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**Original Article**

# Evaluating the efficacy of thinning and prescribed fire for restoring mature forest characteristics in the Eastern Cascades, USA

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## Abstract

Historical fire exclusion, intensive logging of large trees of fire-tolerant species, and even-aged management have contributed to widespread decline of mature/old-growth coniferous forests across the Western USA. To investigate silvicultural approaches for reducing disturbance risk while accelerating restoration of mature/old-growth forest characteristics, we used 20-year data from the Goosenest Adaptive Management Area study in Northern California, USA. Established to evaluate the alternatives for reducing fuels and accelerating the development of late-seral characteristics in ponderosa pine (*Pinus ponderosa*)/white fir (*Abies concolor*) mixed-conifer forests, the Goosenest Adaptive Management Area study consists of (i) an untreated Control, (ii) a Big Tree treatment using thinning from below to favor large trees of any species, (iii) a Pine Emphasis treatment combining thinning from below with radial thinning, group selection harvesting, and artificial regeneration to favor ponderosa pine while increasing structural complexity, and (iv) a Pine Emphasis with Fire treatment with postthinning prescribed burns added to (iii). Our objectives were to determine whether and how (i) treatments altered stand structure and composition and (ii) the dynamics of ecologically valuable large trees and snags varied by treatment. To accomplish this, we built generalized linear mixed models to compare treatment effects on stocking, structural complexity, composition, growth dominance, large-tree dynamics, and large-snag dynamics. We found that all the treatments initially lowered stocking relative to the Control, but Pine Emphasis with Fire was notably more successful in maintaining the stocking/fuel reduction. Both Pine Emphasis treatments maintained vertical and horizontal structural complexity. Pine Emphasis with Fire was most effective in restoring composition toward ponderosa pine dominance. Treatments did not discernably alter growth dominance, large-tree recruitment/mortality, or the large-snag recruitment/decay condition. Our results indicate that the Pine Emphasis with Fire treatment shows the greatest potential for accelerating restoration of mature/old-growth characteristics in ponderosa pine/mixed-conifer forests, while reducing longer term risk from fire and other disturbances.

*Keywords:* structural complexity; mature/old-growth forest; forest restoration; hazardous fuel treatment; ponderosa pine

## Introduction

Mature forest ecosystems have a number of unique characteristics that contribute to both high ecological value and stability in the face of disturbance (Franklin et al. 2007). Low- to mixed-severity fire regimes, which involve negligible to partial overstory tree mortality, are key forces shaping the structure and composition of fire-adapted conifer forests (Perry et al. 2011). In addition to maintaining shade-intolerant, disturbance-adapted tree species (Frelich and Reich 1999), mature stands of fire-adapted forest types are characterized by a mosaic of age and size classes (O'Hara 2014), which helps insure these structures against disturbances targeting a single tree size. Large maximum tree sizes provide important wildlife habitat and carbon storage values (Curtis 1997, Lundmark et al. 2018), while snags provide nesting habitat, supply coarse woody debris, and carry biological legacies across severe disturbances (Franklin et al. 2007). The widespread loss of primary forests has created global demand for silvicultural approaches for restoring these and other mature/old-growth forest attributes (Bauhus et al. 2009).

In the dry, fire-dependent, coniferous forests of the Western USA, low- to mixed-severity wildfires historically maintained fire-tolerant tree species, low stand densities, and a patchwork of age and size classes (Bekker and Taylor 2010, Hagmann et al. 2019). These forest structures were robust against disturbances such as drought, severe fire, and insects (North et al. 2022). Beginning in the 19th and early 20th centuries, high grading removed ecologically valuable large trees of fire-tolerant species, even-aged management simplified forest structure (Allen et al. 2002), and fire exclusion promoted denser stands of fire-sensitive, shade-tolerant tree species (Bekker and Taylor 2010).

Silvicultural approaches to restoring the historical forest structure, composition, and function in dry coniferous forests must balance several competing objectives: reducing vulnerability to severe disturbance, providing habitat for key species of

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concern, and bolstering the adaptive capacity to climate change (Stephens et al. 2021). Traditional fuel reduction treatments reduce the near-term fire risk by promoting uniform tree size, spacing, and overstory cover, thus controlling ladder fuels, suppressing ground vegetation (Matthews 1989), and aiding fire suppression (McKinney et al. 2022). Although such prescriptions could also promote large, fire-resistant, ecologically valuable trees (Ritchie and Harcksen 2005), thinning to uniform spacing has limited the capacity to create mature forest structural characteristics such as age class diversity and structural complexity (Franklin and Van Pelt 2004).

Extending thinning treatments to incorporate uneven-aged management techniques may help provide for a wider range of disturbance resistance, habitat, and climate change adaptation objectives (Long and Smith 2000, Muller et al. 2019, York et al. 2021). Uneven-aged management introduces age class and structural diversity, which can help restore the desired shade-intolerant, fire-tolerant species composition (Bigelow et al. 2011) and support the food webs critical to predator species of special concern (Long and Smith 2000). However, traditional uneven-aged management involving group selection harvests intended to foster natural regeneration (Matthews 1989) allows for little control over stock or species (O'Hara 2014). To address this shortcoming, planting within harvested groups can be used to promote the regeneration of historical fire-tolerant conifers (York et al. 2021) while incorporating assisted migration to address climate change (Muller et al. 2019). Another potential limitation of traditional group selection uneven-aged management is that this approach may take several harvest entries to foster detectable changes in structural complexity or composition (O'Hara 2014) compared to more contemporary heterogeneous thinning approaches (Franklin et al. 2007; Churchill et al. 2013).

Reintroducing fire can complement mechanical treatments by further reducing forest fuels to lower the risk of severe wildfire (McKinney et al. 2022). Combining prescribed fire and thinning improves the ability of treated stands to resist subsequent wildfires (McKinney et al. 2022, Brodie et al. 2024) and provides greater treatment longevity (Davis et al. 2024). Fire can help restore the forest composition by controlling the regeneration of fire-sensitive, shade-tolerant species that could otherwise dominate harvested gaps (Brodie et al. 2023). Reintroducing fire also restores nutrient cycling benefits and restores the broader ecology and evolution of fire-adapted plant communities (Korb et al. 2012, Ganzlin et al. 2016). Prescribed fire, however, may present tradeoffs for mature/old-growth forest attributes, potentially augmenting snag recruitment for wildlife habitat (Schwilk et al. 2009) but reducing structural complexity if not carefully executed and coordinated with mechanical treatments (York et al. 2021).

The 810 ha Goosenest Adaptive Management Area (AMA) study was established in 1998–2000 to evaluate alternative approaches to restoring mature forest characteristics and reducing hazardous fuels in fire-dependent ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson)/mixed-conifer forests (Ritchie 2005). To accomplish this, the Goosenest study compared an untreated control and three treatment approaches: (i) thinning from below to uniform spacing to favor large vigorous trees of any species, (ii) combining thinning from below to favor ponderosa pine with radial thinning to release dominant and codominant trees, group selection harvests targeting concentrations of white fir, and artificial regeneration of ponderosa pine in harvested gaps to promote the fire-adapted pine and increase structural complexity, and (iii) adding prescribed burning to the treatments described in (ii) to reduce fuels (Ritchie 2005). Results 6–14 years posttreatment indicated that treatments reduced stand density and did not substantially promote large-tree recruitment relative to the control (Ritchie and Harcksen 2005; Ritchie 2005, 2020). Whether treatments fostered these and other aspects of structural complexity over the longer term remains unknown.

We examined 20-year results from the Goosenest AMA study to examine tradeoffs among treatments when seeking to restore mature/old-growth forest attributes. Our goals were to determine whether and, if so, how (i) treatments altered stand structure and composition over the longer term and (ii) the dynamics of ecologically valuable large trees and snags varied with treatment. Our overarching purpose was to better inform the design of durable silvicultural approaches for accelerating the restoration of mature/old-growth overstory structural attributes in ponderosa pine/mixed-conifer stands.

# Methods

The Goosenest AMA study was established in 1998–2000 within the larger Goosenest AMA in Klamath National Forest near Tennant, Siskiyou County, California, USA (Fig. 1). Located northeast of Mt Shasta, the study sites are representative of moderately productive, interior ponderosa pine/mixed-conifer forests in the southern Cascade Range. Soils are volcanic with a pumice layer several inches thick that forms a natural barrier to planting success without site preparation. (Ritchie 2005). The climate is generally continental, but with a Mediterranean pattern of precipitation concentrated in the form of winter snowfall. Modeled mean annual precipitation over the 1991–2020 period was 782 mm per year (ClimateNA; Wang et al. 2016). Average daily winter temperatures ranged from a low of −3°C to a high of 5°C and average daily summer temperatures from a low of 10.7°C to a high of 25.5°C (ClimateNA; Wang et al. 2016).

Ponderosa pine and white fir [*Abies concolor* (Gordon & Glend.) Lindl. ex Hildebr.] are the primary tree species, with minor amounts of sugar pine (*Pinus lambertiana* Douglas), incense cedar [*Calocedrus decurrens* (Torrey) Florin], lodgepole pine (*Pinus contorta* subsp. *murrayana* Balfour), and red fir (*Abies magnifica* A. Murray). Shrub species included greenleaf manzanita (*Arctostaphylos patula* Greene), snowbrush (*Ceanothus velutinus* Douglas), and mahalamat (*Ceanothus prostratus* Benth.). Please see Ritchie (2005) for a full list of tree and shrub species. Prior to transfer to the US Forest Service, the study area was subject to high-grade logging in the 1920s to 30s with a focus on pine removal. Since the mid-20th century, the study area has been subject to fire suppression and limited removal of dead or dying trees (Ritchie 2020).

The Goosenest AMA study consists of twenty 40 ha experimental units, randomly divided among four treatment alternatives for five replicates per treatment:

1) An untreated Control represented the no-action alternative.

2) A Big Tree treatment sought to change the diameter distribution by releasing large, vigorous trees of any species from competition by thinning from below to a 5.5 m tree spacing. Retention criteria were based solely on tree spacing, size, and condition (Ritchie 2020).

3) A Pine Emphasis treatment sought to restore the relative abundance of ponderosa pine (i.e. a target ponderosa pine relative density ≥ 80% of the stand basal area) while improving age class diversity and stand structural complexity. This treatment retained all codominant and dominant ponderosa pine during harvesting, with retained trees (which also included large, vigorous white fir where pine was not locally present) released through radial

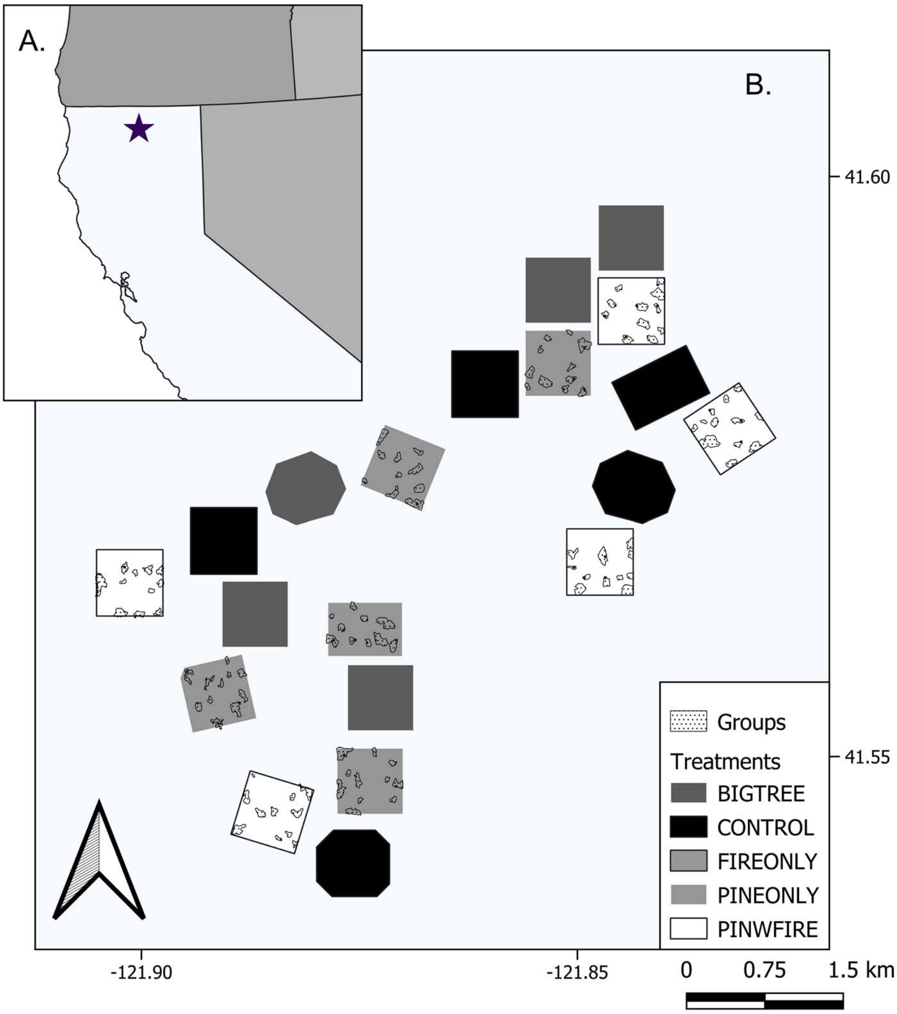


**Figure 1.** Map of the Goosenest Adaptive Management Area (AMA) study showing (A) location of the study site within the US state of California and (B) detail of treatment units and group selections. In addition to a (i) no-management alternative (CONTROL), treatments include (ii) BIGTREE, thinning from below to an even spacing with no species preference, (iii) PINEONLY, thinning from below with a ponderosa pine (*Pinus ponderosa*) species retention preference and planting harvested groups of white fir (*Abies concolor*), and (iv) PINWFIRE, identical to (iii) but adding mild prescribed fall burns in 2001 and 2010. Stippled "groups" denote the location of harvested and planted group selections within PINEONLY and PINWFIRE units.

thinning. Pine dominance, age class diversity, and structural complexity were further promoted through group selection harvests as openings and comprised a target 15% of the stand area. Group selections centered as much as possible on denser pockets of white fir and ranged in size from 0.2 to 1.4 ha. In 2000–2002 following harvest, harvested gaps were planted with 2-year-old bare-root ponderosa pine seedlings at an effective spacing of 3.4 m. Site preparation involved ripping to enhance early survival by tilling the upper pumice layer (Ritchie 2005).

4) A Pine Emphasis with Fire treatment was identical to the pine treatment but added prescribed burning in 2001 and 2010 to reduce forest fuels and natural regeneration of fire-sensitive fir. Burns were performed in fall after the start of the rainy season to moderate fire behavior, with tree-centered firing used in 2000 and backing firing in 2010. In the 2010 burn, the low flammability of shrubs within group openings aided in excluding fire from gaps to prevent mortality in planted pines (Ritchie 2020).

## Tree and sapling monitoring

A grid of monitoring plots was established across the Goosenest AMA study area prior to treatment. This grid consisted of precision-surveyed points spaced every 141.5 m, with a permanent monitoring plot established at each sample point for a density of ~0.5 plots per hectare. A nested fixed-radius sample plot design sampled overstory trees (>29 cm diameter at breast height, DBH), midstory trees (9.1 cm < DBH < 29 cm), saplings (0 cm < DBH < 9.1 cm), and seedlings (height < 1.37 m). Overstory and midstory trees were monitored for survival, damages, DBH, total height, and height to live crown base on 0.081 and 0.02 ha plots, respectively. Total height was measured to the height of the tallest live branch junction in the case of trees with dead tops. DBH was assessed at 1.37 m. Live saplings, measured within 0.004 ha microplots, were tallied by species and assigned to one of three diameter classes: 0–3.7, 3.8–6.3, and 6.4–9.1 cm DBH. Live seedlings were tallied by species within the same 0.004 ha microplots but not analysed for this study. Snags (standing dead trees ≥ 3.04 m height) were monitored for decay class (Thomas et al. 1979). Data were summarized to the unit level except for snag condition, which was retained as an individual-tree variable. Posttreatment measurements were available for 2002, 2005, 2013, and 2019, representing 3-, 6-, 14-, and 20-year posttreatment results, respectively. We made use of data from all four measurement periods. Data from a variable-radius pretreatment cruise

Table 1. Variables used in modeling stand structure, structural complexity, composition, large-tree and snag dynamics.

| Symbol | Question | Description | Interpretation | Units |
|---|---|---|---|---|
| SDI | 1 | Stand density index calculated with Reineke's QMD method | Higher values = higher stand density | No. of 25-cm trees per hectare |
| Gini | 1 | Gini coefficient of basal area; index of vertical structural complexity | Higher values = greater structural complexity | Ratio |
| $SD_{BA}$ | 1 | Index of horizontal structural complexity based on standard deviation of plot basal area within a unit | Higher values = greater horizontal complexity | Z scores |
| %Pine | 1 | Proportion of ponderosa pine by basal area | Higher values = greater pine component | Percentage |
| Growth dominance | 1 | Growth dominance coefficient based on tree contributions to basal area increment vs contributions to stand basal area | Values < 1 = small-tree growth disproportionately high; values = 0 signify growth is proportional, values > 0 = large-tree growth disproportionately high | Unitless (−1 to 1 scale) |
| Large-tree recruitment | 2 | Proportional basal area gains of large trees >60.7 cm DBH | Higher values = faster large tree recruitment | Percentage |
| Snag recruitment | 2 | Proportional basal area loss due to fall of snags >34.0 cm DBH | Higher values = faster snag recruitment | Percentage |
| Large-tree mortality | 2 | Proportional basal area rate of loss of snags >34.0 cm DBH due to mortality | Higher values = faster large-tree mortality rate | Percentage |
| Snag fall | 2 | Proportional basal area rate of loss of large trees >60.7 cm DBH due to mortality | Higher values = faster snag fall rate | Percentage |

conducted in 1996 was not directly comparable to posttreatment data, precluding before–after/contrast intervention analysis (Ritchie 2005).

## Stand structure, structural complexity, and composition

We evaluated stocking in terms of Reineke's (1933) stand density index (SDI); for a description of all the variables used in modeling, please see Table 1. We compared SDI values and trends in log–log-transformed quadratic mean diameter (QMD) vs trees per hectare space to calculate the relative density in relation to key density management thresholds—full site occupancy (35%) and the onset of elevated self-thinning mortality (60%)—referencing the maximum metric SDI of 1084 established by Long and Shaw (2005) for ponderosa pine. We incorporated both trees and saplings when examining for all the variables except snag and large-tree responses to better account for potential contributions of planted ponderosa pine and natural regeneration to the total stocking.

To evaluate treatment implications for structural complexity, we calculated the Gini coefficient (Gini) of the individual-tree basal area (Lexerød and Eid 2006). The Gini has a demonstrated ability to discriminate among diameter distributions varying in shape, is sensitive to variation in tree sizes and thus vertical structural complexity (del Río et al. 2016), and is relatively insensitive to variations in sample size (Lexerød and Eid 2006). A coefficient of 0 indicates that trees share the stand basal area equally and coefficients approaching 1 indicate that a few trees monopolize most of the stand basal area. We calculated the Gini for each unit and year:

$$\text{Gini} = \left( \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \mid \text{ba}_i - \text{ba}_j \mid}{2n^2 \text{ba}_{\bar{x}}} \right) \quad (1)$$

where $n$ is the total number of trees per unit, $\text{ba}_i$ is the basal area of tree of rank size $i$, $\text{ba}_j$is the basal area of a tree of rank size $j$, and $\text{ba}_{\bar{x}}$ is the mean tree basal area.

A key structural characteristic of historical mature ponderosa pine/mixed-conifer stands is horizontal variation in stand density, reflecting sporadic patches of tree mortality and regeneration due to mixed-severity fire (Churchill et al. 2013). To evaluate whether treatments affected this horizontal variation in stand density, we calculated the standard deviation of plot-level basal area ($SD_{BA}$) for each treatment unit by year.

We evaluated whether treatments shifted the balance of tree species composition by calculating mean ponderosa pine (%Pine), the relative basal area comprising ponderosa pine, for each treatment unit and period.

Differences in growth rates across size classes may promote tree size differentiation, with greater inequality in growth corresponding with higher monopolization of stand production by large trees (Forrester 2019). Because mechanical thinning is known to influence growth inequality (Moreau et al. 2020), our final metric of structural complexity sought to determine whether treatments altered growth inequality across the distribution of tree sizes as a means of evaluating treatment effects on the growth efficiency of retained trees (Bradford et al. 2010). Binkley (2004) proposed an index of growth dominance that compares the proportional contribution of different-sized trees to total stand density against their proportional contribution to total stand growth. This index ranges from a coefficient of −1 to 1, with negative values signifying disproportionately high small-tree contributions to stand production, neutral values signifying tree-size-proportional contributions to stand production, and positive values signifying disproportionately high large-tree contributions to stand production. We followed West's (2014) formula to calculate the growth dominance coefficient for each unit and year:

$$\text{Growth dominance} = \sum_{i=1}^{n} \left(\text{BA}_i - \text{BA}_{i-1}\right)\left(\Delta\text{BA}_i + \Delta\text{BA}_{i-1}\right) \quad (2)$$

where $n$ is the number of trees in the unit, $\text{BA}_i$ is the cumulative proportional basal area of tree $i$, and $\Delta\text{BA}_i$ is the cumulative proportional basal area increment of tree $i$. Because individual sapling-sized stems were not tracked across measurements, growth dominance was calculated for trees (DBH ≥ 8.9 cm).

Growth dominance was not estimated for year 3 due to lack of comparable pretreatment growth data.

## Large-tree and snag dynamics

To address our second research question, we examined whether treatments differed in their potential to foster the recruitment of large, ecologically valuable trees and snags. To evaluate treatment effects on large-tree recruitment, we estimated the basal area of large trees (DBH ≥ 61.0 cm) that were recruited over each measurement period. To evaluate treatment effects on snag dynamics, we estimated the basal area of standing dead trees ≥34.0 cm, which are generally of higher value to wildlife in ponderosa pine forests (Chambers and Mast 2005). We calculated large-tree and snag recruitment for each unit and period using the formula of Nakagawa et al. (2000):

$$\text{recruitment} = 100 \times \left[(1 + X/N)^{1/t} - 1\right] \quad (3)$$

where "recruitment" is the percentage change in basal area per hectare per year, $X$ is the basal area of trees recruited by category over the measurement period, $N$ is the initial basal area of trees by category at the beginning of the measurement period, and $t$ is the length of the measurement period in years. We estimated large-tree recruitment for years 6, 14, and 20 and snag recruitment for years 14 and 20, due to large snags being entirely absent from some units in earlier years.

We calculated large-tree mortality using the formula of Sheil and May (1996) for each unit and period:

$$\text{mortality} = 100 \times \left[1 - (1 - D/N)^{1/t}\right] \quad (4)$$

where "mortality" is the percentage change in basal area per hectare per year, $D$ is the basal area of large dead trees, and other variables are as defined above. We calculated large-tree mortality for years 6, 14, and 20. The recruitment and mortality equations have the advantage of making recruitment and mortality rates proportional to initial population sizes, adjusting for the smaller number of trees in treated stands relative to the control.

We investigated trends in decay condition for snags ≥ 34.0 cm DBH across treatments and time. Given that the overall rarity of snags precluded binning snags by precise decay condition for an ordinal analysis, we simplified snag condition from the original ordinal 3–7 decay class scale (Thomas et al. 1979) to a binary scale, recoding classes 3–5 as sound and 6 and 7 as rotten, respectively. These sound vs rotten snag classifications correspond with sound vs coarse woody debris (Moussaoui et al. 2016). For each unit and year (3–20), we calculated the mean proportion of rotten snags. We also considered estimating snag fall but found these events were inconsistently recorded.

## Statistical procedures and model selection

We used graphically examined trends in QMD and trees per hectare relative to stocking guidelines for ponderosa pine (Long and Shaw 2005). All the response variables were summarized to the unit (stand) level for analysis. We used generalized linear mixed modeling to formally analyze the SDI, Gini, $SD_{BA}$, growth dominance, and %Pine response variables. Generalized linear mixed modeling was also used to analyze the recruitment of large trees and snags, large-tree mortality, and snag condition.

We constructed a set of five basic hypothesis models for each response. All the models included the random effect of unit to accommodate the repeated-measures structure of the data. Under our null hypothesis model (Table 2), responses varied with the intercept and the unit random effect. Our first alternative hypothesis was that responses varied with the main effect of year. We coded year as a factor given the unequal interval and limited number of measurement periods. In our second alternative hypothesis, responses varied with treatment. Under our third hypothesis, responses varied with the main effects of year and treatment. Our fourth and final alternative hypothesis included the year and treatment main effects, as well as the year × treatment interaction.

We evaluated relative support for each hypothesis model using the information-theoretic approach (Burnham and Anderson 2002) based on corrected Akaike's information criterion (AICc; Sugiura 1978). We considered models with ΔAICc values within 6 units' distance of the best-approximating model that did not contain better-supported nested models (Richards 2008) to be plausible. We dropped models that were within two ΔAICc of simpler nested alternatives (Burnham and Anderson 2002). We performed AICc model comparisons using the MuMIn package (Bartoń, 2017). We relied on AICc for model selection and inference and present pseudo-$R^2$ statistics for descriptive purposes only.

All the analyses were conducted in R (R Core Team 2018). We used the emmeans package (Lenth et al. 2020) to summarize main effects and interpret interactions when present. The SDI, Gini, $SD_{BA}$, and growth dominance responses were analyzed with a Gaussian error distribution. We analyzed the proportional %Pine and large-tree recruitment responses with a logit link to the beta distribution. Large-tree mortality, snag recruitment, and snag condition data were right-skewed but also had zero values, which we accommodated by using a log link to the Tweedie distribution (Foster and Bravington 2013). We graphically examined models for normality and homogeneity of model residuals (Zuur et al. 2010), using simulated residual plots for responses with non-Gaussian error distributions (Hartig 2018).

# Results

## Stand structure

The SDI varied by the main effects of treatment and year in the best-supported model (Table 3, Fig. 2A). Three years posttreatment, the SDI was highest in the Control (mean ± SEM; 1077.4 ± 103.5), corresponding with a relative density index of 99.4% of the maximum SDI for ponderosa pine (Long and Shaw 2005). The 3-year mean SDI was similar in the big tree (384.2 ± 18.3), pine emphasis (392.6 ± 46.4), and pine emphasis with fire (362.4 ± 46.4) treatments, corresponding to relative density indices of 35.4%, 36.2%, and 33.4%, respectively. By 20 years posttreatment, the SDI had risen to 1164.0 ± 58.7, or 107.4% relative density index in the control. The 20-year SDI was 558.4 ± 40.8 in the Big Tree and 564.2 ± 33.3 in the Pine Emphasis treatments, corresponding to relative density indices of 51.5% and 51.9%, respectively. The Pine Emphasis with Fire treatment saw the smallest gains, with a 20-year SDI of 417.1 ± 50.5 and a relative density index of 38.5%. We did not find support for any alternative SDI model.

Plotting treatments over time in size–density space revealed more nuanced patterns (Fig. 3). QMD and trees per hectare in the control fluctuated little over time, with QMD slightly increasing and trees per hectare slightly declining while consistently approaching the maximum stocking frontier for ponderosa pine. Stocking in the Big Tree and Pine Emphasis treatments increased to overlap the threshold of substantial density-dependent mortality by year 20, while stocking in the pine emphasis with fire

**Table 2.** List of hypothesis models by research question and response[a].

| Question | Responses | Hyp. | Terms | Random effect |
|---|---|---|---|---|
| **1** | SDI, Gini, SDBA, %Pine, growth dominance | 0 | 1 (intercept-only) | Unit |
| **1** | SDI, Gini, SDBA, %Pine, growth dominance | 1 | Year | Unit |
| **1** | SDI, Gini, SDBA, %Pine, growth dominance | 2 | Treatment | Unit |
| **1** | SDI, Gini, SDBA, % Pine, Growth dominance | 3 | Treatment + year | Unit |
| **1** | SDI, Gini, SDBA, % Pine, growth dominance | 4 | Treatment + year + treatment × year | Unit |
| **2** | Tree/Snag recruitment/loss | 0 | 1 (intercept-only) | Unit |
| **2** | Tree/Snag recruitment/loss | 1 | Year | Unit |
| **2** | Tree/Snag recruitment/loss | 2 | Treatment | Unit |
| **2** | Tree/Snag recruitment/loss | 3 | Treatment + year | Unit |
| **2** | Tree/Snag recruitment/loss | 4 | Treatment + year + treatment × year | Unit |

[a]Hyp, hypothesis; Gini, Gini coefficient; SDBA, standard deviation of plot-level basal area; SDI, stand density index; %Pine, relative basal area composed of ponderosa pine.

**Table 3.** Summary of supported model comparison results for stand structure, complexity, and composition.

| Response | Hyp. | Fixed effects | LogLik | ΔAICc | Pseudo-$R^2$ |
|---|---|---|---|---|---|
| **SDI** | 3 | Year + treatment | −436.5 | 0 | 0.9 |
| **SDI** | 0 | Intercept-only | −491.9 | 96.6 | 0 |
| **Gini** | 4 | Year + treatment + Year × treatment | −132.5 | 0 | 0.6 |
| **Gini** | 3 | Intercept-only | −96.1 | 36.4 | 0 |
| **$SD_{BA}$** | 2 | Year + treatment | −151.1 | 0 | 0.6 |
| **$SD_{BA}$** | 0 | Intercept-only | −147.9 | 16.2 | 0 |
| **%Pine** | 4 | Year + treatment + year × treatment | 147.3 | 0 | 0.4 |
| **%Pine** | 0 | Intercept-only | 116.4 | 20.8 | 0 |
| **Growth dominance** | 0 | Intercept-only | −34.6 | 0 | 0 |

Note: Please see Table 1 for abbreviations and Table 2 for list of hypothesis models. Intercept-only null model statistics are presented to demonstrate fit relative to plausible alternative hypothesis models, even when lacking sufficient evidence to be included in the model set.

treatment remained below this threshold. In years 3 and 6, the Big Tree, Pine Emphasis, and Pine Emphasis with Fire treatments were characterized by similar QMD and trees per hectare, with values of ∼40 cm QMD and 125 trees per hectare. Between years 6 and 14, QMD declined as trees per hectare dramatically increased in the Big Tree and Pine Emphasis treatments. By comparison, QMD only weakly declined in the Pine Emphasis with Fire treatment, while trees per hectare only mildly increased.

The best-supported model of the Gini, our indicator of structural complexity, included the main effects of treatment and year, and the treatment × year interaction, with higher numbers indicating greater complexity (Table 3, Fig. 2B). The Gini of the control (0.35 ± 0.01) was distinctly higher than that of the Big Tree treatment (0.26 ± 0.01) in year 3, with little change by year 20 (0.36 ± 0.01 and 0.26 ± 0.01, respectively; Fig. 2B). The Gini of the Pine Emphasis treatment (0.29 ± 0.01) was lower than that of the Control in year 3 but overlapped with the Control by year 20 (0.34 ± 0.2). The Gini of the Pine Emphasis with Fire treatment (0.28 ± 0.01) was also lower than that of the Control in year 3, recovering more slowly than the Pine Emphasis treatment to overlap with the Control by year 20 (0.33 ± 0.04).

The most plausible model of $SD_{BA}$ featured the main effects of treatment (Table 3, Fig. 2C). The mean $SD_{BA}$ of the Control (14.2 ± 0.5) was higher (greater horizontal structural complexity) than that of any of the treatment types (Fig. 2C). The Big Tree treatment (7.3 ± 0.4) had the lowest horizontal structural complexity of any group. The $SD_{BA}$ of the Pine Emphasis treatment (13.0 ± 0.4) was nearly comparable to that of the control and the highest of any treatment. The Pine Emphasis with Fire treatment (10.5 ± 0.5) was intermediate between the Control and the Big Tree treatment. We did not find substantial support for any other $SD_{BA}$ model.

As a measure of stand composition, %Pine varied with the main effects of treatment and year as well as the treatment × year interaction (Table 3, Fig. 2D). Under the treatment × year interaction, %Pine in year 3 was lowest in the Control (41.8 ± 5.2%) and declined by year 20 (37.8 ± 4.8%; Fig. 2D). In year 3, %Pine was second lowest in the Big Tree treatment (52.2 ± 7.6%), remaining equivalent to the Control by year 20 (53.4 ± 7.2%). The Pine Emphasis treatment increased in %Pine between years 3 (58.9 ± 8.3%) and 20 (66.1 ± 6.2%), shifting toward distinctly greater pine dominance than the Control. The Pine Emphasis with Fire treatment had the highest initial %Pine of any treatment and was already distinct from the control by year 3 (65.4 ± 9.1%), a separation that grew by year 20 (70.3 ± 7.8%).

We found that mean growth dominance did not vary by either treatment or year and the intercept-only null model had the strongest support (Table 3). Mean growth dominance values were positive (0.30 ± 0.02), indicating that stand growth was disproportionately concentrated on large trees irrespective of treatment or time (data not shown).

## Large-tree and snag dynamics

The recruitment rate of large, ecologically valuable trees (DBH ≥ 61.0 cm) did not vary with treatment or time, with the intercept-only null model having the strongest support (Table 4). The mean rate of large-tree recruitment across all units and periods was 4.4 ± 0.3%.

Large-tree mortality rates did not vary with the effect of treatment or year. The study-wise average large tree mortality rate was 0.5 ± 0.2%. No other model was plausible.

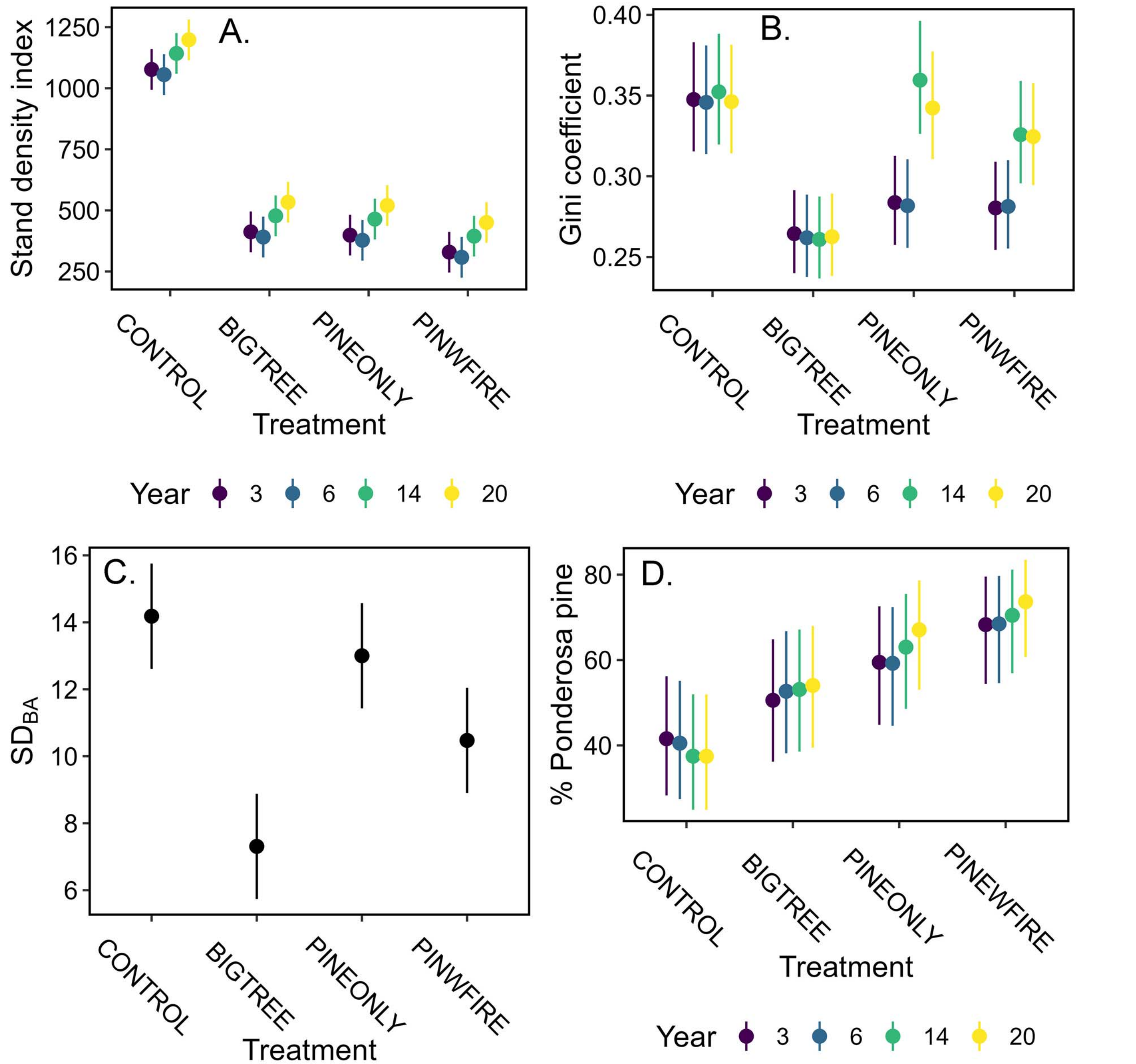


**Figure 2.** Dot plots (estimated marginal mean ± 95% confidence interval) of stand structure metrics across treatments and years since treatment based on the live trees and saplings. Displayed effects are based upon the best-supported models for each response. (A) Stand density index, with a dashed line referencing Long and Shaw's (2005) maximum of 1084 trees per hectare for ponderosa pine; (B) Gini coefficient of basal area; (C) standard deviation of within-stand basal area; and (D) percentage ponderosa pine relative basal area.

**Table 4.** Summary of supported model comparison results for large-tree and snag dynamics.

| Response | Hyp. | Fixed effects | Random effect | LogLik | ΔAICc | Pseudo-$R^2$ |
|---|---|---|---|---|---|---|
| **Large-tree recruitment** | 0 | Intercept-only | Unit | 145.2 | 0 | 0 |
| **Snag recruitment** | 1 | Year | Unit | 208 | 0 | 0.17 |
| **Snag recruitment** | 0 | Intercept-only | Unit | 202.3 | 9 | 0 |
| **Large-tree mortality** | 0 | Intercept-only | Unit | 104.9 | 0 | 0 |
| **Snag condition** | 0 | Intercept-only | Unit | 26.6 | 0 | 0 |

Note: Please see Table 1 for abbreviations and Table 2 for list of hypothesis models. Intercept-only null model statistics are presented to demonstrate fit relative to plausible alternative hypothesis models, even when lacking sufficient evidence to be included in the model set.

The recruitment rates of large snags (DBH ≥ 34 cm) varied with the main effect of year (Table 4, Fig. 4A). Large snags were not present in all units until after year 6. Snag recruitment rates were 6.6 ± 1.1% by year 14 and increased to 14.5 ± 2.7% by year 20. No other model was plausible for this response.

The large-snag condition varied by the main effect of year (Table 4, Fig. 4B). By year 3, 43.7 ± 8.2% of snags were rotten vs sound. The percentage of rotten snags declined to 14.8 ± 4.5% and 13.3 ± 2.9% in years 6 and 14, respectively. By year 20, the percentage of rotten snags had risen to 39.1 ± 4.6%. No other snag condition model was plausible.

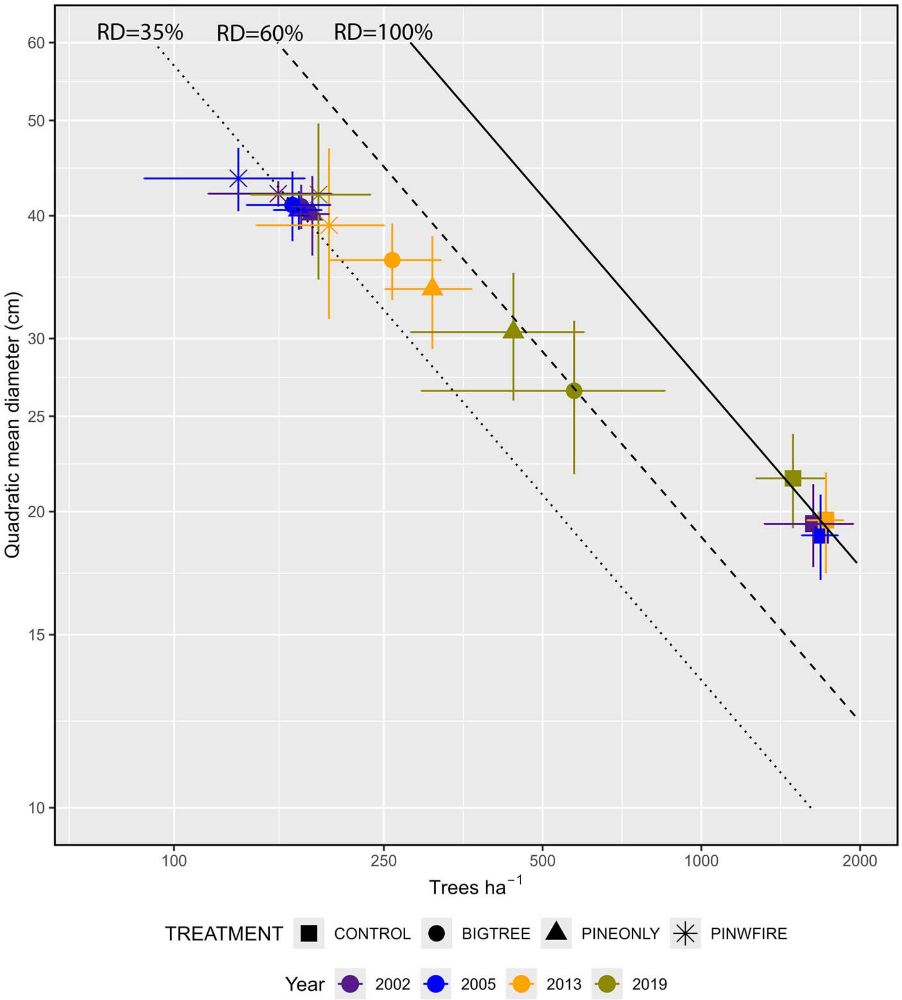


**Figure 3.** Density management diagram style plot of four Goosenest AMA treatments over time in log-transformed quadratic mean diameter vs trees per hectare space (unadjusted mean ± 95% confidence interval). RDI = relative density index or observed stand density index relative to Long and Shaw's (2005) maximum of 1084 for ponderosa pine.

# Discussion

## Stand structure

All three Goosenest AMA treatments were initially successful in reducing stand density relative to the Control. Three years postthinning, the three treatments showed roughly equivalent reductions in SDI, with relative SDIs of 33%–35% of maximum stocking (relative density index) for ponderosa pine (Long and Shaw 2005). While these values achieve full site occupancy while maintaining the potential for rapid stand growth and carbon sequestration, they are higher than historical reconstructions of pine-dominated mixed-conifer forest in the Sierra Nevada, where the relative density index averaged 23% (North et al. 2022). By 20 years posttreatment, only the Pine Emphasis with Fire treatment remained near the lower end of the density management zone for ponderosa pine, with a relative density index of 38.5%. With relative density indices of 51.5% and 51.9%, respectively, the Big Tree and Pine Emphasis treatments were approaching the threshold of accelerated self-thinning, while the Control exceeded the typical maximum for ponderosa pine at a relative density index of 107.4%.

The QMD and trees per hectare results revealed nuances in the stocking patterns that emerged later in the study period. The Big Tree and Pine Emphasis treatments declined in QMD despite overall increases in SDI, whereas the QMD remained fairly stable in the Pine Emphasis with Fire treatment. Our incorporation of the sapling layer into stand structure calculations made it possible to detect these trends, which were not apparent in the analysis of 14-year results where only trees with DBH ≥ 9.1 cm were included (Ritchie 2020). The Pine Emphasis with Fire treatment had a lower mean white fir sapling density (27.3 ± 24.2 stems per hectare; data not shown) compared to either the Big Tree (409.1 ± 120.0 stems per hectare) or Pine Emphasis (221.8 ± 86.7 stems per hectare) treatments by year 20. Tree regeneration and ingrowth can pose a major constraint on fuel treatment durability by contributing to overstory crown scorch and ladder fuels (Tinkham et al. 2016). When the 2021 Antelope Fire burned over the Goosenest AMA, the Pine Emphasis with Fire treatment was the most successful at both moderating fire behavior and mitigating tree mortality (Brodie et al. 2024). In addition to fuel reduction objectives, the recovery of the SDI over time impacted bark beetle resistance, with Pine Emphasis with Fire the only treatment to demonstrate durability against mountain pine beetle (*Dendroctonus brevicomis*) attack over the duration of the study (Fettig 2016). The relative success of the Pine Emphasis with Fire treatment at maintaining the initial SDI, QMD, and trees per hectare is in agreement with previous study findings that mechanical treatments generally

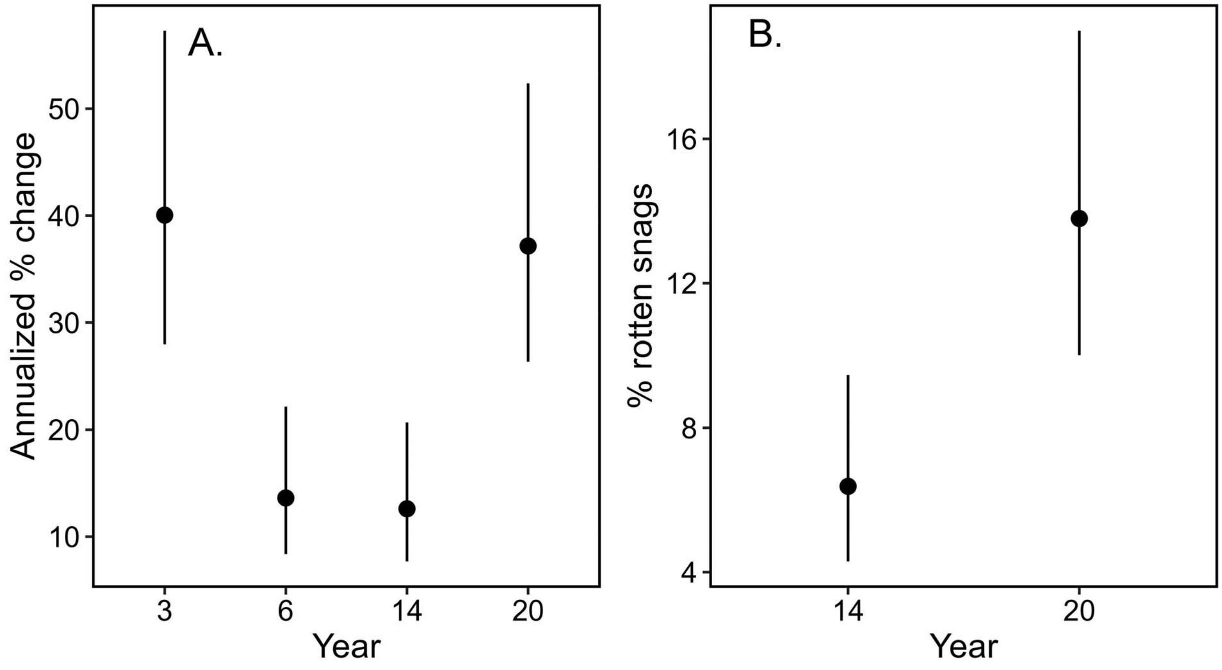


**Figure 4.** Dot plots (estimated marginal mean ± 95% confidence interval) of large-snag dynamics across years since treatment. (A) Snag recruitment. (B) Snag condition. Displayed effects are based upon the best-supported model for each response.

decline in durability after 10 years unless combined with prescribed fire (Davis et al. 2024).

Treatments contrasted in terms of vertical structural complexity, or the vertical arrangement of stand biomass as reflected in the Gini coefficient of tree basal area. Vertical structural complexity was lowest in the Big Tree treatment relative to both the Control and Pine Emphasis and Pine Emphasis with Fire treatments for the duration of this study. In contrast, the Pine Emphasis and Pine Emphasis with Fire treatments recovered vertical structural complexity comparable to the Control by 14 years posttreatment. Positive trends in vertical complexity in the Pine Emphasis and Pine Emphasis with Fire treatments appear to correspond with the ingrowth of planted ponderosa pine within the group selection units by 2014 (Ritchie 2020). Higher vertical structural complexity could translate into greater ladder fuels, but in practice group selection appears to be an effective regeneration method for California mixed conifer that accommodates prescribed fire (York et al. 2021).

Horizontal structural complexity, or the patchiness of biomass across the stand, is an important feature of ponderosa pine and dry mixed-conifer forests under intact fire regimes (Stephens and Gill 2005). This variation in stand structure historically mitigated crown fire risk while also providing habitat for key wildlife species such as the Northern Goshawk (Long and Smith 2000). We found that the Control supported the highest absolute $SD_{BA}$, likely reflecting the denser patches of fir that were either thinned from below to an even spacing in the Big Tree treatment or targeted for removal through group selection in the Pine Emphasis treatments. Spatial analyses of southwestern mixed-conifer reference sites found that white fir tends to form clumps and aggregate near large ponderosa pines, reflecting a combination of microsite preferences, fir fire refugia, and shade tolerance (Rodman et al. 2016). Another possible driver of spatial heterogeneity in the Control is more recent sanitation and salvage harvesting in several units (Ritchie 2005). The Big Tree treatment displayed the strongest decline in $SD_{BA}$ relative to the Control, while the Pine Emphasis treatment was comparable to the Control in all years. The Pine Emphasis with Fire treatment had lower structural complexity compared to the Control until 20 years posttreatment. Repeated low-severity prescribed fires can promote structural uniformity (York et al. 2021), which at the Goosenest AMA could largely reflect the susceptibility of white fir to secondary postfire mortality (Fettig et al. 2010). Traditional group selection may also take several cutting cycles to foster detectable changes in structural complexity (O'Hara 2014). As an alternative to group selection, single-tree selection with the residual basal area-maximum diameter-diminution quotient (BDq) method could approximate presettlement forest structures in pure ponderosa pine, particularly addressing the deficit of small, vigorous trees needed to maintain large-tree populations over time (Bailey and Covington 2002). However, single-tree selection has proved problematic in California mixed conifer where it typically promotes shade-intolerant species (York 2015). Future applications of group selection in dry mixed-conifer forests might instead consider incorporating variable-density thinning into the matrix to diversify stands more rapidly (Kern et al. 2017).

In addition to their structural objectives, the Goosenest AMA Pine Emphasis prescriptions sought to restore ponderosa pine to at least 80% of the relative basal area. We found that while generally falling short of this target, the Pine Emphasis with Fire treatment successfully shifted composition toward ponderosa pine by 3 years posttreatment. However, it is worth noting that despite randomization, our study's lack of research-grade pretreatment data prevented us from conclusively disentangling initial compositional differences from compositional effects. The Pine Emphasis treatment also restored the ponderosa pine composition, albeit more gradually. Again, because we incorporated saplings into our composition estimates, contrasts with the fir-dominated control were starker and detectable at an earlier age than in the 14-year Goosenest AMA study results (Ritchie 2020). The effectiveness of the Pine Emphasis treatments at promoting ponderosa pine is a positive outcome from the perspectives of restoring historical forest composition (Bekker and Taylor 2010), improving drought tolerance, and facilitating the reintroduction of fire (Levine et al. 2020). While artificially regenerated groups deviated from the traditional concept of the group selection system as a natural regeneration method (Matthews 1989), the Goosenest AMA provides a proof of concept for contemporary studies that combine artificial regeneration with uneven-aged management to foster climate change adaptation (e.g. Muller et al. 2019).

Growth dominance differed from the other structural complexity metrics in that it considered how growth, rather than static tree size, was distributed throughout each stand (Binkley et al. 2006). Previous studies of ponderosa pine have found that both plantation (McGown et al. 2015) and old-growth stands (Binkley et al. 2006) exhibit reverse growth dominance, with stand growth disproportionately concentrated on small trees. In contrast, we found that these stands, which were dominated by a cohort dating to the early 1900s, had stand growth disproportionately concentrated on large trees. Positive growth dominance is consistent with expectations for stands in the self-thinning phase of stand development (Binkley et al. 2006). Accordingly, the consistency of positive growth dominance may signal that all the treatments were still overly dense and near the threshold of self-thinning. In terms of consequences for forest structure, positive growth dominance is expected to promote more homogeneous stand structures as more vigorous larger trees increase self-thinning in smaller trees (Pretzsch and Biber 2010). The stability of positive growth dominance among treatments may help account for our findings that large-tree recruitment did not vary with treatment, as treatments did not improve the already high growth efficiency of larger trees.

## Large trees and snag dynamics

The Goosenest AMA prescriptions sought to accelerate the recruitment of large, ecologically valuable trees, defined as ≥61.0 cm DBH. In agreement with the 14-year results (Ritchie 2020), we did not detect differences in terms of large-tree recruitment or mortality rates among treatments 20 years posttreatment. Early studies of ponderosa pine responses to restoration treatments suggest that both young and old trees responded positively to release (Fajardo et al. 2007). Over the longer term (>10 years posttreatment), several studies report sustained higher growth rates in older ponderosa pine (Crotteau and Keyes 2020, Fulé et al. 2022), while at the Goosenest AMA and nearby Blacks Mountain Experimental Forest, growth release was most evident in smaller trees (Crotteau and Ritchie 2014, Ritchie 2020). One likely factor behind the slow emergence of differences in large-tree recruitment was the initial rarity of large trees across the study, with the 61 cm cutoff representing the 96th percentile of DBH in the Control at 2 years posttreatment. The initial residual stand density of Goosenest AMA treatments was relatively high at 31%–34% of the maximum for ponderosa pine (Long and Shaw 2005), whereas lower residual densities may achieve longer gains in large-tree growth (Crotteau and Keyes 2020). Prescribed burns were also conducted under mild fall conditions, which may have minimized crown and root damage as well as their impacts on large-tree growth and mortality (Fajardo et al. 2007).

The large-snag recruitment and condition did not vary with treatment, and large snags were too rare before 14 years posttreatment to permit formal analysis of recruitment in earlier periods. The divergent mortality responses of the two main species in this study could account for the lack of a treatment effect on snag recruitment. White fir mortality was elevated in the Pine Emphasis with Fire treatment, while ponderosa pine mortality was elevated in the Control relative to the three treatments (Fettig et al. 2010, Looney et al. 2024). In contrast to the elevated mortality that Kolb et al. (2007) observed in old-growth ponderosa pine following prescribed fire, the largely 20th century cohort of large pines in this study experienced low postfire mortality (Ritchie and Harcksen 2005). A synthesis of Fire and Fire Surrogates study results, which included the Goosenest AMA following the installation of an auxiliary burn-only treatment (Ritchie 2005), found that posttreatment increases in snag density were most pronounced when burning was conducted without preliminary mechanical treatments, while the positive effect of combined mechanical and burning treatments on snag populations was generally weaker and more variable (Schwilk et al. 2009). Instead, our finding that snag recruitment rates and decay condition varied over time may signal climate-driven snag recruitment, which in Eastern California forests corresponds with drought events (Landram et al. 2002). Ponderosa pine snags decay more rapidly than white fir, but after 10 years snags of both species typically transitioned from sound to rotten (Landram et al. 2002). If higher large-snag recruitment rates are desired, future prescriptions could be modified for deliberate deadwood creation or to retain more large trees at risk of mortality (Palik et al. 2020).

A limitation of our study was a lack of research-grade pretreatment data precluding a before/after, control/intervention analysis design. While we considered integrating pretreatment variable-radius cruise data (Ritchie and Looney 2024), we found stand density estimates with these data were universally lower than expected for all treatments and likely reflected fundamental differences in inventory design. This limitation reduced our ability to disentangle potential pre-existing site variation from treatment effects, and we instead relied entirely upon randomization. For comparatively subtle responses such as large-tree and snag dynamics, shorter time series and analytical limitations could have potentially made the difference between detecting treatment effects and our findings of treatment nonresponses. Given the large investments that operational-scale silviculture studies represent, our experience highlights the value of allocating sufficient resources to pretreatment monitoring.

# Conclusion

The Goosenest AMA study provided a uniquely extensive, long-term opportunity for comparing silvicultural approaches for simultaneously reducing disturbance risk and promoting mature/old-growth forest characteristics in ponderosa pine/mixed-conifer forests. While traditional fuel-reduction treatments combined with uneven-aged management to favor ponderosa pine appeared effective at meeting these goals in the short term, their durability declined over time. In contrast, the addition of regular posttreatment prescribed burning extended treatment durability through the end of the study period. Our results suggest that combining fuel-reduction treatments with uneven-aged management and posttreatment prescribed burns is the most effective and durable of the silvicultural approaches tested for reducing vulnerability to fire and other disturbances while accelerating restoration of mature/old-growth structural characteristics in Western US ponderosa pine/mixed-conifer forests.

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## Author contributions

Christopher Looney (Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing—original draft, Writing—review & editing) and Martin W. Ritchie (Data curation, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing—review & editing)

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## Data availability

The data used in this manuscript are currently in use by the authors. The corresponding author will furnish raw data and the R script used to generate derived data upon request.

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