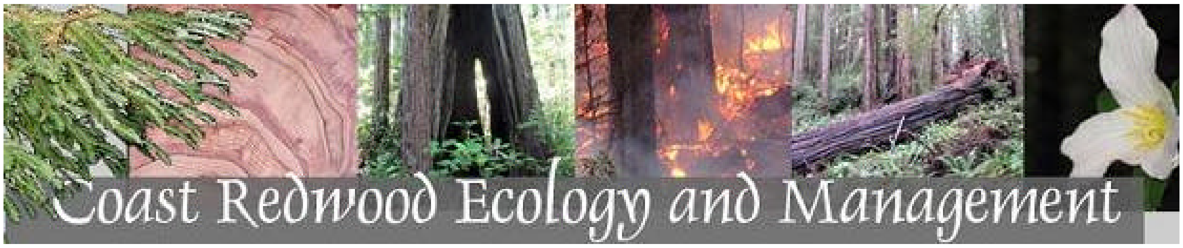

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I. Abstract

Coast redwood forests rank among the most significant natural features of North America, yet our understanding of how they came to be and how we might sustain them has been beset by scientific and management uncertainty for decades. A key part of this controversy has been the historical importance of fire given the mild coastal climate and small number of lightning ignitions. In the northern part of the coast redwood range, past research found that fire was uncommon, but results conflicted with others that found fire to be as frequent as in any dry forest of western North America. We established tree-ring based fire histories from across the northern coast redwood range to redress this conflict. We found that methodological shortcomings were responsible for the long fire intervals obtained in other studies, and that fire had burned with high frequency in the majority of sites examined during recent centuries. This discovery is supported by converging evidence from the pattern of basal fire cavities across the landscape. We use ethnographic and archaeological data to explain why this pattern of historical fire from scars and cavities deviates from what is expected from latitudinal and coast-to-interior climate gradients. We describe the extraordinary productivity of fuels in this forest type using an extensive array of fuels transects. While results show that these forests are not limited by fuels, fire in coast redwood is conditionally limited by ignitions and fire weather. Insights from this research help inform where prescribed fire can be used to balance the competing objectives of sustaining forest diversity that often results from fire and minimizing the loss of ancient coast redwood trees that often die because of fire.

II. Background and purpose

Fire science has made great progress during recent decades by documenting the historical and functional importance of fire in a wide range of forest types. Fire regimes are now known to change in response to temporal variation in climate, fuel-generating events, fuel accumulation time, and how and where ignitions occur (Keeley 2002; Swetnam 1993; Westerling et al. 2006). The three factors that drive fire regimes—climate, fuels and ignition—are important issues in coast redwood (*Sequoia sempervirens* D. Don) forests, but in ways that differ from others forests. The biomass and fuel production here is exceedingly high. The climate is often cool and moist during the fire season due to maritime influence including fog-stratus cover; and this causes fire hazards to vary over short distances. Most historical ignitions are thought to have been set by people, but the largest fires of recent years were caused by lightning. Together, coast redwood's fuels, climates and ignitions present a distinct combination of factors that make fire regimes here interesting to scientists, but frustrating for managers seeking applied information that is relevant to local area needs.

Environmental and ignition gradients

The traditional way that scientists and managers view fire history and fire hazards in coast redwood reflects the climate gradients that generally mirror changes in coast redwood forest vegetation. The best developed coast redwood forests are in the north, in Mendocino, Humboldt and Del Norte Counties, where most old growth parks and reserves are now located. The southernmost coast redwood forests of the Santa Lucia Mountains are largely riparian due to the interaction of the warmer climate and fire regimes there. In many respects, the interior coast redwood forests of the north resemble those of the south, being increasingly confined to riparian areas and northern slope aspects. Topographic gradients provide important local variability in vegetation and fire (Fig. 1). These physical gradients provide a foundational model that is thought to link climate with vegetation and disturbance regimes. What this model neglects is the spatial complexity of historical ignitions.

Figure 1: Recent lightning-ignited wildfires in the coast redwood region have varied in effects from low intensity patchy burns as seen on the alluvial flats of Montgomery Woods State Reserve from a July 2008 event (left) to high intensity fire in even-aged Douglas fir on the upper slopes of Humboldt Redwoods State Park in September, 2003 (right).

Ignitions have been attributed to both lightning and humans near the coast and in the interior, and each source is likely to have contributed to historical fire regimes. Historically, human ignition densities may have been highest in mesic coastal and riparian areas where population densities were greatest (Vale 2002), yet Native Americans also managed fire along trails and in remote locations for wide-ranging resource benefits (Anderson 2005; Waterman 1920). The density of lightning strikes generally increases inland (van Wagtendonk and Cayan 2008; Stuart and Stephens 2006), but near-coast canopy fires from lightning are not uncommon and may have varied in importance over time. Yet for ignitions to be effective, fire must be able to spread, and ignition efficacy is sensitive to fuels and local fire weather. Fuel production and fire weather generally trend in opposite directions along environmental gradients. While coastal and riparian areas may have been least flammable, Native Americans had the capacity to exploit the narrowest fire weather opportunities as these varied in availability with climate over centuries. These issues make coast redwood fire regimes as complex as those of any other forest type on earth.

Fire use and tradeoffs

Difficulties with understanding past fire regimes have not prevented managers from adopting a cultural burning model for the upper slopes of the coast redwood zone (Underwood et al. 2003). Aggressive fire use followed realization that in the absence of fire, conifers were encroaching on grasslands that were valued for a number of reasons. Extending human fire regimes to coast redwood forests involves higher stakes and more complex risks—including affecting mortality rates of the tallest living trees on Earth; individual trees that have often lived for over 1,000 years. In addition, fire would alter habitat for federally and state listed species including the Northern Spotted Owl and Marbled Murrelet and perhaps soon the California Condor. Air quality conflicts can easily be breeched by large, long-duration fire and fire in many areas involves risks of fire escape and fire safety issues associated with hazard tree management. In coast redwood forests, how to avoid the risks associated with fire use have been clearer than have the long-term threats associated with wildfire or successional change.

Defining "long-term" effects and tradeoffs is difficult for coast redwood forests because trees can live for over a millennium. To understand fire regimes for this species, how fire varied and how fire influenced stand development over the life of the forest, we need to think at a time scale that planners, managers and scientists find difficult. In addition our understanding of fire is limited to where our experiences or research took place, and strong spatial gradients suggest that local insights may be incomplete. It is not surprising then that our knowledge of past fire regimes has been confounded by conflicting research results (Lorimer et al. 2009). Veirs (1980, 1982, 1996) found that significant fires were rare on humid sites, as uncommon as every few centuries to a few times per millennia. Others found fire to be moderately frequent (Fritz 1931, Stuart 1987). Yet others found that fire was as frequent as in most any dry forest of the West (Brown and Swetnam 1994; Brown and Baxter 2001; Finney and Martin 1989, 1992; Stephens and Fry 2005). Managers have been left wondering if (1) these differences reflect strong environmental and ignition gradients and coast redwood's broad tolerance for a range of fire regimes, or (2) if these differences reflect methodological shortcomings. This current research was designed to resolve a core part of this fundamental controversy about historical fire regimes in coast redwood.

Fire management decisions are informed by past fire regimes, but they are often constrained by present-day conflicts that relate to fire behavior and fire effects. These conflicts are directly or indirectly tied to fuels. Coast redwood fuel production is thought to be comparable to its extraordinary biomass (Fujimori 1977, Porter and Sawyer 2007), yet our understanding of fuels is limited due to the complexity of environmental gradients. The research reported here was designed to address how much fuel exists along these gradients.

Our efforts to characterize old growth coast redwood forests through the parallel fields of fire history and fuel hazards will lead toward a more cohesive perspective on fire management that can inform decisions regarding wildfire and prescribed fire use.

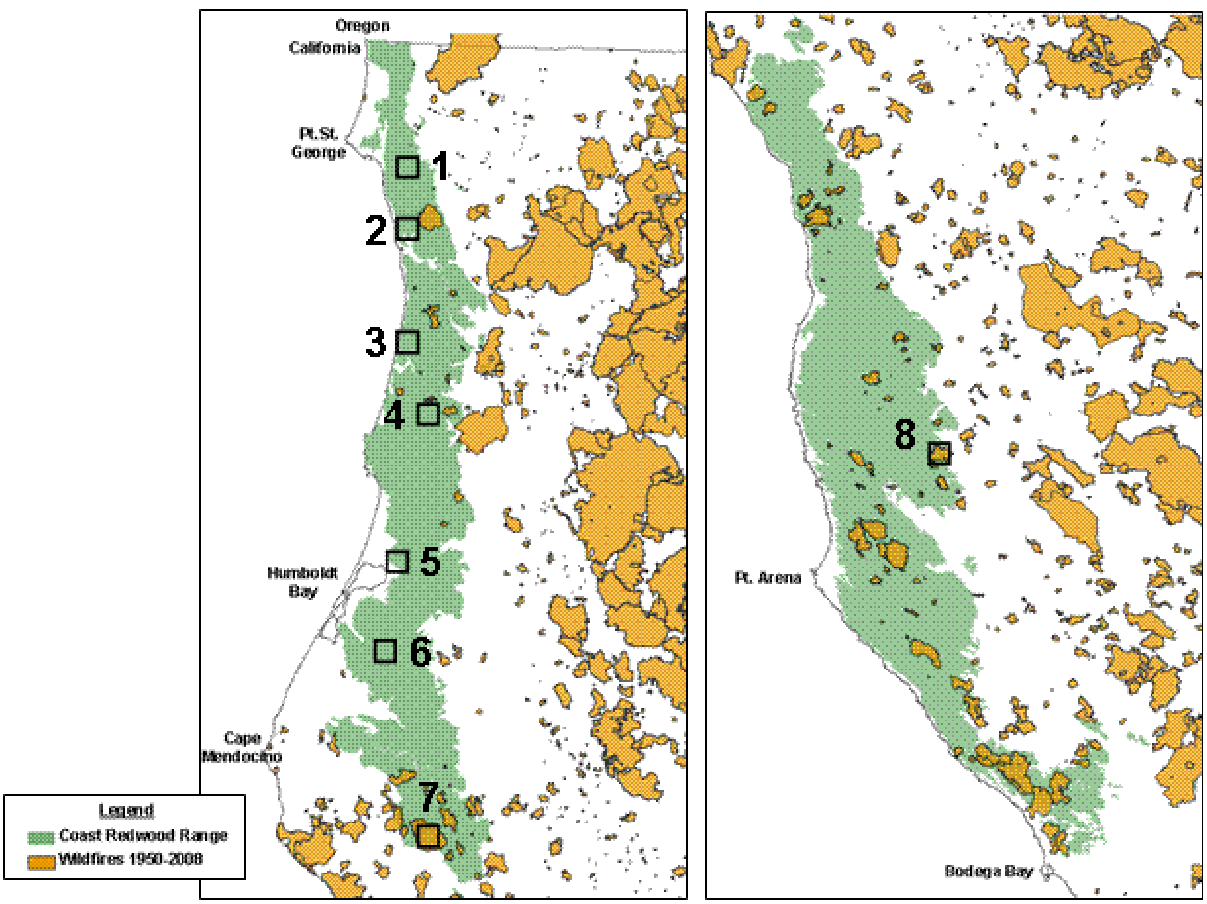
III. Study description and locations

Study area

Coast redwood forests extend from just north of the California-Oregon border to the Santa Lucia Mountains of Monterey County in the south (Olson et al. 1990). Forests with the greatest biomass and continuous coast redwood cover dominate in the northern third of the range. In contrast to its 725 km-long latitudinal extent, coast redwood is confined to a belt between 8 and 56 km wide, not far from the coast. Maritime influence moderates temperature extremes compared to the interior during winter and summer. The summer fire season is characterized by cooler temperatures than are found inland, often because of the high frequency of mid-day fog-stratus cover. The severity of fire weather generally increases inland and toward the south.

Unlike the Klamath Mountains to the east, fires have been relatively few in recent decades (Figure 2). This difference is caused by the more moderate climate of the coast and fewer lightning ignitions (Stuart and Stephens 2006, Oneal et al. 2006). Two notable fire seasons in coast redwood have occurred during the last decade. In 2003, the 4,500 ha Canoe fire burned an extensive portion of Humboldt Redwoods State Park and in 2008, thousands of ha burned in Montgomery Woods State Reserve and surrounding private lands. Both fires were started by lightning. In the last few years, lightning fires have been extinguished in Prairie Creek Redwoods State Park and in Headwaters Forest Reserve. Lightning fire may become increasingly important in the future with a warming climate.

Figure 2: Research sites (squares) relative to the northern coast redwood range (green) relative to recent wildfires in California (1950-2008) orange. From north to south, sites are (1) Jedediah Smith and Del Norte Coast Redwoods State Park, (2) USFS Redwood Experimental Forest, (3) Prairie Creek Redwoods State Park, (4) Redwood National Park (Bald Hillls), (5) Arcata Community Forest, (6) Headwaters Forest Reserve, (7) Humboldt Redwoods State Park, (8) Montgomery Woods State Reserve.



Past fires in coast redwood are thought to have been largely set by humans, particularly the Native Americans that inhabited this area for centuries and the settlers and who arrived after 1850. Both cultural groups used fire judiciously until Native populations were decimated after 1850 and policies of fire exclusion were widely adopted and enforced after the 1930s. Since then, fire has been used as a means of reducing slash associated with logging. In Redwood National Park, fire has been reintroduced to manage grasslands (Underwood et al. 2003).

Research conducted and methodologies

Three types of research were conducted as part of this project: (1) characterization of fuels using line transects; (2) fire history using fire scars in coast redwood wood samples; and (3) an assessment of fire cavities. Research sites are in Figure 2.

Fuels research

Fuels data were collected from six sites including Jedediah Smith Redwoods State Park, the Redwood Experimental Forest (Yurok RNA), Prairie Creek Redwoods State Park and two alluvial and one upland site in Humboldt Redwoods State Park.

All woody and forest floor fuels were inventoried using line intersect sampling (LIS) protocols (Van Wagner 1968, Brown 1974). Logs were inventoried according to decay classes based on their bark, branch, color and vertical position. Vegetation was sampled using releves that provided percent cover of all species by vertical structural position (Sawyer and Keeler-Wolf 1995). Litter and duff were measured, collected, oven-dried and weighed to calculate mass. See Graham (2009) for detailed sampling and laboratory protocols used in this study. In total, over eight kilometers (8,100 m) of fuel transects were established along topographic and latitudinal gradients in 58 plots (n=174 transects).

Fire history research

Research was conducted in Del Norte Coast Redwoods State Park (Mill Creek), Redwood National Park (Bald Hills), Headwaters Forest Reserve and Humboldt Redwoods State Park (after the 2003 Canoe fire). Secondary fire history samples were collected from the Redwood Experimental Forest, Prairie Creek Redwoods State Park, and Montgomery Woods State Natural Reserve (after the 2008 Orr Complex).

Sampling in Del Norte Coast Redwoods State Park was designed to capture fire regimes along two different types of gradients—first, a coast-to-interior gradient informed by distance from the coast, the normal fog-stratus line seen on MODIS satellite imagery, and vegetational attributes and second, gradients of Native American cultural fire use (e.g., Anderson 2006) as inferred from ethnographic and archaeological data (Waterman 1920). Fire history samples were collected from 3-5 stumps within a 1 ha sampling area to minimize the risk of small patchy fires that could artificially increase estimates of fire intervals. To better interpret the results found by prior studies that sampled at stump height, cross sectional samples were collected from a variety of heights, down to the soil surface as defined by root separation discovered by shovel excavation or at the depth where scars disappeared (because that height was below the soil surface). Samples were dried, sanded and viewed under 10-40x magnification in the laboratory. In addition, Douglas fir age structure was determined in the field from eleven recent clearcuts to establish fire effects on those sites.

Sampling in Redwood National Park with Leonel Arguello involved of an array of sites in forested and prairie-edge sites to address how fire regimes varied based on vegetation type and possible Native American use. Stump samples were removed from 1 ha areas, generally at between 15 and 25 cm height which was lower than that recommended by others. These coast redwood forests are the highest-elevation stands that exist and are adjacent to areas that were actively managed with fire based on the ethnographic record. A tree ring chronology from Douglas fir was collected here to help crossdate fire history samples, given the species known problem with dating (Fritz 1940, Brown and Swetnam 1994).

Research in Headwaters Reserve with former BLM ecologist Greg Jennings involved a fire and vegetation component. We sample fire history from stumps from four sites, collected Douglas fir age structure by coring trees from paired mesic and xeric sites and combined these data with 300 timber cruise plots that had been established when the Reserve was purchased from the Pacific Lumber Company in the late 1990s. These three lines of evidence were used to interpret how historical fire regimes contributed to the development of old growth in the Reserve. The Douglas fir cores collected provided not only age structure and disturbance information (i.e., scars, growth suppressions and growth releases), but a tree ring chronology to help crossdate the coast redwood fire record.

Fire history research in Humboldt Redwoods State Park conducted with Stephen Underwood involved sampling hazard trees that had been felled along fire lines during the 2003 Canoe fire. 3-5 stumps were sampled from 1 ha collection areas from alluvial flats along the South Fork of the Eel River and Canoe Creek Flat and multiple upland sites. Douglas fir trees were cored to help crossdate the coast redwood fire record and to help date disturbances.

Lesser fire history collection were conducted opportunistically including (1) two fire history sites at the USFS Redwood Experimental Forest; (2) from felled hazard trees dating from the 2004 Newton fire and scattered wind thrown trees removed from the Newton B. Drury Highway in Prairie Creek Redwoods State Park; and (3) from two coast redwood trees that were felled in Montgomery Woods following the 2008 Orr Complex.

Fire cavity research

Cavity research was conducted to help develop a parallel line of fire history evidence that could provide managers with a **rapid assessment tool** for better understanding fire regimes in coast redwood. Such a tool could provide insights in areas logged long ago or in residual old growth, while avoiding the expense of funding fire history research everywhere, given the complexity of historical fire gradients.

Fire cavity research was conducted in Del Norte Coast Redwoods State Park, Prairie Creek Redwoods State Park, the Arcata Community Forest, Headwaters Forest Reserve, Humboldt

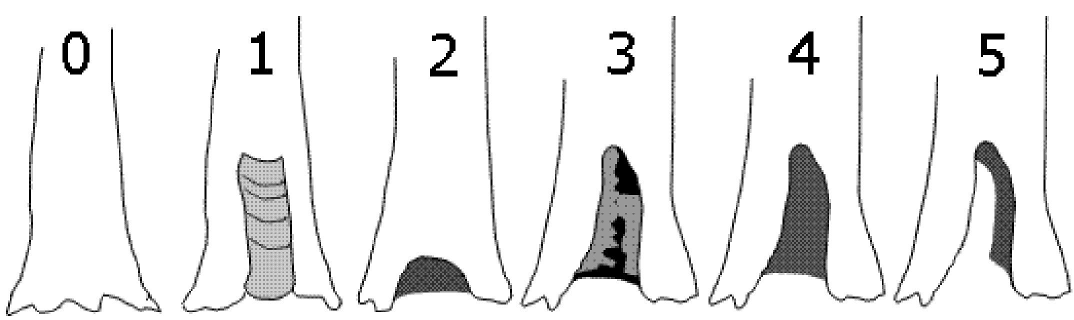
Redwoods State Park (after the 2003 Canoe Creek fire), and Montgomery Woods State Reserve (after the 2008 Orr Complex).

In the five sites other than the Arcata Community Forest, 12 plots were established having 10-12 trees each across a range of moisture classes for a total sample of 684 trees. Sampling captured a broad range of topographic and latitudinal variation. Both the Humboldt Redwoods and Montgomery Woods sites had burned recently. All five locations were in unlogged old growth coast redwood forest.

In a parallel study involving stumps rather than old growth in the Arcata Community Forest, 504 stumps were sampled in 42 randomly placed plots uniformly stratified across three site moisture classes as determined in GIS. Each plot consisted of 12 coast redwood stumps logged in the decades after 1880. Scar evidence from sprouts indicates that the area burned several times after logging occurred as was a common practice of the period. This research differs from the above effort because it has a stand reconstruction focus. That is, if patterns are comparable in old growth and in areas logged long ago, stump cavity characterization may provide rapid and inexpensive indicator of pre-logging fire regimes to help guide restoration efforts in parks and reserves.

In both studies stumps or trees were classified according to their diameter at breast height, estimated to the nearest 0.5 m for three size classes and cavity attributes were generalized based on how well the tree fit the cavity development scheme shown in Figure 3. Due to the unique way that basal fire cavities form in coast redwood, cavities reveal a lot about the type of fires that burned and fire scar history (Finney 1996). Shallow cavities (type 1) result from radiant heat from adjacent trees or as a result of pockets of fuel at the tree's base. Classes 2-5 result from repeated fire scars, decay and healing that under certain conditions can lead to the formation of large cavities and increase mortality risk over the life of the tree. A plot-level "Redwood Cavity Index" was developed based on the average value of 12-trees so that plots can be compared across tree size classes and environmental gradients.

Figure 3: The fire cavity classification scheme used as a rapid assessment tool in coast redwood to interpret fire history and help interpret the hazard of tree fall. A "Redwood Cavity Index" is calculated by averaging the cavity class numerical values for 12 trees at a site.



IV. Key findings

Fuels research findings

The volume of fuels in old growth coast redwood forests exceed that of any other forest type known at 618.7 Mg ha^{-1} at Prairie Creek Redwoods State Park. This is 11 percent greater than any previously published down woody debris mass estimate (Graham 2009). Of the six areas studied total mass of woody and vegetative detritus ranged from 252 to 619 Mg ha^{-1} and volume ranged from 540 to 1400 m3 ha^{-1}. Eighty six percent of downed woody debris (DWD) mass consisted of logs > 7.6 cm diameter, four percent consisted of particles = 7.6 cm diameter, and ten percent of DWD mass was litter and duff. Forest floor bulk density ranged from 4.9 to 6.3 Mg ha^{-1} cm^{-1} and depth between 7.4 and 10.9 cm among sites. Average surface fuel heights ranged from 26.2 to 46.4 cm.

The high fuel accumulations were not just from large logs that may or may not burn in a fire. Over half of the 1000-hr fuels were <20 cm diameter. These fuels can burn for long periods of time in ways that can girdle standing redwood trees or lead to the formation of large scars that have long-lasting ecological effects.

Fire history research findings

Fire scar sampling revealed that prior research that relied on sampling over a meter above the soil surface had methodologically shortcomings. Fire cavities can harbor scars at that height (Jacobs et al. 1985), but many scars are lost due to cavity enlargement and decay during and after fire events (Finney 1996; Brown and Baxter 2003). On stumps with no fire cavity, frequent scars were regularly observed at 15-25 cm height, but they were typically absent or rare above 30 cm; (Fig. 4). Research that found fires were rare in the northern coast redwood forest was conducted in the field and at stump height, which is normally at 150 to 250 cm in coast redwood.

This evidence reduces the credibility of fire history methodologies in coast redwood that did not aggressively sample at low heights. My sampling efforts also demonstrate that for this species in this humid part of the range, the best record of fire is rarely associated with fire cavities. Scars embedded in near-surface buttresses or flutes provide well-preserved long-term records of fire that are absent in most cavities. Sampling this portion of the tree greatly reduces the need for finding cavities with rare well-preserved fire records and reduces the need for compositing fire records from multiple trees that can lead to questions about non-overlapping burn areas or fire patchiness.

Fire regime characterization efforts typically rely on mean, median and range values that are collected for a specific period of time. These values vary over time due to changing climate and human ignitions. Results from Del Norte Coast Redwoods State Park demonstrate this variability well. On one site near the fog-stratus line (where mid-day temperatures are often reduced by cloud cover during the fire season) with a 1000-year long fire record, fire was absent for nearly four centuries until ca. 1370, when fires averaged 38 years (median 28, range 16-86) through 1700. From 1700-1920, fire burned with an average fire interval of 24 years (median 15; range 6-69) with the longest interval falling during the late eighteenth-early nineteenth century transition (LEENT)—a known climate anomaly. Not coincidentally, this may have also been a period of reduced Native American activity, based on evidence of a Cholera epidemic around that time. Toward an argument of ignition-sensitivity, some archaeologists hypothesize that Native populations changed ca. 1300 (Frederickson 1984), which is about when fire increased in this long-term record. No other site provided a comparable record for comparison. In recent centuries, fire within this Del Norte Coast Redwood study area generally burned with than 35 year intervals, peaking at 11-15 years, and the range of variation increased closer to the coast, consistent with what is expected given gradients of fire spread, given the fire climate (Appendix A; Norman, submitted).

Sampling at two sites in the USFS Redwood Experimental Forest failed to produce evidence of frequent fire, despite the discovery of individual scars on samples. Only mesic sites were sampled here. These areas were dominated by very large redwood trees and few other conifers or hardwoods. A similar pattern of rare scars was observed from the scattered fallen trees sampled in humid portions of Prairie Creek Redwoods State Park.

Figure 4: While fire scars are common close to the ground surface (right), decay is also common, and this often destroys the fire record (left). This sample from an alluvial flat in Humboldt Redwoods State Park shows that a cavity formed from frequent fire during the early 1800s was able to heal over after the last fire (right).

Fire history research conducted in the upper elevations of Redwood National Park suggests that the current pattern of forest and grassland edge is not a good predictor of fire frequency. Fire was frequent, normally between 6-15 years in interior forests and near the grassland edge with two exceptions. Fires were even more frequent at Gans Prairie, in the north and similarly frequent in a nearby forest that is thought to have been more open in the past. These sites exhibited a peak frequency of 1-5 years (Appendix A). This provides strong evidence that these coast redwood forests were intensively managed by the Yurok tribe for centuries (Waterman 1920).

The fire regimes of Headwaters Forest Reserve differ from Redwood National Park in ways that are not predicted by its more southern location. While the lower frequency record found may reflect the suboptimal cutting heights that were often necessitated by the heavy use of tractor logging methods here during the 1980s, this fire chronology is well supported by multiple stumps, Douglas fir age structure and growth suppressions tied to these fire events. Fire averaged 24 years (median=24; range= 8-47) prior to the last fire in 1936 (which was a severe fire season across the north coast redwood range). The longer fire intervals that were found here can help explain the distinctive even-aged patch structure of Douglas fir that followed these fire events. Establishment pulses of Douglas fir were also documented from Del Norte Coast Redwoods State Park and Humboldt Redwoods State Park where fire was frequent, but Headwaters may have been less used by Native Americans than these other areas. It is worth noting that these fire data are consistent with fire intervals reported from prior research at Humboldt Redwoods State Park (Fritz 1931, Stuart 1987).

At Humboldt Redwoods State Park, fire frequency was similar on upland and alluvial sites. These results are consistent with what is known about Native American use of this area from historical, archeological and ethnographic data. The Lolangkok spent their summers in villages along the South Fork of the Eel and much of their summer at high elevations. This provided them with a range of reasons for igniting fire across the landscape. Fires typically burned here every 10-15 years, roughly twice as often as had previously been thought for alluvial flats and slopes (Fritz 1931, Stuart 1987).

Two samples were collected from felled trees in Montgomery Woods State Natural Reserve after the 2008 Orr Series fire. The smaller stump had likely been standing-dead after being killed by a fire that occurred there only 30-40 years earlier. As a result, no sapwood remained and calendar dating of fire events was not possible. A second sample was taken from a large tree that was felled adjacent to the first, and it had a continuous record of growth through 2008. This site revealed 12 intervals going back to the turn of the 19^{th} century (ca. 1805), with a mean interval on the alluvial flat of 10 years (median=9; range 4-15). This area is at the eastern edge of the coast redwood range and the short fire intervals here are not unlike that reported by Brown and Baxter (2003) from the coast.

The fire intervals reported here are shown in graphical form in **Appendix A** along with fire interval distributions from all or a portion of selected other studies that used larger collection areas.

The seasonal position of fire scars varied among sites but growing season fires were well represented particularly at the high elevations of Redwood National Park. While tree phenology may have been delayed there compared to lower elevation sites; there is supportive ethnographic evidence that Native Americans deliberately burned there during the growing season prior to collection of tanoak acorns. As demonstrated by the Orr Complex that burned Montgomery Woods in July of 2008, fires that occur during the cooler-wetter time of year can have less severe fire effects than those that burn during August or early September.

In Del Norte Coast Redwoods State Park, growing season fires were preceded by an average fire interval that was 10-years shorter than for dormant season fires. This suggests that Native American fires may have reduced fire effects in two separate ways at once (see Martin and Sapsis 1996): (1) by reducing the time between fires and the associated risks of increased fuel accumulation and (2) by burning during more mild fire weather.

Fire-climate relationships were difficult to establish due to the episodic reliability of crossdating. While several samples in Del Norte Coast Redwoods, Redwood National Park, Headwaters Forest Reserve and Humboldt Redwoods State Park were successfully crossdated using nearby published chronologies or those developed from Douglas fir as part of this study, the climate of the coast is complex due to the confounding influence of fog-stratus cover. Disturbance associated growth variation (from wind damage and fire) is common in Douglas fir cores, making long-term comparisons of fire history with climate difficult.

In interior sites, regional drought does seem to play a controlling factor to the occurrence of fire, as indicated by drought reconstructions of the region and long-term fog data from the National Weather Service office in Eureka. High pressure associated with drought may cause the cooling effects of fog-stratus to extend further inland, thereby reducing the fire hazard in coastal areas while it becomes greater east of the fog line. In other years, moderate conditions in the interior may allow more fire to burn in coastal areas that would otherwise be cooled by cloud cover.

Fire cavity research findings

Deep fire cavities that result from extended periods of relatively frequent fire were found across the coast redwood range, including sites that were previously thought to have burned rarely. Type 4 and 5 cavities are thought to form from relatively frequent fire scar-decay cycles that persist through the life of the tree. Their rare presence at western Prairie Creek Redwoods State Park suggests that the old growth there did not develop with the same frequency of fire as did other sites. Surprisingly, but consistent with nearby fire history results, this same pattern of low cavity incidence did not hold up in humid Del Norte Coast Redwoods State Park, where deep cavities constituted around 15% of the trees in the forest. The fire regimes that caused these different outcomes likely reflect local patterns of Native American fire use.

Trees with no visible cavity constituted over half the trees examined at all sites except Canoe Creek, where these trees consist of about 46% of the population. Prairie Creek ranked highest having 75% of its trees exhibiting no evidence of past cavity-generating fire. Fire scars are common in this forest though, in the form of bark notches in trees, but bark char can result from low intensity patchy fires that smolder for days or from a single fire event.

Headwaters Reserve ranks highest of these five sites in the frequency of shallow type 1 cavities that are thought to result from pockets of debris that scar previously unscarred trees. Deep type 4 cavities are also common here, suggesting a moderate fire interval may be most likely. This unique pattern of cavities is consistent with the longer fire intervals found here. Longer fire intervals may have led to more fuel accumulation and more type 1 scars.

Shallow and deep fire cavities occurred across all sites in the near-coastal Arcata Community Forest, but cavity indices are highest in the largest trees (>2.5m diameter) on dry and moderate sites and least on small trees (<2.0 m) on moderate and mesic sites. Mesic sites showed a reduced cavity index consistent with expectations that higher fuel moistures on mesic sites reduced fire intensities.

V. Management implications

Compared to the past, coast redwood forests are ignition-limited. This makes the issue of fire one of fire exclusion more than suppression. In that sense, management has much in common with eastern North America much of which also burned for centuries due to the influence of people (Main and Haines 1974; Nowacki and Abrams 2007). However, many of the effects of fire exclusion here have parallels with dry forests of the West. There remains a risk of wildfire across most of the coast redwood range that could have undesirable long term implications.

Old growth paradigms

Building an appreciation for how long-term human management contributed to the character of old growth is difficult in a vegetation type that defines the word superlative (e.g., Noss 2000; Sillett and Van Pelt 2007). Yet many of the valued attributes of old growth coast redwood forests resulted from a long history of human fire use, in particular those associated with Douglas fir and hardwoods that provide important wildlife habitat. For us today, this means that these forests attributes are not simply ignition-limited, but core old growth values are human ignition-dependent.

The long lifespan of individual coast redwood trees allows them to become legacies of long-term changes in culture and climate. That is, their density and character does not necessarily reflect the fire regimes of the recent past. Restoration of the fire regimes of the 1700s and 1800s is not likely to lead to compositional and structural restoration when the fire regime of 200-700 years earlier was different. Coast redwood forests are a system in flux, and sustaining their desired attributes requires a sophisticated understanding of how those attributes came to be and how they might be sustained (see Pickett and Parker 1994). This results from historical context. Viewing coast redwood forests within a historical timeline model, rather than as a system balanced within a “fire cycle” defined by a mean fire interval helps us understand valued forest elements as legacies rather than as some inherent attribute of old growth systems. This management paradigm allows novel outcomes that can deter success to be better anticipated (Fig. 5).

Coast redwood flammability and fire hazards

Charred bark, fire cavities and scars found across the range demonstrate that fire hazards are a range-wide phenomenon for coast-redwood. Deep fire cavities occur in humid coastal forests, including Del Norte Coast Redwoods State Park and riparian areas in Prairie Creek Redwoods State Park; and these do not form without repeated fires burning over an extended period of time (Finney 1996). Their more spotty prevalence on humid coastal sites suggests that fire behavior and intervals differed there from dryer sites, not that fire did not repeatedly occur.

Given the massive amounts of fuel and advanced decay present on humid sites, wildfire may be most difficult to manage there. Large trees with complex disturbance histories are common there and trees exhibit considerable inner decay and highly complex crown fuels (Finney 1996, Sillett and Van Pelt 2007). Either is difficult to extinguish during a wildfire event without cutting the tree down. While necessary from a practical fire management perspective, the loss of these legacy trees as they experience normal fire behavior is inconsistent with other management objectives. Strategic use of prescribed fire in these areas can reduce fuel and decay hazards while supporting long-term ecological objectives. That decisionmaking requires cooperative and comprehensive pre-planning.

Figure 5: Several even-aged Douglas fir stands that experienced high severity fire during the 2003 Canoe Fire were colonized by invasive species including Jubata grass (*Cortaderia spp.).* While many of these areas were tree-invaded grasslands suggesting that high severity fire here was restorative, this novel outcome is inconsistent with management objectives.

The high production of fuels in coast redwood forests can lead to undesirable ecological consequences apart from making fires more difficult to manage during fire events. Concentrated fuels (Graham 2009) are an important outcome and driver of gap dynamics, as patchy higher intensity fire causes localized tree mortality. High amounts of fuel at the base of legacy trees can increase fire duration which is the driving cause of scar formation and cavity initiation. To minimize the deleterious long term effects of increased fuels and wildfire, active use of prescribed fire during moderate fire weather provides a logical solution.

Is coast redwood dependent on fire for its perpetuation?

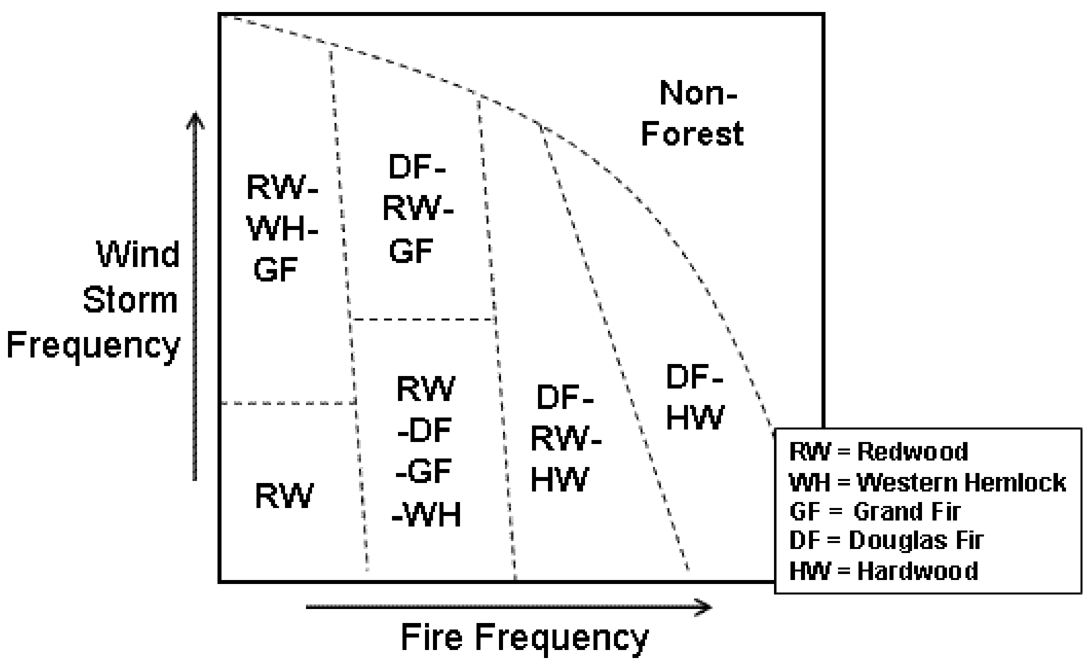
In the popular mind, coast redwood forests are thought to be self-perpetuating because long-lived coast redwood trees can outlast competitors and sprouting helps ensure site persistence. This view reflects the lingering argument that forest change is a goal-seeking process leading toward a climax vegetation type. This is inconsistent with how other ancient forests came about (Swetnam

1993), and evidence presented here suggests that this perspective is no less valid in coast redwood given the degree to which climate and cultures have changed.

The evolutionary importance of fire for coast redwood remains ambiguous (Lorimer et al. 2009), although the effects of fire on redwood individuals are better known (Finney 1996). The competitive implications of fire at the community level depend on how forests are defined.

Many compositional and structural values that exist today in humid and dry coast redwood forests resulted at least in part from frequent fires of the past. Fires are the source of basal and canopy cavities that increase coast redwood mortality and crown complexity (Fritz 1931; Finney 1996, Sillett and Van Pelt 2007). Coast redwood's vulnerability to fire reduces its competitive advantage, allowing Douglas fir, hardwoods and understory species to exist (Veirs 1982; Norman and Jennings, in prog.). In concert with wind and flood disturbance, but with spatial effects that differ, fire has been responsible for a large part of coast redwood's forest diversity (Fig. 6).

Figure 6: Decisions to exclude fire or to only allow wind to dominate upland coast redwood forests lead to compositional tradeoffs. (This is an upland model, as coast redwood dominates stands with high fire frequency on alluvial flats because flood deposition buries fire scars and precludes competition (Stone and Vasey 1968)). The position of these vegetational borders varies along environmental and regional disturbance gradients, as winter storms are greatest on exposed coastal slopes of northern latitudes while wildfire hazards dominate the eastern and southern portions of the coast redwood range where species viability is also patterned by microclimate.



VII. Relationship to other recent findings and ongoing work on this topic

The fine-scale spatial patterns of large fuel that were documented in this study are generally consistent with the fine scale structures documented from stand structure analysis on coast redwood flats (Dagley 2008) and the importance of gaps for species regeneration (Sugihara 1992). Pockets of fuels can lead to higher intensity fire than elsewhere in the stand. More intense fire can reduce understory competition and increase the quality of the soil substrate for seeding species, such as Douglas fir and even coast redwood (Veirs 1982; Norman and Jennings, in prep.). Alternatively, fire can reduce the viability of wood to act as nurse logs for species regeneration (see Porter and Sawyer 1996; Lorimer et al. 2009). The effects of this extreme heterogeneity of fuels provide a key direction for ongoing research, particularly knowledge derived from experimental pre- and post-fire research.

The high fire frequencies documented in tree rings from across a wide array of sites on the north coast redwood range demonstrate that few areas did not burn with at least moderate fire frequency in recent centuries. Many northern forests burned with frequencies similar to that found in the dry southern portions of the range (Brown and Swetnam 1994; Brown and Baxter 2003; Finney and Martin 1989, 1992; Stephens and Fry 2005), and two coast redwood sites in upper slopes of Redwood National Park burned with a frequency distribution that peaked at less than 6 years likely due to intensive use by the Yurok tribe there. The loss of frequent fire explains why tree encroachment has been so extensive there (Fritschle 2009). Where no fire history data were collected, fire cavity attributes support the argument that broad scale frequent to moderately frequent fire was typical over most of the coast redwood range.

There were undoubtedly places where fire was less common prior to 1850, namely humid sectors of Prairie Creek Redwoods State Park and the western portion of the Redwood Experimental Forest (adjacent to where the fuels research reported here was conducted (Graham 2009)). These stands were nearly entirely dominated by large old growth coast redwood, with few other tree species. While fire history sampling found an occasional fire scar on samples, this was not enough to meaningfully establish fire intervals, and the most likely interpretation is that fire was uncommon here, or preferentially patchy. This is consistent with the model of infrequent fire of Veirs (1982) and Fritz (1931), yet research does not necessarily support either's explicit argument for where infrequently burned areas were located as their data was based on fire scars observed at stump height in field surveys. Ongoing work in these seemingly less flammable forests involves defining these areas to better understand them and how windstorm effects differ.

Headwaters Forest Reserve provides an example of moderate fire frequency that has a high potential for fire in the east. This forest burned less in the past than did other areas, presumably because of less intensive Native American fire use. Prior to 1850, the Reserve was in a relatively remote section of Wiyot territory and that tribe relied on coastal and bay resources for their sustenance. This suggests that Headwaters provides a special example of an old growth coast redwood forest that may have been dominated by lightning ignitions in the past. A lightning fire was extinguished there in 2008 and the forest last burned 72 years earlier—the current fire-free period has been nearly twice as long as the longest fire interval known prior to that time (1766-1808).

VIII. Future work needed

Fire regimes reflect the interactions of fuels, climate and ignitions, and each of these needs to be better understood along with understanding fire effects across seasons. Some specific questions include:

- How do fuels and vegetation respond over time to fires of different intervals seasons and severities?
- How do fuels from other disturbances differ, including windstorms, floods and logging?
- How will fuels and fire hazards change with the loss of the tanoak understory to Sudden Oak Death?
- How long-lasting are the effects of fuels reductions on fire behavior and tree mortality?
- Do understory shrub fuels decrease with canopy closure? That is, is there an advantage to not burning frequently on these sites?
- How do discrete wildlife habitat elements respond to different fire management alternatives?
- How can long-smoldering old growth trees be managed?
- How has fire changed over the last 1,500 years with climate
- How will local fire hazards change across climate change scenarios?
- What are the constraints to coast redwood regeneration from seed?

IX. Deliverables cross-walk

Proposed	Delivered	Status
Project website	http://www.redwood.forestthreats.org/	Completed. Updated as needed
Fire history and fire effects from coast redwood forests	(1) Norman, S.P. A long-term record of fire from a *Sequoia sempervirens* forest near the northern limit of its range. (2) Norman, S.P., Arguello, L. Fire history along a forest to grassland gradient, Redwood National Park, California. (3) Norman, S.P., Jennings, G. Fire-mediated coexistence of coast redwood and Douglas fir in the Headwaters Forest Reserve. (4) Norman, S.P., Underwood, S. Modeling long-term change to coast redwood forests using insights from fire history. (5) Norman, S.P. Reconstructing fire regimes from stump attributes in a bay-side coast redwood forest.	(1) Submitted; J. of Biogeography (2) Manuscript in progress; Expected 2010. (3) Manuscript in progress; Expected 2009. (4) Manuscript in progress; Expected 2009. (5) Manuscript in progress; Expected 2009.
Fuels characterization in old growth coast redwood forests	(1) Graham, B. 2009. Structure of downed woody and vegetative detritus in old-growth *Sequoia sempervirens* forests. MS Thesis. Humboldt State University. Available at: http://dscholar.humboldt.edu:8080/dspace/handl	(1) Completed

	e/2148/506 (2) Graham, B., Varner, J.M. Down woody debris in old growth coast redwood forests in northwestern California, USA. (Canadian Journal of Forest Research)	 (2) Manuscript in progress; Expected October 2009
Reference conditions atlas	Maps to be accessible through this portal: http://www.redwood.forestthreats.org/	Model in progress December 2009
Reference conditions synthesis	(1) Lorimer, C.G.; Porter, D.G.; Madej, M.A.; Stuart, J.D.; Veirs, S.D.; Norman, S.P.; OHara, K.L; Libby, W.J..2009. Presettle-ment and modern disturbance regimes in coast redwood forests: Implications for the conservation of old-growth stands. *Forest Ecology and Management* 258:1038-1054. http://www.treesearch.fs.fed.us /pubs/33548 (2) Norman, S.P. The fire cavity index: a rapid assessment tool for understanding fire regimes in coast redwood forests.	(1) Completed (2) Manuscript in progress
Public information brochure	See pdf entitled "Fire In The Coast Redwood Forest"	Revised as needed
Workshop	See workshop overview in **Appendix B** and presentations	Completed

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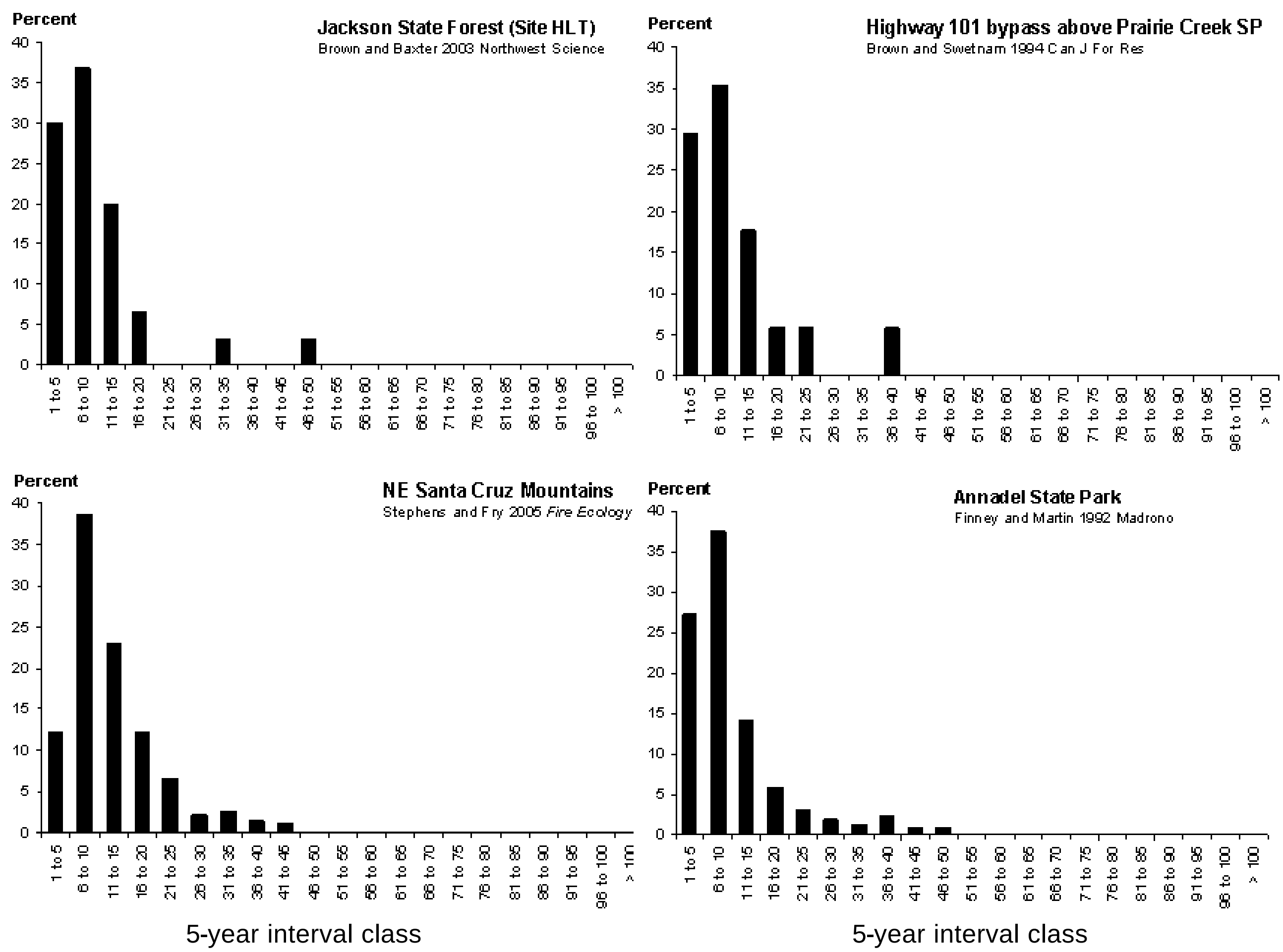
APPENDIX A

HISTORICAL FIRE INTERVAL DISTRIBUTIONS

Prior research

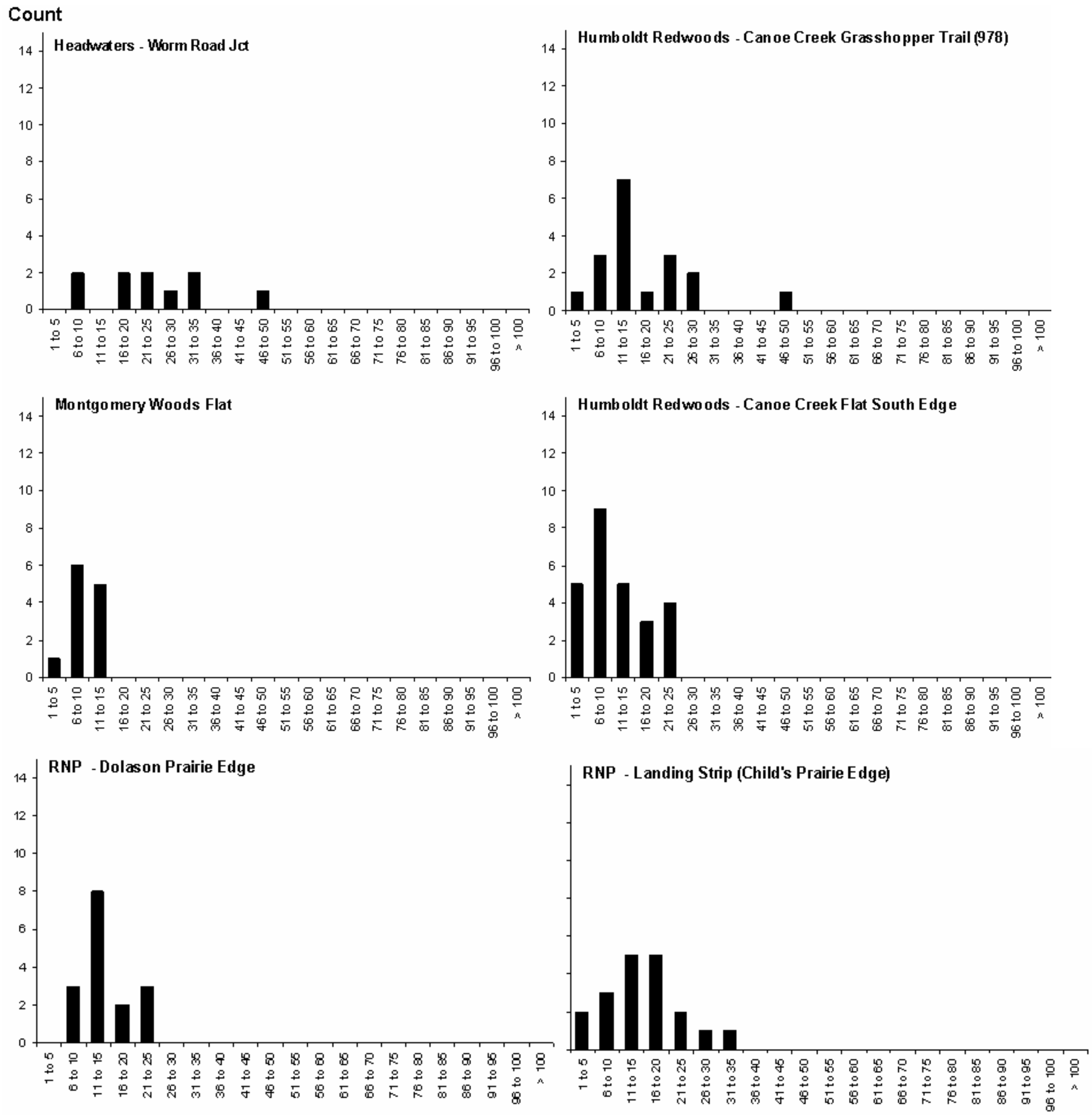
Most previously published fire histories do not provide data in a format that allows comparisons of fire interval distributions. Selected re-graphed results from studies that do are shown below. These are from the ridgeline east of Prairie Creek Redwood State Park (Brown and Swetnam 1994); from the Jackson State Forest near the coast (Brown and Baxter 2003-site HLT); Annadel State Park just south of Santa Rosa (Finney and Martin 1992); and the Santa Cruz Mountains south of San Francisco (Stephens and Fry 2005). Time periods used vary among research efforts.

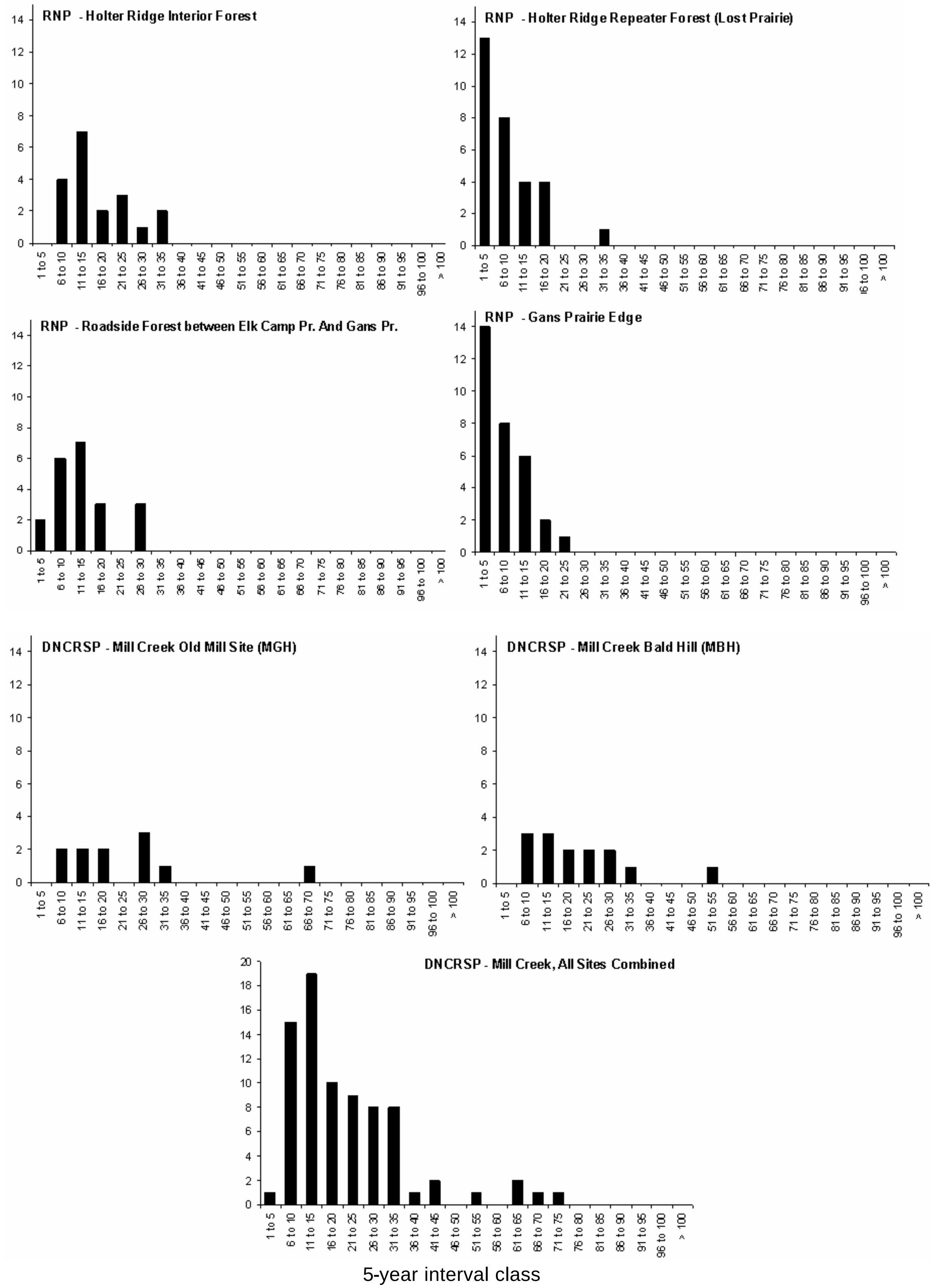


New fire history research

The fire history data reported here represent a small collection area usually well less than 1 ha and from multiple samples collected at 10-30cm height (normally 20-25 cm height). These data are not presented as percent of all scars, but as the number of scars within a 300 or less year window prior to the last fire interval recorded. This period usually covers the period from the late 1600s through the early 20th century.

Areas reported here include one plot in Headwaters Forest Reserve; the Montgomery Woods Flat; two sites from the Canoe fire of Humboldt Redwoods State Park (an upland site along Grasshopper trail and a site at the edge of Canoe Creek flat); six sites from near the Bald Hills road in Redwood National Park; and two from Del Norte Coast Redwoods State Park (Mill Creek) along with a composite record from all eight sites used in that study. Results from the Redwood Experimental Forest and Prairie Creek Redwoods State Park are not shown to the paucity of fire intervals on individual samples.




RNP - Holter Ridge Interior Forest
RNP - Holter Ridge Repeater Forest (Lost Prairie)
RNP - Roadside Forest between Elk Camp Pr. And Gans Pr.
RNP - Gans Prairie Edge
DNCRSP - Mill Creek Old Mill Site (MGH)
DNCRSP - Mill Creek Bald Hill (MBH)
DNCRSP - Mill Creek, All Sites Combined
5-year interval class

APPENDIX B

COAST REDWOOD MANAGEMENT WORKSHOP

An online workshop was conducted on Sept 30, 2009 entitled, "Fire and fuels management in coast redwood forests" for managers and others. The two hour 20 minute event successfully brought a broad range of managers together from across northern California and the US without the expenses normally associated with travel. Due to travel restrictions, several people were in attendance that would otherwise not have been able to attend.

There were 32 participants representing Redwood National Park, California State Parks of two different districts, Bureau of Land Management, US Geological Survey, California Department of Forestry and Fire Protection, The Nature Conservancy, UC Davis Cooperative Extension Service, Humboldt State University, a private timber company, the US Forest Service Pacific Southwest Research Station and the Forest Service Southern Research Station. The audio-visual workshop consisted of two half hour presentations by Drs. Steve Norman and Morgan Varner, followed by a period of questions and discussion.

Agenda:

Introductions-- Yana Valachovic, UC Davis Extension

Changing fire regimes of coast redwood forests—Dr. Steve Norman

- Fire in coast redwood: a brief introduction
- Fire regimes from fire cavity attributes
- Fire regimes inferred from fire scars
- Interpretation and management implications

Reference condition fuels in old growth coast redwood ecosystems—Bradley Graham and Dr. J Morgan Varner

- Rationale for the study
- How much fuel?
- What is the variation across stands?
- Are estimators fair approximations?
- What patterns emerge from surveying several stands?
- How does redwood fit with other forested ecosystems?
- How does fire affect redwood fuel loading?

Discussion points:

- Whether to burn old growth
- Tradeoffs and obstacles related to wildfire management and prescribed fire use
- Manager's plans to burn in coming years and research opportunities

Presentations will be made available online with a sound track accessible through the project website: http://www.redwood.forestthreats.org.

Submitted files:

- Norman_2009_RedwoodWorkshop.ppt
- Varner_2009_RedwoodWorkshop.ppt