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

# Summary

Interest in the concept of multiaged forestry, or managing stands with more than one cohort, has existed for centuries but its practice and popularity have ebbed over time and across locales. This is partly due to the complexity of multiaged compared to even-aged management and many questions remain regarding its implementation in unique and varied forest ecosystems. In response to this need, a manipulative experiment has been established in the redwood forests of Mendocino County, California to explore a range of dynamics associated with transition from even-age to multiaged management in this forest type. This remeasurement and analysis of that experiment, 10 years after its initiation will provide valuable information about sprout growth dynamics, new regeneration, and surface fuel dynamics associated with different residual overstory densities while documenting the recent thinning that was conducted to reduce 10-year-old sprout density. These data will be used to support planning for subsequent harvests and for prescribed fire and wildfire. It will be useful for guiding the implementation of multiaged systems in this region and for validating existing models.

# Background

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 an objective of interest for silviculturists as a key alternative to the conceptually and logistically simpler, even-aged management (Schütz, 1999). At a basic level, multiaged silviculture refers to the retention of trees of distinctively different age classes, growing together within the same stand. These cohorts may intermingle at the tree level, or exist 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 redwood regenerate reliably via stump sprouting and are relatively shade tolerant. Redwood forests have been shown to exhibit very high leaf area, suggesting their suitability for a multi-layered forest structure (Berrill & O’Hara, 2007; Van Pelt et al., 2016). Redwood forests also rank among the most productive forests and redwood timber is highly valued making their management a keen interest of private timber producers. Despite redwood's fitness for multiaged stand structures, the successful development of subordinate cohorts depends on adequate access to light, and lacking this, young sprouts and understory trees can succumb to reduced vigor and death (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, 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 suppression combined with timber harvest has led to crowded stand conditions, proliferation of more fire-sensitive species, and an accumulation of surface fuels as well as suppressed young trees (Safford & Stevens, 2017; Stephens et al., 2009). This situation combined with climate change has led to increased size and frequency of high-severity fires (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 is no stranger to fire disturbance (Varner & Jules, 2017). More concretely, there have been at least six large fires in redwood ecosystems since 2003, burning at least 466,000 acres 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).

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 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 single-tree selection, but fuel dynamics represent a potentially important decision variable to consider when managing forest stands that may be subjected to intentional or unintentional fire.

# Objectives

The objective of this study is to determine if there are significant plot level differences from different levels of partial harvests in redwood forests ten years after treatment. We looked for differences in three response variables including:

1. Surface fuels
2. Redwood and tanoak sprout size
3. Regeneration

# Methods

## Site description

The 20,000-ha JDSF was established in 1947 after being cut over (multiple times in some places) starting in 1862. The mission of JDSF is to remain in timber production for research and demonstration purposes. The predominant cover type is redwood, tanoak, and Douglas-fir forest with an elevation range of 20 to 700 m. 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 an elevation of 130 to 300 m on well-drained, sandstone-derived soils. Sites are located on various aspects of mid to upper-slope positions ([fig\_site\_map](#fig_site_map)). Site quality is classified as Site Class II (Lindquist & Palley, 1963; Webb et al., 2012).

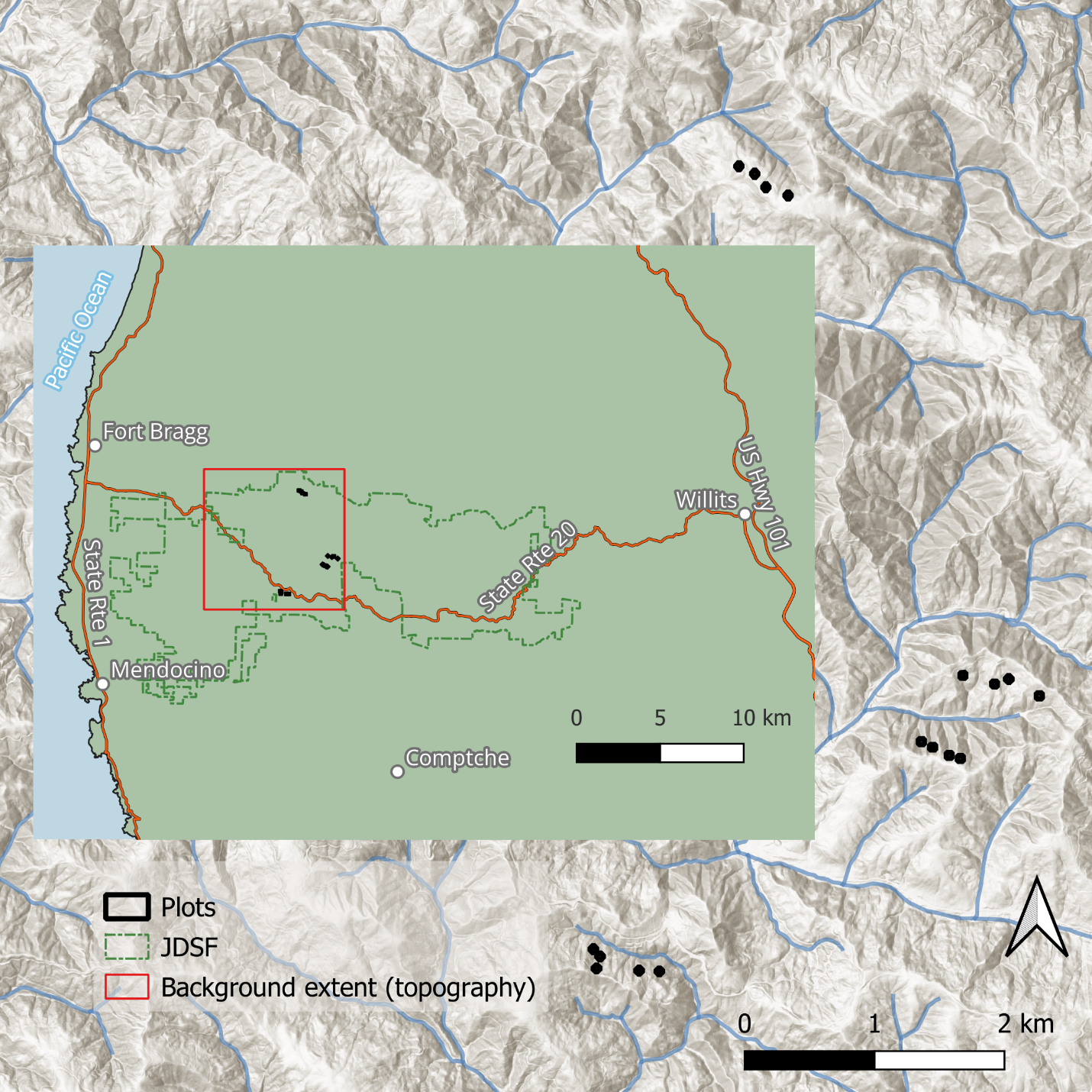


Fig-site-map. Site location and topography for our study plots. The red box delineates the area of the topographical map (background). JDSF = Jackson Demonstration State Forest.

## Study Design

In 2012, four treatments were replicated at four different sites. Treatments were group selection (GS), high-density dispersed retention (HD), high-density aggregated retention (HA), and low-density dispersed retention (LD, [fig-study-design](#fig_study_design)). The GS treatment is comprised 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-ha treatment units and the target post-harvest density was specified in terms of relative stand density index (SDI) using the assumed upper limit of SDI for redwood, 2470 stems/ha (Reineke, 1933). The target residual relative density for the HA and HD treatments was 21% (SDI = 520), and for the LD treatment, it was 13% (SDI = 320). These densities were chosen to balance the objectives of stand volume production and individual tree growth, assuming a subsequent, similar harvest after 20 years (Berrill & O’Hara, 2009).

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

Ten years after the initial harvest, regeneration plots and fuel transects were established within the macro plot (@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 “stations” at the 5- and 9-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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Fig-study-design. Schematic representation of the experimental design. Black points are fuel transect corners, and line segments represent individual transects. The outline represents the macro-plot boundaries within which trees and sprouts were measured.

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Fig-plot-layout. A diagram of the fuel sampling design depicting a 0.2-hectare macro plot, fuels transects, transect stations, and vegetation sub-plots. Large green circles are vegetation monitoring plots (which are mostly used for tracking species composition) and the small orange circles are transect stations where duff, litter, and live and dead vegetation density were measured.

## Data collection

### 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. Sprout heights were measured 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 upslope, level with the height of the sprout. Sprout DBH for only redwood was collected in year 10.

### Regeneration

Ten years after the initial harvest, four 4-meter-radius regeneration plots were established within the macro plot ([fig\_plot\_layout](#fig_plot_layout)). All regenerating trees (sprouts and seedlings) within the plot were tallied by species and size class. This allows for an estimation of sprout and seedling density.

### Fuels

At the same time, 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). Transect lengths for 1-, 10-, and 100-hr fuels were 1, 2, and 4 meters respectively. Coarse woody fuels were measured along the entire 10-meter transect.

Redwoods like other species of the 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 leafy redwood sprays (Graham, 2009), where larger pieces were considered 1-hr fuel and smaller pieces were considered litter. This may have led to underestimates of 1-hr fuels, relative to other studies.

Live vegetation percent cover and average height were estimated in 1-meter radius virtual “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 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 2 meters were estimated with the help of a clinometer. I made this decision to capture the vertical continuity of fuels that were continuous with the ground. Live vegetation percent cover was estimated for four vegetation classes: live and dead woody fuels, and live and dead herbaceous fuels. The reason for recording dead “live” vegetation, is that dead branches attached to live or standing trees are not counted as fine woody debris, but they are also expected to behave differently than live fuels during combustion. Average vegetation height was recorded for two classes: the average combined (live and dead) height of woody and the average combined height of herbaceous fuel. The average height and percent-cover estimates are visual estimations and efforts were made to discuss these frequently to ensure that estimates between observers were consistent. Percent cover estimates were discrete, rounded to the nearest class in the set: 0.5, 3, 10, and then all subsequent 10 percent increments up to 100 percent.

The depth of duff and litter was measured at two stations along a transect, and the percentage of litter was estimated. The location of the measurement was chosen from within the 1-m-radius sampling cylinder to be representative of the conditions within the whole cylinder. Representative conditions were sometimes difficult to identify when conditions within the cylinder varied greatly.

Fuel bed depth was estimated as the average height of the fine and coarse woody debris components within the sampling cylinder at each station. Theoretically, this included litter, but not duff. This estimate was not described in the Firemon protocol, but it was designed to be made similarly to the estimates of average vegetation height that are described there (Lutes et al., 2006).

## Analysis

The analysis was carried out 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, which are published together with code and results on a public website. 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 model if their variance estimate was non-zero. Because the objective was to describe differences between treatments, treatment was used as the primary independent variable. Model selection was performed using AIC and BIC and based on parsimony.

### Fuels

Fuel load in Mg ha-1 per hectare was estimated for 1-hr, 10-hr, 100-hr, duff and litter, 1,000-hr, and live vegetation fuels ([fig\_raw\_fuel\_hist](#fig_raw_fuel_hist)). Fuel load for 1- through 1,000-hr fuels were calculated using the method in Brown (1974). The required size-class specific parameters of specific gravity, particle inclination, and average diameter were derived from the literature by averaging over applicable sources. Duff and litter load were estimated using depth-to-load equations from the literature. Live vegetation loading was estimated roughly as the product of percent cover, vegetation height, and a scaling factor used in the Firemon protocol (Lutes et al., 2006).

These fuel loads were then modeled in a multi-level, Bayesian context using the R package brms (Bürkner, 2017). Using a Bayesian model allowed for a quantification of the uncertainty regarding our estimates, which is an important step towards the quantification of uncertainty in fire behavior predictions to inform critical decision-making. The selection of priors balanced domain knowledge and the goal of obtaining data-driven results. A comparison of the prior and the posterior distributions was used to justify the choice of priors. The model performance was assessed with posterior predictive checks.

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Fig-raw-fuel-hist. Histograms of raw fuel-load transect data.

### Sprout size

Sapling sprout height data ([fig\_raw\_sprout\_hist](#fig_raw_sprout_hist)) was modeled in a frequentist context with multi-level models using the R package glmmTMB (Brooks et al., 2017). Height data for all three measurement years were included in the model and measurement year entered the model as a categorical variable to avoid parametric assumptions about the relationship between year and height. I tried models with different fixed and random effects, as well as different fixed effects to model dispersion. I tried gamma and Gaussian modeling with log links. Model selection was based on parsimony, model correctness, and AIC. The selected model residuals were checked using the R package DHARMa (Hartig, 2022).

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Fig-raw-sprout-hist. Raw sprout height histograms of the data used for developing sprout height models.

### Regeneration

Regeneration will be summarized by species, diameter class, and treatment. Species will include all species of regeneration that were recorded. If there appear to be significant trends, statistical tests may be performed to quantify differences in size class distributions, e.g., with a chi-squared test, or differences in composition e.g. with a PERMANOVA test applied to Bray-Curtis dissimilarities (Anderson, 2001, 2017).

# Timeline

My target graduation date is the summer of 2024. This means there are about 24 weeks from the beginning of February. To leave time for final writing as well as multiple revisions, with 2-week turnaround times for advisor reviews, the analysis should be finished in the first 10 weeks. This will leave about another 10-14 weeks for committee review, editing, and revision. To accomplish this, writing will need to happen along with analysis, so that the final writing will mostly consist of crafting the discussion, editing, and honing my final abstract.

A timeline for analysis steps follows.

Week 1 (02/01 – 02/06):

* Revise this proposal
* Invite final committee member
* Schedule the first committee meeting

Week 2 and 3:

* Prepare committee presentation
* Work on advancement to candidacy paperwork

Weeks 4 and 5 (02/22 – 03/06):

* Do regeneration data analysis
* Review and revise the website and other analyses
* Have the first committee meeting

Weeks 6 – 7

* Revise analysis
* Write results

Week 8:

* Write discussion

Weeks 9 and 10 (04/04 – 04/10):

* First draft of thesis
* Send out for review

Weeks: 11, 12, and 13 (04/18 – 05/08):

* First draft revisions
* Analysis revisions
* Send out the second draft

Week 14 (05/09 – 05/15):

* Meet with committee members to discuss revisions

Weeks 15 – 19:

* Revisions

Week 20 (06/20 – 06/26)

* Defense (Zoom or Hyflex option)

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**Alternative titles:**

Redwood Regeneration and Fuel Loads 10 Years after Transformation to Multiaged Management

Evaluating the Influence of Overstory Retention on Regeneration and Fuel Load 10 Years After Transformation of Redwood Stands to Multiaged Management

How Does Variation in Overstory Retention Affect Redwood Regeneration and Fuel Load 10 Years after Partial Harvest?