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Coast redwood fire history and land use in the Santa Cruz Mountains, California

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COAST REDWOOD FIRE HISTORY AND LAND USE
IN THE SANTA CRUZ MOUNTAINS, CALIFORNIA

A Thesis

Presented to

The Faculty of the Department of Environmental Studies

San José State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Gregory A. Jones

August 2014

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COAST REDWOOD FIRE HISTORY AND LAND USE
IN THE SANTA CRUZ MOUNTAINS, CALIFORNIA

by

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APPROVED FOR THE DEPARTMENT OF ENVIRONMENTAL STUDIES

SAN JOSÉ STATE UNIVERSITY

August 2014

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ABSTRACT

COAST REDWOOD FIRE HISTORY AND LAND USE IN THE SANTA CRUZ MOUNTAINS, CALIFORNIA

By Gregory A. Jones

Physical evidence of past fires, left in the form of cambial scars, suggests that low and moderate intensity fires have burned periodically for centuries in the coast redwood (*Sequoia sempervirens*) forest in California's central coast bioregion. These fires may have played an important role in shaping stand age structure and composition. Nonetheless, the ecological role of fire in shaping successional processes in the redwood ecosystem is not well understood. The extent to which both aboriginal and more recent burning practices have affected the central coast landscape is also uncertain. Standard dendrochronology techniques were used to reconstruct and analyze the fire history of the coast redwood forest in the Santa Cruz Mountains based on the fire scar record. Three hundred and seventy-three fire scars were identified in 70 cross-sections that were removed from redwood stumps, downed logs, and trees in select locations between Davenport and Año Nuevo, California. The earliest recorded fire occurred in 1352 and the most recent in 2009. The grand mean fire return interval (FRI) for single trees (point) was 60.6 years, and the median FRI was 40.1 years. Fire scars were found most frequently in the dormant and latewood portions of the annual growth rings, signifying that fires tended to occur in the late summer and fall. A high degree of variability in the data set suggests that cultural burning practices occurred on fluctuating temporal and spatial scales.

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INTRODUCTION

Recent large wildfires in California's central coast bioregion have renewed research interest in the fire ecology of California's coast redwood (*Sequoia sempervirens* (D. Don) Endl.) forests. Throughout their range, the trees' bark and burned basal cavities display evidence of past fires (Jacobs *et al.* 1985, Stephens and Fry 2005). This physical evidence suggests that, for centuries, fires of low and moderate intensities have periodically burned in this forest type, contributing to the development of uneven-aged stands (Stephens and Fry 2005, Lorimer *et al.* 2009). Moreover, redwoods are extremely resilient following disturbances such as fire (Ramage *et al.* 2010, Lazzeri-Aerts and Russell 2014). Despite research documenting adaptations of *Sequoia sempervirens* to disturbance, the ecological role of fire in shaping successional processes in the coast redwood ecosystem is not well understood (Lorimer *et al.* 2009).

The extent to which both aboriginal and more recent burning practices have affected the central coast landscape is also uncertain. An extensive body of literature suggests that Native Americans regularly used fire to manipulate the coastal landscape for a variety of purposes (Keeley 2002, Stewart 2002, Lightfoot and Parrish 2009). Indeed, California's central coastal ranges have experienced multiple burning regimes originating from different groups' land use practices (Greenlee and Langenheim 1990). However, both the spatial scale and frequency of fires and the extent to which burning practices affected vegetation communities and contributed to the landscape physiognomy remain in question. Examining the historic transitions from one style of fire management

to the next may contribute to the understanding of the complex dynamics of human-fire-vegetation interactions in this bioregion (Bowman *et al.* 2011).

Despite the abundant fire history research produced from many other western forest types, a distinct gap in the literature exists regarding the fire regime in the southern range of coast redwoods (Davis and Borchert 2006). Numerous studies examine past fire frequency in coast redwood's northern and central range, but only two studies of this nature have been conducted in the southern range (Greenlee 1983, Stephens and Fry 2005).

The goal of this study was to reconstruct and analyze the fire history of the coast redwood forests in the Santa Cruz Mountains, California, based on the fire scar record. Specifically, the objectives were 1) to describe the fire regime in terms of fire return interval and seasonality; 2) to determine the fire frequency for three distinct time periods (pre-settlement 1352-1849), settlement (1850-1924), and post-settlement (1925-2013); and 3) to assess potential relationships between fire frequency and elevation, slope, aspect, distance from the coast, and both historic and pre-colonial burning practices. The following null hypotheses were tested:

- H_01 : There is no statistically significant difference in the mean fire return interval for each of the three time periods.
- H_02 : There is no statistically significant relationship between the fire return interval and elevation, slope, aspect, distance from the coast, distance from significant Native American cultural sites, and distance from logging-era sawmills.

METHODS

Study Area

This study was conducted in the Santa Cruz Mountains north of Davenport, California, approximately 26 km northwest of Santa Cruz and 100 km south of San Francisco in close proximity to the Pacific coast. Fire scars were collected primarily in three watersheds: Whitehouse Creek, Waddell Creek, and Scotts Creek. A few scars were collected in the Gazos and San Vicente Creek watersheds. The Scotts Creek watershed encompasses approximately 7700 ha, and Waddell Creek encompasses approximately 6990 ha. The Whitehouse Creek watershed is smaller, draining approximately 1300 ha. Elevations range from sea level at the coast to 800 m near the upper reaches of the watersheds. All the watersheds fall within the Central Coast Hydrologic Basin as defined by the California Department of Water Resources (2003). The topography is relatively complex with moderate to steep slopes that range from 30 to 60% with occasional steeper slopes occurring adjacent to the numerous generally east-west-oriented drainages.

Present day large property owners in the study area include Big Basin State Park, the Big Creek Lumber Company, California Polytechnic State University's Swanton Pacific Ranch, Lockheed Martin Corporation, and CEMEX Redwoods, a 3453 ha parcel which was recently acquired by a consortium of San Francisco Bay Area land conservation organizations. Both Swanton Pacific Ranch and Big Creek Lumber employ selective harvesting and uneven-aged forest management practices on their respective land holdings (Swanton Pacific Ranch 2011). Big Basin State Park has conducted

prescribed fires of various sizes periodically since 1978 (Biswell 1989), and Swanton Pacific Ranch has conducted small prescribed burns for research purposes, but all unplanned ignitions in the area are aggressively suppressed. Indeed, Cal Fire documents a 94-98% initial attack success rate in the local conifer fuel types on land under their jurisdictional responsibility in Santa Cruz and San Mateo Counties (California Department of Forestry and Fire Protection 2004).

The climate can be characterized as Mediterranean with cool, wet winters and dry summers. Temperatures are generally mild, ranging from 6.5°C to 23°C, and the mean annual temperature is approximately 15°C. Mean precipitation is approximately 107 cm, falling mostly in the winter and spring in the form of rain with occasional snow on the higher peaks and ridges. Summer fog tends to moderate the seasonal summer drought cycle (Dawson 1998, Johnstone and Dawson 2010). Complex physiographic variation and distance from the coast influences rainfall patterns, the fog gradient, and temperatures (Davis and Borchert 2006). Additionally, the fog gradient is considered a significant determinant in the distribution and the inland extent of coast redwoods (Cooper 1917).

Forest types include stands that are coast redwood-dominant and mixed stands that include common associates such as Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), tanoak (*Notholithocarpus densiflorus* Hook.), California live oak (*Quercus agrifolia* Nee), Pacific madrone (*Arbutus menziesii* Pursh), knobcone pine (*Pinus attenuate* Lemmon), California nutmeg (*Torreya californica* Torr.), and California bay (*Umbellularia californica* [Hook & Ar.] Nutt.). Common understory species include

bracken fern (*Pteridium aquilinum* Kuhn) and Pacific poison oak (*Toxicodendron diversilobum* [Torr. & Gray] Greene). Stands dominated by coast redwood are limited primarily to the lower and middle extents of the numerous drainages and riparian corridors.

Land Use History

The study area provided an ideal site in which to address the study objectives because coastal California is an area where information regarding Native American burning practices derived from oral and recorded histories and ethnographic research can be compared to a fire scar chronology (Stephens *et al.* 2007). Additionally, several of the large property owners have detailed records on past land use, logging history, and fire occurrence on their lands. Because natural (i.e., lightning-ignited) fires are rare and thus not thought to have been a major determinate factor in the dominant fire regimes in the central California coastal ranges, fire occurrence has been primarily limited to anthropogenic origins.

The central coast of California has been inhabited by Native Americans, Spanish explorers and missionaries, Mexican land grant recipients, early Anglo settlers, and its current inhabitants. Fire ecologists often examine land use history to assist in explaining past fire occurrence (Greenlee and Langenheim 1990, Baisan and Swetnam 1997, Gassaway 2007). McBride (1983) proposed that fire history studies include the classification of fire regimes based on land use, and Stuart (1987) distinguished land use history into the following periods: pre-settlement (pre-1875), settlement (1875-1897), and post-settlement (1898-1940). Greenlee and Langenheim (1990) classified five different fire regimes: Ancient (up to 11,000 years before present), Aboriginal (11,000 years before present-1792 A.D), Spanish and Mexican (1792-1848), Anglo (1848-1929), and Recent (1929-present). Alteration of vegetation patterns occurred with the arrival of the first humans to the California coast in the early Holocene (Davis and Borchert 2006),

and Native American burning practices were well documented by the Spanish explorers. In 1792, José Longinos Martinez wrote, “In all of New California from *Fronteras* northward the gentiles have the custom of burning the brush” (Anderson 2005: 273).

The area encompassing the San Francisco peninsula south to Monterey is a region known to have once supported a sizeable native population separated into politically autonomous communities (Milliken 1995). In the vicinity of the study area, the Cotoni tribal band resided near present day Davenport and the Quiroste tribal band lived along the coast adjacent to Point Año Nuevo. The Quiroste tribe has been described as possibly the most prominent polity on the San Francisco Peninsular coast (Milliken 1991). Archaeological and historical information indicates that numerous developments existed during the middle- and late-Holocene including a prominent site that is located in the Quiroste Valley Cultural Preserve (Hylkema and Cuthrell 2013). This 91 ha land parcel encompasses the remains of the “Casa Grande,” a tribal community with pyramidal plank houses and a central large hemispherical structure, first described by the Portolá expedition in October, 1769 (Stewart 2002, Cuthrell 2013). In addition to the Quiroste Valley site (CA-SMA-113), at least eighteen other culturally significant sites have been identified by the presence of prehistoric archaeological remains including mortars and pestles, milling slabs and handstones, cobble tools, chipping debris, projectile points, shells, bones, human remains, and other miscellaneous artifacts (Hylkema 1991).

Although the ecological effects of aboriginal burning practices remain uncertain, an extensive body of literature suggests that Native Americans intentionally used fire as a tool to manage the landscape throughout the middle-to late-Holocene,

effectively creating a mosaic of landscape patches (Keeley 2002, Anderson 2005, Stephens and Fry 2005, Lightfoot and Parrish 2009). Additional research suggests that aboriginal burning may have created selection pressures on vegetation, altering species composition, density, and type (Greenlee 1983). From 500 A.D. until the establishment of the missions in the late 1700s, tribal bands used fire extensively to convert shrubland to grassland endeavoring to improve hunting and food gathering along the coastal plain (Keeley 2002). In addition, fire may have also been used to ease travel; to increase seed, bulb, and fruit production; to increase water resources; and even for fire mitigation around villages (Biswell 1989, Greenlee and Langenheim 1990, Blackburn and Anderson 1993, Gordon 1996, Keeley 2002). Relative to herbaceous communities that establish under high fire frequencies, undisturbed shrublands had fewer resources to offer and restricted access to resources of value (Keeley 2002). While it is improbable that Native Americans burned in dense redwood stands, it is conceivable that fires from coastal shrublands and grasslands spread into the heavier vegetation when both local weather and fuel conditions were conducive to fire propagation.

While the use of fire by Native Americans on the central coast is undeniable, the scale and frequency of these fires, as well as the extent to which these burning practices affected vegetation communities and contributed to the landscape physiognomy, are largely unknown. Although Sawyer *et al.* (2000: 27) characterize the impacts of Native Americans in this area as “relatively light and benign” others contend the landscape was deliberately managed by its native inhabitants (Blackburn and Anderson 1993). Sawyer *et al.* (2000) also claim that the redwood region, in general, supported high human

population levels during the late Holocene. Because fire constituted one of the few tools that Native American populations employed to manage natural resources at the landscape scale, it is probable that their practices accelerated natural fire frequency by burning more frequently than lightning-ignited fires would have. These practices may have also decreased the potential for future lightning fires by reducing receptive fuel beds (Greenlee and Langenheim 1990, Keeley 2002). Nonetheless, the opinion persists that the case for Native American landscape-level fire management is overstated (Vale 1998, Barrett *et al.* 2005). Most likely, the native people altered vegetation assemblages through burning but did not do so with the same intensity in all areas they occupied (Swetnam and Baisan 1996). Considering that pre-colonial population density on the central coast was among the highest in North America (Milliken *et al.* 2009), there appears to be a strong case that Native American burning practices impacted and altered the vegetation and ecology of the central coast (Keeley 2002).

After European contact, native fires were often attributed to carelessness or indifference, and colonial attitudes and racial prejudice may have contributed to the prevailing opinion that Native Americans did not systematically manage their environment in a deliberate fashion (e.g., Clar 1959). The Spanish viewed Indian-set fires as quite destructive, and this burning was put to an end when, on May 31, 1793, the Spanish Governor Arrillaga issued a decree to the missions detailing punishment for Indians convicted of starting fires (Blakely and Barnette 1985). This order, combined with the forced relocation of the native population to the missions and the subsequent

population decline, effectively marked the end of the Native American fire regime on the central coast.

Beginning in 1776, the Spanish engaged in a period of settlement of Alta California, including new construction of the Presidio and Mission of San Francisco. In 1777, these endeavors were followed by the construction of *Mission Santa Clara de Asís* (Mission Santa Clara) and *El Pueblo de San José de Guadalupe* (Pueblo of San Jose) which was the first civil settlement established in Alta California under Spanish control. Despite this flurry of new activity, early demands on local timber resources were not significant as the Spanish, originating from a semi-arid Mediterranean landscape, had developed an architectural style in which other building materials were substituted for wood. Structures were primarily built from adobe bricks with tile roofs with coast redwood generally used only for ceiling beams and rafters, door frames, and windows. As these settlements grew, however, demand for timber increased. Most likely, the timber from the “Pulgas Redwoods” situated at the base of the northeastern reaches of the Santa Cruz Mountains in the area of present-day Woodside and Portola Valley supplied most of the timber for the early Spanish settlements (Brown 1966). By the late 1780s, logging increased to build-out the new settlements, but these harvests were sporadic and only conducted as needed due to the significant distance the timber had to be hauled on primitive wooden *carretas* drawn by teams of oxen. In addition, the Indian neophytes, often referred to as “Indian axemen,” were used to both cut and transport the hewed timber from the mountains (Brown 1966). Mission Santa Cruz was established in 1791 and likely contributed to the exploitation of timber resources on the western side of the

Santa Cruz Mountains, but it did not require these resources on such a sufficient scale to have a large ecological impact. In addition to building construction, the Spanish used timber resources from the Santa Cruz Mountains for shipbuilding and bridge construction beginning with several bridges constructed by the Portolá expedition.

The first records of fire are from 1799 when guards of the “Indian axemen” were injured by a fire in the woods (Brown 1966). Forest fires set by the Spanish loggers were likely set only by accident, as no records exist indicating that fire was used intentionally in support of these early timber harvests. There is some evidence to suggest that the Spanish stockmen engaged in burning chaparral to extend areas of suitable forage and some of these intentionally set fires may have spread into the heavier timber as well (Gordon 1996). Interestingly, the Spanish did engage in fire suppression activities to some degree, as they routinely used companies from the Presidio and Native American labor from the missions to suppress the fires (Brown 1966). It is likely that this fire suppression did not extend far beyond the reaches of the missions and settlements.

The era immediately following the Mexican revolution in 1822 can be characterized by a general deterioration in governmental authority and control. Nonetheless, the Mexican government did believe that the cutting of forests should be restricted and appointed *Guardaboques* (forest wardens) to supervise and regulate timber cutting and grazing. These early attempts to regulate natural resource exploitation may constitute the first official land management policies in California. The *Californios* generally did not engage in timber felling themselves, as they viewed lumbering as

“Indian work” (Clar 1959). There were at least four large Mexican land grants in the general vicinity of the study area (Table 1).

Table 1: Mexican land grants in the Santa Cruz Mountains in the vicinity of the study area.

Land grant	Establishment date	Size (ha)
Rancho Arroyo de la Laguna	1840	1788
Rancho Punta del Año Nuevo	1842	7184
Rancho Aqua Puerca y Las Trancas	1843	1789
Rancho San Vicente	1846	8085

There was no continuous or large-scale exploitation of timber resources on the western side of the Santa Cruz Mountains, at least by the *Californios*, during the era of Mexican control. The Mexican ranchers burned scrub areas but avoided burning grasslands that they needed as year-round forage for cattle (Sugnet 1984). Historic accounts of fire occurrence or management from this era are limited, but it may be assumed that little official action was taken when accidental or unwanted fires did occur.

The first 70 years of timber harvesting by the Native American neophytes, the *Californios*, and an assortment of other “foreigners” left a marginal impact on the forested central coast landscape (Brown 1966). No continuous timber resource exploitation occurred until the early 1830s when the first commercial mills were constructed by the recently arrived Anglo-Americans to meet the needs of the increasing population and for export to foreign markets. By the close of the 1830s, the scale of logging operations increased substantially. Even though homesteads were being established in the Santa Cruz area as early as 1823, the vast majority of logging activity was occurring on the lower flanks of the east side of the Santa Cruz Mountains.

Isaac Grahm built the first sawmill on the west side of the Santa Cruz Mountains in 1842 on Zayante Creek, a tributary of the San Lorenzo River (Stanger 1967). Timber harvests near the coast and the study area increased in the 1860s. There were at least eight mills that operated in the vicinity of the study area from the early 1860s into the early 1900s (Stanger 1967, Mowry 2004). The majority of the mills used wagons to haul lumber to Point Año Nuevo for shipment via Waddell's 215 m wharf, which was located on the south side of Point Año Nuevo. Up to two million board feet of lumber per year were shipped from this wharf between 1864 and 1880 (Stanger 1967). By the late 1880s, the majority of the accessible virgin timber had been logged (Mowry 2004).

Both fire frequency and intensity likely increased with the arrival of homesteaders and loggers after the onset of the gold rush in 1848. Homesteaders increased available farming and grazing acreage by fire as well while loggers were known to have set fires to ease both travel and yarding and to reduce the considerable quantity of slash that was generated during felling and limbing operations. It was not uncommon for loggers to burn the same area both before and after logging (Adams 1969). Logging has continued from the early 1900s up to the present day on varying scales that have largely depended on timber demand and prices. The practice of clear-cutting has left a legacy of even-aged stands of second-growth coast redwood and Douglas-fir, and the evidence of burning can be witnessed on fire-scarred stumps and charred standing trees (Swanton Pacific Ranch 2011).

General apathy towards the practice of both indiscriminate and accidental burning eventually waned. Even before California officially achieved statehood, concerns over

destructive fires in the redwood region were being voiced and received attention at the inaugural session of the California State Legislature (Clar 1959). Initially the State avoided any state-sponsored fire control efforts since it perceived fire prevention to be a personal responsibility. However, a series of subsequent acts passed at both the State and Federal level institutionalized the systems of universal fire suppression currently in place (Clar 1959).

Despite these policies and the relatively high success rates demonstrated by initial attack fire suppression resources, large fires continue to occur periodically in the Santa Cruz Mountains. The Pine Mountain Fire burned 6400 ha in 1948 (Stephens *et al.* 2004), the Summit Fire burned 1728 ha in May 2008, and the Lockheed Fire burned 3163 ha in August 2009. Notwithstanding recent incidences, widespread fires are not the norm in the current era; the mean fire size in the Santa Cruz Mountains from 1929 to 1979 was 34.6 ha (Greenlee 1983).

Fire History

The primary objective of this study was to reconstruct and analyze the fire history of the coast redwood forest in the Santa Cruz Mountains using standard dendrochronology techniques (Stokes and Smiley 1968, Arno and Sneek 1977). Fire scar dendrochronology is a well-established methodology for reconstructing fire regimes in forests that experience low- and moderate-intensity surface fires. Redwood trees often display fire scars in their annual growth rings and triangular-shaped, burned-out basal cavities (Jacobs *et al.* 1985, Stephens and Fry 2005). Fire frequency and seasonality in this study area were reconstructed by determining the position of these scars within the context of the annual growth rings.

One hundred and three cross-sections were removed from 95 coast redwood trees in select locations in three watersheds in 2012 and 2013 (Figure 1). Fire-scarred specimens were identified and sampled on an opportunistic basis. Such targeted sampling has been demonstrated to yield comparable results to random or grid-based sampling (Van Horne and Fule 2006) and has often been necessary to obtain adequate data sets for this forest type (Brown and Baxter 2003, Stephens and Fry 2005). Entire or partial cross-sections (approximately 5-8 cm thick) were extracted from both live and remnant wood (i.e., stumps, downed logs, and snags) using a chainsaw (Arno and Sneek 1977, McBride 1983). Less than 10% of the cross-sectional area of the boles of snags and live trees was removed, thus minimizing the potential for mechanical failure (Heyerdahl and McKay 2008). Both young and old specimens were selected in order to maximize the length and completeness of the temporal record (Farris *et al.* 2010).

Initially, adequately preserved stumps with intact sapwood, downed logs, and trees that were not overly decayed or degraded and that displayed multiple externally-visible fire scars were prioritized for sampling (Speer 2010). However, subsequent examination of the cross-sections revealed that scars were often completely healed-over and thus were not visible on the exterior surfaces of the wood (Stephens *et al.* 2004). Therefore, the practice of exclusively targeting samples with external scars was deemed inadequate and was subsequently abandoned. Units that were recently logged in the post-Lockheed Fire salvage operation were often preferentially selected to increase the prospect of having intact bark and sapwood that assisted in assigning accurate calendar dates. Sections were removed from a variety of locations on the basal flutes and tree boles to accurately capture the most complete scar record possible. Some research suggests that extracting cross-sections from the base of basal flutes or buttresses near the ground surface may provide the most complete inventory of scars (Brown and Swetnam 1994, Norman 2007, Norman *et al.* 2009). This method was employed when possible. The following information was recorded for all the samples: date sample taken, location (UTM coordinates), condition (snag, stump, log, or live tree), height of the cross-section on the bole (cm), vegetation cover, diameter (cm), aspect (cardinal directions), slope steepness (%), position on slope, elevation (m), fire scar orientation (degrees from upslope), and harvest date (if known). Sampling locations were recorded using Global Positioning System [GPS] technology and photographed, but were not permanently marked. All fire-scarred samples were labeled and packaged for transport to the University of California, Berkeley for preparation and laboratory analysis.

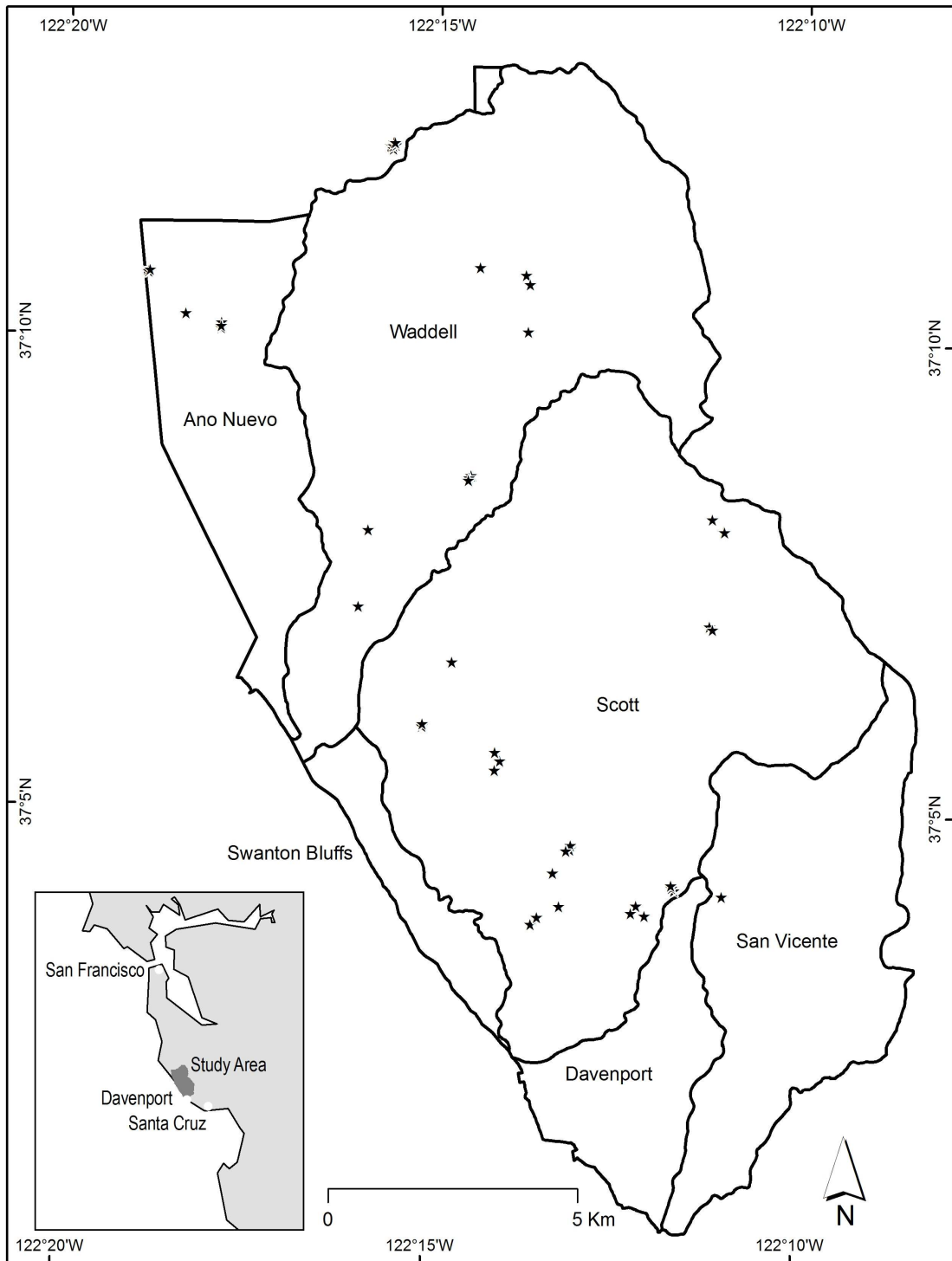


Figure 1. Coast redwood fire history study sites (indicated by stars) in the Santa Cruz Mountains, California within labeled watersheds.

An inventory of fire scars with the broadest possible temporal and spatial distribution from samples that were representative of the study area with respect to terrain and vegetation was assembled (Stephens *et al.* 2003, Swetnam and Baisan 2003, Stephens and Fry 2005). Where possible, clusters of five to seven well-preserved stumps in areas of five ha or less were sampled where fire spread throughout the entire plot was assumed (Dieterich 1980, Stephens and Fry 2005). Although cross-dating was not conducted in this study, collecting clusters of scars was useful for plot-level comparisons of fire frequency.

Emphasis was placed on targeting areas in close proximity to Native American settlements (Gassaway 2007, Norman 2007). The locations of these settlements originated from site-specific archaeological and ethnographic data that were provided through collaboration with the California State Parks (Santa Cruz District) and the Northwest Anthropological Information Center in Rohnert Park, California.

Decay and degradation of stumps, logs, and snags due to logging and subsequent fire, combined with general constraints property owners placed on cutting into live trees, severely limited the amount of material that was deemed suitable for sampling and prevented the desired sampling intensity in many locations. Only four plots of five ha or less contained an adequate number of samples for comparative analysis.

Fire-scarred specimens were prepared and analyzed using standard dendrochronology techniques (Stokes and Smiley 1968, Orvis and Grissino-Mayer 2002). Samples were air-dried and sanded to a high sheen starting with 40 grit and progressing to 400 grit sand paper. The process of using progressively finer sand paper eliminated

scratches in the wood left by the coarser grits of paper (Speer 2010). The wood surfaces were sanded until the cellular structure within each annual growth ring and the position of the fire scars within the ring series could be viewed clearly under a stereo microscope with 7-45X magnification. Counting the annual rings was initiated inward from the bark or the outermost visible ring, with this ring being the year the tree was sampled or died (year zero). Fire scars were identified by the presence of a charred gap within the ring and subsequent overlapping curvilinear growth that is characteristic of the tree's healing pattern. (McBride 1983). In addition, other fire-associated ring characteristics including traumatic resin ducts, double latewood, and growth releases were used to confirm the presence of a scar often found elsewhere along the circumference of the cross-section (Brown and Swetnam 1994). The season of fire occurrence was determined by assessing the position of the scar within the annual growth ring (Caprio and Swetnam 1995). Many fire historians have identified season to the specificity of early earlywood, middle earlywood, late earlywood, latewood, dormant, or undetermined (Ahlstrand 1980, Dietrich and Swetnam 1984, Caprio and Swetnam 1995) but this study grouped all three earlywood distinctions into the single category of earlywood.

Accurate cross-dating of redwoods has proven notoriously difficult (Fritz 1940, Brown and Swetnam 1994, Waring and O'Hara 2006, Lorimer *et al.* 2009). Consequently, fire return intervals (the number of years between successive fire events in a designated area) were based on ring counts between consecutive fire scars (Romme 1980, Jacobs *et al.* 1985, Finney and Martin 1989, Agee 1993, Stephens and Fry 2005). Attempts were made to corroborate common fire dates for the datable samples between

trees in close proximity to one another, but intervals from separate trees and clusters were not composited.

Of the 70 cross-sections that were analyzed, 51 were floating chronologies that provided undated interval data and 19 proved datable because they were either extracted from live trees ($n = 11$) or had reliable harvest dates ($n = 8$). All dates were considered estimates because cross-dating was not conducted. Each sample had to exhibit at least two scars, thus providing a minimum of one fire interval to be included in the analysis. Additionally, intervals were only computed from scar to scar; the period from the tree origination date to the first fire scar (*sensu* Baker and Ehle 2001) was not used in calculations.

A tree was considered a recorder tree if it had scarred at least one time, thus becoming more susceptible to future scarring on the exposed sapwood. For each cross-section from recording trees, the point minimum, maximum, median, mean, and range of fire return intervals were calculated. The point (single tree) mean fire return interval was defined as the statistical average of all fire intervals in each individual sample and was calculated by recording the number of annual growth rings between each successive fire scar, summing the fire intervals, and then dividing this result by the total number of intervals. The point mean number of scars per sample was determined for the entire data set, as well as the grand mean (point) FRI for single trees. A frequency distribution, which displays the percentage of intervals found within each five and ten year time period was made for each plot and the entire data set.

Analysis of variance (ANOVA) was used to test the null hypothesis that the grand mean FRI for each cluster was not significantly different from one another. A non-parametric, two-sample Kolmogorov Smirnov (K-S) was used both to test the null hypothesis that the distributions were not significantly different and to test if each data set was normally distributed and was consistent with a lognormal distribution.

FHX2: Fire History Software, a DOS-based utility, was used to analyze the datable samples, including the calculation of the mean number of recorder years, as well as the analysis of the seasonality and fire frequency data (Grissino-Mayer 2001). Proper data format was verified using the Format File Module, and a chronology graph was created in the Graphics Module of the Fire History Analysis and Exploration System (FHAES). FHAES is based on FHX2 but uses a JAVA platform.

The total number of scars by ten-year time periods was determined and a curvilinear regression analysis was conducted to assess the potential relationship between time period and the incidence of scarring. This study delineated the three following time periods for fire regime comparisons: pre-European settlement (1352-1848), settlement (1849-1924), and post-settlement (1925-2013). Point fire return intervals were determined and ANOVA and K-S tests were used to assess significant differences in the mean FRI and interval distribution for each time period. Potential relationships between the FRI and elevation (m), slope (%), aspect (degrees), distance from coast (m), distance from archeological sites (m), and distance from sawmills (m) were assessed for the entire study area using a multiple linear regression analysis. Significant independent variables

were tested in a stepwise regression in order to build a predictive model of fire frequency drivers.

RESULTS

One hundred and three cross-sections were removed from 95 trees in select locations in three watersheds. Decay and degradation of remnant wood, due to post-harvest fires, restricted the number of cross-sections suitable for study. All cross-sections were sanded and prepared for analysis. Thirty-three samples were omitted from analysis because they had no fire scars ($n = 10$), only displayed one fire scar and thus contained no fire interval data ($n = 15$), or were too degraded to provide reliable data ($n = 8$). Of the 70 samples deemed suitable for analysis, 11 were removed from living trees. The remainders of the samples were remnant material removed from stumps, logs, and snags. One sample was removed from a lateral limb that displayed a datable fire scar from 1895, but was excluded from analysis because of lack of subsequent scarring (Table 2).

Table 2. Sampling data summary from the Santa Cruz Mountains, California.

Total trees sampled	95
Live trees	11 (15.7%)
Stumps	78
Logs	4
Snags	9
Limbs	1
Total cross-sections	103
Cross-sections omitted	33
Cross-sections analyzed	70
Cross-sections dated *	19

* Dates are considered estimates as cross-dating was not employed.

Three hundred seventy-three fire scars were identified in 70 whole or partial cross-sections. Elevation, slope, aspect, position on the slope, and distance from the coast varied for each sampling location. The mean number of fire scars on a tree was 5.3

(median 5; range 2-13; SE, 0.37). The grand mean fire return interval (FRI) for single trees (point) was 60.6 years (range of means 7.5-518 years; SE, 8.90.) Because this data set had a high degree of variability with some very long fire-free intervals, the median (40.1 years) was a more reliable metric of central tendency. Four plots were established that contained clusters of fire-scarred specimens in a less than 5 ha area. The grand point mean FRI for each cluster ranged from 34.1 to 47.0 years (Table 3).

Table 3. Grand point fire return interval data from the Santa Cruz Mountains, California. SE = standard error of the mean.

Cluster	Count	Fire scars (#)	Intervals (#)	Mean FRI (yr)	SE	Median FRI (yr)	Range
Study Area	70	373	303	60.5	8.90	40.1	511 (7-518)
1	7	50	43	59.8	12.57	47	85 (26-112)
2	8	30	22	35.3	7.19	34.1	65 (8-73)
3	6	31	25	62.8	22.71	36.8	142 (29-172)
4	5	19	14	39.3	5.65	36.9	32 (29-61)

The FRI frequency distribution for the entire study area exhibited a positive (right) skew (Figure 2). For the entire study area, many of the fire intervals were relatively short, and there was an equal percentage of intervals in the ≥ 10 year and 11-20 year interval classes (1-10 = 21.1%, 11-20 = 21.4%). Of all intervals, 13% fell within the 21-30 year interval class, while 11% of the intervals fell within the 31-40 year interval class. The longer interval classes encompassed the remaining 33% of the intervals. Although the longest interval class captured all intervals that exceeded 200 years, there were three intervals (1.3%) that exceeded 300 years. A similar pattern was detected for the distribution based on 5-year interval classes (Figure 3).

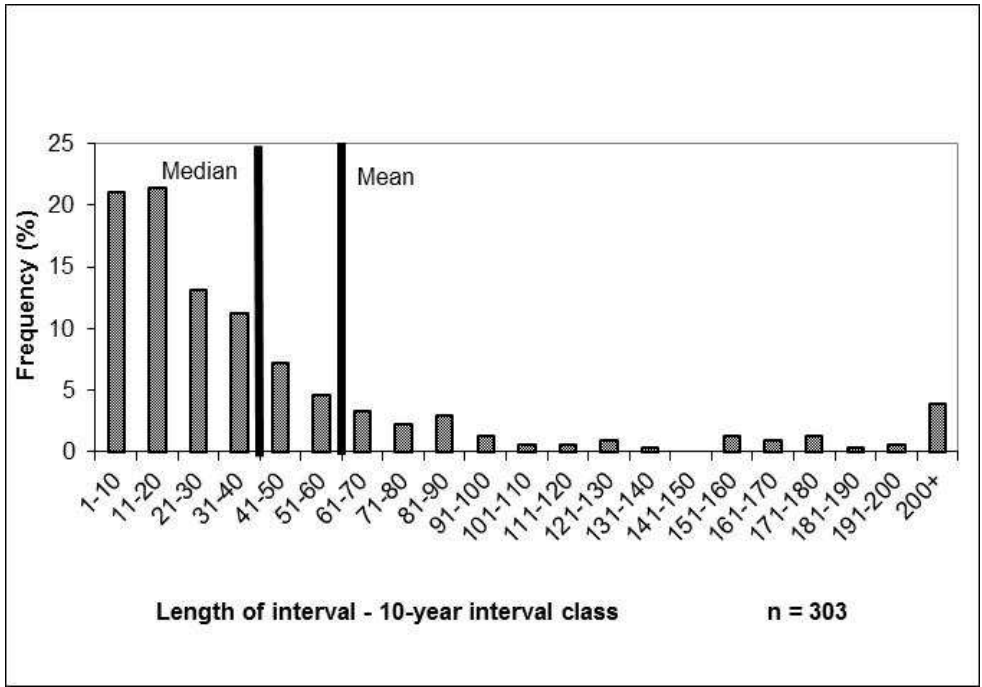


Figure 2. Fire return interval frequency distribution in ten year increments for a coast redwood forest in the Santa Cruz Mountains, California.

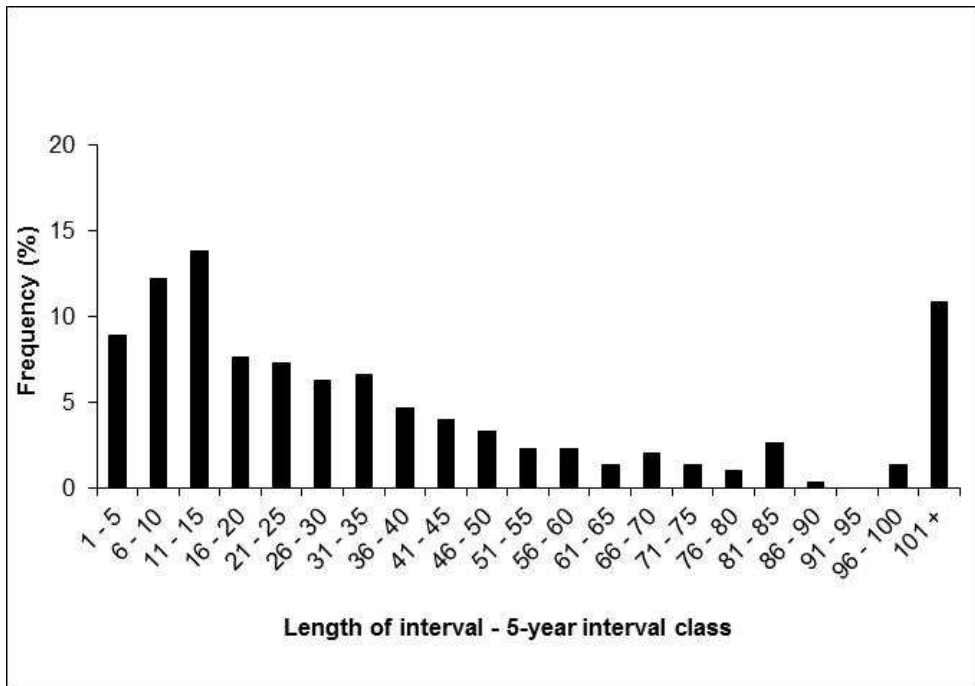


Figure 3. Fire return interval frequency distribution in five year increments for a coast redwood forest in the Santa Cruz Mountains, California.

Similar to the frequency distribution for the entire study area, the distributions for each of the four clusters exhibited positive skews (Figures 4, 5, 6, and 7). Further, non-parametric, two-sample Kolmogorov-Smirnov (K-S) tests failed to detect significant differences in the clusters' distributions (i.e., the distributions were not drawn from the same distribution; P values ranged from 0.27 to 0.93). Additionally, the K-S tests determined that none of distributions were normally distributed and that all the distributions (with the exception of that of cluster #3) were consistent with a lognormal distribution. Cluster #3 exhibited a higher percentage of fire intervals in the 11-20 year interval class (36% of the distribution) relative to the other clusters, but it exhibited a marked decline in the number of intervals in the 21-30 year interval class relative to the other three fire interval frequency distributions (Figure 6). Analysis of variance (ANOVA) testing failed to detect statistically significant differences in the grand point mean FRI of each cluster ($P = 0.36$).

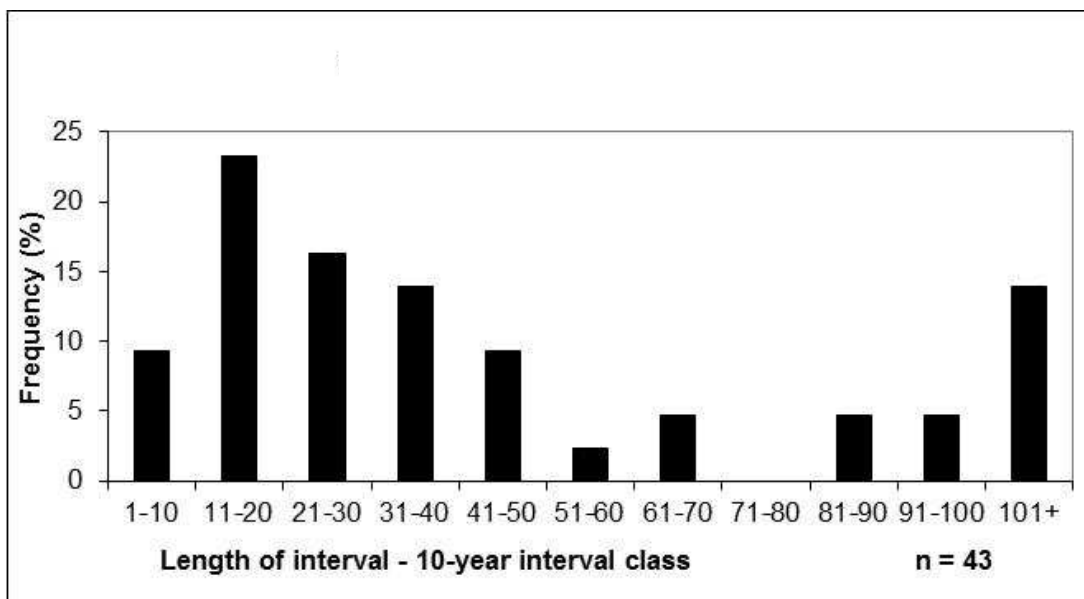


Figure 4. Fire return interval frequency distribution in ten year increments for cluster #1 in the Santa Cruz Mountains, California.

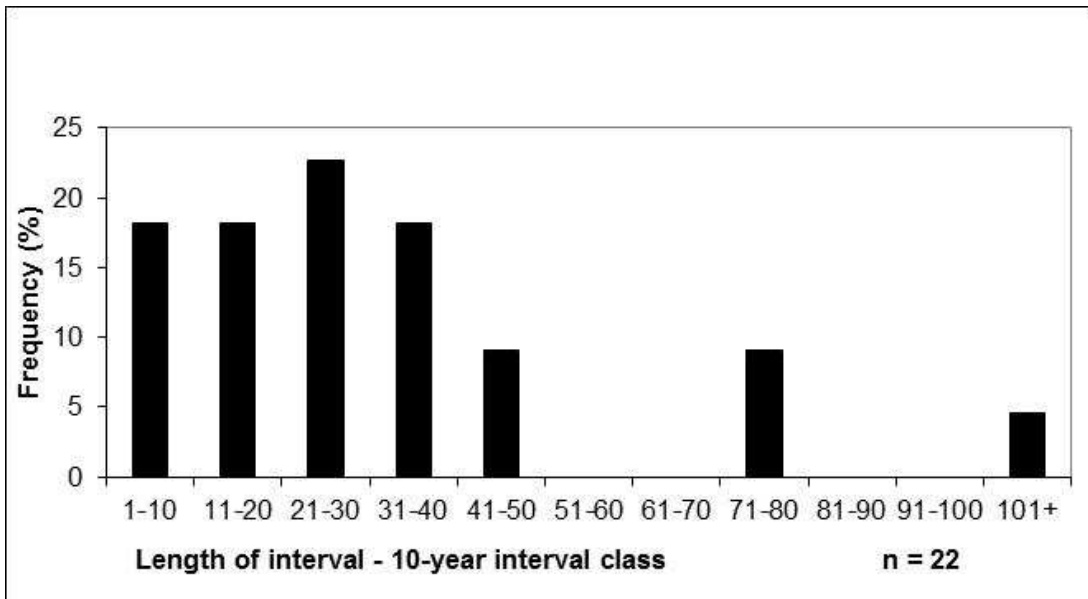


Figure 5. Fire return interval frequency distribution in ten year increments for cluster #2 in the Santa Cruz Mountains, California.

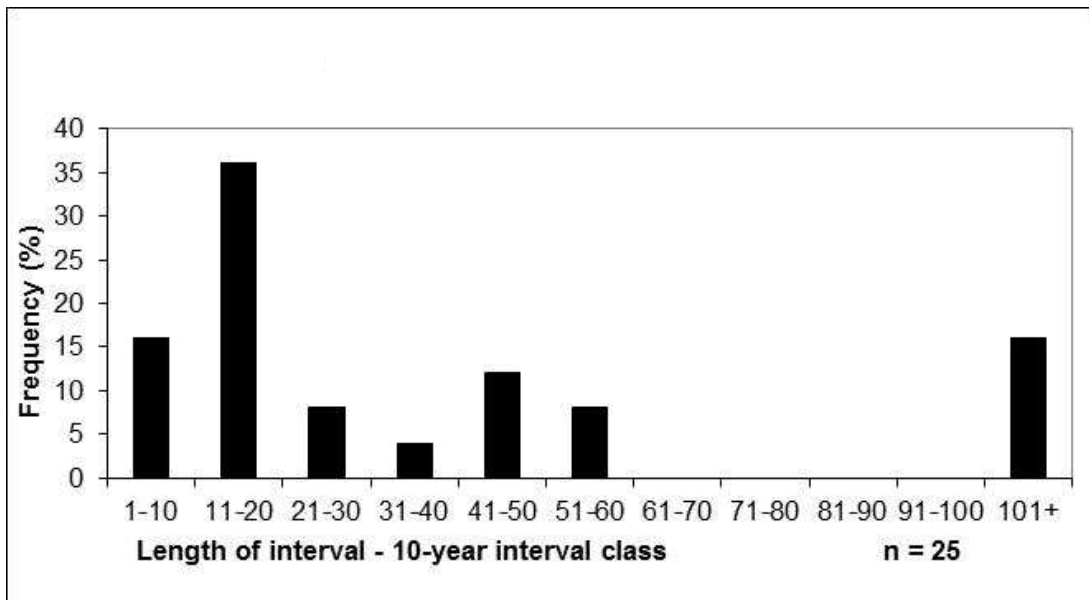


Figure 6. Fire return interval frequency distribution in ten year increments for cluster #3 in the Santa Cruz Mountains, California.

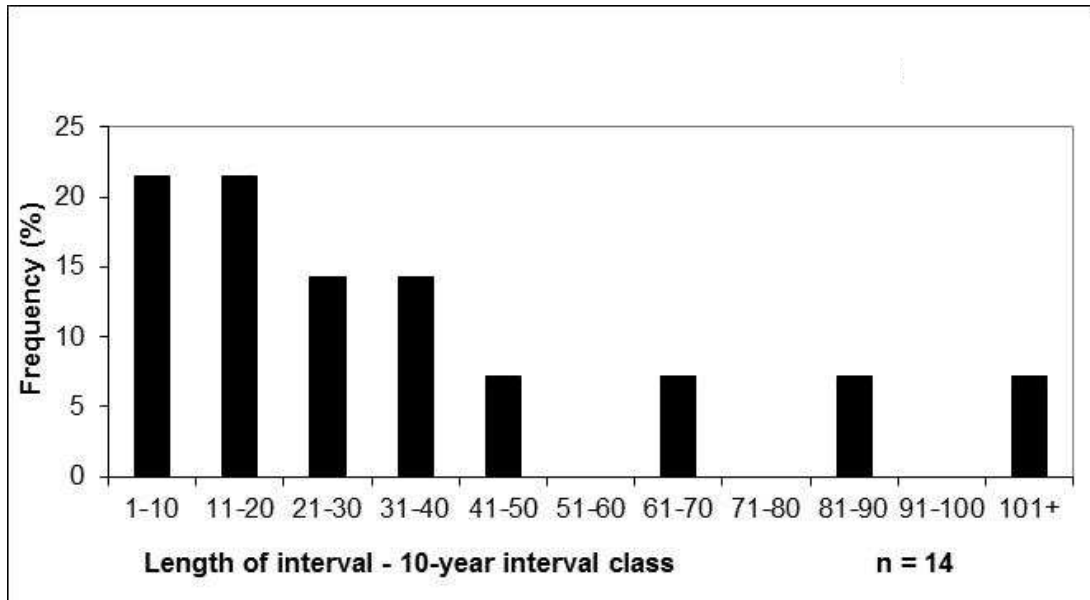


Figure 7. Fire return interval frequency distribution in ten year increments for cluster #4 in the Santa Cruz Mountains, California.

Eleven samples were extracted from live trees, and reliable bark dates were determined for an additional eight samples based on consultations with land owners. For these dated samples, 110 fires and 91 fire return intervals were recorded from 4395 total recorder years (all sample series combined). The total range of years for the samples was estimated to be 1182 to 2013. The mean tree-ring series length was 402 years (range 96-828 years; SE, 45.8). The mean number of recorder years was 225 (58% of the total series; range 64-658 years; SE, 37.5). The mean number of scars per sample was 5.7 (SE, 0.82) with a range of 2-13 scars per sample. The minimum fire return interval (FRI) was a single year, and the maximum interval was 188 years. Point mean intervals for individual trees ranged from 10.4 to 128 years. The earliest fire scar indicated a fire date of 1352 and the most recent a fire date of 2009; presumably the 3163 ha Lockheed Fire (Figures 8 and 9).

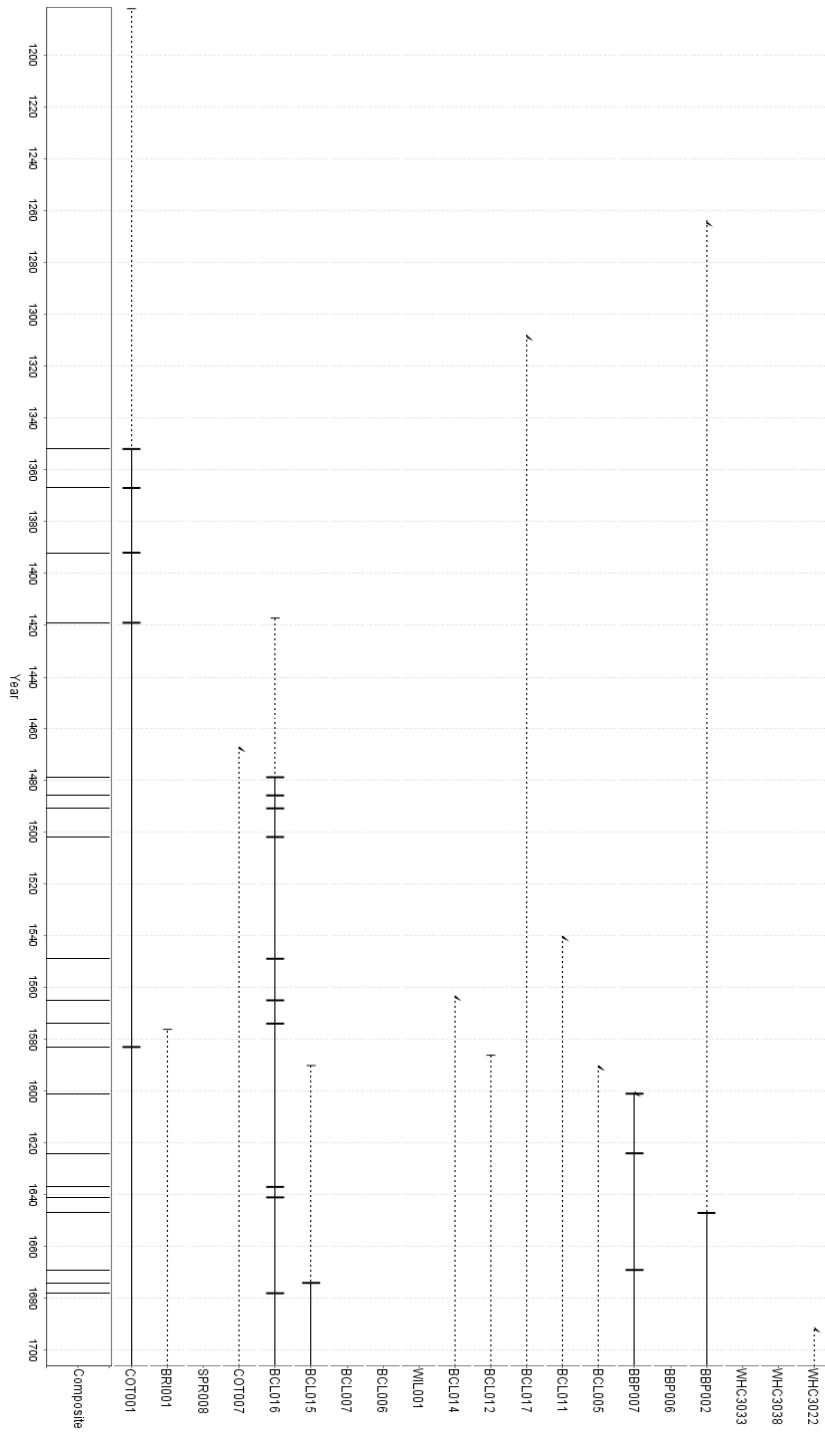


Figure 8. Chronology for dated samples (1182-1700) in the Santa Cruz Mountains, California. Horizontal lines are individual fire scar samples and vertical ticks indicate fire scars. Null years are indicated by horizontal dotted lines and recorder years by horizontal solid lines.

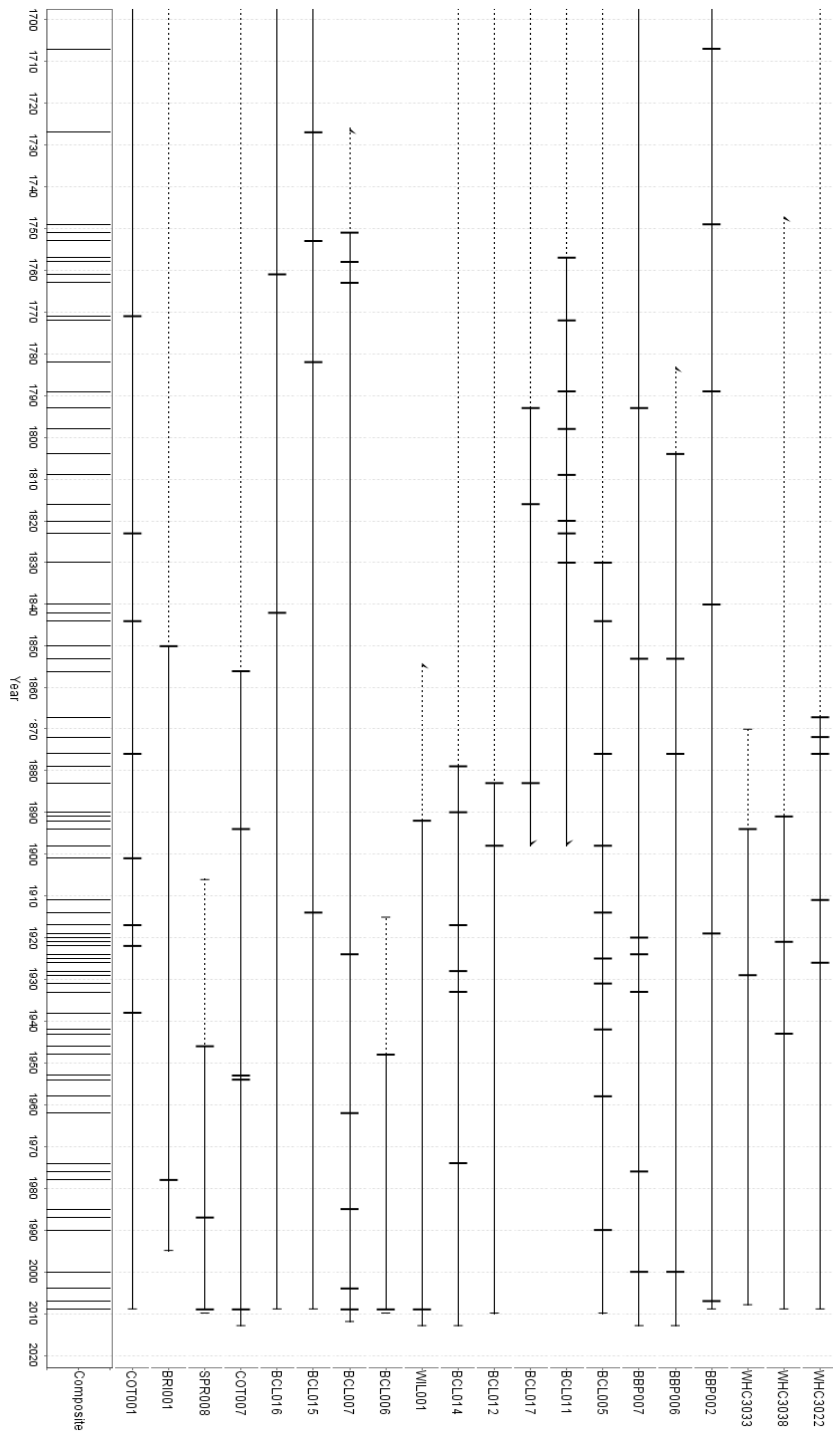


Figure 9. Chronology for dated samples (1700-2013) in the Santa Cruz Mountains, California. Horizontal lines are individual fire scar samples and vertical ticks indicate fire scars. Null years are indicated by horizontal dotted lines and recorder years by horizontal solid lines.

Although it appears that multiple trees were scarred in the same years on 16 separate occasions, indicating periods of relatively widespread fire, these fire dates cannot be considered absolute. The mean number of fire scars per sample was variable until *ca.* 1770 when the incidence of scarring increased. This trend continued until *ca.* 1920 when the incidence of scarring peaked. This increase in scarring was temporary as scarring decreased after the 1930s. The curvilinear regression analysis illustrates these trends in the incidence of scarring but variability in the data set may have contributed to a relatively weak relationship ($R^2 = 0.3407$) between each ten year time period and the mean number of fire scars per sample (Figure 10).

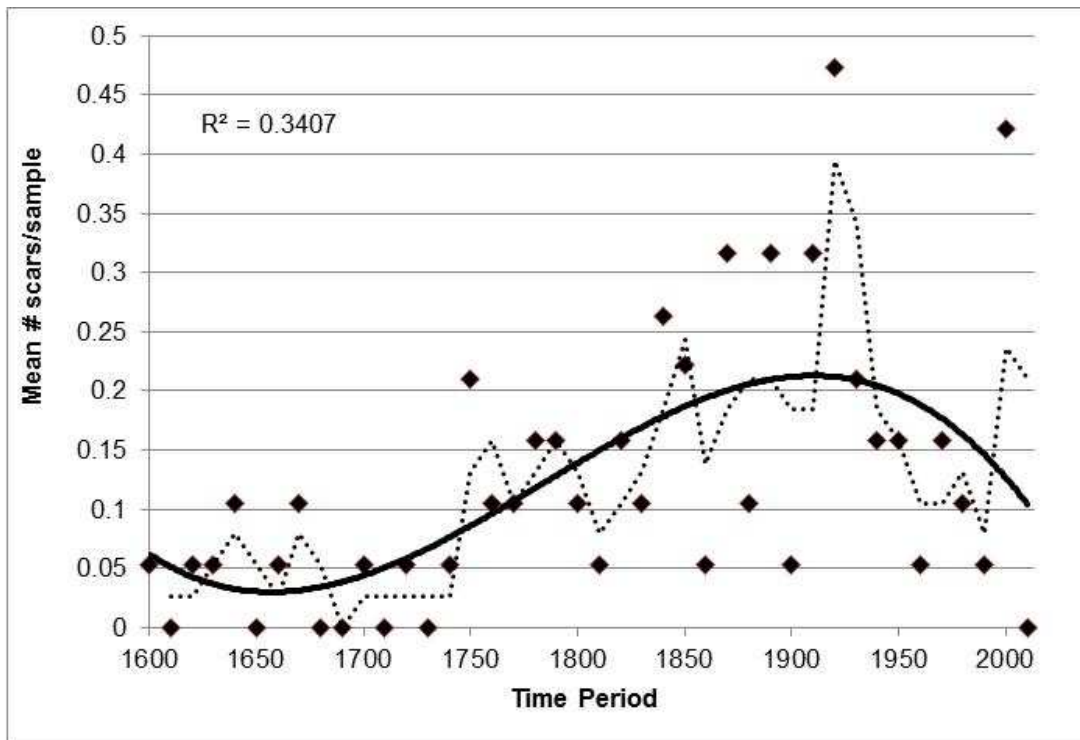


Figure 10. Fire scar frequency per ten year periods (1600-2013) in the Santa Cruz Mountains, California. The dotted trend line indicates a two-period moving average and the solid trend line displays a cubic polynomial curve.

Point fire return intervals were examined in the context of three distinct periods correlated with land use: pre-settlement (1352-1848), settlement (1849-1924), and post-settlement (1925-2013). The earliest fire recorded was in 1352. For the period from 1352 to 1848, the mean point FRI was 43.3 years (median, 26.5; range, 3-185; SE, 6.90). For the period from 1849 to 1924, the mean FRI length decreased to 30.7 years (median, 23; range, 4-128; SE, 6.18). For the period from 1925 to 2013, the mean FRI increased slightly to 32.3 years (median, 22.5; range, 1-124; SE, 5.93). Analysis of variance testing failed to detect a significant difference in the mean FRI for each time period ($P = 0.34$) (Table 4). Non-parametric, two-sample Kolmogorov-Smirnov tests also failed to detect differences in the time periods' FRI distributions (P values ranged from 0.32 to 0.90).

Table 4. Fire return interval data for dated samples by time period in the Santa Cruz Mountains, California. SE = standard error of the mean.

Time period	Fire scars	Intervals (#)	Mean FRI (yr)	SE	Median FRI (yr)	Range
1352-1849	49	44	43.3	6.90	26.5	185 (3-188)
1850-1924	36	23	30.7	6.18	23.0	124 (4-128)
1924-2013	27	24	32.3	5.93	22.5	123 (1-124)

Seasonality of fire occurrence was determined for 296 of the 373 (79.4%) fire scars found in the entire study area. The majority of the fires were detected in the latewood (17.7%) and dormant (53.4%) portions of the annual growth rings, indicating that most fires occurred in the late summer and fall. By contrast, only 8% of the fires were detected in the earlywood (Figure 11).

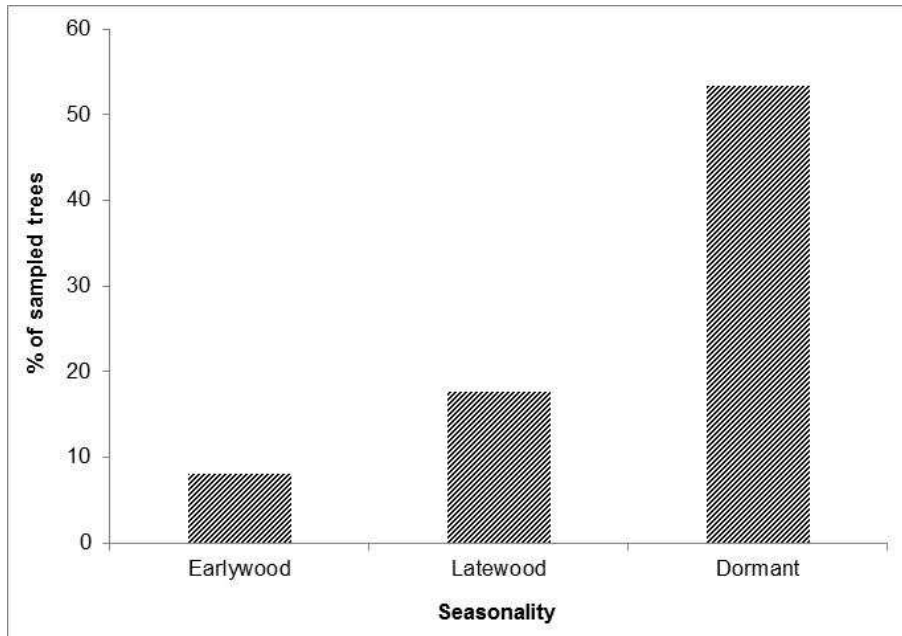


Figure 11. Percentage of fire scar intra-ring positions in the Santa Cruz Mountains.

A multiple linear regression was conducted to estimate potential relationships between fire frequency and elevation, slope, aspect, distance from the coast, distance to closest known archaeological site, and distance to the closest historic sawmill (distances were calculated in a Geographic Information System [ArcGIS] using the proximity function). This analysis detected no significant relationship between the FRI and elevation, slope, and distance from the coast (P values = 0.083, 0.202, and 0.095, respectively). Significant linear relationships were detected for aspect, distance from the closest archaeological site, and distance to the closest historic sawmill. These three variables were used in a stepwise regression to build the most robust model of fire interval predictors. Backward elimination deleted aspect as an independent variable, leaving both distance to closest known archaeological site and distance to the closest historic sawmill as significant predictive variables (P values = 0.017 and 0.018, respectively; $R^2 = 0.025$).

DISCUSSION

Evidence of fire throughout the range the coast redwoods is ubiquitous, but past reporting of fire frequency has been highly variable. Robust comparisons of fire frequency in this forest type are confounded by differing field and analytical methods, as well as the reporting of frequency metrics on varying spatial scales (Finney and Martin 1992, Stephens and Fry 2005). Sampling in varying degrees of relative dominance of forest cover may affect the FRI as well. This study presents longer, and likely more conservative, estimates of fire frequency than previously reported in the southern range of redwoods. The difficulties in cross-dating redwoods have been previously discussed and no attempts were made to cross-date this data set; thus, fire return intervals in this study are reported as point (single tree) or grand mean point estimates (the average of single tree estimates) rather than composite estimates. Whenever absolute calendar dates are assigned to tree-ring series through the process of cross-dating, compositing at the plot level may be a more accurate metric of the true fire frequency (Dieterich 1980) because individual trees can be poor recorders of every fire event (Dieterich and Swetnam 1984). This assertion seems especially relevant to the coast redwood whose thick bark can protect the cambium from scarring during low-intensity fires (Finney and Martin 1989). Importantly, the estimate of the composite fire return interval can be up to half as long as the point estimates (Agee 1993). Some studies report composite estimates of the FRI for the coast redwood without cross-dating, thus producing substantially lower estimates of fire frequency than this study. This difference in analytical methods makes comparisons between studies challenging.

Differences in field methods may also account for variation in FRI reporting. Some research suggests that removing cross-sections from as low as possible on the tree's bole (up to 22 cm) provides the most complete fire record (Brown and Swetnam 1994, Norman *et al.* 2009). This study attempted to emulate this method and removed cross-sections from a mean of 22 cm above the ground. One 9.5 cm thick cross-section displayed two scars on the bottom of the cross-section and no scars on the top, thus lending credibility to assertions that the location on the trunk from which a sample is removed can influence the quantity of fire scars that are found.

Relatively short fire return intervals ranging from 6.2 to 12.4 years have been recorded for inland groves where the coast redwood tend to grow in isolated clumps (Finney and Martin 1992, Stephens and Fry 2005). These fires were likely a subset of fires that burned in adjacent or nearby grass or brush vegetation types that may have different fire regime characteristics that include more frequent fire occurrence (Stephens and Fry 2005). This study, in contrast, was conducted in coast redwood-dominant stands. Jacobs *et al.* (1985) reported mean intervals of 22 to 27 years in Muir Woods National Monument in southwestern Marin County, approximately 19 km north of San Francisco. These estimates were produced from stands that more closely resemble those sampled for this study, and the intervals reported are closer to the results found in this study with a median FRI of 34.1 to 40.1 years. Greenlee (1983) estimated a mean FRI of 56 years from two stumps in Big Basin State Park, an area that was included in this study, and his estimate of fire frequency falls within the range of intervals found in this study as well. These results are consistent with previous findings, as more mesic forests found near

coastal areas and in canyon bottoms burn less frequently than more xeric inland sites because higher relative humidity results in moist fuels which are less available to ignite and promote fire spread (Veirs 1985, Martin and Sapsis 1991, Heyerdahl et. al 2001).

Commonly reported metrics of central tendency for fire frequency statistics are the mean, median, and Weibull Median Probability Interval (Grissino-Mayer 1995). Although it is apparent that the median may provide a more accurate representation of central tendency than the mean in non-normal, positively skewed distributions, the variability in the remainder of the distribution to the right of the mean or median is often under-emphasized. Further, neither the mean nor the median FRI may be representative of the interval variability found in longer records from non-stationary fire regimes (Swetnam 1993). Analyzing the variation between intervals within a single study area may be more important in developing an understanding of how fire effects landscape heterogeneity (Skinner 1997, Taylor and Skinner 1998). Variability in the fire return interval may contribute to heterogeneity by influencing forest composition and structure, competitive dynamics, and patterns of floral and faunal diversity (Martin and Sapsis 1991, Ramage *et al.* 2010).

The fire return interval distribution from this study are similar to distributions from other coast redwood studies in that relatively short intervals comprise the majority of the distribution, thus creating a positive skew. However, these results are distinguished by an elevated frequency of longer intervals, thus creating more variability in the data set (Figures 12 and 13).

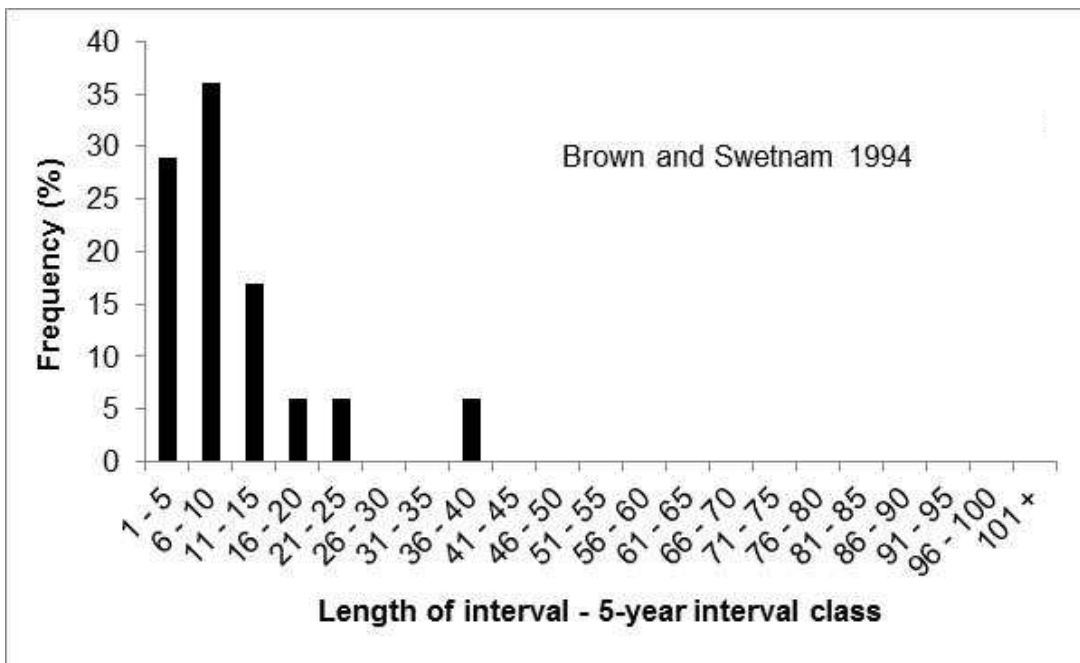
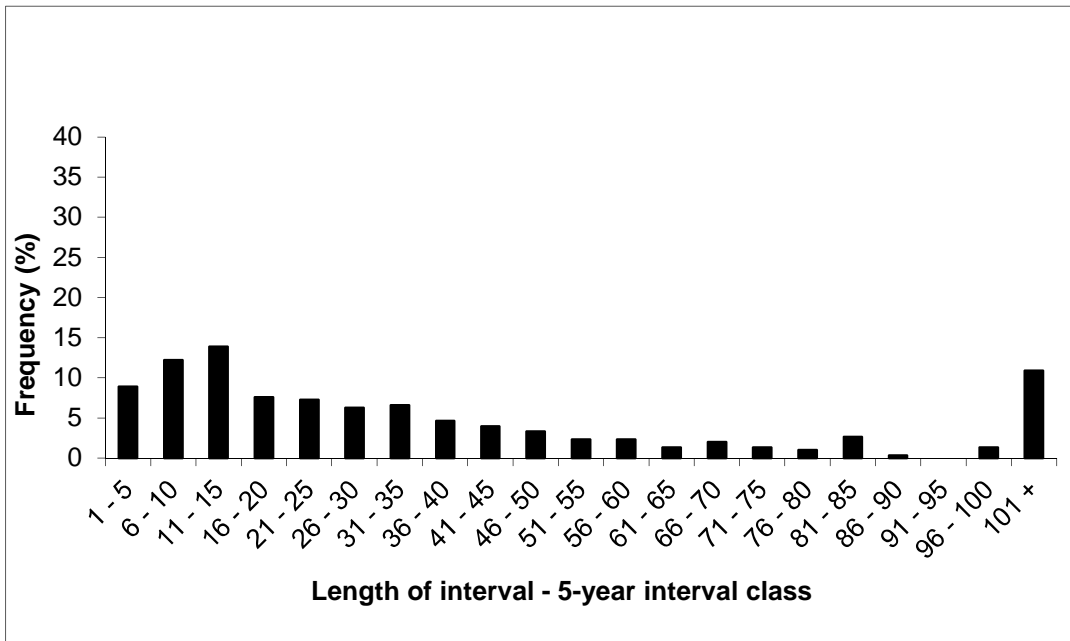


Figure 12. Fire history distributions from this study (top) and from Prairie Creek Redwoods State Park (bottom). Lower graph adapted from Norman *et al.* (2009).

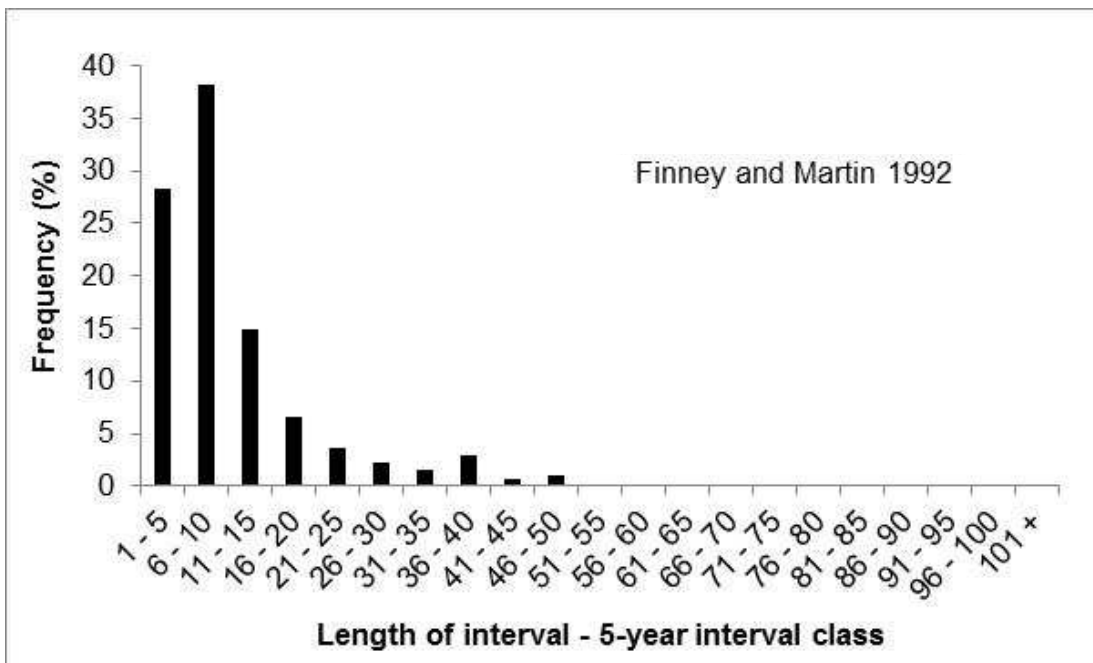
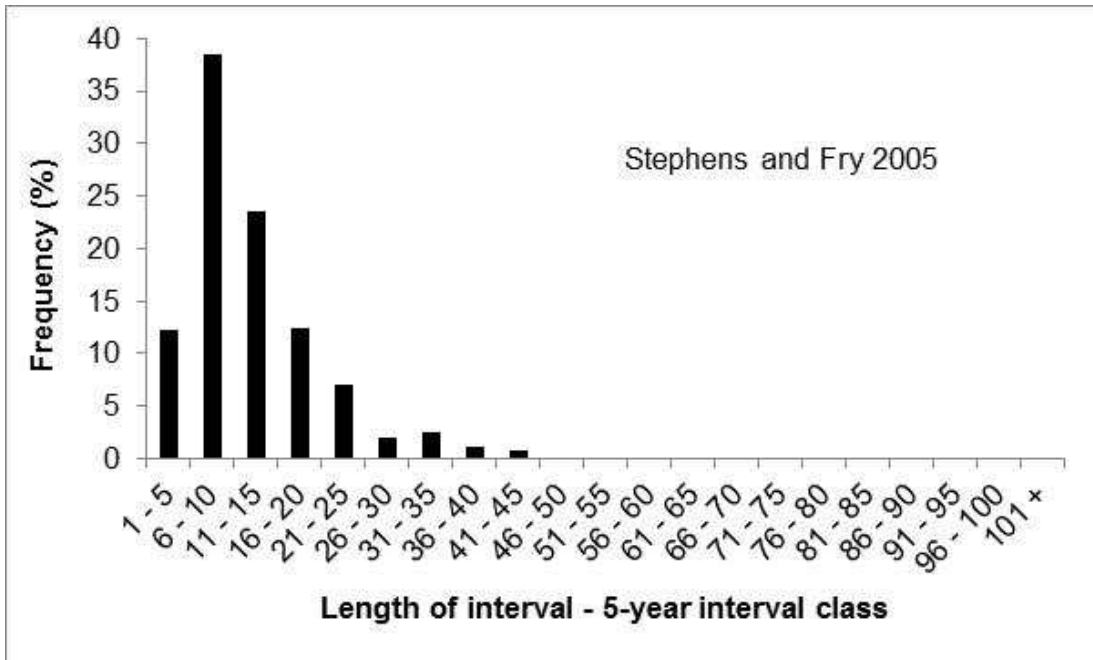


Figure 13. Fire history distributions from the northeast Santa Cruz Mountains (top) and Annadel State Park (bottom). Graphs adapted from Norman *et al.* (2009).

Fire frequencies in the three distributions presented for comparison drop off after 40 years, whereas, in this study, intervals longer than 40 years comprise 33% of the remaining distribution. The reason for this marked difference in the frequency distributions is unclear. As discussed previously, both the study sites from San Mateo County (Stephens and Fry 2005) and the study from Anadel State Park in Sonoma County (Finney and Martin 1992) were from more inland and xeric environments, which may preclude longer fire return intervals. However, Brown and Swetnam (1994) reported few longer intervals in Prairie Creek Redwoods State Park in Humboldt County, which is closer to the Pacific coast than this study area. It is possible that both pre-colonial and historic land use practices and burning patterns in this study area were highly temporally and spatially variable, creating a mosaic of fire regime characteristics dispersed across the landscape (Lightfoot and Parrish 2009). An additional potential explanation relates to how fire frequency is reported. If FRI statistics are presented as composites as opposed to point estimates, the aggregation of the data will tend to reduce the frequency of very long fire intervals (Finney and Martin 1989). Neither Stephens and Fry (2005) nor Finney and Martin (1992) reported composite intervals, but Brown and Swetnam (1994) were able to successfully cross-date their samples and, thus, to report composite FRI statistics. Whether this disparity in these four FRI frequency distributions can be attributed to reporting differences, to geographic and environmental factors (bottom-up controls), or to land use, these findings deserve further inquiry.

The temporal trends in fire occurrence found in this study correspond to anecdotal evidence of anthropogenic land use and burning patterns in this region. There are many

historical accounts from the Spanish expeditions of Native American burning on the central coast of California, and current research suggests that the tribes in this area used fire extensively, particularly near the coastline in the vicinity of Point Año Nuevo (Cuthrell 2013). The probable increase in fire frequency, intensity, and extent during the era of active logging yielded to an era of fewer but, perhaps, larger fires once fire suppression became the dominant fire management paradigm. However, results from the comparison of fire frequency among the three different time periods did not reveal statistically significant differences in the mean fire return interval. One possible explanation is that there was a high degree of variability around the mean FRI of each era. Increased sampling intensity may produce a more prominent mean as the signal to noise ratio increases, thus allowing more significant differences in fire frequencies to emerge. In the modern era of fire suppression (1925-2013), the cubic polynomial curve appears to indicate a trend toward declining fire frequency. Further refinement of the eras used for comparison may produce results that would support the observed trend. Even though fire suppression was codified and institutionalized at the national level in 1924, the resources available to mount an effective suppression campaign were limited until the early 1950s when post-war manpower and equipment became more readily available (Pyne 2010). It was not until 1948 that the first aerial fire-detection patrols were used in the redwood region (Adams 1969). Dividing the modern era into pre-1950 and post-1950 for comparative analysis may detect the advancements in fire suppression capabilities that likely account for the observed decline in fire frequency. Because this study did not consider fire dates as absolute, critical examinations of the transition from

one style of fire management (pyric phase) (Bowman *et al.* 2011, Scott *et al.* 2014) to the next were problematic.

Numerous fire history studies address the influence of land use on fire regime characteristics (Greenlee and Langenheim 1990, Baisan and Swetnam 1997, Gassaway 2007), while other studies explore the influence of bottom-up controls including local physiographic features and forest composition and structure on fire regimes (Bekker and Taylor 2001, Heyerdahl *et al.* 2001, Stephens and Fry 2005). Further, many studies explore the influences of a combination of both top-down and bottom-up controls on the fire regime (Gill and Taylor 2009, Yocom 2011), but disentangling the various forces that act to shape the fire regime is challenging. Regression analyses from this study suggest that, although the redwood fire regime may be influenced by an intricate synergy of both bottom-up and top-down controls, patterns of land use and burning practices may have offset local environmental drivers. Caution is urged, however, in making strong interpretations of this model until it can be subjected to more rigorous testing, which may reduce error and uncertainty. Further, the analyses were conducted with both dated and undated fire events. Without certain knowledge of the dates of fire events, it is difficult to determine which fires were associated with Native American burning, Spanish-era burning, or Anglo logging practices and homesteading. A predictive model may be improved initially by bracketing fire intervals into time periods that would provide, at minimum, general estimates of the dates of fire occurrence. Despite analytical limitations, significant relationships were found between the FRI and both pre-colonial and historic cultural features (i.e., Native American archaeological sites and the

logging-era sawmills). These relationships warrant further examination. It seems reasonable that in these mesic forests, where fire occurrence is limited by ignitions, by fuel availability, and by the dominant local weather patterns, the specific location and the season of anthropogenic burning may have overshadowed the influences of other these local environmental variables (Norman *et al.* 2009).

Knowledge of the coast redwood fire regime is important for resource managers who may assess the appropriate role of fire in modern coast redwood forests. However, it is challenging for managers who wish to reintroduce fire as a disturbance process into redwood ecosystems to find a useful set of reference fire regime attributes on which to base restoration objectives. If anthropogenic burning practices affected the landscape by increasing biodiversity and influencing forest structure and composition in manners that contributed to the persistence of the redwood, then prescribed burning could serve as a proxy for both pre-colonial and historic ignitions, now absent from the landscape. This study suggests that managing fire for regularity based on a mean or median fire return interval and subsequent fire return interval departure (Caprio *et al.* 2002) may not be appropriate, as these metrics are only marginally illustrative of the inherent variability of the redwood fire regime in this area. Moreover, reintroduction of fire to forests based on these metrics of central tendency may be justified in a landscape where lightning accounts for a substantial percentage of ignitions, but it may be less appropriate for an almost exclusively anthropogenic fire regime. One restoration model that may prove useful is the practice of restoring cultural landscapes where management activities are centered on incorporating components of traditional resource and environmental

management (Fowler and Lepofsky 2011). This model has already been successfully implemented in Redwood National Park, California, where the Bald Hills are burned regularly to maintain the ethnographic landscape (Underwood *et al.* 2003). In addition, opportunities for patch mosaic burning should be investigated as fires in the coast redwood are likely highly spatially and temporally variable (Brockett *et al.* 2001). Resource managers may have to employ a suite of fire management strategies in coast redwood forests that are firmly grounded in a context of adaptive management, regardless of the restoration model used. Findings from this study may prove particularly useful for ecologists and resource managers who are committed to applying adaptive management strategies in the southern range of the coast redwoods.

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