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.

## Acknowledgements

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# 1. Introduction

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 and 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 and 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, Stancioiu, and Spencer 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).

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 and 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 and 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, Belanger, and Burley 1998), seasonal drought leads to cured fuels, especially during extended breaks in coastal fog (Jacobs, Cole, and McBride 1985), and numerous physiological adaptations suggest that redwood has evolved under fire disturbance pressure (Varner and 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 and Jules 2017).

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.

## 1.1 Thinning effects on fuel summary

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 (Schwilk et al. 2009; Burton et al. 2022; Vilà-Vilardell et al. 2023). Far fewer studies have been conducted in coastal forests.

Mechanical thinning and harvest treatments, except for whole tree removal, usually increase surface fuel loading in the short term (Stephens et al. 2009). The resulting increase is variable and likely reflects the treatment mode, intensity, and pre-existing conditions (Schwilk et al. 2009). Additional research is needed to clarify the effects of these factors (Schwilk et al. 2009; Stephens et al. 2009; Hood et al. 2020), as well as the long-term effects (Stephens, Collins, and Roller 2012; Hood et al. 2020).

The fine dead fuels (< 8 cm) generated by treatment activities typically decompose within 10 years (Stephens, Collins, and Roller 2012; Hood et al. 2020; Burton et al. 2022; O’Hara et al. 2017; Martinson and Omi 2013). But vegetative fuels, which respond vigorously to increased growing space, often persist or increase over time (Keyes and 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).

Duff and litter loads are frequently lower in more open stands, which 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).

## 1.2 Thinning effects on sprouting

### 1.2.1 Probability of stump sprouting and sprout density

Different metrics are used to quantify sprouting response following harvest or thinning treatments. The most commonly used are probability of sprouting, the which is usually defined as the percent of stumps that have at least one sprout, sprout density, or the number of sprouts on a stump, or ocassionaly, within a sprout clump, and sprout development, which can include average height, top height—the height of the tallest sprout in a clump—or caliper, the sprout diameter at a given height. Because these metrics capture different characteristics of sprout resposne, 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. This complexity makes it difficult to sum up sprout response dynamics succinctly.

An important consideration in comparing sprout response across studies is the time of measurement. Sprout growth in most species is initiated by the moblization of carbohydrates stored in the underground portions of the tree. Sprout clumps can consist of 100 or more stems the first year after cutting, but rapidly self-thin in full light and under overstory competition, this loss may proceed even more rapidly, possibly resulting in the mortality of the entire clump. Thus early sprout clumps which could have as many as 100 or more stems in the first year, may have substantailly fewer in the 4 year (or cease to exist) and by year 20 or 30 may have only a few remaining stems.

It is common among many sprouting species for sprouting probability 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. In redwoods, some authors have found evidence of this trend, while others have not. This may be due to the very wide range of tree size and ages possible with redwoods. It has been suggested that probabitly of sprouting may initally increase up to a certain point, and then decrease with trees older than around 2 to 400 years. The decreasing probabilitiy in sprouting has been demonstrated for tanoak, and other coastal hardwoods.

Generally, the clearest relationship is the positive one between sprout growth and overstory density.

#### 1.2.1.1 redwood

* Studies in old growth and young growth
* Studies are inconclusive:
  + weak inverse relationship between residual basal area and percentage of sprouting (lindquist, second-growth)
  + data suggest similar relationships for number of sprouts and number of clumps (lindquist)
  + differing reports of percent sprouting relation to stump size or age
    - percent sprouting not related to size (lindquist, 1979; Barrette, 1966)
    - percent sprouting negatively related to size and age (Neal, 1967)
    - percent sprouting negatively related to size and age (Wiant and Powers, 1966)
  + Number of sprouts not related to overstory basal area (Barrett, 1988)
  + Number of sprouts may increase with stump size up to a point and then decrease (O’Hara, 2007)

There are conflicted reports regarding the effect of overstory oppenness on sprouting density or probability in redwood forests. This is the case for eastern hardwoods as well. Some studies have shown increased sprout abundance This is related to rapid self-thinning observed in multiple species, which has also been found to be un-related to overstory density.

#### 1.2.1.2 tanoak

### 1.2.2 Sprout development

#### 1.2.2.1 redwood

#### 1.2.2.2 tanoak

### 1.2.3 Composition

* ☐ rapid self-thinning: for oaks and redwood - not related to retention
* ☐ below ground competition for resources
* ☐ In other species, number of sprouts and sprouting probability depends on stump size/age, but this has not been shown for redwood.
* ☐ Sprout height growth depends on stump diameter
* ☐ Shade tollerance of redwood, tanoak, and Douglas-fir
* ☐ Number of sprouts not related to residual overstory (Barrett 1988)
* ☐ Early sprout growth expected to be a function of carbohydrate reserves (O’Hara, Stancioiu, and Spencer 2007)
* ☐ Sprout growth (height and diameter) dependent on overstory retention
* ☐ Sprouters vs seeders relationship with overstory retention
* ☐ Redwood is unique among conifers for sprouting ability
* ☐ special consideration: bear damage

## 1.3 References

# 2. Methods

This will be the methods.

# 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

This will be the discussion

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