A 500-year record of fire from a humid coast redwood forest

A report to Save the Redwoods League

Steven P. Norman[1]
March 19, 2007

ABSTRACT

California's coast redwood (*Sequoia sempervirens*) forests have long been associated with moderately frequent to frequent fire, particularly in the southern and interior portions of the species range. The historical importance of fire in northern coast redwood forests is generally thought to be much less because lightning ignitions are rare, and cool coastal temperatures and summer fog ameliorate the fire hazard. Support for this climate-fire gradient hypothesis has been limited because of insufficient fire history data from the northern coast redwood range. Past efforts to test this hypothesis range-wide are made difficult because of methodological differences among studies and problems with scar preservation in redwood. This research revisits the fire history of an area thought to have experienced fire only a few times per millennium in Del Norte Coast Redwoods State Park. I found that fire frequency was substantially more frequent than previously thought. Between 1700 and 1850, mean fire intervals within 0.25 to 1 ha sample areas varied from 11 to 26 years. Fire intervals did not correspond to a latitudinal, coast-interior or a topographically defined moisture gradient. Instead, patterns of fire frequency better fit a cultural burning gradient inferred from the ethnographic and historical record. Areas close to aboriginal villages and camps burned considerably more often than areas that were probably less utilized. Summer season fires, the ones most likely set by the Native Tolowa for resource needs, were 10 years shorter than the mean fire interval of autumn season fires. In the dryer eastern portion of the study area, frequent fire resulted in unimodal or bimodal pulses of Douglas fir (*Pseudotsuga menziesii*) establishment suggesting moderate to high fire severity. Near a Tolowa village site, a frequent fire regime before the late 1700s initiated a pulse of Douglas fir establishment that dominated the forest canopy for centuries; long after the village was abandoned, possibly due to epidemic disease. While variability in coastal fog-stratus and drought may also influence fire regimes, these relationships provide a weaker explanation than human ignition history. Variable human and climate influence on old-growth redwood fire regimes suggests that old growth redwood forests are not in equilibrium, but are dynamic due to a long history of variable human influence. Remnant old growth forests are likely to continue to evolve in response to human management. Efforts by managers to restore and sustain these remarkable forests can be enhanced by understanding how complex histories give rise to biodiversity.

Keywords: coast redwood, *Sequoia sempervirens*, California, Native American fire, Tolowa, cultural burning gradient, climate-fire relationships, climate change, fog-stratus, Douglas fir, *Pseudotsuga menziesii,* tanoak, *Lithocarpus densiflorus,* fire scars, pyrodiversity, historical ecology.

[1] USDA Forest Service Southern Research Station. Current address: Forest Service Redwood Sciences Laboratory, 1700 Bayview Dr. Arcata CA 95521; Phone: (707) 822-2910; Email: stevenorman@fs.fed.us

At the height of one meter,
there was just one scar on MBH28.
At ten cm there were eleven.

INTRODUCTION

Fire scientists and forest managers of the American West have long thought that differences in fire regimes among forests are largely explained by variation in the fuel. According to this model, the periodicity of fire reflects the time needed for fuel to accumulate to levels where fire will spread. It further presumes that the fire weather necessary for fire to burn occurs on a regular basis and that ignitions are not a limiting factor. During resent decades, research has demonstrated that fire regimes in the Western United States are strongly driven by broad-scale variation in regional and hemispheric climate (Swetnam 1992, Kitzberger et al. 2006). While combustible fuel is clearly important for fire spread, this discovery in the importance of broad-scale drivers has eroded the previously held belief that local conditions drive fire regimes as much as was once thought, with broad implications for climate change. Recent research has also shown that certain ecosystems are strongly ignition-limited. For example, the historical and modern fire regimes of coastal southern California are dependent on human ignitions more than lightning (Keeley 2002). If climatic controls on fire regimes are weak in such ignition-limited systems, local ignition factors rather than top-down controls define the fire regime.

Like coastal southern California, the cool and humid forests of northwestern California experience few lightning ignitions (Fritz 1931, Stuart and Stephens 2006). Further, the coastal portions of the region are buffered from substantial variation in climate during the summer and autumn because of the moderating influence of the ocean on temperatures and frequent fog-stratus cover (Filonczuk et al. 1995). It has long been argued that this moderate and relatively stable climate of the coast explains why the area harbors the most superlative stands of coast redwood (Cooper 1917, Olson et al. 1990, Sawyer et al. 2000). It has also long been thought that patterns of climate also restrict redwood fire regimes (Viers 1982, Stuart 1987). Over a century ago, Fisher (1903; p. 15) wrote, “In the damp northern part of the redwood belt the forest is too wet to burn.” While fires in the northern redwood forest have been rare in recent decades (Oneal et al. 2006), there is abundant evidence in the form of fire generated basal hollows and charred bark that fires have burned in the past (e.g., Zielinski and Gellman 1998). Clearly, the northern coast redwoods do not comprise an “asbestos forest” that never has nor can burn.

Pasts efforts to quantify historical fire regimes in coast redwood have led to inconsistent and controversial results that have not led to a cohesive theory of fire for the forest type. The most widely accepted hypothesis of fire in coast redwood forests describes historical fire frequencies as varying along a north-south and east-west climate gradient. More coastal and northern portions of the coast redwood range are generally thought to have burned less frequently than southern and interior sites. Using stump-top fire scars and inferences from forest age structure, Viers (1980a, 1980b, 1982, 1996) described fire intervals of up to 600 years on humid northern coast redwood sites and 33-50 years for interior sites. In contrast, on two upland interior sites east of Prairie Creek State Park, Brown and Swetnam (1994) found ground-level fire scars on individual trees with a mean interval of 21 years, and by pooling fire scars from nearby trees, 10 years. Farther south along the Mendocino coast, Brown and Baxter (2003) found similarly short mean point fire intervals of 9-20 years. Researchers working in the drier portions of the coast redwood range reported point intervals between 6 and 45 years (Table 1). Given this variability, the evidence for a historical climate control on fire frequency in redwood is contingent on the long fire intervals reported by Viers. Researchers generally agree that the paucity of lightning ignitions along the coast suggests that most historical fires were of human origin (Fritz 1931, Stuart and Stephens 2006). However, the extent of human influence in the coast redwood was strongly limited by these natural climate gradients.

A very different view of fire regimes characterizes social science research in coast redwood. Early twentieth century ethnographers documented the pervasive land use traditions of Native American groups across the coast redwood range. Research has documented the extent to which the livelihoods of tribes were enhanced by active fire use (Anderson 2005 Lewis 1973). In parallel, archaeological evidence has documented the presence of humans in and near the coast redwoods for several times the live span of the oldest known coast redwood (Frederickson 1982). While cultural and tribal traditions appear to have been inconsistent over the millennia, the considerable length of human presence in and near the coast redwood suggests that ignitions may not have been a limiting factor in some coastal forests for a very long time. In contrast to the pattern expected from a broad-scale moisture gradient, a cultural burning model associates areas most in use by Native Americans with frequent fire, and in northwestern California, villages were concentrated along the coast and along riparian corridors (Waterman 1920; Baumhoff 1958). Such places are least likely to burn according with a moisture gradient hypothesis. In addition, the coastal tribes of California extensively utilized interior forests for procurement of food and materials. While extensive human influence across the coast redwood landscape has been questioned (Vale 2002), the actual impact of Native Americans remains an open question.

From the perspective of modern managers, these two fire-gradient hypotheses impact how the status and dynamics of coast redwood forests are interpreted. Portions of the landscape that harbor ecological legacies of Native American fire use may be experiencing certain undesirable effects from fire exclusion (Underwood et al. 2003). In contrast, locations that rarely burned in the past may warrant passive management strategies and they can provide analogs for how second-growth forests, now managed by federal and state parks, might develop under a long-term policy of fire exclusion. More broadly, the identification of a pervasive Native American footprint in one of the oldest and most renowned old growth forests on Earth would challenge popular perceptions about the stability and timelessness of old growth. If human fires have been pervasive across the coast redwood range, this superlative forest may not be as “natural” as is commonly thought.

In this paper, I describe the fire history of a humid coast redwood forest along a coast to interior gradient and across slopes. I then compare fire regimes to the known pattern of Native American land use described by early 20th century ethnographers to determine which of these two competing hypotheses best explains the historical fire regime of this coast redwood forest.

STUDY AREA

Del Norte Coast Redwood State Park is located in central Del Norte County California and consists of old growth and second growth forest. It extends from the Pacific Ocean, south of Crescent City California, through the Mill Creek watershed to encompass the entire core portion of the coast redwood range. The Mill Creek and Rock Creek portions of the Park consist nearly entirely of second growth forest and were only recently acquired. By 1926, logging was restricted to the western edge of the Mill Creek region (Weber 1926) and it continued through 2000, shortly before the area became part of the Park (Stillwater Sciences 2002).

Coastal Del Norte County, California is among the wettest portions of California, receiving 152-381 cm of precipitation annually, mostly during the winter (Stillwater Sciences 2002). Mean and extreme temperatures vary with distance to the coast. The average monthly maximum and minimum temperature at Crescent City is 8-19^{o}C (41-67^{o}F).

The study area varies in elevation from 60 to 700 m (200-2,300 ft) and slopes from 20-40% are common, slopes less than 10% are largely restricted to the alluvial bottomlands and slopes exceeding 50% are typical of lower and mid-slope positions near the headwaters. The northeastern edge of the study area includes ultramafic soils that do not favor coast redwood. Extreme ultramafic soils are dominated by Jeffrey pine (*Pinus jeffreyi*) and native grasses and herbs. Dry upper slopes are dominated by Douglas fir, tanoak (*Lithocarpus densiflorus*) and Pacific madrone (*Arbutus menziesii*). Knobcone pine (*Pinus attenuata*) is common on eastern ridgetops in association with giant chinquapin (*Chrysolepis chrysophylla*). Western hemlock (*Tsuga heterophylla*) occurs on mesic slopes in the west, is restricted to riparian areas in the central portion of the study area and is largely absent in the east. The current shrub understory is strongly associated with time since logging and where present, is dominated by evergreen huckleberry (*Vaccinium ovatum*), red huckleberry (*Vaccinium parvifolium*), rhododendron (*Rhododendron macrophyllum*), and salal (*Gaultheria shallon*). On dry sites in the east, Oregon grape (*Berberis* sp.), Ceanothus (*Ceanothus* spp.), manzanita (*Arctostaphylus* sp.) and beargrass (*Xerophyllum tenax*), used in Indian basketry, contributed fire spread in the Douglas fir-hardwood forest where coast redwood was sparse.

The people known as the Tolowa have lived here for centuries and are thought to have been the primary sources of human ignitions before 1850. Based on a change in material culture seen in the archaeological record, the Tolowa are believed to have entered the area from Oregon around A.D. 1300, displacing an earlier people (presumably the ancestral Karuk). In 1850, the Tolowa lived in several coastal villages, from near the mouth of the Smith River south past present day Crescent City (Waterman 1920). Interior village sites existed along the Smith River and near the confluence of the east and west forks of Mill Creek within the study area, but these villages are thought to have harbored fewer people than the villages on the coast (Drucker 1937).

The seasonal pattern of Tolowa resource use was similar to that of neighboring tribes. Families had seasonal camps in the mountains where they went to gather acorns, harvest seeds and to hunt. For several weeks during the summer or early fall, the coastal villages were largely abandoned as family groups dispersed to these inland sites (Drucker 1937, Gould 1975). Tanoak acorn gathering was performed by women while men hunted for venison. Berries supplemented the Tolowa diet and were collected as they became available over the growing season. Salmon were procured from the Smith River and its tributaries including Mill Creek. The sea provided supplemental food and materials including fish, seals, mussels and whales. Seals were killed using sea-worthy canoes made of redwood.

The use of fire by the Tolowa is well-established in the ethnographic record. According to Drucker (1937; p. 233), "informants maintain that nearby hills were kept clear of brush by annual burning; this also improved the grass, so that deer frequented such clearings and could be shot easily." He further relates that "Late spring, when the old fern was quite dry and the new growth just starting, is said to have been the time for burning off the hillsides to improve the hunting grounds" (p. 232). As with other neighboring tribes, tanoak acorns provided a primary food source and regular burning of tanoak groves reduced the filbert worm and filbert weevil infestation that would otherwise reduce the quality of the annual harvest (Anderson 2005). In the words of Klamath River Jack of Del Norte County in a letter from 1916, "Fire burn up old acorn that fall on ground. Old acorn on ground have lots worm; no burn old acorn, no burn old bark, old leaves, bugs and worms come more every year…Indian burn every year … so no bug can stay to eat leaf and no worm can stay to eat berry and acorn. Not much on ground to make hot fire so never hurt big trees, where fire burn." (cited in Anderson 2005, p. 146). Other Tolowa informants reported that burning was also conducted to make the acorns drop off and a Yurok informant stated that burning was intended to reduce the leaf cover so fallen acorns were more visible (Driver 1939). Other reasons for burning tanoak stands may have included a desire to stimulate oak shoot and beargrass production for basketry, reduce the severity of fires, to encourage edible mushrooms, and to increase seed production in grasses (Anderson 2005). Within the study area, early 20th century ethnographic accounts mentions two summer camps where acorn collection likely occurred: one is at Bald Hill northeast of the study area and the other is on the east-west-trending ridgeline between the east and west forks of Mill Creek (Drucker 1937).

The ethnographic record does not tell us if the Tolowa or neighboring tribes on the North Coast deliberately burned significant portions of the coast redwood forest that had no tanoak component. To the south, the Lolangkok Sinkyone Indians were apparently responsible for the frequent fires in the pure redwood forests of the alluvial flats of Humboldt Redwoods State Park, but these areas were used as winter villages sites (Norman et al. 2003). Fires in the shaded understory may have reduced unwanted downed wood, duff and litter, or fires may have stimulated the production of specific herbs or shrubs of value that primarily grew in these humid sites, such as ferns (Lewis 1973). In other areas, fires may have only occasionally spread into redwood stands from adjacent forests that were actively burned.

The first formal contact between the Tolowa and Euro-Americans probably occurred during the 1828 Jedediah Smith Expedition (Thornton 1984). Decades earlier, indirect contact is suggested by both archaeological evidence and oral tradition. Members of the Yurok tribe, immediately to the south of the Tolowa, were visited by ships commanded by Juan Francisco de Bodega in 1775 and George Vancouver in 1793 and by 1775, the Yurok settlement at Trinidad already had acquired iron (Heizer and Mills 1952). These early contacts with Europeans are thought to have triggered a cholera epidemic that led to the abandonment of a village at Point Saint George near present day Crescent City before 1850 (Gould 1978). Due to further epidemics and killings inflicted by Euro-American settlers after that time, the Tolowa population declined from around 2,400 people before then to 316 in the 1850s and 200 by 1870 (Thornton 1984, Gould 1966).

The settlement of northwestern California by Americans from the east coast, Europe and Asia was triggered by the discovery of gold in California in 1849. A population boom in the Klamath Mountains to the east led to a supply line to Humboldt Bay to the south (Lewis 1943). A rapid transformation of the Tolowa's homeland soon followed.

METHODOLOGY

Fire history

Following review of GIS logging and vegetation layers, ethnographic data for the area collected in the early 20th century (Drucker 1937), and a reconnaissance of the research area, eight fire collection sites were non-randomly selected to balance competing research needs and logistical limitations: First, prospective sites were preferentially filtered to have sites near and far from known Native American centers of activity based on the ethnographic record (i.e., near the main village site and the two summer camp sites). Second, prospective sites were considered according to where they fell along an east-west and topographically defined moisture gradient. For logistical reasons, sampling sites were further constrained according to time since logging and accessibility. Given the well-established limitations of dating redwood tree rings (Fritz 1940, Brown and Swetnam 1994), recently logged units were preferentially selected whenever they were available to increase the chance of having intact sapwood that would help fix dates if crossdating was not possible. Finally, the actual trees collected were preferentially selected if they fell within 100 m of a road for logistical reasons related to the terrain and accessibility.

The approach used in this study differs from that of past studies because I limited the sample collection area to 1 ha or less. Many past researchers have pooled fire scars recorded on multiple trees collected from an area from a few tens of hectares to hundreds of hectares to ensure a "complete" record of fires. This approach has been criticized because reliance on large collection areas when fires were small results in broad-scale statistics that are difficult to interpret. Fire patchiness may have been important in coast redwood because fuel moistures may have been marginal for burning and conditions may have been more influenced by nuances of micro-topography and canopy cover than dryer forests. Moreover, such broad scale statistics are of limited practical use for ecologists interested in local fire effects and managers concerned with scheduling prescribed fire. I found that most trees harbored an excellent and well-preserved record of fire in basal flutes between 0 and 30 cm height, so the problem of interpreting fire scars aggregated over a large collection area was avoided.

Analysis

Collected samples were dried for a period of one to four months then polished with up to 400 grit sandpaper to reveal cell structure. Samples were examined under a 10-40x boom binocular microscope to identify the location of partially absent rings (Fritz 1940). When possible, samples were crossdated for all or a portion of their ring sequence. Crossdating was attempted using a number of chronologies from northwest California, but the only reliable one found was a riparian Port Orford cedar chronology collected from the Oregon-California border not far to the north (Carroll and Jules 2005).

I compared fire intervals among sites according to two moisture gradients: distance from the coast and a topographic integrated moisture index (TIMI). TIMI is a relative measure of surface moisture derived from a digital elevation model that includes three process-based components. August solar radiation calculated using Solar Analyst, an extension for ArcView GIS software, a wetness index based on flow accumulation and slope, and topographic position calculated at a 2 km-radius scale. These three variables were categorized from 1-100, then combined into a single index by weighting components 40%, 40%, and 20%, respectively. I then compared fire intervals based on their proximity to known Tolowa village and camp sites to determine if fire intervals are better explained by a cultural burning gradient or a topographic or coast-to-interior moisture gradient.

The season in which fires occurred was inferred based on the position of the fire scar within the annual growth ring. Where fire season was unclear on one portion of a fire scar due to narrow growth, obscure cell growth or decay, it was usually evident where it occurred elsewhere on the tree. This allowed me to identify the seasonal position for 90% of fire events. Native American fires are thought to have occurred earlier in the growing season than lightning fires and Natives likely reduced the time between fires (Lewis 1973; Martin and Sapsis 1992). To explore this relationship, I calculated the mean fire return interval for fires occurring during each of three seasonal positions (earlywood, latewood, dormant season) before and after 1850.

The strength of regional moisture gradients is unlikely to have been consistent over time, given the inherent variability in the climate mechanisms that cause drought and coastal fog. I compared five tree-ring based proxy records of climate variation to the fire records of an interior and a more coastal site having relatively well-dated and long fire records. I compared fire events to the local climate reconstruction used in crossdating (Carroll and Jules 2005), an ENSO index for the Nino3 equatorial region (D'Arrigo in press), two reconstructions of the Pacific Decadal Oscillation (PDO)(MacDonald 2005; D'Arrigo 2001), and the Atlantic Multi-decadal Oscillation (AMO)(Gray 2004). As neither fire history site was crossdated for the entire 500 year period, no formal statistically analyses were conducted.

As variability in coastal fog may be linked to climate-driven variation in fuel moisture and fire regimes, a long-term record of summer (July-October) fog from Eureka, California (1887-2002) was compared with known fires since 1887 in Del Norte County based on this study and California Department of Forestry records.

Age structure

Most recently logged sites were clear cuts dominated by Douglas fir and hardwood. The tree rings of Douglas fir stumps were sufficiently well-preserved to permit an age structural analysis to provide insight into the fire regimes of those sites. Eleven plots 0.25 to 1 ha in area were located within recent clearcut units and the diameter, species and age was recorded for a 25-tree sample of conifers greater than 20 cm diameter at stump height. When large redwood stumps were present, I also estimated their age based on ring counts. No attempt was made to inventory or date hardwoods. Given the obscuring effect of dense 1-3 m high brush and the difficulty finding stumps in some units, plot areas were not fixed. Fire scar data was collected in or near five of these eleven vegetation plots (Fig 1).

RESULTS

Fire history sampling

Fire scar samples were successfully collected from eight sites across the study area from a range of vegetation types (Table 2). Only one moist, coastal site (MGH) was found that had been logged recently, so two sites logged decades earlier were selected (MWM 1957 and MWT in 1967). In addition, one dryer interior site near a Native American summer village site (MVT) had been logged in 1967. In this humid climate, trees logged prior to 15 years ago rarely have sapwood due to the high decay rate. In coast redwood, not having growth rings since a known event, such as the logging date, can result in a "floating chronology" if the ring sequence can not be crossdated (e.g., Finney and Martin 1992). We overcame this limitation by sampling from the portions of stumps where the vascular cambium had been kept alive by stump sprouts. Even after a half century since logging, the sapwood on the parent stumps was well preserved behind this live cambial tissue, even though annual growth rings were virtually indistinguishable due to the strength of the growth suppression. The full year of growth before the suppression corresponded to the year before the logging date from mill records. On stumps from MWM and MVT, this logging date was further confirmed by crossdating.

The fire scars and growth rings of samples that could not be crossdated were matched with the most reliable sample collected at each site based on having few partially absent rings. Cross-matching was accomplished by adjusting fire intervals by no more than five years (typically 1-3) and only then when a missing ring was likely, given certain characteristics of the sample. Missing rings were more common on samples with narrow growth rings and following fire event (see Brown and Swetnam 1994). Samples from several sites were discarded due to excessive missing rings.

Only two sites (MRC and MCN) were crossdated using the Carroll and Jules chronology for the entire fire scar period. MWM, MGH, MVT and MBH were crossdated for portions of their record, but complacent growth reduced confidence during a portion of the record. Neither MWT or MRR were crossdated. The fire chronology of MWT was based on a ring count from a sample with live sapwood. The fire record of MRR is least reliable and was dated based on the approximate number of years of eroded sapwood on well-dated samples from the study area (mean=55.1, s.d.=18.3; range=19-86; n=10) and a fire interval common to MVT in the mid 19th century.

Multiple samples were obtained from most trees in an exploratory fashion that involved the careful examination of samples as they were removed from the tree. Fire scar cavities were sampled when present, but they provided a poor record across the study area due to the high rate of decay. The best record was routinely found in basal flutes that had no outward evidence of scarring. Trees were sampled at or below ground height up to 30 cm. Fire scars in these stumps were often absent above 20 cm height, and many scars were only recorded below 15 cm. I collected 1-7 samples from individual trees, often at multiple heights and in different portions of the tree's circumference. On several trees, scars disappeared from samples when I sampled below the pre-logging ground surface. Between 2 and 5 trees were sampled at each site, always within a homogeneous one hectare collection area.

Fire history

Frequent fire occurred on all eight sites, often interrupted by periods with less fire (Fig. 2). The fire record extends back in time through A.D. 1500 on six sites, begins in the mid 1700s at MVT, where the three redwoods sampled initiated concurrently, and in the mid 1800s at MCN, the one site with a record in Douglas fir. The distribution of fire intervals prior to 1920 reveals that the most common interval was between 11-15 years, and that the bulk of fire intervals fell between 6 and 35 years (Fig. 3). Only 14% of the fire intervals exceeded 35 years and all were less than 90.

Mean or median fire return intervals between 1700 and 1849 do not consistently follow either a topographic or east-west moisture gradient (Fig. 4). Short intervals occur on moist and dry coastal and interior sites. Maximum fire intervals partially vary with distance to the coast, but this relationship is not consistent among sites. Minimum intervals show no consistent relationship either.

During the period 1700-1849, fires were well-represented during all portions of the growing season from the early portion of the earlywood through tree dormancy (Table 3). This near-uniform proportion of fire seasons changed after 1850 as dormant season fires became more common.

Short fire intervals were associated with early season fires before 1850, but not after (Fig. 5). Between 1700 and 1849, the mean fire interval for fires that scarred earlywood was 14.5; this was 10 years less than that of dormant season fires (Table 3).

Age structure

Conifer age structure was determined in eleven clearcut units logged since 1991. With two exceptions (Fig 1; plots 10 and 11), plots are only representative of dry upper slope sites that are dominated by Douglas fir and hardwoods. This reflects the fact that the redwood-dominated forests closer to the coast had been logged long ago and Douglas fir stumps had eroded beyond my ability to date them in the field.

All eleven sites exhibited a strong unimodal or bimodal pulse in Douglas fir establishment (Fig. 6). In plots 4 and 10, these pulsed cohorts surrounded centuries-old redwood stumps and a multi-stemmed 100-year old redwood sprout was recorded in plot 5. A pulse of knobcone pine established with Douglas fir around 1900 in plot 2 and knobcone pine established during two separate pulses with Douglas fir with old redwood in plot 4.

Fire scar dates from plot 3 (MCN), plot 4 (MBH) and plot 7 (MRC) reveal that these pulses of Douglas fir and knobcone pine followed fires. At MCN, two fires (1880 and 1889) occurred between the first and second Douglas fir pulse in plot 3 and none after. This probably indicates that all of the seedlings that germinated following the 1880 fire were killed by the 1889 event, given the 9 year interval. Fires occurred in 1894 and 1918 in plot 4, immediately before pulses of establishment. Similarly, a fire in 1918 preceded the single Douglas fir pulse in plot 7.

A tree age-fire relationship at plot 10 (MGH) is more difficult to interpret. The Douglas fir component of this stand is old, having established between about 1720 and 1800. Because these large stumps were aged 2-3 m above the soil surface, establishment dates are less accurate than are stumps in the other plots. The fire history of the site (Fig 2: MGH) indicates that this pulse in establishment did not initiate following a single severe fire, but during a period of frequent fire in the early to mid 1700s.

The relationship between Douglas fir age and stump diameter was weak (Fig. 7). Even-aged post-fire cohorts showed tremendous variability in diameter within plots and across the study area.

Climate analysis

Given my limited confidence that fire dates reflected true calendar dates on most sites, only a superficial fire-climate analysis was conducted. This limitation is greatest for analyses involving climate reconstructions with high interannual variability, including annual drought and variation in El Niño/Southern Oscillation. To partially overcome this limitation, comparisons for these two reconstructions are performed using a 10-year moving average of the indices. Two sites with long and well-dated records (MBH and

MGH) were used to compare fire with the climate indices (Fig. 7). Fires were associated with both droughty and non-droughty climate extremes as reconstructed by Carroll and Jules (2005) (Fig. 7A). Similarly, no relationship is apparent in the smoothed Niño3 data (Fig. 7B).

Correlations between fire and the longer-term climate variation inherent in The Pacific Decadal Oscillation and Atlantic Multi-decadal Oscillation are less likely to suffer from minor fire dating errors. Variation in fire shows no consistent relationship to either cool or warm phases of either PDO reconstruction, nor to secular changes in the AMO (Fig. 7C, D, and E).

Comparison of the long-term fog record at Eureka (1887-2002) (Fig. 8) with recent fires suggests a possible relationship between coastal fog and fire. In this study, recent fire scars were dated for the years 1889, 1890 1893, 1894, 1905 and 1918. Of these, the four earliest fires burned during the foggiest third of the years of record, and both 1905 and 1918 were in the middle third. Twentieth century fire dates from the California Department of Forestry records (FRAP) for Del Norte County report fires within the redwood range for the years 1918, 1924, 1935 and 1988. The year 1924 was an exceptional drought year across northern California, and unlike the fires above, it occurred during the least foggy third of the record. The year 1935 was also dry, but it was near average in the number of fog days. In 1988, nearly 2,500 ha burned in the Hunter and Turwar Creek watersheds in southern Del Norte County, and 1988 was the 5th foggiest year of the 116 year record. This 1988 fire event is consistent with the relationship between frequent fog in Eureka and fire as seen for the 1889-1894 events. Years with frequent fog on the coastline can be tentatively associated with extreme fire years in interior sites. This relationship is consistent with the observation that when northern California’s interior is especially warm relative to the coast, the low inland pressure draws the marine layer inland (Justham 1974).

DISCUSSION

Fire regimes

The fire intervals documented from this study indicate that fire was substantially more frequent than previously thought in this portion of the humid north coast redwood forest. While areas with long fire intervals in the coast redwood forest probably do exist, it is unlikely that the difference between this research and that done previously in the area reflect site differences. Viers’ (1982) plot 4 was within about 1 km of MGH. It is likely that the long fire intervals previously reported simply reflect the heights at which scars were surveyed. The study demonstrates that coast redwood only consistently record scars near the ground surface. Fires in these forests probably had very low flame lengths that only could scar trees at low heights.

Broad pulses of Douglas fir and western hemlock establishment in these forests have also been interpreted to mean establishment after a severe fire event (Viers 1982). The age structure and fire dates from my age plots suggest that Douglas fir cohorts establish after individual fire events on dryer interior sites, broad-scale pulses also establish following a change in the fire regime (Fig 2: MGH; Fig. 6: plot 10). On mesic sites, Western hemlock can survive fires of low intensity and may not provide an accurate indicator of time since fire.

The greatest shortcoming of the methodology that I employed is that the effort made to obtain a full record from individual trees limited the number of trees that could be collected at a site. If fires were missed, the relatively frequent fires reported here still underestimate the past frequency of fire in these forests. In that case, the median fire return interval is a closer approximation of the typical fire interval that characterized these forests than the mean.

Human modification of the redwood environment

Native Americans have lived in or near the Mill Creek watershed for thousands of years. The population of the region may have markedly increased with the arrival of the Tolowa about AD 1300 (Frederickson 1984), but temporal and spatial changes in human use across the landscape are difficult to reconstruct with certainty. Consistent with a cultural burning gradient, the fire record of individual sites corresponds well to what is expected from the ethnographic record. Sites near villages and camps (MBH, MVT, MGH and to some degree MWM) burned more frequently between 1700-1849 than more distant sites (MRC, MRR and MWT). Either of the interior sites MBH and MRC may have received fires spreading from an ignition source far to the east. Many fires on this site scarred latewood, and they presumably burned during mid to late August. The relative lack of earlywood fires here compared to more coastal sites may reflect phenological differences in redwood growing on different sites.

An apparent reduction of fire between the late 1700s and the mid 1800s in the four western sites contrasts with those in the interior (Fig. 2). The non-coherency of the eastern and western sites can be explained by either a change in the fire climate or in human ignitions. An extension of the marine layer inland during this period may have prevented fires from burning and not changed the fire regimes of interior sites. However, other than a deepening of the AMO during this period, the proxy evidence does not strongly support that such a change occurred (Fig. 7). Fire regimes elsewhere in northern California are known to have changed during this same general period (Norman and Taylor 2003). The synoptic mechanisms that link sea surface temperature to summer fog-stratus and the summer fire climate of the interior are complex and have yet to be explained. In addition to climate variation, the sudden localized decline in fire after about 1780 could be explained by a reduction of human use of the area. A decline of the Tolowa population is known to have occurred about that time due to a cholera epidemic that followed the early visits of Europeans to the north coast (Gould 1978). The continuity of burning at MBH, MRC and MVT could be explained by localized burning by survivors from other villages who continued to use their traditional grounds.

The fire record at MRC in the eastern portion of the study area above Rock Creek also suggests human influence on fire regimes. The mean fire interval of all other sites either stayed the same or lengthened after 1850, but the fire interval here decreased from 26.4 to 13.0 (Table 2). Early Euro-American prospectors and settlers introduced their own culture of fire use, and frequent fire here may have been associated with mineral exploration or prospecting activities along lower Rock Creek.

Vegetation dynamics

The results of this study suggest that fires of mixed severity occurred in the dryer interior portion of the coast redwood range. The unimodal and bimodal pulse establishment of Douglas fir and knobcone pine (Fig. 6, plots 1-9) indicate that moderate to high severity fires occurred on upper slopes and across slope aspects. Coast redwood trees were rare on these sites, but stumps are common in drainages suggesting that the severity of fire events increased upslope. Also consistent with this topography-based mixed severity model, knobcone pine has serotinous cones that are associated with higher severity fire.

The vegetation dynamics of plot 4 are interesting because old coast redwood is in close association with Douglas fir and knobcone pine that appear to have regularly burned with moderate severity (Fig. 6). The three redwoods sampled for fire history from this site (MBH) were uneven aged, establishing in 1309, 1464 and 1693. A growth release on the oldest redwood around 1690 suggests that the 1693 redwood established after fire. The mean fire return interval after 1700 was 15 years (Table 2). Based on an aerial photograph from 1958, forty years after the last fire, the redwood overstory was relatively sparse, possibly because frequent fire during the 1700s had eroded a more continuous redwood forest (Fig. 9). By 1918, Douglas fir and hardwood trees and shrubs were dominating the site. High severity fire in these stands would likely have resulted in strong growth suppressions in redwood, and only minor growth suppressions associated with fire were found. Moderate severity fires would explain the bimodal age structure of Douglas fir (and presumably hardwoods) that occurred here before logging. Had the redwood, Douglas fir and hardwoods shown in this photo not been logged between 1987 and 2000, high fire severity would now be more likely than in the past, given the extended period of fire exclusion since 1918 and the fire weather that is now typical of wildfire events. An active program of prescribed fire management in these and similar fire-prone interior forests may be the only way to restore desired compositional and structural attributes.

The ecological implications of fire exclusion in more coastal redwood forests is complex because of the historical importance of variable human ignitions in the past. The time since the last fire has only recently matched the long interval that occurred during the late 1700s and early 1800s, and 20th century logging has so altered the system that the role of fire is constrained by factors other than those of old growth reserves. Fire undoubtedly contributed to the biodiversity of this area’s landscape, however, as the fire-sensitive tree species that occur in the forest are also those that require gaps to establish (Viers 1982). According to early Soil-Vegetation maps (1952), few forests of pure redwood existed in this area before logging, as redwood was associated with Douglas fir, western hemlock, grand fir and Sitka spruce across topographic gradients. While this compositional diversity also reflects disturbance from windstorms, the frequency of fire in this forest indicates that a substantial fraction of it is likely to have resulted from fire. Prescribed fire may be needed on intermediate and interior sites to retain and restore desired structural and compositional elements.

An integrated theory of fire in redwood

The frequent fire found in this humid northern portion of the coast redwood's range indicates that a latitudinal climate gradient model is not useful for predicting fire regimes before 1920. The mean and median fire intervals reported here are similar to those reported from sites much farther south (Table 1, Table 3). If a latitudinal gradient existed, it may be found by revisiting studies conducted to the south that may have under-represented fire frequency given their sampling methodologies. Had I collected samples above 30 cm height, I would have documented few fires on any site.

Similarly, a coast-interior climate gradient is not supported by the fire scar record. Areas closer to the coast than where I sampled are also unlikely to provide exceedingly long fire intervals, given the abundance of large fire-formed basal hollows there (Zielinski and Gellman 1999). Such cavernous basal hollows develop from frequent fire over centuries, not rare fires that allow scars to heal over (Finney 1996). Most areas closest to the coast are where Native American density was greatest.

Of interest, wildfires that burned during the suppression era appear to relate to both a natural coast-interior and latitudinal climate gradient (Oneal et al. 2006). This fact may reflect the ease with which modern fires can be suppressed in redwood given the slow rate of spread associated with cool, moist forests. In the past, during the period when old growth forests developed, fire frequency and extent were not related to suppression efforts, but to factors related to ignition and spread. The prevalence of early season fires in the historical record suggests that if fuel conditions allowed, fires could have burned from the early fire season in mid-summer through the first rains of October or November. Only moist coastal areas and sites farthest from Native American ignitions are likely to have been refugia from fire. Such sites appear to have been relatively uncommon in the landscape.

The historical fire regimes that occurred in this landscape correspond to a cultural fire gradient as defined by the ethnographic record. Short fire intervals occurred across the forest, but frequent fire regimes were restricted to the areas that were most likely influenced by Natives. Their early season fires were targeted toward specific resources uses, such as preparing the acorn grounds before harvest, and the higher frequency of early season fires is consistent with this pattern. Further, the mixed frequency of the coastal redwood sites is also consistent with a cultural burning model. The reduction of fire at the most ignition-sensitive coastal sites during the late 1700s and early 1800s can be explained by a change in human ignitions or by the effectiveness of human ignitions, given a change in climate. Over time, such variation in fire intervals and the characteristics of fire events, such as their season or intensity, can have a strong influence on floral assemblages (Bond and van Wilgen 1996). This spatial-temporal complexity of the natural climatic and cultural burning gradients likely contributed to the diversity of the redwood forest landscape (Martin and Sapsis 1992; Anderson 2006).

Archaeological and linguistic evidence suggests that like most Native peoples of the northern redwood forest, the Tolowa arrived relatively recently, around A.D.1300 (Frederickson 1984). Seven hundred years is well within the lifespan of a large minority of the redwood trees of the area's forest. While other tribes lived in and near the area's redwoods for millennia, migrations and natural increases in the resident population likely led to substantial variation in human ignitions over the centuries. This inconstant influence of human ignitions is analogous to variation in fire regimes caused by changes in climate (Swetnam 1992). Over time, changes in either ignition and the fire climate are likely to lead to not only diverse vegetation, but to non-equilibrium conditions. This is especially true for forests dominated by long-lived sprouting coast redwood that can retain attributes of prior environmental conditions for centuries.

Acknowledgements

This study was supported by grants from Save the Redwoods League and the Joint Fire Sciences Program. Further support was provided by the USDA Forest Service Southern Research Station. Thanks to John E. Harris, California State Parks and Recreation for providing site access, to Chester Ogan of the Forest Service's Pacific Southwest Research Station Redwood Sciences Laboratory for cutting samples in the field, and to Frank Lake, also of the Pacific Southwest Research Station, for his valuable insights into Native American culture and fire use.

References cited

Anderson, M.K., 2005. *Tending the Wild: Native American Knowledge and the Management of California's Natural Resources*. University of California Press, Berkeley.

Anderson, M.K., 2006. The use of fire by Native Americans in California. *In* N.G. Sugihara, et al. *Fire in California's Ecosystems*. University of California Press, Berkeley. pp. 417-430.

Baumhoff, M.A., 1958. Anthropological Records. Vol. 16:5 California Athabascan Groups. University of California Press, Berkeley.

Bond. W.J. and B.W. van Wilgen, 1996. *Fire and Plants*. Chapman Hall, London.

Brown, P.M. and W.T. Baxter, 2003. Fire history in coast redwood forests of the Mendocino Coast, California. *Northwest Science*. 77(2)147-158.

Brown, P.M. and T. W. Swetnam, 1994. A cross-dated fire history from coast redwood near Redwood National Park, California. *Canadian Journal of Forest Research*. 24: 21-31.

Carroll, A.L. and E.S. Jules, 2005. Climatic assessment of a 580-year *Chamaecyparis lawsoniania* (Port Orford cedar) tree-ring chronology in the Siskiyou Mountains, USA. *Madroño* 52(2):114-122.

Cooper, W.S., 1917. Redwoods, rainfall and fog. *The Plant World*. 20(6):179-189.

D'Arrigo, R., E. Cook, R. Wilson, R. Allan and M. Mann. In press. On the variability of ENSO over the past six centuries. Geophys. Res. Letters. Available online at http://www.ncdc.noaa.gov/paleo/recons.html.

D'Arrigo, R., R. Villalba, and G. Wiles, 2001. Tree-ring estimates of Pacific decadal climate variability. *Climate Dynamics*, Volume 18, Numbers 3-4, pp. 219-224.

Driver, H.E. 1939. Anthropological Records, Vol. 1:6. Cultural Element Distributions: X Northwest California. University of California Press, Berkeley.

Drucker, P., 1937. The Tolowa and their Southwest Oregon Kin. University of California Publications in American Archaeology and Ethnology. 36(4):221-300.

Filonczuk, M.K., D.R. Cayan and L.G. Riddle, 1995. Variability of marine fog along the California coast. Climate Research Division, Scripps Inst. of Oceanography, La Jolla, Calif. SIO Reference No. 95-2.

Finney, M.A. 1996. Development of fire scar cavities on old-growth coast redwood. *In*. J. LeBlanc (technical coordinator) Proceedings of the conference on coast redwood forest ecology and management, June 18-20, 1996, Humboldt State University, Arcata, Calif. pp. 96-98.

Finney, M.A. and R.E. Martin, 1989. Fire history in a Sequoia sempervirens forest at Salt Point State Park, California. *Canadian Journal of Forest Research*. 19:1451-1457.

Finney, M.A. and R.E. Martin, 1992. Short fire intervals recorded by redwoods at Annadel State Park, California. *Madroño*. 39(4) 251-262.

Frederickson, D.A., 1984. The north coast region. In M.J. Moratto, *California Archaeology*. Academic Press, Orlando. pp.471-527.

Fritz, E., 1931. The role of fire in the redwood region. *Journal of Forestry*. 29:939-950.

Fritz, E., 1940. Problems in dating rings of California coast redwood. *Tree ring Bulletin*. 6(3):19-21.

Gould, R., 1966. Indian and white versions of "The Burnt Ranch Massacre" *Journal of the Folklore Institute*. 3(1)30-42.

Gould, R.A., 1975. Ecology and adaptive response among the Tolowa Indians of Northwestern California. *Journal of California Anthropology* 2(2): 149-170.

Gould, R., 1978. Tolowa. *In* R.F. Heitzer, *Handbook of North American Indians, Vol. 8. California.*

Gray, S.T., L.J. Graumlich, Betancourt, J.L. and G.T. Pederson, 2004. A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D. *Geophysical Research Letters* 31: L12205.

Heizer, R.F. and J.E. Mills, 1952. The four ages of Tsurai: a documentary history of the Indian villages on Trinidad Bay. University of California Press, Berkeley.

Jacobs, D. F., D.W. Cole, and J.R.McBride, 1985. Fire history and the perpetuation of natural coast redwood ecosystems. *Journal of Forestry*. 83:494-497.

Justham, S.A., 1974. The spatial distribution of fog/stratus in northern California; A descriptive and statistical analysis: Summer 1970. Ph.D. Dissertation. University of Illinois, Urbana-Champaign.

Keeley, J.E., 2002. Native American impacts on fire regimes of the California coastal ranges. *Journal of Biogeography*. 29:303-320.

Kitzberger, T., P.M. Brown, E.K. Heyerdahl, T.W.Swetnam, and T.T. Veblen, 2007. Contingent Pacific-Atlantic ocean influence on multicentury wildfire synchrony over western North America. *Proceedings, National Academy of Science*. 104(2) 543-548.

Lewis, H.T. 1973. Patterns of Indian burning in California: Ecology and Ethnohistory. Ballena Press Anthropological Papers 1.

Lewis, O. 1943. *The Quest for Qual-a-wa-loo: A collection of diaries and historical notes pertaining to the early discoveries of the area now known as Humboldt County, California*. San Francisco, Calif.: privately published.

MacDonald, G.M. and R.A. Case, 2005. Variations in the Pacific Decadal Oscillation over the past millennium. Geophysical Research Letters, 32: L08703, doi:10.1029/2005GL022478.

Martin, R.E. and D.B. Sapsis, 1992. Fires as agents of biodiversity: pyrodiversity promotes biodiversity. In Symposium on biodiversity in northwestern California. R.R.Harris et al. (techn. coord.) *Wildland Resources Center Report 29.* University of California, Berkeley.

Norman, S.P. and A. H. Taylor, 2003. Tropical and north Pacific teleconnections influence fire regimes in pine-dominated forests of north-eastern California, USA. *Journal of Biogeography*. 30:1081-1092.

Norman, S.P. Fiori, R. and S. Underwood. 2003. Report to Save the Redwoods League on preliminary fire history research conducted within the area burned by the 2003 Canoe Fire.

Olson Jr., D.F., D.F. Roy, G.A.Walters. 1990. Sequoia sempervirens (D.Don) Endl. *In* R.M Burns and B.H.Honkala (techn. cords.) *Silvics of North America Vol. 1. Conifers.* pp. 541-551.

Oneal, C.B., J.D. Stuart, S.J. Steinberg, L.Fox III. 2006. Geographic analysis of natural fire rotation in the California redwood forest during the suppression era. *Fire Ecology* 2(1):73-99.

Sawyer, J.O., S.C. Sillett, W.J.Libby, T.E. Dawson, J.H.Popenoe, D.L.Largent, R.VanPelt, S.D.Viers Jr., R.F. Noss, D.A. Thornburgh, P.Del Tredici. Redwood trees, communities, and ecosystems: A closer look. In R.F.Noss (ed.) *The Redwood Forest: History, ecology and conservation of the coast redwoods*. Island Press, Washington, D.C. pp. 81-118.

Soil-Vegetation Map. 1952. USDA Forest Service Pacific Southwest Forest and Range Experiment Station. Quadrangles 9A-3,4 and 9D-2 and 9D-1.

Stephens, S. L. and D. L. Fry. 2005. Fire history in coast redwood stands in the northeastern Santa Cruz Mountains, California. *Fire Ecology* 1(1): 2-19.

Stillwater Sciences, 2002. Mill Creek Property Interim Management Recommendations. Prepared for Save-the-Redwoods League, San Francisco, California.

Stuart, J.D. 1987. Fire history of an old-growth forest of *Sequoia sempervirens* (Taxodiaceae) forest in Humboldt Redwoods State Park, California. *Madroño*. 34(2):128-141.

Stuart, J.D. and S.L. Stephens. 2006. North Coast Bioregion. In .N.G. Sugihara et al. *Fire in California's Ecosystems*. University of California Press, Berkeley. pp. 147-169.

Swetnam, T. W. 1993. Fire history and climate change in giant sequoia groves. *Science*. 262:885-889.

Thornton, R. 1984. Social organization and the demographic survival of the Tolowa. *Ethnohistory*. 31(3):187-196.

Underwood, S., L. Arguello & N. Siefkin. 2003. Restoring ethnographic landscapes and natural elements in Redwood National Park. *Ecological Restoration* 21:278-283.

Vale, T.R, 2002. The pre-European landscape of the United States: Pristine or humanized? In T.R. Vale (ed.) *Fire, Native Peoples, and the Natural Landscape*. Island Press, Washington. pp. 1-39.

Viers Jr. S.D., 1980a. The role of fire in northern coast redwood forest dynamics. In. Proc. Second Conf. Scientific Research in National Parks (Nov. 26-30, 1979) San Francisco, Ca_ vol. 10: Fire Ecology, National Park Service, Washington D.C. pp. 190-209.

Viers Jr., S.D., 1980b. The influence of fire in coast redwood forests. Proceedings of the fire history workshop, Oct 20-24, 1980. Tucson, Az. USDA Forest Service GTR-RM81.

Viers Jr. S.D., 1982. Coast redwood forest: Stand dynamics, successional status and the role of fire. In Means, J. E. (ed.) Forest Succession and stand development research in the northwest. Forest Research Laboratory: Oregon State University, Corvallis, OR. Pp.119-141.

Viers Jr. S.D., 1996. Ecology of the coast redwood. *In*. J. LeBlanc (technical coordinator) Proceedings of the conference on coast redwood forest ecology and management, June 18-20, 1996, Humboldt State University, Arcata, Calif. pp. 9-12.

Waterman, T.T. 1920. Yurok Geography. University of California Publications in American Archaeology and Ethnology 16(5):177-315.

Weber 1926. Redwood Cutover Lands. Map on file, USDA Forest Service Pacific Southwest Research Station, Redwood Sciences Laboratory.

Westerling, A.L., H.G.Hildalgo, D.R. Cayan, and T.W. Swetnam, 2006. Warming and earlier spring increases western forest wildfire activity. *Science*. 313(5789):940-943.

Zielinski, W.J. and S.T. Gellman, 1999. Bat use of remnant old-growth redwood stands. *Conservation Biology*. 13(1): 160-167.

Figure 1: Map of the Mill Creek study area within Del Norte Coast Redwoods State Park showing the locations of fire scar collection sites (red triangles) and age plots (green circles). The background is a topography-based moisture index (TIMI) ranging from blue (wet), to green (mesic), to yellow (dry) and red (very dry). See text for explanation.

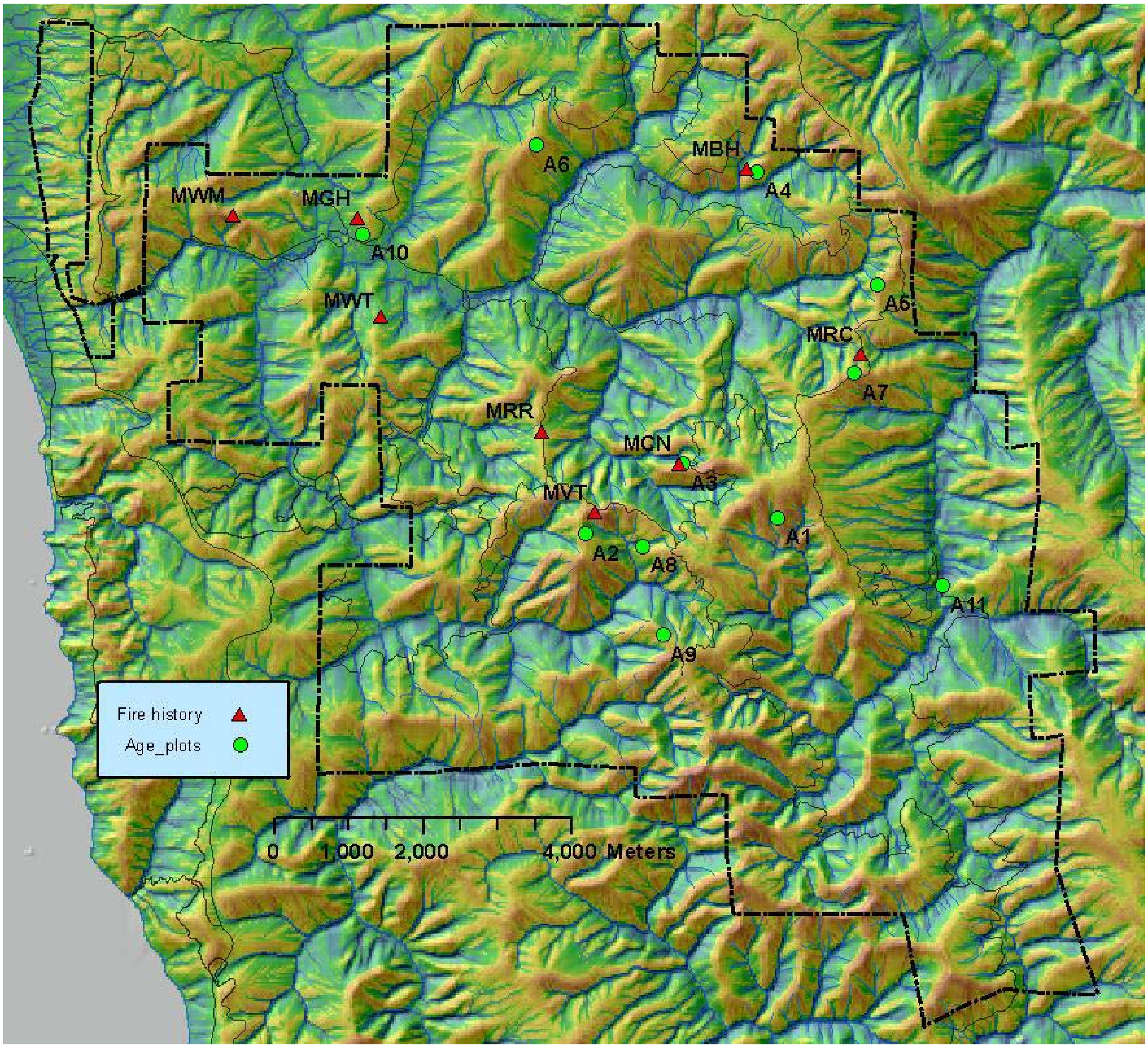


Figure 2: Composite fire scar chronologies for eight sites in the Mill Creek study area. Squares represent individual fire events and open diamonds show tree establishment dates and the beginning of the fire record. The horizontal grey lines represents the composite period of record for each site during which fires were capable of leaving a record had they burned.

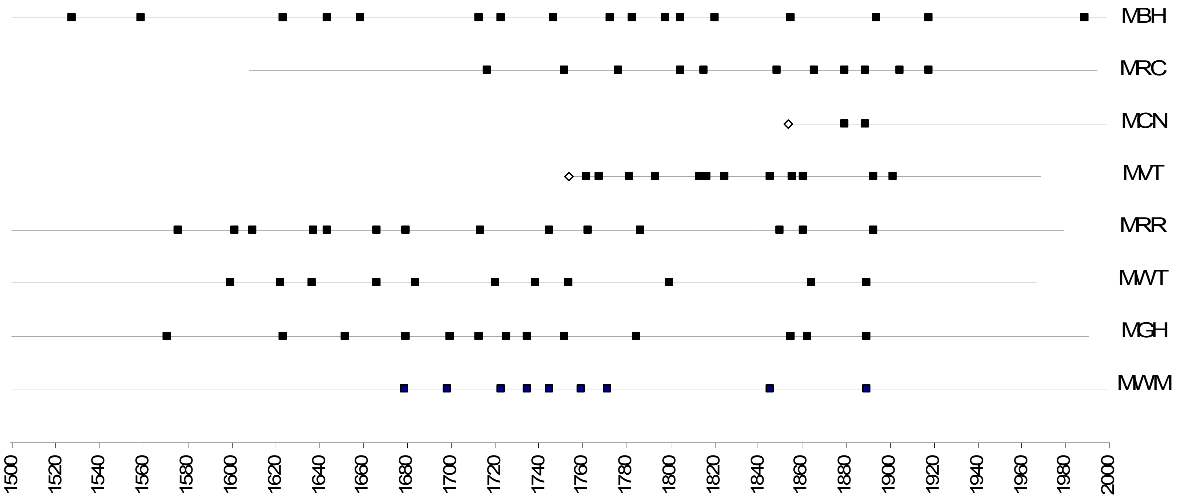


Figure 3: Distribution of fire intervals among all eight sites before 1920. Earliest period varies by site. Long and moderate intervals may reflect extensive fire-free periods or periods with fire that failed to scar trees.

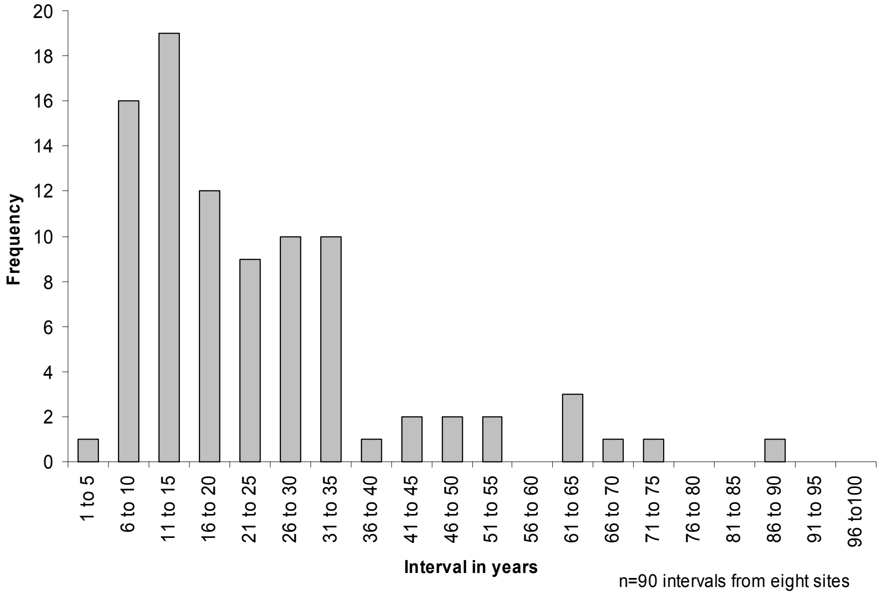


Figure 4: Mean fire return intervals for seven sites during the 1700-1849 period (from Table 2) displayed along two moisture gradients: a topography-based moisture index (TIMI: 0 dry to 100 wet) and the site's location relative to the coast. The wettest sites are in the upper left of each graph; the driest are in the lower right.

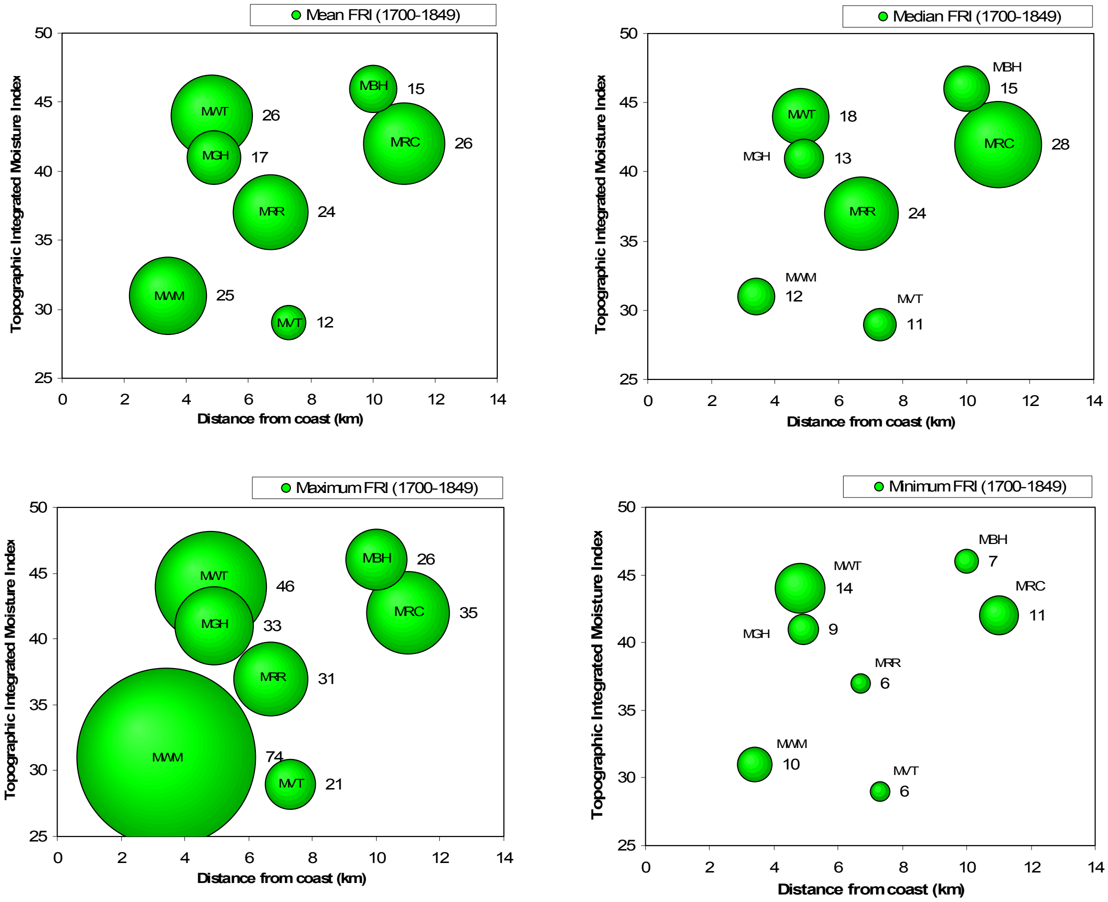


Figure 5: Mean fire interval prior to fires occurring during different portions of the growing season. *Early* is lighter colored earlywood, *Late* is darker latewood forming near the end of the growing season and *Dormant* scars formed after growth ended for that year. Prior to 1850, fires occurring early in the fire season are more frequent than those after 1850. This relationship was reversed after the arrival of Euro-American settlers. See Table 3 for details.

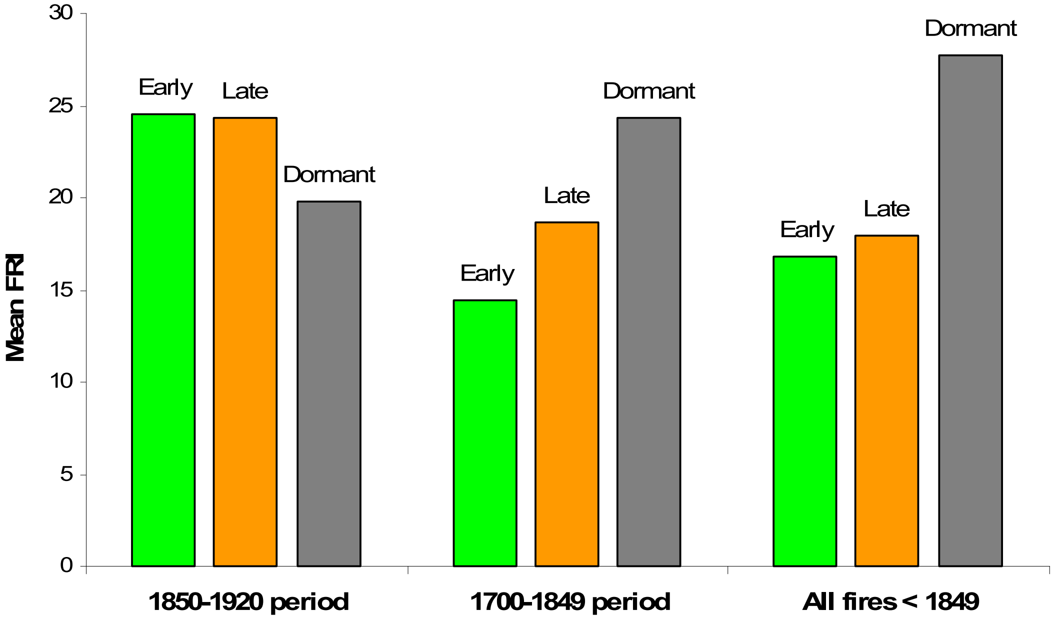
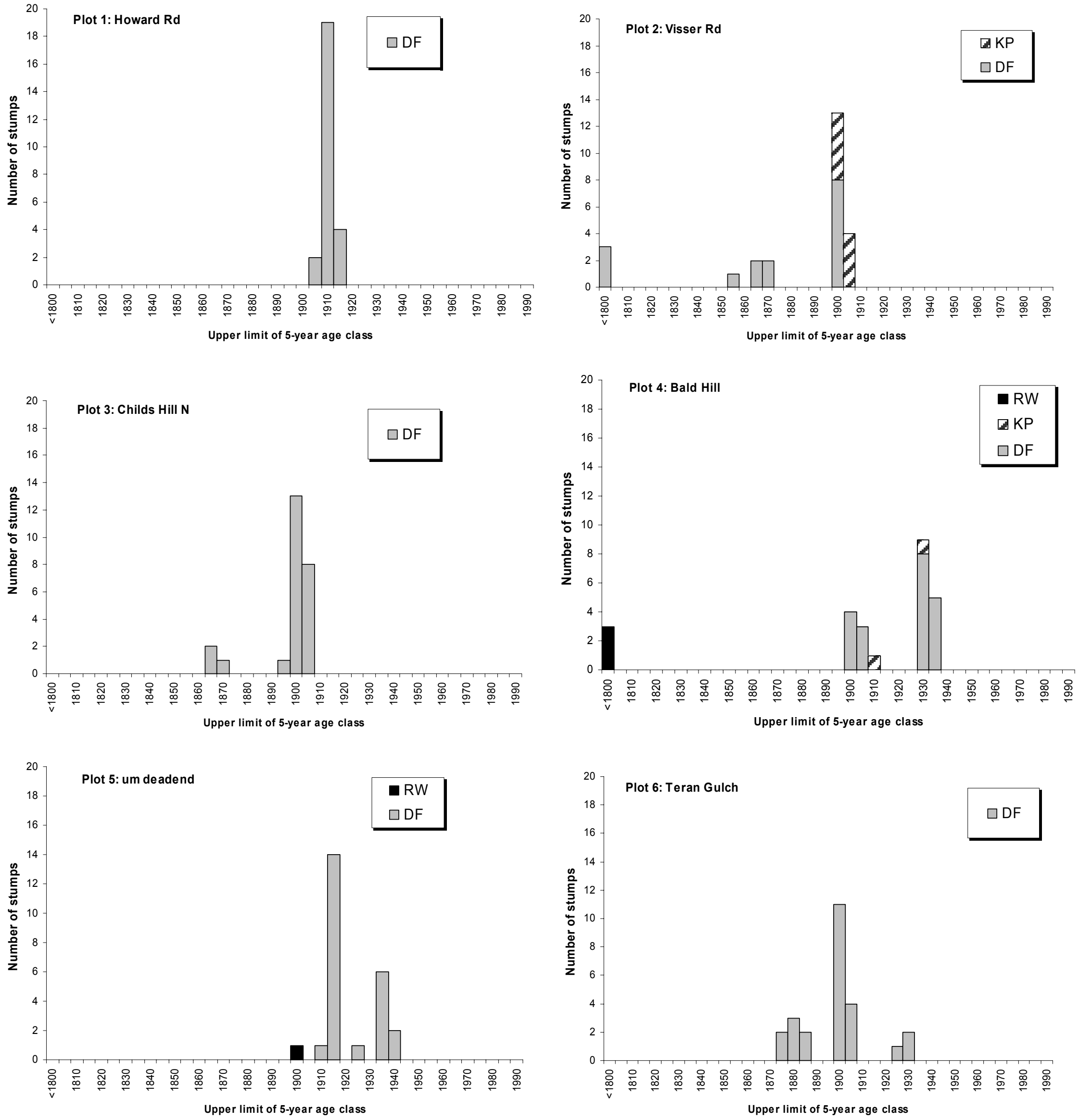
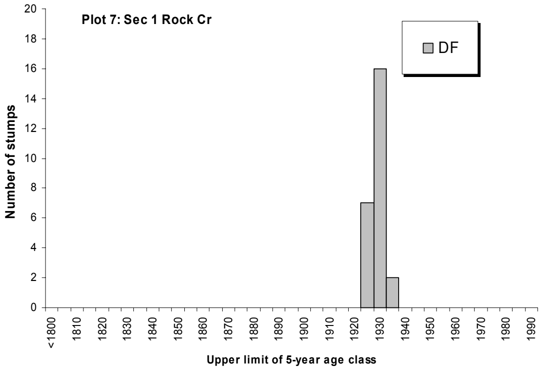
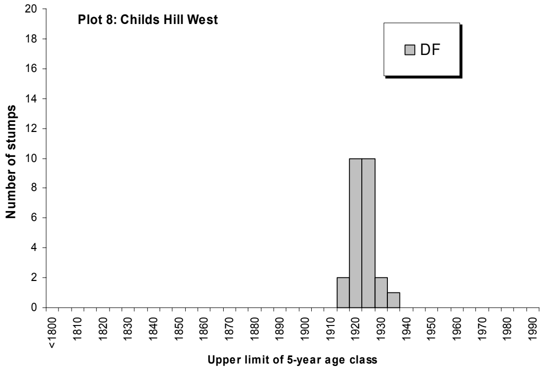


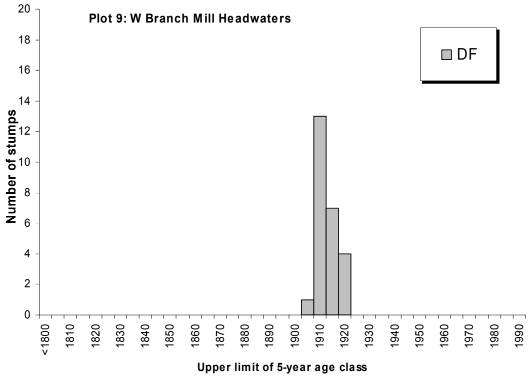
Figure 6: Age structure of recently harvested units in the Mill Creek study area of Del Norte Coast Redwoods State Park. Age plot locations are shown on Figure 1.



(Figure 6 continued)







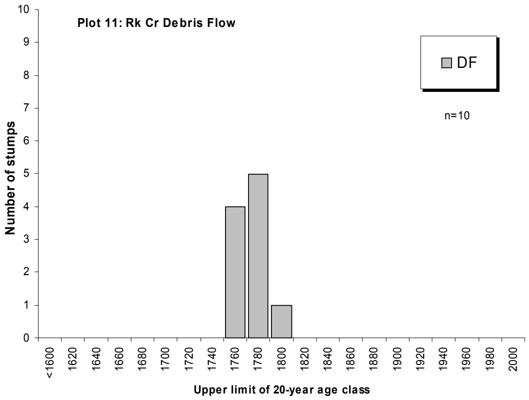


Figure 7: Age-diameter relationship of Douglas fir (Pseudotsuga menziesii) from 11 plots.

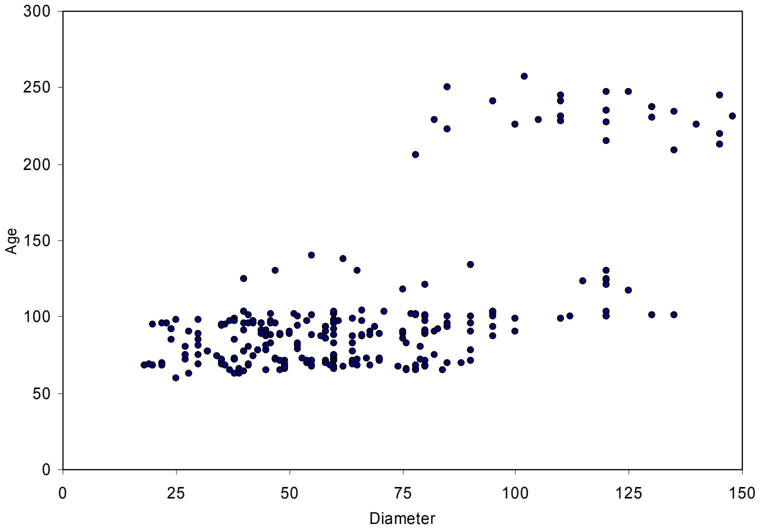
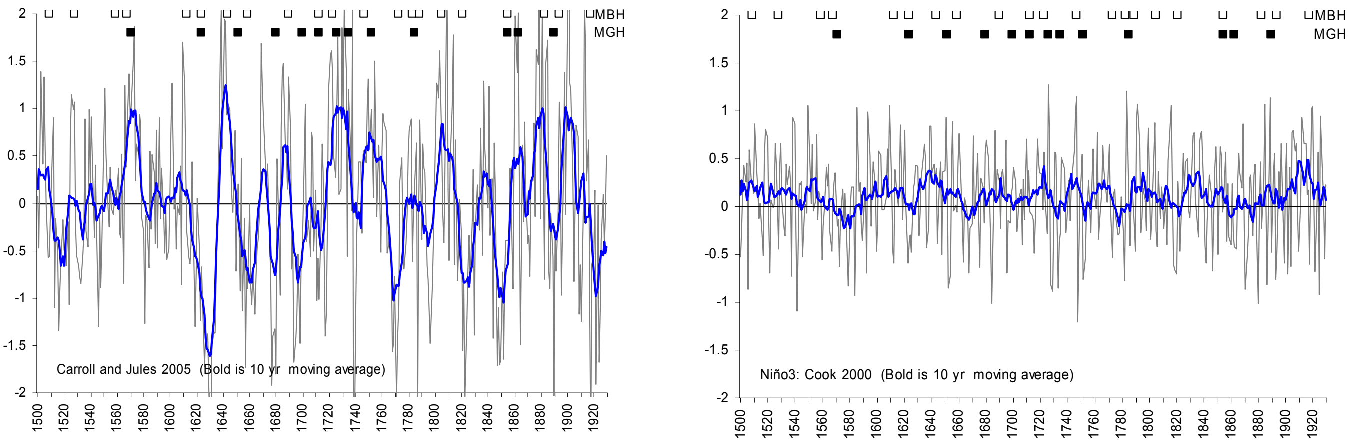
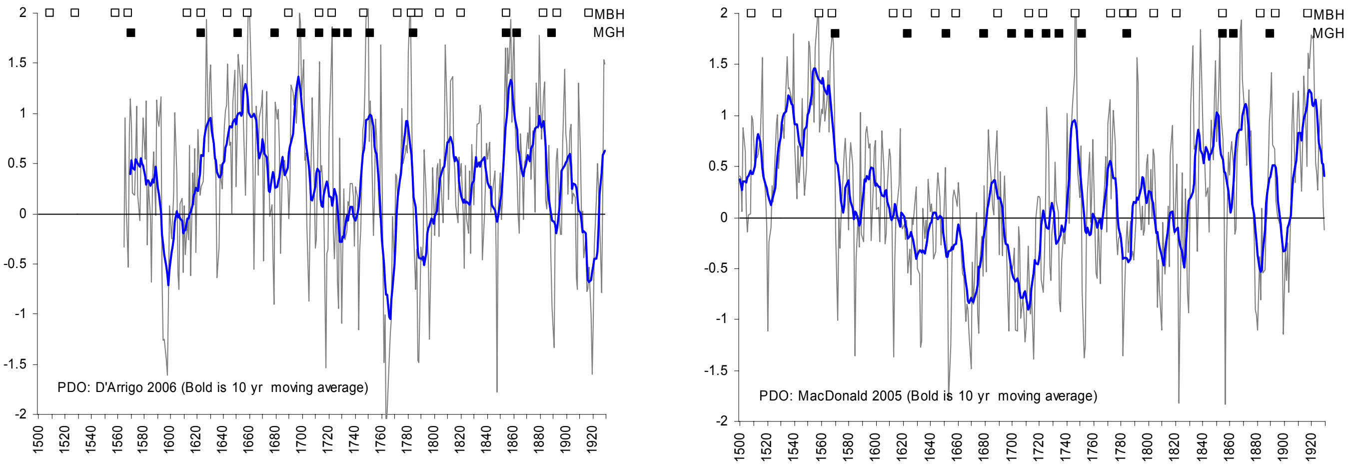


Figure 7: Climate reconstructions and fire history for an interior site (MBH) and a more coastal site (MGH). The y-axis represents the z-score for A and reported values for the others.



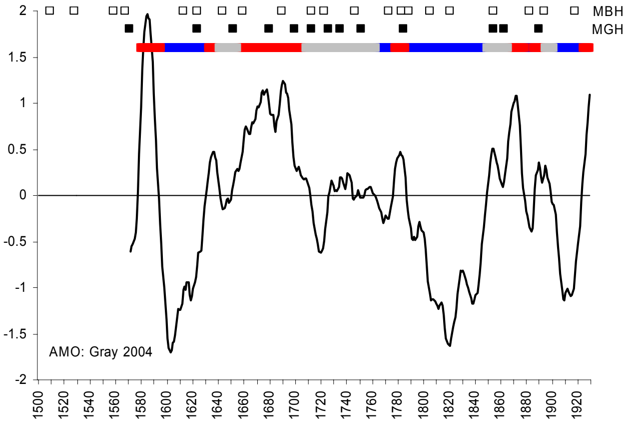
A. Local climate (Carroll and Jules)

B. Niño3 Index (D'Arrigo et al.)



C. Pacific Decadal Oscillation (D'Arrigo et al.)

D. Pacific Decadal Oscillation (MacDonald & Case)



E. Atlantic Multi-decadal Oscillation (Gray et al.)
Red bar is + AMO phase, blue is –, gray is not significant

Figure 8: Days reporting heavy fog (visibility <0.4 km (0.25 mi)) during the July through October fire season, Eureka, California, 1887-2002.

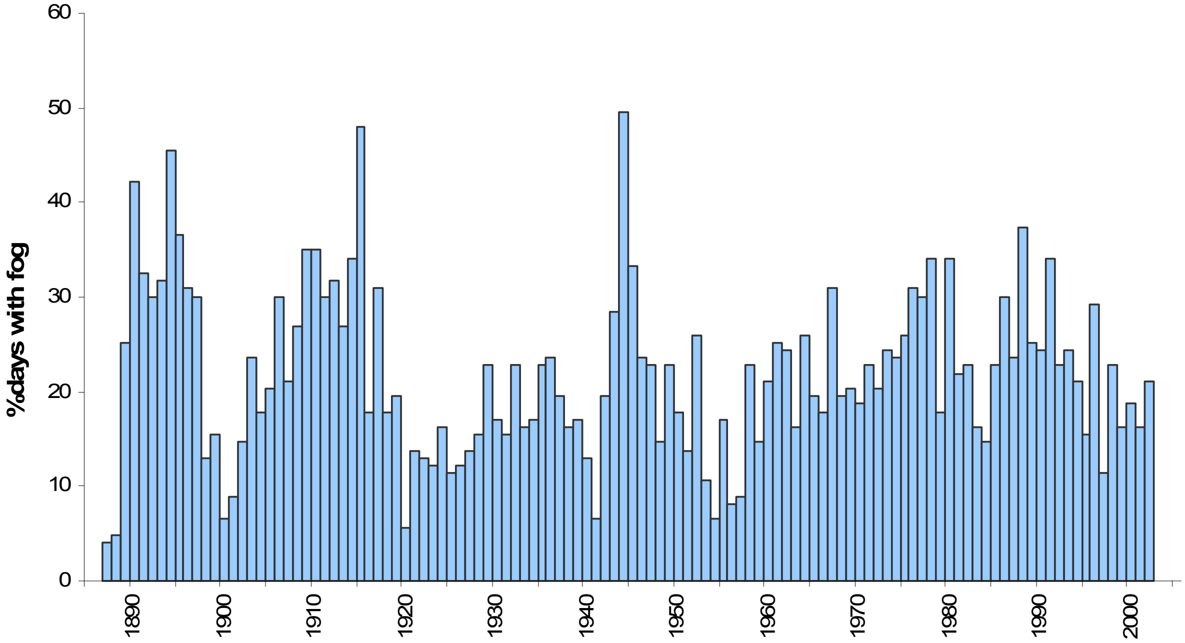


Figure 9: A 1958 aerial photograph showing the pre-logging emergent redwood forest structure in and around plot 4 (MBH) in the northeastern portion of the study area. During the century and a half before 1850, fires burned through this redwood forest with 7-26 year intervals.

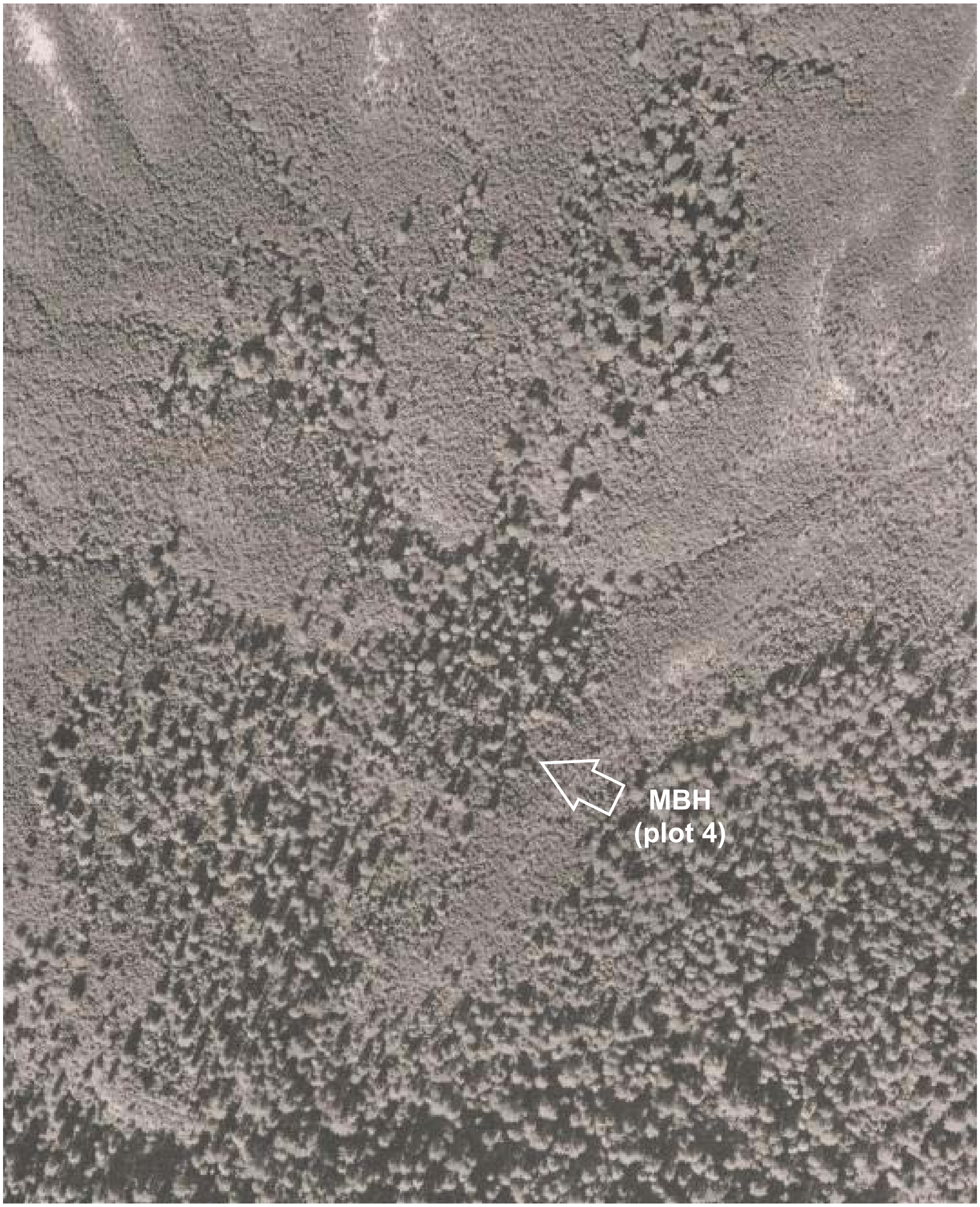


Table 1: Mean point fire return intervals (from scars on individual trees) reported from coast redwood forests.

Authority	**Location**	**Fire severity (stated or implied)**	**Mean point fire return interval (years)**
Viers (1982)	Del Norte and northern Humboldt Counties	Low (humid sites) Mixed (xeric sites)	125-500 (humid) 50 (xeric)
Brown and Swetnam (1994)	East of Prairie Creek State Park, Humboldt Co.	Low	21
Norman et al. (2004)	Canoe Creek watershed, Humboldt Redwoods State Park	Low	9-25
Brown and Baxter (2003)	Mendocino coast	Low	9-20
Finney and Martin (1989)	Salt Point State Park	Low	20-29
Finney and Martin (1992)	Annadel State Park	Low	6-23
Jacobs et al. (1985)	Muir Woods National Monument	Low	22-27
Stephens and Fry (2005)	Santa Cruz Mountains	Low	6-45

TABLE 2: Environmental and ecological attributes of fire history sites in the Mill Creek study area. TIMI is a topographic moisture index (see text for explanation). Logging date is from logging company records and was confirmed on several sites with tree ring analysis. Soil-vegetation classification provides structural dominance (relative species order) and compositional information (tree species are RW=Redwood; DF=Douglas fir; TO=Tanoak; PM=Pacific Madrone; WH=Western Hemlock; and GC=Giant Chinquapin). UTM coordinates for these sites are provided in Appendix 1.

Site	Distance to coast (km)	Elevation (m)	Slope aspect (octant)	TIMI value	Logging date	Late-1950s soil-vegetation classification
MWM	3.4	260	South	31	1957	TO-RW-DF*
MGH	4.9	115	Southwest	41	1991	DF-RW
MWT	4.8	195	Northeast	44	1967	RW-WH-DF
MRR	6.7	410	Northeast	37	1980	RW-TO
MVT	7.3	545	South	29	1967	TO-RW
MCN	8.4	500	North	36	1999	TO-PM-DF
MRC	11.0	495	North	42	1995	TO-PM-RW-DF
MBH	10.0	400	West	46	2000	TO-PM-GC-RW-DF

* This site was logged shortly before the field survey occurred. The probable old-growth composition and structure is inferred from the tree species indicated in the post logging survey and recent (2006) observations of stumps and tanoak sprouts at the site.

TABLE 3: Composite fire intervals from eight sites in the Mill Creek study area. Fire scar dates either reflect true calendar dates or they are within a few years because only a portion of samples could be crossdated due to limited interannual variation and partially-absent rings. # Trees used refers to the trees used to generate the composite record.

	MWM	**MGH**	**MWT**	**MRR**	**MVT**	**MCN**	**MRC**	**MBH**	**GRAND**
# TREES USED:	3	2	4	2	3	2	2	3	**21**
AREA (ha):	1.0	0.25	0.25	0.5	0.25	0.25	1.0	1.0	**---**
PERIOD 1850-1920									
Frequency (yrs/fire)	71	23.7	35.5	23.7	17.8	22.0**	14.2	17.8	**28.2**
Mean	---	17.5	25.0	21.5	15.3	17.5	13.0	21.0	**18.7**
Median	---	17.5	25.0	21.5	9.0	17.5	13.5	24.0	**17.5**
Standard Dev.	---	13.4	---	14.8	14.6	12.0	2.9	8.9	**---**
Max. Interval	---	27	25	32	32	26	16	28	**32**
Min. Interval	---	8	25	11	5	9	9	11	**5**
# Intervals	0	2	1	2	3	2	4	3	**17**
PERIOD 1700-1849									
Frequency (yrs/fire)	25.0	25.0	37.5	37.5	10.4*	---	25.0	18.8	**25.6**
Mean	24.6	17.0	26.3	24.3	11.5	---	26.4	15.4	**20.8**
Median	12	13	18	24	11	---	28.0	15.0	**15.0**
Standard Dev.	27.67	9.38	17.10	6.51	4.72	---	9.5	7.3	**---**
Max. Interval	74	33	46	31	21	---	35	26	**74**
Min. Interval	10	9	14	6	6	---	11	7	**6**
# Intervals	5	5	3	3	8	---	5	7	**36**
TOTAL PERIOD THROUGH 1920									
Frequency (yrs/fire)	26.8	30.6	29.0	24.6	12.8	22.0	18.5	23.1	**23.4**
Mean	26.4	30.6	28.9	24.4	12.3	17.5	20.1	24.4	**23.1**
Median	17.5	27.0	24.0	24.0	10.0	17.5	16.5	22.0	**19.8**
Standard Dev.	22.2	21.9	15.8	14.9	7.5	12.0	9.4	16.0	**---**
Max. Interval	74	86	65	63	32	26	35	65	**86**
Min. Interval	10	8	14	6	5	9	9	7	**5**
# Intervals	8	17	12	13	12	2	10	16	**90**
Years of record	241	550	377	344	166	66	203	392	**---**

* Calculated based the period of record since establishment in 1755.

** Calculated based on the period of record since establishment after a ca.1854 fire.

Table 4: Seasonal position of fire scars within annual growth rings. .

	Percent of known	Mean FRI	Count
1700-1849 PERIOD			
Dormant season	32.4	24.3	12
Latewood season	37.8	18.6	14
Earlywood season	29.7	14.5	11
All known seasons	100.0	19.2	37
ALL FIRES BEFORE 1850			
Dormant season	38.6	27.7	22
Latewood season	29.8	17.9	17
Earlywood season	31.6	16.8	18
All known seasons	100.0	21.4	57
1850-1920 PERIOD			
Dormant season	42.9	19.8	9
Latewood season	28.6	24.3	6
Earlywood season	28.6	24.5	6
All known seasons	100.0	22.4	21

APPENDIX 1: Location of fire scar collection sites and age plots in the Mill Creek study area.

Fire Site	Site Name Explanation	Logging Date	UTM Coordinates (Zone 10; NAD 1927)
MWM	West Mill	1957	0407471-4620749
MGH	Greenhouse	1991	0409215-4620684
MWT	Wind throw	1967	0409487-4619378
MRR	Road to Rock Creek	1980	0411619-4617861
MVT	Visser Tanoak	1967	0412317-4616811
MCN	Childs Hill North	1999	0413476-4617388
MRC	Rock Creek (Sec. 1 Rd)	1995	0415965-4618957
MBH	Bald Hill	2000	0414439-4621384

Age Plots	Site Description	Logging Date	UTM Coordinates (Zone 10; NAD 1927)
A 1	Howard Road	1999	0414802-4616698
A 2	Visser Road	1994	0412209-4616489
A 3	Childs Hill North	1999	0413476-4617388
A 4	Bald Hill	2000	0414439-4621384
A 5	UM dead end	1999	416143-4619856
A 6	Teran Gulch	1999	411554-4621719
A 7	Sec 1 Rock Creek	1995	415830-4618664
A 8	Childs Hill West	1997	412984-4616280
A 9	W Branch Mill Headwaters	1997	413252-4615133
A 10	Mill Site / Greenhouse	1991	0409215-4620684
A 11	Rock Creek Debris Flow	1996	0417037-4615774