time and space within and between sites. The user has great flexibility in the information that can be displayed on this composite axis by using any one or a combination of three filters: (1) minimum percentage of samples scarred during any year (calculated using only recorder trees), (2) minimum number of samples scarred, and (3) minimum number of samples. These filters are designed to help identify fire years that may have been particularly widespread across the study site, and assumes that higher percentages indicate progressively greater areas burned within an individual site (Swetnam 1990; Grissino-Mayer and Swetnam 1995; Touchan *et al.* 1996). For example, a year in which fire scarred 75% of the samples may have had a more significant impact on the environment than a year in which fire scarred only 5% of the samples. Filtering of fire data can also provide information concerning the spatial distribution of fire across the study site. For example, a higher percentage of trees may have been scarred in one portion of the

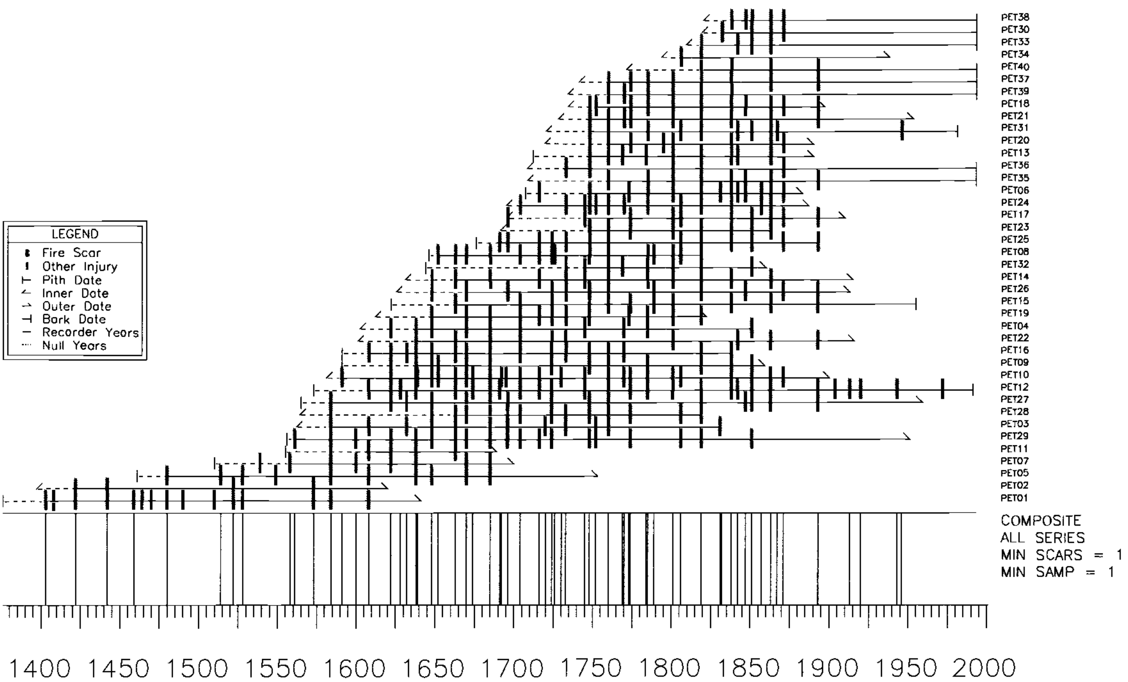

Figure 2. A master fire history graph created for Peter's Flat, a mixed-conifer site in the Pinaleño Mountains of southeastern Arizona (Grissino-Mayer *et al.* 1995), sorted by the first year of each series. This type of sorting more clearly demonstrates the spatial patterning of past fires, and can also be used to evaluate dates for stand origins after possible high-intensity fires. Note the living trees in the upper portion of the graph that show few fire scars during the 20th century.

study site, indicating possible effects due to local topography, local microclimatology, or human-related disturbances. Such spatial differences in fire regimes are important when designing fire management guidelines.

To suppress the display of those years when only one tree was scarred, the user can set the minimum number of trees scarred to two samples or higher. The body of the graph can also be filtered using these same composite filters to create a graph that highlights major fire years. All fire history information from the composite axis (*i.e.* the site composite) can be exported to a separate data file, which can automatically be merged with composite information from other sites to create a regional data set for display and further analyses. The data from the composite information can also be exported and used in the superposed epoch analysis.

Printer and plotter drivers are supplied with the FHX2 system for immediate printing. A useful option is the ability to create files using the Hewlett-Packard Graphics Language (HPGL), a standard format that can be imported into many graphics packages.

STATISTICAL ANALYSES

FHX2 provides basic summary information for each sample and performs a number of statistical tests and functions to help evaluate the fire history for any given site. The Statistics Module can output summaries for individual series and create a table showing the (1) changing sample depth over time, and (2) the changes in fire frequency and/or percentage of trees scarred during running 10, 25, or 50 year periods. Analyzing changes in fire frequency over time is important when assessing the effects of local or regional factors (such as human disturbance and climate change) on fire regimes. This table can be imported into standard spreadsheet programs for graphing. It is good practice to print out and archive all summary information for a given site.

Table 3. Descriptive statistics output by the FHX2 Statistics Module for analyzing fire intervals.

Statistic	Description
Total Intervals	(number of fire years) − 1
Mean Fire Interval	(sum of all fire intervals)/n, n = number of intervals
Median Fire Interval	midpoint interval in array of ordered interval data
Weibull Modal Interval	the mode of the Weibull distribution
Weibull Median Interval	the median (50th percentile) of the Weibull distribution
Fire Frequency	(1/MFI), in FHX2 calculated as (1/Weibull Median Interval)
Standard Deviation	square root of variance, measures dispersion about the mean
Coefficient of Variation	a measure of variability, defined as (standard deviation/mean)
Skewness	measures distribution imbalance left and right of the mean
Kurtosis	measures peakedness of the distribution
Location parameter	locates Weibull distribution on the interval class axis
Scale parameter	locates Weibull distribution across the interval class axis
Shape parameter	characterizes the unique shape of the Weibull distribution
Minimum Fire Interval	shortest fire interval
Maximum Fire Interval	longest fire interval
Lower Exceedance Interval	delimits unusually short intervals
Upper Exceedance Interval	delimits unusually long intervals
Maximum Hazard Interval	fire interval associated with the maximum hazard rate

The seasonality of fire is an important property of fire regimes, and can be estimated in the tree-ring record by observing the intra-annual position of the fire scar within the annual tree ring (Baisan and Swetnam 1990). By analyzing the frequency of the various scar positions, the dominant season of fire occurrence can be determined, if one exists. FHX2 can analyze these (if seasonal designations were recorded and entered) to determine the distribution of the seasonal timing of past fires, and help note whether any changes in fire seasonality have occurred. Assigning actual calendrical seasons to a past fire event, however, will depend on the phenology of the tree species being analyzed, which itself is influenced by elevation, topography, soil conditions and composition, climatic influences, and forest composition and structure.

The analysis of fire intervals is an important tool for analyzing fire regimes. FHX2 uses the Weibull distribution to model fire interval data (Johnson and Van Wagner 1985; Grissino-Mayer 1995, 1999), a flexible distribution that can be fit using a variety of shapes (representing different models) to fire interval data. The Weibull distribution helps define fire regimes by providing statistical descriptors (Table 3) that bracket the historical range of variability. These descriptors include two important measures of central tendency. The Weibull Median Interval (MEI) is the fire interval associated with the 50th percentile of the fitted distribution, while the Weibull Modal Interval (MOI) is the fire interval that contributes the greatest amount of area under the probability density function. In a recent study, the MOI was found to be a superior overall measure of central tendency, and appeared to identify a common underlying structure in Southwestern fire regimes independent of habitat type and environmental gradients (Grissino-Mayer 1999). The interval data can be filtered by percentage scarred classes, and results from fitting of the Weibull distribution can be output to tables and imported into spreadsheet programs.

Finally, the Statistics Module provides parametric and nonparametric tests for evaluating whether changes have occurred (1) temporally between two or more independent periods, and (2) spatially between two or more sites or subsites. Often, changes or differences may be observed in (1) the fire frequency at an individual site or between two sites, (2) the percentage of trees scarred by fires within and between individual sites, or (3) the synchrony of fires between periods and between sites. Three basic tests are used to determine whether differences in the mean fire intervals or percentage of trees scarred are statistically significant between two independent periods. FHX2 uses a Student's

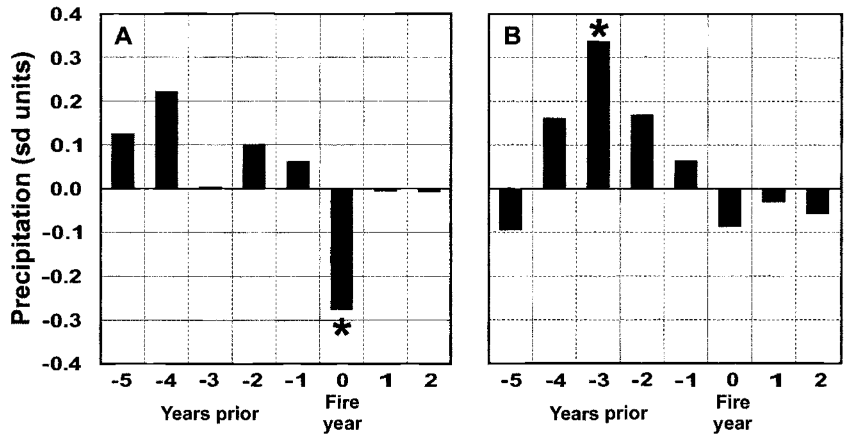

Figure 3. Results from the superposed epoch analysis are tabulated and can be imported into a spreadsheet program to generate simple bar graphs that show the months when climate may have significantly influenced fire occurrence. (A) Fires primarily occurred during severe drought years preceded by generally wet years, but the latter were not significant. (B) Drought during the year of fire was not a significant factor, but rainfall preceding the fire years was significant. This suggests a preconditioning of fire occurrence by the amounts of fine fuels produced in response to generally wetter antecedent conditions, a pattern found in a number of fire history studies in semiarid Southwestern forests (Swetnam and Betancourt 1998; Grissino-Mayer and Swetnam 2000).

t-test to test whether a difference in mean fire intervals or percentage of trees scarred exists, calculated for both equal and unequal variances, whichever is appropriate. An F-test is used for evaluating differences in the variance of fire interval or percentage-scarred data sets between two independent periods. FHX2 then uses a two-sample Kolmogorov-Smirnov (K-S) test for analyzing differences in the distributions of fire interval or percentage-scarred data between two periods.

FHX2 can also analyze whether differences exist spatially between two independent data sets containing fire history information. The samples in the fire history data set are first grouped based on site information. For example, one group may contain all samples collected on the lower half of a hill slope, while the second group may contain all samples collected on the upper half. To test whether differences exist between these two independent data sets, FHX2 again uses the same t-test, F-test, and K-S test. FHX2 can also test for synchrony of fires between these two independent data sets using an array of diagnostic tests. First, two types of chi-squared tests are used, the first using a 2 × 2 contingency table (with cells containing presence-absence totals for 1–1, 0–1, 1–0, 0–0, where "1" denotes the presence of a fire for that year, and "0" denotes absence of a fire in that year) and the second using a 2 × 1 table (a 1–1 cell containing synchronous fire years versus a combined cell containing 0–1 and 1–0 non-synchronous years). Grissino-Mayer (1995) suggested that the 2 × 2 is appropriate for sites distant from each other, while the 2 × 1 is more appropriate for sites that are essentially contiguous.

FHX2 also computes an array of similarity indices commonly used in ecological analyses for testing association (Hubalek 1982; Ludwig and Reynolds 1988), including the Ochiai Index, Jaccard Index, Dice Index, Kulczynski Index, Yule Index, and the Baroni-Urbani and Buser Index. Finally, a Wald-Wolfowitz Runs Test (Downie and Heath 1959) is performed to determine whether the number and length of runs of synchronous and asynchronous fire years in the two data sets were generated by a random process.

SUPERPOSED EPOCH ANALYSIS

Superposed epoch analysis (SEA) is a powerful tool used to analyze the influence a particular variable has prior to and during a certain event (Figure 3) (Swetnam 1993; Swetnam and Baisan 1996; Veblen *et al.* 2000). In fire history studies, SEA is used to analyze the influence of climate on fire occurrence in years preceding, during, and following fire years. Although climate in years $t + 1$, $t + 2$, *etc.* does not exert any influence on a fire in year t, analyses that include these years may help detect important *patterns* of climate prior to and following a fire year. Two variables are required: (1) the list of fire years to be analyzed (created using the Composite Axis export function in the Graphics Module), and (2) either a tree-ring chronology that spans the length of the desired period to serve as a proxy of climate, or an actual reconstruction of a particular climate variable based on tree-ring data. Climate conditions in years prior to and during fire years are averaged after all fire event years have been "superposed" (*i.e.* stacked one on top of another and set to year zero). Second, bootstrapping methods are employed (Mooney and Duvall 1993) on simulated events (windows picked at random) to provide robust levels of confidence.

The first portion of the output provides statistics on the climate or tree-ring variable being used. The second portion provides information and summary statistics on climate (whether based on an actual reconstruction or on a tree-ring chronology serving as a proxy for climate) for years prior to, during, and following the fire years. This portion of the output is critical because the user can quickly scan the mean values to determine the characteristics of climate during the event window. Confidence limits are also provided in this portion of the output. The third part of the output provides similar information and statistics for the number of simulations conducted. Windows of similar length are randomly selected and mean values calculated for all years, regardless whether a fire year occurred or not. This provides the "control" information with which to test the information in the previous section. The fourth portion of the output provides a graphical display of the results. The range of values for each year of the window is displayed as a vertical line on which symbols designate the 95%, 99%, and 99.9% confidence intervals. All tables can be imported into a spreadsheet or graphics program.

SUMMARY

Many agencies currently wish to reintroduce fire back into areas where fire has long been excluded due to effective fire suppression. This restoration is designed primarily to prevent the catastrophic, high intensity fires that have become more common now than the low-intensity surface fires that occurred prior to widespread Euro-American settlement (Swetnam 1990). Restoration of fire, however, is challenging because the historical range of variation in fire frequency for many areas is not well known. In addition, fire management is further complicated by sites with complex geology, diverse habitat types and ecotonal boundaries, and various human-related factors (*e.g.* grazing, logging, road construction, and fire suppression) that influence the landscape.

Temporal and spatial aspects of past history can be documented by analyses of fire scars embedded within the annual rings of trees, but these analyses generate large volumes of data. FHX2 provides an efficient means for entering, analyzing, and archiving of fire history information derived from tree-ring data. The program combines graphical techniques and statistical analyses that together help clarify properties of fire regimes as they existed prior to human interference. The documentation of these properties provides critical information on the range of natural variation in fire regimes, information that is useful when designing and implementing fire management plans and policies. The use of FHX2 can help document and model the frequency of past wildfires, delimit critical threshold fire intervals that indicate severe fire hazard, and analyze the spatial properties of past fires.

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