

silviculture

Long-Term Stand Growth of Interior Ponderosa Pine Stands in Response to Structural Modifications and Burning Treatments in Northeastern California

Justin S. Crotteau and Martin W. Ritchie

The Blacks Mountain Experimental Research Project created two distinct overstory structural classes (high-structural diversity [HiD]; low-structural diversity [LoD]) across 12 stands and subsequently burned half of each stand. We analyzed stand-level growth 10 years after treatment and then modeled individual tree growth to forecast stand-level growth 10–20 years after treatment. Net stand growth was compared between treatments and with adjacent Research Natural Areas (RNAs). An analysis of variance of growth in total aboveground tree biomass suggested that growth was greatest in unburned stands ($P = 0.001$) and in LoD stands ($P = 0.039$). We formed iteratively annualized nonlinear models to forecast individual tree growth. Modeled diameter growth, height growth, and mortality were used exclusively for forecasting and highlighting growth and mortality trends in the data (i.e., not testing effects). Forecasts of stand board foot volume suggested that HiD and LoD stands may be no different in net growth in the second decade since treatment ($P = 0.355$). Differences between logged and unlogged stands appeared to be much greater: we predict that RNA stands will net -136 board feet ac^{-1} in the forecast period, whereas HiD and LoD stands are expected to net 627 and 485 board feet of volume per acre. We also tracked the large tree (dbh >23.5 in.) component stand density index (SDI) over the measurement and forecast periods. We found that the unburned HiD treatment had a net positive effect (13% increase over 20 years) on relative density, whereas the burned HiD was not expected to change ($P = 0.803$), and unlogged stands tended to exhibit a declining SDI over time (-16%).

Keywords: eastside ponderosa pine, old-growth structure, prescribed fire, large tree, research natural area

Over a century of fire exclusion in western forests has led to an increase in surface and crown fuels (e.g., Dodge 1972, Taylor 2000), shifts in composition toward late-seral species (Parsons and DeBenedetti 1979, Ritchie et al. 2008), and an increased susceptibility to

mortality of historically fire-resistant species in fire-prone forested environments (Thomas and Agee 1986, Sackett et al. 1996). Departures from normal ecosystem structure and function may be most evident and detrimental in ecosystems with historically frequent fire regimes (e.g., Laudenslayer et al.

1989). The results of these trends are dense stands with fuel continuity that increases the risk of high-severity fire. Increased probability of atypical catastrophic fire in dry forested ecosystems (Miller et al. 2009) has begun to alter historic fire suppression policies in the United States and help bring the importance of ecosystem health, diversity, and fire resilience into the focus of land managers (e.g., US Department of Agriculture 2004).

Land managers seek to ameliorate the effects of fire exclusion by prescribing ecosystem restoration treatments. Management of and for old-growth structure in ponderosa pine ecosystems has been complicated by fire exclusion, historic extensive logging of large trees, and bark beetle epidemics (Kolb et al. 2007). Restoration treatments may take a variety of forms, but a common approach is to thin from below and/or broadcast burn to mimic historical stand structure (sensu Youngblood et al. 2004). These activities reduce stand density and woody fuels to diminish the fire hazard potential. Restoration of ponderosa pine (*Pinus ponderosa* Dougl. P. & C. Laws. var. *ponderosa*) ecosystems

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(see Graham and Jain 2004) is often geared to favor the retention and development of large-diameter, fire-resistant pine to promote a resilient stand structure historically suitable for floral and faunal diversity (e.g., Reynolds et al. 1992, Covington and Moore 1994, Laughlin et al. 2004, Spies et al. 2006). Effective restoration methods and techniques are valuable across broad regions and useful for managers with multiple resource management goals.

Land managers may opt to increase or decrease existing stand structural diversity in efforts to emulate natural stand structures and manage for multiple resources (e.g., old-growth structural attributes). Treatments that increase structural heterogeneity provide multiple canopy layers and openings, as may have been created and maintained naturally by varying degrees of fire tolerance, fire evasion, or consumption of substand tree groups by frequent patchy fire (Agee 1993, p. 322–336). Treatments that decrease structural diversity homogenize the forest canopy and may over time increase productivity by featuring younger, faster growing trees. In conjunction with low soil moisture availability, large footprint frequent burns inhibit mass tree recruitment and create widespread, open stands in the latter type of dry pine forests on the eastside of the Sierra Nevada and Cascade ranges (Norman 2002). Although strict even-aged and multiaged ponderosa pine silvicultural systems have been examined in years past to emulate these structural attributes (e.g., Meyer 1938, McDonald 1969, Fiedler 1996, O'Hara and Gersonde 2004, Youngblood 2004, Uzoh and Oliver 2008), the typical silvicultural approach has had the singular objective of maximizing sustained timber yield. Alternatively, a designed, long-term experiment that underscores “natural” variations of structural stand diversity can provide helpful information for land managers with multiresource or ecosystem restoration objectives.

This study leverages an experimental design intended to highlight differences in stand structure and the use of prescribed fire to examine individual tree and net stand growth over time. Although it is common practice for managers to establish multiuse stands across the western United States, few large-scale experiments have been designed to test the effect of mimicking old-growth structural attributes on overall stand growth. In this study, we consider overstory dynamics across three divergent stand overstory structures, 10 years after the Blacks Mountain

Ecological Research Project (BMERP)'s first posttreatment measurement. The two primary research objectives were, first, to evaluate stand-level net board-foot volume and total aboveground biomass growth across treatments over the observed 10-year period and, second, to forecast stand-level net volume and biomass growth 10 years into the future. To accomplish the second objective, we model individual tree growth and mortality rates from within the observed period and then forecast and reaggregate trees into stand-level values for a 10-year forecast, to 20 years since treatment. As a final component of the forecast analysis, we also examine the response of the large trees (dbh > 23.5 in.) to the treatment.

Methods

Study Area

The Blacks Mountain Experimental Forest (BMEF) is a 10,000-acre portion of the Lassen National Forest in northeastern California, located at 40°40' N and 121°10' W (Figure 1). The topography is flat to gently sloped (<25%) and elevation ranges from 5,500 to 6,800 ft above sea level. The climate is typified by warm, dry summers and cold, wet winters. Mean annual temperature is 49.6° F; mean annual precipitation is 20 in. and is primarily manifested as snow. Soils at BMEF are typically between 3 and 6 ft deep and range from mesic Typic Argixerolls to frigid Andic Argixerolls with increasing elevation (Alexander 1994).

Overstory vegetation at BMEF is the interior (eastside) ponderosa pine type (Eyre 1980), where eastside refers to the lee side of the Sierra Nevada and Cascade ranges. The

overstory is principally composed of ponderosa pine and Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) with a mix of white fir (*Abies concolor* [Gord. & Glendl.] Lindl.) and incense-cedar (*Calocedrus decurrens* [Torr.] Florin). There is some evidence that the current levels of fir and incense-cedar at BMEF are higher than historic norms (Ritchie et al. 2008). For simplicity in this study, Jeffrey pine will be absorbed into the greater ponderosa pine class and therefore treated as the same species. Typical woody understory vegetation in the experimental forest includes *Artemisia tridentata* (Nutt.), *Arctostaphylos patula* (Greene), *Ceanothus velutinus* (Douglas ex Hook.), *Prunus emarginata* (Douglas ex Hook.) D. Dietr., *Purshia tridentata* (Pursh) DC, and *Ribes cereum* (Douglas).

Reconstruction of eastside ponderosa pine forest conditions suggests that multicohort stands were historically typical on the landscape scale (Youngblood et al. 2004), although spatially heterogeneous gaps and patches supported scattered, small-scale, single-cohort stands or substands. The historic stand structural variation was highly influenced by heterogeneity of fire spatial scale and severity patterns (Skinner and Taylor 2006, Table 10.5); median composite fire return intervals in these forests ranges from 12 to 14 years (Norman 2002).

Experimental Design and Sampling

The BMERP was designed to determine the effects of divergent stand structures as established by mechanical treatment and prescribed burning on ecosystem function and health (Oliver 2000). The BMERP began in 1991 and was established on the

Management and Policy Implications

Active land management in dry, fire-prone western forests must be dynamic to facilitate multiple objectives. Our study follows stand growth under six different management scenarios: overstories were mechanically treated to mimic old-growth structural attributes, mechanically treated to maximize timber growth for the proceeding 20 years, or not mechanically treated. Half of the stands in our study area were subsequently broadcast burned with low-intensity prescribed fire. We found that net stand growth is influenced by overstory and burning treatments in the first decade since treatment, but that logged stands may be more similar in growth during the second decade. This study supports two findings: that both the canopy-homogenizing low-diversity and the old-growth structure accelerating high-diversity mechanical treatments increase stand productivity beyond that of the no-cut RNA and that retained large (>23.5 in.) ponderosa pine relative density may increase over the course of 20 years only in high-structural diversity stands that were not burned. Our observations suggest that mechanical treatments that favor ponderosa pine retention such as those implemented at Blacks Mountain Experimental Forest will encourage remnant tree growth and maintenance of large-tree structural elements, as is sought in the management of eastside ponderosa pine ecosystems for either timber or old-growth.

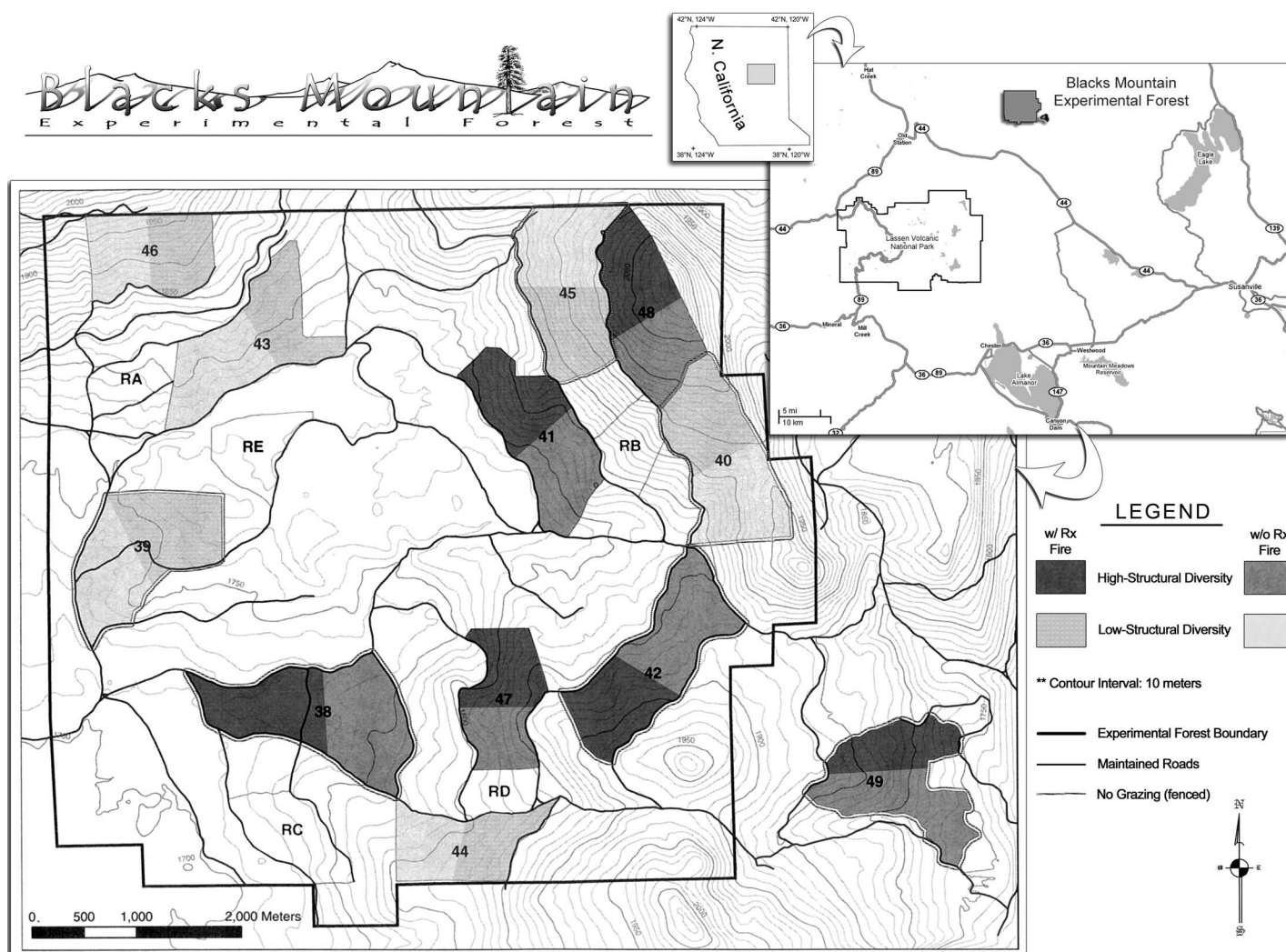


Figure 1. Map and layout of the Blacks Mountain Experimental Research Project treatment units on the Lassen National Forest. Split-plot stands are labeled by unit number and combination of structural diversity class by prescribed fire treatment. Pseudocontrols are Four Research Natural Area (RNAs) RA through RD.

BMEF, an eastside ponderosa pine ecosystem in northern California. Stand structures included in this study represent management strategies for uniform canopy stands, multiaged structural old-growth stands, and no-action scenarios. Since establishment, the interdisciplinary BMERP team of scientists has synthesized a significant body of literature based on the immediate to 5-year posttreatment results to aid regional forest management and understanding of ecosystem response to management activity or inactivity (e.g., Fettig et al. 2008, George and Zack 2008, Maguire et al. 2008, Zhang et al. 2008).

The BMERP established two overstory structure classes among 12 randomly selected stands (6 stands per treatment level, each approximately 250 acres in size) (Figure 1). Treatments were blocked by increasing elevation such that pure pine stands were

located in the lower elevation block and the greatest proportions of white fir were located in the upper elevation block (Oliver 2000). The overstory structures were designed to emulate two contrasting management pathways: a high-structural diversity (HiD) and a low-structural diversity (LoD) condition, where *diversity* refers to both horizontal and vertical heterogeneity. The HiD condition was designed to approximately emulate the structure (not age) of an uneven-aged stand, maintaining large trees, relic snags, numerous small openings, and high-density, small-diameter caches of conifers. The LoD stand condition was designed to promote a single-layer canopy, approximating a relatively open even-aged stand with few, large gaps; the largest and smallest trees were removed from these stands for a unimodal diameter distribution (Oliver 2000). Next, a random half of each stand was treated with pre-

scribed fire 1–2 years after the logging operation in a split-plot design, for a total of 24 experimental units. The broadcast burn treatments were low-intensity surface fires set during the fall months, just prior to snowfall. Burns were done under moderate to high moisture and low wind conditions to increase control; these conditions resulted in an underburn that was characterized by very low severity to mature trees. Treatments were completed over a 5-year period (Table 1). Residual densities are presented as year 0 in Table 2. The timber sale and prescribed fire treatment were conducted by research partners from the Lassen National Forest Eagle Lake Ranger District. An experiment of this scale on national forestland cannot be successfully implemented without a strong partnership between research and management. In particular, implementation of the National Environmental Policy Act of 1969

Table 1. BMERP treatment establishment and stand measurement years.

Block	Unit	Cut year	Burn year	Measurement 1	Measurement 2	Measurement 3
I	38, 39, 41, 43	1996	1997	1998	2003	2008
II	42, 44, 45, 47	1997	1999	2000	2005	2010
III	40, 46, 48, 49	1998	2000	2001	2006	2011
	RNA C		1997	1998	2003	2009
	RNA A, D			1999	2007	2012
	RNA B		1999	2000	2006	2009

Note that period 1 is the growth between measurement 2 and measurement 1. Similarly, period 2 is the growth between measurement 3 and measurement 2.

Table 2. Live overstory characteristics in years from initial measurement of the BMERP: observed 0 and 10 year measurement, projected forecast of year 20.

	Year	High diversity		Low diversity		RNA	
		Burned	Unburned	Burned	Unburned	Burned	Unburned
Density (stems ac ⁻¹)	0	155 (45)	122 (25)	92 (27)	81 (12)	347 (104)	397 (80)
	10	132 (31)	141 (42)	70 (15)	84 (17)	283 (24)	403 (45)
	20	117 (28)	131 (37)	64 (14)	77 (17)	255 (41)	381 (28)
Basal area (ft ² ac ⁻¹)	0	108 (11)	103 (19)	42 (8)	38 (7)	144 (18)	149 (9)
	10	109 (9)	117 (15)	49 (7)	54 (9)	133 (2)	150 (10)
	20	117 (13)	129 (14)	58 (10)	67 (12)	134 (16)	154 (12)
Volume (bd ft ac ⁻¹)	0	7,770 (2,254)	8,185 (2,209)	1,060 (224)	1,052 (249)	7,673 (818)	8,310 (395)
	10	7,620 (1,337)	9,089 (2,248)	1,610 (217)	1,833 (407)	6,947 (1,192)	7,623 (1,433)
	20	8,165 (1,482)	9,798 (2,343)	2,014 (232)	2,400 (539)	6,654 (534)	7,643 (1,559)
AGB (t ac ⁻¹)	0	52 (9)	51 (13)	15 (4)	15 (4)	58 (0)	63 (8)
	10	53 (9)	58 (12)	19 (4)	22 (5)	54 (6)	62 (2)
	20	57 (12)	63 (12)	23 (7)	27 (7)	53 (0)	63 (2)

Data are mean (1 SE). Four Research Natural Area, RNA.

and other related administrative documentation for the timber sale required close interaction between research and management branches.

Four Research Natural Area (RNA) (Cheng 2004) compartments (approximately 116 acres each) on the experimental forest serve as untreated controls with no history of past harvest (Oliver 2000). Although not true, full-size, split-plot controls to the experiment, these stands are assumed to be the characteristic, dense, unmanaged forest condition given the lack of management activity. These pseudocontrols provide this study with a reference condition to gauge treatment efficacy. Prescribed fire was applied to two of the four RNA units to complement the designed BMERP experiment.

We installed a permanent, geo-referenced, systematic grid to sample the stands on the BMEF. Sampled plot locations were established with a 464-ft square spacing. We permanently tagged and measured standing live trees within nested, fixed-area, circular plots, centered on grid points: trees with dbh of >11.5 in. were sampled on a 0.20-acre plot; trees with 3.5 in. < dbh ≤ 11.5 in. were sampled on a 0.05-acre plot. Dbh (nearest 0.1 in.) was measured for all trees.

Height (nearest 1 ft) was measured for all trees of >11.5 in. dbh but for only a subsample of trees of ≤11.5 in. dbh.

Stand-Level Analysis

To address our first objective, we calculated and aggregated individual tree yield values from 10-year observations. Selected yield metrics were Scribner's board foot volume and aboveground biomass (AGB), derived by species-level biomass equations, expressed as a function of diameter and height. Merchantable volume to a 6 in. top with a 6 in. stump was calculated using equations developed by Walters and Hann (1986) for 32-ft logs, using species-specific coefficients. Total AGB was calculated for ponderosa pine using an equation specific to our site and time since treatment (Ritchie et al. 2013; model 6 after 10 years). Total AGB was also calculated for white fir (Jenkins et al. 2004), but incense-cedar calculations were limited to total stem plus bark biomass to an assumed 6 in. stump (Jenkins et al. 2004). Net growth was defined as the difference between total live board foot volume and AGB in stands at the beginning and end of the total 10-year observation period.

Differences in stand growth by experimental treatment type were tested with anal-

ysis of variance (ANOVA). Because this study uses a split-plot design experiment layout, we tested growth with a strict regard to the nested structure of the data. Furthermore, we did not include the RNA in statistical analysis of growth, because the RNA stands are pseudocontrols, not randomly assigned split-plots, and the determination of appropriate ANOVA *P* values was, therefore, indeterminable. Thus, growth in RNA is evaluated numerically but not tested statistically against the treated stands. In the manner of Zhang et al. (2008), the following statistical model was used for the stand-level ANOVA

$$Y_{ijkl} = \mu + \text{block}_j + \text{diversity}_i + \varepsilon(a)_{ijl} + \text{burn}_k + \text{diversity}_i \text{ burn}_k + \varepsilon(b)_{ijkl} \quad (1)$$

where Y_{ijkl} is the 10-year period stand net growth in block j (1, 2, 3), structural diversity treatment i (1, 2), prescribed burn treatment k (1, 2), and replicate l (1, 2). In this model, the structural diversity treatment is evaluated with respect to error term $\varepsilon(a)_{ijl} \sim N(0, \sigma_{\varepsilon(a)}^2)$, and the burn and treatment interaction terms are evaluated with respect to error term $\varepsilon(b)_{ijkl} \sim N(0, \sigma_{\varepsilon(b)}^2)$. The

elevation-derived blocking terms were not tested due to lack of replication.

Development of Individual Tree Models

The second objective in this study required a forecast of future stands. To facilitate forecasting of future stand development across the treatments of this study, we took the approach of developing growth and mortality models using nonlinear and logistic regression techniques. Models were created based on measurements taken in the second of two 5-year measurement periods (Table 1).

The models fit in this study were exclusively for forecasting. That is, they were not developed for testing treatment effects on individual tree growth. Therefore, we do not present a table of model coefficients, standard errors, and *P* values. Nevertheless, these models are useful for predicting growth and mortality at the tree level, which can then be expanded to the stand level for subsequent testing.

We accessed the nonlinear modeling function `nls` (stats package; R Core Team 2013, Vienna, Austria) within R statistical software to develop nonlinear growth models. Solutions were derived following the Gauss-Newton algorithm. Tree dbh growth exhibited a peaking function over diameter. Model form for the diameter growth model was

$$E[\Delta \text{dbh}_{ijk}] = e^{\beta_{0,jk} + \beta_1 \ln \text{dbh}_i + \beta_2 \text{dbh}_i^{0.5} + \beta_3 I_{\text{HiD},i} \ln \text{dbh}_i + \beta_4 I_{\text{HiD},i} \text{dbh}_i^{0.5} + \beta_5 I_{\text{LoD},i} \ln \text{dbh}_i + \beta_6 I_{\text{LoD},i} \text{dbh}_i^{0.5}} \quad (2)$$

where β_0 was allowed to vary by species ($j = 1, 2, 3$) and split-stand ($k = 1-26$). Here, $E[\Delta \text{dbh}_{ijk}]$ is the expected annual dbh growth of tree i , dbh is tree i 's initial diameter, I_{HiD} and I_{LoD} are indicator variables for structural diversity treatment, and β_0 through β_6 are model parameters to be estimated.

Tree height growth exhibited a peaking function over height. The height growth model had the form

$$E[\Delta \text{height}_{ijk}] = e^{\beta_{0,jk} + \beta_1 \ln \text{height}_i + \beta_2 \text{height}_i^{2.5} + \beta_3 I_{\text{HiD},i} \ln \text{height}_i + \beta_4 I_{\text{HiD},i} \text{height}_i^{2.5} + \beta_5 I_{\text{LoD},i} \ln \text{height}_i + \beta_6 I_{\text{LoD},i} \text{height}_i^{2.5}} \quad (3)$$

where β_0 was allowed to vary by species ($j = 1, 2, 3$) and stand ($k = 1$ to 26). Here, $E[\Delta \text{height}_{ijk}]$ is the expected annual height

growth of tree i , height is tree i 's initial height, and β_0 through β_6 are model parameters to be estimated.

Logistic models were fit to tree mortality observations using a binomial glm (stats package; R Core Team 2013). The form of the mortality model was

$$\text{Prob}(\text{Mortality})_{ijk} = \frac{e^{\beta_{0,jk} + \beta_1 \text{dbh}_i + \beta_2 I_{\text{HiD},i} \text{dbh}_i + \beta_3 I_{\text{LoD},i} \text{dbh}_i}}{1 + e^{\beta_{0,jk} + \beta_1 \text{dbh}_i + \beta_2 I_{\text{HiD},i} \text{dbh}_i + \beta_3 I_{\text{LoD},i} \text{dbh}_i}} \quad (4)$$

where β_0 was allowed to vary by species ($j = 1, 2, 3$) and stand ($k = 1-26$). Here, Prob(Mortality) is the expected probability of annual mortality of tree i , dbh is tree i 's initial diameter, and β_0 through β_3 are model parameters to be estimated. It should be noted that the mortality models address second-order fire mortality and stand background mortality; trees immediately killed from fire were not measured for this study.

Model response variables were annualized for each of the dbh, height, and mortality models for standardization. We did not assume a strict linear annualization; rather we optimized an estimate of interpolation proportion, q , using fitted models to iteratively modify the linear annualized response (McDill and Amateis 1993), following Vaughn et al. (2010). Annualized growth and mortality models, given the rates observed in period 2 (Table 1), were used to predict stand net growth 10 years into the future.

We do not present estimates of model parameters and standard errors for the model fits, because the pseudoreplication in this data set results in biased precision. As coarse measures of overall model fit, we present model root mean squared errors (RMSEs) and pseudo- R^2 values. We calculate pseudo- R^2 to be

$$\text{pseudo-}R^2 = 1 - \frac{\text{SSE}}{\text{SST}} \quad (5)$$

where SSE is the sum of squares of model residuals and SST is the total (corrected) sum of squares.

Analysis of Forecast Stands

To fulfill our second objective, we used the above-fitted models to predict growth and death of individual trees. The data set of trees at the final measurement (year 10) was input into the annualized models and iteratively run to predict the attributes of the future stands at 20 years since initial measure-

ment. Both treated stands and RNA stands have been forecast to year 20.

Following the forecast of the tree data set, forecasts were aggregated to the stand level. We then conducted an ANOVA of estimated future net growth given treatment type. The ANOVA model was formulated in the exact manner as for the observed data (Equation 1), with the exception that future net growth was calculated as the difference in standing volume (and biomass) at 20 years since the initial measurement minus the volume standing at 10 years since the initial measurement (the end of measurement period 2).

As a final component of our second objective, we analyzed trends in the relative density of the large tree component in the BMERP. Reineke's stand density index (SDI) was calculated to address tree density relative to maximum stand capacity (Reineke 1933). Specifically, the summation form of SDI (Shaw 2006) was used to calculate the density of the large tree component. We calculated the overall change in SDI between years 10 and 0 since treatment, as well as the change in SDI between years 20 and 0 since treatment. Simple linear regression of change in SDI on treatment groups was performed for each of these two responses to assess trending change in the component SDI of large trees. The SDI model was fit without an intercept term so that each estimated coefficient is tested against no change (0). These models took the form

$$E[\Delta \text{SDI}_i] = \beta_1 I_{\text{HiD:Burned},i} + \beta_2 I_{\text{HiD:Unburned},i} + \beta_3 I_{\text{RNA},i} \quad (6)$$

where $I_{\text{HiD:Burned},i}$ is an indicator variable for a HiD stand i that was burned, $I_{\text{HiD:Unburned},i}$ is an indicator variable for a HiD stand that was not burned, $I_{\text{RNA},i}$ is an indicator variable for an RNA stand, and β_1 , β_2 , and β_3 are parameters to be estimated. The RNAs were not segregated into burned and unburned because there are only two stands in each treatment level. Furthermore, LoD stands were not included in this analysis because trees in the LoD do not exceed 24 in. in dbh.

Results

Net Growth Over 10-Year Measurement Period

Mean observed standing board foot (bd ft) volume and total AGB by treatment and

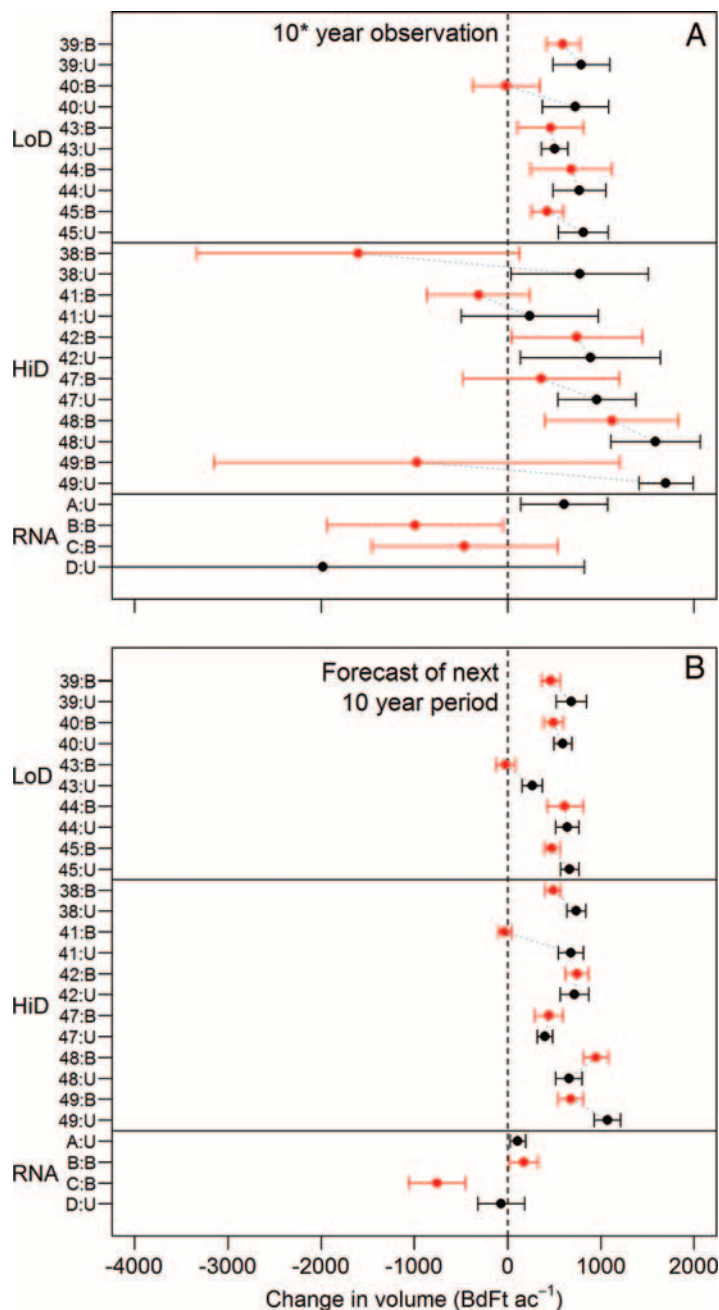


Figure 2. Net merchantable volume growth by burn split (red, burn; black, unburned) and overstory diversity structure, as observed in the total posttreatment measurement period (A) and forecast 10 years into the future to year 20 (B), as predicted by this study's growth and mortality models. Mean and 95% confidence intervals by stand number and burn treatment (split-plot identifiers) are shown. Confidence intervals in panel B result from model predictions (means) and therefore do not completely reflect future variability. *The measurement period was 9 years for RNA B and C and 13 years for RNA A and D.

burn levels are presented in Table 2 (years 0 and 10). On our final measurement (year 10), net volume growth by overstory diversity was 377.0, 665.6, and -707.0 bd ft/acre for the HiD, LoD, and RNA, respectively. Pooled net volume growth by burn treatment was -108.6 and 332.3 bd ft/acre for the burned and unburned stands, respectively. Growth by split-plot is presented

graphically in Figure 2A. The greatest mean growth ($1,697$ bd ft) was observed in the unburned HiD, whereas the lowest mean net growth ($-1,979$ bd ft) was observed in the unburned RNA. The ANOVA of stand-level growth in board feet, given the experimental units (HiD and LoD), is presented in Table 3. There is some evidence that net board foot growth may be significantly dif-

ferent among prescribed fire treatments at this point in time ($P = 0.06$), but there was insufficient evidence for an effect of overstory structural diversity and treatment interaction ($P = 0.15$ and 0.23).

At year 10, net AGB growth by overstory diversity was 3.58, 5.53, and -2.84 tons/acre for the HiD, LoD, and RNA, respectively. Net AGB growth by burn treatment was 0.10 and 4.08 tons/acre for the burned and unburned stands. The same stands that were observed to net the greatest and least amount of board foot growth (above) net the greatest and least tons of AGB: 9.82 and -8.74 tons/acre, respectively. The ANOVA of stand-level growth in tons, given the experimental units (HiD and LoD), is presented in Table 3. There is mild evidence that net AGB growth significantly differs among overstory treatments at this point in time ($P = 0.04$) and strong evidence that 10-year growth varies by using prescribed fire in this study ($P = 0.001$). We do not have enough evidence that there is an interaction effect for this response ($P = 0.16$).

Individual Tree Models

The dbh growth model had a pseudo- R^2 of 0.370 and a RMSE of 0.0685. A normal quantile plot on model residuals showed an approximate normal distribution with slightly longer tails than expected, as might be seen in large growth data sets. The model residual plot by predicted values suggested homoscedastic variance. The combined initial dbh terms in the complete model exhibited a peak in annual growth for HiD and RNA trees; trees with dbh of 12.3 in. in the HiD and 11.6 in. in the RNA had the greatest growth rates. Growth rates in the LoD approached a peak, but annual dbh growth did not reach the apex of the modeled curve in the range of our data (99% of trees were <21.2 in. diameter). The dbh growth models indicated that the annual dbh growth was greatest for trees in the LoD treated stands and lowest for trees in the untreated RNA. Diameter growth was greatest in fir and lowest in pine. The variability of diameter growth at 12 in. dbh (near the function's peak for HiD and RNA) is shown in the following example: a 12 in. diameter white fir tree in the LoD is predicted to grow between 0.164 and 0.211 in. in diameter per year, between 0.102 and 0.195 in. in the HiD, and between 0.073 and 0.101 in. in the RNA. In another example, a large ponderosa pine (dbh = 30 in.) in the HiD is predicted

Table 3. ANOVA table of stand periodic growth (in board foot volume and tons of ABG) by structural diversity and prescribed burn treatment.

Source	df	Bd ft volume			ABG		
		MS	F value	Pr > F	MS	F value	Pr > F
Year 0–10 periodic increment							
Block	2	1,040,716.70			102.15		
Structural	1	735,428.80	2.55	0.1545	145.20	6.37	0.0396
Error (<i>a</i>)	7	288,644.40			22.81		
Burn	1	2,534,734.40	4.56	0.0616	673.74	21.66	0.0012
Structural × burn	1	925,022.90	1.66	0.2294	74.88	2.41	0.1552
Error (<i>b</i>)	9	556,369.80			31.11		
Year 10–20 periodic increment							
Block	2	193,042.81			157.80		
Structural	1	66,213.80	0.98	0.3551	2.04	0.08	0.7914
Error (<i>a</i>)	7	67,526.63			27.00		
Burn	1	149,085.72	3.91	0.0793	40.10	2.21	0.1712
Structural × burn	1	0.01	0	0.9997	4.95	0.27	0.6141
Error (<i>b</i>)	9	38,110.62			18.14		

See Equation 1 for ANOVA model form and error structure definition.

to grow between 0.042 and 0.081 in., whereas diameter growth in the RNA expected to be only 40–55% of the tree growth in the treated area.

The height growth model had a pseudo- R^2 of only 0.112 and a RMSE of 0.7017. A normal quantile plot on model residuals showed an approximate normal distribution but with much larger tails than expected. The large tails in this response are a result of repeat measures and compounding measurement error, despite sufficient training. Model residual plot by predicted values suggested generally constant variance but revealed some high-leverage positive-residual trees outside of the greater predicted height growth range. The combined initial height terms in the complete model exhibited a peak in annual growth in the HiD and the RNA, but modeled annual height growth in the LoD exhibited a reverse-J curve in the range of these data. The fastest growing trees in the HiD and RNA were 50 and 46 ft tall, respectively. Height growth was greatest for pine and lowest for white fir. The range of height growth for a 48 ft tall tree (between the HiD and RNA functions' peaks) is bounded in the following example: a 48 ft ponderosa pine in the LoD is predicted to grow between 0.25 and 1.00 ft in height per year, between 0.41 and 0.85 in the HiD, and between 0.30 and 0.49 in the RNA. Regardless of species and burn treatment, large trees (height of ≥ 100 ft; note that $<1\%$ of trees at BMEF are taller than 120 ft) are not expected to grow more than 0.24 ft/year.

The mortality model in this study had a deviance-derived pseudo- R^2 of 0.091 and a RMSE of 0.0518. The mortality model was

not inspected for normality of errors because the model was logistic in nature and predicts means of binomial responses. In this study's model, the slope between mortality and diameter varied by structural diversity treatment. The probability of mortality was inversely related to tree diameter in the HiD, had a slight positive relationship to diameter in the LoD, and had a null to slight positive relationship to diameter in the RNA units. Larger diameter trees were penalized more in the RNA than in the HiD. Expected probability of mortality was greatest for white fir and lowest for incense-cedar. Using the same tree example as in the diameter growth example above, a 12 in. dbh white fir has an annual probability of mortality ranging from 5.8×10^{-7} to 4.07% in the LoD, from 0.31 to 3.49% in the HiD, and from 0.76 to 2.65% in the RNA. Similarly, a 30-in. diameter ponderosa pine in the HiD has a predicted annual mortality rate of 0.07 to 0.75%; a similar tree in the RNA is expected to have a rate of 0.48 to 1.69%.

Predicted Net Growth to Year 20

Forecast mean standing board foot volume and total AGB by treatment and burn levels are presented in Table 2 (year 20). We predict that the future 10-year period (to year 20) net volume by overstory diversity will be 626.7, 485.4, and -136.2 bd ft/acre for the HiD, LoD, and RNA, respectively. Net volume by burn treatment is forecast to be 218.4 and 432.2 bd ft/acre for the pooled burned and unburned stands, respectively. Growth in yield by split-plot is presented graphically in Figure 2B. The greatest predicted mean growth over the future 10-year

period is in an unburned HiD (1,069 bd ft) and the lowest stand board foot growth (-757 bd ft) is forecast for the burned RNA. The ANOVA of stand-level growth in board feet, given the experimental units (HiD and LoD), is presented in Table 3. There is some marginal evidence that net board foot growth may be different among burned and unburned treatments in the forecast period ($P = 0.08$). The structural diversity and interaction terms in the predicted growth ANOVA suggest that no statistical differences are expected in net growth between experimental stands.

Our models predict that the future 10-year period net AGB by overstory diversity will be 4.83, 4.76, and -0.09 tons/acre for the HiD, LoD, and RNA, respectively. Net AGB by burn treatment is forecast to be 2.39 and 3.94 tons/acre for the burned and unburned stands. Greatest net growth in tree AGB is expected in the burned HiD (20.32 tons/acre), whereas the lowest net growth is forecast to be in the burned RNA (-12.35 tons/acre). The ANOVA of stand-level growth in tons, given the experimental units (HiD and LoD), is presented in Table 3. There is insufficient evidence that forecast net AGB growth is significantly different among these treatments over the future period ($P > 0.17$).

Cumulative SDI of trees >23.5 in. dbh ranges from 25 to 79 over time (Figure 3). At 10 years since treatment, there appeared to be evidence of differences in the change in SDI since treatment by group (model $P = 0.0317$), where groups were the two HiD burn split classes and a pooled RNA class. There is insufficient evidence that the

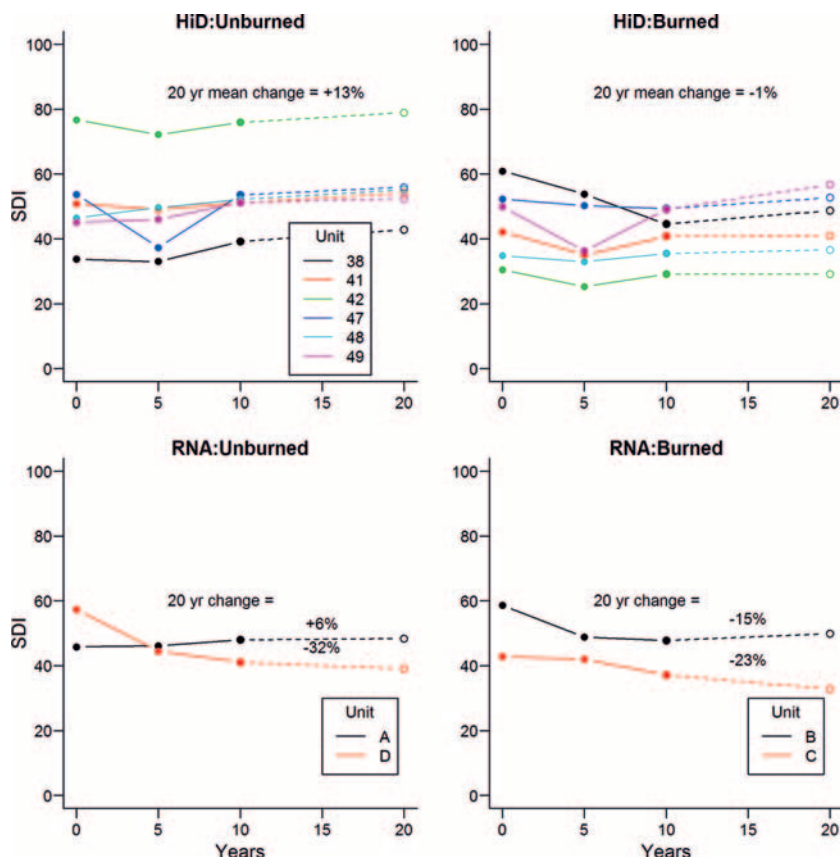


Figure 3. Time series of the large-tree component (>23.5 in dbh) SDI, by overstory structure and burn split.

change in SDI between year 10 and year 0 is different from 0 in the HiD stands, but SDI in pooled RNA stands has decreased 13.78% ($P = 0.024$). There was also a significant effect by treatment in the model of change in SDI from 0 to 20 years (model $P = 0.0202$). Simple linear regression of the large-tree component SDI on treatment groups indicated that unburned HiD stands are predicted to increase significantly from 0 to 20 years posttreatment (12.6%; $P = 0.023$). The change in burned HiD stands is not statistically different from 0 (coefficient $P = 0.8025$), but SDI in pooled RNA stands is expected to decrease significantly (-16.1% ; $P = 0.0184$). Because moderate-diameter trees actively enter into the large-tree component (>23 in.), we briefly conducted a separate analysis of trees 16 in. < dbh ≤ 23.5 in. A similar simple linear regression model of the moderate-tree component SDI on treatment groups suggests the relative density of this overstory component will significantly increase 65.72 and 68.05% in the HiD unburned and burned stands, respectively ($P = 0.0004$ and 0.0003) from 0 to 20 years. Percent change in the RNA is

not different from 0 (linear regression slope coefficient $P = 0.5705$).

Discussion

Measured Net Growth

One of the reasons this study was designed was to contrast multiple-use stands with stands optimized for maximum individual tree growth in the eastside ponderosa pine ecosystem. This study's HiD stands aimed to restore ponderosa pine ecosystems by reestablishing structural heterogeneity, thus managing for old-growth structural attributes, while reducing understory competition (Figure 4). The LoD stands, on the other hand, were created to form a strong contrast; stands were typified by uniform crown structure and tree spacing. Thus, the HiD and LoD treatments both altered stand structure to reflect current management concerns, practices, and goals.

This study examines differences in net stand growth between treatment types. This study does not address trees of <4 in. in diameter nor does it account for the shrub and herb stratum. If we included trees of all

sizes, we would expect very little difference in stand basal area ($\pm 2 \text{ ft}^2 \text{ acre}^{-1}$), but a marked difference in tree density (23–73% greater) (Zhang et al. 2008). We expect that overall stand AGB may increase by a small amount if we included trees of <4 in. in diameter, although board foot volume would be unaltered by the inclusion of sub-merchantable biomass. One final caveat regarding AGB is that tree biomass equations typically predict large-tree biomass with poor precision. Therefore, the AGB values presented for the HiD and the RNA, both of which have a high proportion of large trees, are suspected to be associated with a greater degree of uncertainty.

According to the calculated stand yield metrics in this study, net growth from the measured 10-year period (both board foot volume and AGB) differed between treated units as a result of prescribed fire. Differences by burn treatment between pooled HiD and LoD stands were expected, despite the use of low-intensity fire. That is, second-order stem mortality as a result of prescribed fire treatment after a long period of fire exclusion is common in western US dry forests (Sackett et al. 1996, Hood 2011). Because net growth is total stand growth minus the trees that died within a period, we expected that the loss of trees not immediately killed by fire would negatively influence net growth. The fact that average net growth in burned experimental stands was only 24% of unburned stands in board foot volume suggests that stem mortality was not limited to small, understory trees. Rather, the prescribed burn negatively influenced a wide range of tree sizes (as in Zhang et al. 2008). In another BMERP study, postburn, insect-caused mortality was observed through 5 years since treatment (Fettig et al. 2008, Fettig and McKelvey 2010). Although not tested in this study, mortality rates appeared to be reduced in the second 5-year measurement period (period 2) as compared with period 1 (J. Crotteau, University of Montana, pers. observ., Oct. 1, 2013). Regardless, lower net growth in the burned units reflects a detrimental postburn effect that inhibited stand growth compared with that for the no-burn treatment. It may be postulated that the low postburn net growth is a product of reintroducing fire after a long, fire-free period; future installments of low-severity fire may or may not exhibit such adverse effects.

Stand net growth in AGB also varied by overstory treatment. Net growth in the LoD



Figure 4. Forest structure and composition typical of the high-structural diversity (HiD) treatment at the Blacks Mountain Experimental Forest. Unit 38 pictured, at 8 years post-treatment. (Photo credit: Martin Ritchie.)

was 54% greater than that observed in the HiD. This effect is probably due to the quality of trees retained in the LoD. The LoD maintained a uniform cohort of trees in the 8–12 in. diameter class. In fact, the majority of the LoD trees are younger and more vigorous than the dominant trees in the HiD overstory. Greater individual tree growth in the LoD than the HiD was expected for this very fact, but it is surprising that such low-density stands (SDI of average stand = 76) accumulated AGB more rapidly than the fully-stocked HiD stands (SDI of average stand = 181). Whereas board foot volume is biased toward large trees, the change in AGB is more sensitive to smaller trees, which may explain why this difference is evident in AGB but not board foot volume.

It is clear that significant differences in stand growth exist between the experimental treatments in this study. Although we cannot determine whether there is a *statistical* difference between the RNA and experimental stands, certain practical and biological differences are evident. For instance, net growth in the RNA over the course of the measurements is calculated to be -706.9 bd ft/acre, and -2.84 tons/acre. The difference between RNA stand growth means and the HiD means is 231% greater than the statistically significant difference between HiD and LoD for net AGB. Furthermore, the difference in stand growth between burned and unburned RNA stands appears to be negli-

gible in terms of board foot volume. We believe that the observed poor net stand growth is driven by high levels of competition-based mortality and growth stagnation (average RNA stand SDI = 286). The RNA stands are most similar to HiD stands in terms of diameter distribution and tree age classes, but use of logging is associated with positive net growth in the HiD, whereas we observed negative net growth in the unlogged RNA.

Model Insight

Despite the number of terms in our models, their predictive capacities are lower than we had anticipated. Pseudo- R^2 values must be interpreted cautiously. Nonetheless, pseudo- R^2 values for the height growth and mortality model were quite low. Although this may be expected for a mortality model, the low predictive power of the height growth model suggested that growth trends are highly variable and weakly related to predictors. Errors were probably due to tree top damage and a lack of measurement precision, which may often accompany repeat measurements on standing tree height.

The models presented in this study did not test for the effects of tree size nor location in the experimental forest. Rather, we specified terms that we hypothesized would maximize stand-level expression and not inhibit emergent trends. Thus, each species and stand had its own intercept, and we al-

lowed slopes to vary with treatment type. Models were used to forecast stands so that testing for significant differences in the experiment could be done on the back end of the process, after aggregating individual trees into stands.

Although we cannot statistically test predictors in our models, the shape of model prediction curves does provide some insight on individual tree growth at BMEF. For instance, predictions in the LoD reveal some interesting trends. First, diameter growth appears to be greater overall in LoD than HiD and RNA stands. Individual trees in the LoD are quite vigorous and have not yet peaked in terms of diameter growth. This finding suggests that the LoD treatment may have long-lasting effects on tree diameter growth that may not be diminished after 10–20 years in eastside ponderosa pine. Second, shorter trees seem to be growing in height much more quickly than the largest trees in the LoD, which is a sharp contrast to tree height growth in the lower canopy stratum in both the HiD and RNA. The predicted height growth curve was reverse-J in shape, where the poorest mean height growth was approximately the same as typical height growth in the HiD. Thus, small trees appeared to be released from competition in the LoD, whereas trees in the dominant canopy position were able to allocate carbon to lower order survival needs (as in Oliver and Larson 1996, p. 75) where height growth is no longer the most imperative survival mechanism.

A third trend that the models highlighted in the LoD was that the probability of tree mortality tended to increase slightly with diameter. This observation was unexpected, considering the overall vigor of the stands. According to the data used to model mortality, 14% of white fir stems died over the course of period 2, whereas mortality in the other species was between 1.0 and 1.5%. Although white fir exhibited greater diameter growth than ponderosa pine and incense-cedar, our data suggest that it also experienced a higher rate of mortality. White fir mortality rates suggest that the species is subject to secondary burn-related mortality due to *Scolytus ventralis* (Fettig and McKelvey 2010), but increased mortality of larger diameter trees may indicate an increase in environmental stressors on the fir component. We believe that mature white fir at BMEF may not tolerate the open stand condition that followed from removing the dominant pine overstory, despite its ability to grow in

full sunlight (Laacke 1990). White fir has poorer stomatal control than ponderosa pine (Lopushinsky 1975) and may be more sensitive to drier conditions that result from increased windflow in the current open condition. Furthermore, white fir is a shade-tolerant species (Laacke 1990), and most individuals were established under a pine canopy in the BMEF. Changes in the quality and quantity of solar radiation after years of stagnation may have confounded the release of white fir. Whether due to increased light, wind, insect attack, or some other unseen factor, notable mortality rates among white fir as a result of the BMERP treatments prompts favor of ponderosa pine in future treatments if the goal is to retain trees with robust growth and superior postdisturbance survival.

Individual tree growth in the HiD appears to fit well with the multiaged structure that the overstory treatment maintained. Diameter and height growth models point to the fact that trees in our data set had nonlinear, inconstant growth patterns with increasing tree size. Diameter growth was greatest for trees 11–13 in. in dbh, and height growth was greatest for trees 35–55 ft tall, which resonates with the theory of hydraulic limitation on growth on a poor site such as ours (Ryan et al. 1997). On this forest, site index is 72 ft at a base age of 100. That the best growing mature trees are in the small sawlog size class does not necessarily mean that these trees are younger than the dominant overstory trees, yet we believe that many of the white fir in this class are, in fact, younger than the competing pines (Ritchie et al. 2008). In addition, white fir individuals retained by the BMERP mechanical treatment were more likely to be superior in terms of phenotypic expression and live crown size because treatment favored retention of pine and only the best white fir specimens. Finally, interspecies mortality trends in the HiD appeared to be more homogeneous than in the LoD, although the greatest mortality was observed in white fir. We observed a 5.9% periodic mortality rate for white fir, which was equal to the combined total of both ponderosa pine and incense-cedar periodic mortality rates. It is interesting to note that white fir exhibits higher average growth rates in treated versus untreated stands, yet it simultaneously has greater average rates of mortality in the open-stand conditions.

The distribution of the predicted values in this study's dbh and height models sug-

gests that there may be some differences in individual tree growth between the treated stands (HiD and LoD) and the untreated RNA. Apart from poorer average growth rates of trees in the RNA in comparison to trees in mechanically treated stands, we observed that a greater proportion of large diameter trees in the RNA died over the course of the measurements (periodic mortality rate of trees of > 24 in. dbh = 11.3% compared with 3.0% in the HiD). We attribute the high rates of mortality in the RNA to stem crowding. In the absence of frequent fire, overstories in interior ponderosa pine stands are being converted from ponderosa pine to white fir, resulting in denser growing conditions than was typical historically (Ritchie et al. 2008). In light of the most recent mortality rates observed, it appears that a single prescribed burn in the RNA may be insufficient to reverse the compositional trajectory toward white fir dominance in these stands, as it only removed the smallest of trees (Skinner 2005).

Forecast Net Growth

Projection of tree volume and biomass inventory is integral for forest managers, investors, and carbon accountants. There is much concern that contemporary forest health may be susceptible to changing climate, more frequent fire, and epidemic insect breakouts (Kolb et al. 2007). Barring high-severity, extreme cases, managing for better overall growth may help the stand to persevere amid such disturbance agents.

We forecast yield in both experimental and pseudocontrol stands. Stand growth from 10 to 20 years posttreatment was calculated by board foot volume (32 foot logs, 6 in. top and stump) and total AGB. Our ANOVA findings indicated only one potential difference: that there may still be marginally less board foot volume growth in the burned than in the unburned stands, as observed in the measured period data. This appears to be because of the mortality rates observed in period 2, which were used to forecast our tree-level observations. Measurement period 2 mortality rates in burned units were 0.8–2.2% higher than those in unburned units. If mortality rates similar to those in period 2 persist, then we may expect a slight difference among burn treatments. One important shortcoming of measuring on a 5-year return interval is that annual mortality rates observed are coarse. We are not sure whether the majority of stem mortality occurred by year 6 or all the way

through year 10 since treatment. Therefore, it is possible that the “excess” mortality evident in the burned units is due to latent second-order fire mortality and that actual mortality rates over the course of the forecast period may improve with time since fire (Fettig and McKelvey 2010).

Another key finding from the ANOVA of forecast growth is that the effect of overstory structure on board foot volume periodic growth and similarly the effects of overstory structure and burn treatment on AGB may be expected to fade over time (note increasing *P* values between periods in Table 3). From a timber growth perspective, this can be interpreted as a successful treatment in two ways: the multiuse stands that were designed to restore structural diversity can be equally as productive as an even-aged management strategy; and low-density, open stands have the capacity to produce as much net yield as stands with full-site occupancy and large-diameter trees. These results emphasize that stands in the HiD and LoD may be able to sequester carbon and accumulate volume at nearly equal rates in the second decade since treatment.

According to our forecasts, RNA stands will net a mean of –122% of the board foot volume growth in HiD stands 10 years in the future. Under an alternative management strategy, i.e., fully-stocked even-aged management, interior ponderosa pine stands of similar site index should produce nearly 400% more volume than even the mean of forecast HiD stands (Meyer 1938). Our forecast suggests that the net AGB of the RNA stands may also be negative. RNA net stand productivity appears to be stifled by stem crowding in terms of both board foot volume and stand AGB. As with the analysis of the measurement period growth above, we cannot make any claims of statistical difference between logged and unlogged stands for the forecast period growth. However, the observed practical difference is substantial.

If tree-level growth trends hold and without future management, we expect that net growth in the logged stands will increase in accretion rate for some time, whereas the RNA stand productivity may exhibit further decline. Although current management practices may not be based on retaining solely vigorously growing stands, our results suggest that logging and burning may effectively maintain a diverse variety of natural stand structures while restoring primary productivity in addition to wildfire resili-

ience (Ritchie et al. 2007). If management objectives are to restore these ecosystems to historic conditions or a future resilient state, it may be necessary to mechanically alter stand structure to create more open canopy conditions that may favor the more fire-tolerant pine than the shade-tolerant fir. Although the pseudocontrols limit the inferential capacity of our observations, the character of the RNA is representative of both the designed experiment's reference condition and remnant untreated old-growth stands in the region.

Trees of >23.5 in. dbh make up 36–43% of aboveground tree biomass in the RNA and HiD, respectively; at 58 and 60% of total merchantable board foot volume, these are perhaps the most influential assets in BMEF stands. The SDI component analysis emphasizes that the relative density of large trees, although initially hampered by burning, may be positively affected by treatment. Whether burning produced significantly different results within the RNA is not answerable in this study due to insufficient replication, yet the high levels of inter-tree competition in the pooled burned and unburned stands threatens a decline in overall vigor of the large tree component. Previous studies have also indicated that large-diameter trees are prone to dying after reintroduction of fire (e.g., Thomas and Agee 1986, Swezy and Agee 1991, McHugh and Kolb 2003). However, we suspect that protracted, second-order fire mortality effects are concluded after 10 years posttreatment and that the rate of SDI accretion in the burned HiD stands may increase more than indicated in this study's forecast. The results of this long-term study suggest that large-diameter trees may be susceptible to increased mortality rates even without the reintroduction of fire and increased resource availability via a mechanical reduction of stand density may increase survival of the large-tree component.

As managers continue to cultivate large ponderosa pine for timber and biomass or restoration of historic fire regimes, diameter distributions, and species composition in ponderosa pine ecosystems, our success story provides evidence that multiresource management can be at once productive and restorative. Furthermore, we qualitatively assert that logged stands, in the manner of this study's HiD treatments, have the potential to be more structurally diverse and resilient to endogenous ("background") mortality than natural stands subjected to a century of

fire exclusion in the dry eastside ponderosa pine ecosystem.

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