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Coast Redwood Stand Composition, Structure, and Fuel Load Following Prescribed Fire in Big Basin Redwoods State Park

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COAST REDWOOD STAND COMPOSITION, STRUCTURE, AND FUEL LOAD
FOLLOWING PRESCRIBED FIRE IN BIG BASIN REDWOODS STATE PARK

A Thesis

Presented to

The Faculty of the Department of Environmental Studies

San José State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

David Albert Cowman

May 2020

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The Designated Thesis Committee Approves the Thesis Titled

COAST REDWOOD STAND COMPOSITION, STRUCTURE, AND FUEL LOAD
FOLLOWING PRESCRIBED FIRE IN BIG BASIN REDWOODS STATE PARK

by

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May 2020

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ABSTRACT

COAST REDWOOD STAND COMPOSITION, STRUCTURE, AND FUEL LOAD FOLLOWING PRESCRIBED FIRE IN BIG BASIN REDWOODS STATE PARK

by David Albert Cowman

With the prevalence of catastrophic wildfires increasing as a response to a century of widespread fire suppression, shifts in weather patterns, and other external factors, land managers throughout the United States have sought methods to increase the resiliency of landscapes to fire. With a host of adaptations to periodic disturbance, *S. sempervirens* has a competitive advantage over other species when fire is present. Utilizing sixty 10-meter diameter plots from sites previously burned in 1999, 2007, and 2011, and 60 unburned control sites, data was collected on forest stand composition and structure as well as understory species composition and dominance. Line intercept transects were used to assess downed woody fuel accumulation and receptive fuel bed depth. Permutational multivariate analysis of variance (PERMANOVA) results indicated statistically significant differences in stand composition, fuel load, and receptive fuel bed depth metrics. Kruskal Wallis and Spearman's rank order correlation indicated increased density of juvenile and mature hardwood tree and shrub species, increased duff and litter depths, and increased load of coarse woody fuels in plots that had not experienced prescribed fire, while dominant overstory canopy species and understory non-woody plant species remained equivalent between treatments. These results suggest that prescribed fire can provide beneficial reductions in fuel load and juvenile tree and shrub species density without impacting overstory canopy or shade tolerant understory species.

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Chapter 1: Introduction

Motivation and Scope

Fire plays a formative role in many vegetation types around the world, with both natural and anthropogenic sources influencing fire frequency, intensity, and seasonality. Landscapes in the western United States have been heavily influenced by burning practices dating back 11,000 years. However, the introduction of prominent Anglo-European influence in the 19th and 20th centuries marked the beginning of a period of fire suppression (Greenlee, 1983). Fire suppression has the potential to effect significant changes to vegetation composition, structure, and fuel load, and may increase the probability of catastrophic outcomes for future wildfires (Greenlee & Langenheim, 1990). In order to mitigate the unintended effects of fire suppression, land managers in some areas have reintroduced fire, under managed settings, in order to build the fire resiliency of the landscape by reducing fuel load and to return vegetation composition to a pre-suppression condition (Engber, Teroaka & Mantgem, 2017).

In the coastal forests of California, where natural ignition sources are low, the impact of indigenous burning was profound, creating fire return intervals (FRI) measured in decades rather than centuries, and vegetative patterns requiring fire in order to persist (Greenlee, 1983; Greenlee & Langenheim, 1990). Coast redwood (*Sequoia sempervirens*) forests are not generally thought to have been the focus of indigenous burning practices; however, fires set in adjacent vegetation types frequently expanded into the coast redwood forest (Jones & Russell, 2015). While it is impossible to say with any precision what the cumulative effects of centuries of intentional burning had on

community composition and structure, evidence suggests that it tended to favor *S. sempervirens* dominance over other canopy species. This in turn, reduced overall fuel load and the potential for crown fire (Greenlee & Langenheim, 1990). The reintroduction of fire, after decades of fire suppression, is in effect, an attempt to restore the indigenous-imposed fire regime in order to recover more disturbance-resilient stand conditions.

Literature Review

Forest ecology and disturbance. Several biotic and abiotic factors influence the composition and structure of a forest. On a landscape scale, climate, landform, and soils influence the species present in given geographic locations. These factors coupled with subtle differences in microclimate, soil chemistry, water availability, and disturbance history, produce a mosaicked forest structure and composition (Frelich, 2016).

Disturbance, or lack thereof, is a major factor in determining the composition of ecosystems throughout the globe. In forest settings in particular, disturbance is a driving force in determining plant community assemblages and heterogeneity or homogeneity within a system. Within forest ecosystems, sources of disturbance include tree fall gaps, wind, fire, landslides, floods, as well as several other exogenous or endogenous factors (Attiwill, 1993; Pickett & White, 1985).

A key factor for land managers tasked with stewarding forest systems is the maintenance of historic disturbance regimes that have shaped the system or various systems within the landscape (Attiwill, 1993). With significant variability in sources of disturbance and temporal and spatial heterogeneity, even within similar plant

communities, the task of emulating natural disturbance regimes requires intimate knowledge of the forest system.

Fire ecology and behavior. Fire in western North America is a frequent disturbance that has been shaping the landscapes in this region for thousands of years. Wildfire is characterized as having a mosaicked effect on the landscape. This variability is created by the temporal, spatial, and intensity differences in wildfire, and how these differences affect individual plants and plant species composition (Foster, Barton, Robinson, Macgregor & Lindemayer, 2017). In addition, site characteristics such as slope, aspect, climate, soil type, etc. all play important roles in determining how fire will impact a given landscape or plant community.

Fire behavior is impacted by several variables, but most notably weather, fuel, and topography. Dead fuel is broken down into time-lag classes including 1-hr fuels, 10-hr fuels, 100-hr fuels, and 1,000+- hr fuels. Time-lag classes refer to rough estimations of the time necessary for the moisture within the dead fuel particle to reach 2/3 equilibrium moisture content with the surrounding atmosphere. Time lag classes are also roughly based upon the diameter of the fuel particles (Biswell, 1989). Live fuel moisture is the moisture content of living vegetation and is highly dependent upon seasonality, rainfall, and other climatic factors and physiological characteristics of the plant. In essence, however, the lower the moisture content of the fuel, the greater the chance of ignition of the particle. Continuity of fuels, or the vertical and horizontal arrangement of various fuel particles, also plays an important role in how fire will spread. A fire occurring in a

continuous fuel type will spread faster both vertically and horizontally than one occurring in a patchy, discontinuous fuel type (Biswell, 1989).

In addition to fuels, topography plays an important role in fire behavior. Convective heat produced by fire has the tendency to rise. When the fire occurs at the bottom of a steep slope, the convective heat produced by the fire will pre-heat the fuels up-slope. This in turn increases the rate of spread vertically when fuel is available above the fire. Conversely, when a fire is backing down a hill, against the slope, the fire will have a tendency to move slowly as it works against the slope and against its own convective energy (Biswell, 1989). Fire is likely to increase in energy and rate of spread when occurring in narrow canyons or along steep slopes.

Lastly, weather has a determining factor in fire spread and behavior. Moisture content of fuels helps determine the likelihood of ignition and moisture content is highly variable based upon weather. In addition, fire spreads more rapidly when exposed to extreme wind events as well as high temperature and low relative humidity events. Exposure to sunlight and wind events is highly dependent on topography and aspect, which affects the fuel types present and their orientation in a given landscape. In the northern hemisphere, south facing slopes tend to be hotter and drier than north facing slopes and along the west coast of California prevailing winds tend to originate from the north west (Biswell, 1989).

Ecology of the coast redwood forest. *Sequoia sempervirens* is a tall, long-lived conifer species found exclusively in a coastal strip ranging from southern Oregon to the central coast of California in southern Monterey County (Barbour, Borchert, Popper,

Whitworth, & Evarts, 2001). Occupying roughly 720 km from Oregon to California and 56 km inland, *S. sempervirens* serves as either a dominant or codominant overstory species in the entirety of its range. Although dominant in the majority of its range, variability in size, associated plant communities, and ecology exists along both the coastal-inland gradient as well as south-north gradient of its range (Griffith, 1992).

Typically, the southern extent of the *S. sempervirens* range exhibits relatively shorter trees, clustered predominantly around perennial waterways due to drier weather and more frequent fire pressure. In addition, higher fire frequency, higher temperatures, and lower rainfall in the southern extent of the range change the stand composition and structure when compared to the northern portion of the range (Carroll, Sillett, & Kramer, 2014). In the northern extent of their range, the largest *S. sempervirens* individuals can be found in alluvial fan sites along perennial rivers, where trees can range upwards of 100 m in height, thriving in deep nutrient rich soils (Griffith, 1992).

Along the entirety of its range, *S. sempervirens* occurs in a maritime Mediterranean climate, typified by cool rainy winters, and dry summers. The dryness of the summer months is alleviated by a strong marine layer presence throughout the range. Although dependent on this coastal fog layer to reduce stress during the summer, *S. sempervirens* individuals are intolerant of salt spray and thus primarily occur with a gap between the coast and *S. sempervirens* stands. On an elevational gradient, *S. sempervirens* primarily occur from sea level to 914 m depending on site-specific characteristics (Barbour et al., 2001; Griffith, 1992).

Sequoia sempervirens is a shade tolerant species and produces plentiful sprouts and seedlings following disturbance (Lazzeri-Aerts & Russell, 2015), which affords the species the ability to capitalize upon disturbance events and outcompete associated tree species. In addition, *S. sempervirens* sprouts and seedlings can enter a state of dormancy while confined to the understory, and when exposed to increased resources following disturbance events can exhibit vigorous growth (Griffith, 1992). Studies have shown that among associated tree species, *S. sempervirens* exhibits the highest germination and sprouting rates, canopy retention, and survivorship following fire events (Lazzeri-Aerts & Russell, 2014).

Several varieties of associated tree species are found in conjunction with the *S. sempervirens* forest in the Santa Cruz mountains. The most common associated overstory tree species is Douglas fir (*Pseudotsuga menziesii*), with common subcanopy tree species including tanoak (*Notholithocarpus densiflorus*), Pacific madrone (*Arbutus menziesii*), California bay (*Umbellularia californica*), and several oak species (*Quercus* spp.). To a lesser extent, big leaf maple (*Acer macrophyllum*) can also be found in the *S. sempervirens* subcanopy, primarily within riparian zones (Martin, 1998). Understory species associated with the *S. sempervirens* forest in the Santa Cruz mountains include California huckleberry (*Vaccinium ovatum* Pursh), thimbleberry (*Rubus parviflorus*), and California hazelnut (*Corylus cornuta* spp. *californica*). The non-woody herbaceous ground cover species can be comprised of five-finger fern (*Adiantum aleuticum*), wild ginger (*Asarum caudatum*), and sword fern (*Polystichum munitum*), as well as several other species (Martin, 1998).

Wildlife that depends upon coast redwood habitats include several federally threatened and endangered species. Most notably, an endangered seabird, the marbled murrelet (*Brachyramphus marmoratus*), nests in old-growth *S. sempervirens* and *P. menziesii* trees (Barbour et al., 2001; Waldron, 1998). Other notable bird species that can be found in the coast redwood forest include the northern spotted owl (*Strix occidentalis caurina*), pileated woodpecker (*Dryocopus pileatus*), and downy woodpecker (*Dryobates pubescens*) (Waldron, 1998). Mammals that frequent the coast redwood forest include Roosevelt elk (*Cervus Canadensis roosevelti*) in the north, and black tail deer (*Odocoileus hemionus columbianus*) (a subspecies of mule deer) throughout the entirety of the range, as well as several species of bats.

In terms of aquatic species, of particular importance to land managers are the salmonid species, which utilize streams and debris located in and produced from the coast redwood forest. Along the extent of the *S. sempervirens* range, chinook salmon (*Oncorhynchus tshawtscha*), coho salmon (*Oncorhynchus kisutch*), and steelhead trout (*Oncorhynchus mykiss*) can all be found in the rivers and streams weaving their way through the coast redwood understory (Barbour et al., 2001). Santa Cruz County serves as the southernmost spawning range for the locally endangered coho salmon and near the southern extent for the threatened steelhead trout (Hafs, Harrison, Utz, & Dunne, 2014; Rischbieter, 2000). Both salmonid species rely heavily on the deposition of coarse woody debris in streams and waterways in order to survive and thrive (Hafs et al., 2014).

Old-growth coast redwood stand characteristics. Although relevant literature lacks a single unifying definition of “old-growth” (Bolsinger & Waddell, 1993) it is commonly defined as stands that have never been harvested (Sawyer et al., 2000). Along the entirety of its ~720 km range, only 3-5% of the historic distribution of old-growth *S. sempervirens* stands are still present (Barbour et al., 2001; Griffith, 1992). The majority of the remaining *S. sempervirens* forests represent relatively even-aged second-growth stands existing as a result of heavy logging pressure during the late 19th and early 20th centuries. The largest remaining tract of old-growth *S. sempervirens* stands, south of San Francisco, is located in Big Basin Redwoods State Park, near the town of Boulder Creek (California Department of Parks and Recreation, 2003).

Old-growth *S. sempervirens* stands are commonly contrasted with second-growth stands based off characteristics such as stand density, tree size, stand structure, and understory herbaceous species composition. However, significant variation exists between unharvested old-growth stands. Some studies typify old-growth stands based upon unifying old-growth characteristics, however high variability between old-growth stands limits the usefulness of this exercise. In addition, in their study, Russell and Michels (2010), found that several stand-level metrics in previously harvested second-growth coast redwood stands (including stand density) reached old-growth equivalence in less than a century. Of concern from a fuel loading perspective, is the potential increased stand density of many second-growth coast redwood stands compared to old-growth stands. When the aboveground portion of a coast redwood experiences a mortality event, such as logging or high intensity wildfire, coast redwoods have the ability sprout from

dormant buds along the root crown or remaining stump creating a phenomenon often referred to as a “fairy ring.” When this occurs, on average five successful clonal sprouts attain harvestable maturity from a single stump (Boe, 1975; Griffith, 1992). As a result of this vigorous sprouting following a top kill event, second-growth forests can exhibit significantly higher stand density than their old-growth counterparts as the natural senescence of clonal cohorts proceeds (Guisti, 2007).

In addition to low stand density, the presence of reiterated trunks and large diameter lateral branches in the forest canopy are considered characteristics of *S. sempervirens* old-growth stands, compared to second-growth stands (Sawyer et al., 2000; Sillet & Van Pelt, 2007). These reiterated trunks and lateral branches create a complex crown structure that can support several special status flora and fauna in the coast redwood overstory (Sawyer et al., 2000; Sillet & Van Pelt, 2007).

As a result of the long-lived nature of the *S. sempervirens* species and its resilience to disturbance, the presence of hollow caves in the basal area of *S. sempervirens* trees is another indicator of an old-growth *S. sempervirens* stand (Gellman & Zielinski, 1996). These hollow caves are a result of a cyclical pattern of fire and decay, characteristic of the habitat type (Barbour et al., 2001; Gellman & Zielinski, 1996). Often non-impactful to the short-term mortality of the tree, the subsequent creation of fire caves can eventually lead to an increased prevalence of mortality due to windthrow and the loss of structural integrity at the base of the tree (Barbour et al., 2001).

In addition, the floristic composition of the *S. sempervirens* understory varies based upon stand age and ultimately between old-growth and second-growth stands (Russell &

Michels, 2010). Studies have shown that due to natural recovery of *S. sempervirens* stands, floristic composition can reach old-growth equivalence over a relatively short time scale (80-120 years) (Russell & Michels, 2010). Common species associated with old-growth *S. sempervirens* forests in particular include Hooker's fairy bells (*Prosartes hookeri*), Pacific starflower (*Lysimachia latifolia*), Pacific trillium (*Trillium ovatum*), redwood violet (*Viola sempervirens*), and redwood sorrel (*Oxalis oregana*) (Russell & Michels, 2014).

Ecology of associated tree species.

Douglas fir (*Pseudotsuga menziesii* var. *menziesii*). In the Santa Cruz mountains, the most common associated overstory tree species in the coast redwood forest is *P. menziesii* var. *menziesii* (Martin 1998). *Pseudotsuga menziesii* var. *menziesii* ranges from British Columbia to the central coast of California, with the Santa Cruz mountains serving as the southern extent of its range (Uchytil, 1991). *Pseudotsuga menziesii* var. *menziesii* is a coniferous, evergreen tree species, generally adapted to wetter climates. Older *P. menziesii* var. *menziesii* trees are relatively fire tolerant, when compared to similar conifer species, with fire tolerance increasing significantly with age. Larger *P. menziesii* var. *menziesii* individuals can withstand moderate intensity understory fires due to the development of thick, corky bark and a canopy layer that often begins towards the upper portion of the bole (Uchytil, 1991). Unlike *S. sempervirens*, *P. menziesii* var. *menziesii* is unable to basally sprout and thus relies on seed dispersal for reproduction. *Pseudotsuga. menziesii* var. *menziesii* are relatively shade tolerant and able to germinate in moderate shade and outcompete associated hardwood species, in the absence of

disturbance events such as fire (Cocking, Varner, & Sheriff, 2012). Along the entirety of its range, *P. menziesii* var. *menziesii* occurs from sea level to above 1524 m and grows best in deep, well-aerated soils (Uchytel, 1991).

Tanoak (*Notholithocarpus densiflorus*). The majority of the *S. sempervirens* habitat found in the Santa Cruz mountains, is classified as upland coast redwood communities. *Notholithocarpus densiflorus* is a common species inhabiting the subcanopy layer within this community type, occurring most often on mesic slopes. *Notholithocarpus densiflorus* occurs from southern Oregon throughout California with the southern extent of the range occurring near Santa Barbara (Fryer, 2008). *Notholithocarpus densiflorus* typically occur as a tree or shrub, attaining a maximum height of about 24.4 m (Fryer, 2008). In Big Basin Redwoods State Park, in one study, it was determined that the average diameter at breast height (DBH) of understory *N. densiflorus* in old-growth *S. sempervirens* and *P. menziesii* var. *menziesii* forests was around 50.8 cm (Hunter & Parker, 1993).

Notholithocarpus densiflorus is capable of both direct seeding and basal sprouting following damage to the above ground portion of the tree (Plumb, Timothy, & McDonald, 1981). Historically, some Native American groups ignited low intensity understory burns after acorn harvesting, in order to kill predatory insects as well as reduce the understory shrub layer which made navigating the understory easier (Pavlik, Muick, Johnson, & Popper, 1991). A result of vigorous basal sprouting following top-kill events is that *N. densiflorus* have the potential to create considerable live fuel loads in the understory. In addition, *N. densiflorus* create a heavy litter layer in the understory. *Notholithocarpus*

densiflorus leaves are highly flammable, containing a significant content of resin, oil, and wax (Stuart & Stephens, 2006). This, coupled with the vertical continuity of the shrub and subcanopy layers of *N. densiflorus* in the *S. sempervirens* understory give high concentrations of *N. densiflorus* the potential to create moderate to high intensity fire events.

Sudden Oak Death (*Phytophthora ramorum*) has been gaining severity in the Santa Cruz mountains and has a significant presence in both Castle Rock and Big Basin Redwoods State Park. Sudden Oak Death often leaves *N. densiflorus* individuals standing dead or as snags, with a decreased foliar moisture content compared to their live counterparts (Kuljian & Varner, 2010). *Sequoia sempervirens* and *P. menziesii* var. *menziesii* stands with high rates of Sudden Oak Death have been shown to exhibit increased surface fuels and the potential for increased fire behavior due to longer flame lengths and higher rates of spread (Forrestel, Ramage, Moody, Moritz, & Stephens, 2015).

Pacific Madrone (Arbutus menziesii). Pacific madrone (*A. menziesii*) is another common subcanopy tree species found within the southern portion of the *S. sempervirens* forest range. *Arbutus menziesii* is a broadleaved, evergreen tree species found from British Columbia to southern California. The species has irregularly shaped, curving branches and smooth trunks with peeling bark. *Arbutus menziesii* is generally drought resistant, resistant to windfall, and capable of both sexual and asexual reproduction through direct seeding as well as burl sprouting (McDonald & Tappeiner, 2002). The species typically exhibits a low to moderate shade tolerance and are often found in

conifer stands after disturbance events (Veirs, 1981). In *S. sempervirens* stands, *A. menziesii* is considered a fire-dependent, seral species (Veirs 1981). Although exhibiting a low resistance to fire, *A. menziesii* depends upon fire in order to compete with taller associated species that can shade out this shade intolerant species (Veirs, 1981). Within Big Basin Redwoods State Park, in particular, *A. menziesii* in mixed evergreen and *S. sempervirens* forests are typically found on east and south facing slopes within the park, often in drier, high elevation portions (Martin, 1998).

Coast redwood fire ecology and historic regimes. Disturbance events contribute to the pattern of vegetation in the *S. sempervirens* forest, creating a patchwork of discontinuous spatial and temporal landscape variation (Barbour et al., 2001; Sousa, 1984). Fires in the *S. sempervirens* plant communities are a common occurrence. Visual evidence can be provided by charred boles, burnt basal cavities, and evidence in annual growth rings (Barbour et al., 2001). Significant variability in fire frequency and effects of fire have been found for *S. sempervirens* forests in the central coast region (Greenlee, 1983; Jones & Russell, 2015; Stephens & Fry, 2005).

Stephens and Fry (2005) determined a grand mean fire return interval (FRI) of 16.3 years in the northeastern portion of the Santa Cruz mountains. However, these numbers varied greatly from site to site. The oldest recorded fire in the northeastern Santa Cruz mountains was determined to be in approximately 1615, with the latest recorded fire in 1884 (Stephens & Fry, 2005). In addition, they found that surface fires were common until the late 19th century, when widespread fire suppression became prevalent throughout much of the United States. Before the 1770s and introduction of the first

European settlers, it is believed that the indigenous people in the area were the primary source of ignition for fires in the coast redwood understory (Greenlee, 1983). Fire scars indicate that the majority of fires occurred during the dormant stages of the *S. sempervirens* life cycle, from October until April (Stephens & Fry, 2005).

Jones and Russell (2015) utilized similar methodologies, however yielded different results. Their study analyzed fire scars from individual stumps, downed logs, and live trees, in order to determine the fire return interval for the southern portion of the *S. sempervirens* range. They determined that the mean FRI across all point samples was 60.6 years, however further breakdown indicated a pre-European settlement mean FRI of 43.3 years and 30.7 years for the period between 1850 and 1924. Between the years of 1925 and 2013 the mean FRI was determined to be 32.3 years (Jones & Russell, 2015). These calculations differ from Stephens and Fry (2005), indicating a higher (less frequent) FRI for the pre-settlement era and a higher mean FRI for the region in general. Microclimatic and topographic variations within the sampled location yielded drastically different FRIs for point sample measurements (Jones and Russell, 2015), further illustrating the overall variability of wildfire frequency and intensity within close geographic proximity. In addition, although the majority of samples yielded relatively short FRIs, several samples demonstrated uncharacteristically long FRIs, altering the overall mean and median FRIs within the study (Jones & Russell, 2015).

Along the northern coast of California, several studies have looked at fire regime histories in *S. sempervirens*/ *P. menziesii* var. *menziesii* dominated forests in Point Reyes National Seashore, Jackson State Forest, and Redwood National Park. Although fire

history reconstructions proved to be an extremely difficult task, it was determined that historic regimes in these regions trended towards frequent surface fires, likely with anthropogenic origins due to the low occurrence of lightning in forests along the California coast (Brown, 2007; Brown & Baxter, 2003; Brown, Kaye & Buckley, 1999; Brown & Swetnam, 1994).

Possibly, the most comprehensive study on the fire history of in the Santa Cruz Mountains in particular, utilized Big Basin Redwoods State Park as a study site and was performed by Greenlee (1983). In a portion of the study, he utilized fire scar cores sampled from within the park, to determine fire history and frequency. It was determined that composite mean FRI was 45.4 years within the park, again with the majority of the ignitions occurring in the late fall and early winter months during the latewood and dormant portions of the *S. sempervirens* phenological cycle (Greenlee, 1983). In the entire temporal range of his study, the mean fire interval was about 70 years. In addition, Greenlee (1983) divided the fire history within the region into five distinct eras, characterized by the primary causality of ignition over a temporal scale. Time periods included ancient, defined as prior to 11,000 years ago, aboriginal usage (11,000 years ago to 1792), Spanish and Mexican influence (1792 to 1848), Anglo-European (1848 to 1929), and present time (1929 to the present).

Although varying in frequency, causality, and intensity, it is evident that fire has been an integral facet of the ecology of *S. sempervirens* in the southern portion of its range. Similar to the variation in frequency with which fire occurs in the *S. sempervirens* forest, the response of *S. sempervirens* and associated tree species vary as well. *Sequoia*

sempervirens are largely considered a fire-adapted rather than fire-dependent species. In a study of both old-growth and second-growth *S. sempervirens* stands, researchers determined that *S. sempervirens* outcompeted associated tree species in both bole survival as well as post-fire basal sprouting (Ramage, O'hara, & Caldwell, 2010). It was also demonstrated that *S. sempervirens* reacted more favorably to high severity fires than did associated tree species (Ramage et al., 2010). In a study of *S. sempervirens* response to fire in the southern portion of their range, Lazzeri-Aerts and Russell (2014) found similar results, with *S. sempervirens* exhibiting lower mortality, sprouting, seeding, and canopy retention, following fire events than associated tree species.

It is likely that with the onset of widespread fire suppression during the 20th century, the structure and composition of *S. sempervirens* forests took a drastic shift (Brown, 2007). Frequent, low intensity understory fires promote a low density stand composition by killing fire intolerant young trees and other associated fire intolerant species found in the *S. sempervirens* forest. In addition, it's believed that frequent, low intensity fires likely reduce the abundance of shrubs, dead and downed coarse and fine woody fuels, and duff layer (Brown, 2007). It is also likely that fires of this type break up vertical fuel continuity by the elimination of young hardwood and fire intolerant species, before they can reach the coast redwood canopy layer. With the prevalence of fire suppression in the 20th century, the accumulation of the above-mentioned fuel loading and stand composition and density changes may result in an increase in the abundance of high-intensity crown fires and stand killing events (Brown, 2007).

Some of these factors, including fuel bed depth and biomass, were investigated in a study by Greenlee (1983), looking at the fuel loading of burned and unburned areas of Big Basin Redwoods State Park after a fire in October of 1974. The results indicated a significantly decreased duff depth in the burned portion of the park compared to the unburned. However, aboveground-downed biomass was variable in both unburned and burned plots. In general, burned plots exhibited fewer fine woody fuels compared to unburned plots and more coarse woody fuel due to fallen branches. In this same study, Greenlee (1983) challenged the notion that fire suppression has had an increase on fire intensity over the last 100 years, however, found evidence to support the idea that the frequent understory burning performed by indigenous groups decreased the overall fuel loading of the *S. sempervirens* forests in that region (Greenlee, 1983). In addition, the current era, characterized by fire suppression, began around 1927 (Greenlee & Langheim, 1990), indicating that *S. sempervirens* fuel loading and compositional changes will have future repercussions on wildfire intensity.

Indigenous fire history in the Santa Cruz mountains. The occurrence of fire in the *S. sempervirens* understory in the Santa Cruz mountains is evident through the prevalence of fire scars and other indicators of past fire history. In the central and northern coasts of California, naturally occurring fire events are relatively rare due to a frequent marine layer, as well as low occurrences of lightning events (Lorimer et al., 2009; Keeley, 2002; Stephens & Fry, 2005). Instead, anthropogenic fires have been more prevalent for the last several thousand years in this region (Brown, 2007; Greenlee, 1983; Greenlee & Langenheim, 1990; Jones, 2014; Stuart & Stephens, 2006). In the northeastern Santa

Cruz mountains, a researcher from one study determined that lightning sourced fires, prior to indigenous ignitions, ranged from about one every 100 to 150 years (Greenlee, 1983). Subsequently, during the time of heavy indigenous presence in the region the mean FRI dropped significantly and continued to remain low through the periods of heavy Spanish and Mexican influence, early white settlers, and has begun to increase since the era of fire suppression beginning in the early 1900s (Greenlee, 1983; Greenlee & Langenheim, 1990).

Intentional indigenous use of fire in California has been widespread and heavily researched (Greenlee, 1983; Greenlee & Langenheim, 1990; Jones & Russell, 2015). The Monterey Bay area historically hosted one of the densest indigenous populations in California and in all of North America (Greenlee & Langenheim, 1990). Existing primarily on the coast and in oak woodlands and prairies, indigenous groups in the Monterey Bay area likely did not frequent or inhabit the *S. sempervirens* understory, due to its general lack of resources and the prevalence of grizzly bears prior to Spanish and European settlement (Greenlee & Langenheim, 1990). Although it is unlikely that Native Americans intentionally burned in the *S. sempervirens* understory, it can be inferred that ignitions in adjacent vegetation types likely spread to the coast redwood understory and accounted for the increase in fire frequency exhibited during periods of heavy indigenous usage (Greenlee, 1983; Greenlee & Langenheim, 1990; Jones & Russell, 2015). Prior to influence from Spanish missionaries, it is believed that indigenous groups in the central coast of California primarily utilized fire as a tool for managing grass and shrublands as well as encouraging the growth of acorn-bearing tree species found in that region and to

create fire breaks and clearings around settlements (Keeley, 2002; Pavlik et al., 1991).

These periodic anthropogenically sourced burns likely had effects on the composition and types of plant communities found in this region for the past 11,000 years (Greenlee, 1983).

The fire regimes of the *S. sempervirens* understory along the southern portion of its range, more specifically the Monterey Bay area, can be broken down into five distinct time periods, mentioned earlier (Greenlee, 1983; Greenlee & Langenheim, 1990). The first distinct period, occurring up to 11,000 BP, is characterized by relatively long FRIs with primarily lightning caused ignitions. The second distinct period, occurring from 11,000 BP until 1792 AD, is characterized based upon the influence of aboriginal/indigenous tribes and anthropogenically sourced ignitions. During this time period, it is believed that fire return intervals began to decline as these intentional anthropogenically sourced fires gained prevalence. The introduction of the Spanish missionaries in 1792 marked the beginning of the third time period, in which anthropogenically sourced fires continued to be the primary driving force for *S. sempervirens* forest ignitions. With the introduction of Anglo-European settlers in 1848, the fourth distinct period was characterized by frequent, low intensity fires in the *S. sempervirens* forest, although primarily thought to be either unintentional or a means of removing post-logging slash. Finally, the period from 1929 until present time can be characterized by increasingly longer FRIs and low fire frequency. Primarily due to suppression of fire and low overall usage of fire as a landscape management tool (Greenlee & Langenheim, 1990).

Prescribed fire as a management tool. Goals of prescribed fire in forested ecosystems typically centralize around two general themes; managing landscapes for pre-European forest stand compositions by implementing a historic fire regime (Knapp, Lydersen, North, & Collins, 2017; Scherer, D'Amato, Kern, Palik, & Russell, 2016; Engber et al., 2017), or reducing fuel load by attempting to decrease dead and downed woody fuel and fire intolerant species (Norman et al., 2009). Results vary based upon dominant overstory species, the time-gap since a previous disturbance, seasonality, as well as several other factors (Biswell, 1989).

Long term studies allow researchers and land managers to assess the impacts of prescribed fire and other fuel treatments over timescales that are more comparable to natural disturbance regimes. Results have been varied; however, in western conifer forests, researchers have found increases in tree spacing, age and size heterogeneity, and beneficial shifts in species composition following prescribed fire (Knapp et al. 2017; Scherer et al. 2016). In one study in particular, by Scherer, D'Amato, Kern, Palik, and Russell (2016), researchers found sites dominated by *Pinus resinosa* (red pine) treated with prescribed fire over a span of 60 years, had an increase in large diameter trees as well as a decrease in stand density and basal area. Larger, more widely spaced trees tend to show an increased individual vigor and resiliency to fire damage as well as fire spread. In a comparable study by Zachman, Shaw, and Dickson (2018), researchers determined similar shifts in tree density and individual growth, however found a decrease in large diameter trees following prescribed fire, in mixed conifer forests in the Sierra Nevada.

Assessments of fuel loading, of dead and downed woody fuel are typically more variable than stand composition. Fuel treatments such as variable density thinning, which often accompany prescribed fire (Knapp et al. (2017), can result in artificial loading of surface fuels and thus potential increases in fire behavior and ignitions sources. However, studies by Knapp, Lyderson, North and Collins (2017) and Zachmann et al. (2018), have shown that treatment prescriptions of combining variable density thinning and prescribed fire, as well as isolating prescribed fire, show reductions in surface fuel loading, when compared to untreated plots and plots treated only with variable density thinning.

Prescribed fire in the coast redwood forest. The varied and inconsistent fire regimes and fire return intervals for the *S. sempervirens* forest create a host of problems for land managers attempting to manage the landscape both for ecological integrity and human usage. The task of mimicking a historic fire regime in a given landscape becomes more difficult when the dominant species is unusually long lived, and the habitat type and region has experienced varied disturbance regimes.

Goals of prescribed fires in the *S. sempervirens* understory can be broken down into two scenarios. In one scenario land managers utilize prescribed fire in an attempt to reduce stand density, reduce fuel load, and increase relative dominance of *S. sempervirens* (Engber et al., 2017). Second-growth *S. sempervirens* stands often exhibit high stand density, simple canopy structure, and codominance of shade tolerant Douglas fir. In the absence of large-scale disturbance events, which naturally occur on a relatively long time scale (centuries), *Pseudotsuga menziesii* var. *menziesii* and other less

disturbance adapted conifer species have the potential to outcompete *S. sempervirens* in the short term (Engber et al., 2017). In addition, forests exhibiting even-aged, young stand structures are less disturbance tolerant on a landscape perspective and have the potential of increasing wildfire intensity in a given region (Engber et al., 2017).

Another scenario involving prescribed fire in the *S. sempervirens* understory is to utilize fire as a management tool in old-growth *S. sempervirens* stands (Norman et al., 2009). Old-growth *S. sempervirens* stands exhibit the highest fuel accumulation on a volumetric scale of any forest type on earth (Norman et al., 2009). Ignition of deadfall and duff accumulated around old-growth *S. sempervirens* trees has the potential to girdle standing trees, eventually leading to mortality (Norman et al., 2009). In addition, an increase in wildfire intensity could have potential adverse effects on surrounding commercial timber operations, an ever-growing wildland-urban interface, as well as various flora and fauna that inhabit the *S. sempervirens* forest. Through the use of low intensity, intentional understory burns during wetter months, hazardous fuel loading can be mitigated, and the potential deleterious effects of wildfire can be avoided, such as individual old-growth tree mortality (Norman et al., 2009).

As a means of reducing stand density and increasing relative dominance of *S. sempervirens* in second-growth stands, the results of prescribed fire are variable. In a study by Engber, Teraoka, and Mantgem (2017), looking at the use of prescribed fire in second-growth stands in Redwood National Park, low intensity fire was shown to have almost no effect on overstory canopy composition (Engber et al., 2017). Some mortality of trees smaller than 30 cm diameter was exhibited, however for the most part medium to

high intensity fire was required to reduce the density of even aged Douglas fir. In addition, within seven years fine woody fuels had fully recovered in the majority of the plots treated with prescribed fire (Engber et al., 2017).

Big Basin Redwoods State Park, in Boulder Creek is the oldest State Park in California, containing the largest stand of continuous *S. sempervirens* trees south of San Francisco (California Department of Parks and Recreation, 2003). Since 1978, land managers at Big Basin have performed varying sized prescribed fire operations in mixed-age *S. sempervirens* stands during the fall/winter months of October through January (personal communication, Environmental Scientist Tim Hyland, 2018). Prescribed fire operations have occurred roughly every 2 to 3 years, ranging from 5.5 to 160 ha and while prescribed fire operations have varied somewhat based on time of year, size, and dominant habitat type in a given site, fires have primarily been limited to low intensity burns in the understory. According to the California Department of Parks and Recreation (2010) specific objectives within old-growth *S. sempervirens* stands include:

- Mortality of 90% of *A. menziesii* and *N. densiflorus* under 10.16 cm.
- Mortality of 40% of stems of intermediate size classes.
- Mortality of 5% of trees greater than 30.5 cm DBH.
- Duff layer reduction of 80% with maintenance of 20% layer to prevent erosion.
- Reduction of 75% of downed woody fuels.
- Reduction of brush species and huckleberry.

General objectives centralize around reintroducing fire in a managed setting, protecting park resources and adjacent private land, and maintaining forest late seral stages and

natural vegetative mosaics (Department of Parks and Recreation, 2010). With nearly four decades of anecdotal evidence, little empirical monitoring supports the achievement of the aforementioned goals.

Problem Statement

While the effects of prescribed fire are well studied in other forest types, little published research exists regarding the effects of prescribed fire in old-growth *S. sempervirens* stands. In addition, although the California State Park system has an extensive and established prescribed fire program, little if any empirical monitoring has been performed on previous burn sites to assess effectiveness of prescribed fires in regards to fuel loading of both live and dead woody fuel accumulation. Further gaps in knowledge exist regarding monitoring of stand and understory compositions following prescribed fire in the southern range of *S. sempervirens* as well. Post-fire mortality following wildfire in this region has been analyzed (Andrews & Dicus, 2012; Lazzeri-Aerts & Russell, 2014), however no studies assessing the fuel load and stand composition following prescribed fire in the region exist.

With catastrophic fires increasing in frequency in California and in the Western United States in general, understanding the effects of a century of fire suppression on forest stand and understory ecosystems is paramount. Furthermore, developing steps towards attaining a healthy, fire-tolerant and biodiverse ecosystem is essential, in the current ecological context. Due to the high productivity of the *S. sempervirens* understory (Norman et al., 2009), fire suppression increases the risk of higher intensity wildfires in the future. In redwood forests, the natural effects of fire and their influence

on the landscape are well studied; however, the means of best replicating and reintroducing these disturbance regimes are not well understood.

Research Objectives

The objectives of this study were to: 1) determine how prescribed fire affects fuel load in *S. sempervirens* stands of different post fire ages; and 2) to describe how prescribed fire influences stand characteristics and composition, as well as floristic composition, in *S. sempervirens* stands of different post fire ages in burned versus unburned locations.

Research Questions and Hypotheses

Question 1: Does prescribed fire have an effect on fuel load in the *S. sempervirens* understory?

- 1a. Do duff, litter, and fuel depths change with presence or absence of prescribed fire, and time since prescribed fire?
- 1b. Does downed fine woody fuel (1-hr, 10-hr, 100-hr size class) accumulation vary with presence or absence of prescribed fire, and time since prescribed fire?
- 1c. Does coarse woody fuel (<1000-hr + size class) accumulation vary with presence or absence of prescribed fire, and time since prescribed fire?
- 1d. Do sites treated with prescribed fire exhibit a different size class distribution than sites that did not experience prescribed fire?

Hypothesis 1: Fuel load will increase with time since prescribed fire, with all burn sites exhibiting less fuel loading than the unburned reference area.

1a. Duff, litter, and fuel depths will be higher in sites treated with prescribed fire and increase with time since prescribed fire.

1b. Downed fine woody fuel accumulation will be higher in sites treated with prescribed fire and increase with time since prescribed fire.

1c. Downed coarse woody fuel accumulation will remain constant with time since prescribed fire and between burned and unburned sites.

1d. Sites treated with prescribed fire will exhibit a size class distribution favoring older more mature trees than unburned sites.

Question 2: Does stand density differ between sites treated with prescribed fire and sites not treated with prescribed fire, and time since prescribed fire?

Hypothesis 2: Stand density will be greater in sites not treated with prescribed fire and increase with time since fire.

Question 3: Does basal dominance of *S. sempervirens* and associated tree species between sites treated with prescribed fire and site not treated with prescribed fire, and time since prescribed fire?

Hypothesis 3: *Sequoia sempervirens* will exhibit an increased basal dominance in sites treated with prescribed fire, and *N. densiflorus* will exhibit an increased basal dominance in sites not treated with fire.

Question 4: Does canopy cover vary with presence or absence of prescribed fire and time since prescribed fire?

Hypothesis 4: Presence or absence of prescribed fire and time since prescribed fire will have no effect on canopy cover.

Question 5: Does prescribed fire affect *S. sempervirens* understory plant composition?

5a: Does understory species richness change with presence or absence of prescribed fire and time?

5b: Does understory associated plant species abundance change with presence or absence of prescribed fire and time since fire?

Hypothesis 5: Prescribed fire will have an effect on *S. sempervirens* understory plant composition.

5a: Understory species richness will be higher in sites treated with prescribed fire.

5b: Abundance of associated understory species will increase in sites treated with prescribed fire.

Chapter 2: Journal Article

Abstract

Background: With the prevalence of catastrophic wildfire increasing in response to widespread fire suppression, and shifts in climatic patterns, land managers have sought methods to increase the resiliency of landscapes to fire. The application of prescribed burning in ecosystems adapted to fire can reduce fuel load and fire potential while minimizing the impacts of mechanical fuel treatments. Coast redwood forests have experienced fire historically from both natural and anthropogenic sources, and are likely to respond favorably to its reintroduction.

Results: Random sampling across a chronosequence of burned and unburned reference sites in an old-growth coast redwood forest was used to collect data on downed woody fuel and receptive fuel bed depth, as well as forest structure and understory species composition. Fuel load, duff depth, and litter depth were found to be significantly lower on sites treated with fire compared to unburned sites. Density of live fuels, including the juvenile stems of the dominant subcanopy species tanoak (*Notholithocarpus densiflorus*) and a variety of woody shrub species, exhibited lower levels on plots that had been treated with prescribed fire, compared to those that had not. Both downed wood fuel and live fuel measures were positively correlated with time since last burn, with the lowest measures on the most recently burned sites. Density of the dominant overstory canopy species coast redwood (*Sequoia sempervirens*) and Douglas fir (*Pseudotsuga menziesii* var. *menziesii*) remained consistent between treatments. In addition, shade tolerant

herbaceous understory plant species associated with coast redwood forests appeared to not be impacted by burning.

Conclusion: Results indicate that prescribed fire can provide beneficial reductions in fuel load and juvenile tree and shrub species density without impacting overstory canopy or shade tolerant understory species.

Keywords: Coast redwoods, prescribed fire, *Sequoia sempervirens*, tanoak, *Notholithocarpus densiflorus*, stand composition, stand structure, fuel load, fuel reduction

Background

Ecological systems are rarely in a static state, but rather are influenced by dynamic disturbances that shape ecological communities and resource availability (Pickett & White 1985; Reice 1994). Within forested ecosystems, disturbance can take many forms including wind events, landslides, floods, and fires (Barbour et al. 2001). Frequency, intensity, and seasonality of disturbance, coupled with environmental factors, form heterogenous vegetative mosaics on the landscape (Romme and Knight 1982; Foster 1988a; Peet 1988; Veblen et al. 1992; Hadley 1994). Along the coast of California, fire has historically been and will continue to be a driving force behind species composition and ecosystem development. Unlike other forested ecosystems within California, the plant communities that characterize the *Sequoia sempervirens* forest do not require disturbance in order to reproduce, colonize, or persist into a seral state (Busing & Fujimori 2002), but rather have adapted to this potentially frequent disturbance.

Throughout the last 11,000 years, due to limited natural ignition sources, anthropogenically sourced fires have frequented the landscape of western North America. Within the *S. sempervirens* ecosystem, cambial scars in the dormant/latewood portion of sampled trees indicate a history of low-intensity surface fires with increased frequency near grasslands, oak woodlands, and areas with heavy historical indigenous usage (Greenlee 1983; Stephens and Fry 2005; Jones and Russell 2015). Although maintaining a host of adaptations to fire, including prolific vegetative sprouting, fibrous bark, and a high canopy (Barbour et al. 2001), fire may not serve as a primary ecosystem driver within the *S. sempervirens* forest. Past studies on mean fire return interval (FRI) have been variable, with mean FRI in Santa Cruz and San Mateo counties in the 15 to 60 yr range, and a declining frequency with the onset of Anglo-European influence and shifts in land usage and management regimes (Greenlee 1983; Stephens and Fry 2005; Jones and Russell 2015).

Due to its massive size and long-lived nature, *S. sempervirens* produces the largest fuel load of any ecosystem type ever recorded, with some studies estimating total fuel load between 252 and 619 Mg ha⁻¹ (Norman et al. 2009). Occurring primarily in coastal regions experiencing maritime fog, the *S. sempervirens* forest does not occur in a typically fire-prone environment. However, due in part to shifts in climatic factors and land usage, historic disturbance regimes are changing (Turner, 2010). Shifts in plant communities, both native and non-native, can create changes in fuel beds and thus fire behavior, timing, and intensity (Mack and D'Antonio 1988; D'Antonio and Vitousek 1992; Brooks et al. 2004; Metz et al. 2013).

Sequoia sempervirens maintains a competitive advantage over associated tree species including *N. densiflorus* due to prolific reproduction as well as a relatively low mortality following fire (Lazzeri-Aerts and Russell 2014). In addition, larger diameter trees (>30 cm DBH) retain lower mortality rates than smaller diameter trees following fire (Lazzeri-Aerts and Russell 2014; Engber et al. 2017). This is due in part to the thicker bark developed in conifer species in maturity as well as the increase in canopy height with age (Barbour et al. 2001). In a study by Nives (1989), distance between surface fuels and canopy fuels is described as the Fuel Strata Gap (FSG). Increased density of juvenile trees, shrubs, and fire prone species decreases a stand's FSG by creating vertical fuel continuity (or ladder fuels).

The three basic factors that influence fire behavior are fuel, weather, and topography (Biswell 1989). Weather and topography are largely unmanageable and thus fuel reduction and vegetation management are used by land managers to mitigate high intensity wildfires. Vegetation-related factors that influence fire behavior include fuel load of the forest surface, fuel bed depth, density of juvenile seedlings and sprouts, as well as receptive fuel bed moisture content (Keyes and Varner 2006). Fuel type and continuity, both vertical and horizontal, help dictate a fire's rate of spread and intensity. Continuous fine woody fuels (0 to 7.6 cm diameter) allow fire to ignite and spread rapidly, whereas a high loading of coarse woody fuels (7.6 + diameter) are slower to ignite, but will continue to burn longer and generate more energy (Biswell 1989).

As a means of reducing fuel load within the *S. sempervirens* ecosystem, land managers have resorted to several methods including variable density thinning,

strategically situated shaded fuel breaks, and prescribed fire. With a host of impacts associated with the use of manual and mechanical fuel reduction in the *S. sempervirens* fuel type (Loya and Jules 2008; Russell and Michels 2010; Russell and Hanover 2018), prescribed fire may serve as a means of achieving ecosystem functions and fuel reduction goals simultaneously.

Goals of prescribed fire include reduction of downed woody debris, consumption of juvenile and hardwood species, and consumption of receptive fuel beds (California Department of Parks and Recreation 2010). Prescribed fires conceptually attempt to reduce fuel load and break up horizontal fuel continuity and vertical fuel arrangement, or the spacing between fuels on a vertical and horizontal plane (Biswell 1989).

The purpose of this study was to quantify the impacts of several decades of prescribed fire in the *S. sempervirens* understory, in regard to forest stand composition, structure, fuel load, and understory species assemblage. As fire suppression impacts continue to increase, and frequency and intensity of wildfires increases a renewed focus has been placed upon the fire prevention and fuel manipulation phase of forest management, with impacts to understory plant species and overall forest health increasingly becoming a secondary concern.

Abbreviations

ARME: *Arbutus menziesii* (Pacific madrone)

BBRSP: Big Basin Redwoods State Park

CWF: Coarse woody fuels (1000+ hr fuel particles, >7.6 cm diameter)

DBH: Diameter at breast height (measured at 1.4 meters above soil surface on the uphill side)

FRI: Fire Return Interval

FWF: fine woody fuels (1, 10, and 100-hr fuel particles, <7.6 cm diameter)

JREB: Johansen road (east) prescribed burn project (burned)

NERU: North escape road sample site (unburned)

NODE: *Notholithocarpus densiflorus* (tanoak)

OVSF: Ocean view summit prescribed burn project (burned)

PSME: *Pseudotsuga menziesii* var *menziesii* (Douglas fir)

SESE: *Sequoia sempervirens* (coast redwood)

SOD: Sudden Oak Death

SUNU: Sunset trail sample site (unburned)

S2SB: Skyline to the sea prescribed burn project (burned)

S2SU: Skyline to the sea prescribed burn project (unburned)

QU sp.: *Quercus* species

Methods

Study Sites

Big Basin Redwoods State Park (BBRSP) is the oldest State Park in California, located approximately 37 km northwest of the city of Santa Cruz, in the Santa Cruz Mountains.

The park rests in two county jurisdictions, Santa Cruz and San Mateo (California

Department of Parks and Recreation 2003). The majority of BBRSP was set aside in

1902 via the passing of a 1901 State bill creating California Redwood Park. In 1927, California Redwood Park was renamed Big Basin Redwoods State Park. A total of ~3110 hectares were set aside in the initial creation of the park in order to protect old-growth *S. sempervirens* stands from the rapid expansion of logging operations by 1916 (California Department of Parks and Recreation 2003).

Big Basin Redwoods State Park is in the southern end of the Marine West Coast Climatic Zone (Martin 1998). To the south and east of the park lies the Mediterranean Climatic Zone, which heavily influences the climate of the park as well. Due to its proximity to the coast and maritime influence, BBRSP does not experience extreme seasonal changes, and exhibits high relative humidity and consistent temperatures throughout much of the year (Martin 1998).

Elevation within BBRSP ranges from sea level in the western portion of the park to just over 600 m; however, the portion of the park comprised of primarily old-growth *S. sempervirens* ranges on average from approximately 300 to 600 m in elevation. The majority of the roughly 10,800 ha of old-growth *S. sempervirens*, reside on the eastern portion of the park near park headquarters (California Department of Parks and Recreation 2003).

Sample sites for this study were determined using data from the California Department of Parks and Recreation (California State Parks), which included previous prescribed fire sites as well as old-growth designated areas within the park. Utilizing maps created on ArcGIS of prescribed fire plot boundaries overlaid with an old-growth *S. sempervirens* layer, a randomly selected starting point was determined prior to data

collection on each site. Subsequent plot locations were chosen using field randomization methods. “Old-growth” designations were determined using California State Parks map GIS layers as well as field observations.

Study sites sampled represented three previous prescribed fire burn sites (Table 1, Fig. 1, Appendix A), most recently experiencing fire in 1999, 2007, and 2011. Both burned and unburned plots within each site, or sites of similar biotic and abiotic conditions, were sampled, with unburned plots providing reference control sites. The prescribed fire sites included the Ocean View Summit Project (OVSB), Upper Skyline to the Sea Project (S2SB), and the Johansen Road East Project, (JREB) (Table 1). The unburned sample sites included the Skyline to the Sea Project (S2SU), the North Escape Road site (NERU), and finally the Sunset Trail site (SUNU). For all sample sites the last letter of the acronym (B or U) denotes burned or unburned status. Although all of the sampled locations had slight variations in topographic and microclimatic conditions, they had similar overstory plant community compositional structures, seasonal moisture levels, and soil types, allowing credible comparisons regarding fire effects on ecosystem composition (Table 1).

Table 1 Sample site descriptions and characteristics for both burned and unburned locations in Big Basin Redwoods State Park, CA, USA. Sites include, Ocean View Summit (OVSB), Skyline to the Sea (burned) (S2SB), Johansen Road East (JREB), Sunset Trail (SUNU), Skyline to the Sea (unburned) (S2SU), North Escape Road (NERU).

	OVSB	S2SB	JREB	SUNU	S2SU	NERU
Year Burned (Rx)	1999	2004-2007	2011	NA	NA	NA
Year Burned (wildfire)	1936	1936	1936	1936	1936	1936
Area Burned (ha)	~109	146.2	206.7 (min)	NA	NA	NA
Elevation Range (m)	410-472	304-439	413-492	259-340	357-425	307-360
Elevation Average (m)	442	359	453	288	394	336
Mean Aspect (degrees)	142	237	241	240	265	144
Slope Range (%)	0-51	12-65	16-62	14-49	11-55	5-40
Mean Slope (%)	21	30	41	25	32	23
Dominant Soil Texture	Loam/sandy loam	Loam/sandy loam	Loam/sandy loam	Loam/sandy loam	Loam/sandy loam	Loam/sandy loam
Harvesting Evidence	None	None	Limited	None	None	Limited

Fig. 1 Prescribed burn project boundaries in Big Basin Redwoods State Park, Boulder Creek, California, USA. Yellow stars approximate sample site locations. Listed years and names represent previous prescribed fire sites. Data provided from California State Parks.

Sampling Design

Sampling was conducted using twenty randomly selected 10 m diameter plots from burned portions of each of the three prescribed burn projects and twenty randomly selected 10 m diameter plots from unburned portions of each of the three prescribed burn projects or similar unburned sites (Lazzeri-Aerts and Russell 2014; Scherer et al. 2016; Hanover and Russell 2018). This resulted in a total of 120 sampled plots: 60 from areas that experienced prescribed fire, and 60 from areas that did not experience prescribed

fire. A pilot study by Russell and Michels (2010) determined 20 plots as the minimum sample size for this habitat type. However, due to variability within and between sites, all three burned sites and all three unburned sites were combined for analysis. All plots were located at least 10 m from adjacent plots, 10 m from special habitat types (i.e. riparian or rocky outcroppings), and approximately 200 m from paved roads, so as to avoid edge effects on sampled areas (Jones and Russell 2001; Russell and Michels 2010). Ten m diameter plots were chosen because they were large enough to capture tree density data and were small enough to be manageable for meticulous measurements of juvenile tree species density (Reid and Thompson 1996; Brower et al. 1998). All trees with 50% or more basal area within plot delineation boundaries were inventoried and measured. Each plot was further broken down into four quadrants in order to make ocular estimates of ground cover more accurate (Petersen and Russell 2017).

Field Sampling

For each of the 120 study plots, physical and environmental characteristics were taken from plot center. Measurements included slope, aspect, elevation, and canopy cover. In addition, GPS coordinates were taken with a Garmin Etrex 20 GPS unit (Garmin eTrex, Garmin Ltd., Olathe, KS, USA).

In order to determine percent canopy cover within each plot, a convex spherical densiometer was used from plot center, and readings were taken in each cardinal direction (Korhonen et al. 2006). Total woody and non-woody cover/dominance was determined using ocular estimates in the four subdivided quadrants within the plot

(Petersen and Russell 2017). Unknown species were collected and identified using the Jepson Manual (Hickman 1993) or by local botanists.

Each tree with at least 50% of the basal area within the plot boundary and greater than 10 cm in diameter was identified to species and recorded for diameter at breast height (DBH). DBH measurements were taken 1.4 m from the ground surface along the uphill side of the tree. Trees with multiple stems were considered separate if the point of separation occurred below 1.4 m from the soil surface. Trees less than 10 cm in diameter were counted, identified and recorded separately into seedlings/sprouts and sapling delineations (<1 m height or >1 m in height, respectively) (Petersen and Russell 2017). Mortality was determined based upon new or residual growth or foliage (Lazzeri-Aerts and Russell 2014).

In order to assess dead and downed woody fuel load within the burn sites, a modified version (University of California at Santa Cruz 2017) of the planar intersect technique provided in Brown (1974) was utilized. Two transect lines were sampled from the plot center of each 10 m diameter plot with the first extending 11.34 m along the dominant slope of the plot; and the second extending 90 degrees from the first transect line in the clockwise direction. For fuel load assessments the 10 m plots only served to determine the beginning point for transect lines. Duff, litter, and fuel depths were measured at 1.52 m and 3.05 m from plot center. Fuels intersecting the transect line and extending vertically 1.83 m, were broken down into predetermined size classes, which represented 1-hr (0 to 0.64 cm), 10-hr (6.4 to 2.54 cm), 100-hr (2.54 to 7.62 cm), and 1000+ hr (7.6+ cm) fuels, respectively (Brown 1974; University of California at Santa Cruz 2017).

Data Analysis

All statistical analyses were performed using R Software version 3.4.3 (R Development Core Team 2017). An α -level of 0.05 was used to determine statistical significance for all statistical analyses. Since high variability existed between sites and within treatments, data from all sites were combined for their respective treatment types (burned and unburned).

Fine and coarse woody fuels were analyzed using calculations detailed in Brown (1974) to attain mean fuel load in tons per acre and then converted to metric tons per hectare (Mg ha^{-1}) for each time-lag class (1-hr, 10-hr, 100-hr, and >1000-hr). Calculations were made for each individual transect and then averaged across burn sites/projects (Glebocki 2014). In addition, fuel load estimates were made for the total of each sample site, combining transect lengths per sample site. Calculations for fine woody fuels (1-hr, 10-hr, and 100-hr) were determined using Eq. 1, provided by Brown (1974) and Glebocki (2014):

$$\text{Fine Woody Fuel Load (mg/ha}^{-1}\text{)} = \frac{knd^2s_{oc}ac}{Nl} \quad (1)$$

where k is a constant of 11.64 (Brown 1974), n represents the number of individual particles counted in each size class per transect, d^2 is the square of the quadratic mean diameter of each size class, s_{oc} is the composite specific gravity, a is the composite angle correction factor for each size class, c is the average transect slope correction factor, and Nl is the transect length (Appendix B). The slope correction factor (c) for each individual

transect line estimate was dependent upon the slope of that transect line (%), and was calculated using Eq. 2.

$$c = \sqrt{1 + \left(\frac{\text{percent slope}}{100}\right)^2} \quad (2)$$

For composite transect line calculations, yielding a single fuel load estimate per sample site, the mean slope correction factor was utilized. For all other constant values (d^2 , a , and s_{oc}), values found in Brown (1974) were used for non-slash, conifer, and western species.

Fuel load for 1000-hr fuels (>7.62 cm) were calculated using Eq. 3 from Brown (1974) and Glebocki (2014):

$$\text{Coarse Woody Fuel Load (mg/ha}^{-1}\text{)} = \frac{k(\sum d^2)s_{oc}ac}{Nl} \quad (3)$$

where all variables mentioned above are the same and $\sum d^2$ is the sum of the diameters of fuel particles (sound and rotten) squared (Brown 1974; Glebocki 2014). Thousand-hr sound and rotten calculations were made separately and then combined into a single value. For all estimates, calculations were made in inches to yield tons per acre estimates and later converted into metric tons per hectare (Mg ha^{-1}).

Data for variables including duff depth, litter depth, fuel depth, canopy cover, fuel load, understory cover, and stand density, were tested for normality and homogeneity of variance using Shapiro-Wilk and Fligner-Killeen tests, respectively. Spearman rank order correlations were used to determine relationships among dependent variables with

time since burn (McCune and Grace 2002). Time since burn for OVSB at the time of analysis was 20 yr, S2SB was 12 yr, JREB was 7 yr, and all unburned sites experienced wildfire in 1936, making time since burn 83 yr. Separate correlation tests were run for stand composition metrics (n = 20 per site), duff, litter, and fuel depths (n = 80 per site), and fuel load metrics (n = 40 per site).

PERMANOVA (Permutational Multivariate Analysis of Variance) tests were used to compare forest stand composition, fuel load, and receptive fuel bed depth metrics between treatments (burned or unburned) (Anderson 2001). The distance measure utilized was Bray-Curtis for community data (McCune and Grace 2002) and the ‘vegan’ package in R was used (Dixon 2003). Stand composition input variables included canopy cover, stand density of mature trees, stand density of juvenile trees, total basal area, and understory/shrub species cover and richness. To assess differences in stand structure of mature canopy trees, all stems greater than 10 cm DBH were separated into six predetermined size classes (Petersen and Russell 2017). PERMANOVA was then run comparing differences in size class composition of the three dominant tree species (*S. sempervirens*, *N. densiflorus*, and *P. menziesii* var. *menziesii*) between burned and unburned treatments plots. Kruskal-Wallis non parametric tests (one-way ANOVA on ranks) were used to further compare dependent variables between treatment types (burned and unburned control) (McKnight and Najab 2010).

Summary statistics (mean and standard error) were calculated for both combined treatment datasets as well as individually, among sample sites (Appendix C).

Results

Burned and unburned treatments exhibited significant differences in regards to fuel load and receptive fuel bed depth metrics, as well as stand composition variables. In addition, rank order correlation tests indicated noteworthy correlations between several of these measures and the time since the last fire (Table 2).

Fuel Load

Variation was found for fuel bed depth and downed woody fuel between burned and unburned treatments (PERMANOVA, $df = 1$, $F = 32.40$, $P = 0.001$ and $df = 1$, $F = 3.20$, $P = 0.02$, respectively). Coarse woody fuel load, duff depth, and litter depth were all found to be significantly lower in burned versus unburned treatments, while no statistical differences were noted between fine woody fuel load and litter depth (Table 3).

Significant positive rank order correlations were found with time-since-burn for duff depth, litter depth, coarse woody fuel load, and 1-hr fuel load, with duff depth exhibiting the strongest correlation of all dependent variables (Table 2, Fig. 2).

Table 2 Spearman rank order correlation values (rho) for several dependent variables with time-since-burn. Analyses were performed on six sample sites, representing four time-since-burn ages. Time-since-burn ages include 7 yr, 12 yr, 20 yr, and 83 yr, in Big Basin Redwoods State Park, Boulder Creek, California, USA.

Variable	P	Rho
Duff depth (cm)	<0.001	0.60
Litter depth (cm)	<0.001	0.19
Fuel depth (cm)	0.33	-0.045
Coarse woody fuel load (>7.6 cm diameter, Mg ha ⁻¹)	0.014	0.15
Fine woody fuel load (<7.6 cm diameter, Mg ha ⁻¹)	0.94	0.0052
1-hr fuel load (Mg ha ⁻¹)	<0.001	0.40
10-hr fuel load (Mg ha ⁻¹)	0.20	0.084
100-hr fuel load (Mg ha ⁻¹)	0.30	-0.067
Canopy cover	0.002	0.28
<i>S. sempervirens</i> stand density (stems/ha)	0.94	-0.01
<i>N. densiflorus</i> stand density (stems/ha)	0.002	0.29
Total stand density (stems/ha)	0.013	0.23
<i>S. sempervirens</i> relative basal dominance (%)	0.12	-0.14
<i>N. densiflorus</i> relative basal dominance (%)	0.009	0.24
Total basal area (m ² /ha)	0.85	-0.02
Density of stems <10 cm DBH, <1 m height (stems/ha)	0.15	0.13
Density of stems <10 cm DBH, >1 m height (stems/ha)	<0.001	0.52
Understory species richness (number of species per plot)	0.35	-0.09
Understory percent cover (per plot)	0.36	-0.08
Shrub species richness (number of species per plot)	0.006	0.25
Shrub percent cover (per plot)	<0.001	0.34

Fig. 2 Boxplots and stripchart of duff depth (cm) differences with time-since-burn (yr) for six sample sites in Big Basin Redwoods State Park, Boulder Creek, California, USA. Time-since-burn 7 yr, 12 yr, and 20 yr represent sites that were burned in 1999, 2007, and 2011/12, respectively. Time-since-burn 83 yr represents three reference sample sites that were most recently burned in a wildfire in 1936.

Table 3 Comparison of receptive fuel bed (n = 240 per variable per treatment) and fine (FWF; 0 -7.6 cm diameter) and coarse (CWF; 7.6+ cm diameter) woody fuel loading (n = 120 per variable per treatment) between burned and unburned plots in Big Basin Redwoods State Park, Boulder Creek, California, USA.

	Unburned	Burned	Kruskal-Wallis results		
	Mean (SE)	Mean (SE)	χ^2	P	df
Duff depth (cm)	7.47 (0.22)	3.75 (0.15)	145.97	<0.0001	1
Litter depth (cm)	5.23 (0.18)	4.61 (0.15)	7.2094	0.007	1
Fuel depth (cm)	10.1 (1.18)	10.83 (1.20)	2.74	0.098	1
FWF (Mg ha ⁻¹)	6.11 (0.4)	6.39 (0.42)	0.19	0.66	1
CWF (Mg ha ⁻¹)	122.56 (26.67)	71.92 (19.44)	4.66	0.03	1

High variability was noted for 1000+ hr particle size and coarse woody fuel load as a result of the large size of mature *S. sempervirens* trees, with unburned sites exhibiting approximately 63% higher mean coarse fuel load (1000+ hr; Mg ha⁻¹) than burned sites

(Table 3, Fig. 3). The JREB site exhibited the lowest mean coarse fuel load at 25.63 Mg ha⁻¹ and the NERU site had the highest at 243.63 Mg ha⁻¹ (Table 3). When coarse woody fuel load was analyzed as a per site metric, combining separate transect lines within each site, the JREB site had the lowest total fuel load at 29.08 Mg ha⁻¹, followed by SUNU at 64.78 Mg ha⁻¹, S2SB at 81.16 Mg ha⁻¹, S2SU at 101.49 Mg ha⁻¹, OVSB at 126.67 Mg ha⁻¹ and NERU had the highest overall fuel load at 218.82 Mg ha⁻¹.

Fig. 3 Fine woody fuel load (mean $\pm$ SE) for burned (OVSB, S2SB, JREB) and unburned (SUNU, S2SU, NERU) sample sites. Fine woody fuel load was composed of 1-hr (0 - 0.64 cm), 10-hr (6.4 – 2.54 cm), 100-hr (2.54 – 7.62 cm) fuel particles, and coarse woody fuels were composed of 1000+-hr (7.6+ cm) sound and rotten fuels.

Forest Stand Composition and Structure

Variation between treatments was also noted in regard to stand density, basal area, species dominance, and understory cover and composition (PERMANOVA, $df = 1$, $F = 8.29$, $P = 0.001$). There was a 19.3% difference in the total density of all species of mature trees (>10 cm DBH) between burned and unburned sites, with lower density in burned plots. Further, Spearman's coefficient indicated a positive correlation between

stand density and time-since-burn (Table 2). While *Sequoia sempervirens* and *N. densiflorus* exhibited the highest to stand density across treatments, the majority of the variation was in the density of mature *N. densiflorus*, with 61.5% higher density in unburned sites (Table 4); and a positive rank order correlation between time-since-burn (Table 2). No other species-specific differences were noted in mature tree density between treatments (Table 4).

Table 4 Comparison of forest stand density of dominant mature tree species (>10 cm DBH) between burned (n = 60) and unburned (n = 60) plots in Big Basin Redwoods State Park, Boulder Creek, California, USA. With SESE representing *S. sempervirens*, NODE representing *N. densiflorus*, ARME representing *A. menziesii*, and QU representing *Quercus*.

	Unburned	Burned	Kruskal-Wallis results		
	Mean (SE)	Mean (SE)	χ^2	P	df
SESE	207.96 (22.03)	205.84 (19.63)	0.032	0.86	1
NODE	216.45 (21.89)	114.59 (18.08)	12.99	0.00031	1
PSME	42.44 (10.75)	31.83 (10.77)	1.157	0.28	1
QU spp.	6.36 (4.71)	0.00 (0.00)	2.017	0.16	1
ARME	0.00 (0.00)	4.24 (4.24)	1	0.32	1
All tree species	473.22 (27.92)	356.51 (24.55)	7.39	0.0066	1

Total juvenile stem density (<10 cm DBH) exhibited a similar pattern between treatments, with lower density on burned sites (Table 5), and a positive Spearman's rank order correlation with time-since-burn for density for sapling sized trees (<10 cm DBH, >1 m height) (Table 2). As was the case for mature sized trees, the majority of the variation was found for *N. Lithocarpus*, with no significant differences found for the other species present.

Table 5 Stand density (stems/ha) of juvenile tree species (<10 cm DBH; < or > 1 m in height) between burned (n = 60) and unburned (n = 60) sites in Big Basin Redwoods State Park, Boulder Creek, California, USA. Blank values indicate variables that were not included in statistical analysis.

	Unburned	Burned	Kruskal-Wallis Results		
	Mean (SE)	Mean (SE)	χ^2	P	df
SESE (<1 m)	3463.21 (1075.94)	2779.91 (479.04)	2.14	0.14	1
SESE (>1 m)	1239.29 (677.52)	1088.62 (487.68)	0.074	0.79	1
NODE (<1 m)	6992.21 (989.13)	4034.05 (661.12)	14.47	0.00014	1
NODE (>1 m)	3338.01 (337.62)	823.36 (127.34)	41.36	<0.0001	1
PSME (<1 m)	10.61 (6.27)	36.08 (13.57)	-	-	
PSME (>1 m)	10.61 (6.96)	27.59 (15.46)	-	-	
QU (sp.) (<1 m)	40.32 (17.77)	10.61 (6.27)	-	-	
QU (sp.) (>1 m)	4.24 (2.98)	0.00 (0.00)	-	-	
ARME (<1 m)	0.00 (0.00)	8.49 (8.49)	-	-	
ARME (>1 m)	0.00 (0.00)	0.00 (0.00)	-	-	
All (<1 m)	10506.35 (1504.89)	6869.13 (745.38)	4.86	0.027	1
All (>1 m)	4592.15 (683.72)	1939.57 (505.91)	32.55	<0.0001	1

With all size classes (both greater and less than 10 cm DBH) a PERMANOVA of the three most common dominant tree species (*S. sempervirens*, *N. densiflorus*, and *P. menziesii* var. *menziesii*) combined, and separated into predetermined size classes (seedling/sprout, sapling, 10-24 cm, 25-49 cm, 50-99 cm, 100-149 cm, 150-199 cm, 200+ cm) a significant difference was found in stand size class structure between burned and unburned treatments ($F = 6.53$, $P = 0.001$, $df = 1$). Subsequent PERMANOVA tests were run between individual tree species broken into size classes, comparing burned and unburned treatments. Results indicated differences in *N. densiflorus* size class composition, between treatment types ($F=12.12$, $P = 0.001$, $df = 1$) as well as *S. sempervirens* ($F=2.45$, $P = 0.032$, $df = 1$). A PERMANOVA was not run for *P. menziesii* var. *menziesii* due to infrequency of occurrence in sample plots.

Kruskal-Wallis tests comparing individual size class density between treatments, indicated no significant differences for any *S. sempervirens* or *P. menziesii* var.

menziesii size class. However, tests comparing *N. densiflorus* stand density by size class between the two treatments indicated significant differences in both the juvenile size classes (seedling/sprout and sapling), as well as the 10-24 cm and 25-49 cm size classes (Table 6) (Fig. 4). The largest difference was in density of *N. densiflorus* saplings with an approximately 81.44% lower density in burned sites compared to unburned (Table 5); resulting in a visible difference in subcanopy ladder fuels between treatments (Fig. 5).

Table 6 Kruskal-Wallis results of dominant tree species size-class distribution between treatments in Big Basin Redwoods State Park, Boulder Creek, California, USA.

	χ^2	P	df
SESE			
10-24 cm	0.51	0.48	1
25-49 cm	0.074	0.79	1
50-99 cm	0.93	0.34	1
100-149 cm	1.57	0.21	1
150-199 cm	0.18	0.67	1
200+ cm	0.97	0.33	1
NODE			
10-24 cm	11.017	<0.001	1
25-49 cm	4.65	0.031	1
50-99 cm	0.74	0.39	1
100-149 cm	-	-	-
150-199 cm	-	-	-
200+ cm	-	-	-
PSME			
10-24 cm	0.0011	0.97	1
25-49 cm	0.099	0.75	1
50-99 cm	1.28	0.26	1
100-149 cm	1.28	0.26	1
150-199 cm	0	1	1
200+ cm	-	-	-

Fig. 4 Mature size class distribution of three dominant tree species, comparing burned and unburned treatments, in Big Basin Redwoods State Park, Boulder Creek, California, USA. Significant differences in PERMANOVA tests were noted in SESE and NODE between treatments. Within Kruskal Wallis tests, significant differences were noted exclusively within NODE in the 10-24 cm and 25-49 cm size classes.

Fig. 5 Unburned and burned forest stand characteristics in Big Basin Redwoods State Park, Boulder Creek, California, USA. The unburned image (A) is from the North Escape Road site (NERU) and the burned image (B) was from the 2011 Johansen Road East project (JREB). Images depict similar density and diameter distributions of *S. sempervirens* and higher density of *N. densiflorus* in unburned sites.

Mean percent canopy cover varied between burned and unburned treatments ($\chi^2 = 15.092$, $p < 0.001$, $df = 1$); with a mean percent canopy cover of 91.43 ± 0.51 (mean $\pm$ SE) on burned sites compared to 93.92 ± 0.34 on unburned sites. Spearman's rank order also indicated a positive correlation between time-since-burn and mean percent canopy cover (Table 2).

Although no significant differences were noted in total basal area (m^2/ha) of all tree species combined between burned and unburned sites (Table 7), results on species

specific basal dominance complimented species-specific stand density results. Lower basal dominance of *N. densiflorus* was found in plots that experienced prescribed fire compared to unburned control plots based on Kruskal-Wallis tests. Spearman's rank order correlation coefficient further indicated a positive correlation between time-since-burn and *N. densiflorus* basal dominance (Table 2). However, basal dominance of *S. sempervirens*, *Quercus* spp., *A. menziesii*, and *P. menziesii* var. *menziesii* showed no statistically significant differences between burned and unburned locations (Table 7).

Table 7 Comparison of relative basal dominance and basal area between burned (n = 60) and unburned (n = 60) plots in Big Basin Redwoods State Park, Boulder Creek, California, USA. Bold p-values indicate statistically significant differences.

Variable	Unburned	Burned	Kruskal-Wallis results		
	Mean (SE)	Mean (SE)	χ^2	P	df
SESE (%)	0.70 (0.05)	0.76 (0.05)	3.73	0.053	1
NODE (%)	0.17 (0.04)	0.12 (0.04)	9.92	0.002	1
PSME (%)	0.12 (0.04)	0.07 (0.03)	1.31	0.25	1
QU spp. (%)	0.00 (0.00)	0.00 (0.00)	2.017	0.16	1
ARME (%)	0.00 (0.00)	0.00 (0.00)	1	0.32	1
Total Basal Area (m ² /ha)	282.58 (29.66)	314.79 (37.87)	0.049	0.83	1

Understory Plant Composition

Understory plant species were separated into two categories for the purpose of analysis: woody shrubs (including both shrubs and vines); and non-woody understory (including grasses, herbaceous species, and ferns). Kruskal Wallis tests indicated significant differences in shrub percent cover per plot and shrub species richness per plot between burned and unburned control plots ($\chi^2 = 15.77$, $p < 0.001$, $df = 1$ and $\chi^2 = 8.94$, $P = 0.0029$, $df = 1$, respectively). Burned plots had both lower percent shrub cover per plot as well as lower shrub species richness per plot, compared to unburned plots (Table 8), and

Spearman's correlation analysis indicated positive rank order correlations between both shrub species richness and percent cover with time-since-burn (Table 2). In terms of woody shrub species, only *Lonicera hispidula* was found in all six sample sites (Table 9).

Table 8 Comparison of understory and shrub species richness and diversity between burned (n = 60) and unburned (n = 60) plots in Big Basin Redwoods State Park, Boulder Creek, California, USA.

Variable	Unburned	Burned	Kruskal-Wallis Results		
	Mean (SE)	Mean (SE)	χ^2	P	df
Understory richness (species per plot)	1.77 (0.23)	2.07 (0.24)	0.85	0.36	1
Understory percent cover (per plot)	2.93 (0.69)	7.28 (1.96)	1.27	0.26	1
Shrub richness (species per plot)	1.18 (0.12)	0.68 (0.09)	15.78	<0.001	1
Shrub percent cover (per plot)	9.61 (2.02)	1.60 (0.51)	8.94	0.003	1

Table 9 Mean percent cover of all woody/shrub understory plant species found within 6 sample sites in Big Basin Redwoods State Park, Boulder Creek, California, USA.

Woody/Shrub Species	Unburned			Burned		
	NERU	S2SU	SUNU	JREB	S2SB	OVSF
<i>Frangula californica</i>	-	0.025	0.025	-	-	-
<i>Morella californica</i>	-	0.6	-	-	-	-
<i>Rosa gymnocarpa</i>	-	-	0.13	-	0.11	-
<i>Rubis ursinus</i>	0.35	-	-	0.05	-	-
<i>Symphoricarpos albus</i>	-	-	-	-	0.025	-
<i>Symphoricarpos mollis</i>	-	0.025	-	-	-	-
<i>Vaccinium ovatum</i>	4.48	19.8	0.1	0.65	-	1.43
<i>Lonicera hispidula</i>	0.56	1.68	0.54	0.063	0.52	0.43
<i>Toxicodendron diversilobum</i>	0.094	0.013	-	0.05	-	-
<i>Whipplea modesta</i>	-	0.41	-	0.94	0.46	0.088
Total species encountered	4	7	4	5	4	3

No statistically significant differences were indicated for non-woody understory species richness, and percent cover per plot between burned and unburned sites based on Kruskal-Wallis results. Of non-woody understory plant species, only *Iris fernaldii*, *Lysimachia latifolia*, and *Polygala californica* were found within all six sample sites

(Table 10). The only non-native/exotic species identified was *Epipactis helleborine*, which was found in both burned and unburned treatments. Spearman's rank order coefficient indicated no correlations between either non-woody understory richness or percent cover and time-since-burn (Table 2).

Table 10 Mean percent cover of all non-woody understory plant species found within 6 sample sites in Big Basin Redwoods State Park, Boulder Creek, California, USA. Asterisk denotes non-native.

Non-woody Understory Species	Unburned			Burned		
	NERU	S2SU	SUNU	JREB	S2SB	OVS B
<i>Asarum caudatum</i>	-	-	-	-	0.019	-
<i>Bromus sp.</i>	0.0063	0.013	-	-	0.42	0.006
<i>Calamagrostis rubescens</i>	-	-	0.23	-	-	0.74
<i>Carex globosa</i>	0.0063	0.3	-	0.35	1.59	-
Unknown <i>Carex sp.</i>	-	-	-	-	1.24	0.85
<i>Carex tumulicola</i>	-	-	-	-	0.18	-
<i>Dryopteris arguta</i>	0.05	0.038	0.41	-	-	-
* <i>Epipactis helleborine</i>	0.025	-	0.038	0.16	0.013	-
<i>Equisetum arvense</i>	-	-	-	0.013	-	-
<i>Festuca occidentalis</i>	-	-	-	-	0.025	-
<i>Galium californicum</i>	1.081	0.019	-	0.025	0.019	-
<i>Iris douglasiana</i>	-	-	0.43	-	-	-
<i>Iris fernaldii</i>	0.23	0.094	0.14	0.2	0.14	0.33
<i>Lysimachia latifolia</i>	0.038	0.19	0.05	0.14	0.96	0.41
<i>Maianthemum racemosum</i>	0.025	-	-	-	0.056	0.003
<i>Maianthemum stellatum</i>	0.025	-	-	-	-	-
<i>Oxalis oregana</i>	0.49	0.36	3.063	0.21	12.54	-
<i>Pityrogramma triangularis</i>	-	-	-	0.003	-	-
<i>Polygala californica</i>	0.18	0.088	0.13	0.019	0.14	0.11
<i>Polypodium californicum</i>	0.063	-	0.006	-	-	-
<i>Polystichum munitum</i>	0.13	0.038	0.45	0.019	0.038	-
<i>Prosartes hookeri</i>	-	0.013	0.063	-	0.12	0.075
<i>Pteridium aquilinum</i> var. <i>pubescens</i>	-	0.031	-	-	0.006 3	-
<i>Stachys bullata</i>	-	0.038	-	0.05	0.025	-
<i>Trillium ovatum</i>	0.1	0.013	0.025	-	0.038	0.013
<i>Vicia Americana</i> ssp. <i>americana</i>	0.05	0.038	-	0.013	-	-
<i>Viola ocellata</i>	0.013	-	0.013	-	0.075	0.16
<i>Viola sempervirens</i>	-	-	0.05	0.013	0.081	-
Total species encountered	16	14	14	13	20	10

Discussion

Significant correlations were noted between fuel load, juvenile tree species abundance, and mature stand density metrics with time-since-burn indicated a general trend towards increased surface fuel load in the absence of fire. Receptive fuel load and fuel bed depth influence the severity and rate of spread of fire (Nives 1989). In addition, the continuity of fuels from surface to canopy exacerbates the spread and severity fire, so that interrupting this continuity is paramount in reducing fire intensity (Cruz et al. 2004). In old-growth *S. sempervirens* stands in the southern extent of their range, the density of juvenile hardwoods and woody shrubs serve as the primary source of ladder fuels. The reduction of both woody shrub cover, as well as the density of *N. densiflorus* in the smaller size classes (<10 cm DBH, >1 m height), are essential in disrupting fuel continuity in these stands.

Fine woody fuels are reestablished quickly after burning, and the lack of significant differences in fine woody fuel load (<7.6 cm diameter) between treatments in this study was not surprising. Further, these results were consistent with the findings of Engber, Teraoka, & Mantgem (2017) who noted a full recovery of fine surface fuels 7 yr after burning. In the same study, researchers also noted variable recovery in coarse woody fuel load post burn, which is also consistent with our findings. High variability in coarse woody fuels was detected both within treatment types and between burned and unburned sites. However, a statistically significant difference in coarse woody fuels between all burned and all unburned treatment sites combined supports the conclusion that well-

timed prescribed fires promote a reduction in fuel load within the *S. sempervirens* forest type.

In the sites studied, prescribed fire appeared to significantly reduce the dominance and density of *N. densiflorus*, suggesting that *N. densiflorus* potentially loses competitive advantage to *S. sempervirens* in the presence of fire, a result consistent with Ramage et. al (2010) and Lazzeri-Aerts and Russell (2014). In contrast, burning appeared to have little effect on *S. sempervirens* stand density within any of the size classes, which is largely consistent with Engber, Teraoka, and Mantgem (2017) who found no shift in overstory tree composition following prescribed fire. These findings are also consistent with Lazzeri-Aerts and Russell (2014) who found 100% survivorship of *S. sempervirens* greater than 7.5 cm DBH following fire.

Along the coast of California, Sudden Oak Death (SOD), caused by *Phytophthora ramorum*, has led to widespread mortality of several *Quercus* spp. as well as *N. densiflorus* (Metz et al. 2012; Rizzo and Garbelotto 2003). In a study by Metz et al. (2013), it was determined that the synergistic effects of SOD driven *N. densiflorus* mortality and subsequent increase in fuel load led to an unexpected increase in *S. sempervirens* mortality during wildfire events in the southern extent of the range (Metz et al. 2013). A reduction in density of *N. densiflorus*, especially in the smaller size classes, could result in a more fire resilient forest system within uncertain environmental shifts.

Manual and mechanical fuel reduction methods including heavy equipment and stand thinning can have potentially adverse impacts on the *S. sempervirens* understory plant composition (Loya and Jules 2008; Russell and Michels 2010; Russell and Hanover

2018). The absence of shift in understory non-woody plant composition within this study indicates that prescribed fire does not have those same impacts, at least within the old-growth stands sampled. According to Blair et al. (2010), the creation of canopy gaps as a result of logging within *S. sempervirens* stands in Santa Cruz county was the primary driving force in recruiting non-native, invasive species. Although a statistically significant difference was found in canopy cover between burned and unburned plots within our study, there was no difference in species composition or structure of *S. sempervirens*. The difference in mean canopy cover between burned and unburned plots represented less than a 3% shift and was largely due in part to a reduction in the subcanopy layer of hardwood and juvenile tree species, rather than the creation of forest canopy gaps. By and large, the compositional shifts within this study were due to a reduction of woody shrubs and subcanopy *N. densiflorus*.

In the woody shrub layer, the most drastic shift of species composition was in regards to cover and abundance of *V. ovatum*. According to Stuart (1987), within coastal California, the majority of the *V. ovatum* native range has experienced infrequent fire intervals during pre-settlement times. In his study, Tirmenstein (1990) argues that this may have led to poorly developed adaptations to fire within the species. According to Martin (1979), *V. ovatum* rarely reproduces via seed dispersal and has a seed bank and sub-surface root structure prone to mortality in the presence of duff consuming surface fires, with a long residence time. These factors, coupled with the timing of prescribed fires in the ecosystem, during the late Fall/early Winter months, when live fuel moisture

is low, could explain the reduced presence and cover of *V. ovatum* in burned treatment plots.

Conclusions

With significantly lower coarse woody fuel load, receptive fuel bed depth, and fire intolerant woody species, the results of this study indicate that prescribed fire in the southern extent of the *S. sempervirens* range has the potential to beneficially impact forest health while maintaining understory diversity and native species' assemblages. Rank order tests indicated positive correlations between similar variables and time-since-burn, indicating that in the absence of fire, the *S. sempervirens* forest trends towards higher fuel load and less fire tolerant characteristics. With a host of adaptations to disturbance and a relative lack of vulnerability to non-native species establishment, the *S. sempervirens* ecosystem is an ideal candidate for satisfying fuel reduction goals, while maintaining ecological integrity. Evidence points to higher FRIs in the *S. sempervirens* ecosystem with proximity to adjacent grasslands, shrublands, and oak woodlands (Greenlee 1983). Progressing forward into an uncertain climatic future, a crucial aspect of forest management will be thoughtfully chosen fuel reduction projects that minimize adverse ecological impacts, create more fire tolerant ecosystems, and satisfy fuel management goals.

References

- Anderson, M.J. 2001. A new method of non-parametric multivariate analysis of variance. *Austral Ecology* 26:32–46. <https://doi.org/10.1046/j.1442-9993.2001.01070.x>
- Barbour, M.S., M. Lydon, M. Borchert, V. Popper, V. Whitworth, and J. Evarts. 2001. *Coast redwood: a natural and cultural history*. Los Olivos: Cachuma Press.
- Biswell, H. 1989. *Prescribed burning in California wildlands vegetation management*. Berkeley: University of California Press.
- Blair, B.C., D.K. Letorneou, S.G. Bothwell, and G.F. Hayes. 2010. Disturbance, resources, and exotic plant invasion: gap size effects in a redwood forest. *Madroño* 57: 11-19. <https://doi.org/10.3120/0024-9637-57.1.11>
- Brooks, M.L., C.M. D'Antonio, D.M. Richardson, B. James, J.E. Keeley, J.M. Ditomaso, R.J. Hobbs, M. Pellant, and D. Pyke. 2004. Effects of invasive alien plants on fire regimes. *Bioscience* 54:677-688. [https://doi.org/10.1641/0006-3568\(2004\)054\[0677:eoiaipo\]2.0.co;2](https://doi.org/10.1641/0006-3568(2004)054[0677:eoiaipo]2.0.co;2)
- Brower, J.E., J.H. Zar, and C. Von Ende. 1998. *Field and laboratory methods for general ecology*. Boston: WCB/McGraw-Hill.
- Brown, J.K. 1974. Handbook for inventorying downed woody material. USDA Forest Service. General Technical Report INT-GTR-16. Ogden: USDA Forest Service, Intermountain forest and Range Experiment Station. https://www.fs.fed.us/rm/pubs_int/int_gtr016.pdf
- Busing, R.T. and T. Fujimori. 2002. Dynamics of composition and structure in an old Sequoia sempervirens forest. *Journal of Vegetation Science* 13: 785–792. <https://doi.org/10.1111/j.1654-1103.2002.tb02108.x>
- Cruz, M.G., M.E. Alexander, and R.H. Wakimoto. 2004. Modeling the likelihood of crown fire occurrence in conifer forest stands. *Forest Science* 50: 640-658. <https://doi.org/10.1071/wf16218>
- D'Antonio, C.M., and P. Vitousek. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. *Annual Review of Ecology and Systematics* 23: 63-87. <https://doi.org/10.1146/annurev.es.23.110192.000431>
- Dixon, P. 2003. VEGAN, a package of R functions for community ecology. *Journal of Vegetation Science* 14:927–930. <https://doi.org/10.1111/j.1654-1103.2003.tb02228.x>

- Engber, E., J. Teraoka, and P. Van Mantgem. 2017. "Forest restoration at Redwood national park. Exploring prescribed fire alternatives to second growth management: a case study". Paper presented at *Coast Redwood Science Symposium, Eureka, CA, Aug 16, 2016*.
https://www.fs.fed.us/psw/publications/documents/psw_gtr258/psw_gtr258_075.pdf.
- Foster, D.R. 1988a. Species and stand response to catastrophic wind in central New England, USA. *Journal of Ecology* 76:135-151. <https://doi.org/10.2307/2260458>
- Glebocki, R. 2015. Fuel loading and moisture dynamics in thinned coast redwood - Douglas-fir forests in Headwaters Forest Reserve, California, Thesis. Arcata: Humboldt State University.
- Greenlee, J.M. 1983. Vegetation, fire history, and fire potential of Big Basin Redwoods State Park, California, PhD diss. Santa Cruz: University of California at Santa Cruz.
- Hadley, K.S. 1994. The role of disturbance, topography, and forest structure in the development of a montane forest landscape. *Bulletin of the Torrey Botanical Club* 121:47- 61. <https://doi.org/10.2307/2996883>
- Hanover, A. and W. Russell. 2018. Understory recovery in coast redwood communities: A case study comparing a naturally recovering and actively managed forest. *Open Journal of Forestry*. 8: 489-499. <https://doi.org/10.4236/ojf.2018.84031>
- Hickman, J.C. 1993. The Jepson manual: Higher plants of California. Berkeley: University California Press.
- Jones, C. and W. Russell. 2001. The effects of timber harvesting on the structure and composition of adjacent old-growth coast redwood forest, California, USA. *Landscape Ecology* 16: 731-741. <https://www.springer.com/journal/10980>
- Jones, G.A. and W. Russell. 2015. Approximation of fire-return intervals with point samples in the southern range of the coast redwood forest, California, USA. *Fire Ecology* 3: 80-94. <https://doi.org/10.4996/fireecology.1103080>
- Keyes, C.R. and J.M. Varner. 2006. Pitfalls in the silvicultural treatment of canopy fuels. *Fire Management Today* 66: 46-50. <https://www.fs.usda.gov/managing-land/fire/fire-management-today>
- Korhonen, L., K.T. Korhonen, M. Rautiainen, and P. Stenberg. 2006. Estimation of forest canopy cover: a comparison of field measurement techniques. *Silva Fennica* 4: 577-588. <https://doi.org/10.14214/sf.315>

- Lazzeri-Aerts, R. and W. Russell. 2014. Survival and recovery following wildfire in the southern range of the coast redwood forest. *Fire Ecology* 10: 43-55.
<https://doi.org/10.4996/fireecology.1001043>
- Loya, D.T., and E.S. Jules. 2008. Use of species richness estimators improves evaluation of understory plant response to logging: a study of redwood forests. *Plant Ecology*, 194, 179-194. <https://doi.org/10.1007/s11258-007-9283-z>
- Mack, M. C. and C.M. D'Antonio. 1998. Impacts of biological invasions on disturbance regimes. *Trends in Ecology and Evolution* 13:195. [https://doi.org/10.1016/s0169-5347\(97\)01286-x](https://doi.org/10.1016/s0169-5347(97)01286-x)
- Martin, R.W. 1998. *Meteorology: Big Basin Redwoods State Park*. Sacramento: California Department of Parks and Recreation, Northern Service Center.
<https://www.parks.ca.gov/pages/21299/files/bbplant.pdf>
- Martin, P. 1979. Productivity and taxonomy of the *Vaccinium globulare*, V. *membranaceum* complex in western Montana. Thesis. Missoula: University of Montana.
- McCune, B. and J.B. Grace. 2002. *Analysis of ecological communities* (third edition). Glendeden Beach: MJM Software Design.
- McKnight, P.E. and J. Najab. 2010. Kruskal-Wallis test. In *The Corsini encyclopedia of psychology* (volume 2), ed. I.B. Weiner and W.E. Craighead. Hoboken: Wiley.
- Metz, M. R., J.M. Varner, K.M. Frangioso, R.K. Meentemeyer, and D.M. Rizzo. 2013. Unexpected redwood mortality from synergies between wildfire and an emerging infectious disease. *The Ecological Society of America* 94: 2152-2159.
<https://doi.org/10.1890/13-0915.1>
- Metz, M.R., K.M. Frangioso, A.C. Wickland, R.K. Meentemeyer, and D.M. Rizzo. 2012. An emergent disease causes directional changes in forest species composition in coastal California forests. *Ecosphere* 3. <https://doi.org/10.1890/ES12-00107.1>
- Nives, S.L. 1979. Fire behavior on the forest floor in coastal redwood forest, Redwood National Park. Thesis. Arcata: Humboldt State University.
- Norman, S.P., J.M. Varner, L. Arguello, S. Underwood, B. Graham, G. Jennings, Y. Valachovic and C Lee. 2009. Fire and fuels management in coast redwood forests. *JFSP Research Project Reports*, 158.
<https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1156&context=jfस्पresearch>

- Pickett, S.T.A. and P.S. White. 1985. Patch dynamics: a synthesis. In *The ecology of natural disturbance and patch dynamics*, ed. S.T.A. Pickett and P.S. White, 371 – 384. Orlando: Academic Press.
- Peet, R.K. 1988. Forests of the Rocky Mountains. in *North American terrestrial vegetation*, ed M. G. Barbour and W. D. Billings, 46 – 101. New York: Cambridge University Press.
- Petersen, A.K. and W. Russell. 2017. A comparison of stand structure and composition following selective-harvest at Byrne-Milliron Forest. Albany: USDA Forest Service, Pacific Southwest Research Station.
https://www.fs.fed.us/psw/publications/documents/psw_gtr258/psw_gtr258_247.pdf
- Reice, S. 1994. Nonequilibrium determinants of biological community structure. *American Scientist* 82: 424-435. <https://www.jstor.org/stable/29775279>
- Reid, M. and S. Thompson. 1996. Ecological fieldwork methods. In *Essential Environmental Science: Methods and Techniques*, ed. S. Watts and L. Halliwell, 357-388. London: Routledge Press.
- Rizzo, D.M. and M. Garbelotto. 2003. Sudden Oak Death: endangering California and Oregon forest ecosystems. *Frontiers in Ecology and the Environment* 1: 197-204.
[https://doi.org/10.1890/1540-9295\(2003\)001\[0197:sodeca\]2.0.co;2](https://doi.org/10.1890/1540-9295(2003)001[0197:sodeca]2.0.co;2)
- Romme, W.H. and D.H. Knight. 1982. Landscape diversity: the concept applied to Yellowstone Park. *BioScience* 32: 664-670. <https://doi.org/10.2307/1308816>
- Russell, W. and K.H. Michels. 2010. Stand Development on a 127-yr chronosequence of naturally regenerating Sequoia sempervirens (Taxodiaceae) forests. *Madroño* 57: 229-41. <https://doi.org/10.3120/0024-9637-57.4.229>
- Scherer, S.S., A.W. D'Amato, C.C. Kern, B.J. Palik, and M.B. Russell. 2016. Long-term impacts of prescribed fire on stand structure, growth, mortality, and individual tree vigor in *Pinus resinosa* forests. *Forest Ecology and Management* 368: 7-16.
<https://doi.org/10.1016/j.foreco.2016.02.038>
- Stephens, S.L. and D.L. Fry. 2005. Fire History in coast redwood stands in the northeastern Santa Cruz mountains, California. *Fire Ecology* 1: 2-19.
<https://doi.org/10.4996/fireecology.0101002>
- Stuart, J.D. 1987. Fire history of an old-growth forest of Sequoia sempervirens (taxodiaceae) forest in Humboldt Redwoods State Park, California. *Madrono* 34: 128-141. <https://www.jstor.org/stable/41424623>

Tirmenstein, D. 1990. *Vaccinium ovatum*. In *Fire Effects Information System*, Fort Collins: USDA Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. <https://www.fs.fed.us/database/feis/plants/shrub/vacova/all.html>

Turner, M.G. 2010. Disturbance and landscape dynamics in a changing world. *Ecology* 91: 283-284. <https://doi.org/10.1890/10-0097.1>

University of California at Santa Cruz. 2017. *UCSC continuous forest inventory plot methods*. Santa Cruz: University of California at Santa Cruz.

Veblen, T.T., T. Kitzberger and L. Antonio. 1992. Disturbance and forest dynamics along a transect from Andean rain forest to Patagonian shrubland. *Journal of Vegetation Science* 3: 507-520. <https://doi.org/10.2307/3235807>

Chapter 3: Conclusion

Fire has maintained a significant presence within the California landscape for thousands of years. With a changing climate, expanding wildland urban interface, and shifts in forest management, fire has transformed into an iconic theme of the west. Equally, if not more, iconic of the coastal California landscape is the presence of the *S. sempervirens* species. With a suite of adaptations to fire, floods, and other sources of disturbance, the species does not require large scale change in order to persist under natural settings, but rather has developed a resilience to shifts in the environment. The presence of basal cavities, cambial scars, and complex canopy structures indicate that fire in the southern extent of the *S. sempervirens* has been a regular occurrence in the fall/winter months (Barbour et al. 2001, Greenlee, 1983; Russell & Jones, 2015). Fire return interval analyses throughout the entirety of the range have the shortest interval and thus most frequent fires in the southern range, with some studies indicating an interval of between 16 and 60 yr (Russell & Jones, 2015; Stephens & Fry, 2005). With the last recorded fire in the Big Basin Redwoods State Park dated at 1936, and an increasing residential density in the Santa Cruz mountains, both ignition sources and fuel load are elevated within the area.

The results of this study illustrate successful completion of many of the goals outlined in prescribed burn plans for the *S. sempervirens* understory at Big Basin Redwoods State Park (California Department of Parks and Recreation, 2010). Although completion of specific quantitative goals cannot be ascertained, due to the time gap in time-since-burn, general and qualitative goals were accomplished. Goals are centralized around reducing

fuel load, receptive fuel bed depth and continuity, and fire intolerant species, while maintaining old-growth *S. sempervirens* late seral stage characteristics. With a reduction in juvenile and hardwood species density, duff and litter depths, and coarse woody fuel loading, the results of this study indicate a shift in dead fuel load and subcanopy tree and shrub species composition, while maintaining non-woody understory species composition. This study also gives empirical and quantitative support for well-timed and managed prescribed fire in the *S. sempervirens* understory, as a means of reducing fuel load to potentially decrease fire severity and intensity in the occurrence of a wildfire.

References

- Anderson, M. J. (2001). A new method of non-parametric multivariate analysis of variance. *Austral Ecology*, 26, 32–46. <https://doi.org/10.1046/j.1442-9993.2001.01070.x>
- Andrews, G. M. (2012). *Post-fire mortality and response in a redwood/Douglas-fir forest, Santa Cruz Mountains, California* (master's thesis). California Polytechnic University, San Luis Obispo, California.
- Attiwill, P. M. (1993). The disturbance of forest ecosystems: the ecological basis for conservative management. *Forest Ecology and Management*, 63, 247-300. [https://doi.org/10.1016/0378-1127\(94\)90114-7](https://doi.org/10.1016/0378-1127(94)90114-7)
- Barbour, M. S., Lydon, M., Borchert, M., Popper, V. Whitworth, V. & Evarts, J. (2001). *Coast redwood: a natural and cultural history*. Los Olivos, California: Cachuma Press.
- Biswell, H. H. (1989). *Prescribed burning in california wildlands vegetation management*. Berkeley, CA: University of California Press.
- Blair, B. C., Letorneou, D. K., Bothwell, S. G., & Hayes, G. F. (2010) Disturbance, resources, and exotic plant invasion: gap size effects in a redwood forest. *Madroño*, 57, 11-19. <https://doi.org/10.3120/0024-9637-57.1.11>
- Boe, K. N. (1975). *Natural seedlings and sprouts after regeneration cuttings in old-growth redwood*. PSW-111. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station.
- Bolsinger, C. L. & Waddell, K. L. (1993). *Area of old growth forests in California, Oregon, and Washington*. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. Retrieved from https://www.fs.fed.us/pnw/pubs/pnw_rb197.pdf
- Brooks, M. L., D'Antonio, C. M., Richardson, D. M., James, B., Keeley, J. E., Ditomaso, J. M., Hobbs, R. J., Pellant, M., & Pyke, D. (2004). Effects of invasive alien plants on fire regimes. *Bioscience*, 54, 677-688. [https://doi.org/10.1641/00063568\(2004\)054\[0677:coiapo\]2.0.co;2](https://doi.org/10.1641/00063568(2004)054[0677:coiapo]2.0.co;2)
- Brower, J. E., Zar, J. H., & Ende, C. N. von. (1998). *Field and laboratory methods for general ecology*. Boston, MA: WCB/McGraw-Hill.

- Brown, J. K. (1974). *Handbook for inventorying downed woody material. General Tech. Rep. INT*. Utah: US Department of Agriculture, Forest Service. Retrieved from <https://www.fs.usda.gov/treearch/pubs/28647>
- Brown, P. M. (2007). *What was the role of fire in coast redwood forests? General Tech. Rep. PSW-GTR-194*. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. Retrieved from https://www.fs.fed.us/psw/publications/documents/psw_gtr194/psw_gtr194_31.pdf
- Brown, P. M., & Baxter, M. W. (2003). Fire history in coast redwood forests of the Mendocino coast. *Northwest Science*, 77, 147-158. Retrieved from <https://bioone.org/journals/northwest-science/issues>
- Brown, P. M., & Swetnam, T. W. (1994). A cross-dated fire history from coast redwood near Redwood National Park, California. *Canadian Journal of Forest Research*, 24, 21-31. doi:10.1139/x94-004
- Brown, P. M., Kaye, M. W., & Buckley, D. (1999). Fire history in Douglas-fir and coast redwood forests at Point Reyes National Seashore, California. *Northwest Science*, 73, 205-216. Retrieved from <https://bioone.org/journals/northwest-science/issues>
- California Department of Parks and Recreation. (2003). *Big Basin Redwoods state park: Final general plan/final environmental impact report*. Sacramento, CA: California Department of Parks and Recreation.
- Carroll, A. L., Sillet, S. C., & Kramer, R. D. (2014). Millenium-scale crossdating and inter-annual climate sensitivities of standing California redwoods. *PloS One*, 9, 1-18. <https://doi.org/10.1371/journal.pone.0102545>
- Cocking, M. I., Varner, J. M., & Sherriff, R. L. (2012). California black oak responses to fire severity and native conifer encroachment in the Klamath mountains. *Forest Ecology and Management*, 270, 25-34. <https://doi.org/10.1016/j.foreco.2011.12.039>
- Cruz, M. G., Alexander, M. E., & Wakimoto, R. H. (2004). Modeling the likelihood of crown fire occurrence in conifer forest stands. *Forest Science*, 50(5), 640-658. <https://doi.org/10.1071/wf16218>
- D'Antonio, C. M., and Vitousek, P. (1992). Biological invasions by exotic grasses, the grass/fire cycle, and global change. *Annual Review of Ecology and Systematics*. <https://doi.org/10.1146/annurev.es.23.110192.000431>

- Dicus, C. A. (2004, November). Fuel loading and potential fire behavior after harvest in coast redwoods stands. *Proceedings of the Second International Wildland Fire Ecology and Fire Management. Orlando, Florida*. Retrieved from https://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1032&context=nrm_fac
- Dixon, P. (2003). VEGAN, a package of R functions for community ecology. *Journal of Vegetation Science*, 14(6), 927–930. <https://doi.org/10.1111/j.1654-1103.2003.tb02228.x>
- Engber, E., Teraoka, J. & Van Mantgem, P. (2017). Forest restoration at redwood national park. Exploring prescribed fire alternatives to second growth management: A case study. *Proceedings from the Coast Redwood Science Symposium. Eureka, California*. Retrieved from https://www.fs.fed.us/psw/publications/documents/psw_gtr258/psw_gtr258_075.pdf.
- Frelich, L. (2016). *Forest dynamics*. St. Paul, MN: University of Minnesota Center for Forest Ecology.
- Forrestel, A. B., Ramage, B. S., Moody, T., Moritz, M. A., Stephens, S. L. (2015). Disease, fuels and potential fire behavior: Impacts of Sudden Oak Death in two coastal California forest types. *Forest Ecology and Management*, 348, 23-30. <https://doi.org/10.1016/j.foreco.2015.03.024>
- Foster, D. R. (1988a). Species and stand response to catastrophic wind in central New England, USA. *Journal of Ecology*, 76, 135-151. <https://doi.org/10.2307/2260458>
- Foster, C. N., P. S. Barton, N. M. Robinson, C. I. Macgregor, & D. B. Lindenmayer. (2017). Effects of a large wildfire on vegetation structure in a variable fire mosaic. *Ecological Applications*, 27, 2369-381. <https://doi.org/10.1002/eap.1614>
- Fryer, Janet L. (2008). *Notholithocarpus densiflorus*. In *Fire Effects Information System*. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Rocky Mountain Research Center, Fire Sciences Laboratory. Retrieved from <https://www.fs.fed.us/database/feis/plants/tree/notden/all.html>
- Gellman, S. T. & Zielinski, W. J. (1996) Use by bats of old-growth redwood hollows on the north coast of California. *Journal of Mammalogy*, 77(1), 255-65. Retrieved from https://www.fs.fed.us/psw/publications/zielinski/psw_zielinski021.pdf

- Giusti, G. A. (2007). Structural characteristics of an old-growth coast redwood stand in Mendocino county, California. In: R. B. Standiford, G. A. Guisti, Y. Valachovic, W. K. Zielinski, M. J. Furniss (Eds.), *Proceedings of the Redwood Region Forest Science Symposium: What does the future hold? Gen. Tech. Rep. PSW-GTR-194* (pp. 161-168). Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture.
- Glebocki, R. (2015). *Fuel loading and moisture dynamics in thinned coast redwood - Douglas-fir forests in Headwaters Forest Reserve, California* (master's thesis). Humboldt State University, Arcata, California.
- Gray, G. (1999). *Prescribed Burn Project Plan: Ocean View Summit Project*. Santa Cruz, CA: California Department of Parks and Recreation.
- Gray, G. (2004) *Prescribed Burn Project Plan: Johansen Road and Upper Skyline to the Sea Projects*. Santa Cruz, CA: California Department of Parks and Recreation.
- Greenlee, J. M. (1983). *Vegetation, fire history, and fire potential of Big Basin Redwoods state park, California* (doctoral dissertation). University of California at Santa Cruz, Santa Cruz, California.
- Greenlee, J. M., & Langenheim, J. H. (1990). Historic fire regimes and their relation to vegetation patterns in the Monterey bay area of California. *American Midland Naturalist*, 124(2), 239. <https://doi.org/10.2307/2426173>
- Griffith, R. S. (1992). *Sequoia sempervirens*. In *Fire Effects Information System*. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Center, Fire Sciences Laboratory. Retrieved from <https://www.fs.fed.us/database/feis/plants/tree/seqsem/all.html>
- Hadley, K. S. (1994). The role of disturbance, topography, and forest structure in the development of a montane forest landscape. *Bulletin of the Torrey Botanical Club*, 121, 47- 61. <https://doi.org/10.2307/2996883>
- Hafs, A. W., Harrison, L. R., Utz, R. M., & Dunne, T.(2014). Quantifying the role of woody debris in providing bioenergetically favorable habitat for juvenile salmon. *Ecological Modelling*, 285, 30-38. <https://doi.org/10.1016/ecolmodel.2014.04.015>
- Hanover, A. & Russell, W. (2018). Understory recovery in coast redwood communities: A case study comparing a naturally recovering and actively managed forest. *Open Journal of Forestry*, 8, 489-499. <https://doi.org/10.4236/ojf.2018.84031>
- Hickman, J. C. (Ed.). (1993). *The Jepson manual: Higher plants of California*. Berkeley, CA: University California Press.

- Hunter, J. C. & Parker, V. T. (1993). The disturbance regime of an old-growth forest in coastal California. *Journal of Vegetation Science*, 4, 19-24. Retrieved from <https://onlinelibrary.wiley.com/journal/16541103>
- Hyland, T. (2010). *Prescribed Burn Project Plan: Meteor Trial Project*. Santa Cruz, CA: California Department of Parks and Recreation.
- Hylkema, M. G. (1991). *Prehistoric native American adaptations along the central California coast of San Mateo and Santa Cruz counties* (master's thesis). San Jose State University, San Jose, California.
- Jones, C. & Russell, W. (2001). The effects of timber harvesting on the structure and composition of adjacent old-growth coast redwood forest, California, USA. *Landscape Ecology*, 16, 731-741. Retrieved from <https://www.springer.com/journal/10980>
- Jones, G. A. & Russell, W. (2015). Approximation of fire-return intervals with point samples in the southern range of the coast redwood forest, California, USA. *Fire Ecology*, 3, 80-94. <https://doi.org/10.4996/fireecology.1103080>
- Keeley, J. E. (2002). Native American impacts on fire regimes of the California coastal ranges. *Journal of Biogeography*, 3, 303-20. Retrieved from <https://onlinelibrary.wiley.com/journal/13652699>
- Keyes, C. R., & Varner, J. M. (2006). Pitfalls in the silvicultural treatment of canopy fuels. *Fire Management Today*, 66, 46-50. Retrieved from <https://www.fs.usda.gov/managing-land/fire/fire-management-today>
- Knapp, E. E., Lyderson, J. M., North, M. P., & Collins, B. M. (2017). Efficacy of variable density thinning and prescribed fire for restoring forest heterogeneity to mixed-conifer forest in the central Sierra Nevada, CA. *Forest Ecology and Management*, 406, 228-241. <https://doi.org/10.1016/j.foreco.2017.08.028>
- Korhonen, L., Korhonen, K. T., Rautiainen, M. & Stenberg, P. (2006). Estimation of forest canopy cover: a comparison of field measurement techniques. *Silva Fennica*, 4, 577-588. doi:10.14214/sf.315
- Kuljian, H. & Varner, J. M. (2010). The Effects of Sudden Oak Death on foliar moisture content and crown fire potential in tanoak. *Forest Ecology and Management*, 10, 2103-110. <https://doi.org/10.1016/j.foreco.2010.02.022>.
- Lazzeri-Aerts, R. & Russell, W. (2014). Survival and recovery following wildfire in the southern range of the coast redwood forest. *Fire Ecology*, 10, 43-55. <https://doi.org/10.4996/fireecology.1001043>

- Lorimer, C. G., Porter, D. J., Madej, M. A., Stuart, J. D., Veirs, S. D., Norman, S. P., O'Hara, K. L. & Libby, W. J. (2009). Presettlement and modern disturbance regimes in coast redwood forests: Implications for the conservation of old-growth stands. *Forest Ecology and Management*, 7, 1038-054. Retrieved from <https://www.fs.usda.gov/treearch/pubs/33548>
- Loya, D. T., & Jules, E. S. (2008). Use of species richness estimators improves evaluation of understory plant response to logging: A study of redwood forests. *Plant Ecology*, 194, 179-194. <https://doi.org/10.1007/s11258-007-9283-z>
- Mack, M. C. & D'Antonio, C. M. (1998). Impacts of biological invasions on disturbance regimes. *Trends in Ecology and Evolution* 13, 195. [https://doi.org/10.1016/s0169-5347\(97\)01286-x](https://doi.org/10.1016/s0169-5347(97)01286-x)
- Martin, R. W. (1998). *Resource Inventory: Meteorology. Big Basin Redwoods State Park*. Sacramento, CA: California Department of Parks and Recreation.
- Martin, P. (1979). *Productivity and taxonomy of the Vaccinium globulare, V. membranaceum complex in western Montana* (master's thesis). University of Montana, Missoula, Montana.
- McCune, B., & Grace, J. B. (2002). *Analysis of ecological communities, 3rd ed.* Gleneden Beach, OR: MJM Software.
- Mcdonald, P. M. & Tappeiner, J. C. (2002). *California's hardwood resource: seeds, seedlings, and sprouts of three important forest-zone species*. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. Retrieved from <https://www.fs.usda.gov/treearch/pubs/6198>
- McKnight, P. E., & Najab, J. (2010). Kruskal-Wallis test. In *The Corsini encyclopedia of psychology* (volume 2). Hoboken, NJ: Wiley.
- Metz, M. R., Varner, J. M., Frangioso, K. M., Meentemeyer, R. K., & Rizzo, D. M. (2013). Unexpected redwood mortality from synergies between wildfire and an emerging infectious disease. *The Ecological Society of America*, 94, 2152-2159. <https://doi.org/10.1890/13-0915.1>
- Metz, M. R., Frangioso, K. M., Wickland, A. C., Meentemeyer, R. K., & Rizzo, D. M. (2012). An emergent disease causes directional changes in forest species composition in coastal California forests. *Ecosphere*, 3(10), 86. <https://doi.org/10.1890/ES12-00107.1>

- Nives, S. L. (1989). *Fire behavior on the forest floor in coastal redwood forest, Redwood National Park* (master's thesis). Humboldt State University, Arcata, California.
- Norman, S. P., Varner, J. M., Arguello, L., Underwood, S., Graham, B., Jennings, G., Valachovic, Y. & Lee, C. (2009) Fire and fuels management in coast redwood forests. *JFSP Research Project Reports*, 158. Retrieved from https://www.researchgate.net/publication/280662190_Fire_and_fuels_management_in_coast_redwood_forests
- Pavlik, B. M., Muick, P. C., Johnson, S. G. & Popper, M. (1991). *Oaks of California*. Los Olivos, CA: Cachuma Press, Inc.
- Pickett, S. T. A. & White, P. S. (1985) Patch dynamics: a synthesis. In: S.T.A. Pickett and P.S. White (Eds.), *The Ecology of Natural Disturbance and Patch Dynamics* (pp. 371-384). Orlando, FL: Academic Press.
- Peet, R. K. (1988). Forests of the Rocky Mountains. In M. G. Barbour & W. D. Billings (Eds.), *North American terrestrial vegetation* (pp. 46-101). New York, NY: Cambridge University Press.
- Petersen, A. K. (2014). *Coast redwood community structure and composition following selective-harvest: a case study of Byrne-Milliron Forest* (master's thesis). San Jose State University, San Jose, California.
- Petersen, A. K. & Russell, W. (2017). *A comparison of stand structure and composition following selective-harvest at Byrne-Milliron Forest*. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. Retrieved from https://www.fs.fed.us/psw/publications/documents/psw_gtr258/psw_gtr258_247.pdf
- Plumb, R., Timothy, R. & McDonald, P. M. (1981). *Oak management in California*. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. <https://doi.org/10.2737/PSW-GTR-54>
- Ramage, B. S., O'Hara, K. L. & Caldwell, B. T. (2010). The Role of Fire in the Competitive Dynamics of Coast Redwood Forests. *Ecosphere* 1, 1-18. <https://doi.org/10.1890/ES10-00134.1>
- Reeves, S. L. (2010). *Arbutus menziesii*. In *Fire Effects Information System*. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Center, Fire Sciences Laboratory. Retrieved from <https://www.fs.fed.us/database/feis/plants/tree/arbmen/all.html>

- Reice, S. (1994). Nonequilibrium determinants of biological community structure. *American Scientist*, 82, 424-435. Retrieved from <https://www.jstor.org/stable/29775279>
- Reid, M. & Thompson, S. (1996). Ecological fieldwork methods. In S. Watts & L. Halliwell (Eds.) *Essential environmental science: Methods and techniques* (pp. 357-388). London, England: Routledge.
- Rizzo, D. M. & Garbelotto, M. (2003). Sudden Oak Death: endangering California and Oregon forest ecosystems. *Frontiers in Ecology and the Environment*, 1, 197-204. [https://doi.org/10.1890/1540-9295\(2003\)001\[0197:sodeca\]2.0.co;2](https://doi.org/10.1890/1540-9295(2003)001[0197:sodeca]2.0.co;2)
- Rischbieter, D. (2000). *Resource Inventory: Aquatic Life*. Sacramento, CA: California Department of Parks and Recreation.
- Romme, W. H., & Knight, D. H. (1982). Landscape diversity: the concept applied to Yellowstone park. *BioScience*, 32, 664-670. <https://doi.org/10.2307/1308816>
- Russell, W. & Michels, K. H. (2010). Stand development on a 127-yr chronosequence of naturally regenerating *Sequoia sempervirens* (taxodiaceae) forests. *Madroño*, 57, 229-41. <https://doi.org/10.3120/0024-9637-57.4.229>
- Sawyer, J. O., Sillett, S. C., Popenoe, J. H., LaBanca, A., Sholars, T., Largent, D. L., Euphrat, F., Noss, R. F., & Van Pelt, R. (2000). Characteristics of redwood forests. In R. F. Noss (Eds.), *The redwood forest: History, ecology, and conservation of the coast redwoods* (pp. 39-79). Washington, DC: Island Press.
- Scherer, S. S., D'Amato, A. W., Kern, C. C., Palik, B. J., & Russell, M. B. (2016). Long-term impacts of prescribed fire on stand structure, growth, mortality, and individual tree vigor in *Pinus resinosa* forests. *Forest Ecology and Management*, 368, 7-16. <https://doi.org/10.1016/j.foreco.2016.02.038>
- Sillett, S. C. & Van Pelt, R. (2007). Trunk reiteration promotes epiphytes and water storage in an old-growth redwood forest canopy. *Ecological Monographs*, 77, 335-59. <https://doi.org/10.1890/06-0994.1>
- Sousa, W. (1984). The Role of Disturbance in Natural Communities. *Annual Review of Ecology and Systematics* 15, 353-91. <https://doi.org/10.1146/annurev.es.15.110184.002003>
- Stephens, S. L. & Fry, D. L. (2005). Fire history in coast redwood stands in the northeastern Santa Cruz mountains, California. *Fire Ecology*, 1, 2-19. <https://doi.org/10.4996/fireecology.0101002>

- Stuart, J. D. & Stephens, S. L. (2006). North Coast Bioregion. In J. W. van Wagtendonk, N. G. Sugihara, S. L. Stephens, A. E. Thode, K. E. Shaffer, J. A. Fites-Kaufman, & J. K. Agee (Eds.), *Fire in California's Ecosystems* (pp. 146-69). Berkeley, CA: University of California Press.
- Stuart, J. D. (1987). Fire history of an old-growth forest of *Sequoia sempervirens* (taxodiaceae) forest in Humboldt Redwoods state park, California. *Madrono*, 34, 128-141. Retrieved from <https://www.jstor.org/stable/41424623>
- Tirmenstein, D. (1990). *Vaccinium ovatum*. In *Fire Effects Information System*. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. Retrieved from <https://www.fs.fed.us/database/feis/plants/shrub/vacova/all.html>
- Turner, M. G. (2010). Disturbance and landscape dynamics in a changing world. *Ecology*, 91, 283-284. doi:10.1890/10-0097.1
- U.S. National Parks Service. (2015). *Prescribed Fire*. Crescent City, CA: U.S. National Parks Service.
- Uchytel, R. J. (1991). *Pseudotsuga menziesii* var. *menziesii*. In *Fire Effects Information System*. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Library. Retrieved from <https://www.fs.fed.us/database/feis/plants/tree/psemenm/all.html>
- University of California at Santa Cruz. (2017). *UCSC continuous forest inventory guide*. Santa Cruz, CA: University of California at Santa Cruz.
- Veblen, T. T., Kitzberger, T. & Antonio, L. (1992). Disturbance and forest dynamics along a transect from Andean rain forest to Patagonian shrubland. *Journal of Vegetation Science* 3, 507-520. <https://doi.org/10.2307/3235807>
- Veirs, S. D. (1981). Coast redwood forest: Stand dynamics, successional status, and the role of fire. *Proceedings of the Forest Succession and Stand Development Research in the Northwest symposium*. Corvallis, OR.
- Waldron, G. (1998). *Resource Inventory: Animal Life*. Sacramento, CA: California Department of Parks and Recreation.
- Westman, W. E. & Whittaker, R. H. (1975). The pygmy forest region of northern California: studies on biomass and primary productivity. *Journal of Ecology*, 63, 493-520. <https://doi.org/10.2307/2258732>

Zachmann, L. J., D. W. H. Shaw, & Dickson, B. G. (2018). Prescribed fire and natural recovery produce similar long term patterns of change in forest structure in the Lake Tahoe basin, California. *Forest Ecology and Management*, 400, 276-287.
<https://doi.org/10.1016/j.foreco.2017.11.013>

Appendices

Appendix A: Prescribed burn plot boundaries, ignition locations, and areas burned

Figure A1. Prescribed burn plot boundaries, ignition locations, and areas burned for the Ocean view summit project in Big Basin Redwoods State Park, Boulder Creek, California, USA. Map data retrieved from California State Parks.

Upper Skyline to the Sea Burn Project (2007-2008)

Figure A2. Prescribed burn plot boundaries, ignition locations, and areas burned for the Skyline to the Sea burn project in Big Basin Redwoods State Park, Boulder Creek, California, USA. Map data retrieved from California State Parks.

Appendix B: Input variables used to calculate dead and downed woody fuel load

Table B1

Input Variables used to Calculate Dead and Downed Woody Fuel Load Estimates on 240 Transects in Big Basin Redwoods State Park, Boulder Creek, California.

Input variable	1-hr	10-hr	100-hr	1000-hr (sound)	1000-hr (rotten)
K	11.64	11.64	11.64	11.64	11.64
d^2	0.0151	0.289	2.76	NA	NA
s	0.48	0.48	0.4	0.4	0.3
a	1.13	1.13	1.13	1	1
c	Dependent upon transect slope (%)	Dependent upon transect slope (%)	Dependent upon transect slope (%)	Dependent upon transect slope (%)	Dependent upon transect slope (%)
Nl (ft)	5	10	10	37.2	37.2

Note. K denotes an empirical constant, d^2 – square of the quadratic mean diameter (in.), s – composite specific gravity, a – angle correction factor, c – slope correction factor, and Nl – transect length (ft).

Appendix C: Sample site specific variable mean and standard errors

Table C1

Physiographic Sample Site Variable Mean and Standard Errors for Three Burned and Three Unburned Sample Sites in Big Basin Redwoods State Park, Boulder Creek, California, USA

	Total Unburned	Total Burned	OVSF	S2SB	JREB	S2SU	NERU	SUNU
Elevation (feet)								
Mean	339.29	417.87	442.17	340.57	452.89	287.56	393.92	336.39
SEM	6.15	6.36	4.15	7.03	5.48	4.43	4.54	3.74
Aspect (degrees)								
Mean	216.28	204.15	142.32	236.75	240.50	239.85	265.00	144.00
SEM	8.70	9.79	14.80	11.28	11.94	8.65	10.56	9.50
Slope (percent)								
Mean	26.43	30.48	21.40	29.55	40.50	24.70	31.45	23.15
SEM	1.41	2.00	2.91	3.22	2.94	2.21	2.73	2.02
Canopy Cover (percent)								
Mean	93.92	91.43	91.60	89.25	93.45	94.20	93.60	93.95
SEM	0.34	0.51	0.84	0.91	0.66	0.52	0.78	0.44

Note. OVSF stands for Ocean View Summit burn site, S2SB stands for Skyline to the Sea burn site, JREB stands for Johansen Road East burn site, S2SU stands for Skyline to the Sea unburned site, NERU stands for North Escape Road unburned site, and SUNU stands for the Sunset trail unburned site.

Table C2

Fuel Load and Fuel Bed Depth Metric Variable Mean and Standard Errors for Three Burned and Unburned Sample Sites in Big Basin Redwoods State Park, Boulder, Creek, California.

	Total Unburned	Total Burned	OVSB	S2SB	JREB	S2SU	NERU	SUNU
Duff depth (cm)								
mean	7.47	3.75	4.46	4.60	2.20	7.32	7.30	7.81
SEM	0.22	0.15	0.24	0.29	0.17	0.47	0.33	0.32
Litter depth (cm)								
mean	5.23	4.61	4.95	5.42	3.48	3.34	5.75	6.60
SEM	0.18	0.15	0.24	0.31	0.13	0.23	0.26	0.34
Fuel depth (cm)								
mean	10.10	10.83	8.46	16.41	7.61	7.38	12.79	10.12
SEM	1.18	1.20	1.17	2.66	1.99	1.25	2.57	2.08
Fine woody fuels – 1, 10, 100 hr (Mg ha ⁻¹)								
mean	6.11	6.39	6.08	8.01	5.08	6.98	4.86	6.49
SEM	0.40	0.42	0.62	0.84	0.65	0.57	0.67	0.78
Coarse woody fuels – 1000+ hr (Mg ha ⁻¹)								
mean	122.56	71.92	119.18	73.18	23.40	95.54	214.23	60.9
SEM	26.67	19.44	51.62	24.57	8.61	25.25	72.77	15.60

Note. OVSB stands for Ocean View Summit burn site, S2SB stands for Skyline to the Sea burn site, JREB stands for Johansen Road East burn site, S2SU stands for Skyline to the Sea unburned site, NERU stands for North Escape Road unburned site, and SUNU stands for the Sunset trail unburned site.

Table C3

Mean and Standard Error Stand Density of Mature Trees (>10 cm DBH, stems per hectare) for Three Burned and Unburned Sample Sites in Big Basin Redwoods State Park, Boulder, Creek, California.

	Total Unburned	Total Burned	OVSF	S2SB	JREB	S2SU	NERU	SUNU
Coast Redwood								
Mean	208	206	216	197	204	216	140	267
SEM	22	20	36	34	34	37	26	45
Tanoak								
Mean	216	115	108	83	153	242	229	178
SEM	22	18	25	31	36	33	39	42
Douglas fir								
Mean	42	32	45	45	6	76	6	45
SEM	11	11	21	23	6	19	6	23
Live oak								
Mean	6	0	0	0	0	13	6	0
SEM	5	0	0	0	0	13	6	0
Madrone								
Mean	0	4	0	0	13	0	0	0
SEM	0	4	0	0	13	0	0	0
All Tree Species								
Mean	473	357	369	325	376	547	382	490
SEM	28	25	36	42	50	42	43	53

Note. OVSF stands for Ocean View Summit burn site, S2SB stands for Skyline to the Sea burn site, JREB stands for Johansen Road East burn site, S2SU stands for Skyline to the Sea unburned site, NERU stands for North Escape Road unburned site, and SUNU stands for the Sunset trail unburned site.

Table C4

Mean and Standard Error (SEM) Stand Density of Juvenile Trees (<10 cm DBH, stems per hectare) for Three Burned and Unburned Sample Sites in Big Basin Redwoods State Park, Boulder, Creek, California.

	Total Unburned	Total Burned	OVS	S2S	JRE	S2SU	NER	SUN
Coast redwood (under 1 m)								
Mean	3463	2780	1604	3463	3272	1451	1000	7939
SEM	1076	479	390	883	1047	460	559	2945
Coast redwood (over 1 m)								
Mean	1239	1089	1865	713	688	407	134	3177
SEM	678	488	1429	262	239	245	44	1979
Tanoak (under 1 m)								
Mean	6992	4034	4647	1120	6334	6621	4240	10116
SEM	989	661	1154	313	1378	960	552	2640
Tanoak (over 1 m)								
Mean	3338	823	1089	560	821	5093	1954	2967
SEM	338	127	191	199	260	641	362	500
Douglas fir (under 1 m)								
Mean	11	36.	102	6	0	19	13	0.00
SEM	6	14	36	6	0	14	13	0.00
Douglas fir (over 1 m)								
Mean	11	28	83	0	0	19	6	6
SEM	7	15	45	0	0	19	6	6
Quercus spp. (under 1 m)								
Mean	40	11	6	13	13	57	19	45
SEM	18	6	6	13	13	28	10	45
Quercus spp. (over 1 m)								
Mean	4	0	0	0	0	6	0	6
SEM	3	0	0	0	0	6	0	6
Madrone (under 1 m)								
Mean	0	8	0	0	25	0	0	0
SEM	0	8	0	0	25	0	0	0
All species (under 1 m)								
Mean	10506	6869	6360	4603	9645	8149	5271	18099
SEM	1505	745	1155	856	1554	932	770	3856
All species (over 1 m)								
Mean	4592	1940	3037	1273	1509	5526	2094	6156
SEM	684	506	1442	312	332	565	373	1842

Table C5

Mean and Standard Error (SEM) Relative Basal Dominance and Basal Area (m²/ha) for Three Burned and Unburned Sample Sites in Big Basin Redwoods State Park, Boulder, Creek, California.

	Total Unburned	Total Burned	OVSF	S2SB	JREB	S2SU	NERU	SUNU
Coast Redwood								
Mean	0.70	0.76	0.78	0.81	0.77	0.74	0.65	0.78
SEM	0.05	0.05	0.09	0.08	0.08	0.08	0.10	0.09
Tanoak								
Mean	0.17	0.12	0.11	0.08	0.17	0.07	0.31	0.15
SEM	0.04	0.04	0.07	0.05	0.07	0.02	0.09	0.07
Douglas fir								
Mean	0.12	0.07	0.11	0.09	0.01	0.27	0.04	0.08
SEM	0.04	0.03	0.07	0.05	0.01	0.08	0.04	0.05
Live oak								
Mean	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
SEM	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Madrone								
Mean	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SEM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
All Tree Species (total basal area)								
Mean	282.58	314.79	327.22	322.89	294.27	304.78	226.97	315.98
SEM	29.66	37.87	81.91	57.21	57.85	44.98	45.29	62.23

Note. OVSF stands for Ocean View Summit burn site, S2SB stands for Skyline to the Sea burn site, JREB stands for Johansen Road East burn site, S2SU stands for Skyline to the Sea unburned site, NERU stands for North Escape Road unburned site, and SUNU stands for the Sunset trail unburned site.

Table C6

Mean and Standard Error (SEM) Non-woody and Woody Shrub Understory Species Richness and Percent Cover Per Plot for Three Burned and Unburned Sample Sites in Big Basin Redwoods State Park, Boulder, Creek, California.

	Total Unburned	Total Burned	OVSF	S2SB	JREB	S2SU	NERU	SUNU
Non-woody understory species richness								
Mean	1.77	2.07	1.35	3.25	1.60	1.50	1.90	1.90
SEM	0.23	0.24	0.31	0.36	0.42	0.37	0.49	0.34
Non-woody understory species percent cover								
Mean	2.93	7.28	2.70	17.70	1.44	1.28	2.45	5.08
SEM	0.69	1.96	1.11	5.09	0.44	0.39	1.35	1.43
Woody shrub species richness								
Mean	1.18	0.68	0.60	0.80	0.65	1.85	1.05	0.65
SEM	0.12	0.09	0.15	0.16	0.17	0.21	0.15	0.17
Woody shrub species percent cover								
Mean	9.61	1.60	1.94	1.11	1.75	22.58	5.48	0.79
SEM	2.02	0.51	1.04	0.40	1.06	4.31	2.35	0.30

Note. OVSF stands for Ocean View Summit burn site, S2SB stands for Skyline to the Sea burn site, JREB stands for Johansen Road East burn site, S2SU stands for Skyline to the Sea unburned site, NERU stands for North Escape Road unburned site, and SUNU stands for the Sunset trail unburned site.