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

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# Preface

## 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.

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# 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; 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 sprouting, the sprout density, or the number of sprouts on a stump, or occasionally, within a sprout clump, and sprout development, which can include average height, top height—the height of the tallest sprout in a clump—or diameter at some specified height. Because these metrics capture different characteristics of sprout response, they tend to vary differently (or not vary) with factors such as species, site characteristics, over-story density, parent stump age/diameter and geographic province, and even when these variables are acoounted for, un-explained variation may remain between sites (Keyser & Loftis, 2015; Nieves et al., 2022).

An important consideration in comparing sprout response across studies is the time of measurement. Sprout growth in most species is initiated by the mobilization of carbohydrates stored in the underground portions of the tree (Del Tredici, 2001). 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). The thinning of sprout clumps, whether from internal, or external competition may last 20-30 years in the case of eastern hardwoods (Gould et al., 2007), or hundreds of years in the case of long-lived redwoods (O’Hara et al., 2017).

### 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 potentially lead to an increase in less desireable species (Keyser & Zarnoch, 2014). While redwood outcompete tanoak in the first 5 years following stand initiation (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). Unforseen 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).

### 1.2.2 Sprout growth

One of the clearest relationship 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 sprouting 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 size and ages possible with redwoods. It has been suggested that probability of sprouting may initially increase 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 phenomena weak or absent (Barrett, 1988; Lindquist, 1979). Number of sprouts 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) can be expected to sprout (Barrette, 1966; Lindquist, 1979). Percent sprouting in larger trees approachs 50% (Boe, 1975; Neal, 1967). But these numbers can decline quickly in low light environments (O’Hara & Berrill, 2010).

The survival of these recruits in each subsequent year is a function of overstory density, especially when approaching closure of the overstory. Percent sprouting has been found to vary as well 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 factor 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

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# 3. 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-mod-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 interestingly, six times more other species basal area in HD compared to HA (p = 0.014, [Figure 3.1](#fig-mod-regen-ba)).

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). |

### 3.1.2 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-mod-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 3.2](#fig-mod-df-counts)).

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| Figure 3.2: 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-mod-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 3.3](#fig-mod-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 3.3: 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 3.4](#fig-mod-sprout-ht-inc-year)).

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| Figure 3.4: 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-mod-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 3.5](#fig-mod-sprout-ht-yr-10)).

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| Figure 3.5: 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-mod-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 ([Figure 3.6](#fig-mod-fuel-pre-pct)).

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| Figure 3.6: 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. |

### 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-mod-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 3.7](#fig-mod-fuel-post-pct)). One-hour fuels were generally around 2.4 Mg ha-1, but the HA treatment had around half of that amount (p = 0.01 — 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 3.7: 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. |

# 4. Discussion

## 4.1 Composition

## 4.2 Sprout height

## 4.3 Fuel loading

# 5. References

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