Comparison of thinning and prescribed fire restoration treatments to Sierran mixed-conifer historic conditions

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Abstract: Thinning and prescribed fire are widely used to restore fire-suppressed forests, yet there are few studies of their effectiveness in Sierran mixed-conifer forest. We compared stand conditions in replicated plots before and after a combination of thinning and burning treatments against a reconstruction of the same forest in 1865. The historical forest had 67 stems/ha (trees ≥5 cm DBH), equal percentages of shade-tolerant and -intolerant tree species, stems randomly distributed at the stand scale, and a flat diameter distribution across size classes. The pretreatment forest averaged 469 stems/ha, which comprised 84% shade-tolerant and 14% shade-intolerant species, were highly clustered, and had a reverse-J-shaped diameter distribution. Thinning treatments failed to approximate historical composition, spatial pattern, or diameter distribution. Treatments left too many small trees, removed too many intermediate-sized trees (50–75 cm DBH), and retained a reverse-J-shaped diameter distribution. Current old growth comprises fewer large trees than historical conditions, suggesting that treatments should retain more intermediate-sized trees to provide for future large-tree recruitment. Understory thinning with prescribed fire significantly reduced stem density and produced a spatial pattern closest to historical conditions. Mixed-conifer restoration needs thinning prescriptions that vary by species and flexible rather than rigid upper diameter limits to retain some trees in all size classes.

Résumé : L'éclaircie et le brûlage dirigé sont largement utilisés pour restaurer les forêts protégées contre les feux mais il y a peu d'études qui portent sur l'efficacité de ces pratiques dans la forêt mixte de conifères de la Sierra. Nous avons comparé les peuplements dans des places-échantillons répétées avant et après une combinaison de traitements d'éclaircie et de brûlage avec une reconstitution de la forêt de 1865. La forêt ancienne avait 67 tiges/ha (arbres avec un DHP ≥5 cm), un pourcentage égal d'essences tolérantes et intolérantes à l'ombre, des tiges distribuées au hasard à l'échelle du peuplement et une distribution horizontale des diamètres parmi les classes de dimension. Avant le traitement, il y avait en moyenne 469 tiges/ha, 84 % tolérantes et 14 % intolérantes à l'ombre, fortement regroupées et une distribution des diamètres en forme de J inversé. Les traitements d'éclaircie n'ont pas réussi à rétablir la composition, la distribution spatiale ou la distribution des diamètres de la forêt ancienne. Les traitements ont laissé trop de petites tiges, éliminé trop de tiges de dimension intermédiaire (50–70 cm au DHP) et maintenu une distribution des diamètres en forme de J inversé. La vieille forêt actuelle contient moins de gros arbres que dans le passé indiquant que les traitements devraient conserver plus d'arbres de dimension intermédiaire pour assurer le recrutement futur de gros arbres. L'éclaircie en sous-étage accompagnée du brûlage dirigé a significativement réduit la densité des tiges et produit une configuration spatiale qui se rapproche le plus de celle de la forêt ancienne. La restauration des forêts mixtes de conifères requiert des prescriptions d'éclaircie qui varient selon l'espèce et qui sont flexibles plutôt que des limites supérieures de diamètre rigides pour conserver des arbres dans toutes les classes de dimension.

[Traduit par la Rédaction]

Introduction

Sierran mixed-conifer forest, primary habitat for more vertebrate species than any other forest community in California (Mayer and Laudenslayer 1989), has been severely altered as a result of a century of fire suppression. Historically these forests had a mean fire-return interval of 12–17 years, but this has now shifted to more than 600 years by one estimate (McKelvey et al. 1996). Regional plans (USDA Forest Service 2004) and national policies include general restoration guidelines whose language is typified by the Healthy Forests Restoration Act: "In carrying out a covered project, the Secretary shall fully maintain, or contribute toward the restoration of the structure and composition of old growth stands according to the pre-fire suppression old growth conditions" (http://agriculture.senate.gov/forest/forhxadtsec.pdf). One measure of pre-fire-suppression conditions for many western forests is to reconstruct stand conditions from the mid to the late 19th century, when there was an active fire regime (Fulé et al. 1997; Taylor 2004, Landis and Bailey 2005). Whether current efforts to mimic pre-fire-suppression forest conditions in California's Sierra Nevada are

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successful, however, is difficult to assess because most information on 19th-century forest conditions is limited to narratives (LeConte [1875] 1930; Muir 1911), photographic comparisons (Gruell 2001), or early, limited forest surveys (Fitch 1900; Lieberg 1902; Moore 1913; Stephens and Elliott-Fisk 1998; Stephens 2000).

While many methods of restoring Sierran forest are possible, Stephenson (1999) suggested that they can generally be grouped into two approaches: *structural* restoration, which emphasizes first restoring historical stand structure and composition through mechanical thinning, and *functional* restoration, which prioritizes the ecological processes, such as fire, to be used for restoration. Some studies have suggested that Sierran forests cannot be restored without first thinning the forest to reintroduce a clustered age cohort structure (Bonnicksen and Stone 1981, 1982). Others have indicated that prescribed fire can accomplish most stand reconstruction without the need to first thin the forest (Harvey et al. 1980; Stephenson et al. 1991). When thinning is used, treatments have been controversial because prescriptions often propose thinning some intermediate (>50 cm diameter at breast height (DBH)) or large (>75 cm DBH) trees both to restore stand structure and to provide enough revenue for treatments. In spite of these controversies, there has been little research in the Sierra Nevada on the effects of burning and different thinning intensities on structure, composition, and spatial pattern of forests, and how these compare with historical conditions (Fig. 1).

In 1997, we established and mapped permanent plots to be treated with a combination of burning and thinning in 2000 and 2001. We were interested in examining how widely used restoration treatments affect forest structure, composition, and spatial pattern, and how treatments compared with a reconstruction of forest conditions under an active fire regime. Specifically, our objective was to answer three questions. (*i*) How do current forest conditions — stand structure, species composition, and spatial pattern — differ from those in 1865 (the year of the last widespread fire at our study site)? (*ii*) How do fire and thinning treatments affect diameter distribution, species composition, and spatial structure of mixed-conifer forest? (*iii*) Which treatment is most effective at moving current stand conditions toward reconstructed forest conditions produced by an active fire regime? We examined forest conditions intensively at the Teakettle Experimental Forest, where we were able to apply a controlled field experiment to replicated plots of old-growth mixed-conifer forest, and sample ages and fire scars on stumps produced by the thinning treatments.

Methods

Study area

The study took place within the Teakettle Experimental Forest (hereinafter "Teakettle"), a 1300 ha reserve of old growth on the north fork of the Kings River within the Sierra National Forest (Fig. 2). The elevation ranges from 1900 to 2600 m and annual precipitation of approximately 125 cm falls almost entirely as snow between November and April (North et al. 2002). Teakettle's most common soil is mapped as a well-drained, mixed, frigid Dystric Xeropsamment, formed from decomposed granite, typical of many southern Sierra forests (Anonymous 1993).

Within Teakettle, forest type varies by elevation, grading from mixed conifer at lower elevations to California red fir (*Abies magnifica* A. Murr.) (hereinafter red fir) midslope and red fir and lodgepole pine (*Pinus contorta* Dougl. ex Loud.) at higher elevations. Approximately 65% of Teakettle's forest is mixed conifer, which characteristically contains white fir (*Abies concolor* (Gord. & Glend.) Lindl.), California red fir, California black oak (*Quercus kelloggii* Newberry), sugar pine (*Pinus lambertiana* Dougl.), incense cedar (*Calocedrus decurrens* (Torr.) Florin), and Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) (Rundel et al. 1988). At Teakettle, as in most of California's mixed-conifer forests, white fir dominates in terms of stem density and basal area; however, sugar pine and Jeffrey pine are the largest diameter and tallest trees (North et al. 2002). An analysis of fire scars on trees at Teakettle indicated that prior to European settlement, the fire-return interval for the 200-ha experimental area was 11–17 years, and the last widespread fire (>3 ha) occurred in 1865 (Fiegener 2002; North et al. 2005*a*).

Our research focused on a 200 ha contiguous mixed-conifer block with similar soils (all mapped as the Cagwin series; Anonymous 1993) derived from decomposed granite typical of the western slope of the Sierra Nevada. In this area, 18 permanent 4 ha plots were established (Fig. 2) using previous data (North et al. 2002). Plot size (4 ha) was established using variogram analysis to estimate an area large enough to include the range of variable conditions found in mixed-conifer forest. Stand structure and the understory community were sampled on 600 quadrats on a 50 m by 50 m systematic grid across the 200 ha block, and quadrats were grouped by means of cluster analysis. The 4 ha plots were located within the 200 ha block so that each plot included the same proportional representation of the four vegetation conditions (closed canopy, shrub, gap, and rock / shallow soil patches; North et al. 2002) identified in the cluster analysis of the quadrats. An analysis of forest structure and species composition showed no significant pretreatment differences between the 18 plots (North et al. 2002).

Treatments

The 18 plots were assigned to one of six treatments determined by the experimental design, a full factorial, crossing two levels of burn treatments (prescribed fire and no burn) and three levels of thinning treatments (none, understory, and overstory) (Fig. 2). For some plots, management and operational constraints (e.g., the presence of a sensitive species such as the pine marten, *Martes martes* (L., 1758)) limited the treatments that could be used, but after these constraints were applied, treatments were allocated as randomly as possible. The understory prescription followed guidelines in the California spotted owl (CASPO) report (Verner et al. 1992), which remove all trees between 25 and 76 cm (10 and 30 in.) DBH while retaining at least 40% canopy cover. Although designed initially for minimizing impact to spotted owl (*Strix occidentalis* (Xantus de Vesey, 1869) habitat, the CASPO guidelines became standard forest practice in the 1990s and are still widely used as a fuel-reduction treat-

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Fig. 1. Forest conditions in mixed-conifer forest in (A) 1900 (Tuolumne County), (B) Teakettle Experimental Forest before treatment (2000), (C) Teakettle Experimental Forest after an understory thin and burn treatment (2003).

ment (USDA Forest Service 2004). The overstory prescription removed all trees >25 cm DBH except 22 large-diameter trees/ha, which were left at regular spacing (approximately 20 m apart). The overstory thinning was widely practiced in Sierran forests before the CASPO report, and at Teakettle it led to a prescription of cutting dominant overstory trees up to 100 cm (40 in.) DBH. Increasing the diameter limit from 30 to 40 in. was widely debated in the late 1990s as a means of increasing sale revenues so that more stands could be treated for fuel reduction. The thinnings were applied in fall 2000 (thin and burn plots) and early spring 2001 (thin-only plots). Trees were limbed and topped where they fell and merchantable logs removed. The prescribed fire was applied by Sierra National Forest personnel following their standard operating procedures. Fuels from the thinning operations were left to dry for 1 year and the prescribed fires were lit in fall 2001, a week after the first substantial (2 cm) rainfall. All plots were burned within a 1-week period and the fire was extinguished by snow a week later.

Data collection and stand reconstruction

Using a surveyor's total station, all trees and snags (≥5 cm DBH, N = 35 418) in the eighteen 4 ha plots were measured, identified to species, mapped, and permanently tagged during the 1998–2000 field seasons before treatments were applied. Snags were assigned a decay class (Cline et al. 1980) and a visual estimate of height was recorded. Following treatments all plots were resampled and mapped during the 2002–2004 field seasons using the same protocols. All logs (≥30 cm diameter) were tagged and mapped (four corners) and a decay class was assigned (Maser and Trappe 1984). Only logs in decay classes I–IV were inventoried because field technicians could not reliably identify the dimensions of logs in decay class 5. Following treatments, logs were inventoried and mapped again, this time using diameter and azimuth, and identified to species.

To assess canopy cover, 402 hemispherical photographs were taken from regularly spaced sampling points in each plot before and after treatments, using a Nikon Cool Pix 950 digital camera and a Nikkor hemispherical FC-E8 0.21X fisheye converter (180° angle) lens. All photographs were taken in black and white at dawn or dusk under uniformly cloudless conditions, using a level tripod with the top of the photograph oriented to true north.

To reconstruct historical stand structure to 1865 condi-

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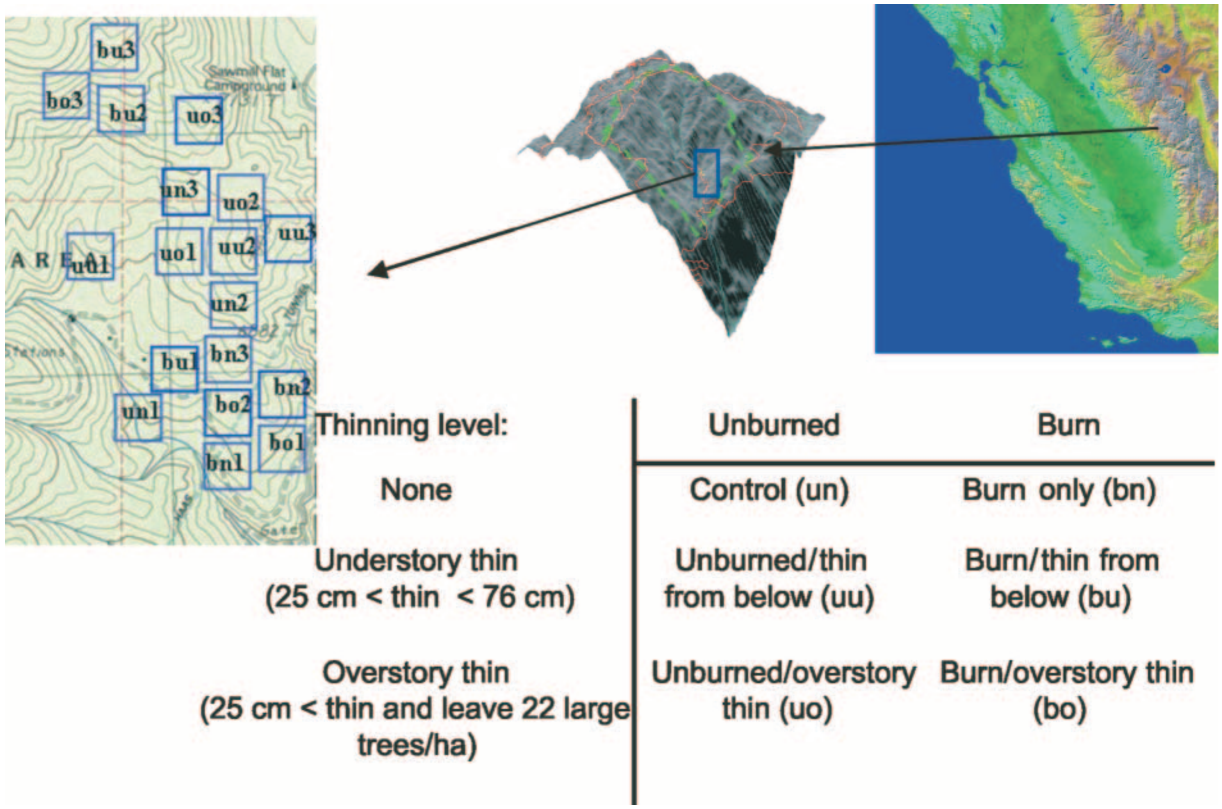
Fig. 2. Location and shape (30 m digital elevation model) of the Teakettle Experimental Forest. The diagram shows the treatments in the full-factorial design and the topographic map indicates the location of each 4 ha plot, treatment, and replicate number (1–3).



tions, we generally followed methods used in Southwest ponderosa pine forests (Fulé et al. 1997; Mast et al. 1999; Moore et al. 2004): the sizes, species composition, and locations of live trees during an active fire period are estimated from data on current live trees, snags, and logs. We modified these reconstruction methods because of the particular mix of shade-tolerant and -intolerant species in mixed-conifer forest, and added a measure of current growing space to refine species-specific past diameter estimates.

First we took 539 ground-level cross-section "cookies" from post-treatment stumps in direct proportion to the species composition (by frequency) of stems within the stand. This provided a much larger sample of the three shade-tolerant species, white fir, red fir, and incense cedar, which should exhibit greater variability in annual basal area increment (BAI) than the shade-intolerant pines (Oliver and Larson 1996). The 539 sample cookies were cut into cross sections and sanded with up to 400 grit sandpaper to improve visual identification of tree-ring boundaries. Tree rings were measured from the last year of growth to the pith using a microscope and a Velmex "TA" tree-ring system (Velmex Inc., Bloomfield, N.Y.). Measurement resolution was 0.001 mm. Series were manually cross-dated using standard procedures (Stokes and Smiley 1968), and the annual BAI for each tree was calculated for each year from 1865 to 2000. We subtracted the 1865–2000 radial increment to estimate the ground-level inside-bark diameter of each stem in 1865. Next we used species-specific equations to estimate the 1865 outside-bark DBH for each tree (Dolph 1981).

We calculated an approximation of local competition for each of the cookie-sampled trees using Thiessen polygons. The size and distribution of Theissen polygons have been used to evaluate the impact of density, growing space, and competition from neighboring plants on plant succession (Mithen et al. 1984; Kenkel et al. 1989). Using the stem map and ARC/INFO software, the area around each tree was bisected by a line equidistant between adjacent stems, and the lines were connected to form a polygon around each cookie-sampled tree. The polygon's area is an approximation of the potential growing space, in square metres, for an individual tree. Polygon size is a function of local stand density, with smaller areas indicative of dense, "dog hair" conditions. Each polygon was then weighted by dividing its area by the basal area of the sample tree to take into account the greater growing space demands (i.e., light, water, and nutrients) of larger trees. This approximation of growing space is estimated from current conditions and its utility is therefore based on the assumption that reductions in BAI due to increases in fire-suppressed stem density will be correlated with present stand conditions.

For each species we built regression models to predict 1865 DBH from 2000 DBH (recorded before the tree was cut) and weighted Theissen-polygon size. Using the best fit equations for each species, we then estimated 1865 diameters for all trees in the 18 plots, using the 72 ha pretreatment stem map and the weighted Theissen polygon calculated for each tree.

In addition to the live-tree estimate, reconstruction estimates were made using the stem map of snags and logs. In

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mixed-conifer forest, the year of death often cannot be determined using increment cores because many pieces have extensive heartwood and sapwood rot. To estimate when a snag died, we used the field rating of the decay class of each snag and applied published estimates for the transition time between decay classes for species in Sierran mixed-conifer forests (Raphael and Morrison 1987; Morrison and Raphael 1993) to estimate the decade in which a snag originated. Using the 539 cookies we calculated mean BAI for each of the five principal species in 25 cm diameter classes. We estimated each snag's live 1865 DBH using the following formula: 1865 DBH = 2000 DBH – [(midyear of death decade – 1865) × (BAI)] + estimated bark thickness (if missing in 2000).

To estimate what tree size a current log would have been in 1865, we used published estimates of log age for different decay classes (Kimmey 1955; Harmon et al. 1987) to estimate the decade in which a log originated. We then used time estimates for snag fall rates in unburned forest (Raphael and Morrison 1987) to estimate the decade of tree death and then applied the above equation to estimate 1865 DBH. This approach should be a conservative estimate of tree size because live trees may be wind-toppled and become logs directly, without going through a snag phase. Field observations, the rarity of tip-up mounds, and the lack of a consistent azimuth in log orientations (Innes et al. 2006), however, suggest that most trees at Teakettle go through a snag phase rather than becoming logs directly, owing to wind events.

While there are several limitations to these reconstruction methods, the most significant concerns our estimate of the density and locations of small trees. Our tally of logs and snags in 1998–2000 would fail to detect small-diameter trees that died after 1865 and completely decayed prior to our survey. Using estimates of log decay rates (Harmon et al.1987) and snag fall rates (Morrison and Raphael 1993) we can roughly estimate that small-diameter (≤25 cm) white fir, the species with the fastest decomposition, that died in 1940 or later would still have at least 20% of their bole mass in 2000 and be detected in our log survey (decay classes 1–4). We have no way of estimating how many small trees died before 1940 or how many are still alive. In an earlier demographic study at Teakettle, many small-diameter white fir from the 1880s were found to be still alive even in high-density thickets (North et al. 2005*a*). Our survey is much more likely to detect larger diameter trees and tree species that have slower decay rates. This bias means that our 1865 reconstruction underestimates small-tree density and small-scale clustering (because small stems are usually clumped). This bias is less likely to significantly affect our estimates of basal area, volume, density of large trees, or large-scale spatial patterns.

Analyses

To develop species-specific models for estimating 1865 diameter from 2000 DBH, we assessed whether BAI and weighted Thiessen polygon values were normally distributed using the Shapiro–Wilk test. Values for the three shade-tolerant species (white and red firs and incense cedar) and all weighted Thiessen polygons values were not normally distributed and therefore were log-transformed.

To evaluate predictive models using combinations of BAI, weighted Thiessen polygon size, and interaction terms, we used Akaike's Information Criteria (AIC) (Burnham and Anderson 2002). All terms were added to the model, and then terms were dropped if their C_p statistic (the likelihood version of AIC in S-Plus® statistical software; S-Plus 2001) was lower than the C_p statistic for the full model.

Current canopy cover was estimated using hemispherical photographs analyzed with Gap Light Analyzer 2.0 (Frazer et al. 2000). We compared measures of stand structure (basal area, density, quadratic mean diameter, volume, and species-composition percentages) between all treatments and the 1865 reconstruction using ANOVA and a Tukey's post-hoc test. All analyses were completed using S-Plus® (S-Plus 2001).

Tests of spatial distribution were carried out using spatial point pattern analysis software (Haase 1995) and univariate Ripley's *K* analyses. Ripley's *K* analysis compares distances between all location points in the same plane (Ripley 1979; Diggle 1983) using the reduced second moment measure, or *K* function, to examine spatial associations. We calculated 99% confidence intervals using 100 Monte Carlo simulations. We examined the distribution of all trees in the 18 plots in estimated 1865 conditions and before and after treatments.

Results

The most parsimonious models for estimating 1865 DBH for all species except Jeffrey pine included two terms: 2000 DBH and weighted Thiessen polygon size. Multiple adjusted R^2 values were 0.69 for white fir, 0.70 for red fir, 0.63 for incense cedar, and 0.73 for sugar pine. The best model for Jeffrey pine used only 2000 DBH and had an adjusted R^2 value of 0.83.

Pretreatment forest conditions significantly differed from the active fire forest reconstruction in stem density, quadratic mean diameter, and species composition (Table 1). Although stem density in the 1865 forest was much lower than in modern conditions (67 vs. 469 trees/ha), there was no significant difference in basal area (51.5 vs. 56.4 m^2/ha) or volume (393.2 vs. 434.6 m^3/ha) between the two conditions, because the fewer trees were larger (49.5 vs. 19.6 cm DBH). A significant shift in forest composition has occurred, with 84% and 14% shade-tolerant and -intolerant species under pretreatment conditions compared with 51% and 49%, respectively, in 1865. Most of this change was due to the significant increase in the percentage of white fir and decrease in the percentages of Jeffrey and sugar pines.

All the thinning treatments significantly reduced basal area below current and historical conditions; however, all except the overstory thin and burn (93.6 stems/ha) retained significantly more stems than were present in 1865 (Table 1). Canopy cover was reduced in direct proportion to thinning intensity, with no significant differences between burn and no-burn plots within the same thinning intensity. None of the treatments produced a quadratic mean diameter significantly different from the others (21.9–28.9 cm); however, all were significantly lower than the historical condition (49.5 cm). All treatments reduced stem volume, but only

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Table 1. Stand structure and composition at the Teakettle Experimental Forest in 1865 (reconstructed), before treatment, and after five treatments.

Stand attribute	1865	Pretreatment	Understory thin only	Overstory thin only	Burn only	Burn / understory thin	Burn / overstory thin
Basal area (m^2/ha)	51.5a	56.4a	41.2b	22.7c	53.7a	37.5b	17.2c
Total density (stems/ha)	67a	469b	239.5c	150.3d	353.8e	143.4d	93.6a
Cut (stems/ha)	na	0	170.8	192.3	0	162.8	198.9
Basal area. removed (m^2/ha)	na	0	20.2	33.9	0	21.3	37.0
Canopy cover (%)	Unknown	80.7a	72.8b	63.4c	80.5a	70.9b	60.2c
Quadratic mean DBH (cm)	49.5a	19.6b	23.4b	21.9b	22.0b	28.9b	24.2b
Volume (m^3/ha)	393.2a	434.6a	397.7a	200.5b	423.0a	372a	141.8c
Shade-tolerant species (%)							
Abies concolor	33.7a	67.6b	67.2b	66.3b	67.6b	64.1b	57.7b
Abies magnifica	2.9a	3.0a	4.7a	1.9a	2.5a	1.2a	1.0a
Calocedrus decurrens	14.5a	13.4a	11.8a	9.5a	15.8a	20.8b	22.4b
Shade-intolerant species (%)							
Pinus jeffreyi	22.1a	6.2b	3.9b	8.1b	3.6b	7.4b	7.6b
Pinus lambertiana	26.8a	7.9b	9.8b	12.1b	9.2b	5.1b	8.8b
Other species*	Unknown	1.9a	2.6a	2.1a	1.3a	1.4a	2.5a
Snags (stems/ha)	Unknown	39.0a	37.8a	32.3a	92.4b	120.3b	123.4b

Note: Species composition percentages were calculated using stem frequency. Numbers of other species and snags could not be estimated for the 1865 reconstruction. Canopy cover was calculated from 67 hemispherical photographs taken in each treatment. Values in the same row followed by a different letter are significantly different (Tukey's post-hoc ANOVA, $p < 0.05$). Species composition percentages for the 1865 reconstruction were calculated using all trees, but only those logs and snags that could be identified to species.

*The following hardwoods: California black oak (*Quercus kelloggii* Newberry), interior live oak (*Quercus wislizenii* A. De Candolle), canyon live oak (*Quercus chrysolepis* Liebm.), bitter cherry (*Prunus emarginata* (Dougl. ex Hook.) D. Dietr.), and willows (*Salix* spp.).

the two overstory thinning treatments (200.5 and 141.8 m^3/ha) significantly reduced volume below both historical (393.2 m^3/ha) and current conditions (434.6 m^3/ha).

Stand composition was only marginally affected by treatment, and still differed significantly from historical conditions. None of the treatments significantly reduced the percentage of white fir (57.7%–67.6%), which was almost double the historical value (33.7%). Both burning and thinning treatments (20.8% and 22.4%) significantly increased the percentage of incense cedar compared with the other treatments (9.5%–15.8%) and current (13.4%) and historical (14.5%) conditions. There was no significant difference in the percentages of either sugar or Jeffrey pine between treatments, but in all treatments percentages of pines were about one third of those in the historical condition. Burning increased small-stem mortality and produced significantly higher snag densities (92.4–123.4 stems/ha), but did not impact species composition, basal area, or canopy cover substantially.

The most significant difference in diameter distribution was between the historical condition and the current forest before and after treatments (Fig. 3). In 1865, the diameter distribution was almost flat, with nearly equal stem numbers in each 25 cm DBH class. In contrast, in all of the treatments, stem numbers in the small-diameter classes were very high and large trees were much fewer. All treatments did not significantly change the reverse-J-shaped distribution in the pretreatment forest. In all thinning treatments the number of 50–75 cm DBH stems (4.2–8.9 stems/ha) was reduced to below historical levels (11.2 stems/ha). In size classes greater than 75 cm DBH, overstory thinning significantly reduced the density of large trees below the historical level. Historically there were more trees in the large size classes (>100 cm DBH) than in current conditions or following any of the treatments, particularly for the largest size class (>150 cm DBH).

Tree spatial patterns changed significantly between 1865 and current conditions, with the most noticeable change being the sparse, low-density distribution in 1865 (Fig. 4A) compared with pretreatment conditions (Fig. 4B). The reconstruction shows that trees were slightly clustered up to 60 m (Fig. 4A) compared with the pretreatment stem distribution, where trees were highly clustered. At this scale, the clustering effect is strongly influenced by the high number of regenerating small trees in existing tree groups (North et al. 2004). Burn treatments (Figs. 4C, 4E, and 4G) killed more small trees, but there was only a small reduction in how highly trees were clustered at small to intermediate distances (0–60 m) over similar treatments without burning. Thinning-only treatments (Figs. 4D and 4F), which did not remove trees under 25 cm DBH, did little to reduce clustering over the 0–60 m scale.

At larger scales (>60 m) the reconstruction shows that the 1865 stem distribution was random (Fig. 4A). Only the burn and understory thin treatment (Fig. 4E) produced a similar distribution at this scale. Burning alone (Fig. 4C) slightly reduced the clustering at large scales below that in the pretreatment condition. Understory thinning (Fig. 4D) reduced clustering at intermediate scales (40–60 m) but did not restore a random distribution at larger scales. As expected, the overstory thin and burn treatment (Fig. 4G), which left 22 large trees/ha evenly spaced, significantly produced regularly distributed stands at large scales. This pattern, however, was not present in the overstory thin-only treatment (Fig. 4F) because many small trees (<25 cm DBH) were left, producing a clustered distribution at larger scales.

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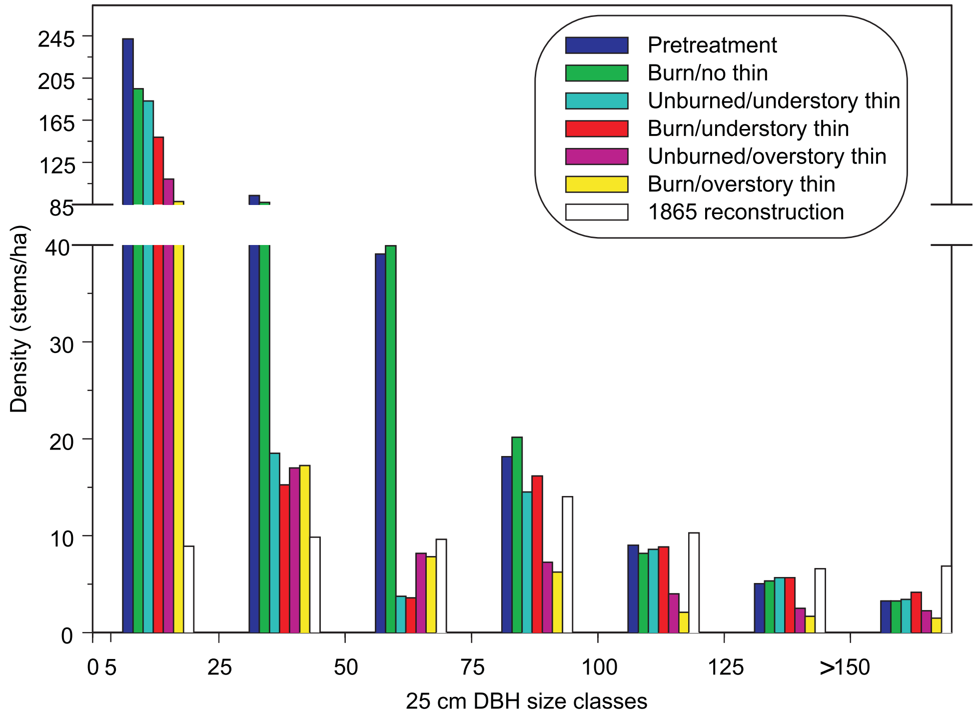
Fig. 3. Density of live trees in seven size classes in seven conditions in the Teakettle experiment. Note that the smallest size class is only a 20 cm range because only trees ≥5 cm DBH were tallied.



Discussion

We compared a 1865 reconstruction with current treated stands to assess whether treatments approximate forest conditions produced by an active fire regime. This comparison, however, is not an endorsement of regressing forests to their pre-European condition. Efforts to recapture a historical condition are probably misguided, as elimination of Native American ignitions (Anderson and Marrato 1996), changes in grazing intensity (Douglass and Bilbao 1975; Rowley 1985), and climate change (Millar and Woolfenden 1999; Pierce et al. 2004) have substantially changed factors that influence forest composition and structure. A goal of effective restoration is reestablishing conditions characteristic of the evolutionary environment of an ecosystem (Falk 1990; Society for Ecological Restoration 1993). Many studies have shown that frequent low-intensity fire has been a key process shaping Sierran mixed-conifer forest (Agee et al. 1978; Vankat and Major 1978; Kilgore and Taylor 1979; Parsons and DeBenedetti 1979). Our comparison with 1865 conditions is intended to provide a reference point for mixed conifer forest conditions produced by an active fire regime and not a strict prescription for contemporary restoration (Falk 1990; White and Walker 1997).

Our analysis supports the concept that stands with an active fire regime were of low density with a high proportion of large trees and a substantially higher proportion of shade-intolerant pine species. Lieberg (1902) describes central Sierra mixed-conifer forests in which densities were low and most stems were >62 cm (25 in.) DBH. Sudworth (1900; G.B. Sudworth, unpublished data),[3] using data from a limited number of mixed-conifer plots, shows a higher average density (92 stems/ha) than we found (Table 1), but a much higher number of very large trees. A large-scale (>2300 plots) 1930s survey of Sierran forests (Bouldin 1999) found much higher mixed-conifer stem densities (140–218 stems/ha) than we did, but this period was already several decades after Sierran fire regimes had changed. Estimates of species composition vary by location (McKelvey and Johnson 1992), with shade-intolerant pines making up 30%–50% of the stems (Sudworth 1900; Fitch 1900; Moore 1913; G.B. Sudworth, unpublished data[3]) in early surveys. However, these historical data sets should be treated with caution because little information is given on sampling protocols or how plots were located. Bouldin (1999), for example, has suggested that Sudworth's (1900; G.B.Sudworth, unpublished data[3]) data are significantly biased because plots were located in exemplary groves of large trees.

Our estimate of 1865 forest conditions should be viewed with caution because it is limited by problems common to reconstruction analyses and the constraints of our field sampling. White and Walker (1997) suggest that all reconstructions be explicit about their spatial and temporal limits and potential biases in their methods. Our analysis is focused on one old-growth area where we have the intensive data needed to reconstruct stand conditions on 72 ha back to the last fire. Reconstructing earlier conditions would be difficult because frequent fires would have consumed woody material. Our reconstruction methods are also limited by imperfect predictive models of past diameter, broad estimates of death date from decay class, and better records for species with slower decay rates, such as incense cedar. Our esti-

[3] G.B. Sudworth. Notes on regions in the Sierra Forest Reserve, 1898–1900.

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Fig. 4. Stem distribution and spatial analysis of all live trees (≥5 cm DBH) in a representative plot in each of the seven conditions: (A) 1865 reconstruction, (B) pretreatment, (C) burn only, (D) understory thin only, (E) burn and understory thin, (F) overstory thin, and (G) burn and overstory thin. Circle size on the stem map is proportional to diameter, and species' color codes are as follows: abco, white fir; abma, red fir; cade, incense cedar; pije, Jeffrey pine; pila, sugar pine; unk, unknown. The graph for each condition shows the spatial distribution calculated using univariate Ripley's *K* analysis. The solid line denotes the stem pattern and the two broken lines denote the 99% confidence intervals. The stem pattern is considered to be significantly aggregated for those distances (m along the *x*-axis) over which the solid line is above the upper broken line and regularly distributed for those distances over which the solid line is below the lower broken line. The stem map and Ripley's *K* analysis in Figs. 4A, 4B, and 4E are for the same 4 ha plot (bu1) in 1865, 2000, and 2003, respectively.

mates of density and spatial distribution are less accurate for small trees than for large trees because our 1998–2000 survey could miss small trees that died within a few decades of Teakettle's last fire, in 1865. Our estimates of 1865 stand conditions, however, are similar to a reconstruction of 19th-century stands in the Lake Tahoe area, which showed comparable stem densities and stands dominated by large pines (Taylor 2004). We know of one contemporary mixed-conifer area, Aspen Valley in Yosemite National Park, with a fairly active fire regime (three understory burns in the last 40 years) that has never been mechanically thinned. Aspen Valley has a higher density of trees than Teakettle's reconstruction (102 vs. 69 stems/ha), and a higher percentage of pines (64%), but a similar low density of small trees and a nearly flat diameter-distribution curve (Monica Buehler, Yosemite National Park Fire Ecologist, unpublished data). We believe that Teakettle's 1865 forest conditions are within the range of historical forest surveys and other reconstructions. Our focus in this research was to compare stand conditions produced by different restoration treatments with those produced by an active fire regime in the same old-growth mixed-conifer forest.

Our reconstruction suggests that effective treatments should drastically reduce densities of small trees (<50 cm DBH), retain some intermediate-sized and all large trees, significantly decrease the percentage of white fir, and reduce stem clustering. None of the treatments in our experiment achieved all of these objectives, but the understory thinning and prescribed burn treatment was more effective than the other treatments.

In all treatments, there were about 10 times more 5–25 cm DBH trees than our rough estimate of this size class in 1865. Our methods underestimated small-tree density, but even with a tripling of our estimate, treatments would still have left more than 3 times too many small trees. Mechanical-thinning prescriptions did not require cutting any tree <25 cm DBH (10 in.), based on the assumption that logging damage and prescribed fire would substantially thin this size class (Mark Smith, Sierra National Forest, personal communication). Logging damage and prescribed fire did reduce the number of stems by 15%–65% in the 5–25 cm size class, but even the most intense treatment, overstory thinning and prescribed fire, still averaged 87 small stems/ha compared with roughly 9 stems/ha in 1865. These small trees are usually unmerchantable, so their reduction in restoration treatments often depends on whether funds are available for a prescribed burn or for their removal with a supplemental service contract. Repeated prescribed burns would also help reduce this size class toward historical conditions.

All thinning and thinning/burning treatments reduced trees to near historical levels in the 25–50 cm size class, but removed too many trees in the 50–75 cm size class (Fig. 3). In the Sierra Nevada some of the controversy over restoration treatments has focused on the 50–75 cm size class because the trees have enough commercial value to help pay for thinning and prescribed fire treatments, but they also provide the next cohort of large, old trees. At Teakettle, the reconstruction suggests that there were approximately 11 trees/ha in this size class, while thinning treatments significantly reduced the density of trees in this size class (4–9 trees/ha) below historical levels (Fig. 3). Trees in this size class remain even in the understory prescription (removal of all trees between 25 and 75 cm DBH) because of errors in marking, the need for wildlife "leave trees", and hazardous trees that are left to fall.

Current Sierran thinning prescriptions (i.e., the understory treatment) leave all trees ≥76 cm (30 in.) DBH, which in our experiment left stem densities in the 75–99 cm size class that were comparable to 1865 conditions. Overstory thinning (removing trees up to 100 cm (40 in.) DBH) significantly reduced the density of large trees (≥76 cm DBH) below 1865 levels and drastically reduced stand basal area and volume, producing a stand structure that substantially departed from historical conditions. For trees ≥100 cm in diameter, 1865 density was higher than in any of the treatments or even current unharvested old-growth conditions. Smith et al. (2005) suggested that this reduction in large trees in current old growth may be due to recent mortality from pests and pathogens during extended droughts. Some studies (Ferrell et al. 1994; Ferrell 1996) suggest that modern increases in stem density increase moisture stress, such that during droughts tree vigor declines and mortality due to pests and pathogens increases. This implies that even in unmanaged old-growth stands, current large-tree density may be lower than under an active fire regime.

Restoration thinning prescriptions sometimes rely on principles of uneven-aged silviculture (Smith 1986), which suggest thinning to a negative exponential or reverse-J-shaped diameter distribution for diversifying structure. O'Hara (2001; O'Hara and Gersonde 2004), however, has pointed out that seral development and local disturbance patterns can produce a wide variety of diameter distributions in natural stands. Although the current diameter distributions at Teakettle and in other old-growth stands (Minnich et al. 1995; Ansley and Battles 1998) have a reverse-J shape, Bouldin (1999) found a wide variety of diameter distributions in stands in the 1930s. The 1865 reconstruction suggests that under an active fire regime, the diameter distribution at Teakettle may have been much flatter. Our reconstruction methods underestimate small-tree densities and lower the left side of the diameter distribution below what it likely was in 1865. We believe, however, that it is unlikely

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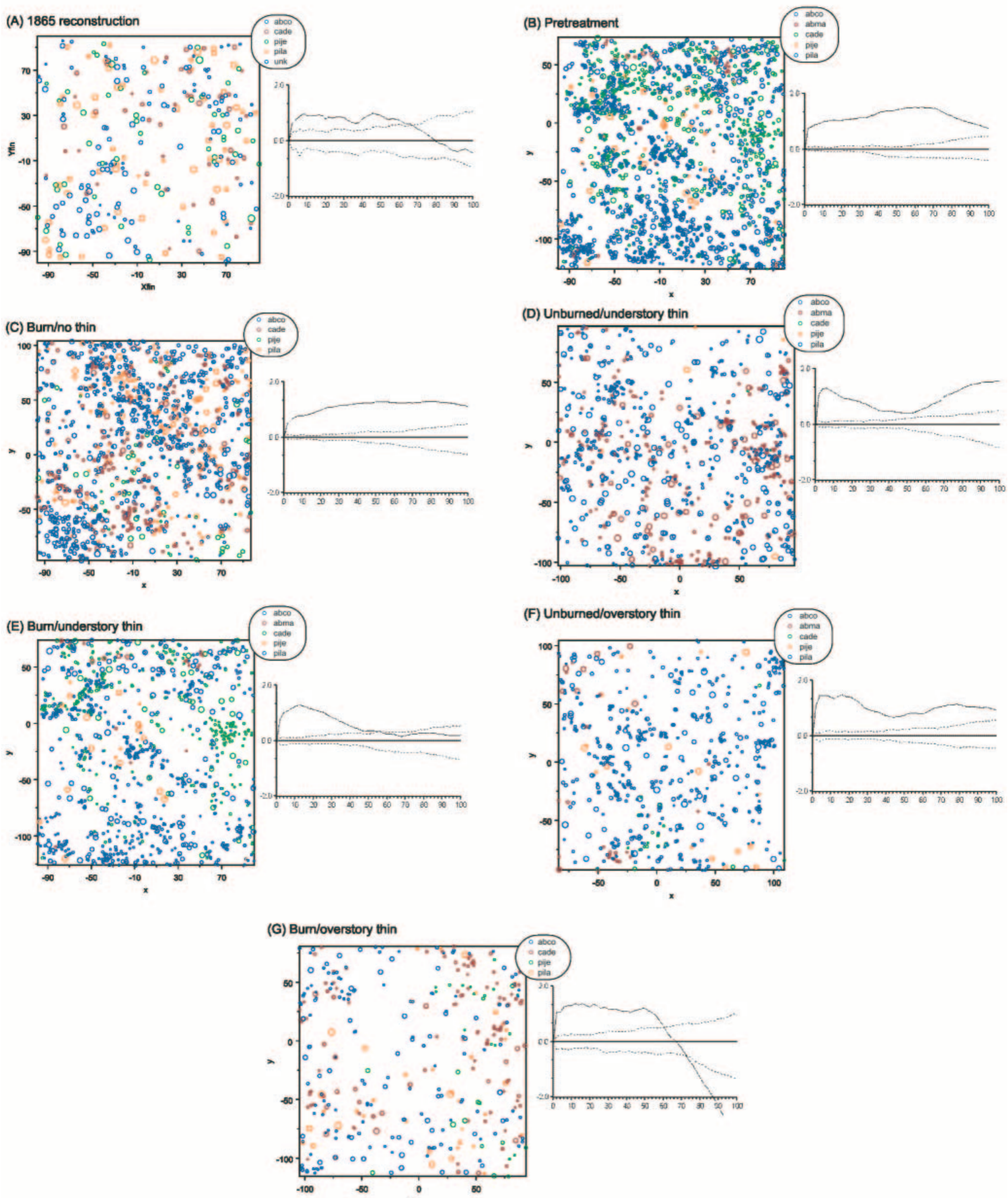

that we have underestimated this size class's density 10-fold, the increase needed to produce a reverse-J-shaped distribution. An earlier study of Teakettle's tree demography revealed frequent episodes of mortality and establishment following fires and wet years (North et al. 2005*a*). This demographic pattern could have produced a fairly flat diameter distribution if diameter was loosely correlated with age in low-density open stands produced by frequent fire.

Species composition in Teakettle's untreated forest has substantially shifted from almost 50% shade-tolerant (fir and cedar) and 50% shade-intolerant (pine) species in 1865 to 84% and 14%, respectively, in 2000. Treatments did not

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fundamentally change this composition. The species composition of the thinned trees was similar to current stand composition because the thinning prescription was based strictly on diameter. White fir, which is considered fire-sensitive, should suffer higher mortality than pines in a prescribed burn. However, in our study and in others (Hanson and North 2006), many white fir were large enough to be resistant to all but the hottest spot burns. As in van Mantgem et al.'s (2004) study, many of our large sugar pines died even under moderate burn conditions. These patterns suggest that more field manipulation studies are needed to assess optimal fire frequency and intensity for increasing the percentage of pines in treated forest stands.

The prescribed fire without thinning treatment had only a moderate effect on stand conditions in our experiment, probably because it was a low-intensity late-fall burn. As is typical in the Sierra Nevada, Teakettle's prescribed fire was lit "off season", in late October, for easier containment and when air-quality conditions allow more burning. Fire may not do as much "work" in this condition of lower temperatures and higher humidity without the addition of thinning slash to fuel fire intensity and increase burn coverage. Prescribed fire may need to be repeatedly applied to help move stand structure toward historical conditions. Stem density was significantly lower and snag density higher in both thinning and burn treatments, where the fire burned hotter than in the other treatments. In these late-fall burns, the importance of thinning before prescribed burning may be that it increases the extent and intensity of the fire.

Small-scale stem patterns appear to have always been clumped, but current and treated forests are significantly more clustered than in 1865. Because of limitations in our reconstruction methods, small-scale clumping may be underestimated; however, we believe that this bias is unlikely to account for the pronounced difference between historical and modern conditions. The reduction in small-scale density can be an important measure of restoration because it contributes to fuel loading (Stephens and Moghaddas 2005), moisture stress (Feeney et al. 1998), and low-light understory conditions that reduce plant diversity (North et al. 2005*b*; Wayman and North 2007) and regeneration of shade-intolerant tree species (Gray et al. 2005). In our experiment, thinning treatments did little to reduce this clustering because there was limited incidental mortality in the 5–25 cm size class caused by mechanical removal of larger trees. Prescribed fire did reduce small-scale clustering, particularly with higher burn intensities in the thinned plots, but still many small trees survived. Effective restoration may require more aggressive removal of stems in this size class, reducing density toward the 10 stems/ha suggested by the reconstruction.

Our study also suggests that restoration treatments need to reduce larger scale (>60 cm) clustering and produce a more random distribution of stems at the stand level. Comparing historical and current conditions in three forest communities (Jeffrey pine – white fir, red fir – western white pine (*Pinus monticola* Dougl. ex D. Don), and lodgepole pine) in the Lake Tahoe Basin, Taylor (2004) also recommended that restoration treatments should reduce clustering and produce a more random distribution. Teakettle's pretreated forest was strongly clustered and most treatments failed to achieve a random distribution at large scales. Understory thinning and burning was the most effective at approximating historical spatial structure because it retained all large trees, reduced stem density, and provided slash, which increased fire intensity and mortality of small trees.

In our experiment one of the main reasons for the failure of treatments to restore active-fire-regime stand conditions was that stands were thinned on the basis of prescriptions that applied a strict diameter limit to all species. Many Sierran mixed-conifer stands have a small percentage of old shade-intolerant trees, and in these cases few if any ponderosa, Jeffrey, and sugar pines need to be thinned. Strict diameter limits also left too many small trees and over-harvested intermediate-sized trees, reducing future replacements for dying large trees. At Teakettle, 2–5 large trees/ha (>75 cm DBH) died following understory thinning and prescribed burn treatments. This loss, combined with the current deficit of large trees (>150 cm), suggests that more intermediate-sized trees need to be retained to provide for large-tree development. The combination of understory thinning with prescribed fire was most effective at moving stand conditions toward those produced by an active fire regime, but new thinning prescriptions are needed that vary by species and that retain more intermediate-sized trees to provide for future large-tree recruitment.

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