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A DENDROECOLOGY-BASED FIRE HISTORY OF COAST REDWOODS (SEQUOIA SEMPERVIRENS) IN CENTRAL COASTAL CALIFORNIA

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A DENDROECOLOGY-BASED FIRE HISTORY OF COAST REDWOODS (SEQUOIA SEMPERVIRENS) IN CENTRAL COASTAL CALIFORNIA

By

Charles Joseph Striplen

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Environmental Science, Policy, and Management

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University of California, Berkeley

Committee in charge:

Professor Lynn Huntsinger, Chair
Professor Scott Stephens
Professor Kent Lightfoot
Dr. Joshua Collins

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ABSTRACT

A Dendroecology-Based Fire History of Coast Redwoods
(*Sequoia sempervirens*) in Central Coastal California

by

Charles Joseph Striplen

Doctor of Philosophy in Environmental Science, Policy, and Management

University of California, Berkeley

Professor Lynn Huntsinger, Chair

This dissertation focuses on fire history reconstructed from select coast redwood stands in the Santa Cruz Mountains, California based on the fire scar record in specimens collected between 2008 and 2013. The research is one component of a larger multidisciplinary examination of indigenous burning practices in the Central California Coast region (Lightfoot et al. 2013). Research presented herein exhibits concordance with results from related studies, including analyses of soil phytolith content (Evett and Cuthrell 2013), faunal assemblages (Gifford-Gonzalez et al. 2013), and microscopic pollen and charcoal evidence (Cowart and Byrne 2013). Fire history research was conducted in three coastal watersheds in Santa Cruz and San Mateo counties, California using standard dendroecological techniques, as well as a novel statistical approach developed to address undated, floating chronologies.

A total of 103 coast redwood samples were collected from 95 sample trees in 19 plots within the study area. The fire return intervals recorded from the dated redwood samples in this study were relatively frequent. Fire information was estimated for three focal management eras: the native and ranching eras (1600-1850), intensive commercial logging (1850-1950), and the modern fire suppression/sustainable harvest era (1950-2013). Results from dated fire scars indicate that fires were less frequent in the native and ranching period (mean FRI 7.6 years; range 1-29) than the intensive logging period (mean FRI 3.1 years; range 1-11), as well as the modern period (mean FRI 4.6 years; range 1-12).

However, use of a generalized linear mixed model (GLMM) on undated, floating chronologies indicated that the probability of fire may have been quite high in the earlier period, and that three independent variables were significant predictors in assessing the annual probability of the occurrence of fire in the study area: physiographic zone; position on slope; and linear distance to pre-colonial, native habitation sites. The GLMM also indicates that fire probabilities are not distributed uniformly in study watersheds. Trees located in close proximity

to native residential sites had a high probability of being burned than those farther away (42-69% vs. 17-38%). Similarly, top of slope fire were more likely in all watersheds and physiographic zones, though varying in degree.

The season of fire occurrence was determined for 85% of the fire scars. Dormant or late season fires accounted for a combined total of 87% of all fires for the entire period of record (1350-2013; 55% dormant, 33% late) – indicating that historic fires most likely took place between approximately mid-August to late March. Early season (approx. April to August) fires accounted for 13% of fires. In the 1600-1850 period, combined dormant and late season fires accounted for 91% of fires (64% and 27%, respectively), with 9% of fires occurring in the early season. During the intensive logging period (1850-1950) combined dormant and late season fires accounted for 85% of fires, and 15% in the early season. In the modern era (1950-2013), dormant and late season fires still account for the majority of fires (86%), but with a marked shift into the drier late season (mid-August – September), which now account for 43% of fires. Early season fires represent 14% of fires in this period.

Though this study faced significant challenges (i.e. low sample density for earlier period specimens, large study area, experimental use of a GLMM), these data reveal interesting and potentially useful patterns of historic fire occurrence in the Santa Cruz Mountains, especially with respect to human influence over coastal fire regimes. All sources of information indicate that coastal Santa Cruz Mountains experienced far more ignitions than would be expected under a lightning-driven fire regime (roughly 4 strikes per century), and that human activity is strongly linked to fire frequency in throughout observable time periods. There is ample opportunity to improve on this data with future work in efforts to inform and refine modern approaches to resource management in this region.

DEDICATION

For my family – Angela, Elianna, Tule, Jasmine, Mario, and Linda.
Without their love, support, patience, and encouragement
– this project would never have seen the light of day.

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I also extend my great thanks and admiration to my orals and dissertation committee: Dr. Lynn Huntsinger (Chair), Dr. Kent Lightfoot, Dr. Josh Collins, Dr. Scott Stephens, and Dr. James Bartolome. I have cherished their wisdom, patience, tutelage, and enduring support throughout my experience at UC Berkeley. I would also like to extend my gratitude to UC Berkeley's College of Natural Resources, and Department of Environmental Science, Policy, and Management. As a non-traditional student engaged in a complex interdisciplinary project, the faculty, staff, students with whom I shared this experience helped create a highly supportive, challenging, and collegial environment

As this project expanded from its initial scope, it could not have endured without the timely intervention and support by the estimable Dr. Rob Cuthrell, Dr. Christine Hastorf, and Dr. Kent Lightfoot. Taking the kernel of an idea, these individuals threw their support, creativity, and reputations behind the endeavor in earnest, helping fashion it into a laudable and noteworthy research initiative that has affected a great many lives in very positive ways.

And to my friend and colleague, Mark Hylkema, Santa Cruz District Archaeologist for the California Department of Parks and Recreation, I extend my great thanks for first introducing me to Quiroste Valley, and for his support and encouragement throughout this project. Mark's advocacy and intellect facilitated and informed much of our work on this project – which would likely not have moved forward without his direct participation.

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I also owe tremendous gratitude to the owners and staff at Big Creek Lumber Company, Davenport, CA. From the earliest day of this project, Lud and Bud McCrary, Janet Webb, Matt Dias, Nadia Hamey, Colin Noyes, Bob Berlage, and many other Big Creek staff volunteered time, knowledge, access, equipment, and advocacy to this endeavor. As one of the oldest families still managing lands on the Central Coast, the McCrary's love for and dedication to the area, its history, residents, and future – was exemplified by their enthusiastic support.

This project received similar support from many other local landowners, including Cal Poly's Swanton Pacific Ranch (Dr. Brian Dietterick and Steve Auten), Ben Wilson, Chuck and Christine Harper, Anne Jones, Dennis Torio and Susan Blake at Skylark Ranch (Girl Scouts of America), The Sempervirens Fund, especially Reed Holderman, Aaron Hebert, and Laura McClendon, Margie Ryan, Ann Blanchard, Anne Dimock, and many others.

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CHAPTER 1

INTRODUCTION

The increasing size, frequency, and severity of wildfires in California has renewed research interest in the fire ecology of California's forests, including coast redwood (*Sequoia sempervirens* (D. Don) Endl.) forests. Throughout their range, the bark and burned basal cavities of redwoods display evidence of past fires (Jacobs et al. 1985; Stephens and Fry 2005). This physical evidence suggests that frequent fires of low and moderate intensities have for centuries periodically burned in this forest type, shaping forest structure and composition (Stephens and Fry 2005; Lorimer et al. 2009). Moreover, coast redwoods are extremely resilient to disturbances such as fire. Despite research documenting this adaptation, the ecological role of fire in shaping successional processes is still 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 documents widespread use of fire by California Indians to manipulate coastal and interior landscapes for a variety of purposes (Lewis 1973, Anderson 2005), as well as the impacts of the cessation of those practices on California's forests and other terrestrial and aquatic ecosystems (Anderson and Moratto 1996). Furthermore, California's central coastal range have experienced a variety of fire regimes since Euro-American colonization, changing in response to evolving cultural land use practices (Lightfoot et al. 2013, Greenlee and Langenheim 1990). However, the manner in which burning practices were applied, affected vegetation communities, and contributed to the landscape physiognomy remains in question, as does the spatial extent and frequency of fires. Examining the transitions between "fire cultures" may contribute to our understanding of the complex dynamics of human-fire-vegetation interactions in this region (Bowman et al. 2011).

Despite the abundant fire history research produced in many other western forest types, significant gaps in the literature exist regarding the fire regime in the southern range of the coast redwoods (Davis and Borchert 2006). Numerous studies examine the past fire frequency in the northern and central range of redwoods north of San Francisco, but only two studies of this nature have been conducted in the redwoods' range south of the Golden Gate (Greenlee 1983; Stephens and Fry 2005). Both studies, consistent with published work from central and northern redwood regions (Brown et al. 1999, 2003, Finney & Martin 1989, 1992, Norman 2007, and others), indicated a greater than expected frequency of fire in these systems as compared to the relative frequency of lightning strikes.

The objective of this study is to conduct a reconnaissance level survey of the fire history in select coast redwood stands in the Santa Cruz Mountains, CA based on the fire scar record in coast redwood specimens. Specifically, this study explores the differences in the fire return interval (FRI) and season (temporal distribution of fires) with respect to environmental gradients (e.g. distance to the coast, slope position, aspect, and elevation), and also examines both historical and pre-colonial burning practices. I place emphasis on determining the range of variability of the fire regimes under three scenarios: ignitions in the pre-colonial period and ranching periods, ignitions in the post-European contact eras of commercial logging (ca. 1850-1950), and the modern age of fire suppression and commercial timber harvest (ca. 1950-2013).

Harvest dates were able to be determined for approximately 28% of the samples, which were analyzed with FHX2 (Grissino-Mayer 1996).

Given the complexity of crossdating the taxon utilized in this study, the availability of accessible plots for data collection, and the lack of available harvest information for a majority of our sample sites, standard dendroecological tools (i.e. FHX2) could not be used on the majority of the samples. For these "floating chronologies", I utilized a generalized linear mixed model (GLMM) to detect possible patterns in the annual probability of fire. The GLMM is a binomial probability model where each annual growth ring represents a "trial", and each fire scarred ring is defined as a "success." This approach was also used to detect patterns of association between annual probability of fire with respect to physical variables, as well as proximity to known (mapped) cultural sites in the study area.

The research presented herein represents just one component of a larger multidisciplinary examination of indigenous burning practices in the Central California Coast region. Shortly after initiating my doctoral research in 2002, I began what would become a rather prolonged search for an adequate site containing the essential attributes to address my research questions. On June 7, 2006, my friend and colleague, Mark Hylkema – Santa Cruz District Archaeologist for CA State Parks – introduced me to Quiroste Valley (Figure 1). This hidden, picturesque valley, rimmed by coast redwoods and Douglas firs, and known only to locals and the occasional hiker and historian, turned out to contain the remnants of a very important native settlement visited by the first Spanish overland expedition into California in 1769 (Crespi and Brown 2001): the great Quiroste village of *Mitinne* (CA-SMA-113, trinomial designation of the California State Office of Historic Preservation). Still present adjacent to the village site are what are likely to have been the very same old growth redwoods noted by the Portola party – surviving centuries of agriculture, timber harvest, and other modern activities.

The adjacent coastal watersheds around the site are sparsely populated, but contain a long and documented history of logging, fishing, and community pride. A great many local land owners and residents proved eager to assist with and learn from my proposed study. The site was also within the ancestral territory of my tribe (Amah Mutsun), a situation that greatly facilitated the quick support and involvement of tribal citizens and leadership.

Realizing the scale and scope of the opportunity provided by Quiroste and by local community interest, I was able to recruit some of the finest regional specialists and researchers to help design, execute, and fund this ambitious endeavor. Ultimately, the broader project initiated in 2007 by myself, Mark Hylkema, Dr. Kent Lightfoot, Rob Cuthrell, and several others, has grown over the last seven years to include a large group of researchers investigating a variety of lines of evidence related to past climatic conditions, vegetation composition, fire history, archaeology, fire ecology, and related topics in and around Quiroste Valley State Cultural Preserve and the Pinnacles National Park. A brief description of the project focusing on Quiroste Valley Cultural Preserve was presented in Lightfoot et al. (2009), and Cuthrell et al. (2009) described aspects of the project's low-impact excavation methodology. A project overview and some preliminary archaeological results of this study were reported by Cuthrell et al. (2012).

Figure 1. Westward view of the 224-acre Quiroste Valley State Cultural Preserve. Monterey Bay in background. Photo by author.

A broader presentation of analytical results and a synthetic discussion of project outcomes to date for the portion of the study focusing on Quiroste Valley Cultural Preserve has recently been published in the journal *California Archaeology* (Cowart and Byrne 2013; Cuthrell 2013; Cuthrell et al. 2013; Evett and Cuthrell 2013; Fine et al. 2013; Gifford-Gonzalez et al. 2013; Hylkema and Cuthrell 2013; Lightfoot and Lopez 2013; Lightfoot et al. 2013; Lopez 2013).

My own role in the project took several forms: principal investigator, promoter, Tribal liaison, landowner liaison, agency liaison, and press and media contact. As designated Tribal liaison to the project, assigned by a Amah Mutsun Tribal Council Resolution, I served as a bridge between the Council and citizenry of the Amah Mutsun, and the various project partners and agencies. I made quarterly presentations on the project's progress to the Council, authored regular columns in the tribe's newsletter, and facilitated participation of Tribal citizens in the various project elements. I also served as the primary liaison between the public and private landowners in the study area, and the various investigating academic and tribal personnel – facilitating access to properties and resources, securing permits where necessary, and troubleshooting any issues that may arise. As press and media contact, I was participated in numerous interviews for major newspapers, local and regional magazines and digests, and radio and documentary producers. My role as agency liaison was particularly key – requiring service as both an advocate for the role of the tribe in the project, as well as an interpreter and strategist with respect to [Tribal] navigation of complex agency bureaucracies. Through this role, I was

able to help facilitate the designation of the Quiroste Valley State Cultural Preserve in 2008 (see Chapter 2).

I present this research in the following five chapters. Chapter 2 presents a synthesis of local documented history, focusing on the watersheds investigated: Whitehouse Creek, Waddell Creek, and Scotts Creek. Histories reviewed were limited to sources that spoke to the evolving relationship between human communities and the resources of the Santa Cruz Mountains, including cultural, settlement, and silvicultural narratives. I explore in some depth the history and distribution of local tribal communities, documentation specific to tribal use of fire in the region, and the fire ecology of redwoods. Here, I also recount the successful effort to establish greater protections for Quiroste Valley. In Chapter 3, I describe the study area and summarize methods employed with respect to the collection, preparation, and analysis of redwood samples from the Santa Cruz Mountains. Chapter 4 presents my results, partitioned by dated and floating chronologies. In Chapter 5, I present my discussion and concluding remarks.

CHAPTER 2

Local History
•
Fire ecology of Redwoods
•
Quiroste Valley State Cultural Preserve

The aboriginal and settlement history of this region of California is well documented and widely published (e.g. Harrison 1892, Lydon & Crespi 1994, Bosso 2006, Perry 2007, Milliken et al. 2009). The history summarized herein synthesizes numerous published accounts of the evolving relationship between human communities and the resources of the Santa Cruz Mountains.

Pre-colonial history and indigenous use of fire

At the time of the first European encounter in 1769, there were two politically discrete tribal territories within the study area (Whitehouse, Waddell, ad Scotts Creeks). The distribution of these tribes and their residential sites indicates that a large number of native people inhabited these watersheds. Through their long term manipulation of the productivity of their natural environment, they in effect created anthropogenic landscapes through hunting, gathering, and gardening practices (Hylkema and Cuthrell 2013, Anderson 2005). The study area lies within the aboriginal territory of the Quiroste and Cotoni peoples (Hylkema and Cuthrell 2013). The Cotoni likely spoke a dialect of the Awaswas language of the Santa Cruz people, while the language spoken by the Quiroste is thought to be more closely related to languages spoken closer to the Monterey area (Milliken et al. 2009). Quiroste Valley, situated within the Año Nuevo State Cultural Preserve (California State Parks), contains the remnants of a large historic village of the Quiroste people first described by the Portolá Expedition in 1769 (Crespi and Brown 2001). The Cotoni of the Scotts Creek watershed represented a politically autonomous group distinct from the Quiroste, and based on ethnographic and archaeological information, distributed themselves more widely among several communities throughout their territory – apparently without a major tribal center – such as the Quiroste's *Mitinne* (Hylkema 1991).

Coastal tribes in this area developed highly complex and wide-ranging, inter-tribal commerce networks designed to transport coastal products to interior peoples and bring interior materials to those on the coast. In spite of a high linguistic diversity, there were commonly held cosmological and wealth systems which expanded significantly prior to colonization, but were abruptly curtailed by the arrival of Spanish explorers in the fall of 1769. At the time, populations were organized by virtue of extended families, which formed clans, villages, and polities. Aggregates of villages, united under the leadership of a Head Man or Head Woman established tribal territories (Hylkema 2011). Kinship data reconstructed from Spanish Mission records indicate that coastal communities assimilated into a larger [San Francisco] Bay Shore alliance network through marriages (King 1994: 203-228; Milliken 1983; 1991; 1995) (Figure 2).

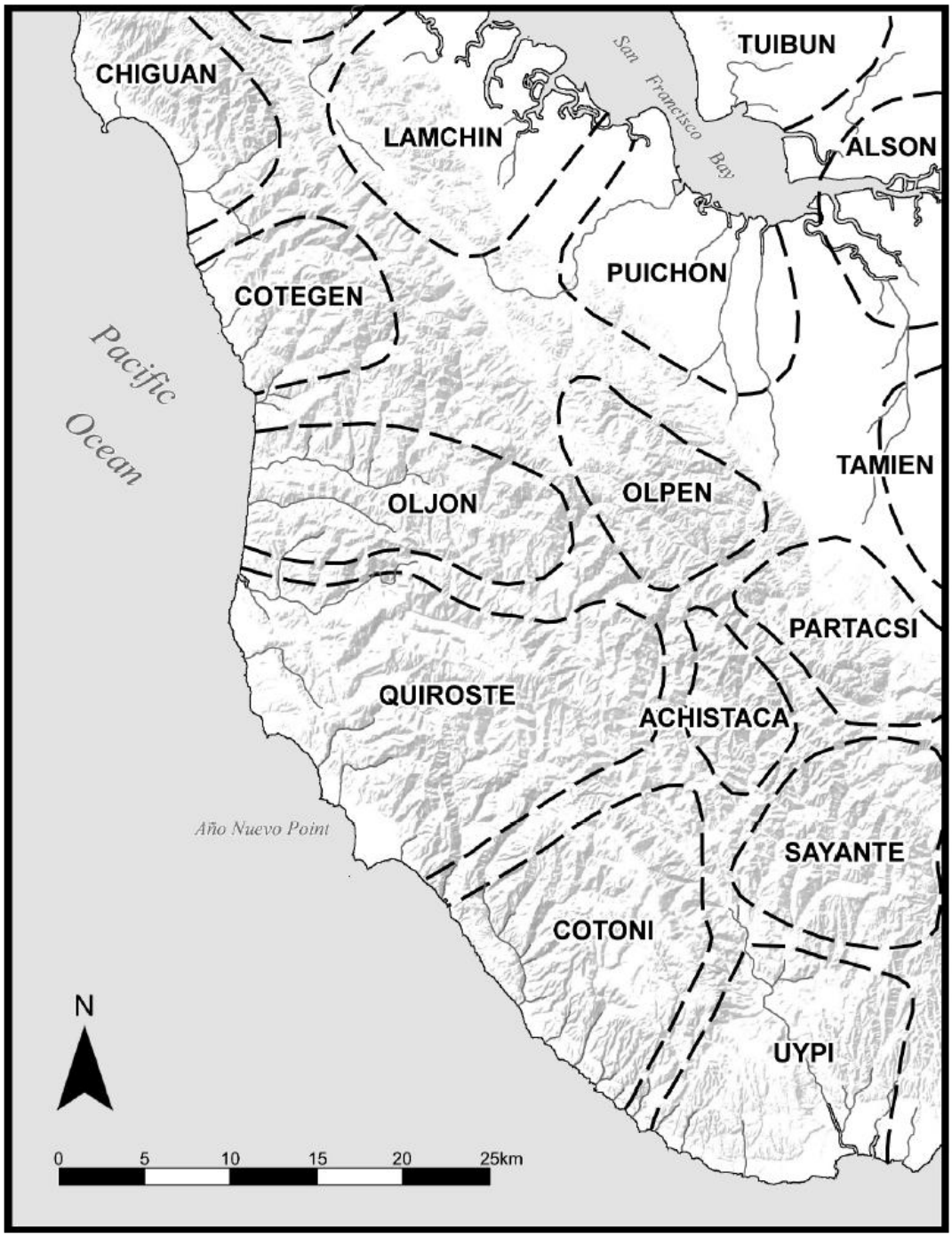

Figure 2. Location and extent of Cotoni, Quiroste, and neighboring tribal communities ca. 1769 (from Hylkema and Cuthrell 2013, including proposed Quiroste boundary expansion, after Milliken1995). Note: Apto and Chaloctaca are located southeast (off map) of Uypi.

Following Cabrillo's expeditions along the California Coast in the 1540s, which provided the first recorded observations of what were likely native applications of fire on the mainland – the party of Gaspar de Portola was the first European group to travel through the project area by foot in 1769.

On October 20th of that year, the party reached Waddell Creek and described is as follows:

> "…we went down to the shore, and over it into a hollow running in among very high mountains, while the sea shoots a good way in at the shore, making a large inlet. We halted at the edge of the stream here, at a small flat with a great deal of grass and at the very shore's edge, which has a great deal of sandy beach and where there is quite a large sand dune. The stream lies about half a league before Point Año Nuevo, at a gap in that the very cliffy mountains make right upon the shore. We came to the stream here with some of our sick men very ill of Luanda sickness, especially three or four of them who had already been anointed. Yet, after a good soaking that they got from heavy showers, when we were expecting that two or three of them would waken only into eternity, instead, these ones and the others all woke up in the morning much improved; wherefore we called it the stream of *San Luis Beltrán,* Saint Luis Bertran, and of *La Salud,* Healing Creek. At this stream the soldiers found madroños laden with ripe fruits, though very small ones, like the beads on our rosaries" (Crespi and Brown 2001:573, 575).

Taking a couple of days respite for the sick to mend and for soaked riggings to dry, the party set out again on October 23rd, upon which they encountered the village of *Mitinne* in what is now called Whitehouse Canyon. Portola diarist Fray Juan Crespi described the setting in vivid detail:

> "…we came to a small valley all surrounded by very grass-grown knolls, where there was a large village of very fine, well-behaved heathens who greeted us with much hubbub and rejoiced a great deal over our coming. The village here had a very large round house like a half orange, grass-roofed, which, by what we saw inside it, would hold the entire village. Around about the large house they had many small houses made of upright split sticks. This village lay in the aforesaid small valley here, all surrounded by very grass-grown ranges of knolls of sheer soil and grass, a well-sheltered spot from the winds and near to shore. The valley has soil which though not extensive could have some irrigated planting done on it, with a good-sized stream with a good flow of very delicious, pure water that runs through the valley here. They have a small, very dense grove of pine-nut pinewoods dropping down through some knolls from the mountains running in back that are grown over with these pine trees.
>
> These heathens here made a present of a great many large black and white pies: the white pies were made of acorns, while the black-colored ones were said to be also very good. They brought two or three pouches of the sort of tobacco that they use, and our people took whatever they wanted of it. One heathen man came up smoking on a very large Indian pipe made of stone.
>
> These heathens almost all of them carry tall red-colored staffs, some of them decorated with a great deal of feathers; four of these staffs they presented to Sergeant Don Francisco Ortega, whom they were best acquainted with because he was the one who had scouted this spot with some other soldiers. Another village of them that lay nearby shortly arrived, coming provided in the same way. Our officers distributed beads to everyone and they were very well pleased. I called this spot the small valley of *San Juan de Nepomuceno*, Saint John of Nepomuk." (Crespi and Brown 2001:577, 579).

Just a few days after leaving the village at Año Nuevo, the Portola expedition inadvertently encountered the San Francisco Bay. While camped along San Francisquito Creek in the present locations of the City of Palo Alto, Crespi described the terrain as being somewhat flat with very rich black soil: " ... though most of the tall grasses had been burned; and the whole grown over with a great many white and live oaks" (Crespi and Brown 2001).

Prior to reaching the Quiroste civilization, Crespi also noted observations of "burnt grass" on numerous occasions, primarily associated with coastal terraces and alluvial valleys. These observations continued upon leaving *Mitinne:*

> October 24, 1769: "We set out at a quarter before nine in the morning from here at the small Saint of Nepomuk valley, course due north – in company with four heathens belonging to this spot who came with us to show us the next watering places and villages – in view of the shore, over very big high ranges of knolls, all with very good soil and very grass-grown, though the grasses has almost all been burnt – everything being very bare of trees; only in the gaps between the knolls could be seen the white range of mountains in back, continuing still overgrown with pinewoods." (Crespi and Brown 2001:579)

Passages such as this, common in early explorer accounts, give us a glimpse of widespread intensive management of coastal grass and shrublands. Crespi noted that the native people of the Santa Cruz coast burned the meadows "...for a better yield of the grass seeds that they eat" (Crespi and Brown 2001). He noted burned meadows on at least 12 occasions as they traveled between Santa Cruz and San Francisco, also noting the abundance of hazelnuts that responded to the regular burnings.

Further in the uplands, burning oak woodlands and the understory of some forest environments had the added benefit of clearing the ground of undesirable insects and plants, fumigating the forest canopy, facilitating travel, visibility, and the collection of nut crops in the fall harvest time. It also reduced the accumulation of ground fuels – affecting fire behavior, extent, and intensity (Lewis 1973).

Current research suggests that tribes residing in this area employed a wide range of burning practices during the middle to late Holocene which influenced patterns of fire occurrence and vegetation mosaics in local watersheds (Cuthrell et al. 2013; Keeley 2002; Stephens and Libby 2006). Observations of the use of fire by tribes throughout the range of late 16th century Spanish overland expeditions in California were perhaps some of the most consistent and noteworthy observations recorded in this era. Almost without exception, explorers and their diarists recorded "burnt ground", often in coastal prairie systems, along much of California's coastline and interior. In and around the watersheds subject to this study, burning was noted along more than two thirds of the proximate coastline (see Figure 3).

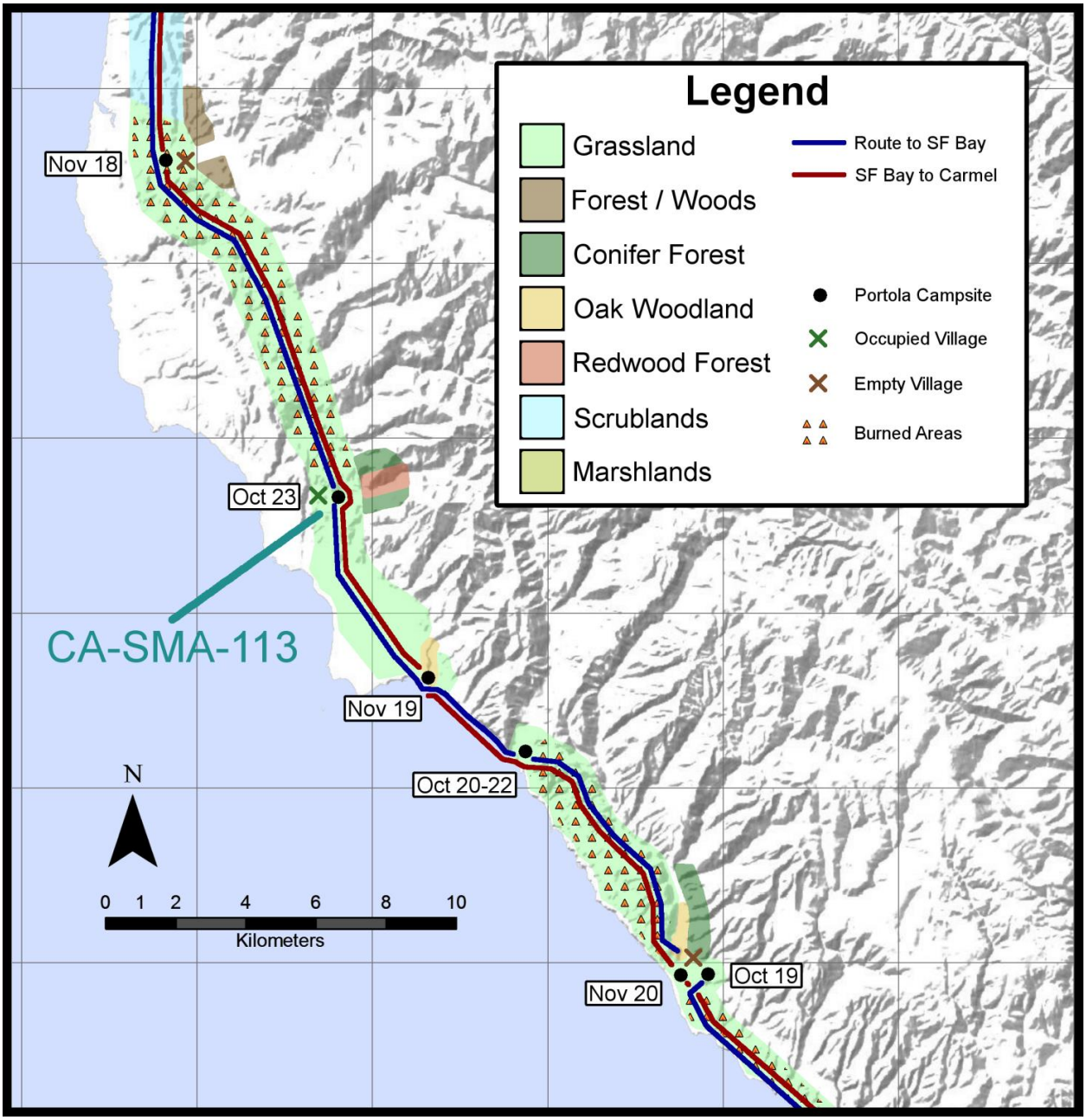

Figure 3. Observations of fire and vegetation cover by the 1769 Portola Expedition in the project area (from Cuthrell 2013)

Local Settlement and logging history

A generation passed before the Spanish became a more permanent presence in the lands of the Cotoni and Quiroste, and their neighbors. Mission Santa Cruz was founded in August of 1791, and between then and 1840, a total of 1,759 Indian people moved through its doors. The population included local Uypi, Apto, Chaloctaca, Sayante, Cotoni, and Achistaca (all Awaswas-speakers; 1,154 people), but also from populations further east (Delta and Northern Valley Yokuts, 539 people; and Sierra Miwok, 38 people. Milliken et al. 2009, Milliken 1995).

Mission Santa Cruz was perennially challenged by the relatively meager local population of Indian laborers. The last local Indians to enter the mission did so in 1796. Once disease had decimated village and mission populations, the mission's "recruitment boundaries" began to overlap with those of other nearby missions, Santa Clara and San Juan Bautista (Milliken et al. 2009).

Despite these challenges, those Indians who did survive operated an impressive cattle operation for Mission priests. Beginning with a herd of 33 in the 1790s, they expanded to 3,300 by 1814, and 42,800 by 1828. They had also delivered 1,100 bushels of wheat and 600 bushels of corn within the mission's first five years (McCrary and Swift 1982).

Mission secularization in 1834 gave rise to an era of opportunistic land barons – initially through Mexican-sanctioned land grants that sometimes exceeding 40-50,000 acres. Patentees such as Don Jose Joaquin Castro and Don Antonio Rodriguez, and their subsequent heirs and extended families ended up with more than a quarter million acres in the Santa Cruz Mountains (McCrary and Swift 1982). Eventually they were subdivided and sold off to Gold Rush settlers and prospectors as California became part of the United States.

The first recorded commercial logging operation on the west coast was established by Thomas Larkin and Jose Amesti in 1832, a mere 63 years after the first Spanish expeditions into California. Rather than the iconic mills of more recent industrial periods, these operations consisted of tedious and dangerous whipsaw or pit sawing processes. The first powered mill in the state was established on Mark West Creek (Sonoma County) by John B.R. Cooper in 1834 (Clar 1957), followed only seven years later by a mill constructed just south of the study area on Zayante Creek (McCrary and Swift 1981) in 1841.

When European-Americans found gold in California in 1849, and the price of timber shot up $200 or more per thousand board feet, industrial logging boomed in the Santa Cruz Mountains. Stands in close proximity to the growing international port of San Francisco, and the main lumber port at Redwood City, were harvested earliest – with Woodside and Los Gatos serving as the "mill hubs" of the region. Prior to railroads, coast side redwoods of the south San Francisco Peninsula served mostly local needs until the Gold Rush. When timber values and powered mills made shipping costs manageable, a water-powered sawmill opened at Purissima in 1854, and another at Pescadero Creek in 1856 (Stanger 1967). By 1865, 27 mills operated out of Santa Cruz County, producing more than 270,000 board feet per day. By 1880, 50 mills operated in the county (Greenlee 1983). At least three landings in or near the project area served as shipping points for timber harvested in the Santa Cruz Mountains: Pigeon Point, Davenport, and Año Nuevo.

Logging within the project area began in earnest in the 1860s. William White Waddell, a businessman from Kentucky and Missouri, settled in the area in the mid-1850s with the intent to make a fortune in the lumber business. Between 1861 and 1864, he set upon the task of developing his own mills and shipping points in the Waddell/Año Nuevo area. By 1867, the 700-foot pier he built at Año Nuevo was handling more than two million board feet per year.

By this time, mills had been established in Waddell and Whitehouse creeks, all shipping their lumber out through Año Nuevo or Pigeon Point. In 1867, the "Chandler and Harrington Mills" (later Glen Mills) began operations, only to close by 1874 (Mowry 2004). The mill site was located in mid-Whitehouse Creek near samples WHC3034 and WHC3038 (see Appendix I).

Logging in Scotts Creek watershed began in the late 1800s, with the earliest known harvests occurring on Big Creek sub-basin in the 1890s, and beginning in Mill Creek sub-basin around 1906. Early transportation of logs was largely accomplished using waterways and oxen (Figure 4). Some of the early logging operations were producing split wood products on site, while lumber was milled locally at a saw mill on Mill Creek (near WIL001).

Between 1906 and 1920, ushered in by the devastating 1906 earthquake in San Francisco, a new and more intense era of timber harvest took place in the Santa Cruz Mountains. Starting in 1907, the San Vincente Lumber Company constructed a railroad up Little Creek and into the upper reaches of Big Creek and into Deadman's Gulch. Logging operations in this era typically manifested as clearcuts, with steam donkeys used for cable yarding, and largely continued in this manner into the 1920s. Logging in this era represented a take of approximately 30% of the watershed's timber resources.

Figure 4. Oxen train at Boulder Creek, California (1899). Transporting 57,000 board feet of redwood timber. Courtesy of the McCrary Family, Davenport, CA.

Likely responding to the post-WWII housing boom, large-scale harvests began in various locations in Scotts Creek, Little Creek, Mill Creek, Winter Creek, Archibald Creek and Queseria Creek in the late 1940s, lasting until the 1960s. These harvests were accomplished largely via

tractor skidding, with extensive skid road construction, but with little permanent road construction. Logging in this era represented a take of approximately 9% of the Scotts Creek watershed.

Current harvest activity has focused on the upper Scotts, Little, and Archibald Creek drainages. Seasonal roads are in place in these drainages, some of which originated from the early railroad logging. Other roads were constructed in the 1980s during logging in the second-growth forests. Modern harvests all used selective cutting methods. During these harvests in 1980, 1988, 1989, 1993, and 1994, standing skyline yarding was used for steep areas, while less steep areas were tractor-yarded (Mark and Dietterick et al. 2000).

Fire Ecology of Redwoods

Since the earliest days of modern forest management, timber cutters and ecologists have recognized the many physical attributes that afford coast redwoods a high measure of fire resistance. From their thick, flame-resistant bark high in moisture – and six to 12 inches thick in some cases – to their ability to sprout from stumps, roots, and burls - redwoods can be exceptionally hardy survivors of most fires. Older specimens are especially resistant, with many older living trees exhibiting large basal cavities ("goosepens") as a result of numerous historical burns. As these goosepens expand, older trees may have a higher susceptibility to stem breakage under high winds or subsequent fires (Brown & Swetnam 1994, Lorimer et al. 2009).

Several factors make coast redwoods useful in fire regime reconstruction. As with many coniferous species, when coast redwoods experience fire of sufficient heat and duration, regions of cambial cells are killed and then covered in subsequent years by radial ring growth from both sides of the wound. Cambial cells differentiate at an accelerated rate, leaving visible scars (Figure 5), which are often completely obscured several years post-fire. Their thick, protective bark may sluff off in these regions, leaving the tree sensitive to further scarring in future fires (Speer 2010).

In addition to these evident scars, redwoods provide other morphological cues indicative of fire, including: growth releases, indicated by abrupt increases in ring width post-fire; double latewood bands; traumatic resin ducts; post-fire micro rings, and ring separations (Brown & Swetnam 1994).

In spite of their longevity and other beneficial factors, however, this taxa can be extremely challenging for dendroecologists to analyze. Since the 1920s, ecologists have noted a variety of factors unique to coast redwoods that challenge accurate observation of age and fire history (Fritz & Averill 1924, Fritz 1940). Coast redwoods often present discontinuous,

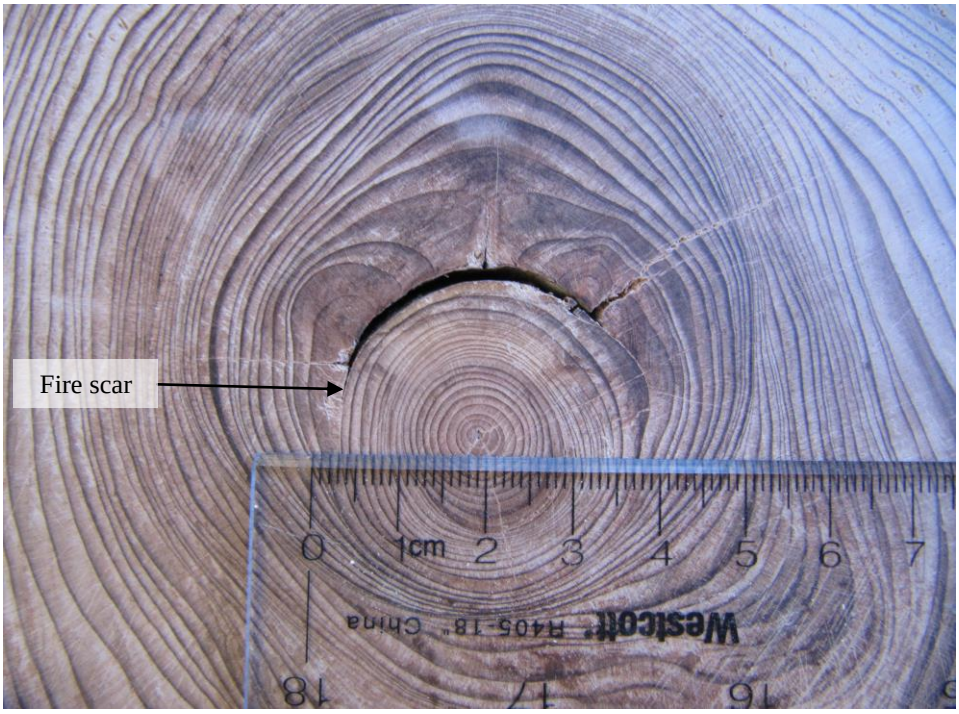

Figure 5. Characteristic fire scar from sample WHC3033.

or complacent growth rings, presenting as annual growth rings which appear to terminate, or compress into adjoining rings – sometimes reappearing elsewhere on the cross-section. This phenomenon essentially precludes the use of increment borers with this taxa, at least on lower portions of the stem. Recent work (Sillett et al 2010) has posited that the complacent ring phenomenon does not persist higher in the canopy, which potentially creates new opportunities for the development of master chronologies in the redwood region. There has been relatively little investigation of this complacency phenomenon in redwoods. Fritz (1940) and Fritz and Averill (1924) investigated a number of challenges related to ring abnormalities in redwoods and postulated that crown injuries, as well as diminished access to light for photosynthesis (via competition or injury) elicits a "peripheral distribution of food materials" response – leading to predictable ring abnormalities. They also postulated that compressive force associated with leaning or wind could lead to similar abnormalities (Figure 6).

Another complicating factor includes the tree's thick bark. This bark, high in tannins and moisture (Speer 2010), can protect cambial tissues from injury – especially in older trees. This can prevent scarring where fires were historically of low intensity, temperature, and duration. In addition, the aforementioned morphological cues (double latewood, traumatic resin ducts, etc.) can complicate analyses by novice investigators. Appropriate equipment, as well as significant time, effort, and consultation are required for investigators to become familiar enough with these anomalies to develop competent recording practices.

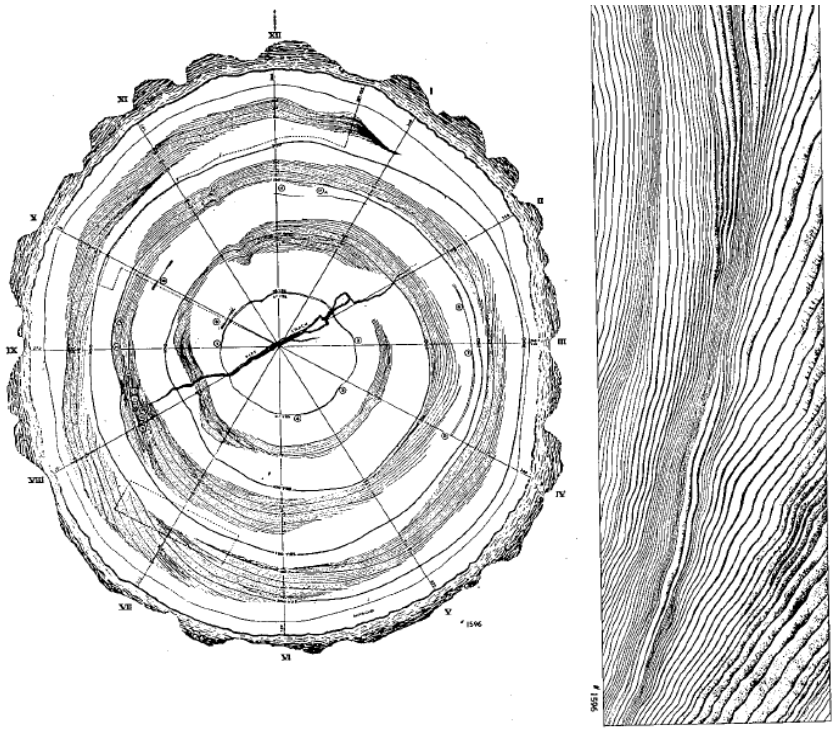

Figure 6. Depiction of spiral compressed growth in coast redwoods (Fritz 1940)

Experimental investigations of fire in redwood forests are still relatively uncommon, with just a dozen or so quantitative studies having taken place in California coast redwood forests in the last 80 years. Emanuel Fritz, as an Associate Professor at the University of California, conducted a number of the earliest quantitative studies on coast redwoods in the 1920s and 30s. Interestingly, Fritz tackled many of the more probative issues pertaining to the science and history of fire in redwoods – many of which still vex fire ecologists to this day. He noted the longevity of the species, and was the first American researcher to publish on possible causes of ring complacency. In a 1924 paper with Averill, they posited that redwoods which experienced crown damage, or were stripped of side branches, suffered a "crippling of food making machinery" –restricting photosynthesis (and thus radial ring growth) to the more branchy side of the tree.

Fritz (1931) also spoke at length on the role of fire in redwood forests, offering treatments on everything from public perceptions of fire in redwoods, to timber harvest operations and their use of fire – to the impact of fire on tourism and local businesses. He even delved into the role of Indians as a source of ignitions of historic fires. Interviews conducted by Fritz seemed to indicate conflicting views on the subject, with some informants offering a rather sophisticated view of "Indian forestry" – a term coined by Fritz –while others portrayed a more prejudice-tinged analysis, challenging assertions that Indians were intelligent enough to employ lucid fire practices. He did note, however, that lightning failed to explain the frequency of fires observed in his own quantitative investigations in Humboldt County. Fritz published an approximate fire return interval of 25 years for this northern redwood territory.

Quiroste Valley State Cultural Preserve

What might be considered a peripheral outcome of this research includes the creation of one of California's newest State Cultural Preserves: Quiroste Valley. As work began on this project in earnest in 2007, and as our team realized that we had very likely confirmed the existence of this major native settlement, steps needed to be taken to protect these important resources for the sake of tribal descendants and future research. Previous efforts by Parks to put a large camp ground on this site were shelved – but no permanent guarantee existed which would provide for the protection of the site's resources. We initiated discussions with Mark Hylkema and other Parks staff about the possibility of rezoning most or all of this Quiroste settlement in 2007, and the protections we sought were approved less than a year later.

Given the nature of our research, and the great support and engagement of the tribe and the local community – we saw this as an opportunity to experiment with a new planning approach which could provide multiple cultural and ecological benefits, while also providing Parks with a new management model potentially suitable for other properties in the State. The process began with informal mutual education.

Engaging in a complex research project on State-owned lands required a deep understanding of park hierarchies, planning and public safety protocols, facilities management, and maintenance on the part of the tribe and researchers. Similarly, Park staff and researchers were exposed to the formal and customary practices of the tribe, and established a better understanding historical land management practices employed by the tribe – and their possible implications on modern resource management.

Tribes have technical-cultural frameworks and methods for natural resource management that developed over many thousands of years (Traditional Ecological Knowledge or TEK, and Traditional Resource and Environmental Management or TREM). Before that knowledge is completely lost, especially with landless tribes like the Mutsun, cooperative and creative measures must be taken to facilitate the tribal community's reengagement with their traditional lands and resources. At the same time, State land managing agencies such as Parks have an obligation to manage those lands such that cultural and biological resources are protected and preserved. By engaging in cooperative, cross-cultural research designed to inform both agency and tribal priorities with respect to resource management (broadly defined), we identified a mutually beneficial policy mechanism to meet those shared goals.

Cultural Preserves are an internal unit classification, or zoning designation, within state park units. Cultural preserves consist of distinct (nonmarine) areas of outstanding cultural interest established within the boundaries of other state park units for the purpose of protecting important historical features (e.g. sites, buildings, or zones which represent significant places or events in the flow of human experience in California) (Parks and Recreation 2014). It was collectively agreed that this mechanism provided the highest level of resource protection, while it could also provide for an active tribal role in on-the-ground management and decision making with respect to cultural and biological resources.

Personal engagement of State Parks leadership was critical in facilitating the redesignation to Cultural Preserve status, as was the General Planning process for Año Nuevo State Park, which began shortly after research was initiated. Direct consultation with State Parks Director, Ruth Coleman, and State Parks Commission Chair, Caryl Hart, culminated in a site visit to Quiroste Valley on April 25, 2008, including tribal and research partners (Figure 7). There, the tribe and researchers were able to make the case for redesignation, and secured agreements from Park leadership to help facilitate the process.

Figure 7. Gathering of State Parks, Tribal, and research partners in Quiroste Valley, April 25, 2008. Pictured (left to right): Val Lopez, Amah Mutsun Tribal Chair; author; Mr. Lopez's spouse; Caryl Hart, State Parks Commission Chair; Chet Bardo, Santa Cruz District Superintendent; Dan Mongradon, Amah Mutsun citizen; Ruth Coleman, Director of Parks; Robin Grossinger, SFEI; Paul Mondragon, Amah Mutsun Vice Chair; Dr. Kent Lightfoot, UC Berkeley; Mark Hylkema, Santa Cruz District Archaeologist; Dr. Rob Cuthrell, UC Berkeley; Scott Green, State Parks Planner.

With vocal support now from local and statewide leadership and staff, as well as that of tribal and local communities, the full California State Park and Recreation Commission met on October 30-31, 2008 to consider and vote on the measure. Earlier that day, we had the opportunity to host the Commissioners at Quiroste where project representatives related the history, context, and importance of the valley's resources. With no meaningful opposition to the designation, the creation of the 224-acre Quiroste Valley State Cultural Preserve received a unanimous vote of the Commission.

This new Preserve, as established by the Commission's vote and articulated in the Año Nuevo General Plan (Plan), allows for a broad set of relationships with tribal peoples and researchers (Parks and Recreation 2008). Within its Declaration of Purpose and Vision, the Plan states:

> "The park's cultural resources include Native California Indian village sites, maritime history, and remnants of historic ranches and other coastal agricultural heritage that reflect a history of human interaction with the land. Interpretation and education programs will enhance the visitor's experience by connecting visitors with the rich natural and cultural heritage found here. These exceptional resources at Año Nuevo State Park will be protected and preserved for future generations" (Parks and Recreation 2008, p.4-6).

The Plan also reflects the importance of the Preserve as a cultural and ecological landscape, prioritizing protection of "significant cultural resources and a unique cultural landscape, while allowing for Native California Indian community and park visitor access." It acknowledges the special relationship between native peoples and the land, while providing for access, use, and culturally-appropriate restoration and management:

> "The management intent in the creation of a cultural preserve is to *provide protection for most of the secluded Quiroste Valley and viewshed as a uniquely preserved and managed cultural landscape and resource that honors the heritage of the historic Quiroste tribe and the Ohlone people* [author emphasis]." The Quiroste Valley *will be managed as a unique cultural landscape and area of important cultural resources* [author emphasis], with provisions for public access and interpretation. A cultural landscape is defined by the National Park Service as 'a landscape containing a variety of natural and cultural resources that associated people define as heritage resources…plant communities, animals, subsistence and ceremonial grounds are often components.' *Management of the cultural preserve may involve vegetation management in order to restore valley conditions to the time of Quiroste occupation* [author emphasis] and the arrival of the Portolá expedition (Parks and Recreation 2008, p.4-19).

Ongoing coordination with appropriate tribal representatives are provided for in the Plan, which will help determine the land stewardship, resource management, appropriate uses, interpretation and education opportunities to be provided in the Quiroste Valley area (Parks and Recreation 2008, p.4-20). Most recently, the Mutsun Land Trust has prepared a Vegetation Management Plan (AMLT 2014), informed by archaeological and fire history information, to guide early improvements to the valley's resources.

CHAPTER 3

Study Area
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Methods

In this chapter, I describe the study area and summarize methods employed in this study with respect to the collection, preparation, and analysis of redwood stump samples from the Santa Cruz Mountains.

Study Area

Initiated as part of a multidisciplinary study focused on the Whitehouse Creek watershed (San Mateo County), funding from the Joint Fire Science Agency (Johnson et al. 2010) allowed us to expand our original study area into two adjacent basins in Santa Cruz Mountains north of Davenport, California, approximately 65 miles (101 km) south of San Francisco and 16 miles (26 km) northwest of Santa Cruz. Details regarding the location and setting of Quiroste Valley is described in detail by Cuthrell et al. (2013). The study area focuses primarily on the Whitehouse Creek, Waddell Creek, Scotts Creek watersheds, but also includes select locations in the Gazos Creek and San Vicente Creek watersheds (Figure 7). The Whitehouse Creek watershed encompasses 5 mi^2 (1,294 ha), Waddell Creek is 24 mi^2 (2,822 ha), and Scotts Creek is 30 mi^2 (7,700 ha). Elevations in the study area range from 37m nearest the coast to 655m near the headwaters of Waddell Creek.

Today, approximately ninety-five percent of the Scotts Creek watershed is in private ownership, with the remaining lands resting in state and federal ownership. Conversely, the vast majority (~86%) of the Waddell Creek watershed lies in the hands of the California Department of Parks and Recreation (Big Basin State Park). The Whitehouse Creek watershed is also largely in public ownership (Año Nuevo State Park), but with significant and long-term private holdings in the lower and central portions of the basin. Sampling locations on in Whitehouse Creek were surveyed, photographed, and mapped starting in 2008, with sampling taking place in 2009 and 2010. Scotts and Waddell Creeks were surveyed, photographed, and mapped in the winter and spring of 2011, with sampling taking place in 2012 and early 2013.

Much of the study area contains highly variable physiographic environments, including multiple, small sub-basins with varying slope/aspect combinations, mid-slope benches, landslide features, faults, rich alluvial bottomlands, and a wide variety of terrestrial vegetation classes – all of which affect the behavior of fire. This variability can be observed within and between basins. While Whitehouse and Waddell Creeks both conform to a typical perpendicular orientation with respect to the coast, Scotts Creek exhibits a more unusual configuration for this part of the coast – running parallel to the coastline for 8 km before veering inland (Mark and Dietterick et al. 2000).

Both Scotts and Waddell Creeks widen into brackish/freshwater marshes just upstream of the Monterey Bay, but only in Waddell can redwoods be found throughout the lower portions of the basin. In Scotts Creek, the distribution of coast redwoods is limited principally to tributaries and the upper/central portion of the riparian corridor, and they are not presently found near the

Scotts Creek Marsh environs. West (2008) posits that in the lower portion of the watershed (flood plain area), seasonal/cyclical periods of flooding may upset the balance between beneficial and pathogenic mycorrhizal fungi, potentially creating a hostile environment for the long-term establishment of redwood colonies.

Whitehouse Creek Canyon presents another physiographic environment entirely. The Pacific terminus of this creek possesses no marsh whatsoever. Its lower reaches are instead confined to significantly incised, sinuous, and riparian-choked stream, whose redwood treeline extends only to within about 3 km of the coast – terminating near the ancestral Quiroste village. The San Gregorio Fault bisects lower Whitehouse Creek just downstream of a concrete dam constructed ca. 1900, and located at a narrow corridor bisecting lower and mid-basin alluvial valleys. Perched just uphill of this feature is an ancient landslide which likely activated several times in recent geologic history, blocking the creek and facilitating the formation of the current mid-basin valley now occupied by more than a dozen private inholdings (Weber and Allwardt 2001; Hayek 2000).

This region provides ideal conditions for exploring questions of aboriginal fire management for several reasons. The documented history of human habitation and settlement in the region is robust, providing adequate information for comparison of pre- and post-colonization human activity (see Hylkema and Cuthrell 2013). Several owners of large properties in the area have occupied and managed these watersheds for a century or more in some cases, maintaining detailed records on past land use, logging history, and fire occurrence for their lands. Because "natural" (lightning-ignited) fires are rare in this part of California (Greenlee 1983, Wagtendonk & Cayan 2008), they are not thought to have been a major determining factor in the dominant fire regimes in the central California coastal ranges. Fire ignitions are thought to have been primarily anthropogenic in origin (Keeley 2002; Stephens and Fry 2005). As such, while this study does not discount lightning as a source of ignition for some fires, this research assumes a predominance of anthropogenic ignitions.

Dendroecology methods

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 triangular-shaped, burned-out basal cavities and annual growth rings (Jacobs et al. 1985; Stephens and Fry 2005). By determining the position of these scars within the context of the annual growth rings, we are able to reconstruct the fire frequency and seasonality in the select sites identified in the study area (Figure 7).

The sampling strategy was designed to assemble an exploratory sample of fire scars over the longest time frame possible from individual sites or plots that represent the topographic, climatic, and structural diversity of the study area (Swetnam and Baisan 2003; Stephens et al. 2004; Stephens and Fry 2005). The study area was oriented around portions of the historical tribal territories of the Quiroste and Cotoni peoples, as well as what is estimated to be a boundary area between the two communities (Waddell Creek) (Figure 2, Figure 7). Where possible, clusters of well-preserved fire-scarred stumps, snags, or downed logs that contain approximately 5 samples in an area of $\leq$ 20 ha or less (with generally homogeneous vegetation and topography)

were prioritized for sampling (Vaillant and Stephens 2009). The aim was to structure sampling to encompass the gradient of land use patterns in the study area (Gassaway 2007).

Figure 8. Map of Study Watersheds, Santa Cruz and San Mateo Counties, CA.

Fire scar 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, Farris et al. 2013) and has often been necessary in prior studies to obtain adequate data sets for this type of study (Brown and Baxter 2003; Stephens and Fry 2005). Entire or partial cross sections (approximately 5 to 8 cm thick) were extracted from remnant wood and live trees using a chainsaw (Arno and Sneck 1977; McBride 1983; Agee 1993). Both young (<150 years) and old specimens (>150 years) were selected in order to maximize the length and completeness of the temporal record (Farris et al. 2010), but adequately preserved stumps with intact bark and sapwood, downed logs, and trees that were not significantly decayed or degraded were prioritized. In Scotts Creek, stands that were recently logged in the post-Lockheed Fire (2009) salvage operation were preferentially selected to increase the prospect of having intact bark and sapwood to facilitate the assignment of accurate calendar dates (Norman 2007). Sections were occasionally removed from multiple locations and heights on the basal flutes and tree boles to capture accurately the most complete scar record possible (Stokes 1980; Dieterich and Swetnam 1984), but great care was taken to collect samples from as close to the root-trunk transition as possible (Norman 2007), and only one count per sample tree is represented in the results. Care was taken to avoid damage to redwood regeneration.

The following information was recorded for samples collected:

- species
- sample identification code (property) and number
- sample collection date
- location (UTM coordinates)
- elevation (in meters, recorded in field using Garmin GPS)
- condition (snag, stump, log, or live tree)
- fire scar orientation (where visible)
- height (from root-trunk transition) and depth of cut
- vegetation cover (visual estimate of species dominance)
- diameter at breast height (dbh)
- aspect (field estimation)
- percent slope (using a clinometer)
- position on slope position on slope (valley bottom to bottom 1/3 of slope = bottom; middle third of slope = middle; and top third of slope to ridgeline or significant topographic crest = top)
- harvest date (if known)

Sampling locations were photographed, but were not be permanently marked in most cases as many property owners requested that we minimize the visual evidence of our work. All fire-scarred samples were labeled and transported to the University of California, Berkeley (Richmond Field Station), for preparation and laboratory analysis. See Appendix I for a sample field data collection sheet.

Additionally, several GIS-based measurements were determined once the positions of individual sample trees were incorporated into the project geodatabase. These included:

- distance from coast (in meters);
- northness/eastness (refinement of aspect; see below for details);
- distance from "culturally significant zone" (defined below);
- distance from known (recorded) archaeological site (defined below);
- distance from (pre-colonial) residential site (defined below);
- and watershed/zone (described below).

Aspect was calculated using ArcGIS and a 10 meter Digital Elevation Model from the National Elevation Dataset (downloaded at Cal-Atlas, http://atlas.ca.gov/download.html#/casil/elevation). Because aspect is a cyclical variable (0 and 360 degrees are equivalent), a transformation of aspect was used in this model: Northness = cos (aspect) and Eastness = sin (aspect).

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 400-600 grit sand paper, 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 annual rings on all samples commenced inward from the bark, with the outermost ring being the year the tree was sampled or died (Year 0).

Samples were counted at least once, with many counted several times to account for complacent rings. Each sample was inspected for regions exhibiting ring complacency, and accounted for by making multiple counts along different radii. Fire affected ring numbers were assigned based on the longest radial count.

Fire scars were identified by the overlapping curvilinear growth in post-fire growth rings that is characteristic of the tree's healing pattern (McBride 1983). The fire season was determined by the position of the scar within the annual growth ring. Although some dendrochronologists have established six different seasonal categories (e.g. Baisan and Swetnam 1990), this study makes use of only three general categories; earlywood, latewood, or dormant season.

Accurate dating of redwoods has proven notoriously difficult due to anomalies in the ring patterns such as locally absent, missing, false, wedging rings, and complacency (lack of sensitivity to limiting environmental variables; Fritz 1940; Brown and Swetnam 1994; Waring and O'Hara 2006; Lorimer et al. 2009). Fire return intervals, the number of years between successive fire events in a designated area, are based on ring counts between consecutive fire events (Jacobs et al. 1985; Finney and Martin 1989; Stephens and Fry 2005). Attempts were made to corroborate common fire dates between trees within individual plots, and between plots where large historic fires could be documented.

The following events and information were also used to calibrate calendar dating and date bracketing:

- Fire scars from known fires, including 2009 (3,163 ha), 1962 (1,310 ha), 1948 (6,400 ha), 1936 (10,400 ha), 1919, and others.
- Timber harvest dates from Big Creek Lumber, Swanton Pacific Ranch, and CalFire timber harvest plan data (furnished by the Sempervirens Fund).
- Timber harvest, blow-down, and prescribed (Rx) burn dates from Big Basin State Park.
- Presence of sapwood on samples.

To be included in the analysis, a tree must have been considered a 'recorder' tree (i.e. a tree that has scarred at least one time, thus becoming more susceptible to future scarring on the exposed sapwood), and have at least one additional scar. Only scar to scar intervals were recorded (e.g. the period from the tree origination date to the first fire scar is not considered an "interval", thus not included in our analysis, see Baker and Ehle 2001). For each cross-section from recording trees, the point minimum, maximum, median, mean, and range of fire return intervals were calculated. The mean fire return interval is the statistical average of all fire intervals in each sampled tree and is calculated by recording the number of annual growth rings between each fire scar, summing the intervals, and then dividing this result by the total number of recorded fires. Mean FRIs are reported herein, as well as data composited at the plot level (Dieterich 1980) and then for each aspect, position on slope, dominant vegetation cover, along distance-from-coast and elevational gradients, and with respect to distance from recorded archaeological sites.

Harvest dates were established for approximately a third of the sample trees. Fire interval information for this subset was analyzed using FHX2 (Grissino-Mayer 1996). FHX2 provides a means for entering, archiving, storing, and editing of fire history information from tree rings, which in turn, provides a more efficient mechanism for data transfer and exchange. Analyses reported via FXH2 include Mean Fire Intervals (MFI), median fire interval, Weibull modal and median intervals, standard deviation, coefficient of variation, skewness, kurtosis, Kolmogorov-Smirnov Test for Goodness-of-Fit, and seasonality information (percent of fires in each season class, % of early vs. late vs. dormant season fires).

Table 1 indicates which samples were included in which plots, excluding four samples which were considered "isolates." For the purposes of the GLMM (see below), isolates were defined as plots 16-19 to capture each samples' physiographic information in the model.

Table 1. Plot designations by sample tree ID.

Plot 1	*Plot 2*	*Plot 3*	*Plot 4*	*Plot 5*	*Plot 6*	*Plot 7*	*Plot 8*
WHC3021	WHC3041	WHC3034	WHC3016	BBP002	ROS001	COT008	COT013
WHC3022	WHC3042	WHC3036	WHC3020	BBP006	ROS002	COT011	COT015
WHC3023	WHC3043	WHC3037	WHC3033	BBP007	ROS003	COT012	
WHC3024	WHC3044	WHC3038			ROS004		
WHC3025	WHC3046	WHC3039			ROS005		
WHC3026	WHC3047	WHC3040			ROS006		
WHC3027	WHC3048						
WHC3029	WHC3049						
WHC3030							
WHC3031							
WHC3032							

Plot 9	*Plot 10*	*Plot 11*	*Plot 12*	*Plot 13*	*Plot 14*	*Plot 15*	*Isolates*
BCL004	BCL011	BCL012	BCL002	COT003	COT006	SPR001	BBP005
BCL005	BCL017	BCL014	BCL003	COT004	COT007	SPR002	BRI001
		WIL001	BCL006		SPR007	SPR009	BRI002
			BCL007		SPR008	SPR012	COT001
			BCL009				
			BCL015				
			BCL016				

Floating Chronologies

Since firm harvest dates for the majority of the sample set were not able to be established, these samples were handled as "floating chronologies." These are defined as intervals between discernible fire events based on rings for which absolute calendar dates cannot be reliably established (Clark and Renfrew 1972). Numerous approaches have been used to align floating chronologies with known or established chronologies, usually by crossdating focal samples with regional master chronologies, or developing a ^{14}C calibration curve from existing master chronologies and linking floating ring series to the resulting radiocarbon age/tree-ring age curve (Yamaguchi 1986, Roig et al. 1996, Kromer et al. 2004). Even if permanent temporal gaps in the tree-ring record exist, wiggle-matching (Baillie 1995) of high precision carbon dates and the ^{14}C record can allow for dating of floating chronologies to within a few decades (Stambaugh and Guyette 2009).

Regional master chronologies for coast redwoods (or the associated ^{14}C calibration) have yet to be established for the study area, so an attempt was made to detect patterns in fire frequency with respect to known cultural and physiographic variables using a novel statistical model.

Zones of indigenous cultural significance (C-zone) were established based on related work in the Santa Cruz Mountains supported by the Sempervirens Fund. As part of a

conservation planning effort (Sempervirens Fund 2013), the Sempervirens Fund included an element designed to inventory, classify, and map culturally important zones within their focal region with the aim of deriving multiple benefits from their redwood-based conservation activities.

C-zone was determined by creating separate cells of "use areas" in a way that would allow for a ranking of resources, thus isolating those areas of greater cultural importance. Archaeological data were used as the basis of evaluation, which would restrict areas of "high value" to those places containing physical evidence (i.e., archaeological deposits and features). The resource base surrounding the archaeological sites constituted the area of high value, and was not restricted to individual site boundaries. For example, a bedrock milling station, typically found among rock outcrops or boulders and manifesting as mortar depressions for processing nut crops, should be considered as a component of the larger area from which the nuts were harvested, and not just the milling station site itself (Hylkema and Cuthrell 2013).

Criteria used in this classification included:

- Residential Landscapes
- Travel Routes
- Fishing Locations
- Seed and Nut Extraction Zones
- Lithic Resources
- Ideological Places
- General Value Areas

These various criteria invariably overlap. Because each of these uses is "significant" to the Native American cultural landscape, the activity zones were bounded together and designated by the multiple uses proposed to be within them. Overlapping boundaries were merged into single contiguous units (Hylkema 2011 and Figure 10).

Distances to archaeological sites were calculated based on their linear distances (measured to polygon center) to recorded archaeological sites (i.e. CA-SMA-113), irrespective of site type. A subset of those sites were classified as "residential" (ResSite) by either the presence of applicable artifact assemblages, proximity to topographically habitable zones, and/or proximity to perennial fresh water sources. Individual site reports were collected from California State Parks (Santa Cruz District), and/or the Northwest Anthropological Information Center in Rohnert Park, CA. Mark Hylkema, Santa Cruz District Archaeologist for CA State Parks, was instrumental in understanding habitation patterns in the region.

Given the high variability of study watersheds, including many smaller physiographic units which strongly impact fire behavior and occurrence, I delineated three "zones" within the project area (Figure 9) for use in the GLMM, which incorporates standard continuous variables for all areas (i.e. slope, aspect, elevation, distance from coast). The northern zone (Zone I) encompasses the environments of mid- and lower Whitehouse Creek, including units sampled between Quiroste Valley, the mid-basin valley and proximate hill slopes – ranging in elevation from approximately 100 to 380 meters. The second zone (Zone II) encompasses mid-elevation,

interior environments in upper Scotts and Waddell Creeks, ranging in elevation from approximately 100 to 790 meters. The third zone (Zone III) encompasses lower elevation, near coast environments in lower Scotts and Waddell Creeks, ranging in elevation from approximately 20 to 600 meters. To represent this physiographic variability in the GLMM, I intersected the watershed and zone to get a finer set of categories to test against the continuous physiographic variables (northness/eastness, elevation, percent slope, distance from coast). See Appendix II for the full model script, which includes steps taken to properly format the data frame for R, including reduction steps.

Generalized linear mixed model (GLMM)

For floating chronologies, I worked with Melissa Eitzel (PhD Cand., UC Berkeley/ ESPM) to construct a generalized linear mixed model (GLMM) to detect possible patterns in the annual probability of fire (Bolker et al. 2009). For the purposes of this study, we utilized a binomial probability model where each annual growth ring represents a "trial", and each fire scarred ring is defined as a "success." Unscarred rings are therefore defined as a "failure." We require a mixed model framework because we treat plots as random effects. We aggregated the return interval data to obtain the number of fire scars per sample in order to estimate this binomial model.

These data possess a number of attributes which made it desirable to use such a model in this case. We chose the binomial successes/failures model to account for the highly variable lengths of the records (ring counts; "trials"). We favor this model of the number of fire scars per sample rather than the fire return interval because the latter is Weibull distributed , and developing a mixed model with a Weibull distribution is beyond the scope of this study. To incorporate spatial autocorrelation in the model, plot designations were treated as random effects. In addition, to account for the unbalanced nature of the overall sample set (varying number of samples per plot) we used likelihood ratio tests to establish significance.

Model estimation and significance testing

For this model, R (R Core Team 2013) facilitates the use of independently scripted functions which were utilized here to model annual probability of fire as a function of continuous and explanatory variables using an unbalanced, non-normally distributed sample set. To estimate the GLMM described above we used glmer ("generalized linear mixed effect regression" in the lme4 package; Bates et al. 2013). This package is traditionally used to fit generalized (non-Gaussian) linear mixed models which have random effects (in this case, plot).

We separately tested the significance of the random effect for plot by fitting the model without the plot effects using the function "glm" and ensuring that the glmer models used maximum likelihood estimation (not restricted maximum likelihood estimation). We tested the significance of the plot effect with all the other fixed effects in the model to account for the potential explanatory power of all the fixed effects (Zuur 2009). Once a fixed effect (i.e. position on slope) was determined to be significant, it was included in subsequent models. To evaluate the significance of the fixed effects, we used a likelihood ratio test: for each predictor variable we estimated a reduced model, calculated the likelihood ratio between the reduced and full

models, and obtained p-values using a chi-squared approximation for the likelihood ratio. Likelihood ratios are valid even in cases with an unbalanced design and therefore our tests should be robust even given the varying number of samples per plot. We used a backward-selection approach (Crawley 2005) to eliminate non-significant variables and produce a reduced model.

Simply stated, this model is designed to estimate which parameters most affect the odds of a fire occurring, or not occurring (success/failure), in any given year. The full model estimates these odds inclusive of the random plot effect and all fixed variables: position on slope; zone (I-III); elevation; aspect; distance to coast; and distance to site types (cultural zone, recorded arch., residential site). As variables "fall out" as non-significant (not predictive of fire occurrence), a reduced model then tests only the remaining variables. Through this "backward selection" process, only those variables which are estimated to most affect the odds of a fire occurring present as significant. Parameter estimates and p-values for this reduced model are presented in the Results section.

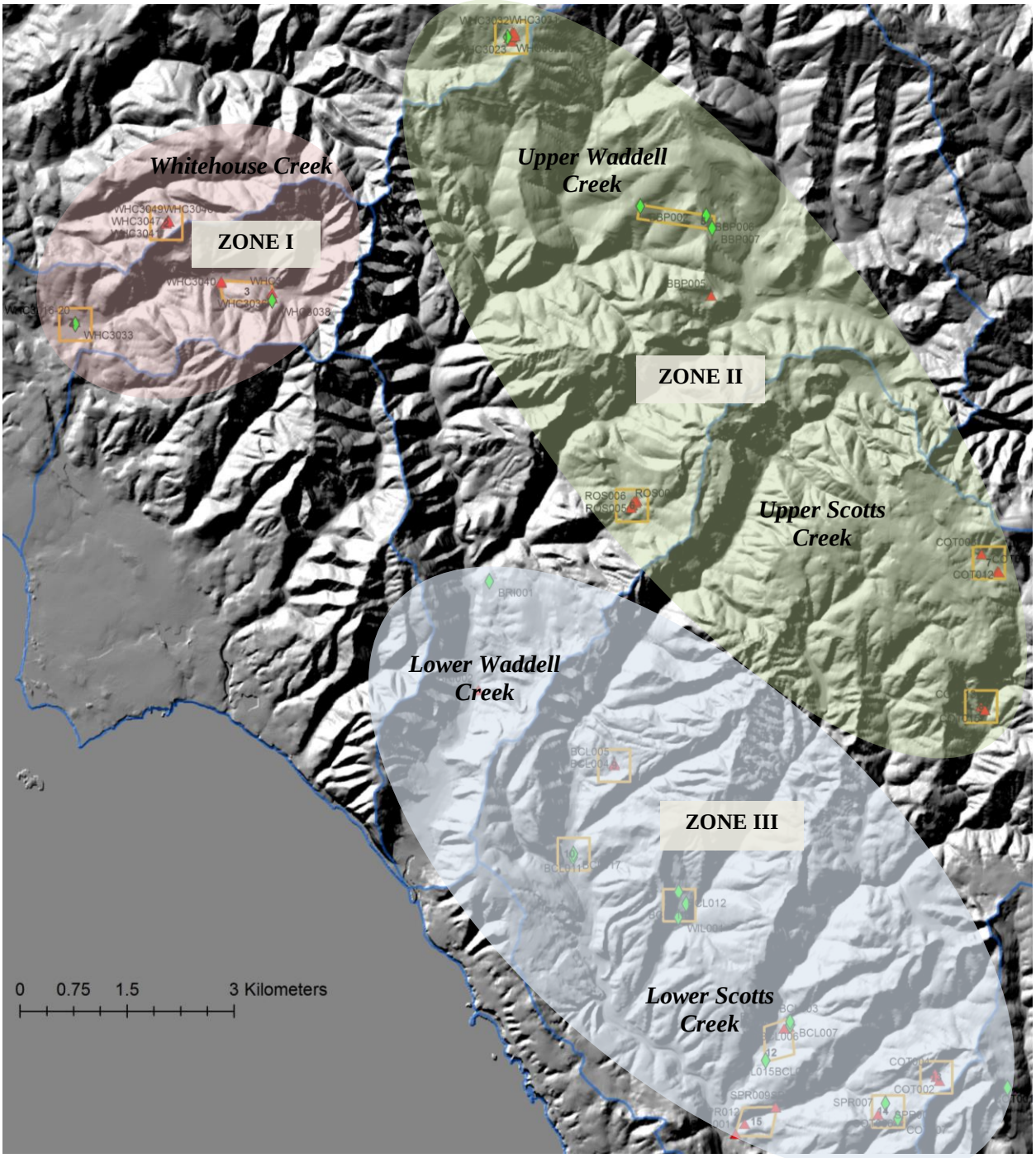

Figure 9. Map of physiographic zones (I-III), Santa Cruz and San Mateo Counties, CA.

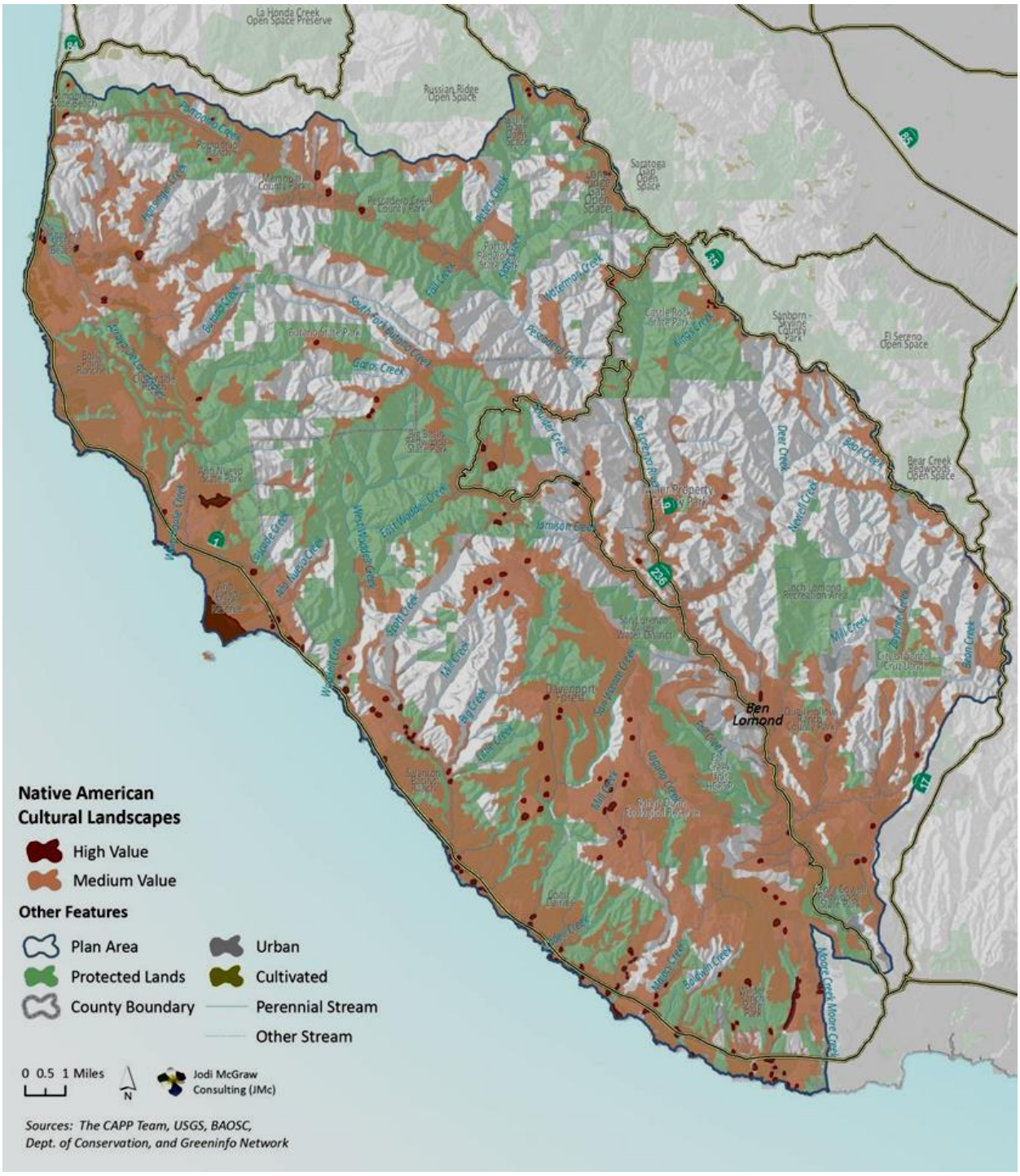

Figure 10. Native American cultural landscapes of the Santa Cruz Mountains (Sempervirens Fund 2013).

CHAPTER 4

Results

A total of 103 coast redwood cross-sections were collected from 95 trees in 19 plots within the study area (Figures 11 and 12). All sites were of predominantly redwood overstory, with a variety of stand and understory characteristics. Thirty-two of the cross-sections were discarded for lack of usable fire interval information (excessive rot, or <1 fire intervals), leaving 73 total cross-sections. Harvest dates could be determined for 20 trees, leaving 53 which could not be firmly dated (floating chronologies). The analysis of those data with the GLMM is discussed below.

Most plots were located on relatively steep slopes (mean 35.1%), with the majority of cross-sections collected from stumps (76%). Other cross-sections were retrieved from downed logs (4.6%), standing snags (8.3%), living trees (10.1%), one from a fallen lateral limb, and one (pre-cut) cross-section was included whose origin could only be determined to within a $1km^2$ area. Other physical attributes of the sample set are summarized in Table 2.

Table 2. Physical attributes of collected redwood samples.

Source (n=103)	*Log*	*Lateral limb*	*Live tree*	*Snag*	*Stump*	*Unknown*
	4	1	11	9	77	1
Bark condition	*Present*	*absent*	*unrecorded*			
Number of cross-sections	49	45	9			
Sapwood	*Present*	*absent*	*unrecorded*			
Number of cross-sections	56	45	2			
Pith	*Present*	*absent*	*Within ~20 rings*	*Unrec.*		
Number of cross-sections	11	87	2	3		
DBH (cm)*	*Mean*	*Median*	*Range*			
	179	168	66-373			
Circumference (cm)	*Mean*	*Median*	*Range*			
	561	528	208-1172			
Position of cut (cm)**	*Uphill*	*Downhill*	*Sidehill*	*Full*	*Unrec.*	
Number of cross-sections	36	19	15	20	13	
Height of cut (cm)***	*Mean*	*Median*	*Range*			
	55.9	53.3	2.5-228.6			
Depth of cut (cm)	*Mean*	*Median*	*Range*			
	115.1	68.6	31.8-716.3			
Percent slope	*Mean*	*Median*	*Range*			
	35.1	40.0	0.0-90.0			

* diameter at breast height ** with respect to hill slope *** from root-trunk transition

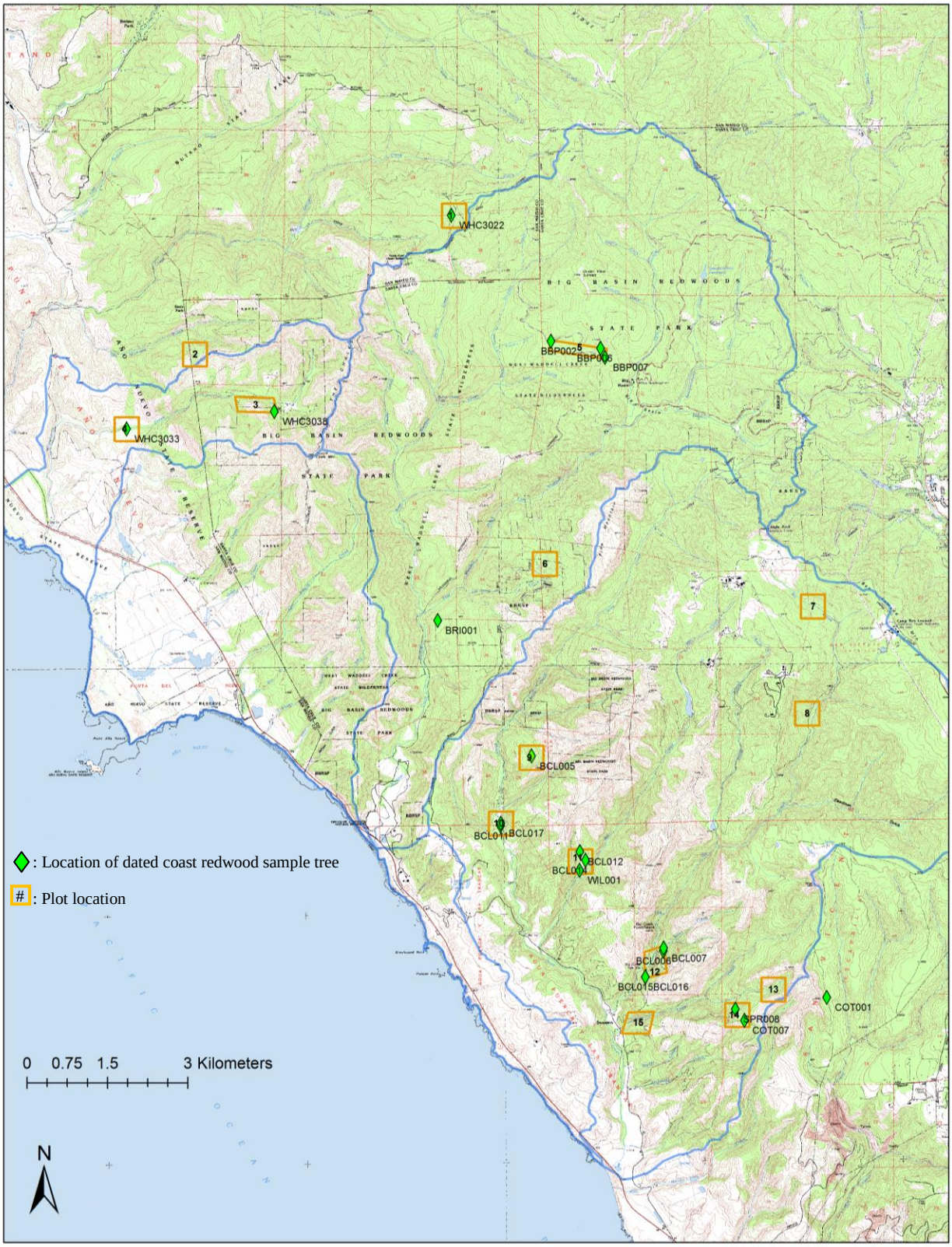

Figure 11. Sample and plot locations for dated redwood sample trees. Empty plots indicate presence of (undated) floating chronologies (Fig. 12); blue lines indicate watershed boundaries.

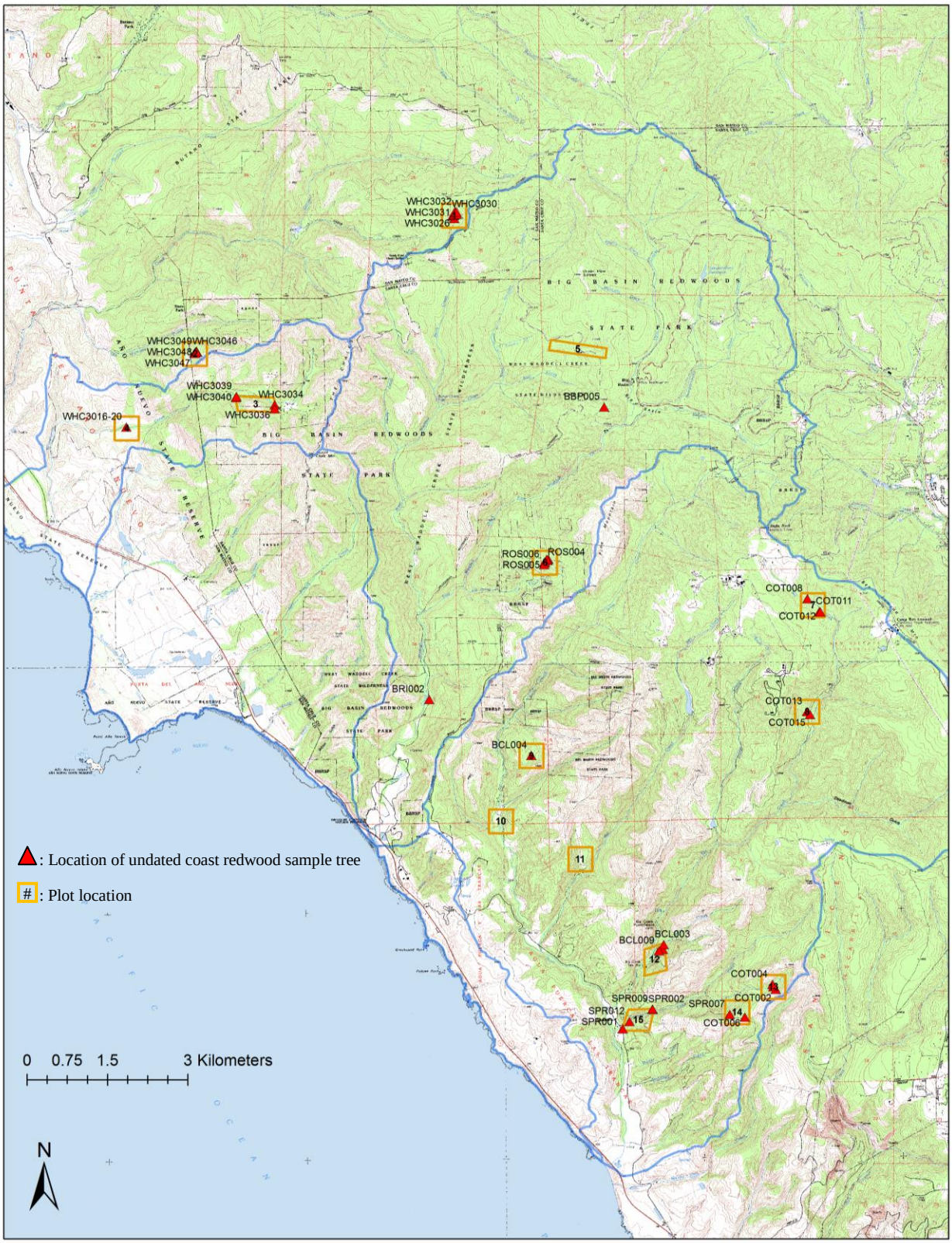

Figure 12. Sample and plot locations for redwood sample trees with floating chronologies. Empty plots indicate presence of dated chronologies (Fig. 11); blue lines indicate watershed boundaries.

The time period described by dated fire scars is roughly 1600-2013, though the lack of crossdating does not allow for precise estimation of this period before 1600. Some of the undated cross-sections almost certainly extended several hundred years beyond 1600. For instance, WHC3034 (Appendix I) had a record of approximately 1,224 years, but this cross-section was retrieved from a top-killed standing old growth snag never subject to harvest, and there was no documentary information or local knowledge that would indicate a firm mortality date for this tree. The owner of this stand, who has logged the area continuously since the 1940s, indicated that it's been a snag as long as the family has owned the property (F. McCrary, pers. comm.). Given the sound condition of the wood, however, it was likely killed in the early 20th century, putting its record of fires back into the 7th century AD.

Dated samples

Summary fire frequency and seasonality information was estimated for dated samples going back to 1350 in order to capture a greater proportion of the fire information for this region, Composite fire information for dated samples by plot was also estimated for the focal management eras: the native and ranching eras (1600-1850), the intensive commercial logging period (1850-1950), and the modern fire suppression/sustainable harvest era (1950-2013).

The fire return intervals recorded from the dated redwood samples in this study were relatively frequent (Table 3, Figure 12). For all sites combined, mean FRI was 6.97 years; the median FRI was 4.0 years. The grand mean FRI for single trees (point) was 39.9 years (range of means 7–518 years). The grand median FRI (point) was 25 years. The mean number of fire scars on an individual sample was 4.12 (range 2-12 scars). The earliest recorded fire in dated samples was in 1351 (COT001), and the most recent fire recorded in many of these trees was the 2009 Lockheed Fire. Several of our samples survived that extreme fire event, only to suffer mortality due to high winds in subsequent years (i.e. WIL001). Fire information based on point estimates is presented in Appendix III.

In several locations, nearby plots were composited where dated sample density was insufficient for analysis in FHX2, and where local physiography does not present significant physical barriers to fire spread. As evidenced by the behavior of many historic and modern fires (Figure 12), the vast majority of the project area, in fact, presents few significant physical barriers to fire spread in the dry season, except in the very lower reaches of the basins.

Though some plots did not contain enough data for analysis for some management periods (see Table 3), those plots containing two or sample trees tended to exhibit similar patterns of fire frequency: recorded fires were less frequent in the native and ranching period (mean FRI 7.6 years; range 1-29) than the intensive logging period (mean FRI 3.1 years; range 1-11), as well as the modern period (mean FRI 4.6 years; range 1-12).

Table 3. Fire frequency and seasonality information.

Samples	All Samples				WHC3022+BBP002+BBP006-7				BBP002+BBP006-7				BCL011+BCL017				BCL005+011+012+014+017+WIL001			
Range	1350-2013 Composite	1600-1850 Composite	1850-1950 Composite	1950-2013 Composite	1350-2013 Composite	1600-1850 Composite	1850-1950 Composite	1950-2013 Composite	1350-2013 Composite	1600-1850 Composite	1850-1950 Composite	1950-2013 Composite	1350-2013 Composite	1600-1850 Composite	1850-1950 Composite	1950-2013 Composite	1350-2013 Composite	1600-1850 Composite	1850-1950 Composite	1950-2013 Composite
Fire Frequency																				
Total Intervals	95	34	34	13	25	10	12	3	20	10	7	3	12	11	--	--	30	13	13	4
Mean Fire Interval	6.97	7.32	2.94	4.62	16.48	24.9	8.17	12	20.6	24.9	14	12	21.33	8.45	--	--	8.53	7.15	5.69	13.75
Median Fire Interval	4	4.5	2	4	12	23	4.5	12	22	23	9	12	9	7	--	--	6	6	5	16
Fire Frequency	0.22	0.19	0.41	0.26	0.09	0.04	0.19	0.1	0.76	0.04	0.12	0.1	0.08	0.12	--	--	0.14	0.16	0.2	0.07
Coefficient of Variation	1.33	1.01	0.87	0.82	0.91	0.57	1.21	0.83	0.76	0.57	1.11	0.83	1.68	0.56	--	--	0.84	0.69	0.74	0.49
Minimum Fire Interval	1	1	1	1	1	4	1	2	1	4	1	2	3	3	--	--	1	1	1	4
Maximum Fire Interval	58	29	11	12	44	42	35	22	44	42	44	22	130	17	--	--	32	17	16	19
Weibull Median Interval (@.500)	4.54	5.36	2.46	3.81	11.39	23.04	5.27	9.85	15.79	23.04	8.54	9.85	12.02	8.01	--	--	6.9	6.3	4.93	13.44
Seasonality																				
Total number of fires for site	112	40	42	19	--	10	12	3	--	10	7	3	--	11	--	--	33	14	14	5
Number with season	95	35	33	17	--	8	8	3	--	8	3	3	--	11	--	--	31	14	12	5
Percentage with season	84.8	87.5	78.6	89.5	--	80	66.7	100	--	80	42.9	100	--	100	--	--	93.9	100	85.7	100
Number undetermined	17	5	9	2	--	2	4	0	--	2	4	0	--	0	--	--	2	0	2	0
Percentage undetermined	15.2	12.5	21.4	10.5	--	20	33.3	0	--	20	57.1	0	--	0	--	--	6.1	0	14.3	0
Number of fires in Dormant Season	52	22	20	6	--	5	4	1	--	5	0	1	--	9	--	--	19	10	9	0
Percentage of fires in Dormant Season	54.7	62.9	60.6	35.3	--	62.5	50	33.3	--	62.5	0	33.3	--	81.8	--	--	61.3	71.4	75	0
Number of fires in Early Season	12	3	5	4	--	2	2	1	--	2	1	1	--	1	--	--	4	1	1	2
Percentage of fires in Early Season	12.6	8.6	15.2	23.5	--	25	25	33.3	--	25	33.3	33.3	--	9.1	--	--	12.9	7.1	8.3	40
Number of fires in Late Season	31	10	8	7	--	1	2	1	--	1	2	1	--	1	--	--	5	3	2	3
Percentage of fires in Late Season	32.6	28.6	24.2	41.2	--	12.5	25	33.3	--	12.5	66.7	33.3	--	9.1	--	--	25.8	21.4	16.7	60

Table 3 (cont'd). Fire frequency and seasonality information.

Samples	BCL012+BCL014+WIL001				BCL014-016+WIL001+BCL006-7				BCL006-7+BCL015-016				SPR008+COT007				SPR008+COT007+COT001			
Range	1350-2013 Composite	1600-1850 Composite	1850-1950 Composite	1950-2013 Composite	1350-2013 Composite	1600-1850 Composite	1850-1950 Composite	1950-2013 Composite	1350-2013 Composite	1600-1850 Composite	1850-1950 Composite	1950-2013 Composite	1350-2013 Composite	1600-1850 Composite	1850-1950 Composite	1950-2013 Composite	1350-2013 Composite	1600-1850 Composite	1850-1950 Composite	1950-2013 Composite
Fire Frequency																				
Total Intervals	10	--	7	--	33	12	9	5	26	12	3	4	8	--	3	5	21	3	8	5
Mean Fire Interval	24.2	--	10.29	--	16.27	17.75	8	10.4	20.65	17.75	12	13	19.62	--	31.33	12	31.52	26.67	11.75	12
Median Fire Interval	11	--	11	--	11	6	5	11	12	6	9	12.5	25	--	30	4	16	21	13	4
Fire Frequency	0.07	--	0.1	--	0.09	0.09	0.15	0.1	0.07	0.09	0.11	0.09	0.08	--	0.03	0.16	0.06	0.04	0.09	0.16
Coefficient of Variation	1.32	--	0.59	--	1.04	1.12	0.88	0.56	1	1.12	0.98	0.72	0.78	--	0.2	1.2	1.57	0.86	0.54	1.2
Minimum Fire Interval	3	--	3	--	1	1	2	4	1	1	2	4	1	--	26	1	1	7	3	1
Maximum Fire Interval	107	--	18	--	63	60	22	19	72	60	25	23	38	--	38	33	188	52	19	33
Weibull Median Interval (@.500)	15.1	--	9.64	--	11.62	11.04	6.53	9.93	14.59	11.04	9.25	11.63	13.32	--	31.77	6.33	16.95	22.79	11.15	6.33
Seasonality																				
Total number of fires for site	--	--	7	2	--	12	9	7	--	12	3	5	--	--	3	5	--	3	8	5
Number with season	--	--	5	2	--	9	7	6	--	9	3	4	--	--	2	4	--	3	7	4
Percentage with season	--	--	71.4	100	--	75	77.8	85.7	--	75	100	80	--	--	66.7	80	--	100	87.5	80
Number undetermined	--	--	2	0	--	3	2	1	--	3	0	1	--	--	1	1	--	0	1	1
Percentage undetermined	--	--	28.6	0	--	25	22.2	14.3	--	25	0	20	--	--	33.3	20	--	0	12.5	20
Number of fires in Dormant Season	--	--	3	0	--	5	4	2	--	5	2	2	--	--	1	2	--	2	4	2
Percentage of fires in Dormant Season	--	--	60	0	--	55.6	57.1	33.3	--	55.6	66.7	50	--	--	50	50	--	66.7	57.1	50
Number of fires in Early Season	--	--	0	0	--	0	0	0	--	0	0	0	--	--	0	1	--	0	1	1
Percentage of fires in Early Season	--	--	0	0	--	0	0	0	--	0	0	0	--	--	0	25	--	0	14.3	25
Number of fires in Late Season	--	--	2	2	--	4	3	4	--	4	1	2	--	--	1	1	--	1	2	1
Percentage of fires in Late Season	--	--	40	100	--	44.4	42.9	66.7	--	44.4	33.3	50	--	--	50	25	--	33.3	28.6	25

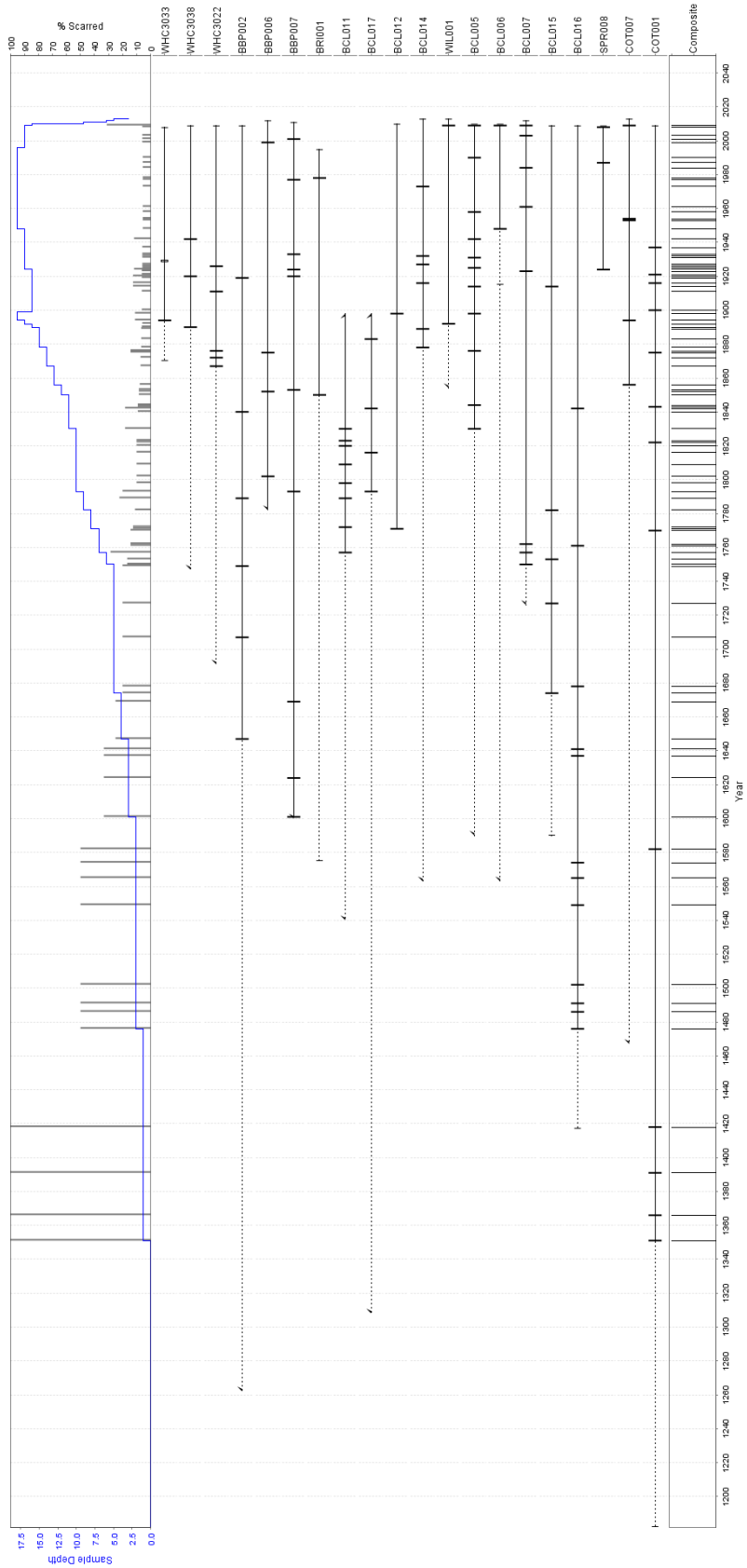

Figure 13. Composite fire frequency information for dated redwood samples in the Santa Cruz Mountains.

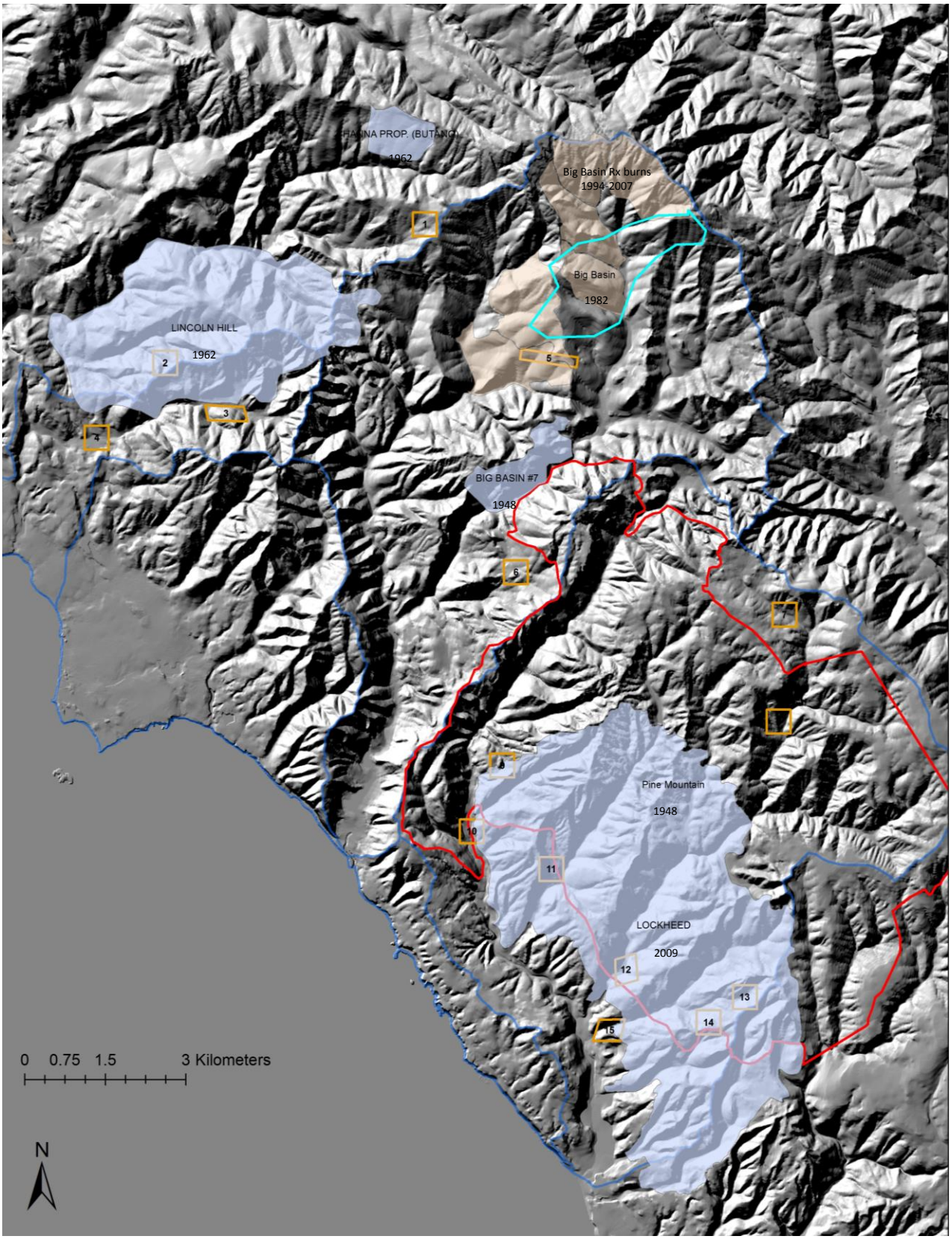

Figure 14. Extent of major recorded fires in study area (1948-2009). Sources: CalFire, California State Parks.

Seasonality

The season of fire occurrence was determined for 85% of the fire scars. As a percentage of those with known seasonality, dormant or late season fires accounted for a combined total of 87% of all fires for the entire period of record (1350-2013; 55% dormant, 33% late) – indicating that historic fires most likely took place between approximately mid-August to late March (Brown and Baxter 2003). Early season (approx. April to August) fires accounted for 13% of fires. In the 1600-1850 period, combined dormant and late season fires accounted for 91% of fires (64% and 27%, respectively), with 9% of fires occurring in the early season. During the intensive logging period (1850-1950) combined dormant and late season fires accounted for 85% of fires (56% and 30%, respectively), and 15% in the early season. In the modern era (1950-2013), dormant and late season fires still account for the majority of fires (86%), but with a marked shift into the drier late season (mid-August – September), which now account for 43% of fires. Early season fires represent 14% of fires in this period.

Fire information based on undated redwood samples (floating chronologies)

Utilizing the GLMM for floating chronologies, only three independent variables ultimately appeared significant in terms of predicting the probability of the occurrence of fire in the study area: physiographic zone ($p = 0.04$), distance to native residential site ($p = .04$), and position on slope ($p = 0.002$). P-values were similar between the default p-values produced by R's 'summary' function and the explicit likelihood ratio test. In addition, the plot random effect is significant ($p << .001$), indicating that it matters *where* in a watershed a sample is collected.

Estimates of the probability of the occurrence of a fire scar in a given year are shown in Table 4. Probabilities are summarized by the combined watershed/zone variable, and are displayed for slope position and linear distances to residential sites.

Table 4. Parameter estimates* for significant predictor variables

Position on Slope

Watershed/Zone	bottom	middle	top
Scotts-2	1.3	1.5	3.0
Scotts-3	32.5	36.0	53.9
Waddell-2	57.1	60.9	76.4
Waddell-3	58.5	62.3	77.4
Whitehouse-1	50.3	54.2	71.1
Whitehouse-2	31.7	35.2	53.1

Distance to Native Residential Site

	min	mean	max
Scotts-2	1.9	1.3	0.6
Scotts-3	42.6	32.5	17.5
Waddell-2	67.2	57.1	37.0
Waddell-3	68.5	58.5	38.3
Whitehouse-1	61.0	50.3	30.9
Whitehouse-2	41.8	31.7	17.0

* probability (as a percentage) of fire in any given year

Parameter estimates for all other predictor variables, including percent slope, distance to coast, aspect, elevation, proximity to site (all recorded arch. sites), proximity to "C-Zone", and watershed were not significant.

These data indicate that there are clear differences in distribution of fire in these watersheds, and that at least one physiographic variable (position on slope), and human activity are likely factors affecting that distribution.

Based on parameter estimates (Table 4), there appears to be a higher probability of fire (or a likelihood of fire scarring trees) at or near the top of slope in all watersheds. This pattern is more pronounced in Waddell Creek and Whitehouse Creek than in Scotts Creek, and the effect of slope position far less pronounced in upper Scotts Creek (Zone II: 1.3-3%) than in lower Scotts (33-54%). In Whitehouse and Waddell Creeks, the potential for top of slope fires is quite high, ranging from 32% in upper Whitehouse (Zone II) to 76% in upper Waddell (Zone II).

Similarly, proximity (linear distance) to native residential sites appears to strongly affect the probability of fire (Table 4). In all but upper Scotts Creek, trees at a shorter linear distance to residential sites exhibit much higher odds of being burned (42-69%) than trees farther away (17-38%). Upper Scotts Creek exhibits a similar pattern, but the likelihood of fires in that zone is far lower generally (.6-2%).

CHAPTER 5

Discussion

The findings presented in this study illustrate a high degree of complexity in patterns of fire ignitions in the Santa Cruz Mountains. Mean FRIs reported from this study are dramatically shorter than earlier investigations of fire frequency in redwood environments (i.e. Fritz 1931, McBride and Jacobs 1978, Greenlee and Langenheim 1990), but largely consistent with more recent findings (i.e. Norman 2007, Stephens and Fry 2005, Finney and Martin 1992) (Table 5).

Earlier studies proposed that fire was relatively rare in redwoods, driven largely by lightning, ranging from an estimated 4 fires per century for the past 1100 years (Fritz 1931) to once every 5-600 years in coastal redwood canyons (Veirs 1982). The earlier scientific paradigms largely discounted the role of native people in redwood fire ecology, despite indications to the contrary. One of the leading early fire researchers, UC Berkeley's Emanuel Fritz noted in his seminal 1931 paper on the "Role of Fire in the Redwood Region":

> *"Fires ran through redwood forests long before the white man arrived. Individual fires have been dated back by wound tissues on stumps to over 1200 years ago. They have become more prevalent and on the whole more severe since the arrival of the white man. The stories of old residents of the redwood region concerning the acts of the Indians are conflicting. Some believe that the Indians set the woods afire every season that there was a sufficient accumulation of litter to support a fire--every four or five years--and that the course of an Indian traveling through the woods could be charted from a distance by the succession of smokes as he set fires. Others say that the Indian was afraid of fire and set it only to drive game or to burn out his enemies, or that his prairie fires escaped into the woods. Others argue that Indians set fires deliberately to make travel easier. Many white men ascribe to the Indian superior powers of intelligence and a forestry knowledge not equaled by present-day students of the forest. This group believes that "Indian forestry", which means frequent burning, is the only kind of forestry that should be practiced in the standing timber today. If this reasoning were good, it is hard to understand why a race to which is attributed such wisdom has been unable to rise to importance in our national life. The early Indian of the redwood region was of a lethargic type. It is certain that he occasionally set the woods afire over many centuries but it is extremely doubtful that he did it with any thought in mind for improving or safeguarding the forest for the trees themselves. He was not a malicious or willful destroyer, yet his fires were doubtless set for his own convenience or needs rather than those of the forest. "*

In this quote, aside from betraying a basis for his personal prejudice on the matter, Fritz interestingly equates "Indian forestry" with "frequent burning", as if that were the conventional wisdom in the professional forestry community. Fritz went on to acknowledge that "[U]nless Indians set them, it is difficult to explain the fires of centuries ago except by spontaneous combustion or lightning" – while ultimately arguing the opposite without substantiation.

More recent studies (Table 5) have acknowledged the role of humans in determining fire regimes for numerous forest types, but only two other studies in California redwoods or related sequoias have made an attempt to quantify this relationship (Norman 2007, Gassaway 2009). Norman (2007) found a positive relationship between fire frequencies in coast redwoods with respect to proximity to Tolowa settlements in Del Norte County, CA. Sample sites near historic villages and camps in the Mill Creek study area burned more frequently between 1700-1849 than more distant sites. He was also able to discount a posited (pre-settlement) coast-interior climate gradient as reflected by the fire scar record – as opposed to suppression era patterns which appear to relate to both a natural coast-interior and latitudinal climate gradient (Norman 2007). Norman also notes, importantly, that the synoptic mechanisms linking sea surface temperatures to summer fog patterns and the summer fire climate of the interior forests are complex and have yet to be fully explained.

Similarly, a study conducted in Yosemite Valley, Gassaway (2009) found that the dendrochronological fire history varied greatly from the historically observed lightning ignition pattern, and that changes in fire regimes corresponded with known archaeological chronologies.

Table 5. Summary of fire history information from studies using annual growth rings conducted in coast redwood forests in California (modified from Stephens and Fry 2005)

Location	Data type	Fire interval (years)	Fire interval range (years)	Time period	Study size (ha)	Source
Northern Humboldt County	Composite	8	2-22	1714-1881	0.25-3	Brown & Swetnam 1994
Southern Humboldt County	Composite	11-44	8-87	Pre1975	7	Stuart 1987
	Interval	25	--	Pre1925	12	Fritz 1931
Western Mendocino County	Composite	6-22	2-34	1700-1900	6-22	Brown & Baxter 2003
	Point	10-25	2-43	1700-1900	6-22	
Northern Sonoma County	Interval	6-9	2-85	1650-1950	200	Finney & Martin 1989
	Point	21-29	2-85	1650-1950	200	
Southeastern Sonoma County	Point	6-23	2-131	Pre1850	<5	Finney & Martin 1992
Western Marin County	Composite	8-13	4-17	1840-1945	--	Brown et al. 1999
	Point	8-12	3-18	Pre1850	--	
	Point	8-22	--	1450-1850	5-10	Finney 1990
Southern Marin County	Point	22-27	2-98	Pre1850	75	Jacobs et al. 1985
Southern San Mateo County	Interval	9-16	2-58	Pre1860	1-3	Stephens & Fry 2005
	Point	12	2-58	Pre1860	1-3	
Southwestern San Mateo/ Northern Santa Cruz County	Composite	5	1-29	1600-2013	--	Striplen 2014
	Point	39	1-167			

The complexity of the story of fire in the Santa Cruz Mountains revealed by this study is compounded by several aspects related to the scope of this effort. Data for this study was collected from a large area (~11,800 ha), with only 5 of the 19 sample plots containing two or more dated samples – a figure lower than is typically desired for fire interval statistical analyses. In addition, as with all fire scar data sets, the quality and depth of the fire scar record declines

with increasing time before present (i.e. 'the fading record' problem in paleo-studies, Swetnam et al. 1999). However, targeted (non-random) vs. probabilistic (random) sampling approaches have proven to be effective in characterizing fire interval and extent information in other forest types (Farris et al. 2013), so with some additional work by other researchers in the area, the data presented herein can likely be useful in constructing more comprehensive fire regime models for the southern redwood region.

With respect to analysis of probability of fire occurrence and proximity to cultural activity, the cultural landscape of the Santa Cruz Mountains is exceptionally complex. In similar studies, conducted in regions with lower population densities, patterns of pre-colonial cultural activity could be established with greater certainty using archaeological and ethnographic information. The tribal communities of the Santa Cruz Mountains, noted by Milliken (1983) as having densities of at least 1.25-1.5 persons per mi^2, were in close proximity to the tribal communities of the San Francisco Bay region, with population densities 4.25-5.0 persons per square mile (Hylkema 1991). Ethnographic and archaeological information for the region document a high degree of trade and intermarriage between Bay and coastal groups, as well as a complex network of trail systems throughout the range. Adding to this complexity is the varying spatial arrangement of individual tribal communities within their home watersheds. Though there were only two politically autonomous groups within the study area, they distributed themselves quite differently on the landscape. The Cotoni of the Scotts Creek watershed distributed themselves more widely among several communities throughout their territory – apparently without a major tribal center (such as the Quiroste's *Mitinne* [Hylkema et al. 2013]), likely affecting the pre-European distribution of fire in their respective watersheds.

Given these challenges, however, the data reveal some potentially interesting patterns of fire occurrence in the project area that would benefit from additional investigation. One such pattern is an apparent discordance between patterns revealed using fixed (dated) fire chronologies vs. the floating chronologies modeled using the GLMM. Dated chronologies indicate a slight increase in fire frequency from the pre-colonial/ranching period to the intensive logging period, which departs from most recently published work in similar coast redwood areas.

Parameter estimates from the GLMM, however, indicate a potentially different pattern. The floating chronologies collected for this study and modeled by the GLMM are likely weighted toward to pre-1950 fire regimes, likely capturing a much greater sample depth for the earlier period (1600-1850). With the exception of upper Scotts Creek (Zone 2), estimated probabilities of the occurrence of fire increased significantly with proximity to pre-colonial residential sites. As described in Chapter 2, the distribution of the tribal community in Scotts Creek may provide a mitigating factor here.

The source of this discordance can possibly be explained by several factors. The replacement of a complex, multi-purpose native fire regime with one almost exclusively dedicated to reducing slash and limb density on downed logs may have facilitated fire behavior more conducive to scarring trees. Early logging operations are known to have used fire to reduce slash piles from logging and limbing activity, with some stands burned multiple times in association with a single harvest to burn off limbs and eliminate slash piles, largely to facilitate faster regrowth of future harvestable stands (McCrary and Swift 1981, Stanger 1967, Mowry

2004). However, sample density was quite low for the earlier period (1600-1850), weighting the data for dated samples toward more recent fire events. With fewer, datable samples reflecting this earlier period – a more recent "skew" is to be expected.

It was interesting that "ResSite" emerged from the GLMM as significant, when linear distances to "site" and "C-zone" did not. It is possible that more "classes" of people may have been igniting fires closer to residential sites (youth, elders, women, men, specialists). There could have been a greater probability of camp or cooking fire escape (higher density of individual "contained" fires), and a greater probability of resource-specific patch burning closer to ResSites. Novel statistical approaches like the GLMM are required to reveal these patterns as there is no dendroecology-based software on the market designed with these considerations in mind. Further examination and clarification of habitation patterns on the landscape could add significantly to our ability to reconstruct anthropogenic "firescapes" – or landscape mosaics driven by factors outside of climate considerations. Very few of the recorded sites in the Santa Cruz Mountains have been fully excavated, and none to the depth represented by our work at Quiroste. As more sites are better characterized, a more nuanced understanding of community-based, long-term resource management practices employed by tribes in this area is certainly possible.

These data also exhibit concordance with information from related studies (Lightfoot et al 2013, Cowart and Byrne 2013). Analysis of the pollen and microscopic charcoal content of a sediment core from Skylark Pond (in the Whitehouse Creek watershed) was recently conducted that supports findings in the fire scar record. The core covers approximately the last 3,000 years and shows an increase in fire activity from the 15th century to the present. Peaks in charcoal at ca. 1425 along with subsequent high charcoal abundance indicate either small, frequent fires ignited by humans or large natural conflagrations. Even through the "Little Ice Age" (ca. 1650-1850), which is known to have been a period of cooler, wetter climate patterns in California (Malamud-Roam et al. 2006), microscopic charcoal remains present at relatively high levels.

Archaeofaunal research conducted in Quiroste Valley also supports the notion that these tribes were employing long-term, systematic burning practices in local environments (Gifford-Gonzalez et al. 2013). Of the 23 mammalian taxa identified at this site (SMA-113), rodents constituted 47% of species identified – with the balance consisting of large land and sea mammals. California voles constitute 25% of rodent sample, and pocket gophers represent 52%. According to Gifford-Gonzalez (2013:309-310,313),

> "…rodents in any archaeological assemblage are not a random sample of the local community but rather a mix of human prey, commensals, and burrowers into middens… [but] habitat-diagnostic species can shed light on the presence or absence of land modification.
>
> The strikingly higher than expected proportions of open habitat adapted voles in the archaeofauna is strong evidence for maintenance of a more open environment than presently characterizes the Quiroste Valley.
>
> The faunal evidence cannot specify to the nature of the processes that maintained vole-friendly plant communities near CA-SMA-113. Intentional human maintenance of such plant associations by fire…is one such possibility."

Archaeological evidence indicates that the Quiroste (and presumably the Cotoni) peoples regularly utilized a wide range of habitats and resources — terrestrial, riverine, and marine — but some patterns in this evidence departs from observed norms in neighboring tribes. For instance, only 228 (4.7%) of the 4,897 specimens taxonomically identified at this site derived from birds (± 13 species). More than half of the identified birds were from water birds, 25% from birds of prey, but none were from commonly hunted and consumed terrestrial birds such as quail and doves. Gifford-Gonzalez (2013:299) contend that the rate of occurrence of birds in the Quiroste Valley assemblage differs significantly from those of other well documented residential sites around Monterey Bay. A local tribal elder (E. Ketchum) indicated that this may indicate a deliberate, cultural motive behind this pattern.

Similarly, phytolith research conducted in Quiroste Valley (Evett and Cuthrell 2013) also supports a largely anthropogenic fire regime in coastal watersheds. Phytoliths are microscopic particles of amorphous silica that are formed in and between plant cells and are deposited in the soil when the plant dies (Piperno 2006). Phytoliths are useful in studying the long-term evolution of terrestrial landscapes, especially in areas once dominated by grass taxa where they can remain suspended in sediments for hundreds to thousands of years (Piperno 2006; Wilding 1967). Grasses produce phytoliths in abundance. Where grassland habitats have persisted for long periods of time, dry weight soil content of phytoliths can reach one to five percent (Evett et al. 2006). This was the case in Quiroste Valley. Evett and Cuthrell (2013:333) assert:

> "Outside of highly unlikely scenarios that lightning-ignited fires were much more frequent in the past, or past climatic conditions were not favorable for woody vegetation, anthropogenic burning was required to maintain grass dominated grassland vegetation for the length of time necessary to produce the observed phytolith content in soils on the valley floor. In addition, because surface soil phytolith content is much higher than elsewhere in California, Quiroste Valley grasslands likely had much higher grass cover than most other Californian grasslands, which were likely dominated by forbs. This suggests that either the anthropogenic burning regime (seasonality and frequency) was fine-tuned to favor grasses, or there were unknown species interactions and/or management practices that enhanced the proportion of grasses in coastal grasslands."

Conclusion

This region holds great promise for further analyses of anthropogenic fire. With additional resources to access more representative areas of these watersheds (i.e. the largely roadless, protected area of mid-Waddell), sample depth for all focal periods could be increased significantly. Additional work classifying the cultural landscape of the Santa Cruz Mountains would also greatly enhance the interpretive potential of dendroecological studies in the area.

For floating chronologies, additional research describing the pre-Forest Practices Act harvest patterns of early mills in the region could reduce the need for novel statistical methods. Recent efforts to derive regional master chronologies for the southern extent of the redwood region (Sillett et al 2010) will also facilitate dramatic improvements in reconstructing past fire regimes.

The GLMM developed for this study could be improved to increase its explanatory power for floating chronologies. For instance, due to the extreme topographic variability of the

region, some continuous variables didn't capture probability of fire as well as the categorical variables. Future work could include (i.e.) aspect as a category (as calculated from a DEM). Utilizing a generalized additive mixed model (GAMM) could potentially capture these non-linear relationships better. We might also consider including discarded samples (those with <2 fire scars) for our binomial model to further reduce sampling bias.

Another encouraging aspect of this study, supported by findings from related investigations, is its immediate and long-term pertinence to management of contemporary landscapes. These findings challenge modern notions of "pristine" landscapes, "wilderness", and "natural" – concepts which manifest themselves in designated wilderness areas, reserved open space, and other designations where human management of natural resources is often minimized or absent. Watt (2002:56-57) notes:

> "The 1964 Wilderness Act defined wilderness as 'untrammeled,' a landscape where 'the nonhuman forces of nature are to be given free rein.' Yet there are almost no places on earth that have not been trammeled at one time or another; in particular, almost all publicly owned lands in the U.S. were at one time roaded, logged, farmed, or utilized in some other way. In an effort to establish a national wilderness system, Congress accepted a less-pure definition of wilderness for purposes of designation (Woods 1998, p. 136, emphasis in original): "The Congressional and judicial rejection of the USFS's purity definition of wilderness suggested that the untrammeled character of naturalness was more forward-looking: wilderness lands were to be managed in such a way that they *would be* untrammeled and *return* to primeval conditions *in the future*."

As the field of historical ecology has expanded its role in modern land use planning (Balee 2006; Grossinger and Striplen et al. 2007), there is a greater realization that historical perspectives increase our understanding of the dynamic nature of landscapes and provide a frame of reference for assessing modern patters and processes (Swetnam et al. 1999). There is greater focus working with conceptual models of landscapes as complex systems of human and biophysical processes and components, and that by taking advantage of the "internal memories" of systems – tailoring management to mimic natural processes – greater resilience can be built into future landscapes (Parrott and Meyer 2012).

In expanding this notion of learning from historical perspectives, it should be noted that perhaps the most interesting finding from this study (GLMM) could not have been revealed without a meaningful partnership with the local descendant tribal organization. A significant assumption underlying this study was that the cultural information uncovered through this research represented the intellectual property of that descendant community. Mapping of cultural sites was conducted under formal and informal agreements with this group, and publication of key findings included tribal members as authors. This model, and similar models employed with and by indigenous communities globally (Uprety et al 2012), has proven successful in revealing important information highly relevant to modern management solutions.

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APPENDIX I

Sample field data collection sheet

Fire History Study Data Summary sheet Date: 2009Nov6 Collected Recorder(s): CS/GJ Sample ID: WHC3034

Watershed: Whitehouse	Site	GPS Location	Description			Photo #'s
Sample Location	Mid-WHC	UTM 562278 4113842	Large snag on flat, central grove			1455-66
	Big Creek Unit					1734
Site information						1982-90
Elevation	706'					2116
Slope (%)	10%					2346-51
Aspect°	N					
Position on Slope	bottom					
# trees in grove	50+					
Dominant Vegetation Cover	Ss					
Distance to watercourse	~50m E to WHC					
Individual sample data			Species:			RW
Condition (Snag, Stump, Log)	tall snag		**Scar count (CS 5/18/13)**			
Tree diameter (dbh)	306cm		Event	Ring#	Year/interval	Season
Tree circumference			Fire 1:	346		D
Scar orientation°	?	snag burned repeatedly	Fire 2:	388	42	D
Width of bark		on all sides	Fire 3:	427	39	D
	Uphill/downhill	Vert. dist. From ground	Fire 4:	462	35	D
Position of cut	uphill		Fire 5:	471	9	D
Depth of cut	51.5"	6"	Fire 6:	705	234	L
Bark date (harvest date)			Fire 7:	716	11	D
# Visible exterior scars	2		Fire 8:	724	8	D
Sample data – increment bore			Fire 9:	736	12	L
Total depth of core			Fire 10:	740	4	D
Width of bark			Fire 11:	986	246	U
Total ring count			Fire 12:	1059	73	D
Fire information						
Total ring count	1222					
Total # scars	12					
MFI total	64.82	Depth to 1st scar	346			

APPENDIX II

GLMM SCRIPT

```
R version 3.0.1 Patched (2013-08-12 r63551) -- "Good Sport"
Copyright (C) 2013 The R Foundation for Statistical Computing
Platform: x86_64-w64-mingw32/x64 (64-bit)

> setwd("C:/<file location>")
> install.packages("lme4")
Installing package into ‘C:/Users/<user>/Documents/R/win-library/3.0’
(as ‘lib’ is unspecified)
> library(lme4)
> SCFH<-read.csv("<target data file>")
> names(SCFH)
 [1] "Sample.ID..scars."    "Float.fixed"          "Total.Ring.Count"
 [4] "RI"                   "Seasonality"          "Plot"
 [7] "Watershed"            "Elevation..m."        "Slope.."
[10] "Aspect"               "Northness"            "Eastness"
[13] "Position.on.Slope"    "X..samples.per.plot"  "Distance.from.Coast"
[16] "Distance.from.C.Zone" "Distance.from.Site"   "Site.ID"
[19] "ResSite"              "Zone"
> class (SCFH$Plot)
[1] "integer"
>
> summary(SCFH)
 Sample.ID..scars. Float.fixed Total.Ring.Count       RI         Seasonality
 COT001 : 13       fixed:108   Min.   :  95.0   Min.   :  1.00   D:200
 BBP005 : 12       float:267   1st Qu.: 290.0   1st Qu.: 11.00   E: 29
 BCL016 : 12                   Median : 420.0   Median : 26.00   L: 68
 WHC3034: 12                   Mean   : 466.3   Mean   : 48.39   U: 78
 WHC3047: 12                   3rd Qu.: 578.5   3rd Qu.: 51.25
 SPR002 : 11                   Max.   :1222.0   Max.   :674.00
 (Other):303                                    NA's   :71
     Plot           Watershed   Elevation..m.    Slope..          Aspect
 Min.   : 1.000   Scott     :152   unknown: 34   0      : 62   na       : 34
 1st Qu.: 2.000   Waddell   : 71   373    : 24   unknown: 34   327.6651 : 17
 Median : 6.000   Whitehouse:152   122    : 17   45     : 32   122.869102: 13
 Mean   : 7.264                   367    : 14   50     : 28   259.642822: 13
 3rd Qu.:12.000                   404    : 13   55     : 26   248.030334: 12
 Max.   :19.000                   241    : 12   5      : 25   26.782    : 12
                                  (Other):261   (Other):168   (Other)   :274
    Northness        Eastness    Position.on.Slope X..samples.per.plot
 na       : 34   na       : 34   B :120            Min.   : 1.000
 0.590221 : 17   0.807242 : 17   M :176            1st Qu.: 3.000
 -0.445228: 13   -0.340068: 13   na: 34            Median : 6.000
```

```
-0.940401: 13   0.895417 : 13   T : 45          Mean   : 5.627
-0.078382: 12   -0.99667 : 12                   3rd Qu.: 8.000
-0.987937: 12   0.154859 : 12                   Max.   :11.000
(Other)  :274   (Other)  :274
Distance.from.Coast Distance.from.C.Zone Distance.from.Site    Site.ID
Min.   :2190        Min.   :  0.0       Min.   :   0       SMA-231:90
1st Qu.:3238        1st Qu.:  0.0       1st Qu.: 610       SMA-244:53
Median :4805        Median :  0.0       Median :1381       SCR-29 :50
Mean   :5639        Mean   :186.5       Mean   :1253       SCR-83 :33
3rd Qu.:9310        3rd Qu.:370.0       3rd Qu.:1876       SCR-122:31
Max.   :9750        Max.   :825.0       Max.   :2809       SCR-253:24
                                                           (Other):94
   ResSite         Zone
na     : 34   Min.   :1.000
730    : 13   1st Qu.:1.000
1500   : 12   Median :2.000
2279   : 12   Mean   :2.088
4103   : 12   3rd Qu.:3.000
910    : 12   Max.   :3.000
(Other):280
>
> SCFH$Plot<-factor(SCFH$Plot)
> levels(SCFH$Plot)
 [1] "1"  "2"  "3"  "4"  "5"  "6"  "7"  "8"  "9"  "10" "11" "12" "13" "14" "15"
[16] "16" "17" "18" "19"
>
> SCFH$Seasonality[SCFH$Seasonality=="U"]<-NA
> SCFH$Elevation..m.[SCFH$Elevation..m.=="unknown"]<-NA
> SCFH$Position.on.Slope[SCFH$Position.on.Slope=="na"]<-NA
> SCFH$Slope..[SCFH$Slope..=="unknown"]<-NA
> SCFH$Aspect[SCFH$Aspect=="na"]<-NA
> SCFH$Northness[SCFH$Northness=="na"]<-NA
> SCFH$Eastness[SCFH$Eastness=="na"]<-NA
> SCFH$ResSite<-as.numeric(as.character(SCFH$ResSite))
>
> SCFH$Position.on.Slope<-factor(SCFH$Position.on.Slope)
> SCFH$Seasonality<-factor(SCFH$Seasonality)
>
> SCFH$Elevation..m.<-as.numeric(as.character(SCFH$Elevation..m.))
> SCFH$Slope..<-as.numeric(as.character(SCFH$Slope..))
> SCFH$Aspect<-as.numeric(as.character(SCFH$Aspect))
> SCFH$Northness<-as.numeric(as.character(SCFH$Northness))
> SCFH$Eastness<-as.numeric(as.character(SCFH$Eastness))
> summary(SCFH)
 Sample.ID..scars. Float.fixed Total.Ring.Count       RI         Seasonality
 COT001 : 13       fixed:108   Min.   :  95.0   Min.   :  1.00   D   :200
```

```
BBP005 : 12       float:267   1st Qu.: 290.0   1st Qu.: 11.00   E   : 29
BCL016 : 12                   Median : 420.0   Median : 26.00   L   : 68
WHC3034: 12                   Mean   : 466.3   Mean   : 48.39   NA's: 78
WHC3047: 12                   3rd Qu.: 578.5   3rd Qu.: 51.25
SPR002 : 11                   Max.   :1222.0   Max.   :674.00
(Other):303                                    NA's   :71
    Plot         Watershed   Elevation..m.      Slope..
2     : 56   Scott     :152   Min.   : 37.0   Min.   : 0.00
1     : 53   Waddell   : 71   1st Qu.:122.0   1st Qu.: 5.00
12    : 36   Whitehouse:152   Median :335.0   Median :42.00
3     : 34                    Mean   :310.6   Mean   :32.07
6     : 31                    3rd Qu.:404.0   3rd Qu.:50.00
15    : 23                    Max.   :648.0   Max.   :90.00
(Other):142                   NA's   :34      NA's   :34
   Aspect         Northness          Eastness        Position.on.Slope
Min.   : 11.52   Min.   :-0.99875   Min.   :-0.99998   B   :120
1st Qu.:122.87   1st Qu.:-0.86607   1st Qu.:-0.62401   M   :176
Median :248.03   Median :-0.07838   Median :-0.10896   T   : 45
Mean   :208.40   Mean   :-0.06282   Mean   : 0.00685   NA's: 34
3rd Qu.:298.75   3rd Qu.: 0.59022   3rd Qu.: 0.79589
Max.   :359.51   Max.   : 0.99451   Max.   : 0.99988
NA's   :34       NA's   :34         NA's   :34
X..samples.per.plot Distance.from.Coast Distance.from.C.Zone
Min.   : 1.000      Min.   :2190        Min.   :  0.0
1st Qu.: 3.000      1st Qu.:3238        1st Qu.:  0.0
Median : 6.000      Median :4805        Median :  0.0
Mean   : 5.627      Mean   :5639        Mean   :186.5
3rd Qu.: 8.000      3rd Qu.:9310        3rd Qu.:370.0
Max.   :11.000      Max.   :9750        Max.   :825.0

 Distance.from.Site    Site.ID      ResSite          Zone
 Min.   :   0       SMA-231:90   Min.   :   5   Min.   :1.000
 1st Qu.: 610       SMA-244:53   1st Qu.: 909   1st Qu.:1.000
 Median :1381       SCR-29 :50   Median :1541   Median :2.000
 Mean   :1253       SCR-83 :33   Mean   :1625   Mean   :2.088
 3rd Qu.:1876       SCR-122:31   3rd Qu.:2279   3rd Qu.:3.000
 Max.   :2809       SCR-253:24   Max.   :4103   Max.   :3.000
                    (Other):94   NA's   :34
>
> SCFH$Zone<-paste(SCFH$Watershed,SCFH$Zone, sep="-")
> SCFH$Zone<-factor(SCFH$Zone)
>
>## density plots of fixed and floating
>
> floating<-density(SCFH$RI[SCFH$Float.fixed=="float"],na.rm=TRUE,bw=20,from=0)
> fixed<-density(SCFH$RI[SCFH$Float.fixed=="fixed"],na.rm=TRUE,bw=20,from=0)
```

```
>
> plot(floating$x,floating$y,type="l",main="Distribution of return
intervals",xlab="years",ylab="")
> lines(fixed$x,fixed$y,col="red")
> legend('topright', lty=c(1,1),col=c("red","black"), legend=c("fixed", "floating"))
>
> floating<-
density(SCFH$Total.Ring.Count[SCFH$Float.fixed=="float"],na.rm=TRUE,bw=100,from=0)
> fixed<-
density(SCFH$Total.Ring.Count[SCFH$Float.fixed=="fixed"],na.rm=TRUE,bw=100,from=0)
>
> plot(floating$x,floating$y,type="l",main="Distribution of total ring
count",xlab="Count",ylab="")
> lines(fixed$x,fixed$y,col="red")
> legend('topright', lty=c(1,1),col=c("red","black"), legend=c("fixed", "floating"))
>
> # subset to use only floating chronologies
> SCFH<-subset(SCFH,SCFH$Float.fixed=="float")
>
> summary(SCFH)
 Sample.ID..scars. Float.fixed Total.Ring.Count       RI         Seasonality
 BBP005 : 12       fixed:  0   Min.   :  95.0   Min.   :  1.00   D   :148
 WHC3034: 12       float:267   1st Qu.: 280.0   1st Qu.: 11.25   E   : 17
 WHC3047: 12                   Median : 445.0   Median : 26.50   L   : 41
 SPR002 : 11                   Mean   : 464.3   Mean   : 52.71   NA's: 61
 WHC3029: 10                   3rd Qu.: 567.0   3rd Qu.: 54.25
 COT011 :  9                   Max.   :1222.0   Max.   :674.00
 (Other):201                                    NA's   :53
     Plot         Watershed   Elevation..m.      Slope..          Aspect
 2      :56   Scott     : 77   Min.   : 37.0   Min.   : 0.00   Min.   : 12.78
 1      :48   Waddell   : 48   1st Qu.:209.0   1st Qu.:10.00   1st Qu.:168.87
 3      :31   Whitehouse:142   Median :354.0   Median :45.00   Median :257.45
 6      :31                    Mean   :337.1   Mean   :35.41   Mean   :216.00
 15     :23                    3rd Qu.:414.0   3rd Qu.:55.00   3rd Qu.:294.20
 7      :22                    Max.   :648.0   Max.   :75.00   Max.   :344.14
 (Other):56                    NA's   :34      NA's   :34      NA's   :34
   Northness          Eastness        Position.on.Slope X..samples.per.plot
 Min.   :-0.9988   Min.   :-0.99998   B   :107          Min.   : 1.000
 1st Qu.:-0.8667   1st Qu.:-0.69785   M   : 94          1st Qu.: 4.000
 Median :-0.1306   Median : 0.09793   T   : 32          Median : 6.000
 Mean   :-0.1157   Mean   : 0.00311   NA's: 34          Mean   : 6.292
 3rd Qu.: 0.5968   3rd Qu.: 0.72962                     3rd Qu.: 8.000
 Max.   : 0.9945   Max.   : 0.99988                     Max.   :11.000
 NA's   :34        NA's   :34
 Distance.from.Coast Distance.from.C.Zone Distance.from.Site    Site.ID
 Min.   :2260        Min.   :  0.0       Min.   :   0       SMA-231:87
```

```
 1st Qu.:4500       1st Qu.:  0.0       1st Qu.: 610       SMA-244:48
 Median :4805       Median :  0.0       Median :1500       SCR-122:31
 Mean   :5933       Mean   :200.1       Mean   :1244       SCR-29 :25
 3rd Qu.:9310       3rd Qu.:240.0       3rd Qu.:1969       SCR-91 :22
 Max.   :9750       Max.   :825.0       Max.   :2525       SCR-UNR:14
                                        (Other):40
   ResSite             Zone
 Min.   :  5   Scott-2    :27
 1st Qu.: 820   Scott-3    :50
 Median :1503   Waddell-2  :43
 Mean   :1576   Waddell-3  : 5
 3rd Qu.:2279   Whitehouse-1:94
 Max.   :4103   Whitehouse-2:48
 NA's   :34
>
##    create 'number of fires' dataset for binomial model
>
> temp<-table(SCFH$Sample.ID..scars.)
> NumFires<-data.frame(Sample=names(temp),NumFires=as.numeric(temp))
> ## the '[]' is keeping only the columns we care about
> ## the 'merge' is R's join function, add "plot" and "watershed" back in
> NumFires<-merge(NumFires, SCFH,by.x="Sample",
+ by.y="Sample.ID..scars.", all.x=TRUE, all.y=FALSE)
> NumFires<-
NumFires[,names(NumFires)[!names(NumFires)%in%c("RI","nRI","logRI","Seasonality")]]
> ## unique makes sure we only have one record per sample.
> NumFires<-unique(NumFires)
> summary(NumFires)
    Sample      NumFires      Float.fixed Total.Ring.Count      Plot
 BBP002 : 1   Min.   : 0.000   fixed: 0    Min.   :  95.0   1     :10
 BBP005 : 1   1st Qu.: 1.000   float:53    1st Qu.: 223.0   2     : 8
 BBP006B: 1   Median : 3.000   NA's :18    Median : 401.0   6     : 6
 BBP007 : 1   Mean   : 3.761               Mean   : 411.2   3     : 5
 BCL002 : 1   3rd Qu.: 6.000               3rd Qu.: 506.0   12    : 4
 BCL003 : 1   Max.   :12.000               Max.   :1222.0   (Other):20
 (Other):65                                NA's   :18       NA's  :18
    Watershed  Elevation..m.      Slope..          Aspect
 Scott     :20   Min.   : 37.0   Min.   : 0.00   Min.   : 12.78
 Waddell   : 8   1st Qu.:194.5   1st Qu.:15.25   1st Qu.:168.85
 Whitehouse:25   Median :338.0   Median :34.00   Median :258.31
 NA's      :18   Mean   :326.4   Mean   :34.33   Mean   :222.88
                 3rd Qu.:429.2   3rd Qu.:55.00   3rd Qu.:298.93
                 Max.   :648.0   Max.   :75.00   Max.   :344.14
                 NA's   :23      NA's   :23      NA's   :23
  Northness          Eastness        Position.on.Slope X..samples.per.plot
 Min.   :-0.99875   Min.   :-0.99999   B   :21          Min.   : 1.00
```

```
 1st Qu.:-0.75409   1st Qu.:-0.71674   M   :19          1st Qu.: 3.00
 Median : 0.01064   Median :-0.07735   T   : 8          Median : 6.00
 Mean   :-0.04066   Mean   :-0.02298   NA's:23          Mean   : 6.17
 3rd Qu.: 0.60605   3rd Qu.: 0.68272                    3rd Qu.: 8.00
 Max.   : 0.99451   Max.   : 0.99988                    Max.   :11.00
 NA's   :23         NA's   :23                          NA's   :18
 Distance.from.Coast Distance.from.C.Zone Distance.from.Site    Site.ID
 Min.   :2260        Min.   :  0.0       Min.   :   0       SMA-231:13
 1st Qu.:3760        1st Qu.:  0.0       1st Qu.: 217       SMA-244:10
 Median :4805        Median :  0.0       Median :1377       SCR-122: 6
 Mean   :5717        Mean   :162.3       Mean   :1184       SCR-29 : 6
 3rd Qu.:8830        3rd Qu.:  0.0       3rd Qu.:1600       SCR-119: 3
 Max.   :9750        Max.   :825.0       Max.   :2525       (Other):15
 NA's   :18          NA's   :18          NA's   :18         NA's   :18
   ResSite               Zone
 Min.   :   5.0   Scott-2     : 5
 1st Qu.: 699.8   Scott-3     :15
 Median :1491.0   Waddell-2   : 7
 Mean   :1428.4   Waddell-3   : 1
 3rd Qu.:1806.8   Whitehouse-1:15
 Max.   :4103.0   Whitehouse-2:10
 NA's   :23       NA's        :18
>
> plot(NumFires~Total.Ring.Count,data=NumFires)
> plot(NumFires~Slope..,data=NumFires)
> plot(NumFires~Elevation..m.,data=NumFires)
> plot(NumFires~Aspect,data=NumFires)
> plot(NumFires~Northness,data=NumFires)
> plot(NumFires~Eastness,data=NumFires)
> plot(NumFires~Position.on.Slope,data=NumFires)
> plot(NumFires~Distance.from.Coast,data=NumFires)
> plot(NumFires~Distance.from.C.Zone,data=NumFires)
> plot(NumFires~Distance.from.Site,data=NumFires)
> plot(NumFires~X..samples.per.plot,data=NumFires)
> plot(X..samples.per.plot~Sample,data=NumFires)
> plot(X..samples.per.plot~Plot,data=NumFires)
> plot(NumFires~ResSite,data=NumFires)
> plot(NumFires~Zone,data=NumFires)
> length(levels(SCFH$Plot))  ##there are 19 plots
[1] 19
> length(levels(SCFH$Sample.ID)) ## and 71 trees/samples
[1] 71
>
> hist(NumFires$NumFires)
>
> NumFires$Slope..<-NumFires$Slope..-mean(NumFires$Slope..,na.rm=TRUE)
```

```
> NumFires$Elevation..m.<-NumFires$Elevation..m.-
mean(NumFires$Elevation..m.,na.rm=TRUE)
> NumFires$Northness<-NumFires$Northness-mean(NumFires$Northness,na.rm=TRUE)
> NumFires$Eastness<-NumFires$Eastness-mean(NumFires$Eastness,na.rm=TRUE)
> NumFires$ResSite<-NumFires$ResSite-mean(NumFires$ResSite,na.rm=TRUE)
> NumFires$Distance.from.Coast<-NumFires$Distance.from.Coast-
mean(NumFires$Distance.from.Coast,na.rm=TRUE)
> NumFires$Distance.from.C.Zone<-NumFires$Distance.from.C.Zone-
mean(NumFires$Distance.from.C.Zone,na.rm=TRUE)
> NumFires$Distance.from.Site<-NumFires$Distance.from.Site-
mean(NumFires$Distance.from.Site,na.rm=TRUE)
>
##  models for binomial success = fire
>
> NumFires$NoFire<-NumFires$Total.Ring.Count-NumFires$NumFires
>
> ## GLMER = generalized linear mixed effects regression
>
>
>

> ## Full model
> bin.fit<-glmer(cbind(NumFires,NoFire)~
+ Slope..#1
+ +Zone#2
+ +Elevation..m.#4
+ +Northness#5
+ +Eastness#6
+ +ResSite#7
+ +Position.on.Slope#8
+ +Distance.from.Coast#9
+ +Distance.from.C.Zone#10
+ +Distance.from.Site#11
+ +(1|Plot),data=NumFires,family=binomial,REML=FALSE)
>
> bin.noplot<-glm(cbind(NumFires,NoFire)~
+ Slope..#1
+ +Zone#2
+ +Elevation..m.#4
+ +Northness#5
+ +Eastness#6
+ +ResSite#7
+ +Position.on.Slope#8
+ +Distance.from.Coast#9
+ +Distance.from.C.Zone#10
+ +Distance.from.Site,#11
```

```
+ data=NumFires,family=binomial)
>
> 1-pchisq(2*logLik(bin.fit)-2*logLik(bin.noplot),1) # 1 is the number of parameters different
'log Lik.' 1 (df=17)
>  # plot is significant
>
> # (B) testing each of the variables using likelihood ratio tests
>
> ## 1) slope
> bin.slope<-glmer(cbind(NumFires,NoFire)~
+ Zone#2
+ +Elevation..m.#4
+ +Northness#5
+ +Eastness#6
+ +ResSite#7
+ +Position.on.Slope#8
+ +Distance.from.Coast#9
+ +Distance.from.C.Zone#10
+ +Distance.from.Site#11
+ +(1|Plot),data=NumFires,family=binomial,REML=FALSE)
>
> ## 2) zone (whitehouse, upper scott/waddell, lower scott/waddell)
> bin.zone<-glmer(cbind(NumFires,NoFire)~
+ Slope..#1
+ +Elevation..m.#4
+ +Northness#5
+ +Eastness#6
+ +ResSite#7
+ +Position.on.Slope#8
+ +Distance.from.Coast#9
+ +Distance.from.C.Zone#10
+ +Distance.from.Site#11
+ +(1|Plot),data=NumFires,family=binomial,REML=FALSE)
>
> ## 4) elev
> bin.elev<-glmer(cbind(NumFires,NoFire)~
+ Slope..#1
+ +Zone#2
+ +Northness#5
+ +Eastness#6
+ +ResSite#7
+ +Position.on.Slope#8
+ +Distance.from.Coast#9
+ +Distance.from.C.Zone#10
+ +Distance.from.Site#11
+ +(1|Plot),data=NumFires,family=binomial,REML=FALSE)
```

```
>
> ## 5) northness
> bin.northn<-glmer(cbind(NumFires,NoFire)~
+ Slope..#1
+ +Zone#2
+ +Elevation..m.#4
+ +Eastness#6
+ +ResSite#7
+ +Position.on.Slope#8
+ +Distance.from.Coast#9
+ +Distance.from.C.Zone#10
+ +Distance.from.Site#11
+ +(1|Plot),data=NumFires,family=binomial,REML=FALSE)
>
> ## 6) eastness
> bin.eastn<-glmer(cbind(NumFires,NoFire)~
+ Slope..#1
+ +Zone#2
+ +Elevation..m.#4
+ +Northness#5
+ +ResSite#7
+ +Position.on.Slope#8
+ +Distance.from.Coast#9
+ +Distance.from.C.Zone#10
+ +Distance.from.Site#11
+ +(1|Plot),data=NumFires,family=binomial,REML=FALSE)
>
> ## 7) res site
> bin.ressite<-glmer(cbind(NumFires,NoFire)~
+ Slope..#1
+ +Zone#2
+ +Elevation..m.#4
+ +Northness#5
+ +Eastness#6
+ +Position.on.Slope#8
+ +Distance.from.Coast#9
+ +Distance.from.C.Zone#10
+ +Distance.from.Site#11
+ +(1|Plot),data=NumFires,family=binomial,REML=FALSE)
>
> ## 8) position on slope
> bin.pos.on.slope<-glmer(cbind(NumFires,NoFire)~
+ Slope..#1
+ +Zone#2
+ +Elevation..m.#4
+ +Northness#5
```

```
+ +Eastness#6
+ +ResSite#7
+ +Distance.from.Coast#9
+ +Distance.from.C.Zone#10
+ +Distance.from.Site#11
+ +(1|Plot),data=NumFires,family=binomial,REML=FALSE)
>
> ## 9) distance to coast
> bin.dist.coast<-glmer(cbind(NumFires,NoFire)~
+ Slope..#1
+ +Zone#2
+ +Elevation..m.#4
+ +Northness#5
+ +Eastness#6
+ +ResSite#7
+ +Position.on.Slope#8
+ +Distance.from.C.Zone#10
+ +Distance.from.Site#11
+ +(1|Plot),data=NumFires,family=binomial,REML=FALSE)
>
> ## 10) distance to Czone
> bin.Czone<-glmer(cbind(NumFires,NoFire)~
+ Slope..#1
+ +Zone#2
+ +Elevation..m.#4
+ +Northness#5
+ +Eastness#6
+ +ResSite#7
+ +Position.on.Slope#8
+ +Distance.from.Coast#9
+ +Distance.from.Site#11
+ +(1|Plot),data=NumFires,family=binomial,REML=FALSE)
>
> ## 11) distance from site
> bin.dist.to.site<-glmer(cbind(NumFires,NoFire)~
+ Slope..#1
+ +Zone#2
+ +Elevation..m.#4
+ +Northness#5
+ +Eastness#6
+ +ResSite#7
+ +Position.on.Slope#8
+ +Distance.from.Coast#9
+ +Distance.from.C.Zone#10
+ +(1|Plot),data=NumFires,family=binomial,REML=FALSE)
>
```

```
> ## 12) aspect
> bin.aspect<-glmer(cbind(NumFires,NoFire)~
+ Slope..#1
+ +Zone#2
+ +Elevation..m.#4
+ +ResSite#7
+ +Position.on.Slope#8
+ +Distance.from.Coast#9
+ +Distance.from.C.Zone#10
+ +Distance.from.Site#11
+ +(1|Plot),data=NumFires,family=binomial,REML=FALSE)
>
> all.bin.results<-data.frame(Variable=c("Slope..","Zone","Elevation..m.",
+ "Northness", "Eastness", "ResSite", "Position.on.Slope",
+ "Distance.from.Coast", "Distance.from.C.Zone", "Distance.from.Site",
+ "Aspect"))
>
> all.bin.results$pvalue<-c(
+ anova(bin.fit, bin.slope)[2,7], #1
+ anova(bin.fit, bin.zone)[2,7], #2
+ anova(bin.fit, bin.elev)[2,7],#4
+ anova(bin.fit, bin.northn)[2,7],#5
+ anova(bin.fit, bin.eastn)[2,7], #6
+ anova(bin.fit, bin.ressite)[2,7],#7
+ anova(bin.fit, bin.pos.on.slope)[2,7],#8
+ anova(bin.fit, bin.dist.coast)[2,7],#9
+ anova(bin.fit, bin.Czone)[2,7],#10
+ anova(bin.fit, bin.dist.to.site)[2,7],#11
+ anova(bin.fit, bin.aspect)[2,7])#12
> all.bin.results$delAIC<-c(
+ AIC(bin.fit)-AIC(bin.slope), #1
+ AIC(bin.fit)-AIC(bin.zone),  #2
+ AIC(bin.fit)-AIC(bin.elev), #4
+ AIC(bin.fit)-AIC(bin.northn),#5
+ AIC(bin.fit)-AIC(bin.eastn), #6
+ AIC(bin.fit)-AIC(bin.ressite), #7
+ AIC(bin.fit)-AIC(bin.pos.on.slope),#8
+ AIC(bin.fit)-AIC(bin.dist.coast),#9
+ AIC(bin.fit)-AIC(bin.Czone),#10
+ AIC(bin.fit)-AIC(bin.dist.to.site),#11
+ AIC(bin.fit)-AIC(bin.aspect))#12
>
> write.csv(all.bin.results,"AllPvalues.csv",row.names=FALSE)
>
> ## remove all non-significant variables
> bin.reduced<-glmer(cbind(NumFires,NoFire)~
```

```
+ Zone#2
+ +Elevation..m.#4
+ +ResSite#7
+ +Position.on.Slope#8
+ +Distance.from.Coast#9
+ +(1|Plot),data=NumFires,family=binomial,REML=FALSE)
> summary(bin.reduced)
Generalized linear mixed model fit by maximum likelihood ['glmerMod']
 Family: binomial ( logit )
Formula: cbind(NumFires, NoFire) ~ Zone + Elevation..m. + ResSite + Position.on.Slope +
Distance.from.Coast + (1 | Plot)
   Data: NumFires

     AIC      BIC   logLik  deviance
 232.8635  255.3179 -104.4317  208.8635

Random effects:
 Groups Name        Variance  Std.Dev.
 Plot   (Intercept) 2.451e-13 4.951e-07
Number of obs: 48, groups: Plot, 15

Fixed effects:
                  Estimate Std. Error z value Pr(>|z|)
(Intercept)        -4.5632080  0.3910131 -11.670  < 2e-16 ***
ZoneScott-3         -0.3710410  0.5889015  -0.630  0.52866
ZoneWaddell-2        0.5009608  0.4974752   1.007  0.31393
ZoneWaddell-3        0.6674935  0.8207596   0.813  0.41607
ZoneWhitehouse-1     0.4222212  0.5250785   0.804  0.42133
ZoneWhitehouse-2    -1.2600832  0.5023460  -2.508  0.01213 *
Elevation..m.       -0.0021681  0.0010657  -2.034  0.04190 *
ResSite             -0.0004326  0.0001665  -2.598  0.00939 **
Position.on.SlopeM   0.2611651  0.1728783   1.511  0.13087
Position.on.SlopeT   1.0245639  0.2581044   3.970  7.2e-05 ***
Distance.from.Coast  0.0002377  0.0001458   1.630  0.10303
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:
            (Intr) ZnSc-3 ZnWd-2 ZnWd-3 ZnWh-1 ZnWh-2 Elv... ResSit Ps..SM
ZoneScott-3 -0.931
ZoneWddll-2 -0.838  0.767
ZoneWddll-3 -0.810  0.792  0.693
ZoneWhths-1 -0.951  0.937  0.814  0.796
ZoneWhths-2  0.302 -0.299 -0.402 -0.342 -0.375
Elevatn..m.  0.153 -0.183 -0.112 -0.098 -0.266  0.438
ResSite      0.504 -0.420 -0.747 -0.452 -0.521  0.741  0.320
```

```
Pstn.n.SlpM -0.352  0.179  0.281  0.270  0.244 -0.502 -0.281 -0.506
Pstn.n.SlpT -0.263  0.138  0.145  0.215  0.234 -0.540 -0.248 -0.335  0.491
Dstnc.frm.C -0.701  0.746  0.605  0.624  0.794 -0.652 -0.715 -0.602  0.374
           Ps..ST
ZoneScott-3
ZoneWddll-2
ZoneWddll-3
ZoneWhths-1
ZoneWhths-2
Elevatn..m.
ResSite
Pstn.n.SlpM
Pstn.n.SlpT
Dstnc.frm.C  0.329
>
> ## distance from coast is non-significant.
> bin.reduced<-glmer(cbind(NumFires,NoFire)~
+ Zone#2
+ +Elevation..m.#4
+ +ResSite#7
+ +Position.on.Slope#8
+ +(1|Plot),data=NumFires,family=binomial,REML=FALSE)
> summary(bin.reduced)
Generalized linear mixed model fit by maximum likelihood ['glmerMod']
 Family: binomial ( logit )
Formula: cbind(NumFires, NoFire) ~ Zone + Elevation..m. + ResSite + Position.on.Slope +
(1 | Plot)
   Data: NumFires

      AIC       BIC    logLik  deviance
 233.4228  254.0060 -105.7114  211.4228

Random effects:
 Groups Name        Variance  Std.Dev.
 Plot   (Intercept) 1.416e-12 1.19e-06
Number of obs: 48, groups: Plot, 15

Fixed effects:
                    Estimate Std. Error z value Pr(>|z|)
(Intercept)        -4.1208980  0.2756124 -14.952  < 2e-16 ***
ZoneScott-3        -1.0906053  0.3898107  -2.798 0.005145 **
ZoneWaddell-2       0.0110371  0.3825662   0.029 0.976984
ZoneWaddell-3      -0.1631283  0.6384339  -0.256 0.798327
ZoneWhitehouse-1   -0.2555917  0.3117377  -0.820 0.412277
ZoneWhitehouse-2   -0.7413737  0.3842969  -1.929 0.053710 .
Elevation..m.      -0.0009251  0.0007471  -1.238 0.215648
```

```
ResSite           -0.0002787  0.0001335  -2.087 0.036866 *
Position.on.SlopeM  0.1577250  0.1581669   0.997 0.318664
Position.on.SlopeT  0.8962637  0.2419923   3.704 0.000212 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:
            (Intr) ZnSc-3 ZnWd-2 ZnWd-3 ZnWh-1 ZnWh-2 Elv... ResSit Ps..SM
ZoneScott-3 -0.856
ZoneWddll-2 -0.722  0.586
ZoneWddll-3 -0.663  0.623  0.502
ZoneWhths-1 -0.905  0.845  0.678  0.625
ZoneWhths-2 -0.304  0.377 -0.016  0.114  0.321
Elevatn..m. -0.686  0.746  0.573  0.634  0.693 -0.062
ResSite      0.095  0.096 -0.573 -0.093 -0.045  0.596 -0.173
Pstn.n.SlpM -0.156 -0.145  0.107  0.062 -0.079 -0.342 -0.008 -0.380
Pstn.n.SlpT -0.043 -0.172 -0.070  0.008 -0.051 -0.443 -0.028 -0.185  0.404
>
> # elevation is not significant, remove.

> ### final model
>
> bin.reduced<-glmer(cbind(NumFires,NoFire)~
+ Zone#2
+ +ResSite#7
+ +Position.on.Slope#8
+ +(1|Plot),data=NumFires,family=binomial,REML=FALSE)
> summary(bin.reduced)
Generalized linear mixed model fit by maximum likelihood ['glmerMod']
 Family: binomial ( logit )
Formula: cbind(NumFires, NoFire) ~ Zone + ResSite + Position.on.Slope +      (1 | Plot)
   Data: NumFires

     AIC      BIC    logLik  deviance
 232.9517  251.6637 -106.4759  212.9517

Random effects:
 Groups Name        Variance  Std.Dev.
 Plot   (Intercept) 5.487e-12 2.342e-06
Number of obs: 48, groups: Plot, 15

Fixed effects:
                  Estimate Std. Error z value Pr(>|z|)
(Intercept)       -4.3600660  0.1988941 -21.922  < 2e-16 ***
ZoneScott-3       -0.7321817  0.2576868  -2.841 0.004492 **
ZoneWaddell-2      0.2839286  0.3239653   0.876 0.380804
```

```
ZoneWaddell-3       0.3428281  0.4931791   0.695 0.486968
ZoneWhitehouse-1    0.0124112  0.2250898   0.055 0.956028
ZoneWhitehouse-2   -0.7654909  0.3840294  -1.993 0.046227 *
ResSite            -0.0003059  0.0001365  -2.241 0.025007 *
Position.on.SlopeM  0.1573938  0.1579046   0.997 0.318878
Position.on.SlopeT  0.8889437  0.2412467   3.685 0.000229 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:
            (Intr) ZnSc-3 ZnWd-2 ZnWd-3 ZnWh-1 ZnWh-2 ResSit Ps..SM
ZoneScott-3 -0.714
ZoneWddll-2 -0.552  0.285
ZoneWddll-3 -0.403  0.291  0.217
ZoneWhths-1 -0.813  0.681  0.481  0.329
ZoneWhths-2 -0.465  0.626 -0.001  0.193  0.494
ResSite     -0.007  0.319 -0.618  0.012  0.075  0.593
Pstn.n.SlpM -0.208 -0.204  0.127  0.080 -0.133 -0.347 -0.378
Pstn.n.SlpT -0.078 -0.224 -0.066  0.030 -0.053 -0.447 -0.183  0.394
>
> table(NumFires$Zone,NumFires$Position.on.Slope)

              B M T
  Scott-2     3 2 0
  Scott-3     5 6 4
  Waddell-2   3 3 1
  Waddell-3   1 0 0
  Whitehouse-1 8 5 0
  Whitehouse-2 1 3 3
>
> bin.reduced.zone<-glmer(cbind(NumFires,NoFire)~
+ ResSite#7
+ +Position.on.Slope#8
+ +(1|Plot),data=NumFires,family=binomial,REML=FALSE)
> bin.reduced.ressite<-glmer(cbind(NumFires,NoFire)~
+ Zone#2
+ +Position.on.Slope#8
+ +(1|Plot),data=NumFires,family=binomial,REML=FALSE)
> bin.reduced.slope.pos<-glmer(cbind(NumFires,NoFire)~
+ Zone#2
+ +ResSite#7
+ +(1|Plot),data=NumFires,family=binomial,REML=FALSE)
>
> final.results<-data.frame(Variable=c("Zone",
+ "ResSite", "Position.on.Slope"))
>
```

```
> final.results$pvalue<-c(
+ anova(bin.reduced, bin.reduced.zone)[2,7], #2
+ anova(bin.reduced, bin.reduced.ressite)[2,7],#7
+ anova(bin.reduced, bin.reduced.slope.pos)[2,7])#8
>
>
> write.csv(final.results,"ReducedPvalues.csv",row.names=FALSE)
>
> expit<-function(x){
+ p<-exp(x)/(1+exp(x))
+ return(p)
+ }
>
> ### Create output tables of the parameter estimates on the probability scale.
> bin.results<-all.bin.results[all.bin.results$Variable%in%
c("ResSite","Position.on.Slope"),names(all.bin.results)!="delAIC"]
> bin.results$Lower<-rep(NA,nrow(bin.results))
> bin.results$Middle<-rep(NA,nrow(bin.results))
> bin.results$Upper<-rep(NA,nrow(bin.results))
>
> zonelevels<-levels(NumFires$Zone)
> zones<-paste("Zone",levels(NumFires$Zone),sep="")
> zones[1]<-"(Intercept)"
>
> for(j in 1:length(zones)){
+ int<-coef(summary(bin.reduced))[zones[j],"Estimate"]
+ mn<-mean(NumFires[["ResSite"]],na.rm=TRUE)
+ minx<-min(NumFires[["ResSite"]],na.rm=TRUE)
+ maxx<-max(NumFires[["ResSite"]],na.rm=TRUE)
+ middle<-int+mn*coef(summary(bin.reduced))["ResSite","Estimate"]
+ top<-int+coef(summary(bin.reduced))["ResSite","Estimate"]*(maxx)
+ bottom<-int+coef(summary(bin.reduced))["ResSite","Estimate"]*(minx)
+ bin.results[1,c("Lower","Middle","Upper")]<-
c(100*expit(bottom),100*expit(middle),100*expit(top))
+
+ bottom<-coef(summary(bin.reduced))[zones[j],"Estimate"]
+ middle<-bottom+coef(summary(bin.reduced))["Position.on.SlopeM","Estimate"]
+ top<-bottom+coef(summary(bin.reduced))["Position.on.SlopeT","Estimate"]
+ bin.results[2,c("Lower","Middle","Upper")]<-
c(100*expit(bottom),100*expit(middle),100*expit(top))
+ print(zonelevels[j])
+ print(bin.results)
```

APPENDIX III
Fire information based on point estimates

Samples:	**WHC3033, 3038**
Time period	**1350 - 2013**
Total Intervals	5
Mean Fire Interval	46.60
Median Fire Interval	35.00
Weibull Modal Interval	41.13
Weibull Median Interval	45.10
Fire Frequency	0.02
Standard Deviation	24.91
Coefficient of Variation	0.53
Skewness	0.35
Kurtosis	-1.87
Scale parameter	52.95
Shape parameter	2.28
Minimum Fire Interval	22.00
Maximum Fire Interval	79.00

Samples:	**WHC3033, 3038**
Time period	**1850 - 1950**
Total Intervals	5
Mean Fire Interval	22.80
Median Fire Interval	22.00
Weibull Modal Interval	21.38
Weibull Median Interval	22.31
Fire Frequency	0.04
Standard Deviation	10.71
Coefficient of Variation	0.47
Skewness	-0.36
Kurtosis	-1.34
Scale parameter	25.64
Shape parameter	2.63
Minimum Fire Interval	7.00
Maximum Fire Interval	35.00

Samples:	**WHC3022, BBP002, BBP006,BBP007**
Time period	**1600 - 1850**
Total Intervals	10
Mean Fire Interval	49.70
Median Fire Interval	46.00
Weibull Modal Interval	36.21
Weibull Median Interval	45.81
Fire Frequency	0.02
Standard Deviation	30.22
Coefficient of Variation	0.61
Skewness	1.30
Kurtosis	1.50
Scale parameter	56.01
Shape parameter	1.82
Minimum Fire Interval	9.00
Maximum Fire Interval	124.00

Samples:	**WHC3022, BBP002, BBP006,BBP007**
Time period	**1850 - 1950**
Total Intervals	12
Mean Fire Interval	25.42
Median Fire Interval	19.50
Weibull Modal Interval	4.96
Weibull Median Interval	19.61
Fire Frequency	0.05
Standard Deviation	23.38
Coefficient of Variation	0.92
Skewness	1.09
Kurtosis	-0.19
Scale parameter	26.88
Shape parameter	1.16
Minimum Fire Interval	4.00
Maximum Fire Interval	74.00

Samples:	**WHC3022, BBP002, BBP006,BBP007**
Time period	**1950 - 2013**
Total Intervals	3
Mean Fire Interval	15.67
Median Fire Interval	13.00
Weibull Modal Interval	15.16
Weibull Median Interval	15.53
Fire Frequency	0.06
Standard Deviation	7.37
Coefficient of Variation	0.47
Skewness	0.47
Kurtosis	-2.00
Scale parameter	17.67
Shape parameter	2.84
Minimum Fire Interval	10.00
Maximum Fire Interval	24.00

Samples:	**WHC3022, BBP002, BBP006,BBP007**
Time period	**1950 - 2013**
Total Intervals	3
Mean Fire Interval	15.67
Median Fire Interval	13.00
Weibull Modal Interval	15.16
Weibull Median Interval	15.53
Fire Frequency	0.06
Standard Deviation	7.37
Coefficient of Variation	0.47
Skewness	0.47
Kurtosis	-2.00
Scale parameter	17.67
Shape parameter	2.84
Minimum Fire Interval	10.00
Maximum Fire Interval	24.00

Samples:	**BCL011,BCL017**
Time period	**1600 - 1850**
Total Intervals	11
Mean Fire Interval	13.45
Median Fire Interval	11.00
Weibull Modal Interval	11.10
Weibull Median Interval	12.76
Fire Frequency	0.08
Standard Deviation	7.20
Coefficient of Variation	0.54
Skewness	0.34
Kurtosis	-1.14
Scale parameter	15.22
Shape parameter	2.08
Minimum Fire Interval	3.00
Maximum Fire Interval	26.00

Samples:	**BCL012,BCL014,WIL001**
Time period	**1850 - 1950**
Total Intervals	7
Mean Fire Interval	25.57
Median Fire Interval	17.00
Weibull Modal Interval	10.90
Weibull Median Interval	21.53
Fire Frequency	0.05
Standard Deviation	20.65
Coefficient of Variation	0.81
Skewness	0.61
Kurtosis	-1.47
Scale parameter	28.11
Shape parameter	1.37
Minimum Fire Interval	5.00
Maximum Fire Interval	57.00

Samples:	**BCL006,BCL007,BCL015,BCL016**
Time period	**1600 - 1850**
Total Intervals	12
Mean Fire Interval	40.50
Median Fire Interval	33.00
Weibull Modal Interval	7.07
Weibull Median Interval	30.81
Fire Frequency	0.03
Standard Deviation	32.56
Coefficient of Variation	0.80
Skewness	0.24
Kurtosis	-1.62
Scale parameter	42.41
Shape parameter	1.15
Minimum Fire Interval	4.00
Maximum Fire Interval	87.00

Samples:	**BCL006,BCL007,BCL015,BCL016**
Time period	**1850 - 1950**
Total Intervals	3
Mean Fire Interval	20.67
Median Fire Interval	26.00
Weibull Modal Interval	0.00
Weibull Median Interval	13.50
Fire Frequency	0.07
Standard Deviation	17.62
Coefficient of Variation	0.85
Skewness	-0.41
Kurtosis	-2.00
Scale parameter	20.09
Shape parameter	0.92
Minimum Fire Interval	1.00
Maximum Fire Interval	35.00

Samples:	**BCL006,BCL007,BCL015,BCL016**
Time period	**1950 - 2013**
Total Intervals	5
Mean Fire Interval	10.40
Median Fire Interval	6.00
Weibull Modal Interval	0.49
Weibull Median Interval	7.44
Fire Frequency	0.13
Standard Deviation	9.94
Coefficient of Variation	0.96
Skewness	0.33
Kurtosis	-1.93
Scale parameter	10.57
Shape parameter	1.04
Minimum Fire Interval	1.00
Maximum Fire Interval	23.00

Samples:	**SPR008+COT007**
Time period	**1850 - 1950**
Total Intervals	3
Mean Fire Interval	39.33
Median Fire Interval	38.00
Weibull Modal Interval	40.03
Weibull Median Interval	39.58
Fire Frequency	0.03
Standard Deviation	15.04
Coefficient of Variation	0.38
Skewness	0.13
Kurtosis	-2.00
Scale parameter	43.81
Shape parameter	3.60
Minimum Fire Interval	25.00
Maximum Fire Interval	55.00

Samples:	**SPR008+COT007**
Time period	**1950 - 2013**
Total Intervals	5
Mean Fire Interval	16.20
Median Fire Interval	3.00
Weibull Modal Interval	0.00
Weibull Median Interval	6.70
Fire Frequency	0.15
Standard Deviation	23.26
Coefficient of Variation	1.44
Skewness	0.98
Kurtosis	-0.95
Scale parameter	11.77
Shape parameter	0.65
Minimum Fire Interval	1.00
Maximum Fire Interval	55.00