RECONSTRUCTION AND INTERPRETATION OF HISTORICAL PATTERNS OF FIRE OCCURRENCE IN THE ORGAN MOUNTAINS, NEW MEXICO

by

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DEDICATION

Dedicated to the memory of my Obachan, Katsu Morino.

TABLE OF CONTENTS

TABLE OF CONTENTS - *Continued*

TABLE OF CONTENTS - *Continued*

LIST OF FIGURES

LIST OF FIGURES - *Continued*

LIST OF TABLES

ABSTRACT

The purpose of this research was to reconstruct and interpret the history of fire in the Organ Mountains, New Mexico. I used dendrochronological techniques to date fire scars on 90 trees comprising ten sites within the Fillmore Canyon watershed. Two fire regimes were identified during the pre-settlement period. Fire Regime I, 1650-1805, was characterized by a high fire frequency (*ca.* once every two years) and a predominance of patchy fires. Fire Regime II, 1805-1874, was characterized by a lower fire frequency (*ca.* once every 3.5 years) and a predominance of widespread fires. During the post-settlement period fire was virtually non-existent. I hypothesize that Apache use-of-fire influenced patterns during the pre-settlement period, while Euro-American land use activities influenced patterns during the post-settlement period. Fire-precipitation associations suggest that low fuel moisture levels were a pre-condition for widespread fires.

1. Introduction

1.1 Overview

Fire is a critical ecological factor that influences vegetation dynamics. By affecting both abiotic and biotic processes (*e.g.*, nutrient cycling, plant regeneration, and plant mortality), fire plays a role in regulating and changing vegetation patterns. The impacts of recurrent fire, both direct and indirect, on plant mortality and establishment produce a continually changing spatial pattern consisting of a mosaic of different-aged patches (Pickett and White 1985). Thus, fire occurrence patterns over time and space have significant consequences for landscape dynamics.

Reconstructing the history of past fire for an area is the first step in evaluating the role fire played in shaping particular landscape patterns. Although the role of fire can be predicted to some extent based on present vegetation associations (Wright and Bailey 1982), this approach fails to consider other important factors that affect fire occurrence patterns at local scales, such as topography and land-use history (Baisan and Swetnam 1990). The influence of site-specific factors in "customizing" fire occurrence patterns make reconstructing fire history the best approach for evaluating the role of fire in vegetation pattern at local scales.

In addition to facilitating our ability to interpret contemporary landscape patterns, fire history studies can be used as a management tool. Management objectives may be based on many criteria: social, economic, biological, and political. However, not all management objectives may be appropriate for the particular system being managed (Allen 1994). Fire history studies provide managers with ecological information that facilitates setting and evaluating management objectives, and designing management strategies (Allen 1994; Kauffman *et al.* 1994; Morgan *et al.* 1994; Swanson *et al.* 1994).

The perspective provided by fire history studies can be used in setting and evaluating management objectives. A large part of natural resource management consists of managing change. It is widely accepted that change is an inherent characteristic of ecological systems. However, managers are left to decide what kinds of change may be considered acceptable and what kinds are not. For example, most areas in the United States have been impacted by human-related activities, *e.g.*, grazing and fire suppression, that have reduced fire incidence. Concurrent changes in landscape and forest structure and composition have stimulated great concern over the potential consequences of human-caused fire exclusion (Leopold 1924; Weaver 1951; Cooper 1960; Swetnam 1990; Covington and Moore 1994). These consequences include the increased potential for catastrophic, stand-replacing fires, and possibly a decrease in biological diversity (Swetnam 1990; Covington and Moore 1994). Are these changes acceptable? One way to make this evaluation is by examining the range and variation of fire regimes in the past. Specifically, historical (pre-settlement) fire regimes may be compared to contemporary (post-settlement) fire occurrence patterns. Then, if changes in fire occurrence patterns are considered unacceptable, fire history studies can be used to develop new fire management strategies by providing the historical range and variation that management may seek to restore.

1.2 Purpose of This Study

The purpose of this study was to reconstruct and interpret the history of fire for the Organ Mountains, a semi-arid mountain range located in south-central New Mexico. Prior to this study, the role of fire in this watershed was unknown. Currently, its montane forests are highly fragmented. Is this pattern due to fire or lack of it? While many fire history studies have been conducted in conifer forests in the Southwest, the Organ Mountains are perhaps one of the more xeric and rugged ranges. Furthermore, the absence of "dog-hair" thickets (dense thickets of pine regeneration), considered by most foresters and ecologists to be the legacy of fire suppression throughout southwestern conifer forests (Covington and Moore

1994), raises the question: Did fire suppression significantly alter fire occurrence patterns in the Organ Mountains? If so, what are the consequences for future vegetation associations?

Fort Bliss is responsible for managing the majority of this range. Their concerns include the preservation of plant communities and rare and biologically threatened species. Fort Bliss is currently working with the New Mexico Natural Heritage program to develop management strategies that focus on the maintenance or enhancement of its ecosystems (Muldavin 1991).

Communities of particular concern include its conifer forests, (*i.e.*, communities dominated by ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco)) because they provide habitat for rare and endemic species, including Organ Mountain Figwort (*Scrophularia laevis*) and possibly Standley's draba (*Draba standleyi*). In addition, management of these communities could impact species downstream such as the Organ Mountain primrose (*Oenothera organensis*; Muldavin 1991). This study was conducted in the Fillmore Canyon watershed because it represents the topographic complexity and ecosystem diversity that is characteristic of the Organ Mountains, including the vegetation communities with which managers are particularly concerned.

1.3 Statement of Objectives

The primary objectives of this study were to:

- reconstruct temporal and spatial characteristics of fire occurrence;
- characterize historical fire occurrence patterns, including the identification of changes in patterns; and
- interpret historical fire occurrence patterns, considering specifically the influence of climatic and human factors.

These objectives were accomplished using dendrochronological techniques to develop both a tree-ring chronology and fire-scar chronology. The tree-ring chronology was developed primarily from increment cores extracted from living trees. Ring patterns from these cores provided an independent dating source for dating fire-scarred specimens, and were used to reconstruct precipitation for investigating fire-climate associations. The fire-scar chronology was developed from living and dead fire-scarred trees.

It is hoped that the information derived from this study will improve our general understanding of the role of fire in the Organ Mountains, and provide specific guidelines for the development of fire management programs.

2. Background

2.1 The Role of Fire in Ponderosa Pine Forest

Based on accounts by early settlers in the Southwest, ponderosa pine forests typically consisted of groups of widely-spaced trees with grassy understories (Cooper 1960; Savage 1991). The influence of fire on pattern in ponderosa pine forest, prior to Euro-American settlement, was primarily due to effects of fire that modified the local environment, thereby affecting establishment and regeneration. Highly localized increased temperatures, generated from the burning of snags and downed logs create optimal conditions for ponderosa pine establishment and seedling growth (Cooper 1960, 1961). Patches of bare mineral soil created by these fires improve seedling establishment success by reducing competition from grass species (White 1985).

Patches of regeneration are usually dense. By the sapling stage, enough litter has accumulated, mostly fallen needles, to support a light surface fire (Cooper 1961). Fires generally kill numerous smaller-diameter saplings, acting as a thinning agent (Weaver 1947). Repeated fires continue to induce mortality, and thin the pine thickets, until the diameter and bark thickness of the tree provides it with sufficient protection from the fire. Frequent surface fires thus perpetuate a ponderosa pine forest consisting of groups of widely-spaced trees with a grassy understory. Likewise, the structure and composition of the ponderosa pine forest, particularly the grassy understory, perpetuate a fire regime of frequent, low-intensity, surface fires.

2.2 The Study of Fire: A Theoretical Framework

Patch dynamics provides a theoretical framework to study fire. Fire is a phenomenon that can induce change on a spatial scale ranging from a few square meters to many square kilometers, and on a temporal scale ranging from minutes to multiple centuries (Delcourt and Delcourt 1991). Patch dynamics refers to the temporal and spatial pattern of creation of open or altered patches, whereby "patches" can be thought of as relatively discrete spatial units that are embedded in an unaffected or less affected matrix (White and Pickett 1985).

Patch dynamics at larger spatial scales is related to landscape ecology, "the study of the structure, function and change in a heterogeneous land area composed of interacting ecosystems" (Forman and Godron 1986). Structure refers to the spatial patterns of the landscape elements, *i.e.*, ecosystems. Function refers to the interactions among elements, *i.e.*, flows of energy, materials, and species between ecosystems. And, change refers to the alteration in the structure and function of the landscape over time.

Some specific areas that are considered in landscape ecology include: the development and dynamics of spatial heterogeneity, interactions and exchanges across heterogeneous landscapes, the influences of spatial heterogeneity on biotic and abiotic processes, and the management of spatial heterogeneity (Turner 1989). The study of fire is relevant to these topics because fire and spatial heterogeneity interact.

Fire plays an important role in determining spatial pattern by influencing patch size, shape, and location; spatial pattern is related to the location, frequency, intensity and spatial extent of fire. On the other hand, spatial heterogeneity plays an important role in fire spread. The different compositions, amounts, and structures of fuels within patches confer variable flammabilities across the landscape. Consequently, fire spread is affected by the spatial arrangement of the component patches of the landscape (Knight 1987; Christensen 1993).

At coarse levels of resolution, landscape pattern may be more of a determinant of fire occurrence pattern than vice versa (McPherson 1995; Clark 1990). The proportion of fire-susceptible patches on the landscape can vary over time and at different rates. Two important factors that can modify landscape patterns are climate and humans. For example, climate can modify the proportion of disturbance-susceptible habitat by influencing fuel accumulation rates. In systems where grasses and other fine fuels play an important role in fire occurrence patterns above-average precipitation may accelerate grass production, thus increasing the proportion of disturbance-susceptible habitat. Humans may influence the proportion of susceptible habitat by burning, logging, livestock grazing, and fire suppression. Typically, use-of-fire by humans and livestock grazing will tend to decrease the amount of disturbance susceptible habitat, while logging and fire suppression will tend to increase the amount of disturbance-susceptible habitat. The influences of both climate and humans are discussed in more detail in the following sections.

2.2.1 Climate and Fire

If weather represents the sum total of atmospheric variables over a brief period of time, then climate represents the composite weather conditions within a specified area over a relatively long period of time (Trewartha and Horn 1980). The effect of weather on fire occurrence on hourly, daily, and even weekly time scales is well-documented and relatively well understood (Rothermal 1983). However, the effect of climate on fire on seasonal to centennial time scales is less well understood (Swetnam and Betancourt 1990). At these time scales, cause and effect may be difficult to experimentally demonstrate; however, by examining climate-fire associations over longer temporal and larger spatial scales, we can reasonably infer cause and effect if repeated patterns occur (McClaran *et al.* 1995) and if other potential factors can be ruled out.

2.2.1.1 Intra-annual Climate

Seasonal climate patterns influence the distribution of fire within the year (Pyne 1984). Barrows (1978) reported that fire occurrence in Arizona and New Mexico was highest during the dry foresummer (*i.e.*, May to July). Interestingly, regional data show that area burned by wildfires was greatest in June, while the highest number of ignitions was recorded in July (Barrows 1978). Baisan and Swetnam (1990) attribute this to "dry" thunderstorms that typically occur in June when fuel moisture levels are extremely low. These storm systems cause lightning activity but release relatively little rain in a spatially patchy pattern. As the summer rainy season approaches, storms tend to occur at a higher frequency and contribute significant moisture to the system. The combination of occasional "dry" thunderstorm and dry antecedent conditions in June result in widespread fires, while the combination of high storm frequency and wetter conditions in July result in relatively high frequency of smaller fires.

2.2.1.2 Inter-annual Climate

In ecological systems where fire regimes are characterized by low-intensity surface fires, the influence of climate on the accumulation and desiccation of fine fuels, *i.e.*, grasses and other herbaceous material, is particularly important. Fuel accumulation is generally a more important factor than fuel moisture in fire spread in semi-arid environments, such as the Organ Mountains because climatic conditions conducive to low fuel moisture levels typically occur on an annual basis (Rogers and Vint 1987; Baisan and Swetnam 1990; Weltzin and McPherson 1995). The strong association between precipitation and plant productivity in semi-arid environments signifies that the occurrence and frequency of bouts of precipitation have an important impact on fuel accumulation.

Previous studies corroborate the importance of precipitation to fuel accumulation in semi-arid systems. For example, Rogers and Vint (1987) found an association between fire size in the Sonoran Desert and the occurrence of two wetter-than-normal winters. The authors suggest that increased winter precipitation increases the production of winter annual species, thus increasing landscape connectivity and therefore the size of subsequent fires. In a statistical summary of Great Basin fire records, Knapp (1995) found in some vegetation types that area burned was associated with 1-2 years above average summer precipitation. Knapp (1995) concluded that area burned increased when climate favors the growth of annual grasses over perennial shrub species. In a fire history study conducted in mixed pine forest in southeast Arizona, Baisan and Swetnam (1990) found that widespread fires were significantly associated with the occurrence of two consecutive years of wetter-than-average conditions. They interpreted these findings as indicating the importance of precipitation in producing fine fuels, *e.g.*, grass, which facilitate the occurrence of widespread fires. In the Southwest, summer precipitation, in particular, may play a important role in fuel accumulation. Many of the grass species found in the Southwest respond strongly to summer precipitation, *i.e.*, July to September: up to 90% of growth occurs during this period (McClaran 1995).

2.2.1.3 Decadal to Centennial Climate

Variability in climate at decadal to centennial scales is assumed to influence characteristics of fire occurrence such as frequency, average size, and possibly average intensity. Generally, a climate-fire association can be inferred when repeated patterns are observed over long temporal or large spatial scales. However, comparing long-term climate variability and fire occurrence patterns is difficult because ecosystems having long, reconstructible histories of both climate and fire are rare. An exception is Swetnam (1993) who compared fire histories from giant sequoia in California to reconstructed climate from long-lived tree species. Swetnam (1993) found that decadal to centennial fluctuations in summer temperature generally tracked long-term variation in fire frequency in giant sequoia groves in California and hypothesized that this association was the result of temperature-related shifts in vegetation which subsequently affected fuel production. Interestingly, reconstructed winter-spring precipitation appeared to affect fire occurrence patterns on much shorter time scales, *i.e.*, inter-annual.

Long fire histories, such as those characteristic of giant sequoia, are not necessarily a requirement for evaluating the influence of long-term change in climate on fire regimes. Changes in fire occurrence patterns that are relatively synchronous over large spatial scales are typically interpreted to represent the influence of climate because few other environmental variables act at these scales (Swetnam 1990). For example, during the first half of the 1800s, unusually long intervals between fires are observed in many southwestern fire history sites; moreover, fires tend to be more widespread compared to events prior to *ca.* 1800 (Swetnam 1990; Swetnam and Baisan *in press*). This change in fire occurrence patterns appears to coincide with a possible change in climate regimes. Grissino-Mayer (1995) reconstructed long-term variability of annual precipitation in northern New Mexico and found the 1800s (up to the mid-1900s) to be one of the wettest periods during the last 900 years. Perhaps more importantly, Grissino-Mayer (1995) hypothesizes that *ca.* 1800 the seasonal distribution of rain began to change from winter- to summer-dominant.

2.2.2 Humans and Fire

Human activities have changed the frequencies, seasonal timing, sizes and severities of fires relative to those ignited by natural causes. Humans have altered fire occurrence patterns in many ways. For example, some Native American groups increased fire frequencies by using fire for hunting, clearing brush to facilitate travel, cooking, fighting enemies, and communicating (Stewart 1956; Pyne 1982). In the southwestern United States, the Apaches were a group that may have used fire extensively (Bahre 1991; Vischer 1886 in Humphrey 1962). Supposedly, all Apaches carried the necessary tools with them at all times to start a fire (John 1989).

Fire occurrence patterns were also affected by livestock grazing, first practiced by the Spaniards, then later by some Native American groups and early western settlers. In areas where low-intensity, surface fires predominated, overgrazing by cattle, sheep, and goats drastically reduced fuel continuity thus impeding or preventing fire spread (Leopold 1924; Humphrey 1962). Moreover, livestock trails served as fire breaks, also affecting fire spread.

More recent human activities affecting fire occurrence patterns include fire suppression and landscape fragmentation (Kauffman *et al.* 1994). Fire suppression is considered to be a primary factor contributing to changes in forest structure and composition in many areas of the Southwest (Weaver 1951; Cooper 1960; White 1985; Sackett *et al.* 1994; Covington and Moore 1994). In the Southwest, one consequence of these structural changes is the increased occurrence of larger, higher-intensity crown fires since the 1950s (Swetnam 1990). In contrast, landscape fragmentation, due to activities such as trail and road construction, has acted to restrict fire spread (Allen 1994). Other activities, such as logging, mining, and fuelwood cutting may also have altered fire regimes. For example, slash left over from logging operations can increase fuel loads and perhaps result in fires of unprecedented intensity.

2.3 Characterizing and Interpreting Fire Occurrence Patterns Using Dendrochronology

A fire regime is a description of fire occurrence over time and space, typically characterized by fire type, fire frequency, spatial extent, and seasonality (Sousa 1984; Pickett and White 1985; Christensen 1993; Heinselman 1981). Using dendrochronological techniques, it is possible to reconstruct most of these characteristics; albeit, with varying levels of accuracy and precision.

2.3.1 Fire Type

Three general types of fire may be defined as: ground fires which occur as smoldering combustion within the organic layer of the soil; surface fires which burn litter, logs and fine fuels on the surface of the soil; and crown fires which burn above the soil surface in the crowns of trees (Wright and Bailey 1982). A fire regime for a particular vegetation association can include a combination of these fire types for a single event, or among different events occurring at different times (Heinselman 1980). Reconstructions of fire history based on fire scars, generally includes only those fires intense enough to injure but not kill all the trees on the site. Fire-scar analysis has been used extensively to reconstruct low-intensity surface fire regimes (Weaver 1951; Dieterich 1980; Swetnam 1983). However, fire-scar analysis can also be used in conjunction with age structure analysis to reconstruct fire regimes that include the occurrence of stand-replacing crown fires (Heinselman 1973; Tande 1979).

2.3.2 Fire Frequency

Fire frequency is the number of events that occur within a specified area and period of time; the inverse of fire frequency is the return interval, or the length of the period between fires (Romme 1980). One strength of using dendrochronological techniques is the high accuracy and precision with which temporal patterns of fire occurrence can be reconstructed. The fundamental principle of dendrochronology is "crossdating" which ensures the exact temporal placement of tree rings by comparing the patterns of ring widths between trees within a site and between sites across a region (Stokes and Smiley 1968; Fritts 1976; Swetnam *et al.* 1985). This principle ensures that the exact year of formation is determined for each individual fire scar (Swetnam and Dieterich 1984). This level of precision means that fire intervals as short as one year can be resolved. Identifying such short intervals is important due to the ecological impacts two such fires can incur (see Zedler *et al.* 1983). Annual-dating resolution also facilitates the comparison of specific fire events with other potentially relevant historical events (*e.g.* Apache-Spaniard or Apache-American encounters), and/or environmental factors operating on similar time increments (*e.g.* drought years or years of above average rainfall).

Another advantage of using dendrochronological techniques is the ability to date fire scars from remnant pieces of wood (portions of dead trees). This practice extends the fire history back in time (see Baisan and Swetnam 1990) and is limited only by the ages of individual trees and the degree of preservation of wood at a site. Analyzing fire occurrence patterns over decadal, centennial and longer temporal scales, confers the ability to identify long-term trends and better characterize fire regime variability.

Reconstructed fire frequency is affected by the size and other characteristics of the study area. Large study areas tend to have higher fire frequencies than smaller study areas simply because the larger areas have a greater probability of including areas or portions of areas burned by other fires (Arno and Peterson 1983). Landscape heterogeneity must also be considered. High fire frequency in a heterogeneous landscape may indicate that many small fires affected different portions of the landscape. Conversely, high fire frequency in homogeneous landscapes may indicate that many widespread fires affected large areas during each burn. These patterns differ in how frequently fire returns to any given point in the landscape and could have different ecological impacts on the vegetation. Thus, inferring the effect of fire frequency on vegetation requires that fire regime assessments consider both the temporal and spatial distribution of past fire (Swetnam 1993).

2.2.3. Spatial Extent

Reconstructing the size of low-intensity fires is less precise than reconstructing fire frequency because the perimeter of the burned area disappears after 2-3 years. Although the presence of a fire scar is irrefutable evidence that fire occurred, the area represented by a single fire scar is limited to the base of that tree, making it a point estimate of fire occurrence. Moreover, the absence of a fire scar during a known fire year may occur because the fire did not occur at the base of the tree, or the fire did burn around the tree but did not reach an intensity that was high enough to scar the tree. In regions where trees are scarred many times, it is argued that intensity probably does not play a major role in affecting the completeness of the record. After a fire injures a tree for the first time, subsequent scarring can be induced at lower intensities due to the concentration of inflammable resins in the vicinity of the open wound.

Inferring relative sizes of fires within the study area is made possible by comparing fire dates from multiple clusters of trees, or a network of sites. Fires recorded on many trees within a site, and/or many sites within a watershed or mountain range probably represent relatively widespread fires, while fires recorded on few trees or in few sites, probably represent relatively small fires (Swetnam and Baisan *in press*).

2.3.3 Seasonality

Fire seasonality can be roughly approximated by examining the position of fire scars within the tree rings. Scar position yields information relating to the timing of the fire to the growing season of the tree (Dieterich and Swetnam 1984; Baisan and Swetnam 1990). For example, fires that occur in the beginning of the growing season tend to produce scars in the early portion of the tree ring (*i.e.*, in the early portion of the earlywood), generally representing spring fires. Similarly, fires that occur later in the growing season produce scars in the later portion of the tree ring (*i.e.*, in the late portion of the earlywood or in the latewood), generally representing late summer or early fall fires. Fires that occur during the dormant season of tree growth are problematic (Clements 1910; McBride 1983). These fires may either have occurred after the tree completed radial growth, in fall, or before the tree initiated radial growth, in spring. In the northern hemisphere, the dormant season spans two calendar years. Dormant-season fire scars are therefore dated according to the prevailing season of fire occurrence based on available historical evidence (Baisan and Swetnam 1990). If fires tend to occur in the fall versus the spring for a given region, then the fire that produced the scar is dated to the year of the ring preceding the scar. Whereas, if fires tend to occur in the spring versus the fall, the fire is dated to the year of the ring formed after the scar.

3. Materials and Methods

3.1 Area Description

3.1.1 Physical Setting

The Organ Mountains are located in south-central New Mexico at 32°20'N latitude and 106°31'W longitude. They lie between the San Andres range to the north and the Franklin range to the south in a relatively continuous chain of north-south trending ranges. The San Andres-Organ-Franklin cordillera is surrounded by shrub desert, flanked on the west by the Rio Grande River and on the east by the Tularosa Valley. Fillmore Canyon, the study site, is located on the west side of the Organ Mountains in approximately the middle of the range. The mouth of the canyon lies approximately 18 km east of Las Cruces.

3.1.2 Geology

Most of the geologic activity that formed the Organ Mountains and Fillmore Canyon occurred as a result of volcanic activity during the middle Tertiary (~32 million years ago; Seagar 1981). Fillmore Canyon, one of the more rugged watersheds within the Organ Mountains, is located at the juncture of the northern, granitic portion and the southern, rhyolitic portion of the mountain range. The northeast third of the watershed consists of granitic rock, while the remaining portion of the watershed consists of rhyolitic and andesitic rock. Two, thin strips of limestone occur in the upper canyon.

3.1.3 Climate

No meteorological records exist for locations directly within the Organ Mountains. However, in nearby Las Cruces (elevation 1200 m), records indicate a unimodal pattern of seasonal precipitation distribution with a dominant summer component. Average rainfall is approximately 21.5 cm/year with over half (53%) generated by summer monsoonal storms that occur between July and September. These months also show the lowest year-to-year variability in rainfall. Average monthly precipitation during the fall, winter and spring is comparatively sparse, averaging less than 2.5 cm/month, but is highly variable from year to year. June precipitation is the most variable from year to year, perhaps reflecting variability in the timing of the onset of the summer rainy season. The July to September period is also typically the warmest with temperature maxima averaging 24.6 °C. The coldest months are December and January with temperatures averaging 5.4 °C and 5.3 °C, respectively. In contrast to precipitation, monthly temperature shows little inter-annual variability.

Another characteristic feature of Las Cruces climate, is the "arid foresummer," which is typical to the Southwest in general (Sellers and Hill 1974). Precipitation decreases during the spring, while temperatures increase. By June, temperatures may equal or sometimes exceed those recorded during the summer months. These dry, hot conditions (arid foresummer) continue until the arrival of the summer rains, generally in late June or early July.

Mountain relief undoubtedly modifies the precipitation and temperature observed in Las Cruces. At elevations above 2400 m, rainfall probably doubles that recorded in Las Cruces, suggesting that precipitation in the upper-most elevations of Fillmore Canyon would be 43 cm. Because temperature decreases at an average rate of 7.5 °C/1000 m (Dick-Peddie and Moir 1970), estimated temperatures in the upper elevations of Fillmore Canyon would be approximately 11 °C. Differences are also evident in the number of frost-free days between Las Cruces (210) and the upper-most elevations of Fillmore Canyon (150; Muldavin *et al.* 1994).

3.1.4 Vegetation

A vegetation survey of the Organ Mountains using remote sensing techniques identified eight vegetation types (Greenlea 1993). Statistical analyses revealed a fairly strong association of vegetation type with aspect and elevation. Vegetation types in order of decreasing elevation and moisture gradient are:

1. Montane Meadow, represented by montane grassland;
2. Mesic Montane Scrub, represented by gambel oak (*Quercus gambelii* Nutt.) scrub;

3. Mixed Woodland, represented by gambel oak woodland;
4. Montane Conifer Forest, represented by ponderosa pine and Douglas-fir;
5. Coniferous Woodland, represented by grey oak (*Q. grisea* Liebm.), piñon (*P. edulis* Englm.), and juniper (*Juniperus deppeana* Steud.);
6. Ravine Coniferous Forest, represented by ponderosa pine and Douglas-fir;
7. Xeric Montane Scrub, represented by mountain mohagony (*Cercocarpus montanus*); and
8. Upper Desert Scrub, represented by desert grassland.

Using ground sampling techniques, Muldavin *et al.* (1994) provided a more detailed description of vegetation communities in Fillmore Canyon. This survey yielded information regarding the species composition of vegetation types, including understory species. Conifer Forest communities, the vegetation type in which the majority of this study was conducted, occur between 2,280-2,590 m, although some communities were found as low as 2,300 m. The distribution of Conifer Forest is discontinuous, interrupted by other vegetation types and/or topographic features. Generally, Douglas-fir is found at higher elevations and/or in sites with deep soils that maintained higher moisture levels throughout the year (*e.g.*, in head slopes and drainages). Ponderosa pine is found on more exposed sites with shallower soils, perhaps reflecting the higher tolerance of ponderosa pine to more xeric conditions. Douglas-fir communities tend to be closed-canopy forests, while ponderosa pine communities ranged from open to closed canopy. Neither ponderosa pine nor Douglas-fir appear to be regenerating well compared to other species such as piñon, gambel oak, and grey oak. Both Douglas-fir and ponderosa pine are often found associated with gambel oak shrub. Ponderosa pine stands tend to have a greater percentage of grass cover than Douglas-fir stands.

3.1.5 Human Land-Use History

3.1.5.1 The Apaches

The Apaches are thought to have arrived in the Southwest sometime between 1400 and the mid-1500s (Opler 1983). Historical documents place the Apaches in the Organ Mountains since at least 1682 until 1880 (Table 1). Archeological evidence from the San Andres range (immediately north of the Organ Mountains) suggests that the Apaches were active in this area even earlier. A fire-cracked rock midden believed to have been used by the Apaches was radiocarbon dated to 1638±50 years (Laumbach and Burton n.d.). The Apaches may have had several uses for the Organ Mountains: (1) apparently as a refuge from Spanish retaliation (Table 1); (2) for hunting deer (Basehart 1974); (3) as a site to replenish "mystical power" (Basehart 1974). Fillmore Canyon may have been of particular interest to the

Table 1. Chronology of quotations and references from documentary sources on Apaches in the Organ Mountains, New Mexico.

Year	Account	Source
1682	"He went there [the Organ Mountains] for two reasons, the first being to see whether there was to be found timber for the settlements which he plans to make, for the temples and casa reales; and second to look about for the enemy Apaches who live in it."	Hackett, 1942
1692	"Other hostile Apache tribes also were pursued, and were defeated in the Sierra de los Organos, the Sierra Florida, and the Sierra Nevada, to the north and west."	Espinosa, 1942
ca. 1750 to ca. 1800	"One group of Mescaleros, concentrated in the Organ Mountains,...were especially troublesome. Their favorite trick was to come to El Paso to negotiate a peace and steal a few horses on their way back to the tribe. Time and time again, they were pursued, and just as regularly the soldiers were turned back by the craggedness of their mountain refuge."	Stanley, 1962:284 Sonnichsen, 1986:52
1766: July	Organ Mountains Mescaleros [Apaches] were surprised and defeated by Captain Pedro Jose de la Fuente.	Stanley, 1962:284; Sonnichsen, 1986:52
1769	Organ Mountains Mescaleros fended off an attack by Captain Lope de Cuellar.	Sonnichsen, 1986:52

Table 1. (con't)

Year	Account	Source
1774	A party of Gileño Apaches go to El Paso to request peace, promising to bring in the Apaches from the Organ Mountains.	Griffen, 1988:33
1776	Spanish troops drove Mescaleros out of the Organ Mountains.	Sonnichsen, 1986:54
1777: Dec 14	Apache emissary from the Organ Mountains goes to El Paso to ask for peace.	Stanley, 1962:95; Sonnichsen, 1986:52; Thomas, 1969:15
1778: Jan	Apache captain of the Organ Mountains rancherias sought peace in El Paso.	Thomas, 1969:16
1779: Apr	Capt. and Inspector-Commissioner Diego Borica proposes that bi-annual campaigns be made against the Apaches, once at the beginning of August, the other in the middle of October, to Organs, Sacramentos and Blancas.	Thomas, 1969:185
1794	A party of Apaches surprised 15 Spanish soldiers in the Organ Mountains.	Griffen, 1988:69
1836	Chief Pescas had located his rancheria in the Organ Mountains.	Griffen, 1988:169

Table 1. (con't)

Year	Account	Source
1850	U.S Topographical Engineer, Captain R.B. Marcy, refers to a group of Apaches inhabiting the Organ Mountains under the leadership of a Chief Gomez.	Betancourt, 1981:53
1852	J.R. Bartlett, of the U.S-Mexican Boundary Commission, recieves a military escort when hiking in the Organ Mountains on account of "these mountains being the haunts of the Apaches;" "fresh Indian tracks" were encountered during the hike.	Bartlett, 1855:392,394
1854	T. Antisell, a geologist with the Pacific R.R Survey, attempts to visit the Modoc mine (at the entrance to Fillmore Canyon) and is prevented from doing so "as several lodges of Apaches were camped close to it."	Lindgren *et al.*, 1910:207
1858	Group of hostile Apaches, led by Shawano, encamped in the Organ Mountains stole horses from Mesilla.	Basehart, 1974:105
1869	Apaches thought to be hiding out in the Organ Mountains.	Bender, 1974:235
1880	Victorio camped in Hembrillo Canyon, Organ Mountains; April 1880 - battle between Victorio and U.S Army, Colonel E. Hatch.	Laumbach and Burton, n.d.; Betancourt, 1981:65

Apaches because it is one of the few canyons where water can be found throughout the year (Seagar 1981).

3.1.5.2 The Euro-Americans

3.1.5.2.1 Grazing

Cattle drives through New Mexico began in the mid-1800s, with the discovery of gold in California (Griggs 1930); however, the larger drives did not begin until the mid-1860s, after the Civil War (Beck and Haase 1969). The development of the cattle industry in southwestern New Mexico was slow due to constant harassment from the Apaches as late as the mid-1880s (Baydo 1970). By 1890, however, the number of cattle in New Mexico was exceeded only by the number of cattle on the ranges of Texas (Cox 1959). In 1893, William Webb Cox bought what became one of the largest cattle ranches in the Organ Mountains, located on the east side of the range, near San Augustine Springs. In the 1890s the ranch was referred to as "the queen of them all" (Keleher 1962). It eventually grew to 4250 ha and continued producing cattle until 1945 when the federal government bought it out for the expansion of military missile ranges (Keleher 1962).

3.1.5.2.2 Mining

Lead and silver mines were discovered in the late 1840s, but mining operations proceeded slowly throughout the next decade due to Apache hostilities (Lindgren *et al.* 1910). The period between 1875-1900 marked the period of highest mining activity in the Fillmore Canyon area (Dunham 1935). One of the larger mines, the Modoc Mine, was located at the mouth of Fillmore Canyon (Figure 1) and was fully operational by 1879 as production was inhibited by the Apache presence. By the end of the 1800s, production in the Modoc mine had developed to such an extent that the Modoc Mine Company constructed a small "town" for the miners and their families near the site (NMSU Archives). The town was constructed in 1900 and subsequently abandoned after 1903 when the Modoc Mine Company went bankrupt (NMSU Archives).

Extensive timber harvesting apparently occurred during this short period (1900-1903), probably o fuel the mine smelters. Several photographs on file in the New Mexico State Archives illustrate very large quantities of wood piled near the mill site. Based on these photographs, it is speculated that a wood-cutting camp was located in the upper elevations of Fillmore Canyon. Because the mill located in the Modoc mining camp was constructed in 1887, timber cutting may have begun as early as the 1880s. Some cutting apparently occurred prior to the construction of the mill based on my dendrochronological dating of stumps which show death dates in the early 1850s.

3.1.6 Site Descriptions and Locations

Samples were collected primarily from ponderosa pine stands, or stands with both ponderosa pine and Douglas-fir (Table 2). Each stand sampled comprised a single site. Sites are generally interspersed among other vegetation types due to the discontinuous distribution of Conifer Forest in Fillmore Canyon. Furthermore, not all parts of the canyon are equally represented by the collection sites (Figure 1) because ponderosa pine is found predominantly on north-facing slopes.

3.2 Tree-Ring Chronology Development

3.2.1 Field Methods

I followed standard field methods to sample ponderosa pine trees for the development of a climatically-sensitive tree-ring width chronology (Stokes and Smiley 1968; Swetnam *et al.* 1985). Trees were selected based on climatic sensitivity and age. Climatically-sensitive trees are trees whose growth is limited primarily by precipitation, temperature or a combination of these two parameters, *e.g.*, drought (Fritts 1976). In arid regions, tree growth is typically limited by effects of precipitation on available soil moisture. Sensitivity to moisture availability was emphasized by coring trees growing in well-drained micro-sites (*i.e.*, steep slopes, south-facing slopes and exposed ridges).

A total of 43 old and young trees were cored.

Table 2. Descriptions of fire-scar sampling sites.

Site Name	**Elev. (m)**	**S**[1]	**Overstory**[2]	**Understory**[2] **/ Substrate**	**Comments**
Old Pine Bluff ***OPB***	2345-2375	G/M	PIPO, PIED	QUGA scrub, rock, grass spp.	-increment core samples suggest that the trees in this area are some of the oldest in the canyon
Snag Saddle ***SSD***	2380-2440	M	PIPO, QUGA Fraxinus sp.	grass spp.	- small stand of maple (ACGL) located approximately 200 m up the drainage - small stand of PSME snags at top of drainage
Rock House Spring ***RKH***	2405-2470	M	PIPO, PSME PIED	QUGA scrub, grass spp.	- PSME snags observed at higher elevations in the drainage - cut stumps found in area

1. Slope categories: G=gradual 5°-15°; M=moderate 15°-25°; S=steep 25°-45°.
2. Species abbreviations: PIPO=*Pinus ponderosa*; PIED=*P. edulis*; PSME=*Pseudotsuga menziesii*; QUGA=*Quercus gambelii*; QUGR= *Q. grisii*; JUDE=*Juniperus deppeana*; CEMO=*Cercocarpus montanus*; ACGL=*Acer glabrum*.

Table 2. (con't)

Site Name	**Elev. (m)**	**S**	**Overstory**	**Understory/ Substrate**	**General Description of Site**
Organ Peak West ***OPW***	2300-2470	M/S	PIPO, PSME QUGA	QUGA scrub rock, grass spp.	- many rocky outcrops - "overstory " QUGA comprised of closed canopy patches of small-diameter (<15 cm dbh) trees - axe cut tree discovered; cutting date: 1851.
Narrows ***NAR***	2135-2225	G/M	PIED, PIPO JUDE, QUGR	QUGA scrub rock, grass spp., Opuntia spp.	- on the south side of the main channel
Side Canyon One ***SCI***	2240-2285	M/S	PIPO, PSME, PIED, JUDE	QUGA spp., rock, grass spp.	- two clusters of samples collected

Table 2. (con't)

Site Name	**Elev. (m)**	**S**	**Overstory**	**Understory/ Substrate**	**General Description of Site**
Side Canyon Two ***FST***	2255-2345	G/M	PIED, PIPO, PSME	CEMO, bare soil, rock, QUGA scrub	- most samples were collected on or near ridgeline - on the ridge, PIED and CEMO dominated; off ridge, PIPO and QUGA dominated
Side Canyon Three ***FSR***	2285-2345	M	PIPO	QUGA scrub, grass spp.	- density of PIPO relatively high - cut stump found at top of drainage
Ledge ***LDG***	2375-2385	G	PIPO	CEMO, bare soil, QUGA scrub, rock, grass spp.	- density of PIPO relatively low - very isolated; most of the perimeter of this site consists of either a rock wall or cliff; the approach to this site is a grassy slope.

Table 2. (con't)

Site Name	**Elev. (m)**	**S**	**Overstory**	**Understory/ Substrate**	**General Description of Site**
Lower Fillmore ***LOF***	2165-2195	M/S	PIPO	QUGA scrub, Agave spp., Opuntia spp. CEMO, grass spp., rock	- density of PIPO relatively high, mostly smaller diameter trees (20 to 40 cm dbh)

Specimens from older trees provided length to the chronology, while specimens from younger trees provided datable ring series through twentieth-century drought periods. An extreme drought in the 1950s severely limited growth in older trees, making it very difficult to distinguish ring-width patterns. The more vigorous younger trees maintained higher levels of growth during droughty periods, and therefore, were more easily dated.

Two increment cores were taken from selected trees at 1.5 m above ground level. Cores were extracted from opposite sides of the tree parallel to the contour of the slope. Cores were placed in paper drinking straws and labelled.

3.2.2 Laboratory Methods

Dry increment cores were glued on grooved sticks so that tracheid cells were vertically oriented. A flat viewing surface was prepared by first using a razor then fine grit sandpaper. A 10X30 variable power binocular dissecting scope was used to view the tree rings.

Calendar dates were assigned to each ring on each core by matching ring-width patterns among trees (Stokes and Smiley 1968; Swetnam *et al.* 1985). This procedure is called crossdating (Fritts 1976). Crossdating is possible when synchronous variations in year-to-year tree growth occur over a broad area. Crossdating enables the dendrochronologist to accurately and precisely determine the dates of formation of all tree rings despite the occurrence of "missing" and "false" rings, or unknown death or cutting dates of dead tree specimens. A "missing" or "locally absent" ring occurs during years when cambial activity is inhibited by stress-inducing events such as extreme climate, *i.e.*, drought (Fritts 1976). During such years, ring formation occurs in only portions of the stem and branches. "False" rings are bands of latewood cells that occur within the earlywood portion of the ring (Fritts 1976). In the southwestern United States, they usually are formed in response to the hot, dry conditions that occur during the middle part of the growing season. In some cases, the morphology of the "false" ring is so similar to that of a "true" ring that without crossdating it would be difficult or impossible to differentiate the two.

A subset of cores and fire-scarred cross-sections were selected for measuring based on a visual assessment of their sensitivity (year-to-year variability in tree-ring width; Fritts 1976) and series length. Specimens that showed high sensitivity were selected; specimens that exhibited periods of growth suppression and surge were avoided. Fire-scarred cross-sections from the sampled snags and logs greatly increased the length of the ring-width chronology. Tree-rings were measured to the nearest 0.01 mm on a sliding stage micrometer interfaced with an IBM personal computer.

Cross-sections were measured along radii distant from decay, fire scars and branches.

3.2.3 Chronology Development

3.2.3.1 Measurement and Dating Verification

Ring-width data for all measured cores and cross-sections were compiled and checked for measurement and dating error using a computer program called COFECHA (Holmes 1983). This program verified the dating and measuring accuracy by computing simple correlations (Pearson r-values) on 50-year segments lagged 25 years between each individual series and a "master dating series" (Holmes 1983). To avoid self-comparison the ring-width series being tested was removed from the master dating series.

Correlations between the segment and the master dating series were made at the dated position as well as at positions shifted forward and backward by ten years. If correlations were not significant at the 95% level at the original dated position, the highest alternative correlation and its corresponding position was reported. Correlation results and other statistical information were listed in the output. Suspected errors were always checked by examining the actual dated material, *i.e.*, the wood specimens. Necessary corrections were made, the new measurements were re-processed by the COFECHA program, and the output was reviewed again for potential problems.

3.2.3.2 Standardization

Generally, tree-ring series show decreasing ring-width and variance with increasing age (Fritts 1976). Relatively larger rings are formed when the tree is younger due to a combination of faster growth rates and smaller diameter bole. This phenomenon is referred to as the age-related growth trend (Fritts 1976). The growth trend observed in a ring-width measurement series makes it meaningless to compare, or average together, measurements of different-aged trees. The process of standardization creates a ring-width index series that is more homogeneous in mean and variance with respect to age (Fritts 1976), and thus, the ring indices can be meaningfully compared and averaged.

I used the computer program ARSTAN (Cook 1985) to standardize measured ring-width series. Each measured tree-ring series was fitted using a 180-year cubic spline (Cook and Peters 1981). Cubic splines of this length are expected to preserve most of the long-term variance having wavelengths less than approximately 100-year length, and virtually all of the intra-decadal and inter-annual variance in the ring series. Ring-width measurements were then converted to ring-width indices by dividing each measurement by the expected value predicted by the curve. Indexed values for each year were then averaged using a robust estimator of the mean to compensate for outliers (Cook 1985; Cook and Holmes 1992). Two mean chronologies were produced.

One was the "standard" chronology and the other was the "residual" chronology. The residual chronology was computed using autoregressive modelling which removed biological persistence, and represents a "white noise" chronology (Cook and Holmes 1992).

3.3 Fire Chronology Development and Analysis

3.3.1 Field Methods

Fire-scarred material was sampled from multiple sites within Fillmore Canyon. Each site was relatively homogeneous with respect to vegetation and topography. Sites were located to obtain a spatial representation of the watershed as extensive as possible; however, site selection was constrained by the distribution of ponderosa pine stands.

Within each site, sampling was conducted to obtain an "inventory" of fire dates that was as long and complete as possible. The "inventory" approach is an intensive search for the best preserved fire-scarred trees with a maximum number of scars distributed as extensively within the study site as possible (Swetnam and Baisan *in press*). This sampling strategy is an efficient way to identify fire dates in forests sustaining fire regimes of high-frequency, low-intensity fires (Baisan and Swetnam 1990; Swetnam 1993; Swetnam and Baisan *in press*). Under these fire regimes, fire-scar formation and preservation is variable. Trees located side-by-side will have many fire dates in common; however, each tree usually also has dates that the other does not (Dieterich 1983; Swetnam and Baisan *in press*). Factors that influence the formation of fire scars include topographic position, fire intensity, previous fire history, and bark thickness; factors that influence the preservation of fire-scarred material include insect boring, rot, weathering, the consumption of old scars by subsequent fires and timber harvesting. Because of this variability in formation and preservation, it is generally not practical, nor efficient, to randomly sample fire-scarred trees in these types of fire regimes.

Both live and dead trees were sampled with a chain saw (Arno and Sneck 1977). Live trees provided a record of fire occurrence in the recent past (during the last 150 years), while dead trees, *i.e.*, downed logs, snags, and stumps, provided an extended record of historical fires (Baisan and Swetnam 1990). Partial cross-sections were taken from live trees and entire cross-sections were taken from dead trees. Dead trees were sampled at multiple heights on the fire-scarred surface to insure a more complete representation of the fires recorded by that tree (Dieterich and Swetnam 1984).

3.3.2 Laboratory Methods

To obtain a high-quality sanded surface, dry samples were re-sectioned with a band saw then sanded with a belt sander using progressively finer grained abrasives (down to 400 grit). Cross-sections (and partial cross-sections) were re-sectioned primarily to make the scar record more visible and to expose buried scars.

Fire scars from each specimen were dated independently based on crossdated ring-width patterns (Stokes and Smiley 1968; Swetnam *et al.* 1985). Injuries were identified as fire scars if they met at least one of the following criteria: (1) charcoal present in the wound; (2) curvilinear growth over the wounded area; and (3) vertical lines on the scar face representing subsequent growth of the tree over the edge of the injured region (Stokes 1980). In most cases it was possible to determine the exact calendrical year of scar formation. Exceptions included instances when extremely reduced growth around the area of the scar prevented accurate dating, and when subsequent fires had burned deeply into previous scars.

The seasonal timing of fires was inferred by noting the position of scars within rings relative to the earlywood and latewood. Scar-position data were interpreted based on our knowledge of cambial phenology in the Southwest (Fritts 1976; Dieterich and Swetnam 1984; Baisan and Swetnam 1994). Based on this knowledge, it was assumed that tree growth in the Organ Mountains, at the elevation we sampled, generally began in mid- to late April and ended in late September to early October. The designated seasons for each scar position overlap to account for differences in growth initiation from year to year as well as possible fluctuations in rate of growth within a growing season.

The following scar-position categories were used:

1) Dormant (D). This scar is positioned at the boundary between two rings. The fire that creates a dormant-season scar occurs after one growing season and before another, *i.e.*, sometime between fall and spring. In the northern hemisphere this period spans two calendar years. I dated the scar to the adjacent earlywood cells formed following the scar, based on the tendency of fires to occur in spring rather than fall in the Southwest (Barrows 1978; Dieterich and Swetnam 1984; Baisan and Swetnam 1990).

2) Early Early (EE). This scar is positioned in the first one-third of the earlywood. These fires were interpreted to have occurred between approximately mid-April and mid-June.

3) Middle Early (ME). This scar is positioned in the second one-third of the earlywood. These fires were interpreted to have occurred between approximately early June and late July.

4) Late Early (LE). This scar is positioned in the last one-third of the earlywood. These fires were interpreted to have occurred between approximately early July and mid-August.

5) Latewood (LA). This scar is positioned in the latewood.

These fires were interpreted to have occurred between approximately early August and early October.

6) <u>Unknown (U)</u>. The position of this scar is indeterminable. Although it was possible to determine the ring in which the scar occurred, it was impossible to assign a position to it. Usually, this was due to highly suppressed growth in the region of the scar.

Fire-scar data were entered using the computer program, FHX2 (Grissino-Mayer 1995). Data consisted of specimen identification number, date of inner-most ring, date of outer-most ring, the dates of all fire scars and unspecified injuries and their corresponding position within the ring. The FHX2 program was used to compile the fire-scar data and compute descriptive statistics. The same program was also used to plot "master fire chronology charts," which are graphic representations of temporal and spatial patterns of fire occurrence (Dieterich 1980).

3.3.3 Analysis

3.3.3.1 Period of Reliability

Fire-scar data provide much information regarding historical fire occurrence. However, degradation of information occurs due to loss of fire scars to subsequent fires, weathering, decay and logging. Consequently, fire-scar data are characterized by a fading record with increasing time before present. It is important to recognize that the completeness of the information transmitted through the fire-scar record is temporally variable. Hence, sample size, *i.e.*, the number of trees sampled, plays an important role in modifying the amount of information transmitted by fire-scarred material.

The influence of sample size on the interpretation of fire occurrence patterns has been recognized and addressed in previous studies (Baisan and Swetnam 1990; Swetnam 1993; Touchan and Swetnam 1995; Grissino-Mayer *et al.* 1994). This study applies a new method to identify the relation between sample size and the probability of detecting certain fire occurrence patterns.

This method is based on the premise that, if other factors are maintained more-or-less constant, the detection of smaller fires is primarily related to sample size (Swetnam 1992). Specifically, a more dense sampling network, or greater number of samples, is required to detect smaller fires. The "other factors" that should remain constant include: (1) sample area size and (2) high sensitivity to fire-scarring. Keeping sample area size constant removes the confounding effect of area on fire frequency estimations (see Arno and Peterson 1983). Maintaining a high sensitivity to fire scarring means that differences in fire intensity will not affect fire frequency estimation, *i.e.*, even the lowest intensity fires must be detected.

The completeness of the record of smaller fires changes over time because sample size typically changes over time. For example, older portions of the fire history are represented by fewer trees since there is less older fire-scarred material. More recent portions of the fire history may also have less trees due to restrictions on the numbers of live trees that can be sampled and decay of the outer portions of dead trees sampled. Thus, the representation of a high frequency, patchy fire regime may be compromised in the early and late portions of the fire history.

The high fire frequencies observed in the Fillmore Canyon fire history indicated that patchy fires were an important component of historical fire regimes. Therefore, it was necessary to estimate the minimum number of samples required to detect these high-frequency, patchy fire regimes, making it possible to evaluate whether changes in fire frequency were due to actual changes in historical fire occurrence patterns and not merely to changes in sample size. To address this problem, I used a computational method to determine the minimum number of samples needed to record the highest fire frequency observed in the Fillmore Canyon fire chronology. The computed minimum sample size was then used to define a period when there were enough samples to reconstruct a patchy fire regime if it existed. I called this period, the "Period of Reliability" after Touchan and Swetnam (1995) although their estimation of this period was different and largely subjective. The following is a description of the method I used to compute the Period of Reliability (hereafter referred to as "PR").

1) *Select the Reference Period*

Minimum sample size was identified as the minimum number of samples that could record the highest fire frequency observed in the fire history. Therefore, the period of highest fire frequency (lowest mean fire interval) was used as the reference period. The highest fire frequency in the Fillmore Canyon fire history occurred between 1723 and 1772 (this period corresponds to the maximum 50-yr fire frequency plotted in Figure 2). During this period, the MFI was 1.4 years.

2) *Compute Probability Intervals*

I then used the computer program, "Sample Size" (SSIZ) (Holmes and Swetnam 1994) to compute fire frequencies and their corresponding sampling distributions at decreasing sample sizes during the reference period. First, SSIZ computed the fire frequency for all trees in the sample set (n=90) during the reference period. Then, fire frequencies were re-computed at sample sizes sequentially reduced by an increment of one sample tree (randomly selected) until sample size was equal to one. At each step, 1000 random simulations were conducted. Based on the sampling distribution created by the computer simulations, theoretical limits were computed that contained 99% of the re-computed MFIs for each possible sample size from n to 1.

3) *Select Minimum Sample Size*

The minimum sample size was the lowest sample size that included the fire frequency of the reference period (1723 to 1772; Figure 3) within the 99% probability intervals. In this case, the minimum number of samples was 35; for this number of samples the mean MFI was 1.7 years with upper and lower limits of 2.8 and 1.4 years, respectively.

4) *Define Period of Reliability*

The beginning of the PR was set at the first year in which the number of trees reached the minimum sample size set by the reference period; the end of the PR was set at the last year before the number of trees dropped below the minimum required sample size. A tree was counted only after it had sustained its first fire scar. Thus, the PR for the Fillmore Canyon fire history was defined as 1650 to 1858. In addition to defining the PR for Fillmore Canyon (pooled data set), PR's were defined for each site to evaluate its temporal representation.

3.3.3.2 Characterization of Historical Fire Occurrence

Fire-interval data were comprised of three groups: (1) sites, (2) watershed (all sites pooled), and (3) fires categorized by size. Relative fire size was estimated by the percentage of sites recording a fire. Small fires included all fires that were recorded by up to 33% of the sites; generally, one to three sites. Medium fires included all fires that were recorded by 34% to 67% of the sites; generally, four to six sites. Large fires included all fires that were recorded in more than 67% of the sites; generally, seven or more sites.

Fire-interval data were analyzed using both qualitative and quantitative methods. Data were illustrated with fire history charts, plots, and bar graphs. A visual assessment of the data facilitated the identification and characterization of fire occurrence patterns. Descriptive statistics were also computed to characterize fire-interval data within the PR, 1650 to 1858.

Spatial patterns were evaluated by comparing the fire-interval data from among sites for a common period (*i.e.*, the PR); in other words, by varying space while keeping time constant. Likewise, temporal patterns were evaluated by comparing fire-interval data among different periods for a common area, *i.e.*, by varying time but keeping space constant.

3.3.3.2.1 Descriptive Statistics

Descriptive statistics were computed for all fire-interval distributions. The shape of the distribution was described by range, skewness, kurtosis, and standard deviation. The coefficient of variation was also computed so that variance could be compared between distributions.

Central tendency was represented by two measures, the mean fire interval (MFI) and the median fire interval (MedFI) to account for the variability of fire-interval distribution shapes. MFI is the arithmetic mean of all fire intervals (Romme 1980) and is an adequate measure of central tendency when the fire-interval distribution is relatively symmetric, *i.e.*, low skewness. For distributions that are asymmetric, the MedFI is a more representative measure of central tendency. The MedFI is the middle value of a ranked list of fire intervals, having an equal number of intervals before and after it.

3.3.3.2.2 Modeling Fire-Interval Distributions

Fire-interval distributions were compared to two distributions, the empirical (an approximation of the normal distribution) and the Weibull, using the Kolgomorov-Smirnov test (Sokal and Rohlf 1981). Distributions were compared to the empirical distribution because some statistical tests are more robust when the data are normally distributed. require that the data are normally distributed. Distributions were compared to the Weibull distribution because the parameters that describe this distribution can improve the characterization of fire-interval data (Johnson 1978; Baker 1989).

The Weibull distribution is a flexible distribution that fits skewed data well (Johnson and Kotz 1970; Bailey and Dell 1973). Fire-interval data are often skewed because it has a lower limit of one year but no upper limit (Baker 1992; Grissino-Mayer *et al.* 1994). The Weibull distribution is described by shape and scale parameters which can provide a more precise characterization of fire-interval distributions. Furthermore, because the Weibull distribution generally provides a better fit to fire-interval distributions than the normal distribution, the WMPI (Weibull Median Probability Interval) can be a better representation of central tendency than the MFI (Grissino-Mayer 1995). The WMPI is equivalent to the interval, in years, at which there is a 50% exceedance probability based on the Weibull probability density curve.

Modelling fire-interval distributions using the Weibull distribution was accomplished using FHX2 (Grissino-Mayer 1995). The fitted Weibull distribution was then compared to the data using the Kolmogorov-Smirnov test. For good fits of the Weibull distribution to the data (prob>d=.95), Weibull shape and scale parameters were reported. WMPIs were reported for all fire-interval distributions.

3.3.3.2.3 Spatial Patterns

I evaluated spatial patterns of fire within Fillmore Canyon by comparing fire-interval distributions and MFIs among sites. I employed the G-test (Sokal and Rohlf 1981) in this analysis. In comparing MFIs among sites, I used random simulations to account for differences in sample size.

Comparison of Fire-Interval Distributions Among Sites

The G-test simultaneously tests multiple frequency distributions with the null hypothesis that the set of distributions tested are not significantly different from each other. The G-test has the ability to determine which subsets of distributions are not significantly different from each other if the entire set of distributions are found to be significantly different from each other. Thus, by using the G-test, I was able to identify groups of sites that have similar fire-interval distributions. When these groups are tested, the critical value for determining significance at the α level is computed using $\chi^2_{\alpha[(a-1)(b-1)]}$, where *a* is the number of fire-interval categories and *b* is the number of distributions. Groups of distributions that yield a G_H-statistic (Sokal and Rohlf 1981:722-723) below the critical value are considered similar to each other, while subsets of distributions that yield a G_H-statistic above the critical value are considered different from each other.

For site data, fire-interval distributions were combined to examine spatially explicit patterns of fire occurrence. The base group consisted of either the two western-most or eastern-most sites (two rounds of G-testing were conducted). Then, fire-interval data from the next closest site were added. For example, starting from the west, the SSD and RKH sites were compared, then the SSD, RKH and OPW sites were compared, then the SSD, RKH, OPW and SCI sites were compared, and so on. The G_H-statistic was computed at each step and compared to the critical value. I added site data until a significant value was obtained.

Differences in MFIs Among Sites

Due to the suspected tendency of larger numbers of samples to have a more complete record of fire occurrence, differences in sample size among sites may introduce a component of heterogeneity among fire-interval data that could not be attributed to location. To simultaneously compare MFIs among sites while accounting for differences in sample sizes, I used the program SSIZ (see Section 3.3.3.1, part 2). MFIs, and their corresponding probability intervals, were plotted against number of samples for the site with the largest sample size (Swetnam 1992). Comparisons were made by positioning observed MFIs from other sites on the MFI curve according to their sample size.

3.3.3.2.4 Temporal Patterns

To evaluate changes in fire frequency, I plotted the cumulative proportion of fire events over time. In this type of graphic, possible changes in fire frequency are represented by changes in slope (Ahlstrand 1980; Johnson 1992). I determined possible inflection points based on a visual assessment of the curve.

MFIs during periods of constant slope were statistically compared. Because most fire-interval distributions were not normally distributed and not directly comparable, statistical comparisons of MFIs were conducted after fire-interval data were power transformed (see Grissino-Mayer 1995). Sequential periods were then compared using the t-test (Sokal and Rohlf 1981). Changes in magnitude over time were assessed only for large fires within the PR (1650 to 1858).

3.3.3.3 Fire-Climate Associations

3.3.3.3.1 Climate and Tree Growth

Historical climate records were not long enough to compare with fire history data. Therefore, I reconstructed climate by first establishing a relation between tree growth and climate. This relation was investigated by cross-correlating ring-width indices with New Mexico NOAA Climate Division Eight monthly precipitation and temperature over the period 1896 to 1991. Divisional climate data were selected over single-site data because preliminary analyses revealed a better relation to tree growth (Fritts 1976; Grissino-Mayer *in press*). Because tree growth is an integrated response to climatic conditions over a period that exceeds one month (Fritts 1976), I compared ring-width indices to seasonalized values in addition to single-month climate data.

The season with the best correlation to ring-width indices was reconstructed. I used half-sample subsets to calibrate and verify the tree-growth/climate relation. For calibration, I used regression analysis to develop a linear model for each subset. Outliers were extracted, one by one, to refine model parameters. Outliers were selected based on Studentized residuals and Cook's d (Grissino-Mayer 1995). Predicted values generated by the final models for each half-sample subset were then verified using actual data from the other subset. In this case, predicted values from the model developed for the period 1896 to 1943 were statistically tested against actual values from the period 1944 to 1991 and vice versa. Verification statistics included Pearson correlation coefficients, reduction of error, product means and signs test (Fritts 1976; Fritts 1991; Rose *et al.* 1981; D'Arrigo and Jacoby 1992; Grissino-Mayer *in press*). A model calibrated over the entire period was used to create the most robust reconstruction of the climatic variable (D'Arrigo and Jacoby 1992; Grissino-Mayer *in press*).

3.3.3.3.2 Climate and Fire

Using reconstructed climate, the relation between climate and fire occurrence was evaluated using superposed epoch analysis, or SEA (Swetnam and Betancourt 1992; Swetnam

1993; Swetnam and Baisan *in press*; Touchan *et al. in press*). Fire dates were superposed onto the times series of reconstructed precipitation. A five-year event window was analyzed, including the fire year plus four prior years. Previous analyses of southwestern fire histories show that antecedent conditions of up to three lagged years are usually sufficient to capture significant climate patterns affecting fire occurrence (Baisan and Swetnam 1990; Swetnam and Betancourt 1990; Swetnam and Baisan *in press*; Touchan *et al. in press*).

The statistical significance of the observed fire-climate relations was evaluated by comparing actual data to simulated data and their probability intervals. For each set of actual fire dates, mean reconstructed precipitation and 95% confidence intervals for each year in the event window were computed. These values were compared to means and probability intervals estimated by randomly re-sampling the data (Mooney and Duvall 1993; Swetnam 1993). A set of "n" years, whereby "n" corresponded to the number of fire years in the actual data set, were randomly selected and treated as "event" years. The average value for each year in the event window was computed. Based on 1000 simulations, means and probability intervals of the sampling distributions for each year in the event window were computed. These were compared to actual data to evaluate the probability of observed patterns occurring by chance.

The relation between climate and fire size was also examined by analyzing fire-climate relations for sets of fire years categorized by size using SEA. In addition to the ten large fires recorded during the PR, two fires occurring before 1650 were also analyzed to evaluate climate-fire relations. The 1557 fire was recorded in seven out of seven sites, while the 1632 fire was recorded in seven out of eight sites. No additional small nor medium fires outside of the PR were analyzed.

4. Results

4.1 Site Fire Histories

4.1.1 Summaries

The fire history of Fillmore Canyon was reconstructed based on 90 fire-scarred trees from 10 sites distributed throughout the watershed. I dated a total of 937 scars which yielded 158 fire dates. The Fillmore Canyon fire history spanned 647 years, from 1347 to 1993. The fire histories of each site were variable in length, age, sample size and number of fires recorded (Table 3). Lengths of individual chronologies ranged from 299 to 531 years ($\bar{x}$=431 years). All sites except one, OPB, had fire records extending into the twentieth century (Figure 4). In general, sites in the upper (OPB and SSD) and lower (FSR, LDG and LOF) parts of the canyon yielded longer fire chronologies relative to sites in the middle portion of the canyon (Figure 4). The number of fire years recorded in each site ranged from 21 to 80.

Approximately one-third (36 out of 110) of the fires recorded in Fillmore Canyon during the PR, 1650 to 1858, occurred in only one site. The majority of "single-site" fires were recorded on only one tree (25 out of 36 fires). The site OPW had the most unique fire dates (n=12), while LOF and OPB had the least (n=0 for both) (Figure 5).

Table 3. Summary of fire-scar information for each site. Fire history length was determined by using the date of the first fire recorded in the site as the first year and outer date as the last year.

Site Name	Inner Date	Outer Date	First Scar Date	Fire History Length (yrs)	Number of Trees	Number of Scars	Number of Fire Yrs
OPB	1312	1836	1347	490	4	27	21
SSD	1509	1992	1557	436	4	36	25
RKH	1449	1993	1463	531	8	84	51
OPW	1550	1993	1625	368	27	356	80
NAR	1608	1992	1656	337	8	67	39
SCI	1595	1992	1694	299	7	77	37
FST	1491	1935	1497	445	10	125	58
FSR	1490	1984	1532	495	7	51	29
LDG	1496	1992	1547	446	7	56	37
LOF	1500	1993	1532	462	8	58	34
				431[1]	90[2]	937[2]	41[1]

1. Average
2. Total

4.1.2 Descriptive Statistics

Periods of reliability calculated for individual sites corresponded, in most cases, to the PR of Fillmore Canyon (1650 to 1858) (Table 4). Three exceptions were OPB, SCI and FSR. A separate PR was not calculated for OPB because the maximum sample size was less than 2 trees for most of the period between 1650 and 1858 (see Appendix 1). The sites SCI and FSR were not well-represented during the early portion of the Fillmore Canyon PR. SCI had no trees

Table 4. Descriptive statistics of fire-interval data for each site. Descriptive statistics for each site were computed within the PR, *i.e.*, fire dates between 1650 and 1858. Sites are ordered from upper canyon (OPB) to lower canyon (LOF). Kolmogorov-Smirnov results are also shown for comparisons of fire-interval distributions to the empirical ("e") and Weibull ("W") distributions. A superior fit is indicated by higher prob>d. "All" refers to the pooled data for all sites, *i.e.*, Fillmore Canyon. "MFI" is Mean Fire Interval; "MedFI" is Median Fire Interval; "WMPI" is Weibull Median Probability Interval; "Std Dev" is standard deviation and "CV" is coefficient of variation.

Site	PR		Intervals					prob>d					Std	
Name	**Beg**	**End**	**Tot**	**Min**	**Max**	**Skew**	**Kurt**	**e**	**W**	**MFI**	**MedFI**	**WMPI**	**Dev**	**CV**
All	1650	1858	109	1	6	1.53	1.96	n/a[1]	.00	1.9	2.0	2.8	1.2	.62
OPB	-	-	8	6	27	1.03	-0.64	.20	.32	12.0	10.0	11.3	7.8	.65
SSD	1632	1992	22	1	9	0.19	-1.12	.69	1.00[2]	5.0	5.0	4.7	2.6	.52
RKH	1662	1860	39	1	13	0.49	-0.61	.03	.74	5.2	4.0	4.7	3.1	.60
OPW	1650	1846	72	1	10	1.49	2.89	.00	.00	2.8	2.0	2.6	1.8	.64
NAR	1656	1890	32	1	24	1.63	1.79	.00	.15	6.0	3.0	3.9	6.0	1.00
SCI	1726	1870	33	1	19	2.10	3.52	.00	.12	4.7	3.0	4.6	4.4	.94
FST	1632	1860	46	1	19	2.40	8.05	.00	.50	4.5	4.0	4.2	3.1	.70
FSR	1745	1849	24	1	29	1.52	2.33	.00	.52	8.1	6.5	6.9	6.5	.80
LDG	1632	1951	21	1	27	0.72	0.05	.04	.81	9.6	10.0	8.2	6.7	.70
LOF	1678	1902	28	1	19	0.74	-0.27	.07	.83	7.2	6.0	6.4	4.8	.67

1. Distribution cannot be modelled.
2. Weibull parameters: b=5.62, c=1.98.

recording fires in the late 1600s, while the sample size for FSR was 3 trees (see Appendix 1).

All fire-interval distributions showed varying degrees of positive skewness (Table 4, Figure 6). Fire-interval distributions were both platykurtic, or flat, (kurt<0) and leptokurtic, or peaked, (kurt>0). Generally, distributions tended to be either somewhat flat or fairly peaked. Kolmogorov-Smirnov tests showed that fire-interval distributions from all sites did not approximate the normal distribution (*i.e.*, unable to be modelled with an empirical distribution) and all but one were different from the Weibull (prob>d=.95; Table 4). The WMPI was always less than the MFI (Table 4). Differences between the MFI and WMPI ranged from 0.2 years to 1.4 years.

MFIs and the MedFIs were variable among sites. Higher values of central tendencies (less frequent fires) were observed in the lower canyon while lower central tendencies (more frequent fires) were observed in the upper and middle canyon (Table 4), suggesting that fire was not evenly distributed throughout the canyon over time.

4.1.3 Spatial patterns

A simultaneous comparison of fire-interval distributions for all sites using the G-test showed heterogeneity (p<.001). However, comparing fire-interval distributions of groups of sites indicated distinct spatial patterns of fire occurrence. Sites in the (1) upper and middle canyon and (2) lower and middle canyon had fire-interval distributions that were homogeneous, *i.e.*, similarly shaped (Figure 7). These results may indicate that the middle portion of the canyon tended to act a a source area for fire ignition.

The highest fire frequencies were recorded in the site OPW (Table 4). However, OPW is also the site with the largest sample size (Table 3). When MFIs were recomputed at reduced sample sizes for OPW and compared to all other sites, results showed that fire frequencies recorded in OPW were more similar to upper than lower canyon sites; however, even among upper canyon sites, except SSD, OPW exhibited the highest fire frequencies (Figure 8).

4.2 Fillmore Canyon Fire History

4.2.1 Overall Fire Frequency

Based on the cumulative proportion of all fire events recorded in Fillmore Canyon, two changes were evident: the first at *ca*. 1720 and the second at *ca*. 1805 (Figure 9). These changes demarcate three periods of temporally distinct fire frequencies: (1) between 1650 and 1720, the MFI was 2.1

years (MedFI=2.0 years); (2) between 1720 and 1805, the MFI was 1.5 years (MedFI=1.0 years); and (3) between 1805 and 1858, the MFI was 3.1 years (MedFI=2.0 years). When sequential periods were compared, transformed MFIs were different ($p<.01$) for both the early/middle and middle/late comparisons. The same pairwise comparisons of fire-interval distributions were also found to be different ($p<.05$) using the Kolmogorov-Smirnov test.

4.2.2 Fire Size and Fire Frequency

Fire frequency and relative size were inversely related (Table 5). The difference in fire frequency between small (<33% sites recording the fire) and medium fires (34-67% recording the fire) and medium and large fires (>67% sites recording the fire) suggested that the inverse relation between fire size and fire frequency was non-linear (Table 5). Similar patterns have been observed in fire history studies conducted in giant sequoia groves in California (Swetnam 1993). More data, however, would be necessary to evaluate this relation. G-test results between fire-interval distributions (Figure 10) of small and medium fires show heterogeneity ($p<.001$). No comparisons were made to fire-interval data of large fires due to low sample size (n=10).

Table 5. Descriptive statistics of fire-interval data for Small, Medium and Large fires within the PR, *i.e*, 1650 to 1858.

	Tot	Int Min	Int Max	S	K	prob>d e	prob>d W	MFI	Med FI	WMPI	Std Dev	CV
S	75	1	11	1.65	3.16	.00	.00	2.7	2.0	2.5	1.99	0.73
M	24	1	49	2.98	9.16	.00	.14	8.2	5.0	6.3	10.00	1.22
L	8	5	59	0.97	-0.63	.17	.60	24.4	18.0	21.8	18.10	0.74

The frequency of small, medium and large fires was variable over time. Small fires exhibited the least variability (Figure 11). Although minor fluctuations occurred over time, including a possible decrease *ca.* 1805, fire frequency remained relatively constant. Medium fires exhibited relatively high variability within the PR. One remarkable feature was that only one medium size fire was recorded after *ca.* 1805 (Figures 11&12). Before *ca.* 1805, two fluctuations in fire frequency can be observed. The first occurs during the first quarter of the 1700s (1703-1723); the second occurs during the third quarter of the 1700s (1752-1778; Figure 11). The timing of both of these changes corresponds to the occurrence of large fires (Figure 12). Finally, large fires exhibited a fire frequency that appeared to gradually increase over time (Figure 11).

4.2.3 Seasonality

I determined scar position for 814 (86.9%) scars. The most common scar position was the dormant season ("D") at 34.8% (Figure 13). Dormant-season scars and scars in the early portion of the earlywood ("EE") combined to account for over 60% of the scar position designations. Only 18 fires did not include scars in either the dormant or early-earlywood positions, and all of these were relatively small fires scarring from 1 to 5 trees ($\bar{x}$=2.1). Only during one fire year, 1557, were no dormant or early-earlywood position scars found for a fire that was not small. The 1557 fire was recorded on eight trees, representing seven sites; seven of these scars were designated as late-earlywood ("LE"), while one was designated as latewood ("La"; Figure 14).

Scar position designation for large fires tended to range from dormant season to late-earlywood and sometimes latewood (Figure 14). Two apparent modes of scar-position distribution were observed for large fires: (1) early season, consisting primarily of dormant season and early-earlywood scars (Figure 14, right column) and (2) middle season, consisting primarily of middle-earlywood ("ME") and late-earlywood scars (Figure 14, left column). This variation in scar position among large fires suggests that conditions favorable to widespread fires may occur at multiple times during the growing season.

4.2.4 Climate-Fire Association

4.2.4.1 Tree Growth-Climate Relation

Correlation analyses between climate variables and ring-width indices indicated a stronger influence of precipitation than temperature on tree growth (Table 6). Results showed statistically significant correlations between ring-width indices and monthly precipitation, indicating a positive response of tree growth to precipitation that lasted over several months from the previous year's fall to the current year's spring (Table 6). Tree growth was negatively correlated with temperature especially during the spring and summer of the current year (Table 6). Precipitation data were then seasonalized using the results from the correlation analysis of individual months to ring-width indices as a guide. The period beginning in previous September (September prior to growth initiation) and ending in July (of the current growing season) yielded the highest correlation ($r=0.65$, $p<.001$) with ring-width indices. Using previous-September-to-July precipitation as the predictand in a regression model, 38.4% (r^2 adjusted for loss of degrees of freedom) of the variability was initially explained by ring-width indices during the period, 1897 to 1991.

Table 6. Correlation coefficients (Pearson r) between ring-width indices (standard and residual chronologies) and monthly climate variables from New Mexico Division 08, 1896 to 1991. "p" before monthly variables indicate months during the previous year.

	Precipitation		**Temperature**	
	Standard	**Residual**	**Standard**	**Residual**
pSept	0.25*	0.23*	-0.24*	-0.19
pOct	0.27**	0.26*	-0.27**	-0.22*
pNov	0.35**	0.26*	-0.07	-0.12
pDec	0.36**	0.28**	0.04	0.01
Jan	0.14	0.13	-0.06	-0.12
Feb	0.32**	0.36**	0.017	0.06
Mar	0.16	0.19	-0.14	-0.19
Apr	0.33**	0.30**	-0.25*	-0.27**
May	0.19	0.19	-0.21*	-0.16
Jun	0.38**	0.42**	-0.33**	-0.30**
Jul	0.13	0.10	-0.32**	-0.30**
Aug	0.05	0.01	-0.14	-0.10
Sept	0.20*	0.22*	-0.20	-0.14
Oct	0.02	0.00	-0.20*	-0.17
Nov	0.22*	0.16	0.06	0.02
Dec	0.25*	0.20	0.06	0.07

* p<.05
** p<.01

4.2.4.2 Climate Reconstruction

Final calibration models showed that tree growth explained 53% and 58% of the variance in precipitation in the early and late calibration periods, respectively (Table 7). To statistically verify the regression between tree growth and precipitation, each model was used to predict precipitation during the period withheld from calibration.

Table 7. Regression models and calibration statistics.

Period	Param. Est.	Const.	F	prob>F	adj r^2	Outliers Removed
1896-1943	3.67	4.75	50.05	0.0001	0.53	1903,1904,1913 1915
1944-1991	4.08	4.81	63.45	0.0001	0.58	1973,1982
1896-1991	3.84	4.81	128.69	0.0001	0.60	1903,1904,1908 1913,1915,1922 1973,1979,1982 1986

Table 8. Verification Statistics. r=Pearson r; RE=reduction of error statistic. All values are statistically significant (p<.05).

Period		r	RE	Product-Means Test	Signs Test
Calibration	Verification				
1896-1943	1944-1991	0.72	0.51	7.10	11
1944-1991	1896-1943	0.59	0.23	5.25	14

All verification tests were significant (Table 8). Based on the strength of these regressions, a model was developed over the entire period, 1897 to 1991 (Figure 15). In the final model, 60% of the variability in previous-September-to-current-July precipitation was explained by ring-width indices during the period 1897 to 1991 (Table 8). Ring-width indices tended to track year-to-year changes in precipitation adequately; however, sometimes the magnitude of change was underestimated, especially for relatively large increases (Figure 16). Outliers deleted in the final models were generally cases when year-to-year changes were not tracked, *i.e*, changes in ring-width were opposite to changes in precipitation.

4.2.4.3 Climate-Fire Patterns

No obvious precipitation patterns were associated with small and medium fires (Figure 17a&b). In contrast, large fires tended to occur during drier-than-average years (Figure 17c). Interestingly, wet antecedent conditions did not consistently occur for all large fires as had previously been observed by Baisan and Swetnam (1990) and Swetnam and Baisan (*in press*). However, for individual large fire years, wet years more often preceded fires in the late 1700s and early 1800s (Table 9).

For large fires, scar position appeared to be related to precipitation during the year of the fire. Large fires occurred during years of either average or below average precipitation; no large fires occurred in years when reconstructed precipitation was above average (Table 9). Large fires that occurred during years having average precipitation tended to be characterized by a predominance of middle-earlywood position scars (Figure 14, left column). Large-fire years that occurred during below-average

Table 9. Event window for each large fire. Symbols represent reconstructed precipitation for years within the event window.

Event Year	lag4	lag3	lag2	lag1	Fire Year	Post FY
1557	++[3]	<[2]	..[1]	..	..	..
1632	..	++	..	<<	<<	<<
1656	..	..	..	..	<	<<
1715	..	..	..	..	..	<<
1760	..	<<	..	..	<<	<<
1765	<<	..	<<	++	..	+
1786	<<	++	++	..	<	+
1802	..	++	<	+	..	..
1819	++	++	..	<<	<<	<<
1838	..	++	..	..	..	+
1851	<	..	++	..	<<	..

1. ".." represent nonsignificant values.
2. "<" and "+" are 95% percentile rank confidence limits; "<" is below average, "+" is above average.
3. "<<" and "++" are 99% percentile rank confidence limits.

precipitation years tended to be characterized by predominantly dormant season scars (Figure 14, right column).

5. Discussion

The results from this study show that, in the past, fire was prevalent in Fillmore Canyon. One of the more remarkable features of the Fillmore Canyon fire history is its low MFI, *i.e.*, high fire frequency. During the PR, between 1650 to 1858, the MFI for all fires was 1.9 years (MedfI was 2.0 years), making it among the lowest of all fire history studies conducted in the Southwestern United States (Swetnam and Baisan *in press*).

The presence of fire in Fillmore Canyon is not nearly as interesting as its variability over time and space. The purpose of this section is to discuss, interpret and, ultimately, better understand how this variability arose. To this end, this section is divided into three parts. Part One pertains to the spatial distribution of fires within the canyon. I discuss topographic features that may have influenced fire spread of fire within Fillmore Canyon. Part Two pertains to the relation between fire occurrence and climate. I discuss the inferred role of climate, specifically precipitation, on fire occurrence. And, Part Three pertains to changes in fire regimes over time. I discuss the possible roles of humans and climate in maintaining and changing patterns in fire occurrence.

5.1 The Distribution of Fire Within Fillmore Canyon

Results show that fire was distributed unevenly within

Fillmore Canyon. Higher fire frequencies and a greater number of unique fire dates in the upper and middle canyon relative to the lower canyon suggest that fires often originated in the upper and middle canyon. The presence of Organ Peak in this area is a possible factor contributing to these higher fire frequencies because large, exposed topographic features may tend to attract lightning strikes resulting in more successful fire ignitions in these areas (Baisan and Swetnam 1990; Bergeron 1991). For example, a recent fire in the Organ Mountains (summer 1994) apparently originated on the west slope of Organ Peak (BLM).

Among the lower-canyon sites, LDG had the highest fire intervals (lowest fire frequency). Its size and topographic position are possible factors contributing to this observed pattern. Because it is a small target for lightning strikes, the probability of fire starting locally due to lightning strikes is low. Meanwhile, fire spread is limited to a narrow grassy corridor that approaches the LDG site from the east; to the north, south and west, LDG is bounded by rocky cliffs.

The topographic position of LDG provides a unique opportunity to infer general patterns of fire behavior in Fillmore Canyon. Examination of LDG fire dates, as well as fire dates from adjacent sites, suggest that fire spread was a more prevalent source of fire than local ignition. During the PR, 22 fires were recorded in the LDG site. Only 2 of these were unique with respect to the whole watershed; 16 were in common with adjacent sites, FST and FSR; and 4 were recorded in other sites in the canyon but not FST and FSR. The distribution of fire dates in common with each of the adjacent sites suggest that fire spread more often from FST, the upper canyon site, than FSR, the lower canyon site. Fires that were recorded in LDG and other sites but not adjacent sites could represent separate ignitions; alternatively, this pattern could reflect the spatial variability in fire intensity or patchiness within individual burns.

5.2 Precipitation-Fire Association

The comparison of fire and reconstructed precipitation yielded unexpected results considering the vegetation and semi-arid climate of the Organ Mountains. First, no evidence was found that indicated a strong association between wet antecedent conditions and widespread fires. Generally, systems where fire occurrence is based on fine fuel dynamics, *i.e.*, ponderosa pine forest where grasses play an important role, show significant associations between wet antecedent conditions and large area burnt (Rogers and Vint 1987; Baisan and Swetnam 1990; Knapp 1995; Swetnam and Baisan *in press*). It is hypothesized that in these systems, fuel amount and continuity can be limiting factors to the occurrence of fire. A period of above-average rainfall which stimulates grass growth, may subsequently lead to greater landscape connectivity, enabling the occurrence of larger fires.

A second unexpected result was the significant association found between drier-than-average years and widespread fires. Generally, this type of association is not observed in drier sites where fire occurrence tends to be based on fine fuel dynamics, but rather in more mesic systems such as mixed-conifer forest (Swetnam 1993; Swetnam and Baisan *in press*). In these systems, fuel amount and continuity do not tend to limit fire occurrence because higher moisture levels yield higher fuel accumulation rates. However, higher moisture levels also result in higher fuel moisture content which tends to be the limiting factor to fire occurrence (Harrington 1981). Drier-than-average conditions decrease fuel moisture to levels optimal for fire ignition and spread.

5.2.1 Why No Wet Antecedent Conditions?

Both climate- and human-based hypotheses can be invoked to explain the apparent lack of a strong association between wet antecedent conditions and widespread fire. In a climate-based hypothesis, widespread fires may be related to the potential importance of summer precipitation. A study by Knapp (1995) in the Great Basin showed that summer precipitation during prior years was significantly correlated with the occurrence of widespread fires, suggesting that, for some vegetation types, summer precipitation can play an important role in fuel accumulation rates. Many grass species found in semi-arid regions tend to show a strong growth response to summer (July-September) precipitation (Kemp 1983; McClaran 1995). Hence, high landscape connectivity would occur during years having favorable summer rains, thus increasing the possibility of a widespread fire during subsequent years. In this study, summer precipitation (July to September) was not reconstructed so it is not possible to evaluate the association between summer precipitation and fire occurrence.

An alternative hypothesis is that the lack of a strong association between wetter-than-average years and widespread fires may have been related to the use of fire by Apaches. Apache use-of-fire may have interrupted climate-induced cycles of fuel accumulation, masking the detection of any climate-based mechanisms that were possibly operating. If Apaches were burning the landscape for their own reasons unrelated to climatic variation, one might expect the occurrence of fires in "unlikely" (from a climate perspective) years, and the absence of fires in "likely" years. For example, landscapes with sub-optimal levels of fuel moisture content (*i.e.*, higher than average) during certain years could have been forcibly burned by Apaches.

Such human-altered landscapes would subsequently lack the necessary fuel continuity for the occurrence of widespread fire during years when extensive fires would have otherwise burned.

The Fillmore Canyon fire history contains what might be considered some "anomalous" fire years. Regional studies of fire occurrence have identified specific years when fires occurred throughout the Southwest (Swetnam 1990). One widely recorded fire year in the Southwest was 1748 (Swetnam 1990; Swetnam and Betancourt 1990). Interestingly, while 1748 was one of the driest years in the Southwest in the past 300 years, 1747 was one of the wettest; in fact, the change in ring-width (and therefore reconstructed precipitation or drought indices) between 1747 and 1748 is the single greatest difference observed in the Southwest (Fritts 1991). This pattern is also reflected in the Fillmore Canyon tree-ring chronology. It is likely that this particular sequence of extreme climatic events affected fuels, fire ignition, and spread patterns, and thereby resulted in the occurrence of widespread fires throughout Southwestern landscapes in 1748.

In Fillmore Canyon, although fire did occur in 1748, it was Small (*i.e.*, recorded in 3 sites). Meanwhile, in 1747, a Medium fire occurred (*i.e.*, recorded in 5 sites). Under an Apache hypothesis, this pattern can be interpreted as a human-ignited fire in the wet 1747 year disrupting fuel continuity and preventing the occurrence of a widespread fire in the dry 1748 year. Hence, the relatively large area affected by the 1747 fire, lends support to the Apache hypothesis. Clearly, it is possible that a lightning strike ignited the 1747 fire; however, as mentioned previously, the large width of the 1747 ring suggests wetter-than-average conditions. The ability of humans to forcibly ignite and spread fire across the landscape under sub-optimal fuel moisture conditions favors humans over lightning as the probable ignition source.

5.2.2 Are Dry Fire Years Unusual?

Widespread fires were significantly associated with drier-than-average years, suggesting that fuel moisture was a limiting factor. Low fuel moisture is a necessary condition for the occurrence of widespread fire in any system; however, these results specifically suggest that a dry period from September to July was a condition for the occurrence of widespread fire. This pattern seems extreme considering the semi-arid character of the Organ Mountains.

Examining individual fire years and fire-scar position data, it appears that multiple types of fire-year climate were conducive to the occurrence of widespread fires. Fire-scar positions for widespread fires during years of below-average precipitation tended to cluster in the dormant and early-earlywood positions (Figure 14); while during average-precipitation years, fire scars tended to cluster in the middle-earlywood and late-earlywood positions (Figure 14). Many of these scars, coincided with the intra-ring position of the false ring, indicating that these fires occurred during the hot, dry foresummer when false rings are typically formed in the Southwest (Fritts 1976). These data suggest that, in Fillmore Canyon, adequately low fuel moisture for a widespread fire can result from either a dry winter/spring or a hot foresummer.

5.3 Fire Regime Characterizations

Three fire regimes were identified during the period 1650 to 1993 based on the analysis of fire-scar data. Fire Regime I (FR-I, 1650-1805) is characterized by high fire frequency and a large proportion of patchy fires. FR-I can be further sub-divided into two parts, Fire Regimes Ia and Ib (FR-Ia and FR-Ib). FR-Ia (1650-1720) has a slightly higher MFI (lower fire frequency) than FR-Ib. The difference in fire frequencies between these regimes can probably be attributed to the slightly lower MFI, *i.e.*, greater number, of Medium fires in FR-Ib (Figure 18). Graphically, FR-Ia differs from FR-Ib in its more open pattern and greater vertical continuity of the bar symbols (Figure 19).

Relative to FR-I, FR-II (1805-1874) has a higher MFI (lower fire frequency) and a larger proportion of widespread fires (*i.e.*, Large fires; Figure 18). During this fire regime, Small fires occur at a slightly reduced frequency while only one Medium fire is recorded. Graphically, FR-II appears more "organized" than FR-I (Figure 20); there is a greater degree of vertical continuity in the bars representing the fire scars.

After *ca.* 1874, very few fires occur. Based on our knowledge of settlement in the Organ Mountains vicinity, FR-I and II comprise the pre-settlement period while FR-III (1874-1993) comprises the post-settlement period. Initially, these dates may seem inconsistent with the settlement pattern of the area: Las Cruces was founded *ca.* 1850 (Griggs 1930). However, the continued presence of the Apaches in the area until they were forced onto reservations in the late 1880s effectively inhibited Euro-Americans from practicing land-use activities such as livestock grazing and mining. Thus, pre- and post-settlement periods are not based on actual settlement dates, but rather on dates when Euro-Americans actually began using the land for their own purposes.

5.3.1 Fire Occurrence Patterns During the Pre-Settlement Period

5.3.1.1 A Climate Hypothesis

In Fillmore Canyon, the fire regime prior to *ca.* 1800 was characterized by frequent, patchy fires. At the turn of the century anomalously long fire-free intervals occurred, then for the remainder of the 1800s, the fire regime was characterized by less-frequent, widespread fires. These two features, *i.e.*, long fire-free intervals and changing fire regime, have also been observed at other sites in the Southwest (Grissino-Mayer *et al.* 1994; Grissino-Mayer 1995; Swetnam 1983; Baisan and Swetnam 1990; Touchan *et al. in press*). The regional synchrony of these fire occurrence patterns, suggests that climate was the responsible factor (Swetnam 1990). How climate has induced this change, however, is unclear.

The relatively long fire-free intervals during the first decades of the 1800s may be related to wetter-than-average conditions. On a regional scale, tree-ring based reconstructions of precipitation indicate that this period was the wettest in the last 400 years in the Southwest (Schulman 1956; Fritts 1991). However, on a local scale, wetter-than-average conditions do not always correspond with long fire-free intervals. For example, in the Pinaleños of southeastern Arizona, a local precipitation reconstruction demonstrated that a combination of low rainfall followed by average rainfall occurred during the fire-free interval of 1819 to 1838 (Grissino-Mayer *et al.* 1994). In the Gila Wilderness of southwestern New Mexico, above-average rainfall, specifically winter-spring precipitation, coincided with a gap in fire occurrence between 1819 and

1840 but not in the late 1700s (Swetnam and Dieterich 1985).

The change in fire regimes, from frequent, patchy fires to less frequent, widespread fires, *ca.* 1800 may be related to a change in long-term climate. If the early 1800s were simply a wetter-than-average period embedded within a more-or-less constant longer-term climatic pattern, one might expect that the fire occurrence patterns observed prior to *ca.* 1800 would reappear by the mid-1800s. However, they did not; moreover, evidence of long-term variation in climate is presented by Grissino-Mayer (1995) who reconstructed annual precipitation from tree-rings in northern New Mexico. Grissino-Mayer (1995) found that the 1800s were one of the wettest periods over the last 900 years. Grissino-Mayer (1995) also suggested that in addition to an increase in annual precipitation, a change in intra-annual distribution of precipitation (from winter to summer dominated) may have occurred in the early 1800s.

Changes in annual long-term precipitation appear to present a reasonable explanation for changes observed in many southwestern fire regimes. This contrasts Swetnam (1993) who did not find consistent associations between long-term variability in precipitation (decadal to centennial) and fire regime change in giant sequoia groves of the Sierra Nevada; year-to-year variability, however, was important. The difference between these two sets of results may be related to differences in vegetation. Further investigation of long-term climate change, especially changes in intra-annual distribution of precipitation, are needed to improve our understanding of the influence of long-term climate change and fire regime change.

5.3.1.2 An Apache Hypothesis

Humans have historically induced abrupt changes in southwestern fire regimes. For example, a dramatic decrease in fire frequency occurred throughout this region at the end of the 1800s and overgrazing is considered to have been an important factor in this decline (Leopold 1924; Weaver 1951; Swetnam 1983) and earlier declines (Touchan *et al*. 1995; Savage and Swetnam 1991). Likewise, in the early 1900s fire suppression drastically influenced fire occurrence patterns (Swetnam 1990). Here, I hypothesize that a change in Apache subsistence patterns *ca*. 1800 caused the corresponding decrease in fire frequencies. Specifically, political events during the late 1700s and early 1800s may have prompted Apaches to change their movement patterns and/or use fire less often, resulting in decreased fire frequency in Fillmore Canyon.

Prior to the late 1700s, the Apaches were an awesome force throughout New Mexico, Arizona, and northern Mexico. In comparison to the Spaniards and the Mexicans, the Apaches were superior in travelling through and fighting in the rugged terrain of this region (Lockwood 1987). During the late 1770s, a major military reorganization of the Spanish northern frontier, *i.e.*, northern Mexico, enabled the Spaniards to increase their military effectiveness against the Apaches, chasing them periodically out of their strongholds (Sonnichsen 1986). For about the next decade and a half, until the early 1790s, campaigns were vigorously carried out by both the Spaniards and Apaches against each other. Such strife could have disrupted the regularity of use (and burning) of the Organ Mountains relative to earlier periods. Moreover, an increased threat posed by the Spaniards may have motivated the Apaches to use fire more sparingly to avoid revealing their position.

Although the reorganized Spanish forces were relatively more effective, Spaniards had the greatest success in Apache relations in the early 1790s when a new Apache policy was enacted. A relative peace was maintained throughout southern Arizona and New Mexico for approximately the next three decades, until *ca.* 1820 (Sonnichsen 1986; Spicer 1992). This was considered by some to be the most peaceful period along the northern Spanish frontier in the last century and a half (Sonnichsen 1986). Part of this policy involved providing the Apaches with a supply of rations based on the premise that a hungry Apache was a dangerous Apache, thus a full one might be harmless (Sonnichsen 1986).

During this peaceful period, Spanish settlements thrived. For example, in El Paso both agriculture and stock raising flourished; by 1806, Don Francisco Garcia owned 20,000 sheep and 1000 head of cattle just outside of El Paso. In fact the livestock industry, in general, flourished across the southern parts of Arizona and New Mexico. One American Indian agent recounted what had been described to him by an older Mescalero (the group of Apaches associated with the Organ Mountains and south-central New Mexico in general),

"... many of them [Apaches] found work as shepherds to watch over the immense herds of cattle or sheep that securely fed in every mountain and in every valley of the country" (Steck 1863 in Sonnichsen 1986:61).

While this description may have been somewhat of an exaggeration, clearly, the implementation of the new policy changed both the Apache lifestyle and land use activities in some mountainous areas. Some ranges would have been affected by reduced Apache activities and/or an increase in grazing, either of which could have resulted in decreased fire frequencies such as those observed *ca.* 1800.

5.3.1.3 An Apache Hypothesis Revisited

If Apaches were a factor in fire occurrence patterns during the 1700s and *ca.* 1800, the reason for decreased fire frequencies during the 1800s is unclear. Historical accounts indicate that the Organ Mountains were used by Apaches at least between *ca.* 1830 and *ca.* 1880 (Table 1). Yet, fire occurrence patterns after this time do not resemble those before *ca.* 1800. If climate changes are discounted as a factor influencing this change, this suggests that Apache use-of-fire was different in the 1800s.

What may have caused this change? One possibility is the reported prosperity experienced by Spaniards during the "peaceful era" (*ca.* 1790 to *ca.* 1820) induced an increase in raiding activity by the Apaches following the collapse of peaceful relations after 1820. Large livestock herds were probably an attractive target for the Apaches. Accompanying an increase in raiding activities was perhaps a reduced use of fire. Raiding might have supplied adequate amounts of food such that fire would have been used less frequently for hunting. Moreover, use of fire, in general, may have been dramatically reduced if Apaches were concerned with drawing attention to their position.

For whatever reason, assuming that the Apaches used fire frequently before *ca.* 1800, it appears that Apaches used fire often less in Fillmore Canyon after *ca.* 1800. As mentioned earlier, their use of the mountain range during the 1800s is fairly well-documented (Table 1). And, based on previous arguments, evidence suggests that the Apaches may have "forcibly" burnt the landscape (see Section 5.2.1). Yet, the fire regime in the 1800s is distinctly different from the fire regime prior to *ca.* 1800. An important implication of this hypothetical change in Apache use-of-fire is that the fire regime during the 1800s (*ca.* 1800 to *ca.* 1880) may represent the fire occurrence patterns least influenced by human activity during the pre-settlement period in Fillmore Canyon.

5.3.2 Fire Occurrence Patterns During the Post-Settlement Period

The change in fire regimes *ca.* 1880 to a decreased fire frequency is a phenomenon observed throughout the Southwest (Weaver 1951; Dieterich 1980; Ahlstrand 1980; Swetnam 1983). This change is generally attributed to changes in livestock grazing followed by government agency fire suppression activities. Regionally, the period between 1850 and the late 1880s is characterized by a decline in Apache activities and increases in Euro-American activities such as mining and grazing. In the Organ Mountains, both grazing and mining activity were heightened during this period. By 1890 livestock numbers in southwestern New Mexico rivalled those in Texas (Cox 1959). In addition to grazing's direct effects on reducing fuels, fuel continuity was probably also disrupted by trails made by livestock herds (cattle, goats, and sheep). The period between 1875-1905 marked the period of highest mining activity in the Organ Mountains (Dunham 1935). One of the more productive mines, Modoc Mine, was located at the mouth of Fillmore Canyon, probably making this watershed a center of activity during this period. Timber-harvesting and fuelwood cutting associated with mining activity would have decreased fuel continuity because of the skid trails made when transporting the trees out of the canyon.

Although mining activities eventually ceased in the early 1900s, grazing continued to be a factor. In 1908, Vernon Bailey of the United States Biological Survey remarked,

"Grass is fairly good on the upper slopes [of the Organ Mountains] and cattle are found all along the canyons and up in many steep and rocky places."

Grazing probably maintained low fire frequencies up until the mid-1900s. The Cox Ranch, which grew to 4,250 ha, was active until 1945 when it was purchased by the federal government.

6. Conclusions and Management Implications

6.1 Conclusions

The purpose of this study was to reconstruct and interpret past fire occurrence patterns in Fillmore Canyon. This study demonstrated that fire occurrence patterns during the pre-settlement period (*i.e.*, before *ca.* 1880) were considerably different from those during the post-settlement period (*i.e.*, after *ca.* 1880). I identified two fire regimes in the pre-settlement period. From 1650 to *ca.* 1800, the fire regime was characterized by frequent, patchy fires; from *ca.* 1800 to *ca.* 1880, fires were less frequent and more widespread. In the post-settlement period, fire was virtually non-existent. I interpreted these patterns by examining associations between (1) fire and climate and (2) fire and humans. Based on these associations I generated reasonable hypotheses concerning the roles of climate and humans in past fire occurrence in Fillmore Canyon.

6.1.1 Climate and Fire

In Fillmore Canyon, annual variability in climate was an important factor affecting the occurrence of widespread fires. Results indicated that widespread fires occurred when moisture was below average. Moreover, results suggest the occurrence of widespread fires was induced either by (1) low precipitation, *i.e.*, after a dry winter/spring or (2) high temperatures, *i.e.*, during the dry and warm foresummer.

Surprisingly, results showed no apparent association between fuel accumulation, *i.e.*, wet antecedent conditions and widespread fires. One possible explanation is that Apache burning may have interrupted any climate-fire mechanisms that were operating (see section 5.2.1). Alternatively, the absence of evidence supporting the importance of fuel accumulation to fire occurrence may indicate that summer precipitation (July to September) was a key factor in producing the amount of fuel necessary for the occurrence of a widespread fire. Unfortunately, reconstructing summer precipitation (July to September) using tree-rings has not yet been successful in the Southwest. Tree-ring samples from the Organ Mountains, however, shows potential for accomplishing this. Sampled trees exhibit tree-ring morphological characteristics ("false rings") which could possibly be exploited to delineate winter and summer components of annual precipitation. In tree-rings that show a false ring, growth prior to the false ring is thought to be derived from winter moisture, while growth after the false ring is thought to come from summer moisture (Fritts 1976). Future work should explore the potential of reconstructing summer precipitation based on false-ring chronologies.

The possible influence of long-term climate (*i.e.*, decadal to centennial) on fire occurrence patterns was not specifically addressed in this study; however, a change in fire regimes was observed in Fillmore Canyon *ca.* 1800 that parallels changes observed at other fire history sites in the southwest. The regional extent of the observed change in fire regimes *ca.* 1800 favors climate as the primary factor effecting this change (Swetnam 1990) and evidence of long-term climate change in northern New Mexico is shown by Grissino-Mayer (1995); however, further research is needed to elucidate the mechanisms by which long-term climate effects change in fire regimes. One particular aspect of climate change that might improve our understanding of fire regime change *ca.* 1800 might be the examination of changes in intra-annual distribution of precipitation.

6.1.2 Humans and Fire

Patterns of past fire occurrence and changes therein coincided with historical events and land-use activity in the Organ Mountains. The fire regime of the 1700s, characterized by frequent, patchy fires coincided with an era when Apaches frequented the Organ Mountains. The reduction in fire frequency *ca.* 1800 coincided with a relatively peaceful period in Spanish-Apache relations that may have resulted in decreased use of fire by the Apaches, changes in Apache movement patterns within the region and increased livestock grazing in some mountainous areas in the Southwest. Any combination of these may have affected the Organ Mountains fire regimes. And finally, the cessation of widespread fires *ca.* 1880 coincided with intense mining activity by American settlers and increased livestock grazing.

The fire-human associations observed in Fillmore Canyon have many implications and raise many questions. First, if Apaches were an ignition source during the 1700s, what was their impact on the natural fire regime? The high frequency of lightning-ignited fires observed throughout the Southwest in the modern period (Barrows 1978) and the frequency of lightning strikes shown by the BLM lightning detection network (Gosz *et al.* 1995) suggests that high frequency fire regimes were within the historical or natural range of variation even without humans adding additional fire ignitions (Swetnam and Baisan *in press*). Thus, if ignition sources were not a limiting factor to fire occurrence, then Apache use-of-fire may have had little effect on fire frequencies. However, the timing and specific locations of Apache-ignited fires may have altered fire-climate interactions hence altering natural patterns. This perhaps is one reason why no evidence of the expected consistent association between wet antecedent conditions and widespread fire was found. Ignitions by the Apaches in conditions suboptimal for lightning ignitions (*e.g.*, 1747) may have altered fuel distribution, thus altering burn patterns of subsequent lightning ignitions.

Second, fire histories conducted throughout the

Southwest show a change in fire regimes *ca.* 1800. If the change in fire regimes *ca.* 1800 can be attributed to a change in Apache behavior in Fillmore Canyon, did the Apaches also cause similar changes observed in other sites throughout the Southwest? Human activity has influenced fire occurrence patterns at a regional scale in at least two other instances: overgrazing in the late 1800s and fire suppression since the early 1900s. However, it is doubtful that the Apaches instigated the fire-regime change *ca.* 1800 across the region because it occurred in areas where Apache activity is thought to have been low or non-existent (*e.g.*, Touchan *et al. in press*). It is more plausible that Apaches may have been a factor in some areas but not others, implying that both Apaches and climate played a role in instigating fire-regime change *ca.* 1800. Future research might concentrate on delineating fire history sites into those with and without a known Apache history in order to elucidate the relative roles of Apaches and climate in the observed change in fire regimes *ca.* 1800. Other historical research on Spanish-Apache relations is also needed.

Third, how does the possible impact of the Apaches compare to the impact of the Euro-Americans? Even if Apache use-of-fire obstructed climate-related fire occurrence patterns, the overall effect of Apaches on landscape structure and function was probably less severe than the effect of Euro-Americans. Apache-augmented fire frequencies probably perpetuated a heterogeneous landscape, thereby maintaining diversity and perhaps also buffering the landscape against extreme climatically-driven fire events, *e.g.*, 1748. However, most fire-related ecosystem processes continued to operate, *e.g.*, nutrient cycling and ponderosa pine regeneration. On the other hand, Euro-American timber and fuelwood harvesting and livestock grazing rapidly and extensively changed forest structure in addition to inducing extensive erosion, while fire exclusion has eliminated or impeded all fire-associated ecosystem processes.

And lastly, if, based on historical documentation, Apaches were in the Organ Mountains throughout the 1700s and most of the 1800s (Table 1), why were there different fire occurrence patterns before and after *ca.* 1800? This pattern underscores the difficulties in evaluating the role of Apaches in fire histories in the Southwest. At least two hypotheses can explain this pattern. First, Apaches added fire to the system resulting in high frequency, patchy fires in Fillmore Canyon prior to *ca.* 1800; however, a change in their behavior after *ca.* 1800, *i.e.*, a decreased use of fire in Fillmore Canyon or decreased use of Fillmore Canyon, resulted in a fire regime consisting of less frequent, but relatively more widespread fires. Second, Apache use-of-fire was neither an important factor before nor after *ca.* 1800 in controlling fire occurrence patterns; fire was influenced more by the interaction between fuel, weather and climate. Both of these hypotheses suggest that the fire regime after *ca.* 1800 (but before the cessation of fires *ca.* 1880) was minimally influenced by humans.

6.2 Management Implications

An important application of this study is to assess the implications of observed results for fire management in the Organ Mountains. Management objectives include the preservation of community diversity and particularly of communities, *e.g.*, conifer forests, that serve as habitat for rare and endemic species. It is hoped to achieve these objectives using fire (Muldavin 1991).

The results from this study may justify the use of fire to achieve some management objectives in that they demonstrate that this area has sustained fire over long periods until an interruption in the late-1800s due to land-use activities. They also suggest that activities practiced by Euro-Americans have been detrimental to the structure and function of the landscape. Results show that during the pre-settlement era, *i.e.*, prior to *ca.* 1880, fire was an integral component of the landscape indicating that, historically, fire played an important role in community and landscape maintenance. In contrast, during the post-settlement era, *i.e.*, since *ca.* 1880, fire was virtually absent, which can be attributed to Euro-American activities including, livestock grazing, mining, and fire suppression.

In addition to fire exclusion, Euro-Americans probably impacted landscape structure by the extensive timber and fuelwood harvesting during the late 1800s and early 1900s. Vernon Bailey of the United States Biological Survey noted in 1908 that,

"Considerable timber has been cut and dragged down the steep slopes to where it could be taken by trains to the valley. There are large old stumps of yellow pine [ponderosa pine] and douglas spruce [Douglas-fir]..."

How fire should be reintroduced is a more complicated issue. This study illustrates a variety of templates that could be selected as models for fire re-introduction, depending on specific management objectives and resources. Managers should be aware that reintroduced fire may not necessarily emulate patterns observed in the pre-settlement period because of (1) landscape alterations induced by Euro-Americans, and (2) a different climate regime. However, the restoration of fire to this landscape would represent the restoration of a keystone ecological process that pervaded the landscape for centuries long before the arrival of Euro-Americans.

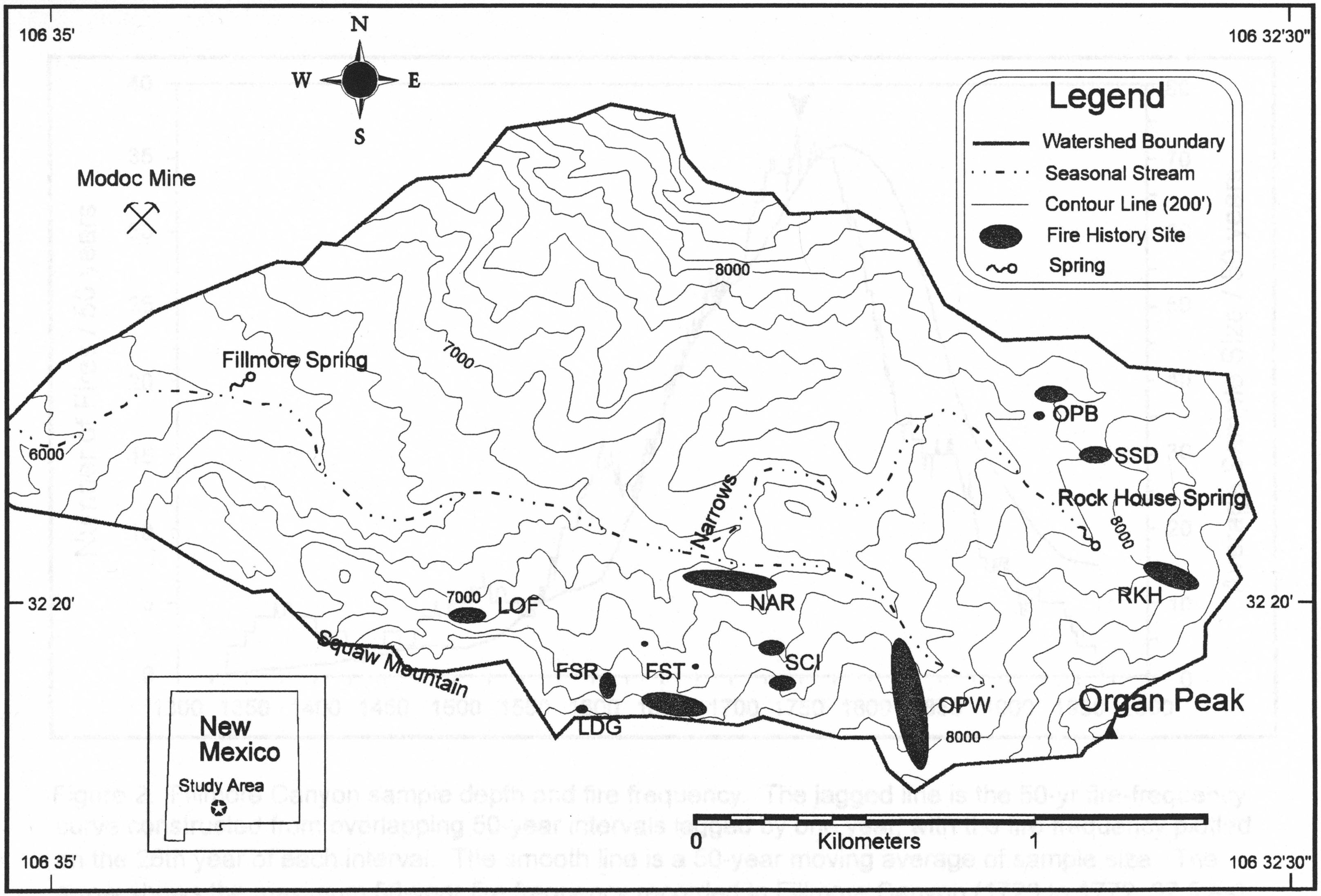


Figure 1. Map of Fillmore Canyon Watershed

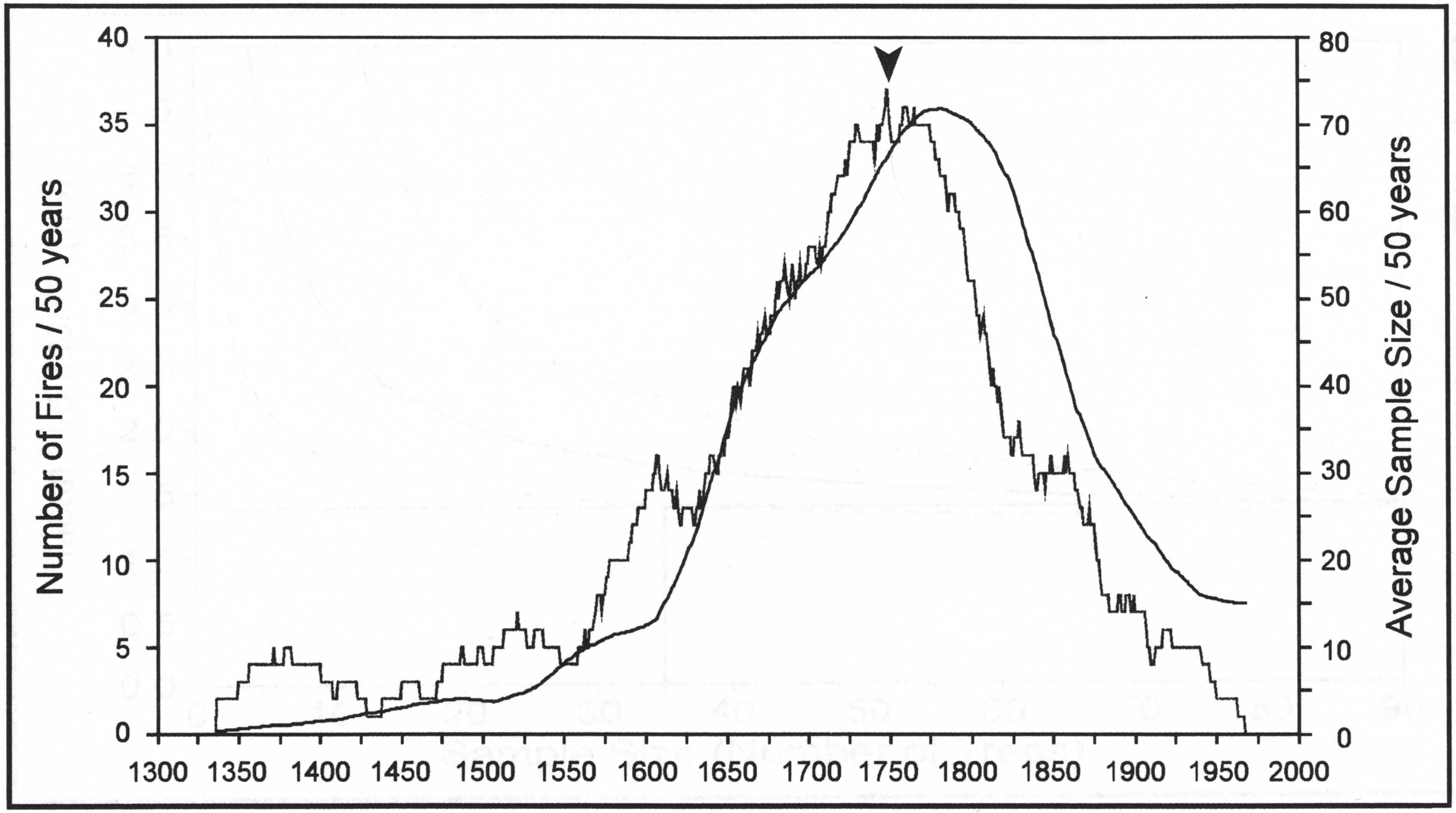


Figure 2. Fillmore Canyon sample depth and fire frequency. The jagged line is the 50-yr fire-frequency curve constructed from overlapping 50-year intervals lagged by one year, with the fire frequency plotted on the 26th year of each interval. The smooth line is a 50-year moving average of sample size. The arrow shows the maximum 50-year fire frequency recorded in Fillmore Canyon (1723 to 1772, 37 fires).

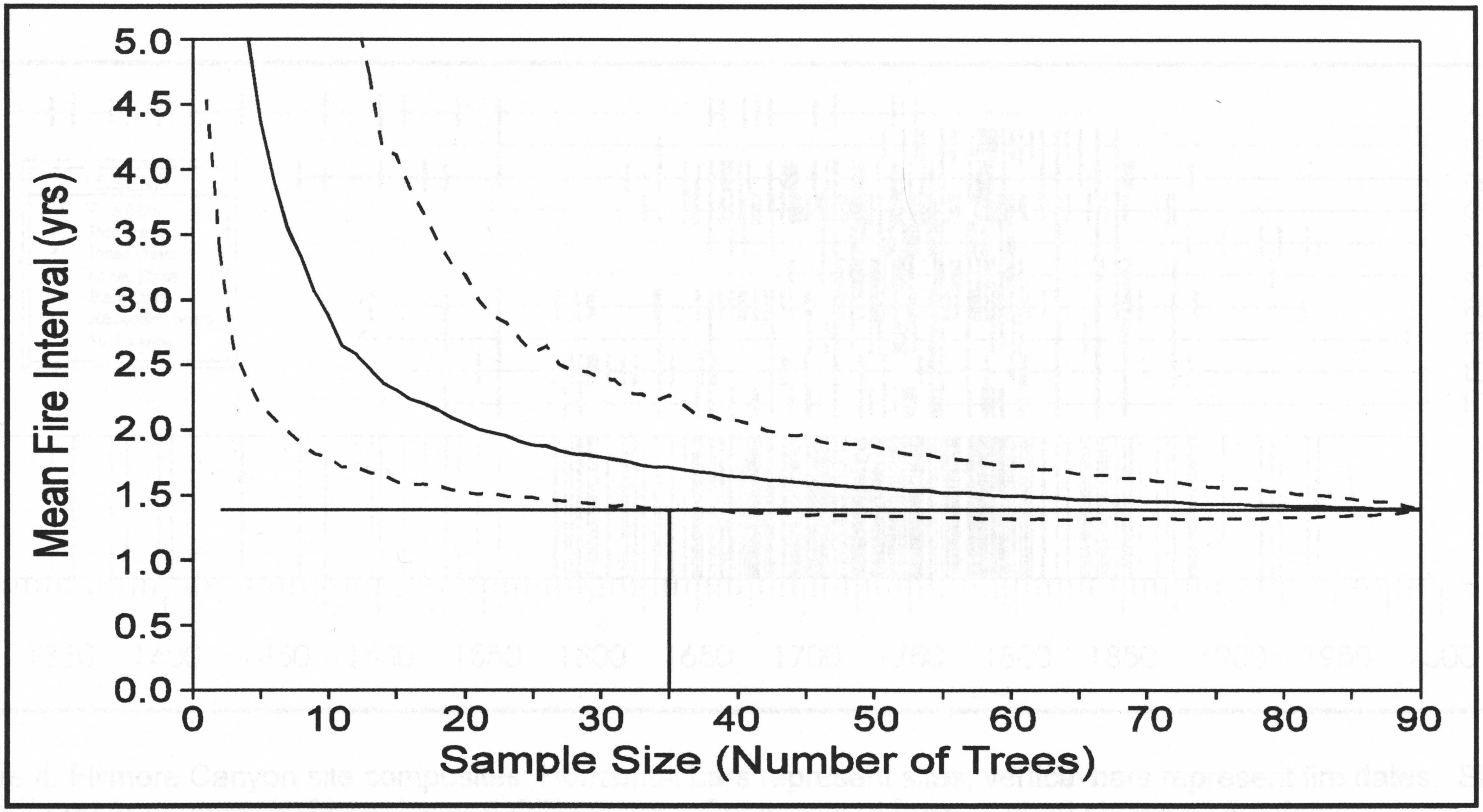


Figure 3. Changes in Mean Fire Interval (MFI) estimates with decreasing sample size. The mean MFI (solid curve) and 99% probability intervals (dashed curve) were estimated for the reference period (1723 to 1772) based on the complete sample set. The actual MFI (1.4 years) of the reference period is shown by the horizontal line. When sample size is less than 35 trees, there is less than a 0.05% probability of estimating the MFI of the reference period.

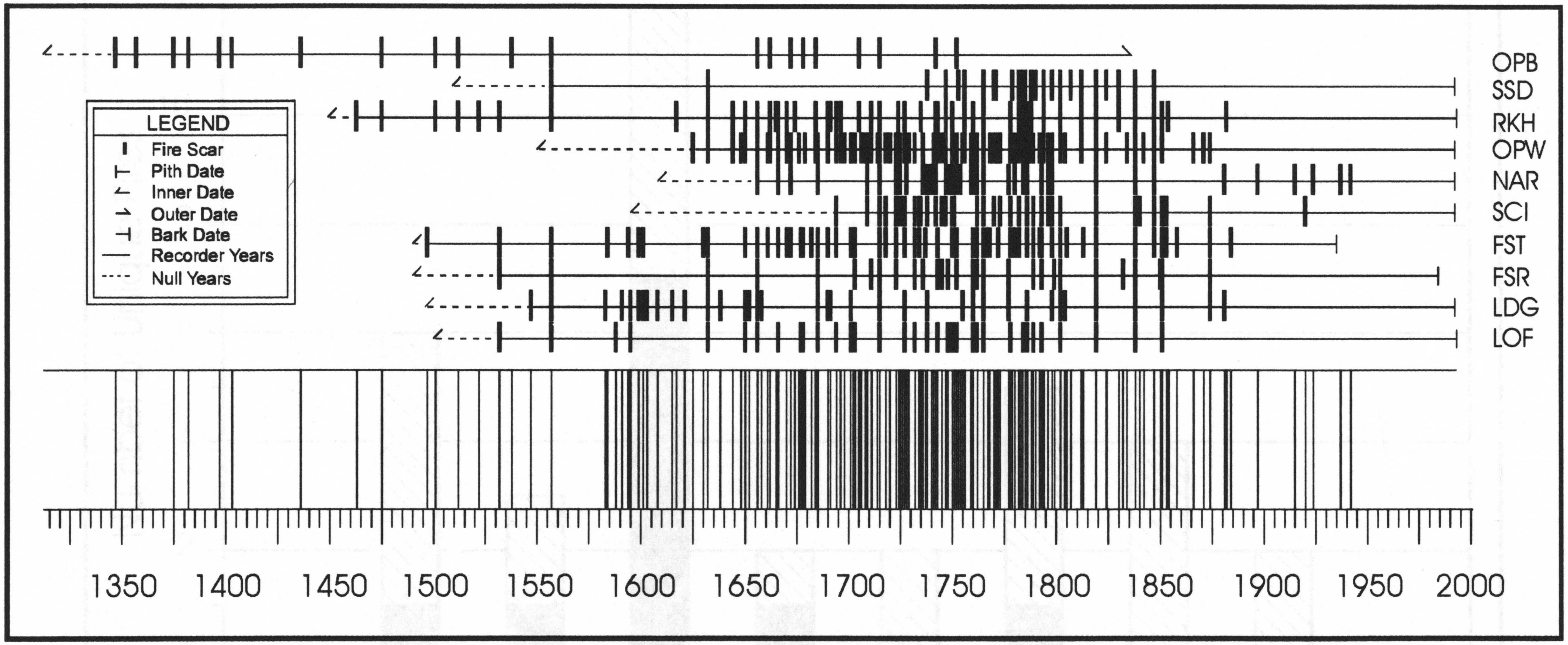


Figure 4. Fillmore Canyon site composites. Horizontal bars represent sites; vertical bars represent fire dates. Sites are ordered from upper (OPB) to lower (LOF) canyon. Composite at base of chart shows all fire dates.

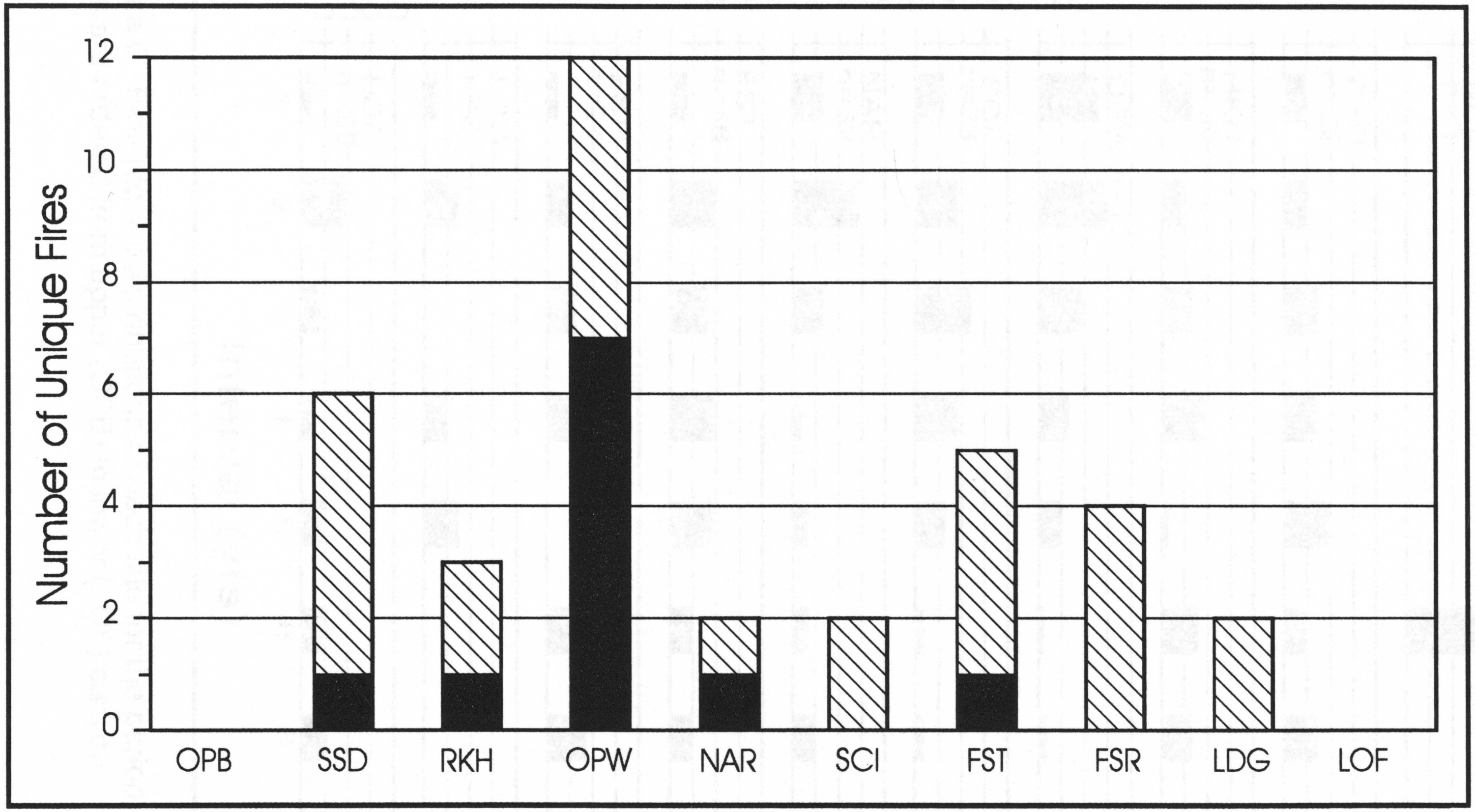


Figure 5. Number of fire dates unique to each site. Fire dates are sorted by those recorded on a single tree (hatched) or more than one tree (solid) for the period 1650 to 1858.

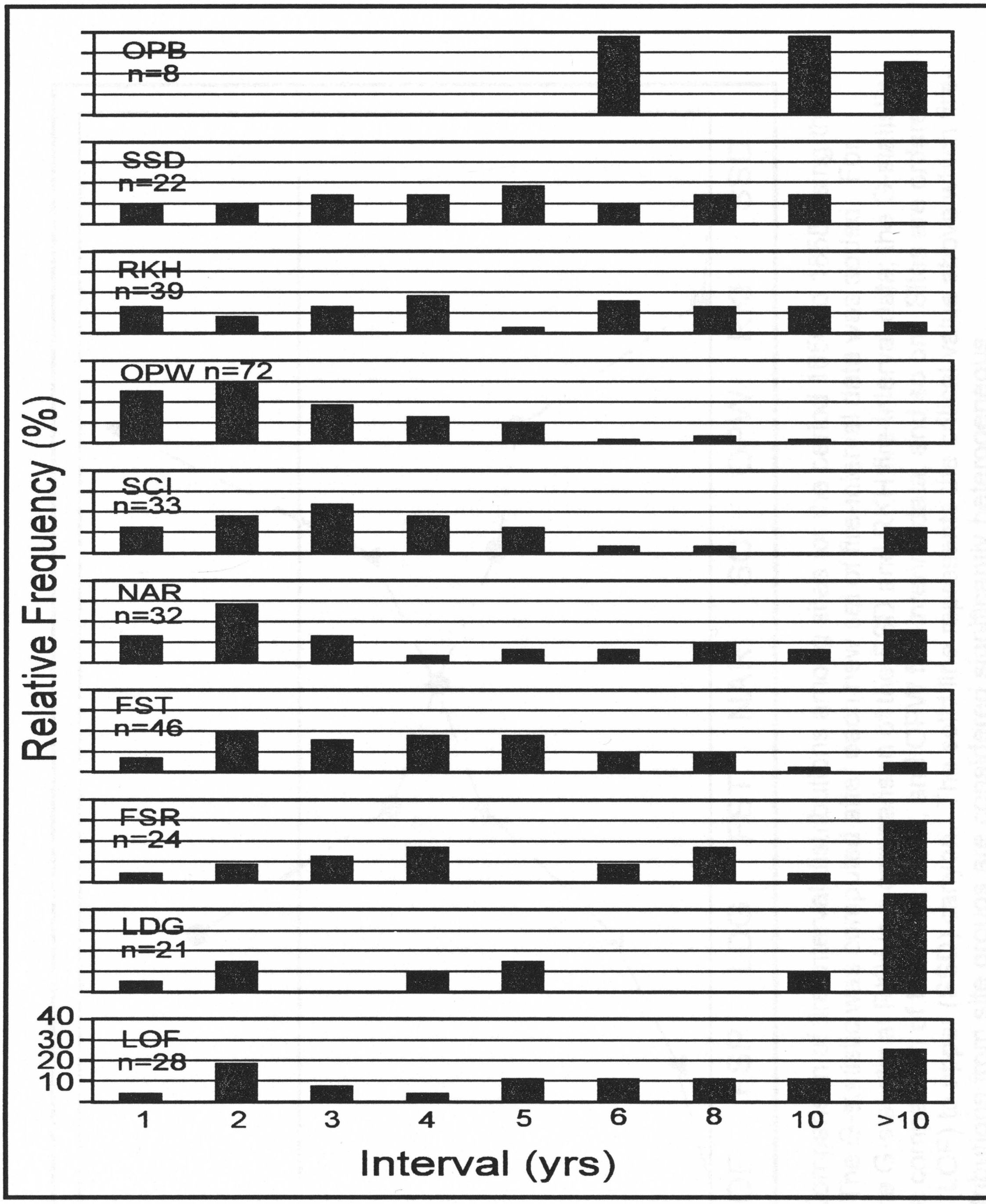


Figure 6. Fire-interval distributions of each site for the period 1650 to 1858. Sites are ordered from upper (OPB) to lower (LOF) canyon.

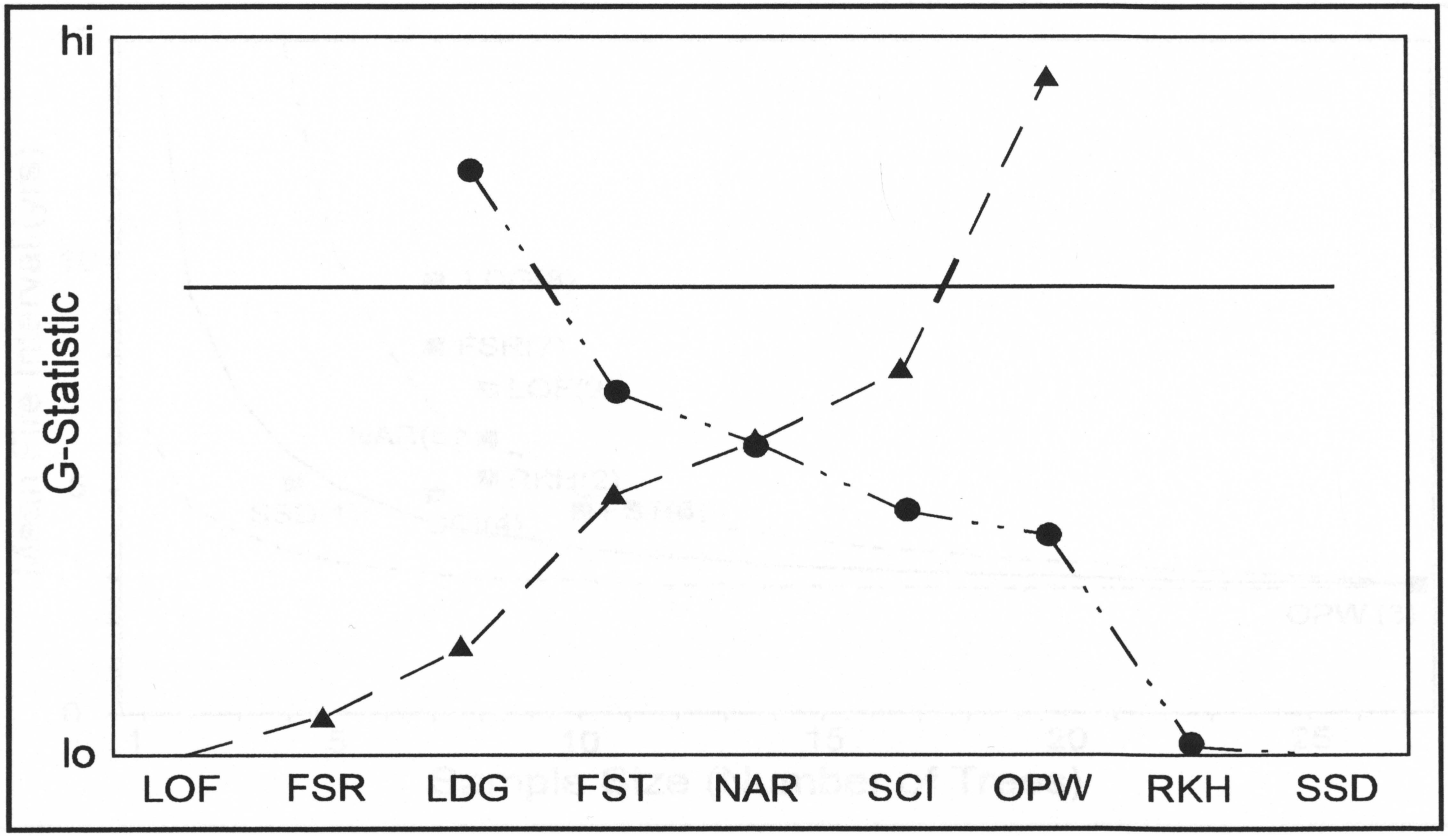


Figure 7. Comparison of fire-interval distributions among sites for the period 1650 to 1858 using the G-statistic. The G-statistic was computed after each new set of fire-interval data was added. For example, the G-statistic at RKH is a comparison of the SSD and RKH fire-interval data; the G-statistic at OPW is a comparison of the SSD, RKH, and OPW fire-interval data, and so on. Sites are ordered from lower (LOF) to upper (SSD) canyon. The solid line represents the critical value above which fire-interval distributions from site groups are considered significantly heterogeneous.

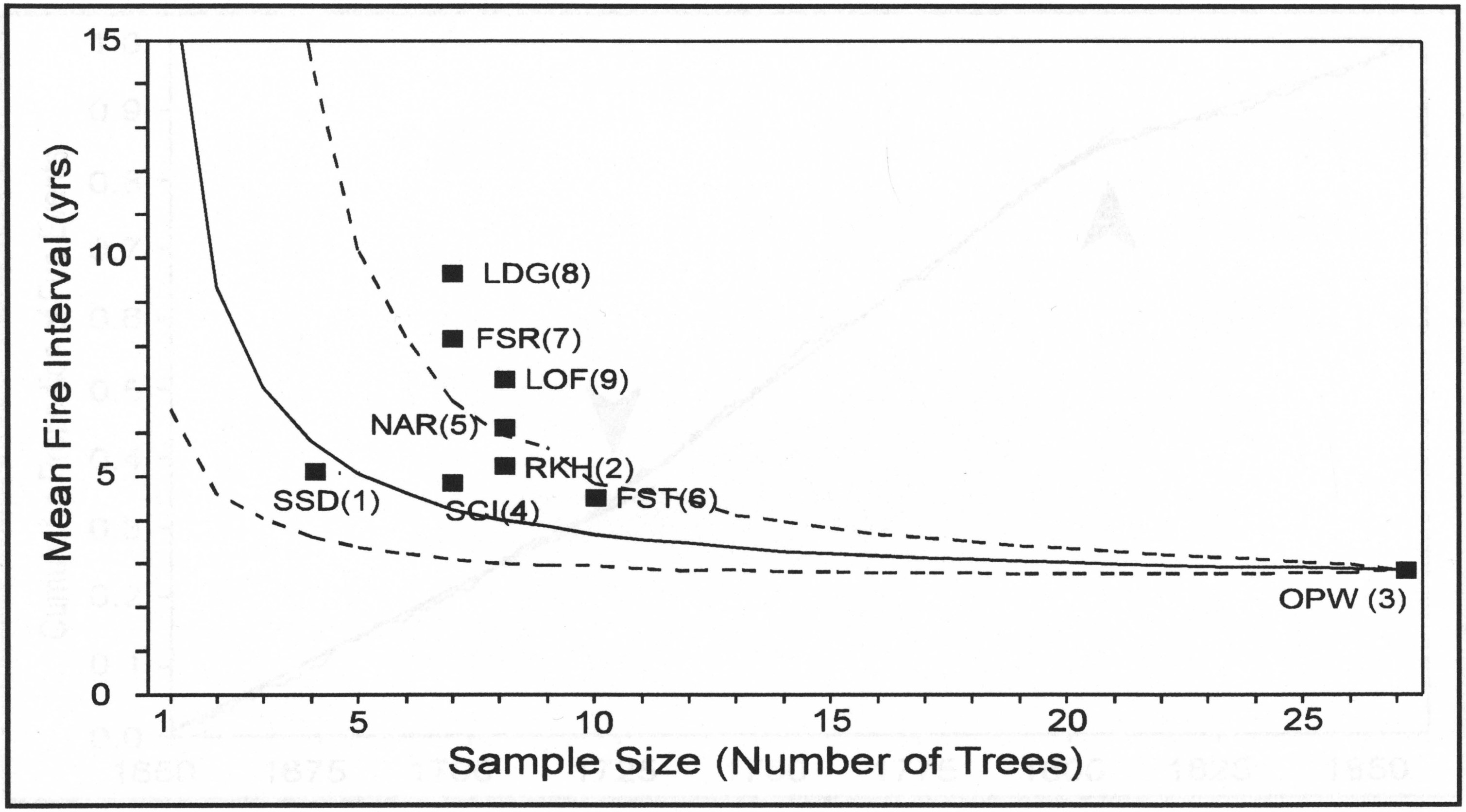


Figure 8. Comparison of Mean Fire Intervals (MFIs) among sites for the period 1650 to 1858, taking into account differences in sample size. MFIs were estimated for OPW at reduced sample sizes and compared to actual MFIs recorded in other sites. The solid line represents estimated mean MFIs and the dashed lines represent estimated 99.9% probability intervals.

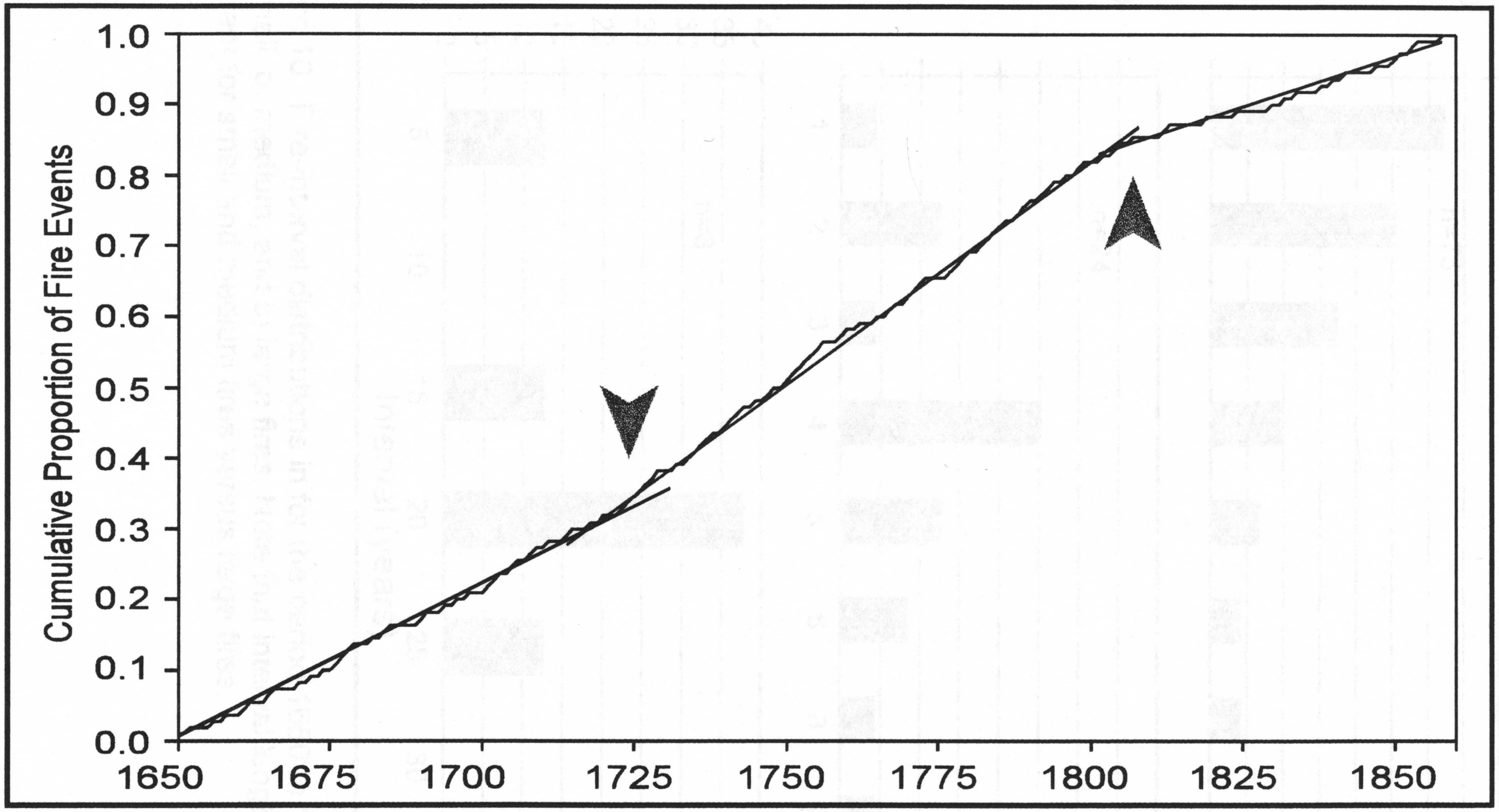


Figure 9. Cumulative proportion of fire events recorded in Fillmore Canyon for the period 1650 to 1858. Lines were fitted by eye. Inflection points at ca. 1720 and ca. 1805 were interpreted as canyon-wide changes in fire frequency.

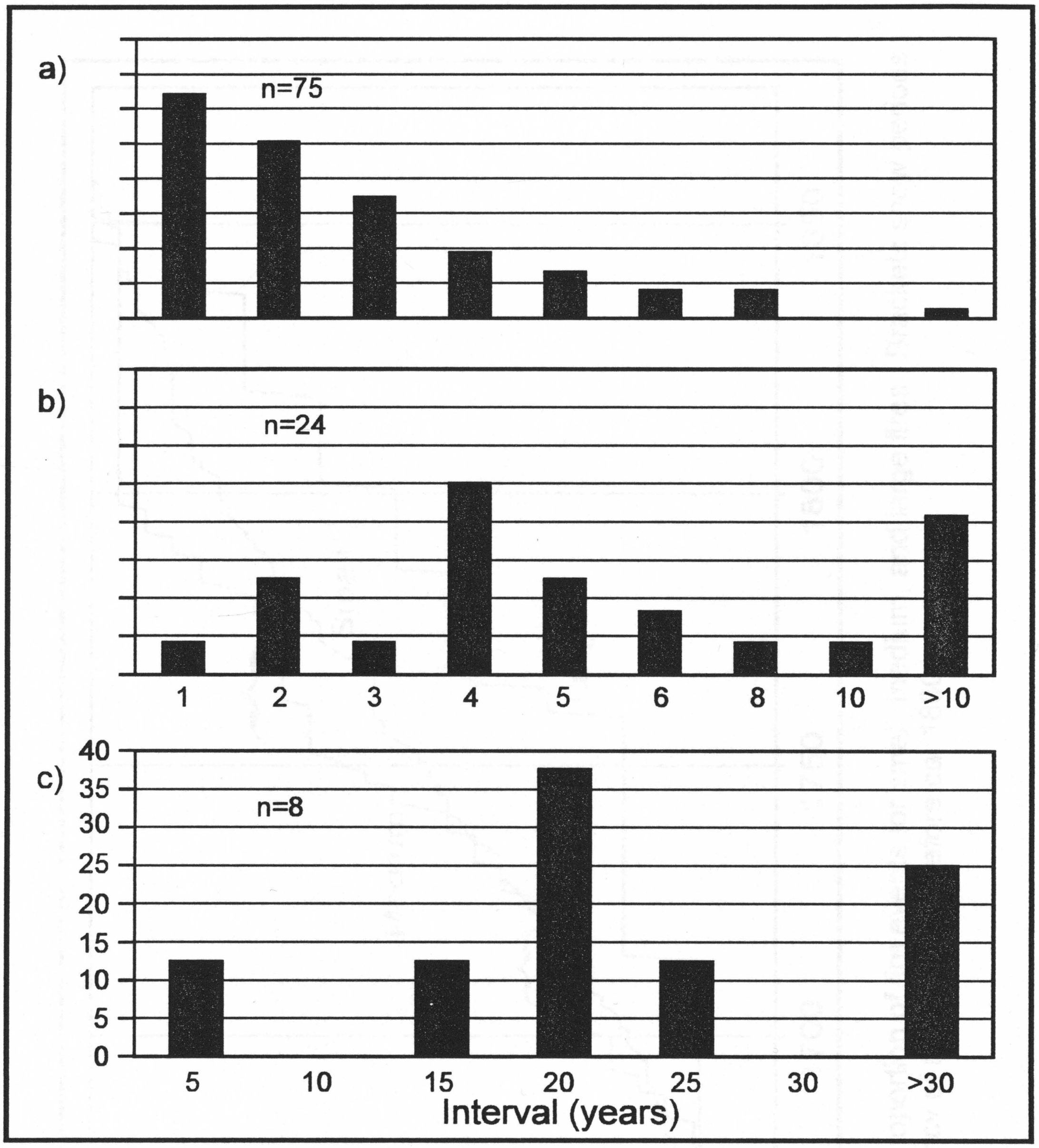


Figure 10. Fire-interval distributions in for the period 1650 to 1858 for a) small, b) medium, and c) large fires. Note that interval lengths are different for small and medium fires versus large fires.

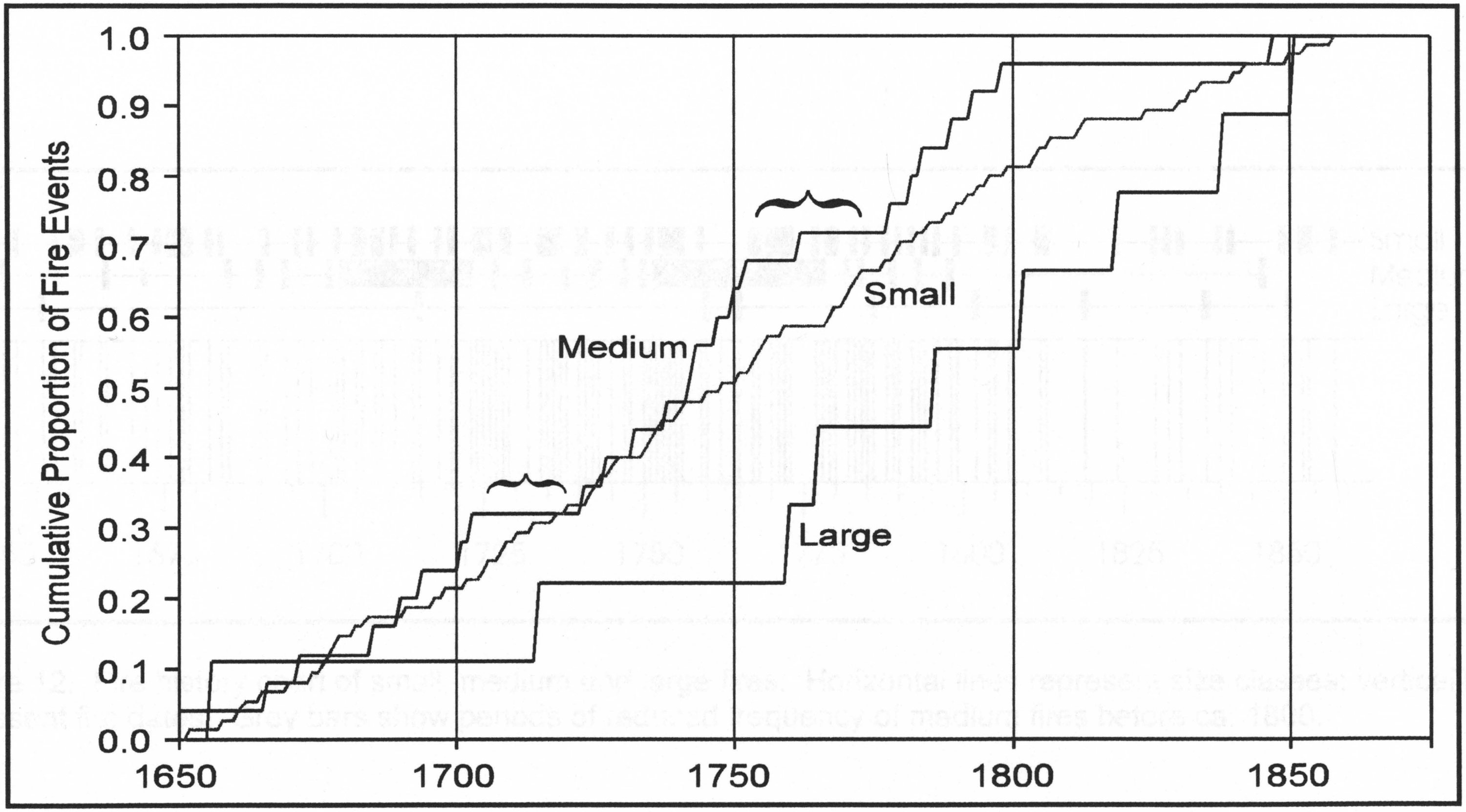


Figure 11. Cumulative proportion of fire events for small, medium, and large fires. Brackets show periods of decreased fire frequency of medium fires before ca. 1800.

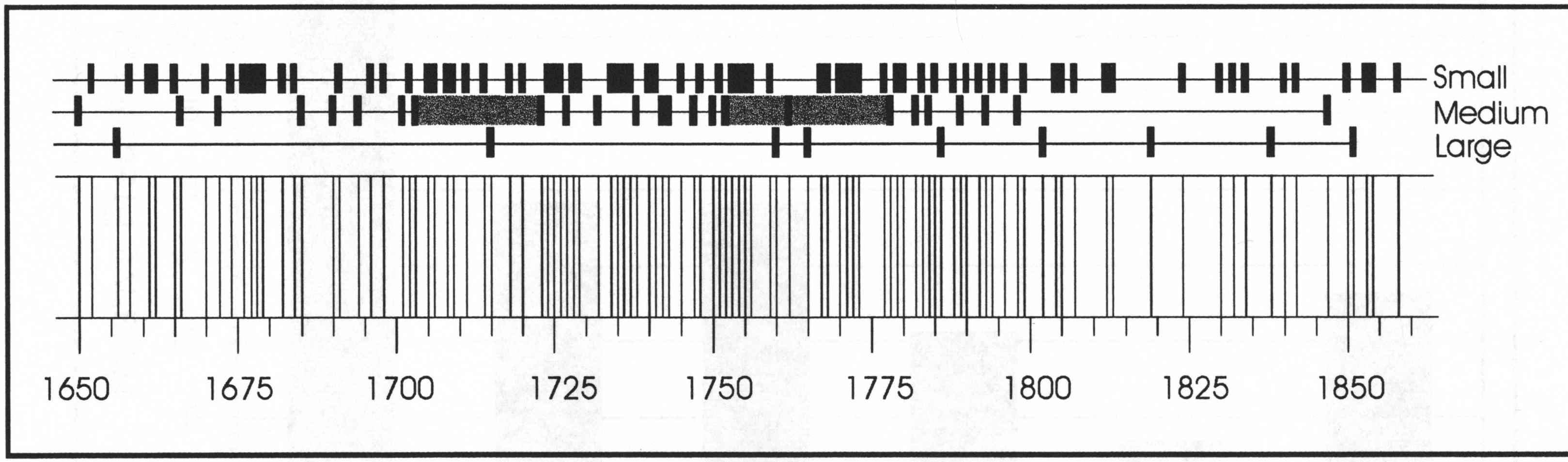


Figure 12. Fire history chart of small, medium and large fires. Horizontal lines represent size classes; vertical bars represent fire dates. Grey bars show periods of reduced frequency of medium fires before ca. 1800.

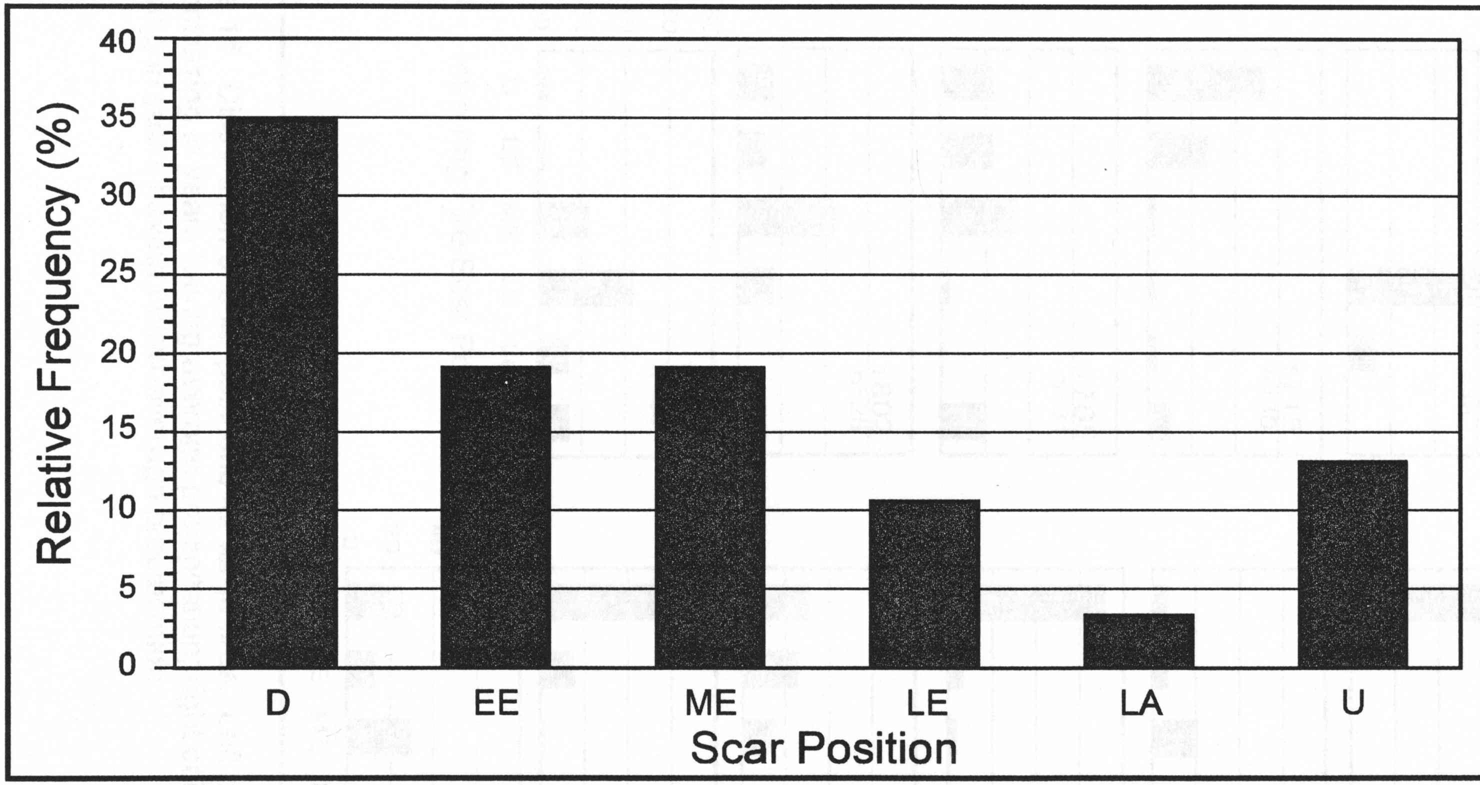


Figure 13. Distribution of scar positions for all fires recorded during the period 1650 to 1858. D=Dormant; EE=Early Early; ME=Middle Early; LE=Late Early; LA=Latewood; U=Unknown.

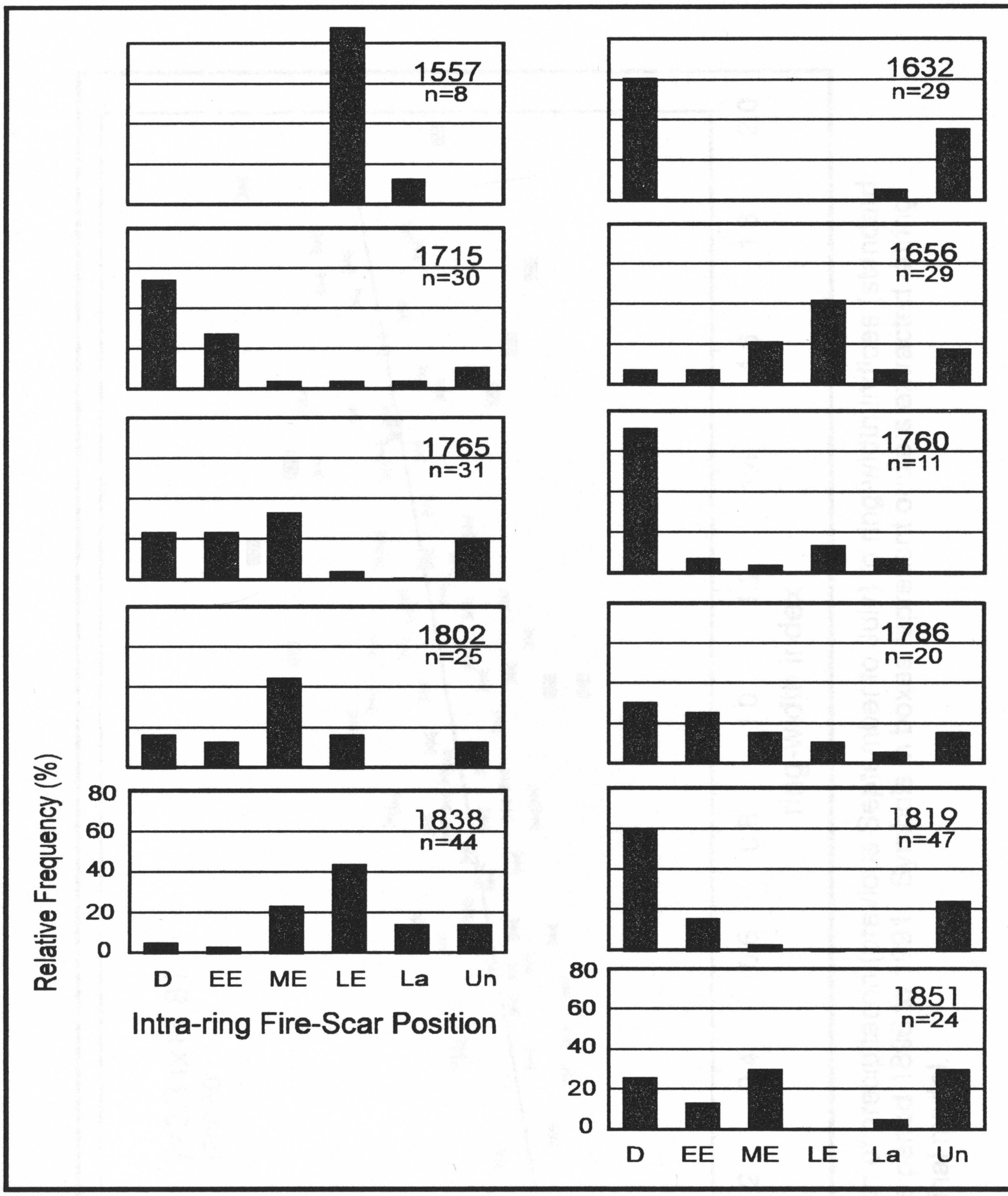


Figure 14. Distribution of scar positions for large fires. Left column shows fires occurring in years having average precipitation; right column shows fires occurring in years having below-average precipitation.

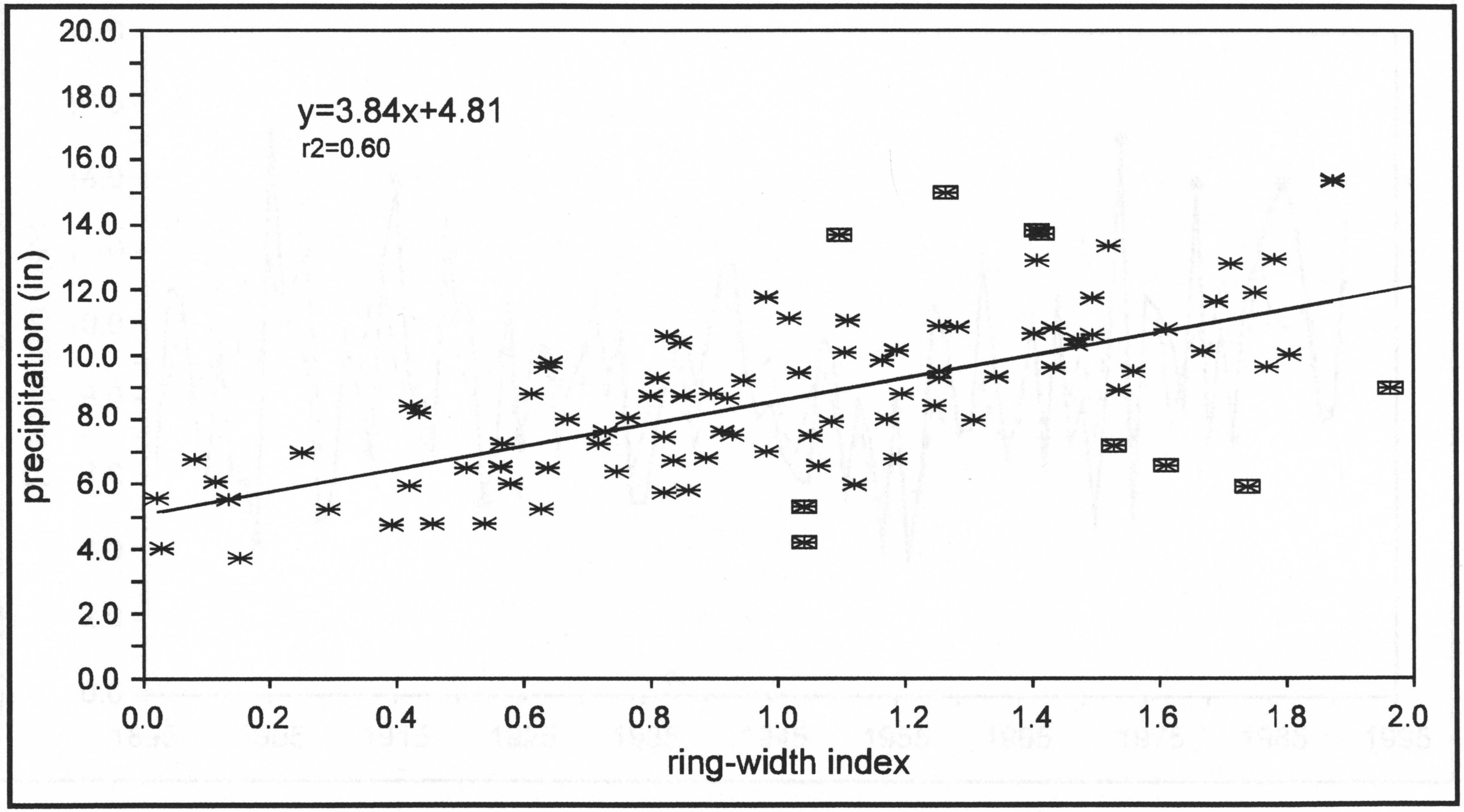


Figure 15. Relation of precipitation (previous September to July) to ring-width indices (standard chronology) for the period 1896 to 1991. Symbols in boxes represent outliers extracted during calibration of the final model.

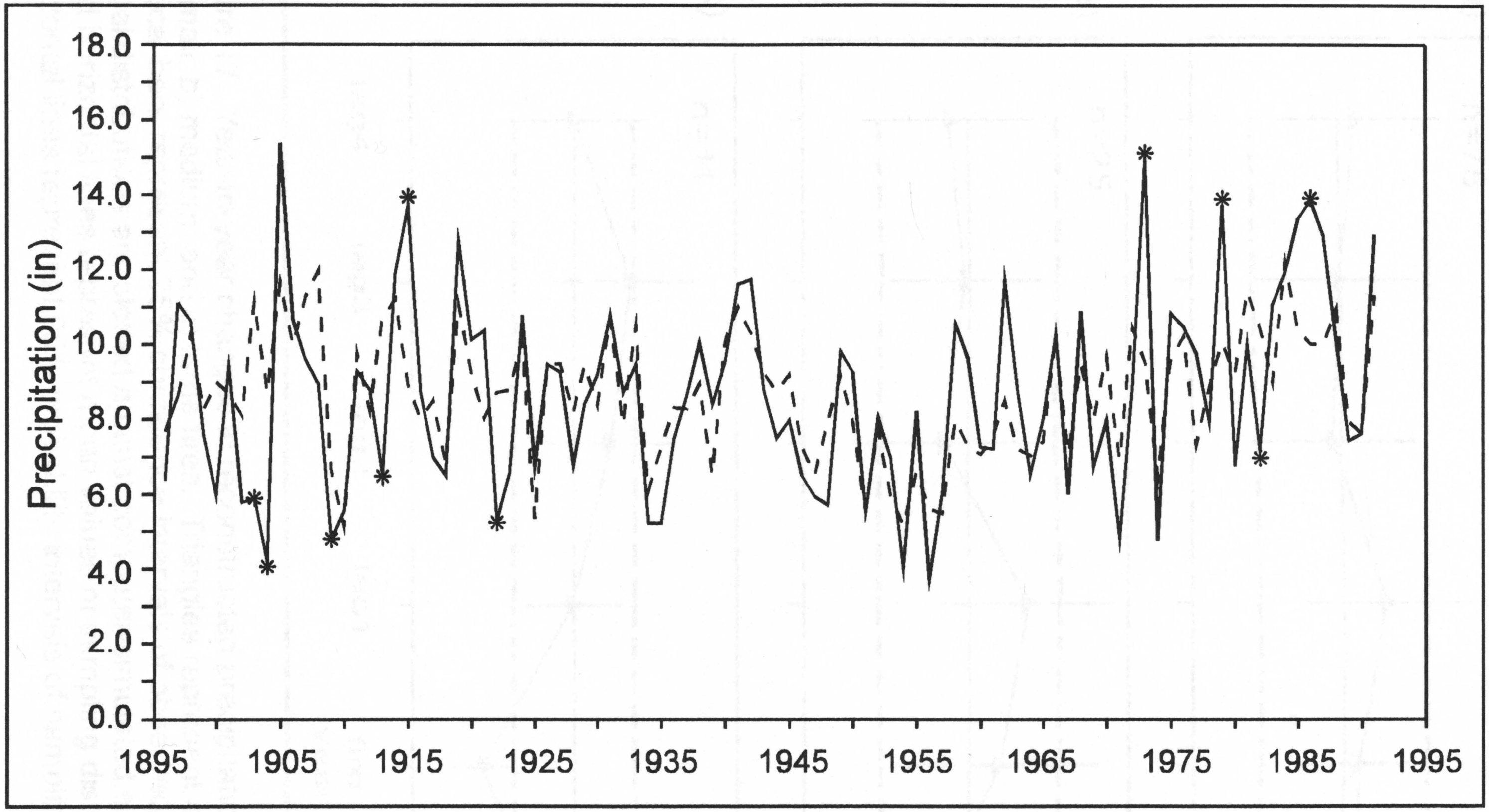


Figure 16. Comparison of actual (solid) and predicted (dashed) precipitation (previous September to July) for the period 1896 to 1991. Symbols show the outliers extracted during calibration of the final model.

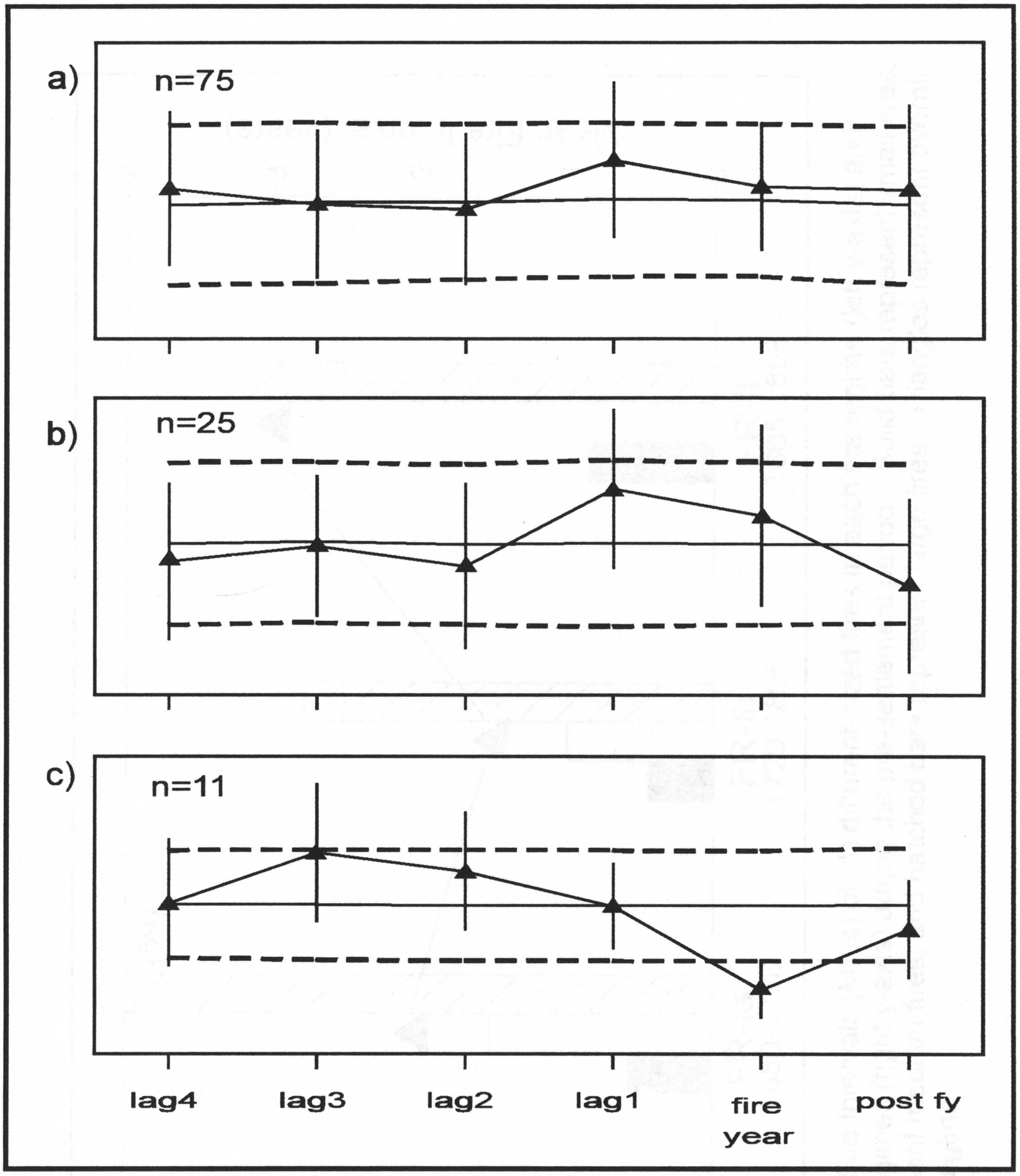


Figure 17. Year-to-year changes in reconstructed precipitation associated with a) small, b) medium, and c) large fires. Triangles represent average values and vertical bars represent 95% confidence intervals of observed events. These actual distributions are plotted against computer-simulated sampling distributions. Solid horizontal lines represent mean values of sampling distributions, dashed horizontal lines represent 95% probability intervals of sampling distributions.

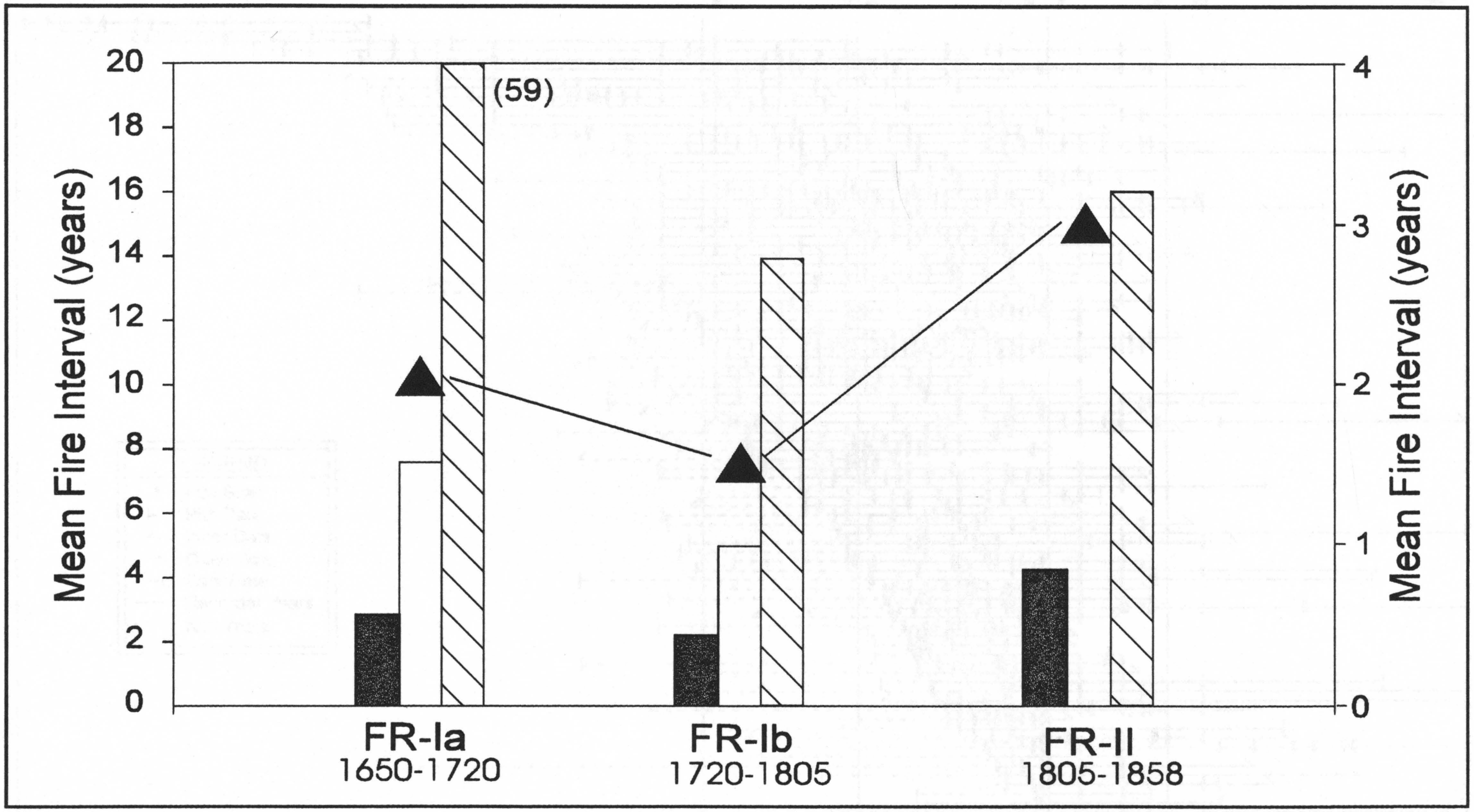


Figure 18. Mean Fire Intervals (MFIs) of (1) different-sized fires in each fire regime (left y-axis) and (2) different fire regimes (right y-axis) during the pre-settlement period. Solid bars represent small fires, empty bars represent medium fires, and hatched bars represent large fires. Triangles represent overall MFI for each fire regime.

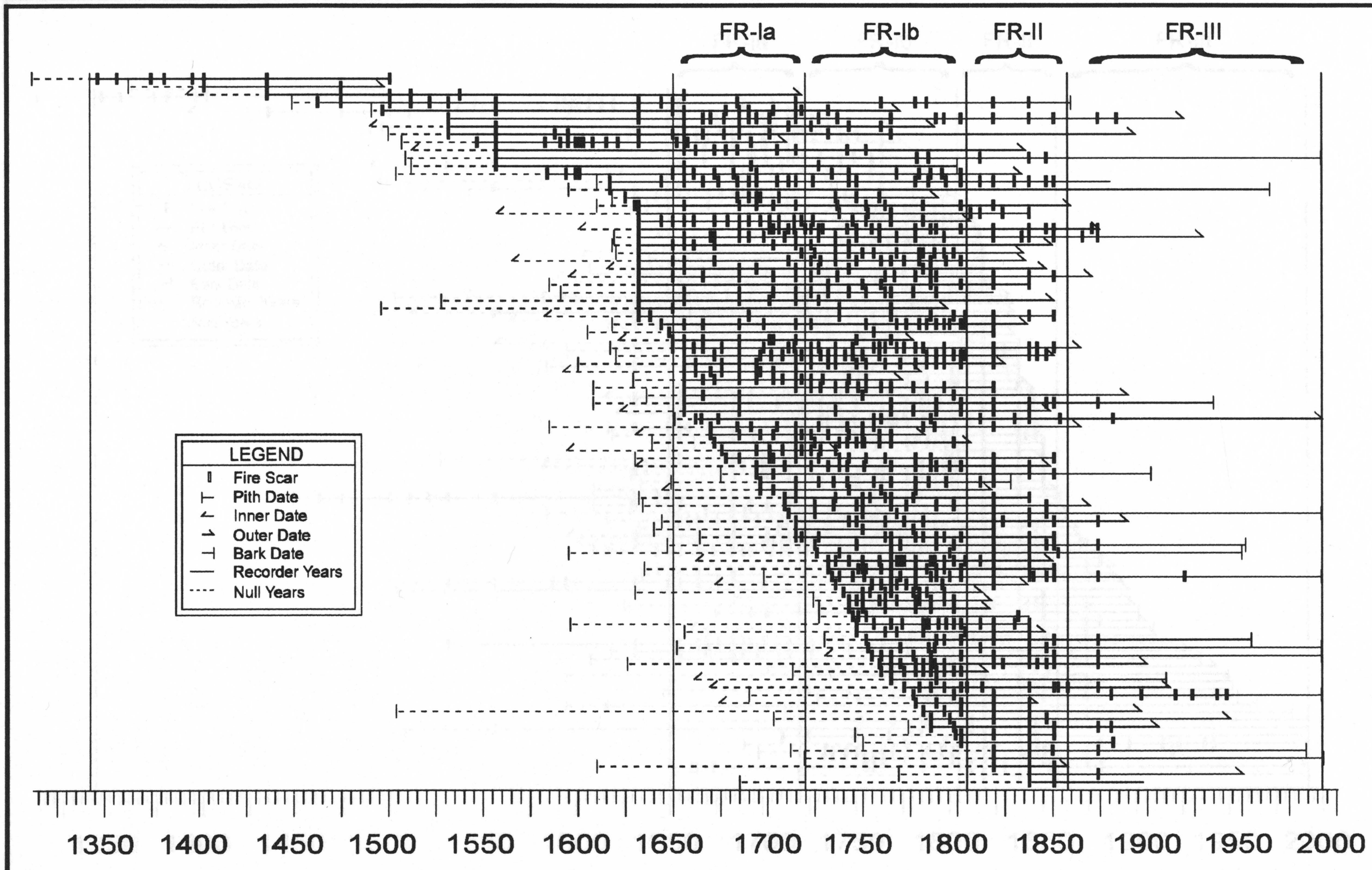


Figure 19. Fire history chart of all samples sorted by first fire scar. Horizontal lines represent individual trees; vertical bars represent fire dates. Vertical lines separate different fire regimes.

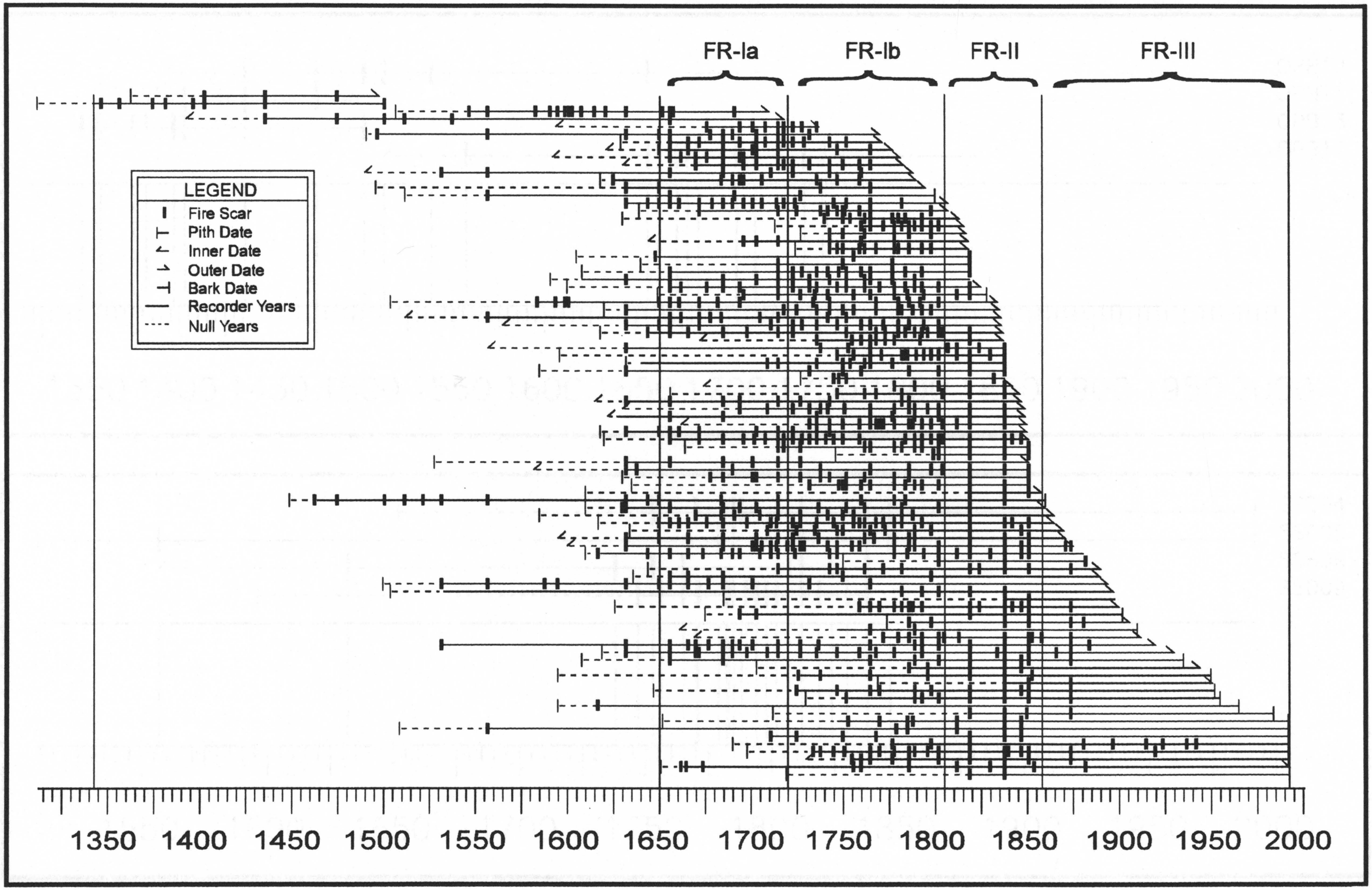
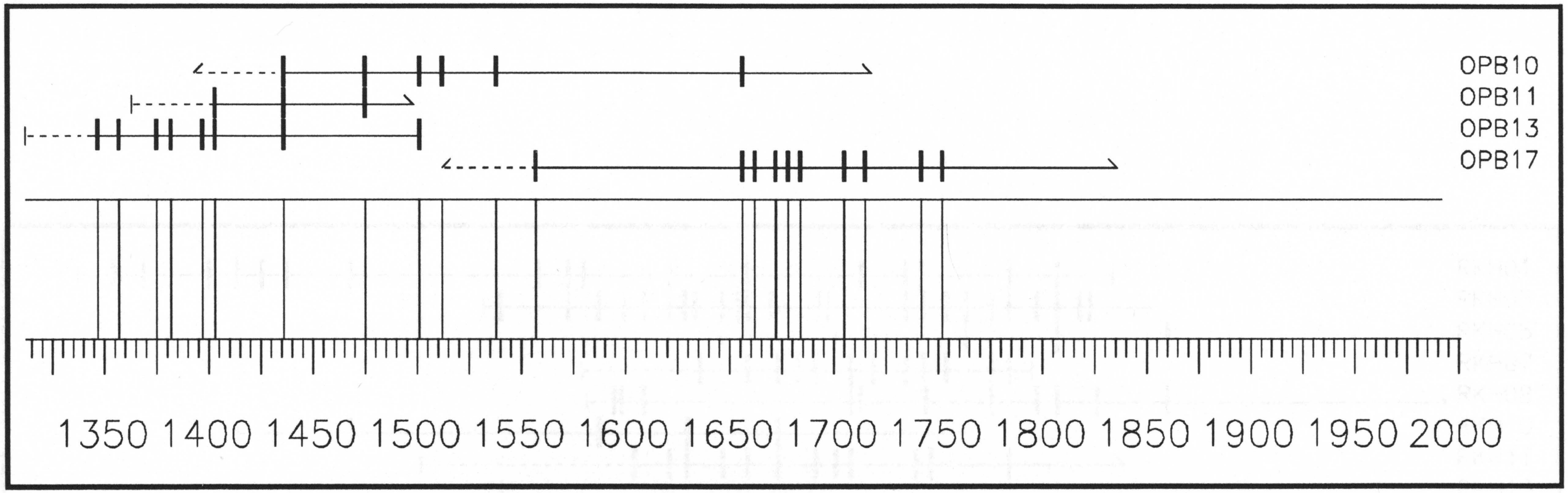
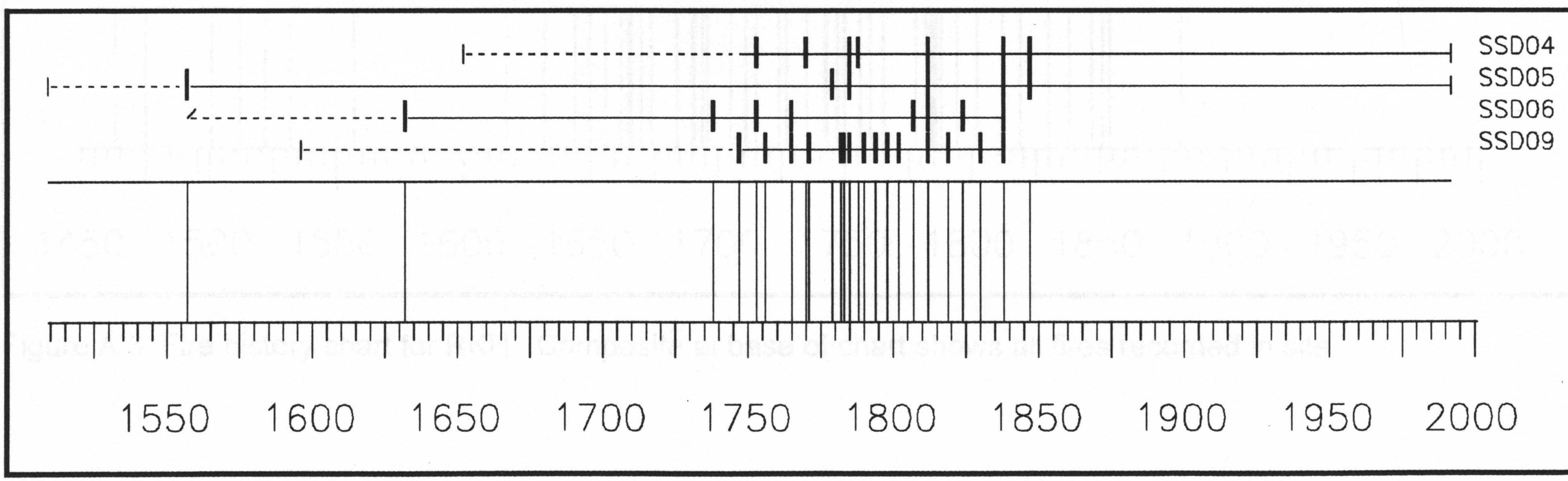


Figure 20. Fire history chart of all samples sorted by last fire scar. Horizontal lines represent individual trees; vertical bars represent fire dates. Vertical lines separate different fire regimes.





Figures A.1 and A.2 Fire history charts for OPB (top) and SSD (bottom). Composite at base of each chart shows all fires recorded in site.

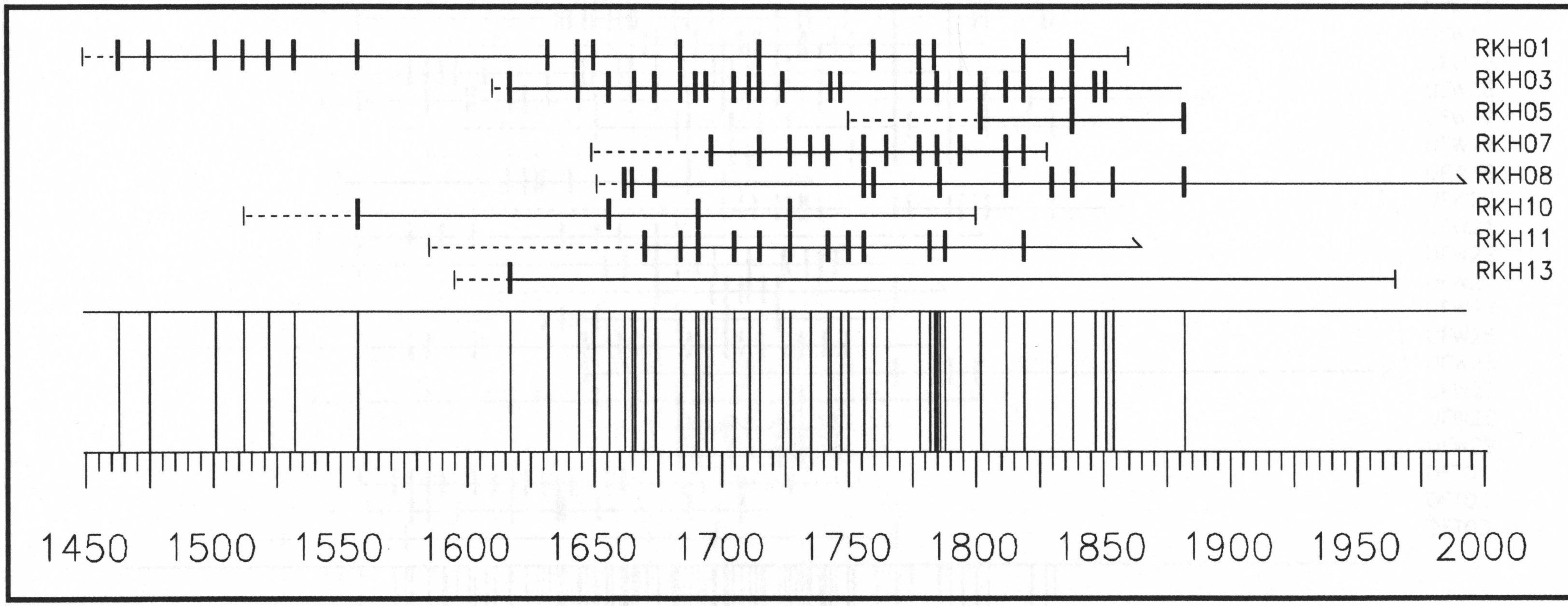


Figure A.3 Fire history chart for RKH. Composite at base of chart shows all fires recorded in site.

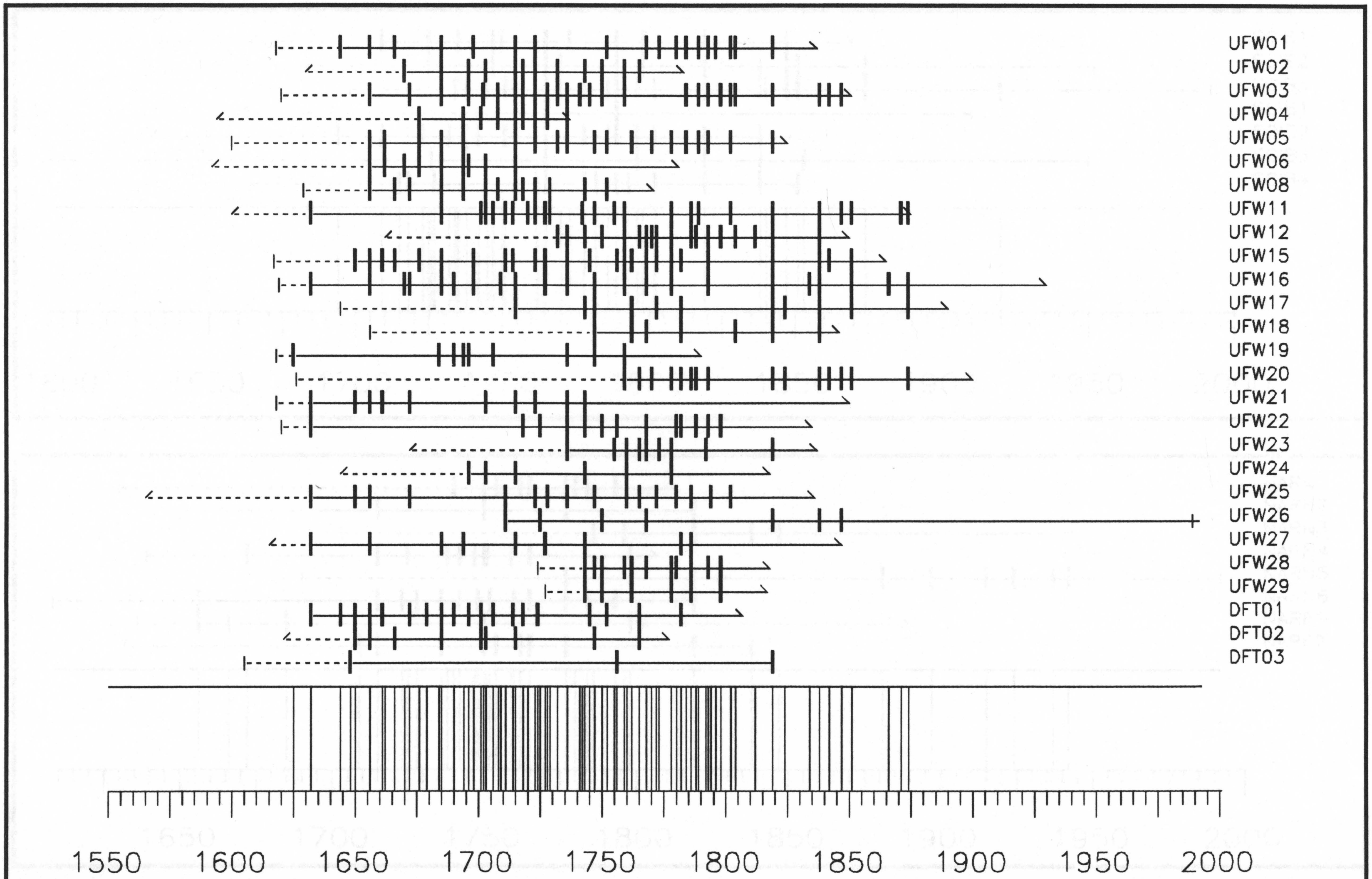
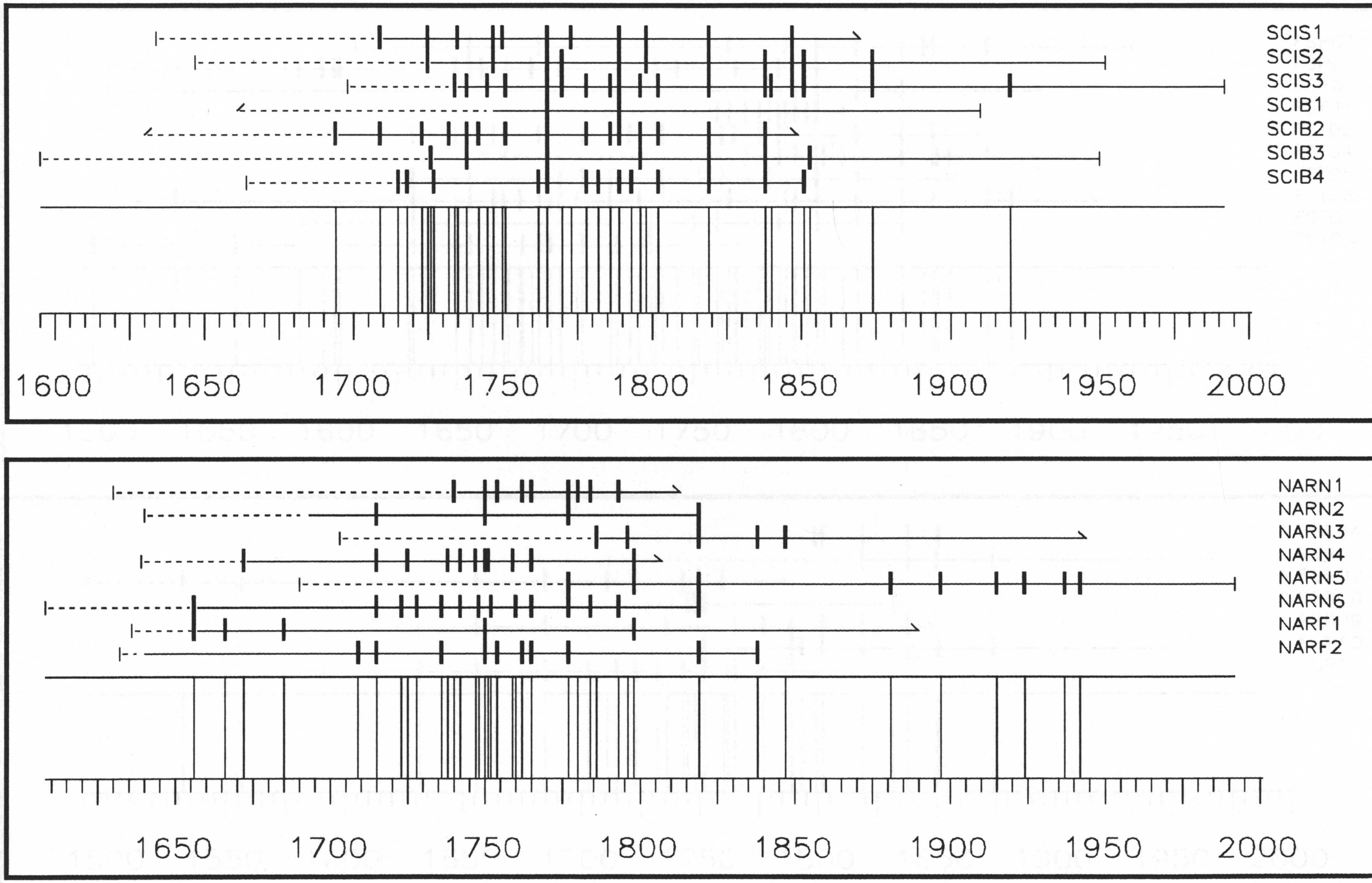
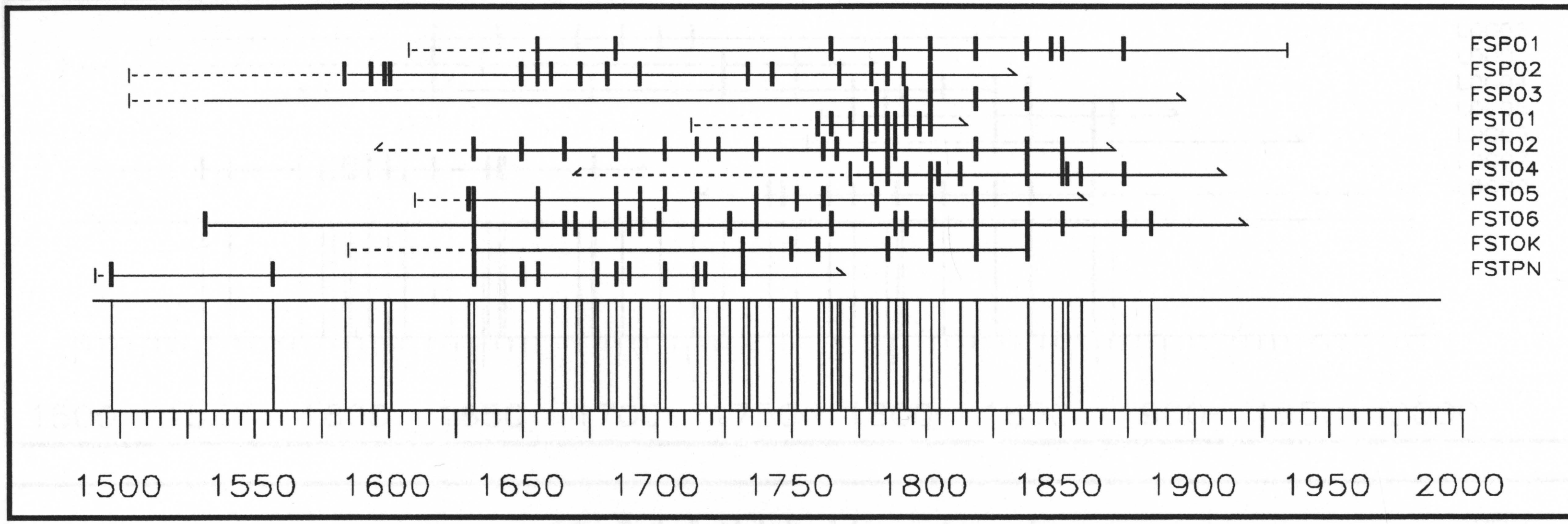
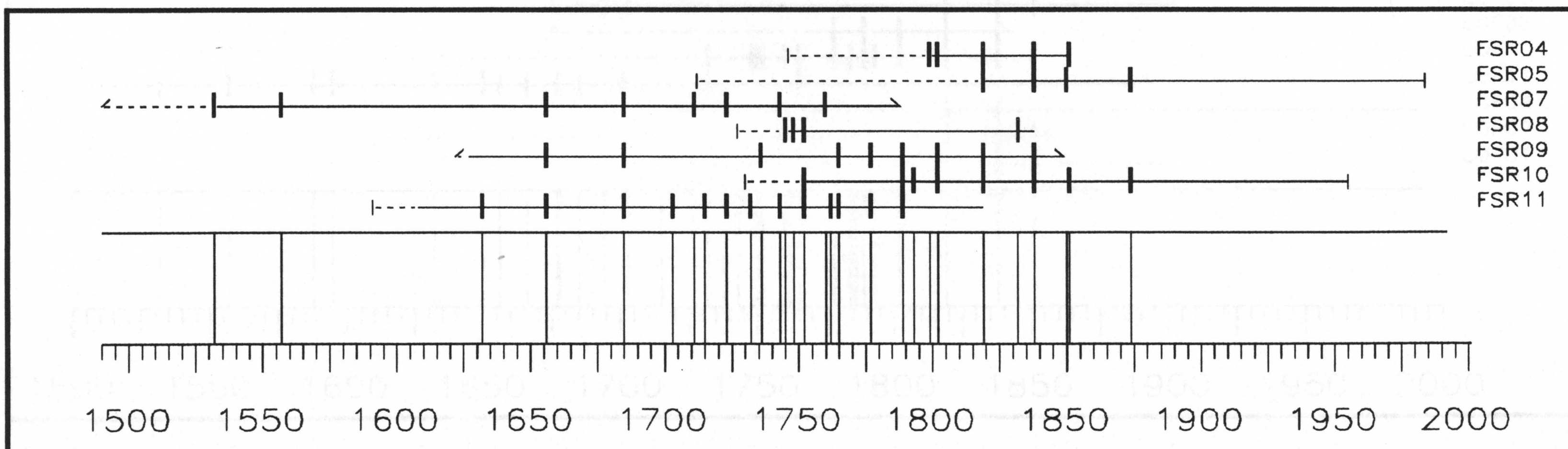


Figure A.4 Fire history chart for OPW. Composite at base of chart shows all fires recorded in site.

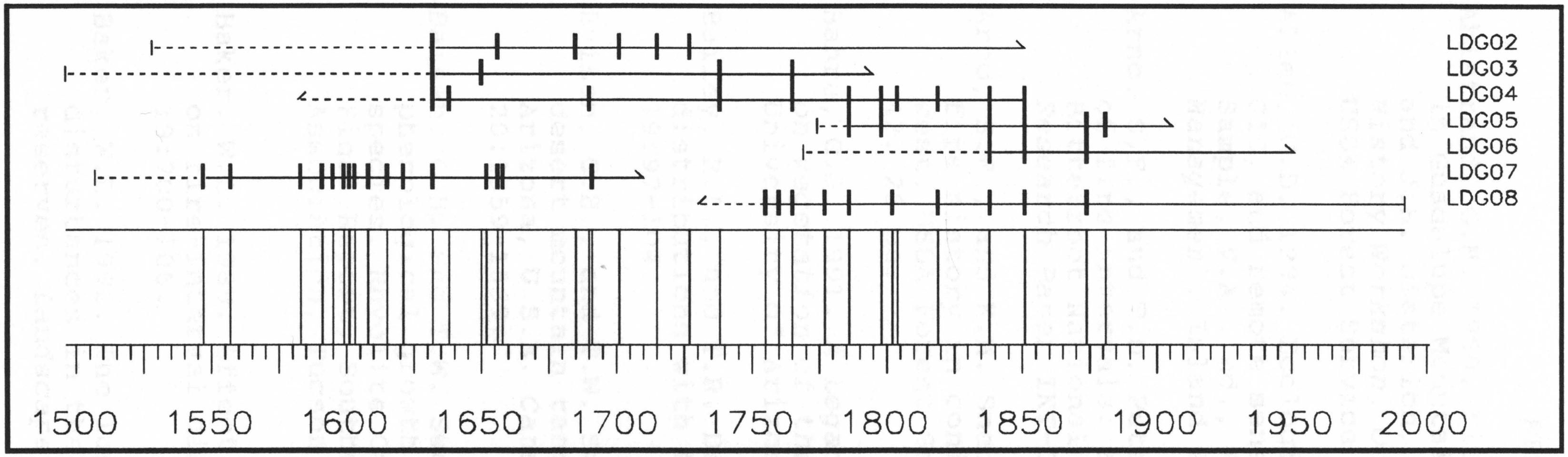


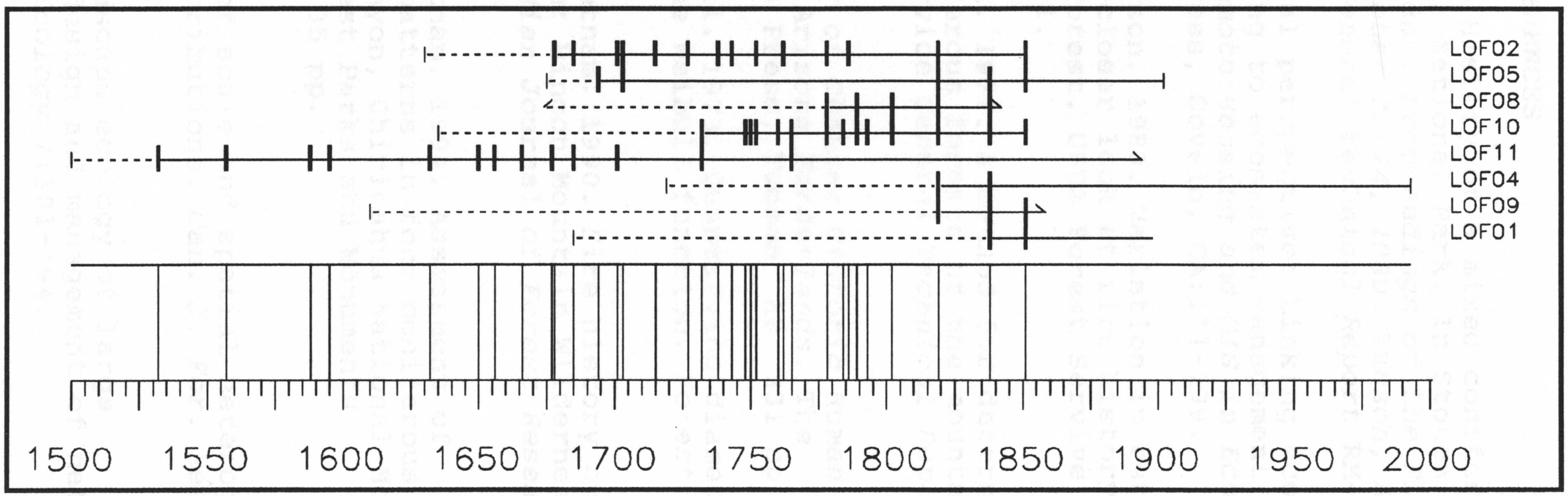
Figures A.5 and A.6 Fire history charts for SCI (top) and NAR (bottom). Composite at base of each chart shows all fires recorded in site.





Figures A.7 and A.8 Fire history charts for FST (top) and FSR (bottom). Composite at base of each chart shows all fires recorded in site.





Figures A.9 and A.10 Fire history charts of LDG (top) and LOF (bottom). Composite at base of each chart shows all fires recorded in site.

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