Growth of Coast Redwood and Douglas-fir Following Thinning in Second-growth Forests at Redwood National Park and Headwaters Forest Reserve[1]

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Abstract

Managers of second-growth forests at Redwood National Park and the Bureau of Land Management's Headwaters Forest Reserve encourage the development of late seral forest characteristics using mechanical thinning, where competing vegetation is removed to promote growth of residual trees. Yet the ability to quantify and reliably predict outcomes of treatments such as these is hindered by the long time scales at which forests respond to thinning. Here we present analyses of tree growth at Redwood National Park (RNP) and Headwaters Forest Reserve (HDWT) from sites that have had > 5 years to respond to thinning treatments.

Compared to untreated stands, thinned stands had lower stem density (trees ha^{-1}) and basal area (m^2 ha^{-1}), primarily due to removal of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). Individual tree growth (basal area increment, BAI, m^2 yr^{-1}) was related to tree size (basal area, m^2) and treatment history, with the highest growth rates observed in large trees. Both redwood (*Sequoia sempervirens* (D. Don) Endl.) and Douglas-fir appeared to have a small, but detectable, positive growth response to thinning treatments. Early results suggest a large degree of variation among sites, with possible systematic differences in growth responses between RNP and HDWT. Future work will focus on identifying site-level differences (site quality, local competition, slope, aspect, stand age, distance from the ocean) to improve our understanding of the growth response.

Introduction

Accelerating structural development of second-growth forests is one of the primary challenges to conserving coastal redwood (*Sequoia sempervirens* (D. Don) Endl.) ecosystems at Redwood National Park (RNP) and the Bureau of Land Management's Headwaters Forest Reserve (HDWT). The need for action is clear; well over half of the coastal redwood forests at the RNP and HDWT have had a history of logging within the past 60 years, resulting in second-growth stand structures that typically impede the recovery of old-growth characteristics (O'Hara et al. 2010, Teraoka and Keyes 2011). Second-growth stands are commonly comprised of dense, even-aged Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and redwood stump sprouts, with simple canopy structure and little understory development. Under these conditions the relatively shade-intolerant Douglas-fir is expected to exclude redwood from the upper canopy until large gaps are formed, a process that may take centuries (Thornburgh et al. 2000). Moreover, many of these young second-growth stands are believed to provide poor habitat for old-growth dependent wildlife species and be vulnerable to disturbance in the form of drought, disease, and fire.

The primary management tool for forest restoration in this system is mechanical thinning, where competing vegetation is removed to improve the growth of residual trees. However, understory

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thinning prescriptions used in earlier treatments may not always encourage redwood dominance (Teraoka and Keyes 2011). Additionally, earlier thinning prescriptions have often created spatially uniform tree spacing (unlike old-growth forests; Dagley 2008, van Mantgem and Stuart 2012). Gaining better information on the effectiveness of thinning operations is difficult, as decades are needed to directly observe the results of these treatments.

Both prospective (projecting forest conditions forward in time) and retrospective (looking backwards in time) analyses are needed to determine how well current thinning treatments are meeting management objectives. Prospective analyses estimate potential long-term responses to thinning using models of forest tree growth (Dixon 2002, van Mantgem and Das 2014). Retrospective analyses consider the effects of past treatments to empirically determine if thinning has actually enhanced growth of residual trees. Long-term information concerning individual tree growth responses to thinning treatments is relatively limited.

Here, we present analyses of tree growth at RNP and HDWT from sites that have had > 5 years to respond to thinning treatments. We also document the differences in thinning responses among stands. If thinning responses are highly variable, it suggests that managers may want to tailor thinning prescriptions to individual sites, precluding simple "one-size-fits-all" prescriptions.

Methods

Study Sites

The region containing RNP and HDWT features a Mediterranean climate, with mild, rainy winters and cool, dry summers (Sawyer et al. 2000). Annual mean temperatures are approximately 15 °C (59 °F), with annual precipitation of about 170 cm (67 inches), mostly occurring as winter rain. Summer fog is common near the coast, moderating the dry summer conditions. Soils are primarily derived from sandstone, mudstone and schist. Historically, fire has shaped coastal redwood forests (Lorimer et al. 2009), but has been largely excluded over the past 100 years (Ramage et al. 2010). The general condition of forest vegetation in RNP and HDWT is a mix of second-growth forest and areas of unmanaged old-growth with no history of logging. Several second-growth stands have been thinned, with thinning prescriptions calling for removal of Douglas-fir, with redwood exempted from removal.

We surveyed second-growth forests that have undergone experimental thinning, where stands have had > 5 years to respond to thinning treatments (30 plots; 23 thinned, 7 unthinned). At RNP several sites meet this criteria, locally known as the "Whiskey 40" and "Holter Ridge" sites. The "Whiskey 40" is a 16 ha area of second-growth forest embedded within old-growth forest. The site was logged in 1963 and features extremely dense stands, consisting of Douglas-fir, redwood sprouts and species seeded in the site following logging (Sitka spruce (*Picea sitchensis* (Bong.) Carrière) and Port-Orford cedar (*Chamaecyparis lawsoniana* (A. Murray) Parl.). A 14 ha area was thinned in 1995, removing all trees ≤ 11.4 cm (4.5 inches) diameter at breast height (DBH; 1.37 m or 4.5 ft) and exotic conifers of all sizes (single-entry treatment) (Teraoka and Keyes 2011). The remaining 2 ha area at the "Whiskey 40" was left unthinned. The nearby "Holter Ridge" site was originally logged in the early 1950s (Chittick and Keyes 2007). In the fall and winter of 1978 and 1979 approximately 80 ha of second-growth forests at Holter Ridge were experimentally thinned, with treatment intensity intended to create 10 m spacing between stems. The "A972" stand was originally harvested in 1968, followed by broadcast burning and aerial seeding. The "A972" was subjected to a range of experimental thinning treatments in 2007, with overstory thinning at 55 percent or 20 percent basal area removal, or understory thinning with 55 percent or 20 percent basal area removal. At HDWT sites were initially logged in the early 1990s. We do not have records on post-harvest treatments. Thinning treatments were executed in 2004. The HDWT thinning treatments were designed to create 4.3 m (14 ft) spacing among residual stems, with coast redwood exempted from cutting. We used untreated second-growth stands in or adjacent to the "Whiskey 40", "Holter Ridge", and "A972" sites as comparison "control" sites to assess thinning effects.

Field Measurements

In 2008 and 2009 study plots (average plot area = 0.16 ha [0.4 ac]) were established in thinned and unthinned second-growth stands at RNP and HDWT. In all plots, we tagged all individual trees, recording species identity, clump affiliation if a stem was part of a stump sprout (to separate genetic from environment effects between redwood sprout clumps), stem diameter measured at the tag (generally DBH), tree height, live crown base height, crown class, canopy condition and noted obvious injuries (bear damage is common in this area). We conducted these surveys again in 2013, 2014 and 2015, searching for any new trees (recruits) that are above the plot minimum stem diameter (20 cm [7.9 inches] DBH) and documenting mortalities of existing trees. Radial growth (mm yr^{-1}) and basal area increment (BAI, m^2 yr^{-1}) for individual trees at each plot was determined from repeated measurements of stem diameter.

Errors in repeated diameter measurements may arise due to inaccurate measurements, bark sloughage, and/or stem moisture. Errors in growth were defined from existing data in mixed conifer forests of the Sierra Nevada of California, as data specific to coast redwood stands are absent. Likely errors in growth measurements were identified as from a single 1 ha plot measured twice in a single year in a mixed conifer forests (primarily white fir, *Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.) in Sequoia National Park. Absolute discrepancies (AD) in the diameter measurements were modeled as a linear function of DBH, best fitted as AD = 0.0035 × DBH + 0.2032. For the lower growth limit, we removed negative growth measurements where the second diameter measurement was more than four times smaller than the potential measurement error given the AD relationship. To identify the upper limit of growth, we fit a gamma distribution to 243,679 annual growth ring measurements from common species collected in mixed conifer forests of the Sierra Nevada. From the gamma distribution, only approximately 1 percent of annual ring widths were > 6 mm yr^{-1} (0.2 inches yr^{-1}) which was used as our upper growth limit. Observations of radial growth beyond the upper and lower limits were likely due to measurement or data recording errors and were removed from analysis. Using these criteria, we removed 135 of 893 redwood (15 percent of our sample) and 85 of 1452 (6 percent of our sample) Douglas-fir from analyses of growth.

Analyses

We calculated differences in forest structure (stand density, trees ha^{-1}; basal area, m^2 ha^{-1}) and growth (BAI) in thinned and unthinned second-growth stands. We also compared average stem size distributions in thinned and unthinned second-growth stands, using the Gini coefficient.

We used linear mixed models (LMMs) (Gelman and Hill 2007) to determine differences in BAI among individual trees, while accounting for plot-level differences. We considered only species where we had sufficient redwood and Douglas-fir data. For each species our model estimated radial growth for individual trees as BAI_{ij} of tree *i* in plot *j* as:

$$BAI_{ij} = \beta_0 + a_j + (\beta_{BA} \cdot BA_{ij}) + (\beta_{Treatment} \cdot Treatment_{ij}),$$
$$a_j \sim N(0, \sigma^2)$$

where BA is the individual tree stem basal area (m^2) at the first measurement, and Treatment is an indicator variable for stand treatment history (control or thinned). The BAI values were log transformed to better fit model assumptions. The variable a_j represents plot-level variations in the regression intercept. We considered varying-intercepts with varying-slope models, but these formulations did not improve model performance. We evaluated improvements to this model, including interaction terms using the Akaike Information Criterion adjusted for sample size (*AICc*) (Burnham and Anderson 2002), with differences in *AICc* ($\Delta AICc$) > 4 used as evidence of substantial model dissimilarity. We calculated averaged estimates for models with similar amounts of support ($\Delta AICc \leq 4$) (Grueber et al. 2011). The proportion of variation explained using the individual-level variables only (marginal R^2) and the combined individual- and plot-level variables (conditional R^2) of the fitted models were calculated following Nakagawa and Schielzeth (2013). Analyses were conducted using the R statistical language (R Development Core Team 2015) with the ‘lme4’ (Bates et al. 2015) and ‘MuMIn’ (Barton 2015) packages.

Results

Relative to the untreated ‘control’ stands, thinned stands had 43 percent lower stand density (trees ha^{-1}) and 38 percent lower basal area (m^2 ha^{-1}) compared to the untreated control stands. These differences were maintained by the second census, where thinned stands had 37 percent lower stand density and 29 percent lower basal area compared to the ‘control’ stands. Average basal area growth for redwood between the first and second censuses in the ‘control’ plots was 2.0 m^2 ha^{-1}(8.7 ft^2 ac^{-1}) (SE = 0.4) while in the thinned plots redwood basal area growth was 4.8 m^2 ha^{-1} (20.9 ft^2 ac^{-1}) (SE = 0.9). Over the same interval, basal area growth of Douglas-fir was 2.2 m^2 ha^{-1} (9.6 ft^2 ac^{-1}) (SE = 0.7) in the ‘control’ plots and 4.1 m^2 ha^{-1} (17.9 ft^2 ac^{-1}) (SE = 0.5) in the thinned plots. Inequality measures suggest similar relative representation of small trees in the thinned and unthinned stands at the first census (Thinned average Gini = 0.18, Control average Gini = 0.19), which remained essentially unchanged by the second census (Thinned average Gini = 0.19, Control average Gini = 0.20) (fig. 1).

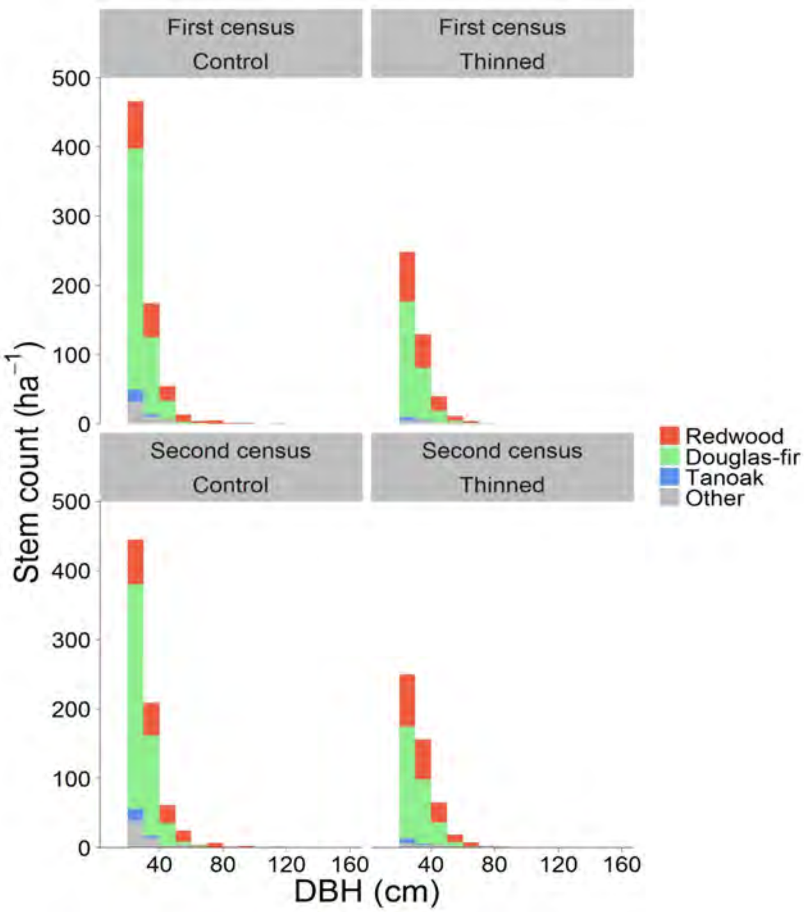

Figure 1—Stem diameter size class distributions in unthinned (‘control’) and thinned plots during the first (2008 or 2009) and the second census (2014 or 2015).

The LMM results showed that the BAI varied by tree size (BA) and history of thinning, with varying average responses between redwood and Douglas-fir (table 1 and table 2). For both species BAI was primarily related to individual tree size (BA), with larger trees showing higher BAI. The LMM model averaged parameter estimates suggested that Douglas-fir BAI increases faster with increasing BA compared to redwood.

Table 1—Model selection for LMMs of growth for common conifers, including terms for tree size (BA, stem basal area) and history of thinning (Treatment = unthinned or past thinning treatment) using *AICc*; evidence for substantial model dissimilarity was Δ*AICc* > 4)

Species	Model predictors	*AICc*	Δ*AICc*
Redwood	BA * Treatment	846.2	1.65
	BA + Treatment	844.5	0
	BA	849.6	5.06
	Treatment	1092.6	248.1
Douglas-fir	BA * Treatment	277.2	0
	BA + Treatment	282.9	5.67
	BA	287.5	10.25
	Treatment	1211.6	934.36

Table 2—LMM parameter estimates for individual-level effects for growth of common conifers (we used average parameter estimates for redwood, where two models had similar levels of support by *AICc*; BA refers to individual stem basal area (m^2); Treatment refers to stand treatment history, with unthinned control stands used as the reference condition)

Species	Individual-level effect	Estimate	Std. error	95 % CI
Redwood	BA	2.97	0.19	2.60 to 3.34
	$Treatment_{Thin}$	0.26	0.10	0.07 to 0.45
	$BA*Treatment_{Thin}$	0.22	0.35	-0.47 to 0.90
Douglas-fir	BA	7.73	0.31	7.07 to 8.36
	$Treatment_{Thin}$	0.30	0.09	0.12 to 0.47
	$BA*Treatment_{Thin}$	-1.09	0.39	-1.88 to -0.33

Thinning treatments were associated with slightly higher BAI, which was potentially more pronounced in large trees for redwood (i.e., a weak but positive BA*Treatment interaction term), but in small trees for Douglas-fir (i.e., a negative BA*Treatment interaction term). Thinning treatments appeared to have similar effects on both redwood and Douglas-fir (CIs for thinning treatments overlapped between species), with redwood perhaps showing slightly stronger response to thinning treatments than Douglas-fir (fig. 2). We found similar effects of thinning when considering radial increment predicted by stem diameter and treatment. The individual-level effects of the model explained a relatively large amount of variation in tree mortality for both redwood and Douglas-fir (marginal $R^2 > 0.31$), though the inclusion of the plot-level effect (plot identity) improved model performance (conditional $R^2 > 0.45$). The models that included thinning effects only explained a small, but non-zero, amount of variance (marginal $R^2 > 0.02$, conditional $R^2 > 0.07$). Estimated random effects suggest high model intercepts for plots in HDWT for both redwood and Douglas-fir, potentially indicating higher growth rates in HDWT relative to RNP.

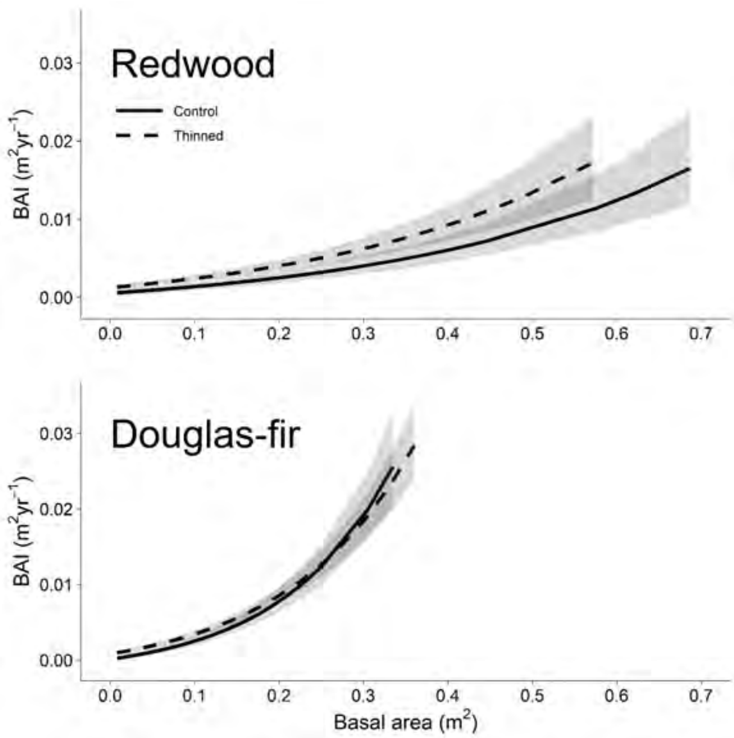

Figure 2—Predicted individual tree growth in thinned and unthinned plots. The heavy lines represent modeled average trends and the shaded band represents 95 percent bootstrapped confidence intervals from uncertainty in the individual-level parameter estimates.

Discussion

Our results suggest that redwood growth continues to be favorable > 5 years following thinning treatments at RNP and HDWT. Residual Douglas-fir also responded positively to thinning treatments, but the stand structures created by these treatments (retention of redwood) likely allowed for enhanced redwood basal area accumulation at the stand level. A more rigorous examination of plot-level thinning effects will require experimental data, rather than the post-hoc results presented here. However, these observations are in agreement with earlier assessments of coastal redwood forest stand development (Teraoka and Keyes 2011), which found that unthinned areas will be very slow to recover redwood dominance. As stand development continues, how long these treatments will remain effective at encouraging redwood growth is not known. Second-entry thinning treatments may be possible in some areas, but funding and the removal of old logging roads as part of an overall restoration treatment following first-entry thinning may limit these operations.

Growth at the individual tree level provides an indication of the range of response that Douglas-fir and redwood may have to thinning treatments. Here, we found thinning to have small, but measurable, effects on basal area growth for redwood and Douglas-fir. Between these species, the growth potential appears to be greater for Douglas-fir compared to redwood in our stands. This confirms earlier findings (using data from some of the same plots considered here) that on a per-individual basis, under current second-growth conditions at our sites Douglas-fir appears to be a better competitor relative to redwood, but that redwood may be better able to exploit growing conditions created by aggressive thinning treatments (e.g., 40 percent stand basal area reductions) (van Mantgem and Das 2014). Next steps include examining height and volume growth, which will be essential to gain a broader perspective of treatment effects.

Our present assessment of thinning effects on individual tree growth would be improved with spatially-explicit data. Individual-level tree growth is strongly influenced by local conditions, which may or may not reflect plot-level averages. But these data are relatively time-consuming to collect and a critical assessment is needed if spatially-explicit models (e.g., van Mantgem and Das 2014) offer a substantial improvement in projecting stand conditions relative to traditional non-spatially explicit models of forest growth (e.g., FVS, CRYPTOS). Comparing estimates from spatial and non-spatial models will help determine if inclusion of this additional information (e.g., clumped, random, or uniform spacing; interior or gap-edge location) strongly influences predictions of residual tree growth.

The relatively large magnitude of plot-level differences identified from the linear mixed models of tree growth suggest that growth responses to thinning may vary substantially among sites. Identifying the environmental factors (e.g., slope, aspect, stand age, distance from the ocean) that contribute to variation in thinning responses will be an important future step. Thinning responses will likely also be strongly correlated to site quality (Berrill 2008), which could also be included in future studies. Collecting data across different thinning intensities, patterns, and treatment frequencies simulated for different site types will demonstrate how site conditions and thinning treatments interact.

Restoring young forests is a key component of coastal redwood forest conservation, not only to accelerate the development of old forest structure, but may also sufficiently reduce competitive pressures among remaining trees so that they may be more resistant (more likely to survive) when faced with environmental stressors, such as drought. Though it is still unclear if thinning treatments will confer resilience to disturbance in coastal redwood forests, observations from other forest types are promising (D'Amato et al. 2013, Fulé et al. 2012). This presumed benefit from restoration thinning may become an increasingly important consideration in an era of climate change.

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