Restoring Forest Heterogeneity with Thinning and Prescribed Fire: Initial Results from the Central Sierra Nevada, California

Eric E. Knapp, Robert L. Carlson, Malcolm P. North, Jamie L. Lydersen, and Brandon M. Collins[1]

ABSTRACT.—Many fire-adapted forests across the United States where fire has been excluded have in-filled with shade-tolerant species, reducing the characteristic spatial heterogeneity. We used 1929 stem maps of historical forest conditions in the Sierra Nevada to develop a thinning prescription designed to restore a pattern of tree clumps, individual trees, and gaps. This "high variability" (HighV) thinning treatment was evaluated in a replicated experimental design along with a more standard regular "leave" tree spacing "low variability" (LowV) thinning treatment, and an unthinned control, all with or without prescribed fire. Both thinning treatments reduced tree density and basal area equally, but differed in spatial pattern, with the HighV thinning leading to greater variability in canopy closure and stem distribution. While creating small gaps with the HighV treatment required the removal of some larger trees, slightly more board foot (BF) volume was removed with the LowV treatment because larger trees often grow in groups and imposing a regular spacing resulted in the removal of some. Any difference in BF volume removed between treatments would likely be minimal on most Forest Service lands in the Sierra Nevada where a 30-inch diameter limit for cutting applies. Both thinning treatments improved tree survival in a severe drought compared with the untreated control. No difference was observed between thinning treatments indicating that leaving some trees in groups did not increase susceptibility to bark beetle attack at the stand scale. While more trees died in the prescribed burn treatments, secondary mortality in thinned units was relatively minor. The HighV with prescribed fire treatment not only produced a structure more closely approximating that of historical stands, but low surface fuel loads should make treated areas more resilient to future wildfires.

Most western U.S. forests that once experienced frequent fire are considerably denser today than they once were (Collins et al. 2011, Moore et al. 2004, Scholl and Taylor 2010). In the absence of fire, gaps in the forest filled with trees (Lydersen et al. 2013), altering the understory light environment and increasing fuel continuity. Composition of forests has also shifted to a greater dominance of shade-tolerant species (Knapp et al. 2013). Structural changes, including a deficit of larger more fire-resistant trees as a result of past harvest practices, plus greater fuel loading and continuity, have all contributed to a greater vulnerability of stands to uncharacteristically intense fires (Steel et al. 2015). Unnaturally dense stands are also more susceptible to elevated bark beetle mortality, especially during drought conditions (Ferrell et al. 1994, Fettig et al. 2007, Graham et al. 2016, Young et al. 2017).

While the need to thin overstocked forests and reduce the accumulated surface fuels is widely accepted, progress in many areas has been slowed by concern that standard approaches may be at odds with habitat needs of key wildlife species (Lehmkuhl et al. 2007, Scheller et al. 2011). Producing a variety of forest conditions with thinning, which is guided by historical

---

[1] Research Ecologist (EEK), USDA Forest Service, Pacific Southwest Research Station, 3644 Avtech Parkway, Redding, CA 96002; Forestry Technician (RLC), USDA Forest Service, Pacific Southwest Research Station, Redding, CA; Research Ecologist (MPN), USDA Forest Service, Pacific Southwest Research Station, Davis, CA; Ecologist (JLL), USDA Forest Service, Pacific Southwest Research Station, Davis, CA; and Research Forester (BMC), University of California Berkeley, Berkeley, CA. EEK is corresponding author: to contact, call 530-226-2555 or email at eric.e.knapp@usda.gov.

reference information, may provide a greater diversity of habitats desired for multi-species management (North and Manley 2012). Heterogeneity may also improve the resilience of stands to wildfire and a changing climate (Stephens et al. 2010), and approaches emphasizing heterogeneity as a central element to forest restoration have been described for many forests historically shaped by frequent fire (Addington et al. 2018, North et al. 2009, Reynolds et al. 2013).

The Variable Density Thinning study at the Stanislaus-Tuolumne Experimental Forest in the central Sierra Nevada, CA, was established in 2009 to test the ecological responses to mechanical thinning designed to restore stand heterogeneity similar to that found in historical prefire suppression forests. This thinning treatment was compared against a more conventional thin-from-below, in which residual trees were relatively evenly spaced such that crown overlap for dominant and co-dominant trees was minimized. Additionally, this study included an untreated control, which along with the two thinning treatments was crossed with a prescribed fire treatment. The objective of the prescribed fire treatment was not only to reduce surface fuels, but to evaluate the capacity of prescribed fire to enhance structural heterogeneity compared to thinning. Recently published results show that thinning generated more within-stand heterogeneity than a single entry prescribed burn (Knapp et al. 2017). In addition, the "high variability" (HighV) treatment increased within-stand heterogeneity more than the "low variability" (LowV) thinning treatment, approaching the historical reference condition at some spatial scales. Analysis of many of the ecological variables being monitored is still underway. Additional lingering questions about the HighV treatment that might discourage wider application include whether the HighV treatment is more difficult to implement, is cost-effective, and whether leaving some trees in denser groups might reduce growth rates while leaving trees more susceptible to mortality caused by bark beetle or self-thinning.

The objectives of this paper are to illustrate differences among treatments, compare the harvested board foot volume and dry tons of biomass removed between a HighV thinning treatment and a LowV thinning treatment, and to report on the initial response of all treatments to a severe drought. The four water years following the thinning treatments (2012-2015) were substantially drier than normal, which led to extensive drought-related tree mortality in the Sierra Nevada (Young et al. 2017), including the area of the study.

STUDY AREA

The Variable Density Thinning study was established across approximately 240 acres of second growth mixed-conifer forest within the Stanislaus-Tuolumne Experimental Forest (Stanislaus National Forest) at elevations ranging from 5700 to 6200 ft. Tree species included white fir (*Abies concolor* (Gordon & Glend.) Hildebr.), sugar pine (*Pinus lambertiana* Douglas), incense cedar (*Calocedrus decurrens* (Torr.) Florin), ponderosa pine (*P. ponderosa* Lawson & C. Lawson), Jeffrey pine (*P. jeffreyi* Grev. & Balf.), and black oak (*Quercus kelloggii* Newb.), in order of abundance.

The study was set up in a split-plot design, with eight blocks of equal size, each randomly assigned a burn treatment (burn or no burn). Blocks were divided into three units and each randomly assigned a logging treatment. Logging treatments were a high variability (HighV) thin, a low variability (LowV) thin, and an unthinned control. The objective of the HighV thinning prescription was to produce a spatial structure, density, species composition, and size distribution consistent with the historical patterns once observed on this site, based on data from nearby forest (Knapp et al. 2013, Lydersen et al. 2013). These historical data and photographs showed the forest consisted of individual large trees, clusters of trees, and gaps—consistent with the individuals, clumps, and openings (ICO) pattern documented in frequent fire forests of the western United States by others (Larson and Churchill 2012).

MATERIALS AND METHODS

The HighV thinning involved cutting trees to produce small (0.1 acre to 0.5 acre) gaps (approximately one per every 2 acres), similar in size and density to those noted on the historical records (Lydersen et al. 2013). The remaining forest was broken up into tree groups of similar size to the gaps, with thinning intensity varying among groups. About a third of groups were thinned more heavily, a third moderately, and a third lightly. Within groups, the best trees (generally the largest trees, trees with the best crown form, or both) were retained, regardless of crown spacing. Additional details of the HighV prescription are found in Knapp et al. (2012). The LowV thinning treatment was marked for cutting by selecting "leave" trees spaced approximately 0.5 crown widths from nearest neighbors. The LowV prescription approximated a standard "thinning from below" treatment at the time the study was planned. Abundance of white fir and incense cedar had increased the most relative to historical conditions (Knapp et al. 2013) and these two species were therefore targeted for cutting over pines. The goal with the two thinning treatments was to produce stands of similar tree density, basal area, size class distribution, and species composition, but with a different spatial arrangement of trees. Most of the smaller trees (<22 inches) were cut with tracked feller bunchers while larger trees were chainsaw felled. All material (whole smaller trees, plus boles and nonmerchantable tops of larger trees) was skidded to landings for processing into logs and other forest products. Small trees (generally <10 inches) and tops of larger trees were chipped and removed as biomass. All logging was completed between July and September 2011. Prescribed burning treatments were carried out in November 2013 using drip torch spot ignition, working fire from higher to lower elevations. This resulted in a mixture of backing, flanking, and short-distance head fire.

Within each unit, trees >4 inches diameter at breast height (d.b.h), within a belt transect 787.4 ft long by 49.2 ft wide, were mapped and measured in 2009, 2 years prior to logging. To fit within the unit, belt transects were broken up into parallel (west to east) segments 98.4 ft apart, with the number of segments depending on the shape of the unit (see Figure 1 in Knapp et al. [2017]). The belt transects represented approximately an 8 percent sample of the study area. After logging, remaining trees within each transect were tagged with an individually numbered metal tag (see Fig. 1 for "before" and "after" cutting comparison). Status (live/cut/dead) was determined, and d.b.h and height of each tree measured in 2012 (year after logging), 2014 (year after prescribed burning), and 2016. Height was estimated using laser rangefinders and/or clinometer and meter tape.

Board foot (BF) volume and biomass removed by logging was estimated from the 2009 (prelogging) tree data together with a list of those which were cut, based on the 2012 (post-logging) survey. Volume for individual cut trees was calculated from d.b.h. and tree height values with the USDA Forest Service national volume estimator library (USDA Forest Service, n.d. b) using individual species equations of Wensel and Olson (1993) with numbers based on the Scribner log rule. Calculations assumed saw logs were processed to a minimum 6-inch top diameter from trees $\geq$10 in d.b.h. Smaller (<10 inches) trees and the tops of saw log trees were assumed to have been chipped and converted to biomass. Amount of biomass was estimated with the Forest Service national biomass estimator library (USDA Forest Service, n.d. a) using equations of Jenkins et al. (2003). The program's functions "bmAboveGroundTotal" were used to calculate bone dry tons for small (<10 inches) trees and "bmStemTop" was used to calculate bone dry tons for tops of saw log-sized trees.

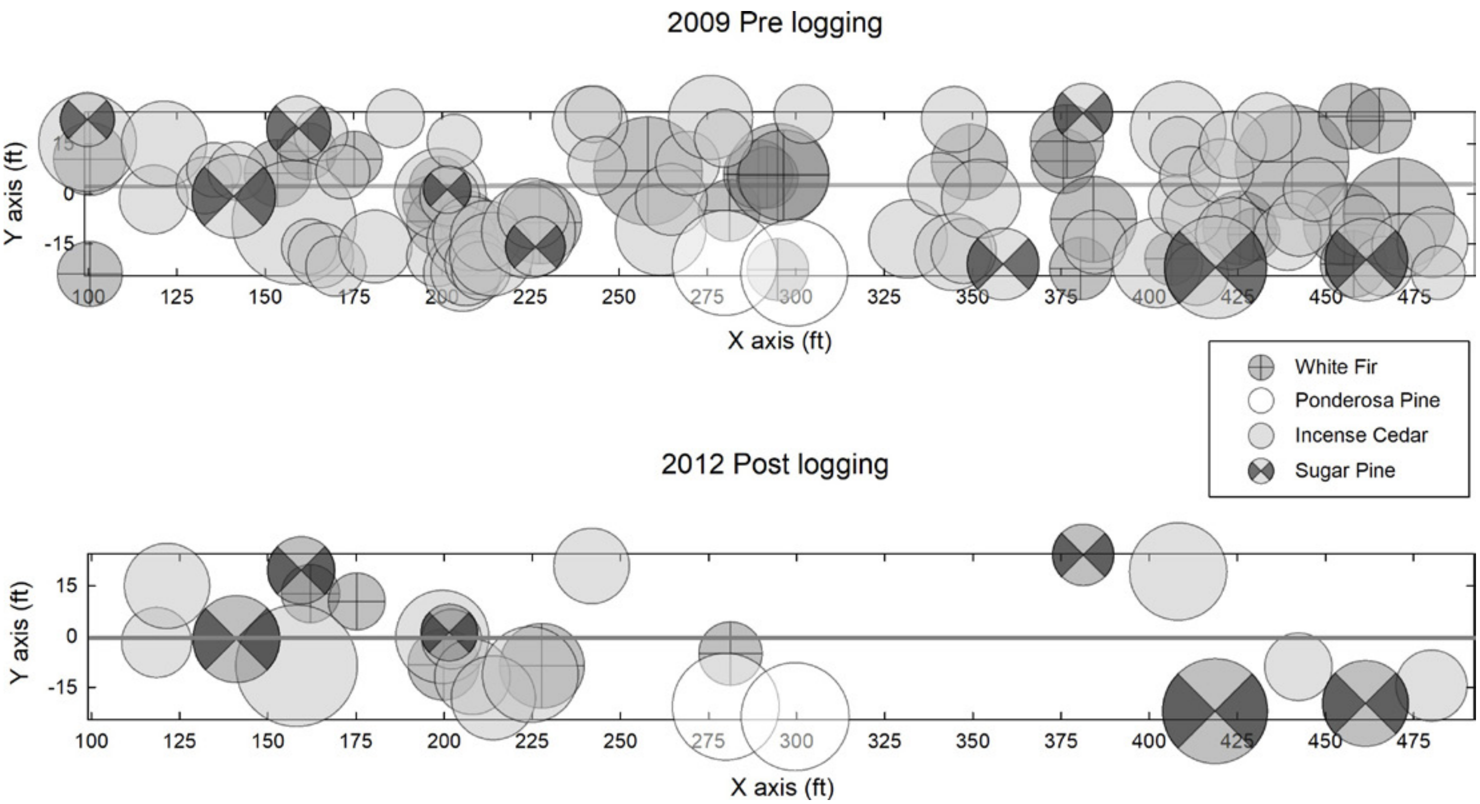

Figure 1.—Illustration of one stand (Unit 15, Transect 1) thinned using a "high variability" (HighV) prescription, showing a 393 ft × 49 ft belt transect through the unit in 2009 (prelogging) and in 2012 (post-logging).

Since tree heights were not measured until after logging, tree heights for cut trees were estimated using post logging (2012) data for all trees without broken tops as determined from field notes. Tree height was estimated for each species using equation 3 of Larsen and Hann (1987) with coefficients b0, b1, and b2 calculated using SAS NLIN in SAS version 9.4, and the coefficients listed in the paper for the tree species as starting values.

$$\text{Height\_ft} = 4.5 + \text{EXP}(b0 + b1{*}\text{DBH\_in}^{b2})$$

Two outliers—the tallest white fir and the tallest sugar pine—were dropped as diameter values were considerably larger than any trees removed by logging. All equations using coefficients (Table 1) derived from 2012 (post-logging) tree diameter data were highly significant ($P < 0.001$), except for Jeffrey pine (PIJE), which had the fewest observations and did not converge. We therefore combined the ponderosa (PIPO) and Jeffrey pine datasets and estimated b0 for each while keeping b1 and b2 constant. The difference between b0(PIPO) and b0(PIJE) was significant.

Significance of differences in prelogging, retained, and removed BF volume between the HighV and LowV treatments was determined using generalized linear mixed effects models (PROC GLIMMIX). Volume was also estimated for hypothetical maximum diameter limits of 30 inches, 24 inches, and 20 inches, and significance of the differences between treatments analyzed using the same method. The three selected diameter limits represent the current upper diameter limit on national forest lands in the Sierra Nevada, the often-used limit resulting from spotted owl guidelines (Verner et al. 1992), and an early 2000s proposed upper limit that was not implemented, respectively. Because pretreatment volume was numerically higher in the LowV treatment, pretreatment volume was used as a covariate in all BF volume removed and retained analyses.

Table 1.—Individual species coefficients for estimating height from diameter at breast height within the Variable Density Thinning study at the Stanislaus-Tuolumne Experimental Forest, using equation 3 of Larsen and Hann (1987)

Species	b0	b1	b2
White fir	5.7418	-7.0241	-0.5806
Incense cedar	6.2967	-6.7234	-0.3904
Sugar pine	5.5006	-8.5938	-0.7291
Ponderosa pine	6.9445	-5.7794	-0.2929
Jeffrey pine	6.7647	-5.7794	-0.2929

Table 2.—Average tree density, basal area, and quadratic mean diameter (QMD), for unthinned control, high variability thin (HighV), and low variability thin (LowV) treatments, all with or without prescribed fire, in 2014, 3 years after logging and 1 year after implementation of prescribed burns. (Standard error in parentheses.) P values (in italics) for main and interaction effects were determined with generalized linear mixed effects models.

		Density (trees ac^{-1})				
Logging Treatment	Burning treatment	Small (4 to 10 in)	Medium (10 to 20 in)	Large (>20 in)	Basal area (ft^2 ac^{-1})	QMD (in)
Control	No Burn	195.3 (39.5)	100.3 (7.2)	32.9 (5.0)	259.4 (17.7)	13.0 (1.1)
Control	Burn	145.3 (21.7)	88.5 (9.1)	41.0 (7.2)	261.1 (30.3)	14.0 (1.1)
HighV thin	No Burn	6.7 (1.6)	26.4 (5.2)	31.5 (2.3)	148.7 (7.8)	22.0 (1.0)
HighV thin	Burn	10.7 (3.6)	25.0 (1.6)	27.2 (4.1)	152.4 (23.0)	22.2 (1.9)
LowV thin	No Burn	13.5 (3.5)	27.0 (7.3)	26.2 (0.5)	139.1 (12.7)	21.0 (1.6)
LowV thin	Burn	5.9 (2.6)	16.9 (6.0)	32.0 (2.4)	157.9 (18.4)	24.7 (2.7)
Logging treatment		*<0.001*	*<0.001*	*0.146*	*<0.001*	*<0.001*
Burning treatment		*0.674*	*0.318*	*0.509*	*0.597*	*0.365*
Logging × Burning		*0.177*	*0.436*	*0.227*	*0.816*	*0.534*

Performance of treatments during a severe drought was evaluated as the change in basal area between 2014 and 2016. Significance of differences among treatments was determined using a generalized linear mixed effects model (PROC GLIMMIX) including main effects (thinning treatment, burning treatment, year) and interaction terms, and block and burning*block as random effects.

RESULTS AND DISCUSSION

Both thinning treatments resulted in a stand with significantly fewer small (4-10 inches) trees, medium (10-20 inches) trees, and basal area, and significantly increased quadratic mean diameter (Table 2). The number of large (>20 inches) trees did not differ significantly among treatments. For all variables where thinning was significant, the HighV and LowV treatments did not differ from each other. Differences between "no burn" and burn treatments were not significant in the year following implementation of the burns. Delayed mortality in the burned units, which was likely exacerbated by the severe drought (Van Mantgem et al. 2013), was substantial, especially in the unthinned control units, but not considered in this analysis. Despite the lack of significant differences among stand-level means, thinning-

Figure 2.—Aerial photograph of a portion of the study area, taken in 2012, 1 year following logging, showing an unthinned control unit (upper left), two high variability thin units (center), and two low variability thin units (right and bottom). Average tree density and basal area did not differ between thinning treatments, only how trees were arranged within units.

produced differences in the forest spatial structure were evident, both visually (Fig. 2) and numerically, thus illustrating the need for new metrics to describe structural heterogeneity. Knapp et al. (2017) found that coefficients of variation for tree density and basal area for the HighV treatment came closer to a historical reference than those produced by the LowV treatment. In addition, HighV thinning led to a broader range of canopy closure values, with more of the treated area in the very low and high canopy closure classes relative to the LowV treatment. The LowV treatment, on the other hand, pushed the majority of the treated area toward the mean value of canopy closure (Knapp et al. 2017). One common concern with thinning designed to meet ecological objectives is that not enough material would be removed for the treatment to pay for itself (i.e., generate revenue). However, data from nearby historical plots illustrate that the current stands are not just overstocked in the smaller diameter tree size classes with low value, but also in intermediate and larger-intermediate sized trees (Knapp et al. 2013).

Using calculated height estimates for the 2009 preharvest stand plus the equation and coefficients described above, no difference in bone dry tons of biomass removed was detected between the two thinning treatments, but total gross BF volume was marginally significantly

Table 3.—Standing volume prior to harvest, residual volume after thinning, and total saw log volume plus biomass removed as chips from units thinned with HighV prescription compared to units thinned with a more even crown spacing treatment (LowV). Saw logs were considered any tree with a d.b.h. ≥10 inches and logs were processed down to a 6-inch top. The actual thinning was done without diameter limits, but saw log volume values are also shown for hypothetical situations using diameter limits of 30 inches, 24 inches, and 20 inches, where no trees larger than the diameter limit are removed. Biomass consists of trees <10 inches and tops. Significance of the difference between logging treatments for BF volume removed and retained were calculated with preharvest volume as a covariate and means are corrected for the covariate. Standard errors are in parentheses and P values are in italics.

				Hypothetical volume removed with diameter limits			
Logging treatment	Preharvest volume	Residual Volume	Volume removed	<30 in d.b.h.	<24 in d.b.h.	<20 in d.b.h.	Biomass removed
	---------------------------------- Volume (BF ac^{-1})----------------------------------						Dry tons ac^{-1}
HighV thin	46,651	34,634	12,533	11,923	9,210	6,017	16.72
	(4,955)	(1,435)	(828)	(751)	(623)	(485)	(1.69)
LowV thin	51,595	31,190	15,396	12,128	8,897	5,410	13.67
	(5,480)	(1,293)	(1,017)	(764)	(602)	(444)	(1.38)
Preharvest covariate	-	*<0.001*	*<0.001*	*0.053*	*0.328*	*0.028*	-
HighV vs. LowV	*0.492*	*0.098*	*0.049*	*0.852*	*0.726*	*0.459*	*0.190*

higher for LowV thinning treatment (P = 0.049), even after correcting for the higher preharvest volume (preharvest covariate P <0.001) (Table 3). We expected that the creation of gaps in the HighV treatment would result in equal, if not more, volume removed. However, because the largest trees in the stand often were growing in groups, cutting of some larger trees was also necessary to enforce the crown spacing guidelines of the LowV prescription. It is possible that this more than balanced out the larger trees that would need to be cut to create small gaps. Much of the difference between the two logging treatments was the result of somewhat greater number of >30 inch trees cut (2.2 ac^{-1} in the LowV treatment vs. 0.3 ac^{-1} in the HighV treatment; mostly white fir with a few incense cedar). The majority of these >30-inch trees were <34 inches, but the average >30 inch cut tree still contained 2,060 BF volume. Under the Sierra Nevada Forest Plan Amendment (USDA Forest Service 2004), if these or similar prescriptions were used on most other (non-Experimental Forest) NFS lands, a 30-inch diameter limit would have applied. The BF volume of trees <30 inches did not differ significantly between the HighV and LowV treatments (P = 0.852) (Table 3). An additional 714 BF ac^{-1} would have been removed in the HighV treatment (618 BF ac^{-1} in the LowV treatment) if logs were processed down to a 4-inch top diameter. Amount of biomass removed would have been correspondingly less. In addition, volume amounts were likely slightly higher than estimated, given that 2 years of additional growth had occurred between the time of tree measurement (2009) and when logging was done.

Volume comparisons between treatments should be interpreted with some caution, given the relatively small sample. Only 8 percent of the harvest area was captured in the tree transects. In addition, the numbers of larger trees cut was relatively low but larger trees contribute disproportionately to volume, thus chance sampling can easily skew results. However, volume estimates were similar to numbers calculated based on a post-marking and preharvest cruise.[2] In addition, the sum of volumes from the two treatments multiplied by the acres treated was very close to the volume that was actually measured when the logs were scaled, giving more

---

[2] Stanislaus National Forest, unpublished data.

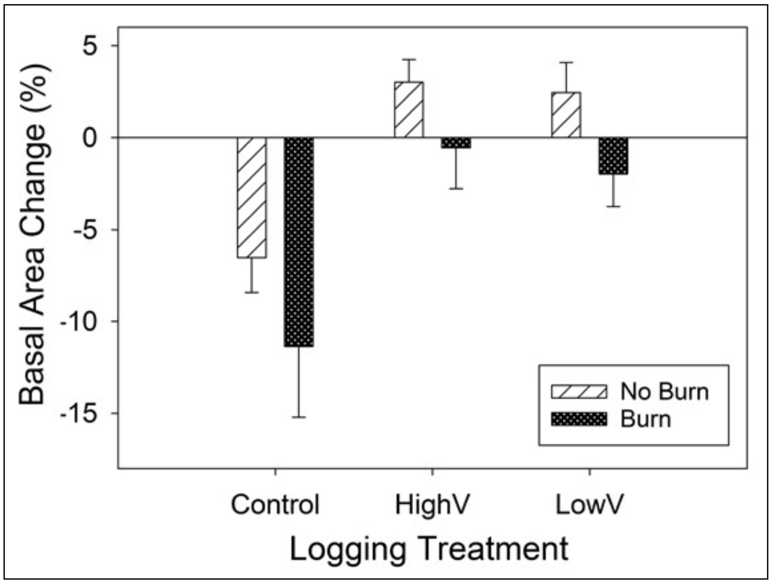

Figure 3.—Percentage basal area change between 2014 and 2016 in unthinned control units, units thinned with a HighV prescription and units thinned more evenly, or LowV, all with or without a follow-up prescribed burn. Thinning was completed in 2011 and prescribed burning in 2013. The study area experienced a severe drought from 2012 to 2015, with high mainly bark beetle caused tree mortality during and immediately following this period. The control treatment lost basal area, while both thinning treatments (averaged across burning treatments) gained a small amount of basal area (growth > mortality).

confidence in the overall numbers. A potentially important confounding variable in this study was that different marking crews were used for the HighV and LowV treatments. For these reasons we believe that for most stands, approximately equivalent volume would be removed with the HighV or the LowV prescriptions, given the same starting volume and same marking crew. In any case, the volume removed for either treatment (Table 3) was more than enough to make the project revenue positive given hauling costs and log prices at the time.[3]

Both thinning treatments experienced lower drought-related mortality than the adjacent unthinned controls. Between the summer of 2014 and the summer of 2016, live basal area dropped 9.1 percent in the untreated controls and increased an average of 0.6 percent in the thinned treatments (thinning × year interaction: $F = 11.55$, $P < 0.001$) (Fig. 3). While some tree mortality occurred within the thinned treatments as well, it was more than balanced by growth of the surviving trees. There was no difference in the basal area change over time between the HighV and the LowV thinning treatments ($P = 0.989$). Thus treatment-wide, at this initial stage of evaluation, we see no evidence that a variable arrangement of trees, including patches of higher density, leads to higher mortality levels. While rate of mortality in relation to density variation within stands was not determined, any elevated mortality in the denser areas within HighV stands (if present) must have been balanced by lower than average mortality in portions of the stand thinned more heavily.

More basal area was lost in prescribed fire treatments than those left unburned (burning × year interaction: $F = 4.99$, $P = 0.038$). This delayed mortality was likely due to the stress caused by coupling of heavy fuel consumption (124 years since the last record of fire) with severe drought. (The historic fire regime in the study area was reported as a median interval of 6 years between fires, with the last fire in 1889 [Knapp et al. 2013]). Still, the basal area in the unthinned and burned control remained at or above historical values (but with many more and smaller trees). While any additional fire-related mortality was not a desired outcome in the thin and burn units, the comparatively minor loss of an average of 1.5 $ft^2\ ac^{-1}$ was within the acceptable range for the burning prescription. Thinning alone without any surface fuel treatment may be not change fire behavior sufficiently to prevent extensive tree mortality in the event of a wildfire (Ritchie et al. 2007).

---

[3] Personal communication, Dave Horak and Maria Benech, Stanislaus National Forest.

In summary, the combination of HighV thinning with prescribed fire not only re-created a variable forest structure similar to what forests historically contained, but the combination of reduced density and lower surface fuel loads also should make treated stands more resilient to drought and wildfire induced tree mortality.

ACKNOWLEDGMENTS

We thank Maria Benech along with the many employees of the Stanislaus National Forest who played a role in writing the NEPA documents, conducting pretreatment surveys, and carrying out the thinning and burning treatments. Logging contractor Sierra Resource Management implemented the thinning treatments. Paific Southwest Research Station field crews collected much of the data. We also thank Martin Ritchie for assistance with developing equations for estimating tree height. This work was supported in part by the USDA, National Institute of Food and Agriculture (NIFA) program, grant number 11-03859.

LITERATURE CITED

Addington, R.N.; Aplet, G.H.; Battaglia, M.A. [et al.]. 2018. **Principles and practices for the restoration of ponderosa pine and dry mixed-conifer forests of the Colorado front range.** Gen. Tech. Rep. RMRS-373. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 121 p.

Collins, B.M.; Everett, R.G.; Stephens, S.L. 2011. **Impacts of fire exclusion and recent managed fire on forest structure in old growth Sierra Nevada mixed-conifer forests.** Ecosphere. 2(4): article 51. https://doi.org/10.1890/es11-00026.1.

Ferrell, G.T.; Otrosina, W.J.; Demars, C.J., Jr. 1994. **Predicting susceptibility of white fir during a drought-associated outbreak of fir engraver, Scolytis ventralis, in California.** Canadian Journal of Forest Research. 24(2): 302-305. https://doi.org/10.1139/x94-043.

Fettig, C.J.; Klepzig, K.D.; Billings, R.F. [et al.] 2007. **The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the western and southern United States.** Forest Ecology and Management. 238(1-3): 24-53. https://doi.org/10.1016/j.foreco.2006.10.011.

Graham, R.T.; Asherin, L.A.; Battaglia, M.A. [et al.]. 2016. **Mountain pine beetles: A century of knowledge, control attempts, and impacts central to the Black Hills.** Gen. Tech. Rep. RMRS-353. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 193 p.

Jenkins, C.J.; Chojnacky, D.C.; Heath, S.H.; Birdsey, R.A. 2003. **National-scale biomass estimators for United States tree species.** Forest Science. 49: 12-35.

Knapp, E.; North, M.; Benech, M.; Estes, B. 2012. **The variable density thinning study at Stanislaus-Tuolumne Experimental Forest.** In: North, M., ed. Managing Sierra Nevada Forests. Gen. Tech. Rep. PSW-GTR-237. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 127-139.

Knapp, E.E.; Lydersen, J.M.; North, M.P.; Collins, B.M. 2017. **Efficacy of variable density thinning and prescribed fire for restoring forest heterogeneity to mixed conifer forest in the central Sierra Nevada, CA.** Forest Ecology and Management. 406: 228-241. https://doi.org/10.1016/j.foreco.2017.08.028.

Knapp, E.E.; Skinner, C.N.; North, M.P.; Estes, B.L. 2013. **Long-term overstory and understory change following logging and fire exclusion in a Sierra Nevada mixed conifer forest.** Forest Ecology and Management. 310: 903-914. https://doi.org/10.1016/j.foreco.2013.09.041.

Larsen, D.R.; Hann, D.W. 1987. **Height-diameter equations for seventeen tree species in southwest Oregon.** Res. Pap. 49. Corvallis, OR: Oregon State University. 16 p.

Larson, A.J.; Churchill, D.C. 2012. **Tree spatial patterns in fire-frequent forests of western North America, including mechanisms of pattern formation and implications for designing fuel reduction and restoration treatments.** Forest Ecology and Management. 267: 74-92. https://doi.org/10.1016/j.foreco.2011.11.038.

Lehmkuhl, J.F.; Kennedy, M.; Ford, P.L. [et al.]. 2007. **Seeing the forest for the fuel: integrating ecological values and fuels management.** Forest Ecology and Management. 246(1): 73-80. https://doi.org/10.1016/j.foreco.2007.03.071.

Lydersen, J.M.; North, M.P.; Knapp, E.E.; Collins, B.M. 2013. **Quantifying spatial patterns of tree groups in mixed-conifer forests: reference conditions and long-term changes following fire suppression and logging.** Forest Ecology and Management. 304: 370-382. https://doi.org/10.1016/j.foreco.2013.05.023.

Moore, M.M.; Huffman, D.W.; Fulé, P.Z. [et al.] 2004. **Comparison of historical and contemporary forest structure and composition on permanent plots in southwestern ponderosa pine forests.** Forest Science. 50: 162-176.

North, M.; Manley, P. 2012. **Managing forests for wildlife communities.** In: North, M., ed. Managing Sierra Nevada Forests. Gen. Tech. Rep. PSW-237. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 73-80.

North, M.; Stine, P.; O'Hara, K. [et al.]. 2009. **An ecosystem management strategy for Sierran mixed-conifer forests.** Gen. Tech. Rep. PSW-220. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 49 p. https://doi.org/10.2737/PSW-GTR-220.

Reynolds, R.T.; Sanchez Meador, A.J.; Youtz, J.A. [et al.]. 2013. **Restoring composition and structure in Southwestern frequent-fire forests.** Gen. Tech. Rep. RMRS-310. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 76 p. https://doi.org/10.2737/PSW-GTR-310.

Ritchie, M.W.; Skinner, C.N.; Hamilton, T.A. 2007. **Probability of tree survival after wildfire in an interior pine forest of northern California: effects of thinning and prescribed fire**. Forest Ecology and Management. 247(1-3): 200-208. https://doi.org/10.1016/j.foreco.2007.04.044.

Scheller, R.M.; Spencer, W.D.; Rustigian-Romsos, H. [et al.]. 2011. **Using stochastic simulation to evaluate competing risks of wildfires and fuels management on an isolated forest carnivore.** Landscape Ecology. 26(10): 1491-1504. https://doi.org/10.1007/s10980-011-9663-6.

Scholl, A.E.; Taylor, A.H. 2010. **Fire regimes, forest change, and self-organization in an old-growth mixed-conifer forest, Yosemite National Park, USA.** Ecological Applications. 20(2): 362-380. https://doi.org/10.1890/08-2324.1.

Steel, Z.L.; Safford, H.D.; Viers, J.H. 2015. **The fire frequency-severity relationship and the legacy of fire suppression in California forests.** Ecosphere. 6(1): article 8. https://doi.org/10.1890/es14-00224.1.

Stephens, S.L.; Millar, C.I.; Collins, B.M. 2010. **Operational approaches to managing forests of the future in Mediterranean regions within a context of changing climates.** Environmental Research Letters. 5(2): 024003. https://doi.org/10.1088/1748-9326/5/2/024003.

USDA Forest Service. 2004. **Sierra Nevada Forest Plan amendment – Final supplemental environmental impact statement.** Vallejo, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Region. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fsbdev3_046095.pdf (accessed April 1, 2020).

USDA Forest Service. No date a. **Biomass volume estimation.** Washington, DC: U.S. Department of Agriculture, Forest Service. https://www.fs.fed.us/forestmanagement/products/measurement/biomass/index.php (accessed April 2020).

USDA Forest Service. No date b. **Volume estimation.** Washington, DC: U.S. Department of Agriculture, Forest Service. https://www.fs.fed.us/forestmanagement/products/measurement/volume/nvel/index.php (accessed April 2020).

Van Mantgem, P.J.; Nesmith, J.C.B.; Keifer, M. [et al.]. 2013. **Climatic stress increases forest fire severity across the western United States.** Ecology Letters. 16: 1151-1156. https://doi.org/10.1111/ele.12151.

Verner, J.; McKelvey, K.S.; Noon, B.R. [et al.]. 1992. **The California spotted owl: a technical assessment of its current status.** Gen. Tech. Rep. PSW-133. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station 285 p. https://doi.org/10.2737/PSW-GTR-133.

Wensel, L.C.; Olson, C.M. 1993. **Tree taper models for major commercial California conifers.** Research Note No. 33. Berkeley, CA: University of California, Berkeley, Department of Forestry and Management, Northern California Forest and Yield Cooperative.

Young, D.J.N.; Stevens, J.T.; Earles, J.M. [et al.]. 2017. **Long-term climate and competition explain forest mortality patterns under extreme drought.** Ecology Letters. 20(1): 78-86. https://doi.org/10.1111/ele.12711.

CITATION: Knapp, Eric E.; Carlson, Robert L.; North, Malcolm P.; Lydersen, Jamie L.; Collins, Brandon M. 2020. Restoring forest heterogeneity with thinning and prescribed fire: Initial results from the central Sierra Nevada, California. In: Pile, Lauren S.; Deal, Robert L.; Dey, Daniel C.; Gwaze, David; Kabrick, John M.; Palik, Brian J.; Schuler, Thomas M., comps. The 2019 National Silviculture Workshop: a focus onforest management-research partnerships. Gen. Tech. Rep. NRS-P-193. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station: 216-226. https://doi.org/10.2737/NRS-GTR-P-193-paper28.