Regeneration and Fuel Loading with Varying Overstory Retention in Redwood Stands 10 Years after Transformation to Multiaged Management

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2024-02-13

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# Abstract

This is an analysis of the 10-year re-measure of the Redwood multi-age experiment which is maintained by Dr. Pascal Berrill, professor of silviculture at Cal-Poly Humboldt, in conjunction with the Jackson Demonstration State Forest in Mendocino County, California. The multi-aged experiment explores the regeneration response of several species following different harvesting techniques including group selection, aggregated retention, and high/low dispersed retention. The 10-year re-measure data includes surface fuel characterization and regeneration density.

## Acknowledgements

I would like to thank my advisor Pascal Berrill and my other committee memebers, Jeffrey Kane, and Rosanna Overholser for their long-suffering support. Completion of my thesis would not have been possible without the administrative support of Nona Minerva, Erin Kelly, and Eric Riggs. My field data would have been measly at best were it not for the dedicated efforts of our field crew: Allen Cooper, JD Wilder…

# 1. Introduction

## 1.1 Multiaged management

Ecological forestry which maintains a wide range of ecosystem services while also supplying timber requires a diverse landscape of highly varied forest structures (Aplet, 1994; Nolet et al., 2018; O’Hara, 2001) . These, in turn, require a variety of silvicultural techniques to implement and sustain (O’Hara, 1998; Schütz, 2002). The development of multiaged stand structures has long been of interest to silviculturists as a key alternative to the conceptually and logistically simpler, even-aged management (Schütz, 1999). Multiaged silviculture refers to the retention of trees of distinctively different age classes, growing together within the same stand. These cohorts may co-occur at the tree level, or in small, even-aged patches within the stand. In the latter case, the distinction between even- and multiaged management can become blurred with increasing patch size, but patches are generally much smaller (often less than 1 ha) than the stands they compose. The pursuit of multiaged stand structures has often met with mixed results (O’Hara, 2002) and this has led to the investigation of several different systems for achieving such structures. Research into the efficacy and results associated with these is ongoing (Beese et al., 2019; Nolet et al., 2018). One such system that has gained popularity in recent decades is known as the retention system, which allows for the retention of a range of tree densities, in dispersed or aggregated spatial patterns and can be used to maintain, multiaged stands, or convert from even-aged management (Mitchell & Beese, 2002).

Redwood forests offer a prime opportunity for multiaged management because coast redwood (*Sequoia sempervirens*) regenerate reliably via stump sprouting and are relatively shade tolerant. The very high leaf areas observed in these forests, suggest their suitability for a multi-layered forest structure (Berrill & O’Hara, 2007; Van Pelt et al., 2016). Additionally, with their high timber value and productivity, Redwood forests are of keen interest to private timber producers. Despite redwood’s fitness for multiaged stand structures, the successful development of subordinate cohorts depends on adequate access to light, and light deficiency can lead to reduced vigor and mortality in young sprouts and understory trees (Barrett, 1988; R. Muma et al., 2022; O’Hara et al., 2007; Webb et al., 2012).

Complicating redwood regeneration and sprout development is the fact that the competing hardwood species, tanoak (*Notholithocarpus densiflorus*), is also shade tolerant and a vigorous resprouter. Tanoak is a keystone species in terms of wildlife habitat and First Nation’s cultural identities, but from a timber production standpoint it is often perceived as a nuisance due to a lack of market development combined with its widespread proliferation following intensive, repeated conifer harvesting (Bowcutt, 2011). While redwood grows more quickly than tanoak in multiaged stands, competition from hardwoods such as tanoak reduce conifer growth and drought resistance (Berrill et al., 2018; Dagley et al., 2023).

## 1.2 Management effects on sprouting

The most commonly used metrics for quantifying sprouting response are percent of stumps sprouting following cutting, the sprout density or the number of sprouts arising from a cut stump or within a sprout clump, and sprout development which can include height and/or diameter.

An important consideration in comparing sprout response across studies is the time between treatment and measurement. Sprout growth in most species is initiated by the mobilization of carbohydrates stored in the underground portions of the tree (Del Tredici, 2001), and differences resulting from external conditions may not be realized early in development. Redwood sprout clumps can consist of 100 or more stems the first year after cutting (Neal, 1967), but rapidly self-thin in full light (Boe, 1975). With overstory competition, this loss may proceed even more rapidly, possibly resulting in the mortality of the entire clump (O’Hara & Berrill, 2010). Whereas the thinning of sprout clumps, whether from internal, or external competition may last 20-30 years in eastern hardwoods (Gould et al., 2007), this process may occur over hundreds of years in long-lived redwoods (O’Hara et al., 2017).

Because the metrics of percent sprouting, sprout density, and sprout development capture different characteristics of sprout response, they often vary with factors such as species, site characteristics, overstory density, parent stump age/diameter, and geographic province. Even when these variables are accounted for, unexplained variation may remain between sites (Keyser & Loftis, 2015; Nieves et al., 2022).

### 1.2.1 Composition

Due to their rapid initial growth, sprouting species may alter the composition of a regenerating stand (Del Tredici, 2001). This can lead to an increase in less desirable species (Keyser & Zarnoch, 2014). In redwood ecosystems, redwood sprouts typically outsize the stump sprouts of tanoak, a common associate, in the first 5 years following partial harvest (R. Muma et al., 2022). It has yet to be seen how these dynamics might change over time, or what their cumulative effect will be on the regeneration of other species (Berrill et al., 2018). Various interactions between treatments and other disturbance factors could lead to differences in regeneration, such as in the case of deer browsing following the use of fire (Wilkinson et al., 1997), heavier deer browsing closer to watercourses (Schneider et al., 2023), or bears preferentially damaging regenerating conifers (especially redwoods) exhibiting rapid diameter growth (Berrill et al., 2017; Dagley et al., 2018).

### 1.2.2 Sprout growth

One of the clearest relationships among sprouting species is the positive one between sprout growth and understory light (Berrill et al., 2018; Gardiner & Helmig, 1997; Keyser & Zarnoch, 2014; Knapp et al., 2017). Like most sprouting species, despite redwoods shade tolerance it requires a certain threshold of light to maintain growth (O’Hara & Berrill, 2010). The effect of understory light is weakest very early in development when growth is dominated by stored carbohydrates in the parent stem and root system (Gardiner & Helmig, 1997; Keyser & Loftis, 2015).

Sprout growth is also dependent on stump diameter, with larger stumps producing more rapid growth. This has been observed in redwood and tanoak (Berrill et al., 2018; Harrington et al., 1992) and is common among eastern hardwoods as well Keyser & Loftis (2015), but varies among species (Knapp et al., 2017).

### 1.2.3 Percent sprouting and number of sprouts

It is common among many sprouting species for percent of stumps sprouting after cutting to decline with increasing tree size or age, but this effect is known to vary by species and may be related to site factors as well. (Johnson, 1977; Nieves et al., 2022). In redwoods, some authors have found evidence of this trend (Neal, 1967; Wiant & Powers, 1967), while others have not (Barrette, 1966; Lindquist, 1979). This may be due to the very wide range of tree sizes and ages possible with redwoods. It has been suggested that percent of stumps sprouting may initially increase with age up to a certain point, and then decrease with trees older than around 200 to 400 years (O’Hara et al., 2007; Powers & Wiant, 1970). Decreasing percent sprouting has been demonstrated for tanoak, among other coastal hardwoods (Harrington et al., 1992).

Residual overstory density may affect the percent sprouting for some species and locales, but detection of this effect has varied across studies and is sensitive to the range of residual basal areas observed in a study (Nieves et al., 2022). Redwood studies have found this phenomenon weak or absent (Barrett, 1988; Lindquist, 1979). The number of sprouts produced by a cut stump for eastern hardwoods is usually not correlated with overstory density (Atwood et al., 2009; Knapp et al., 2017), and this is assumed to be the case in redwood forests as well (Lindquist, 1979; O’Hara & Berrill, 2010).

After cutting, 90-100% of second-growth redwoods (trees smaller than 90 cm dbh) can be expected to sprout (Barrette, 1966; Lindquist, 1979). However, when larger older redwoods are cut, their stumps are less likely to resprout; percent sprouting among larger older trees approaches 50% (Boe, 1975; Neal, 1967). Among cut stumps that do sprout, survival of all the sprouts on a stump is not guaranteed. Entire sprout clumps can die quickly in low light environments (O’Hara & Berrill, 2010). The survival of these new sprouts in each subsequent year is a function of overstory density, especially when approaching closure of the overstory. Percent sprouting has also been found to vary by site and regional factors (Keyser & Loftis, 2015; Nieves et al., 2022). These have not been explored for redwoods, but they represent a possible set of confounding factors in the detection of sprouting trends.

## 1.3 Forest fuels

Throughout many of the fire-adapted forests of California, fire exclusion combined with timber harvest has led to dense, younger stand—often comprised of suppressed trees—proliferation of more fire-sensitive species, and an accumulation of surface fuels (Safford & Stevens, 2017; Stephens et al., 2009). This situation combined with climate change has led to increased size and frequency of high-severity fires in many regions (Parks & Abatzoglou, 2020; Westerling, 2016), prompting widespread interest in fuel treatments and resilient stand structures.

This interest has seen less momentum in the redwood region, likely due to the perceived safety of these typically moist forests from the threat of large wildfires. Yet redwood litter is among the most flammable of conifer litter types (Fonda et al., 1998), seasonal drought leads to cured fuels, especially during extended breaks in coastal fog (Jacobs et al., 1985), and numerous physiological adaptations suggest that redwood has evolved under fire disturbance pressure (Varner & Jules, 2017). More concretely, there have been at least six large fires in redwood ecosystems since 2003, burning at least 189,000 ha including widespread areas of canopy loss. Scientific consensus places the pre-colonization fire return interval for redwood forests at 6-25 years across their range (Lorimer et al., 2009). It is assumed that much of this activity is attributable to indigenous burning (Varner & Jules, 2017).

TODO: summarize fuel loading in various classes found by these studies

There have been several studies that have quantified various fuel strata in redwood forests. Kittredge (1940) did so for duff and litter in a redwood plantation. Greenlee (1983) studied fuels at Big Basin State Park. Stuart (1985) reported on fuels at Humboldt Redwoods State Park. Finney and Martin (1993a, 1993b) reported on fuels in second-growth redwood forests (aged ~100 years) at Annadel and Humboldt Redwoods State Parks. Graham (2009) reported on fuels in old-growth stands across redwood’s range. Glebocki (2015) studied fuels with and without thinning treatments in young (< 50 years) redwood-Douglas fir stands. No fuel studies, to my knowledge, have been conducted in redwood forests actively managed with multiaged silviculture, but fuel dynamics represent a potentially important decision variable to consider when managing forest stands that may be subjected to intentional or unintentional fire.

### 1.3.1 Management effects on fuels

Depending on the method used, thinning and harvest treatments may increase, or not affect surface fuel loading. Whole tree removal results in the least fuel accumulation but is more expensive than other options (Han & Han, 2020). Most other treatment methods increase surface fuels (Agee & Skinner, 2005; Stephens et al., 2009). The magnitude of this increase is variable, reflecting factors such as treatment mode, intensity, and pre-existing conditions (Schwilk et al., 2009). Additional research is needed to clarify the effects of these factors on short (Hood et al., 2020; Schwilk et al., 2009; Stephens et al., 2009), and long-term changes to surface fuel load resulting from specific management actions (Hood et al., 2020; Stephens et al., 2012).

The majority of fine dead fuels (< 8 cm) generated by treatment activities typically decompose within 10 years (Burton et al., 2022; Hood et al., 2020; Martinson & Omi, 2013; O’Hara et al., 2017; Stephens et al., 2012). But live woody fuels, which respond vigorously to increased growing space, often persist or increase over time (Keyes & Varner, 2006). The nature of this response depends on eco-type and the amount of growing space created by the treatment which can become dominated by herbaceous plants (Vilà-Vilardell et al., 2023), shrubs (Odland et al., 2021), or small trees (Hood et al., 2020).

Overtime duff and litter loads are frequently lower in more open stands than stands with a more closed canopy. This may result from increased decomposition rates due to greater insolation and increased throughfall, or reduced deposition rates resulting from fewer canopy fuels (Hood et al., 2020; Keane, 2008).

Most fuel reduction thinning research focuses on ponderosa pine (Pinus ponderosa) forests in the United States, with additional studies from other Mediterranean and semi-arid regions (Burton et al., 2022; Schwilk et al., 2009; Vilà-Vilardell et al., 2023). Far fewer studies have been conducted in coastal forests.

# 2. Methods

## 2.1 Site description

The 20,000-ha Jackson Demonstration State Forest was established in 1947 after being cut over multiple times starting in 1862. The mission of the JDSF is to remain in timber production for research and demonstration purposes. The predominant cover type is redwood, tanoak, and Douglas-fir forest at elevations ranging from 20 m near the coast to 700 m as you move inland. The climate is Mediterranean with cool, wet winters and an average annual precipitation of about 1150 mm. The sites that compose our experiment were all redwood dominated with significant components of tanoak and Douglas fir and were well stocked with trees 80 to 100 years old. All sites are between 13 and 16 km from the Pacific Ocean at elevations between 130 and 300 m, on well-drained, sandstone-derived soils. The sites are located on various aspects of mid to upper-slope positions ([Figure 2.1](#fig-site-map)). Site quality is classified as Site Class II (Lindquist & Palley, 1963; Webb et al., 2012).

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| Figure 2.1: The site locations and topography for our study plots. The red box delineates the area of the topographical map seen in the background. JDSF = Jackson Demonstration State Forest. |

## 2.2 Study design

In 2012, four treatments were replicated at four different sites. The treatments were: group selection (GS), high-density dispersed retention (HD), high-density aggregated retention (HA), and low-density dispersed retention (LD). The GS treatment is composed of a circular 1-ha opening in which all trees were removed, surrounded by a 50-meter buffer of light thinning in which less than 1/3 of the basal area was removed. The remaining treatments were applied over 2-hectare treatment units. The target post-harvest density was specified in terms of relative stand density index (SDI) using an assumed upper SDI limit for redwood of 2,470 stems ha-1 (Reineke, 1933). The target residual relative density for the HA and HD treatments was 21% (SDI = 520), and the for the LD treatment it was 13% (SDI = 320). These densities were chosen to balance the objectives of stand volume productions and individual tree growth assuming a subsequent, similar harvest after 20 years (Berrill & O’Hara, 2009).

After harvesting, 0.2-hectare square macro plot was established in the center of each treatment unit. Approximately 25 redwood and 25 tanoak sprout clumps that were well distributed across the plot, were selected for measurement. Additionally, for redwood, sprout clumps were selected evenly from those with, and without residual standing trees.

Ten years after the initial harvest regeneration plots and fuel transects were established within the macro plot ([Figure 2.2](#fig-plot-layout)). Circular regeneration plots with a 4-meter radius were established 10 meters from each macro plot corner, towards the plot center. Terminating at the center of each of these regeneration plots, 10-meter fuel transects were established parallel to the macro plot edges. Live fuels were estimated in 1-meter radius “sampling cylinders” at the five-, and nine-meter locations along each transect.

Following year 10 measurements, all plots received a pre-commercial thinning treatment where the objective was to release merchantable conifers such as redwood and Douglas-fir from competition. Competing trees and shrubs were cut, lopped, and scattered within the measurement plots and fuel transects were re-measured.

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| Figure 2.2: A diagram of the fuel sampling design depicting a 0.2-hectare macro plot (black outline), fuels transects (black lines), sampling cylinders (orange circles) where duff, litter, and live and dead vegetation were measured, and vegetation sub-plots (green circles), where regeneration density and diversity were quantified. |

## 2.3 Data collection

### 2.3.1 Sprout size

Sprout height data were collected during the winter at years 1, 5, and 10 following the initial harvest. Sprout heights at each period were based on the tallest individual within a clump at the time of measurement with a height pole placed at the same location on the ground at each measurement period. The observer eliminated parallax by observing from a location up-slope, level with the height of the sprout. Sprout DBH for only redwood was collected in year 10.

### 2.3.2 Regeneration

Ten years after the initial harvest, four four-meter-radius regeneration plots were established within each macro plot ([Figure 2.2](#fig-plot-layout)). All regenerating trees (sprouts and seedlings) within the plot were recorded. Regenerating trees less than 2.54 cm at breast height (1.4 m) were tallied by 2.5 cm size classes and the actual DBH of all other regenerating trees were recorded. This allowed for an estimation of sprout and seedling density.

### 2.3.3 Fuels

Also at 10 years after the initial harvest, fuel transects were established and sampled according to the FIREMON protocol (Lutes et al., 2006), with some adaptations that were unique to this project. This protocol is very similar to that of Brown (1974). One-, 10-, 100-hr, and 1000-hr (or coarse woody) fuels were those less than 0.635 cm, 0.635 to 2.54 cm, 2.54 to 7.62 cm and those 7.62 cm and greater, respectively and included only dead and downed woody fuels (not those attached to live vegetation, or standing dead). Transect lengths for 1-, 10-, and 100-hr fuels were one, two, and four meters, respectively. Coarse woody fuels were measured along the entire 10-meter transect.

Redwoods, like other species in Cupressaceae, shed branchlets instead of individual leaves. This leads to difficulty in distinguishing “litter” from 1-hr fuels. We chose to use an estimated cutoff of about 2 mm for redwoods sprays where larger pieces were considered 1-hr fuel and smaller pieces were considered part of the litter layer. We did not distinguish between “leafy” and “awl like” leaf shapes (Graham, 2009).

Live vegetation percent cover and average height were estimated in 1-meter-radius “sampling cylinders” as described in the FIREMON protocol (Lutes et al., 2006). A notable exception is that the sampling cylinders were allowed to extend to the (average) top height of the live fuels that were continuous within less than a meter of the ground. This resulted in average live vegetation heights that could sometimes reach near the height of the sprouts and average heights above two meters were estimated with the help of a clinometer. This decision makes explicit instances when when fuels are vertically continuous with the ground. Live vegetation percent cover was estimated for four vegetation classes: live woody fuels, dead woody fuels, live herbaceous fuels, and dead herbaceous fuels. Dead “live” fuels includes dead fuels attached to live plants, or those still rooted in the ground. Particles in these conditions are not counted as downed woody fuels when tallying fine and coarse woody fuels along fuel transects. These fuels are, though, expected to behave differently during combustion than live “live” fuels. Average vegetation height was recorded for two classes: the average height of all woody fuels and the average height of all herbaceous fuels. These estimates pertain to the particles present in the sampling cylinder, and not the area-average, thus a cylinder with only one percent cover, could still have an average height of two meters, i.e., the empty space within the cylinder does not affect the average height. The average height and percent-cover estimates are visual estimations and efforts were made to discuss these frequently to ensure that estimates among observers were consistent. Percent cover estimates were discrete, rounded to the nearest class in the set: 0.5, 3, 10, and all subsequent 10 percent increments up to 100 percent.

The depth of duff and litter was measured at one representative location within each of the two, 1-meter-radius sampling cylinders along each transect. When duff and litter conditions varied greatly in a single sampling cylinder, a location was chosen to represent the average of conditions within the cylinder.

Fuel bed depth was estimated as the average height of the fine and coarse woody debris components within each sampling cylinder. Theoretically, this included litter, but now duff. This estimate was not described in the FIREMON protocol, but it was designed to be made in a similar manner as described for vegetation heights.

## 2.4 Analysis

The analysis was conducted in three stages, one for each of the three response categories: fuels, sprout size, and regeneration density. All analyses were conducted using R and attempts were made to document all data, decisions, and techniques within a Quarto notebook, which is published at https://fisher-j.github.io/multi-age. All response variables were analyzed using multi-level models to account for the inherent nesting structure of the data, as well as multiple measurements of individuals over time. Grouping levels were included in the models if their variance estiamte was non-zero. Because the overall objective was to detect differences between treatments, treatment was used as the primary independent variable. Model development and selection were carried out using Akaike information criterion, Bayesian information criterion, and visualization of (probability integral) transformed residuals (Hartig, 2022) using the R package GLMMtmb, which provides a consistent framework for exploring different response distributions and link functions (Brooks et al., 2017). This package also includes the ability to model variance as a function of predictors with a logit link and this option was used in fitting some of the models. The final model structures chosen are given in the results section.

## 2.5 Fuels

TODO: add image of percent cover (live and dead).

Fuel load in Mg ha-1 was estimated for 1-hr, 10-hr, 100-hr, combined duff and litter (“duff/litter”), 1,000-hr, and live vegetation fuels. Fuel load for 1- thorugh 1,000-hr fuels were calculated using the method in Brown (1974). The required size-class specific parameters (specific gravity, particle inclination, and average diameter) were derived from a previous study (Glebocki, 2015).

# 3. Results

TODO: I’ve provided all the comparison results, most of which are not statistically significant. Maybe I should also provide grand mean, summary results.

## 3.1 Regeneration composition

### 3.1.1 Basal area

Composition of regeneration in terms of total basal area of each species was modeled as a gamma distribution with a log link with fixed effects for treatment, species, and their interaction and random effects for sites and macro-plots. Dispersion was modeled separately as a function of species, using a log link and the rate of zeros was modeled using the logit link, for each species ([Listing 3.1](#lst-regen-ba)).

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| Listing 3.1  Family: Gamma (log)  Conditional: ba\_ha ~ treat \* spp + (1 | site/treat)  Dispersion: ~spp (log)  Hurdle: ~spp (logit) |

According to this model, we would expect five times as much basal area of other species in LD compared to HA (p = 0.034), and six times more other species basal area in HD compared to HA (p = 0.014), but the presence of other species was generally less than 0.75 m2 ha-1.

We expect 5 times more redwood regeneration basal area in the GS treatment compared to HA (p = 0.03), and 7 times compared to HD (p = 0.02).

For tanoak, we expect about twice as much regeneration basal area in the GS treatment compared to HA (p = 0.03).

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| Figure 3.1: Basal area (m2 ha-1) modeled at the vegetation plot level for four harvest treatments and four species classes (n = 16). Gray bars represent the 95% confidence interval, black dots—the mean, and non-overlapping blue arrows signify statistical significance (α = 0.05). |

[Figure 3.2](#fig-regen-ba-rw-to) shows the same model as [Figure 3.1](#fig-regen-ba), but with an emphasis on treatment comparisons between redwood and tanoak. This shows that we expect on average, five times greater redwood basal area than tanoak basal area in the GS treatment (p < 0.001), and about 2.7 times in the LD treatment (p = 0.039). The two species were most similar in the HD treatment, where redwood basal area is expected to be 1.4 times that of tanoak (p = 0.56). Redwood variability, indicated by the size of 95% confidence intervals, is much greater than that of tanoak’s across treatments, and redwood variability was greater in GS and LD treatments than in the HA and HD treatments ([Figure 3.1](#fig-regen-ba)).

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| Figure 3.2: Basal area (m2 ha-1) modeled at the vegetation plot level for four harvest treatments and two species classes (n = 16). Gray bars represent the 95% confidence interval, black dots—the mean, and non-overlapping blue arrows signify statistical significance (α = 0.05). |

### 3.1.2 Other species

Other speceis included grand fir, madrone, and California wax-myrtle, of which there was a total of 23, 28, and 16 observations across our 16 macro plots (comprising 64 tree density plots). Generally, each plot had between 0 and 9 observations of other species, except for one macro plot with the LD treatment, which had 16 observations (data not shown).

### 3.1.3 Douglas-fir counts

Counts of regenerating Douglas-fir seedlings per vegetation plot (n = 16) were analyzed for differences between harvest treatments using a negative binomial response with a log link, fixed effects for treatment, random effects for site and macro-plot ([Listing 3.2](#lst-df-counts)).

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| Listing 3.2  Family: nbinom1 (log)  Conditional: n ~ treat + (1 | site/treat) |

This model for Douglas-fir counts does not result in any statistically significant differences between treatments. Generally, we expect about 2 seedlings per 4-meter-radius plot, or about 413 seedlings per hectare ([Figure 3.3](#fig-df-counts)).

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| Figure 3.3: Vegetation plot level counts of regenerating Douglas-fir seedlings in four harvest treatments 10 years after harvest (n = 16). Results have been scaled to stems per hectare (4-meter radium plots). |

## 3.2 Sprout heights

### 3.2.1 Height increment

The selected height increment model used a normal response distribution on the identity link. It included treatment, growth period, species, and the interaction of species and growth period as fixed effects. A random intercept was included for tree (multiple observations) and macro-plot, and a random slope was included for species. The dispersion parameter for the response was modeled (with a log link) as a function of treatment, growth period, species and all three-way interactions ([Listing 3.3](#lst-sprout-ht-inc)).

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| Listing 3.3  Family: gaussian (identity)  Conditional: ht\_inc ~ treat + year \* spp + (1 | tree) + (0 + spp | plot)  Dispersion: ~spp \* year \* treat (log) |

The model selected based on AIC lacks a treatment x species interaction, suggesting that there is not evidence that treatments affected species differentially. It also lacks a treatment x year interaction. This means that there was not enough evidence to support that treatment was related to changes in growth rate.

The presence of treatment in the model (0.001 ≤ p < 0.03) suggests that the levels of treatment were associated with different growth rates across species and years. And the species x year interaction (p < 0.001) suggests changes in growth rates are different for redwood and tanoak ([Figure 3.4](#fig-sprout-ht-inc-treat)).

Averaging over growth periods, treatment specific height increments for redwood ranged from 0.66 to 0.86 m yr-1, and for tanoak, from 0.29 to 0.49, with the slowest growth in the HD treatment and the fastest in the GS treatment. Height increment was greater in the GS treatment than the HA and HD treatments by about 0.19 m yr-1 (p < 0.001). The LD treatment was intermediate, but not statistically distinguishable from the other treatments (0.13 < p < 0.28).

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| Figure 3.4: Estimated marginal means for the effect of harvest treatment on redwood and tanoak sprout height increment, averaged over two growth periods, ten years after harvest. Gray bars represent confidence intervals and statistical significance (α = 0.05) is indicated by non-overlapping blue arrows. |

Redwood growth slowed from 0.80 to 0.67 m yr-1 in the second period and tanoak slowed from 0.39 to 0.34 m yr-1.

Redwood grew faster than tanoak, but slowed down more relative to it in the second period. Height increment for redwood was 0.42 m yr-1 greater in the first period and 0.33 m yr-1 greater in the second period than tanoak height increment ([Figure 3.5](#fig-sprout-ht-inc-year)).

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| Figure 3.5: Estimated marginal means for the effect of growth period on redwood and tanoak sprout height increment, averaged over four harvest treatments, from years 1 to 5, and years 5 to 10 after harvest, plotted alongside actual data. Gray bars represent confidence intervals and statistical significance (α = 0.05) is indicated by non-overlapping blue arrows. |

### 3.2.2 Height at year 10

Sprout heights at year 10 were modeled with a normal response and a log link. The best model included species and treatment, but no interactions in the fixed effects. This suggests that treatments do not affect species differentially. It also included a model for dispersion (log link) that had species, treatment, and their interaction as predictors ([Listing 3.4](#lst-sprout-ht-yr-10)).

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| Listing 3.4  Family: gaussian (log)  Conditional: ht ~ treat + spp + (0 + spp | plot)  Dispersion: ~spp \* treat (log) |

Because the best model did not contain a species x treatment interaction, comparisons between treatments is the same for both species. The GS treatment resulted in greater heights in year 10 than the other treatments (0.001 < p < 0.04). Predicted mean height for redwood ranged from 10.29 m in the GS treatment to 6.16 m in the HD treatment. For tanoak, predicted mean height ranged from 5.12 in the GS treatment to 3.04 in the HD treatment. Predicted mean heights followed the pattern GS > LD > HA > HD ([Figure 3.6](#fig-sprout-ht-yr-10)).

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| Figure 3.6: Predicted mean height and 95% confidence intervals (gray bars) for redwood and tanoak stump sprouts 10 years after harvest using four different harvest treatments. Non-overlapping blue arrows indicate statistically significant differences between treatments within a species. |

## 3.3 Fuels

### 3.3.1 Pre-pct

Gamma distributed, linear multi-level models, with a log link were used for all six fuel class responses. Random intercepts were specified for three levels of nesting, representing sites, treatment blocks, and transect corners. All models except for the duff & litter model included a hurdle model to account for zero, which was modeled with a logit link. For the 10-hr fuel model, the hurdle portion was modeled as a function of treatment, and for the others, it was modeled as a single rate for all observations. The 10-hr fuel model also included a dispersion model, which was modeled with a log link, using treatment as a predictor ([Table 3.1](#tbl-fuel-pre-pct)).

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| Table 3.1: Model specifications for six fuel classes before pct.   | class | Family | Link | Conditional | Dispersion (log) | Hurdle (logit) | | --- | --- | --- | --- | --- | --- | | Duff & Litter | Gamma | log | load ~ treatment + (1 | site/treatment/corner) | ~1 | ~0 | | 1-hr | Gamma | log | load ~ treatment + (1 | site/treatment/corner) | ~1 | ~1 | | 10-hr | Gamma | log | load ~ treatment + (1 | site/treatment/corner) | ~treatment | ~treatment | | 100-hr | Gamma | log | load ~ treatment + (1 | site/treatment/corner) | ~1 | ~1 | | 1,000-hr | Gamma | log | load ~ treatment + (1 | site/treatment/corner) | ~1 | ~1 | | Vegetation | Gamma | log | load ~ treatment + (1 | site/treatment/corner) | ~1 | ~1 | |

For Duff & Litter, the largest difference was between the HD and HA treatments. The HD treatment had about 1.4 times more duff and litter (p = 0.07). Generally, all treatments were similar, with estimated loading of around 50 Mg ha-1. One-hour fuels were around 50% higher in the HA treatment compared to the LD and GS treatments (p = 0.07, and p = 0.01, respectively), with mean differences of around 0.5 Mg ha-1. Ten, hundred and thousand-hour fuels were statistically, very similar across treatments (p = 0.7 — p = 1). Point estimates varied by about 1, 3, and <20 Mg ha-1 for ten, hundred, and thousand-hour fuels, respectively. Vegetative fuel loading was greatest in the GS treatment, with an expected value of 28.5 Mg ha-1, which was about 2.7 times greater than in HA (p = 0.01) ([Figure 3.7](#fig-fuel-pre-pct)).

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| Figure 3.7: Estimated marginal means (black dots) confidence intervals (gray bands) and comparisons (blue arrows) of fuel loading across four treatments for six different fuel-class models. Non-overlapping blue arrows indicates statistical significance at the α = 0.05 level. |

Here are the grand means, pre-PCT for each fuel type:

| class | 1 | response | SE | df | asymp.LCL | asymp.UCL |
| --- | --- | --- | --- | --- | --- | --- |
| dufflitter | overall | 46.2706677 | 4.1524064 | Inf | 38.8076665 | 55.168859 |
| onehr | overall | 0.7976222 | 0.1078313 | Inf | 0.6119593 | 1.039614 |
| tenhr | overall | 3.3601573 | 0.2894670 | Inf | 2.8381234 | 3.978212 |
| hundhr | overall | 10.8836851 | 1.1758587 | Inf | 8.8067019 | 13.450507 |
| thoushr | overall | 42.5329141 | 7.4550597 | Inf | 30.1667638 | 59.968275 |
| veg | overall | 17.5463823 | 3.0620652 | Inf | 12.4635619 | 24.702050 |

### 3.3.2 Post-pct

The response for all six, post-pct fuel classes were modeled with a gamma distribution and a log link, and included the same multi-level random effects as for the pre-pct models. Dispersion models with treatment as the only predictor were included for 1-hr and 100-hr fuel classes. All models included a hurdle portion to model zeros using a logit link. For 100-hr fuels, this model included treatment and site as predictors, and for the rest, a constant rate for all observations was used ([Table 3.2](#tbl-fuel-post-pct)).

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| Table 3.2: Model specifications for six fuel classes after pct.   | class | Family | Link | Conditional | Dispersion (log) | Hurdle (logit) | | --- | --- | --- | --- | --- | --- | | 1-hr | Gamma | log | load ~ treatment + (1 | site/treatment/corner) | ~treatment | ~1 | | 10-hr | Gamma | log | load ~ treatment + (1 | site/treatment/corner) | ~1 | ~1 | | 100-hr | Gamma | log | load ~ treatment + (1 | site/treatment/corner) | ~treatment | ~treatment + site | | 1,000-hr | Gamma | log | load ~ treatment + (1 | site/treatment/corner) | ~1 | ~1 | | Vegetation | Gamma | log | load ~ treatment + (1 | site/treatment/corner) | ~1 | ~1 | | Vegetation Difference | Gamma | log | load ~ treatment + (1 | site/treatment/corner) | ~1 | ~1 | |

Post-pct resulted in greater stratification of treatments ([Figure 3.8](#fig-fuel-post-pct)). One-hour fuels for most treatments were around 2.4 Mg ha-1, but the HA treatment had around half of that amount (p = 0.01 to p = 0.02). The GS treatment had the greatest 10-hr fuel loading with 8.8 Mg ha-1, which was about 1.6, 2.3 and 2.9 times greater than the LD, HA, and HD treatments respectively (p = 0.03, p < 0.001, for the others, respectively). The LD treatment also had about 1.7 times more 10-hr fuels that the HD treatment (5.4 vs. 3 Mg ha-1, p = 0.001). Hundred-hour fuels were also greatest in the GS treatment, with an average of about 19 Mg ha-1, which was about 2.6 times greater than in the HD treatment (7 Mg ha-1, p < 0.001). Thousand-hour fuels were greatest in the HD treatment, with 80 Mg ha-1, which was about 2.7 times greater than the LD and HD treatments (p = 0.03 and p = 0.05, respectively). Fuel loading for live vegetation was similar across treatments at around 2.5 Mg ha-1. The pre-post vegetation difference was greatest in the GS treatment at about 31 Mg ha-1, which was 2.5 and 2.8 times the HD and HA treatments, respectively (p ≈ 0.01).

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| Figure 3.8: Estimated marginal means (black dots) confidence intervals (gray bars) and comparisons (blue arrows) of fuel loading across four treatments for six different fuel-class models. Non-overlapping red arrows indicates statistical significance at the α = 0.05 level. Vegetation difference equals the transect level difference in vegetation load in the pre and post-pct conditions. This represents slash fuels recruited to the forest floor following the pre-commercial thinning. |

Here are the grand means post-PCT for each fuel type:

| class | 1 | response | SE | df | asymp.LCL | asymp.UCL |
| --- | --- | --- | --- | --- | --- | --- |
| dufflitter | overall | 46.2706677 | 4.1524064 | Inf | 38.8076665 | 55.168859 |
| onehr | overall | 0.7976222 | 0.1078313 | Inf | 0.6119593 | 1.039614 |
| tenhr | overall | 3.3601573 | 0.2894670 | Inf | 2.8381234 | 3.978212 |
| hundhr | overall | 10.8836851 | 1.1758587 | Inf | 8.8067019 | 13.450507 |
| thoushr | overall | 42.5329141 | 7.4550597 | Inf | 30.1667638 | 59.968275 |
| veg | overall | 17.5463823 | 3.0620652 | Inf | 12.4635619 | 24.702050 |

Pre-commercial thinning led to a small increase in average 100-hr fuel loading, only for the GS treatment, increased 10-hr fuels in the GS and LD treatments, and increased 1-hr fuels for all but the HA treatment ([Figure 3.9](#fig-fuel-pct-comparison)), although these results are not statistically comparable, due to slightly different model structures.

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| Figure 3.9: Estimated marginal means (black dots) and confidence intervals (colored bars) of fuel loading across four treatments and five different fuel classes, before and after PCT. Pre- and Post PCT models within a treatment are from similar, but not necisarily identical models. |

# 4. Discussion

* Forest management for timber and other objectives and prescribed and wild fire are inherently interlinked
* This requires research which considers these historically disjunct realms of research in a wholistic way
* Shifts in species composition / dominance can affect prescribed and wild fire behavior, and vice-versa
* Aspect was likely a confounding factor that we did not control for
* Confounding factors likely contributed to larger 95% confidence intervals
* GS and LD treatments were generally much harder to navigate in the field.
* Cost of treatments
* 1-hr redwood fuels differed from other studies in that we implemented a cutoff
* Discuss the decision to allow surface fuels to extend to greater than 2 meters
* similar bulk densities for duff and litter: stuart. Also, finney combined the two.

## 4.1 Composition

### 4.1.1 Minor species

Our sampling included relatively few minor species and differences across treatments were small. The only statistically detectable difference occurred between the LD and HA treatment where the latter had less basal area of minor species. While this could be due to low numbers overall numbers of occurrences of minor species and high variability within treatments, this phenomena is corroborated by the low vegetation response found in the HA treatment for the separately gathered fuels data ([Figure 3.7](#fig-fuel-pre-pct)), as well as for tanoak sprout basal area where the only statistically supported evidence of treatment difference was between the GS and HA treatments. Potential differences in minor species abundance is likely only relevant for grand fir, due to its shade tolerance (Webb et al., 2012). Red alder and wester hemlock were observed earlier in this experiment, but were not detected with our current experimental design (R. T. Muma, 2019).

Douglas-fir is a minor species of special interest due to it’s commercial value and ability to compete with redwoods in the first 100 years of stand development (Wensel & Krumland, 1986). We didn’t detect statistically supported differences between treatments in terms of basal area ([Figure 3.1](#fig-regen-ba)) or stem counts ([Figure 3.3](#fig-df-counts)). While our observed recruitment density of Douglas-fir seedlings may be sufficient for the eventual production of a viable cohort, only the LD and GS treatments are likely to maintain overstory densities conducive to Douglas-fir seedling development (Miller & Emmingham, 2001; Schütz & Pommerening, 2013) given the overstory basal areas recorded at the initiation of the experiment (R. Muma et al., 2022). Rapidly developing redwood and tanoak sprouts will further comprise Douglas-fir seedlings competitive ability.

* Relevance for biodiversity?
* Douglas-fir: there was no appreciable differences detected among treatments either for basal area or number of stems
  + this suggests that our treatments were not growing-space limiting in terms of df regeneration: compare to other studies of DF regeneration
    - are we above or below the threshold for optimal df growing space?
  + Continued canopy closure could result in light limiting conditions in the future test test
* Like other studies in redwoods the least residual overstory density resulted in the greatest abundance of redwood.
  + RW basal area in LD (the next highest average redwood basal area) was half that of the GS treatment, but large ammount of variability meant that this difference was not statistically distinguishable from 0 at the 95% confidence level.
* Variability dereased with decreasing abundance
  + redwood variabiltiy was greatest
  + variability was greatest in lower density treatments: aspect?
* HA and HD treatments were very similar
* This is all suggestive of quickly declining growth rates associated with increasing overstory density
* Treatment differences for tanoak were relatively similar, but with less difference between GS and LD treatments
* Small (non statistical) difference between HA and HD likely due to un realistic midpoit chosen for stems less than 1 cm.
  + reflects the fact that there were more (small) tanoak stems associated with increasing overstory density
    - perhaps due to slower rate of self-thinning resulting from slower growth
* what would tanoak abundance be if they were not competing with redwood?

## 4.2 Sprout height

## 4.3 Fuel loading

### 4.3.1 Pre-PCT

Fuel loading found in our treatments were comparable to those found in other studies in redwood systems. Our treatment level averages for duff and litter ranged from 40 to 55 Mg ha-1 in plots that had post-harvest basal areas (in 2012) of 0 to 40 m2 ha-1. This was comparable to total duff and litter loading found in 120-year-old redwood stands (range: 29 to 55 Mg ha-1) as well as old-growth stands (averge: 50 Mg ha-1) and our raw average duff and litter depth of 6.2 cm (data not shown) was similar to that found in a <30-year-old mixed Douglas-fir/redwood stand (Finney & Martin, 1993a; Glebocki, 2015; Stuart, 1985). We opted to combine duff and litter into a single metric following previous studies that found similar bulk densities for duff and litter and that separating the two resulted in little difference from and average bulk density, given the wide variability found in duff and litter depthsFinney & Martin (1993a).

Our average total fine woody fuel loading, including one-, ten-, and one hundred-hour-fuels (15 Mg ha-1) was within the range found in 120-year-old stands (9 to 20 Mg ha-1, Finney & Martin (1993b)), double that found in very young, mixed stands (Glebocki, 2015), and 4 Mg ha-1 higher than that found in old growth stands (Stuart, 1985).

In the following I’ll compare the average fuel loadings found in this study to those found in the “old growth” and “very young, mixed” stands referenced above.

Our one-hr fuel loading which, which averaged about 1 Mg ha-1 was similar to that found in the old-growth stand, but about half that found in the very young, mixed stand.

Our average 10-hr fuel loading was higher than in the very young, mixed stand (3.4 vs. 2 Mg ha-1) but similar to the old growth stand.

Our average 100-hr fuel loading of about 11 Mg ha-1 was higher than in both the old growth stands (5 Mg ha-1) and the very young, mixed stands (3 Mg ha-1).

Our average 1,000-hr fuel loading of 42 Mg ha-1 was somewhat lower than found in old growth stands (63 Mg ha-1) as well as in the very young, mixed stands (54 Mg ha-1). These estimates are accompanied by relatively high standard errors, but it would not be surprising that State Park forest, with little to no harvest activity would have a larger amount of large downed logs then an actively managed forest such as ours.

Our elevated average 100-hr fuel loading may be the result of residual fuels left over from the harvest treatment that initiated our experiment which would have been absent from the other sites referenced here. In the very young, mixed stand, 100-hr fuels jumped to 10 Mg ha-1 immediately following a thinning treatment. For our 10-hr fuels, it might be reasonable to suspect that the smaller trees in the very young, mixed stand did not supply as much 10-hr fuels because of the sizes of their branches, whereas branch shedding patterns in the 10-hr time lags class were more similar between our stands and the old growth ones. Our reduced 1-hr fuel loading compared to the very young, mixed forest could be due to differing stand structures and species compositions. That forest was composed of a large proportion very young Douglas-fir and would be expected to have different forest floor characteristics and this notion is supported by our finding of similar 1-hr fuel loading as in the old growth study. Another source of possible error is differences in sampling method for 1-hr fuels. We established a cutoff where redwood particles smaller than roughly 2 mm were considered as litter, rather than 1-hr fuels. If we had counted every redwood leaf-spray, regardless of size, we would have likely found higher 1-hr fuel loads.

That we found similar average fuel loading in our Pre-PCT stands compared to two studies in very different redwood forest structures is congruent with our findings of few statistically significant differences between treatments in terms of fuel loading. This result is common among other studies and is expected due to the highly variable nature of forest fuels (CITATIONS). Statistical difference at the p < 0.05 level were only found among treatments for 1-hr and Vegetation loading, and nearly found for Duff & Litter. In all cases these differences involved the HA treatment, but the nature of the comparisons varied with fuel types. For instance, for Duff & Litter was lowest in the HA treatment and highest in the HD treatment (p = 0.07). This potential difference in fuel load could be indicative of differences in fuel moisture because forest floor decomposition is a function of both moisture and temperature (CITATIONS). Forest floor conditions in the HA treatment would be expected to be somewhat more moist than the more open treatments, but potentially also warmer (due to greater light infiltration) than the HD treatment. Small differences in forest floor moisture can have significant implications for prescribed burning operations because these are often conducted under marginal conditions (CITATIONS). In terms of both 1-hr fuel loading and Vegetation fuel loading, the HA treatment was most similar to the HD treatment. In these cases it is not surprising that a greater density of sizeable trees would result in more twigs and less light available for growth of vegetation at the surface. It is somewhat surprising that the HA treatment did not reveal measurable differences in understory growth. This result does not support our previous supposition in regards to Duff & Litter loading, of differences in understory light (temperature) between the HD and HA treatments. But it could be that understory growth dynamics are more complicated than simple light availability and to this end, other researchers have proposed exploring the potential effects of below-ground competition (CITATIONS). It was also somewhat surprising that the modeled Vegetation fuel loading differences were not more pronounced because, while conducting field work, GS and LD treatments were usually much more difficult to work in due to the amount of understory growth present in these treatments. And these conditions were also indicated by our findings of somewhat elevated basal area of tanoak and redwood in those treatments. Our method of calculating vegetation fuel loading (estimated percent cover times estimated height within an estimated cylinder) might have been overly imprecise. Additionally, given the importance of understory light to the processes of surface fuel decomposition as well as for understory growth, inclusion of the potentially confounding variable: aspect might have led to better explanatory power in our models. Our plots were established over a range of aspects, but it is plausible that differences in aspect outweighed differences between treatments. We had hoped that the inclusion of site and treatment as nested random effects would have captured site and block level differences in aspect. Additionally, aspect is largely a proxy for insolation, and this may have also varied with shade conditions (very large trees or roadcuts) outside of the plot.

### 4.3.2 Post-PCT

Duff and litter are not reported for post-pct stands for two reasons. First, these are not expected to have changed significantly given the relatively short timespan before and after PCT. Second, our sampling protocol did not make it clear how to quantify the loading for leaves attached to recently cut branches, especially given that these “suspended litter” particles were in a state of active transition to the ground, as they dry, abscise, and sift through the coarser woody fuels as they make their way to the ground. This class may deserve more attention because of it’s potentially dynamic relationship with the timing of prescribed fires: as suspeded particles settle and begin to decompose they’re bulk density changes and bulk density is an important determinant of fire behavior.

Crews were guided to thin to achieve the same understory conditions across all four treatments and this is indicated by similar post-PCT vegetation fuel loads ([Figure 3.8](#fig-fuel-post-pct)). Fuel differences resulting from PCT were driven by fuels in the vegetation fuels class, i.e., growth and productivity. Vegetative growth following thinning and harvest is an important consideration for fire informed management. In our experiment, 10 years of growhth (followed by PCT) led to some increase in average 100-hr fuel loading but only for the GS treatment. Ten-hr fuels increased in the GS and LD treatments aparently as a function reducing competition in these treatments ([Figure 3.9](#fig-fuel-pct-comparison)). One-hr fuels increased most, in the GS and LD treatments, but also started out somewhat lower 1-hr fuel loading than the HA and HD treatments, which resulted in the the post-pct fuel loading being simliar, except for in the HA treatment, where unexpectedly low vegetative fuel loading resulted in little to no increase in 1-hr fuels after PCT, likely because much of the existing vegetation (saplings) needed to be retained to meet the presctiption ([Figure 3.9](#fig-fuel-pct-comparison)). Pre-commercial thinning resulted in little change in 1,000-hr fuels, as thinned sapling stems were mostly under three inches, although a potential increase observed in the HD treatment may have been a result of some previosly retained canopy trees being cut (12 inches dbh was the prescribed upper limit for thinning). The model selection process resulted in slightly different models after pre-commercial thinning, compared to before thinning for a given fuel class. These changes may be somewhat arbitrary, as the model selection process was guided by balancing parsimony, AIC, and the production of well distributed residuals. In a few cases, the higher values associated with post-PCT fuel loading predictions tended towards models that accounted for greater (variation in) variability.

The simple method we used probably over-estimated vegetation fuel loading, evidenced by the fact that the large fuel loading differences observed in the vegetation class are not reflected in the increase in fine fuels. Although the contribution of slash foliage is not accounted for, it appears our method may have overpredicted vegetation loading by around a factor of three if we assume that the majority of the difference in vegetation fuels should be captured by the sum of the changes in fine fuels and the decrease in 100-hr fuels after PCT is assumed to be the result of sampling error.

It can be seen from this analysis resulting surfaces fuel conditions are expected to be the result of a complex interaction of productivity and decomposition rate. Whether any of the differences we observed result in a significant difference in prescribed or wild fire will need to be tested by those disturbances. It is possible that the elevated 10-hr loads in the GS and to a lesser degree, the LD treatments may represent greater fuel continuity which could support prescribed fire operations. Likewise, the HA treatment’s lower fuel loading across classes could signify patchy fuel distribution. Surface fuel moisture and windspeed are two variables which we did not study but which have a strong influence on fire behavior and are also affected by overstory density and arrangement. Given the relatively modest differnence we observed in fuel loads, it seems likely that those unmeasured factors could have a greater bearing on fire outcomes.

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