Fuels reduction and group selection in Sierran Mixed-Conifer forest: Effects on stand structure, understory plants, and simulated fire behavior

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Abstract

The Herger-Feinstein Quincy Library Group Forest Recovery Act of 1999was in the vanguard of large national forest management projects in the Sierra Nevada aimed at protecting forests from wildfire. Detailed monitoring was done because of the newness and large spatial extent of the management treatments which included thinning small- and medium-diameter trees, group selection, and prescribed underburning. Response variables were measured before, one year after, and five years after treatment on 64 units and comprised of tree canopy cover and basal area, snag density, down dead wood weight, cover of shrubs and herbs, and simulated fire behavior. Data were analyzed with generalized linear mixed statistical models based on negative binomial or normal distributions. Rate of attainment of predetermined target objectives was evaluated for several of the response variables. Treatments led to significant decreases in canopy cover and basal area; mean canopy cover decreased from 48% to 33% after treatment and remained essentially unchanged for the subsequent four years. Treatments successfully avoided harvesting or otherwise damaging large (≥ 30 inches dbh) trees. The density of large snags (≥15 inches DBH) was halved by treatments, but at five years after treatment the proportion of stands in compliance with retention guidelines (25%) was no different than before treatment. Large log loads also declined by half after treatment but unlike snags showed no indication of recovery; compliance with retention objectives was only 11% at five years after treatment. Understory plant forage species were either resilient to treatments (shrubs) or responded with increased growth [forbs (east side only) and grasses].Fire simulations showed that diminishing the probability of crown fire, a major goal of the treatments, was achievedin large part; the number

of stands with predicted active or conditional crown fire behavior was reduced between 55% and 74% (97thand 90thpercentile weather conditions, respectively). Treatments generally met the primary goal of improving forest health and resilience to wildfire but had mixed success in meeting secondary objectives related to maintenance of habitat quality. Given the ever-increasing threat of high-severity wildfire, the treatments may be judged as having met their overarching goal.

Keywords: Group selection, fuels-reduction thinning, monitoring, Sierra Nevada Mixed-Conifer, canopy cover, snag, down wood, understory plant

Introduction

The national forests at the junction of the Sierra Nevada and Cascade mountain ranges in northern California have undergone many phases of management in the 115 years since their establishment. In the past decade they have been the focus of an unprecedented experiment in community forestry and national forest management (Bernard, 2010). This experiment has involved the U. S. Forest Service's implementation of a forest management plan developed by a stakeholder's group and signed into law as an act of Congress (HFQLG, 1998). Fuels-reduction thinning (generally removing smaller trees and leaving most of the largest trees) and group selection harvest (areas of 1-2 acres where generally all of the trees under 30" diameter are cut and removed) were key features of the management plan, and the law required monitoring of treatment effectiveness. The present report documents short-term and intermediate-term changes in the forest structure resulting from the new management.

Monitoring Program: Targets and Guidelines

The Herger-Feinstein Quincy Library Group Forest Recovery Act contained a provision for reporting of "forest health improvements….and other natural resources-related benefits" resulting from the implementation of the Pilot Project. Questions of particular interest defined by forest managers in collaboration with Quincy Library Group members follow:

- Did silvicultural treatments result in the desired levels of canopy cover?
- Were large trees protected?
- Did treatments produce the desired abundance and distribution of snags and logs?
- Was the amount of early seral stage vegetation enhanced as a result of treatments?
- Did treatments reduce fire hazard?

The rationale for monitoring these elements of forest health are that canopy cover, or the proportion of the forest floor covered by the vertical projection of the tree crowns (Jennings *et al.*, 1999), is associated with wildlife habitat quality (Mayer and Laudenslayer, 1988), regeneration (Moghaddas *et al.*, 2008), and fire hazard (Agee and Skinner, 2005). Large trees (in this context those with diameter at breast height ≥30 inches) provide habitat for many wildlife species, store enormous amounts of carbon, and are resistant to fire. Snags provide habitat for cavity-nesting birds, small mammals, insects, lichens, reptiles, amphibians, and fungi (Bull, 2002; Bunnell *et al.*, 2002; Innes *et al.*, 2008), yet can be dangerous to fire-fighters. Down wood provides habitat for animals from amphibians to mesocarnivores, sequesters mineral nutrients, and may enhance restoration of plant species diversity by creating heterogeneity in burn intensity when fire occurs (Wayman and North, 2007). Understory plants such as shrubs, forbs, and grasses are the largest source of plant species diversity in mixed conifer forests, and they provide forage to early-seral associates such as mule deer, towhees, hummingbirds, and black bear. Monitoring fire hazard, though physics-based models, is key to understanding the success or failure of the treatments. The concept is to simulate fire behavior under conditions of high wind and heat, to predict whether a running crown fire would be initiated and/or sustained if ignition of the understory were to occur (Albini, 1976).

An additional monitoring question regarding how the treatments affected spotted owl habitat, was analyzed with the post-1 year treatment data. However, because only 14 of the post-5 treatment units were considered suitable spotted owl habitat prior to treatment, this analysis was not attempted for the post-5 year data set. See Bigelow et al. (2012) for the spotted owl analysis.

A stand structure monitoring program was established at the outset of the project, in which monitoring plots were established in stands that were scheduled to undergo silvicultural treatment. The study design called for plot measurements prior to, one year after, and five years after treatment. One hundred and seventy pre-treatment plots were established and measured, but because treatment implementation was staggered over many years it was only possible to obtain five-year post-treatment data on 64 of these plots. The present report focuses on the trajectory of these 64 plots from before treatment through five years after treatment. The plots underwent a variety of silvicultural practices (Table 1) and we did not attempt to determine the effects of particular prescriptions on forest elements; our goal was to describe the effects of the management regime as a whole.

Table 1—Allocation of 64 units in Plumas, Lassen, and Tahoe (Sierraville ranger district) national forests to prescription (units in defensible fuel profile zones [DFPZ] or aspen restoration areas), group selection (GS), and/or prescribed understory burning treatments.

DFPZ	Prescription	GS	Unburned	Burned
Y	Hand Thin/Pile	N	0	6
Y	Mastication	N	3	1
Y	Mechanical Thin	N	19	22
Y	Underburn only	N	0	1
Y	Mechanical Thin	Y	2	3
Y	Underburn only	Y	0	1
N	None	Y	5	0

N	Aspen restoration	N	1	0
	Totals		30	34

As the first national forests in the Sierra Nevada to undergo large-scale fire-oriented silviculture treatments, these forests have received intensive monitoring, in part as a test of whether forest conditions can be maintained or improved by fuel-reduction treatments in conjunction with a regime of gap-creation, i.e., group selection. The elements monitored provide a picture of the effects of contemporary, fuels-oriented forest management on the forest environment.

Study Site and Methods

The study took place in Plumas and Lassen National Forests, and the Sierraville ranger district of Tahoe National Forest (Fig. 1). The region is characterized by a Mediterranean climate with wet winters and dry summers. Long-term annual precipitation for the area is 37.4 (11.7) inches (mean and standard deviation), and average precipitation during the June to September summer is 2 inches (1896-2010; data from Chester, Canyon Dam, Greenville, and Quincy weather stations via the Western Regional Climate Center; http://www.wrcc.dri.edu). The forests span the main crest of the Sierra Nevada range; because moisture-laden winds come predominantly from the west, the western slopes tend to have higher precipitation. The long-term minimum winter (December-February) average temperatures is 22.9 (3.3) °F, and average maximum summer temperature (June through September) is 82.8 (1.9) °F.

Forest types in the study were classified as Sierran mixed conifer, white fir, ponderosa pine, east side pine and aspen types in the California Wildlife Habitat Relationship system (Mayer and Laudenslayer, 1988). The 64 units for which five-year post-treatment follow-up data were available comprised 25 Sierran mixed conifer, 9 white fir forest types, 22 east side pine, and 8 ponderosa pine. Most sample units were within the DFPZ network, but many of the group selection stands were not. Treatments included group selection, mechanical thinning, underburning, mastication, and/or hand-thinning and pile burning (Table 1). Under-burning was a scheduled follow-up treatment to reduce surface fuels in many areas, and the first post-treatment measurement was intended to occur after under-burning under the original monitoring design. Because implementation of many burns was delayed, the monitoring plan was modified to allow the first post-treatment stand assessment to occur before under-burning was done.

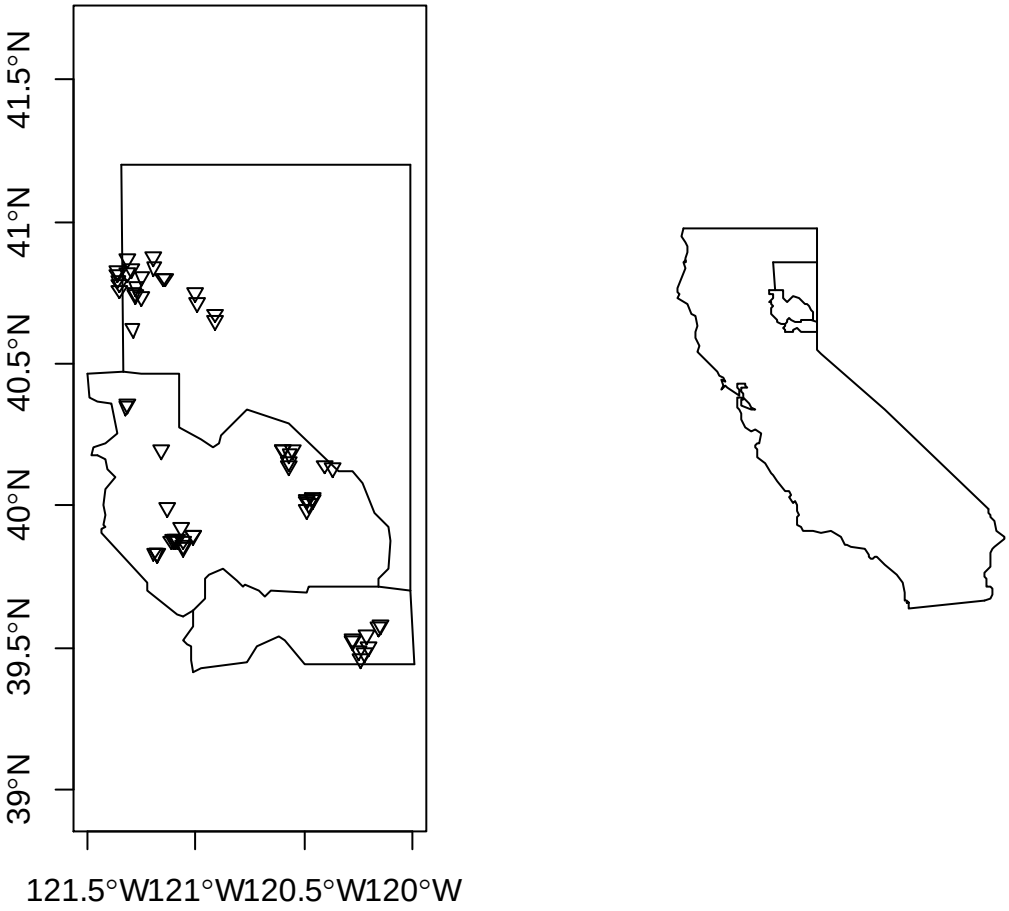

Figure 1. Map of sampling sites (triangles); outlined shapes are Lassen (northernmost), Plumas, and Sierra counties in northern California.

Plot Establishment

Each plot was made up of three ¼ acre rectangular large-tree plots (LTPs) that were located randomly within a sample unit (Fig. 2). The LTPs had dimensions of 165 by 66 ft and contained nested subplots: one medium-tree plot (MTP; 1/8th acre, 165 × 33 ft), one small-tree plot (STP; 1/16th acre plot, 165 ×16.5 ft), five understory tree plots (UTP; 1/250 acre, 13.2 ×13.2 ft), and five understory groundcover plots (UGP; 1/1000 acre, 6.6 × 6.6 ft). Permanent tags were attached to down logs and live and dead trees. Plot boundaries were ≥ 20 ft from roads. Pre-

treatment exams were conducted between 2001 and 2007. Follow-up exams, nominally one year post-treatment, were generally done within one to three years after mechanical treatment. Data on live and dead trees were archived in the US Forest Service's Common Stand Exam database. The Forest Vegetation Simulator was used to summarize data on stand basal area, and output was archived in a dedicated database (TSSM; available upon request to USFS Herger Feinstein Monitoring program). The dedicated database also contains information on prescriptions, dates of treatments, and treatment objectives.

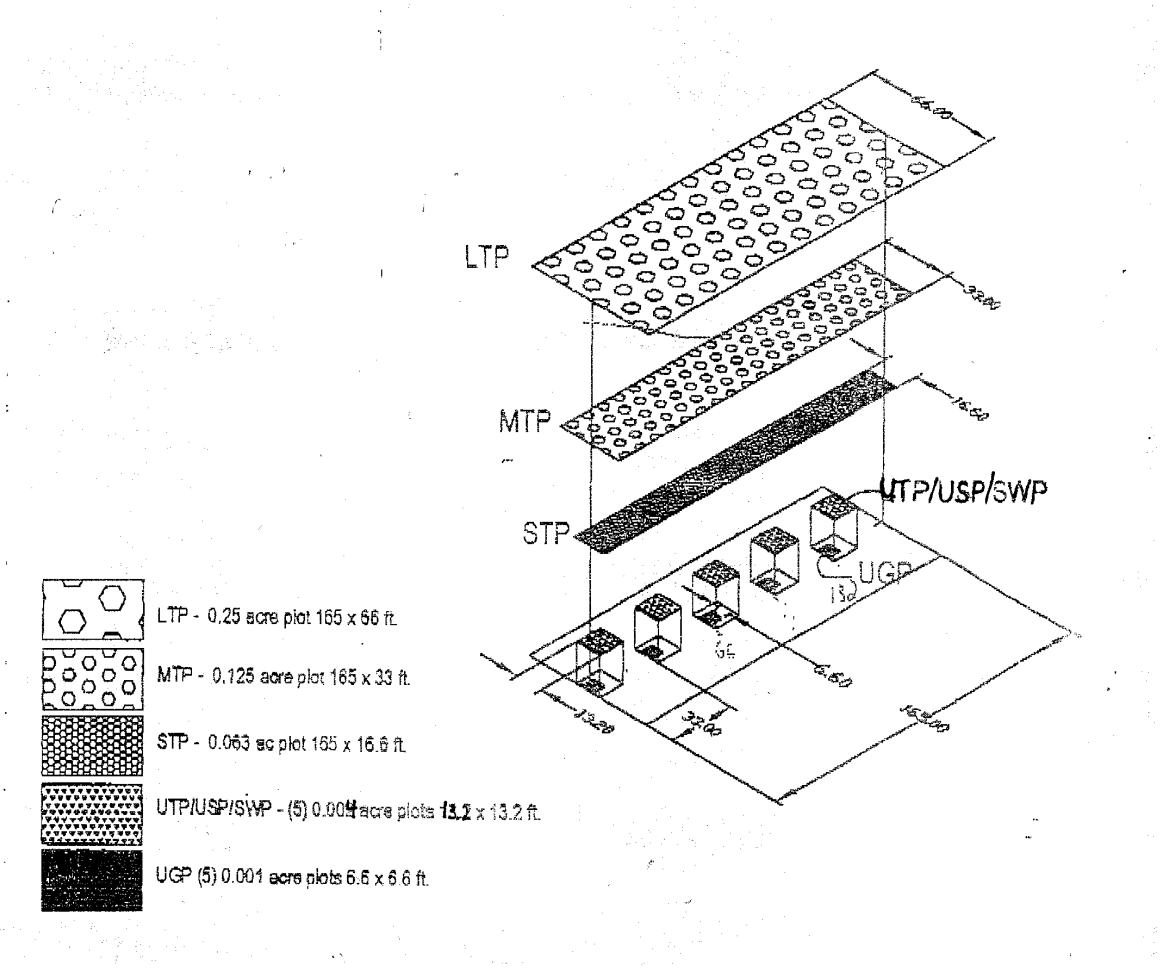

Figure 2.Layout of ¼ acre sampling plots and nested subplots.

Several of the monitored attributes had target ranges suggested in the Sierra Nevada Forest Plan Amendment (USDA Forest Service, 2004)and specified in project planning documents, and we tested exam data for attainment of targets when applicable. Typical canopy cover targets for dense west side stands are 40% whereas targets for eastside stands are usually lower, or in some cases canopy cover was not part of the silviculture prescription. Sierra Nevada Forest Plan Amendment prohibits removal of large trees under most circumstances, and management objectives for most projects include retaining all large trees. Average snag densities should vary from 3 to 8 per acre depending on location within the landscape. Goals for large down woodare to retain 10-15 tons/acre averaged over the treatment unit in west side vegetation types, and three large down logs per acre in east side vegetation types (USDA Forest Service, 2004).

To compare the number of stands in compliance with target objectives among exams we used McNemar's testas implemented in the base R statistical computing language (Agresti, 1990; R Development Core Team, 2012). This test is a variation on the chi-square test of proportions that is appropriate for matched pair data such as sequential measurements on a stand. All three possible treatment comparisons were made, i.e., pre- versus post-1, post-1 versus post-5, and pre- versus post-5 treatments.

Canopy Cover and Basal Area

Vertically projected canopy cover was measured by sighting the canopy at 16.5 ft intervals along three lines in each of the three LTPs per unit with a vertical sighting tube (canopy densitometer; Geographic Resource Solutions, Arcata CA). Canopy cover was expressed as the number of sighting points with foliage vertically overhead divided by the total number of points

(90 points per unit) where sightings were taken. The results were analyzed with the statistical model

$$y_{ik} = \mu + \alpha_i + \beta_j + \gamma_k + \varepsilon_{ik},$$

where, y_{ik} is an individual canopy cover observation, μ is the mean, α is an estimate of the effect of time of exam (*i* indicates pre-, post-1, or post-5 year),β is an estimate of effect of ecological zone (*j* indicates west or east side),γ is a random normally distributed variable for plot (*k* indicates plot number), and the error term ε is also normally distributed. The data set consisted of 192 canopy cover observations, or $i \cdot k$ = 3 exams × 64 plots. Exploratory data analysis showed no interaction between exam and ecological zone. The statistical model was fitted with the *lme* procedure of the *nlme* package in *R* (Pinheiro *et al.*, 2012).

Canopy cover targets were assigned to most projects prior to treatment. Management guides provided suggested canopy cover targets that were specific to ecological zones, but managers were encouraged to define their own targets for their projects (USDA Forest Service, 2004). Most targets were specified as a single value (e.g., “maintain 40% minimum canopy cover”), but some were given as ranges. In order to develop a uniform system, we defined successful attainment as having post-treatment canopy cover within +/- 7 percent canopy cover of target canopy cover (e.g., 33%-47% range for 40% canopy cover target). Only stands with canopy cover targets assigned prior to treatment (53 of 64) were included in the analysis with McNemar’s test.

Basal area was calculated from tree breast-height diameter (DBH) measurements. All trees ≥ 6 inches DBH were measured in STPs (small tree plots), all trees ≥ 16 inches DBH were measured in MTPs, and all trees ≥ 30 inches DBH were measured in LTPs. Stand basal area was

grouped in four DBH classes: 6–11.9 inches, 12–23.9 inches, 24–29.9 inches, and ≥30 inches. Initially all DBH classes were included in a single analysis, but because of interaction between exam and DBH class and differing variances among DBH classes, basal area was analyzed separately by DBH class using the same approach as for canopy cover. In the two smaller size classes, variance was estimated separately for pre-treatment and post-treatment stands because variance decreased sharply after treatment. Total stand basal area (sum of all DBH classes) and quadratic mean diameter (i.e., average individual-tree basal area, converted to diameter; trees ≥5 inches DBH) area were also analyzed statistically.

Snags

Snags were tallied along with live trees following the same system of diameter class cutoffs. Fifteen inches is considered a minimum DBH for snag use by many wildlife species, so we only considered snags greater than or equal to this size. We tested for changes in mean snag density as a result of treatment according to ecological zone. Tests were done with a statistical model similar to that used for canopy cover (i.e., a mixed model with fixed effects for the exam and ecological zone variables and random effects for the plot variable), except that a log-link function was applied to the snag-count response variable and the error term was modeled with the negative binomial distribution(Bolker, 2008). This approach, known as generalized linear mixed modeling, is suitable for count data in which there are many zeros (Atkins *et al.*, in press). Snags were sampled in plots < 1 acre in size then scaled to per-acre density, and density values were rounded to integers for statistical analysis. Interaction between ecological zone and time was not modeled because a likelihood ratio test of statistical models with and without interaction was not significant. Analyses were done with the *glmmADMB* package in R (Fournier *et al.*, 2012).

Snag retention targets, generally 3, 4, or 8 snags per acre, were assigned to projects prior to treatment; the higher targets were assigned to more productive west side sites (p. 69; USDA Forest Service, 2004). A McNemar's chi-squared test of proportions was applied to determine whether post-treatment attainment differed from pre-treatment attainment (Agresti, 1990).

Down Wood

Down logs ≥ 10 inches in large-end diameter and ≥ 10 ft long that had their large end within LTPs were measured for length and large-end diameter. Aluminum tags were nailed to logs during the pre-treatment survey; logs that were too decayed to retain a nailed tag were disregarded. Log weight was calculated by multiplying estimated volume by a coefficient for specific gravity that differed for sound and decayed logs(Brown, 1974). Volume was calculated from log large-end diameter, length, and an estimate of small-end diameter from a taper equation (Biging, 1984). The taper equation required whole-tree height, which was estimated by creating species-specific linear equations predicting height from DBH from the live-tree survey. Parameters for white fir were substituted for species other than the major commercial conifers. Data were summarized in 9-19.9 inch and ≥20 inch large-end diameter classes. Because down wood was distributed patchily, with many plots containing no down wood and few plots containing high loads, data were analyzed in the same way as snag data, i.e., with negative-binomial based mixed model with a log-link function implemented in the *glmmADMB* package in *R*(Fournier *et al.*, 2012).

Suggested targets for large log retention were provided as weights (tons/acre)for west side stands and densities (logs/acre) for east side stands (USDA Forest Service, 2004). To have a consistent metric, we converted log density targets to weights based on the assumption that one log weighs 1000 lb. Attainment of log retention targets was defined as having log weight greater

than or equal to the target. To allow for the possibility that our sampling scheme had underestimated log weights due to lack of measurement of highly decayed wood, we adjusted target weights. We used an independent dataset from the same area (HFQLG soils monitoring group) to estimate the fraction of total down wood weight contributed by sound logs (0.6 = sound log weight/total log weight), and multiplied minimum target weights by that fraction. Change in target attainment from pre- to post-treatment was analyzed with McNemar's test (Agresti, 1990).

Understory plants

Shrub cover was assessed in UTPs (understory tree plots) and forb and grass or grass-like (graminoid) plant cover was assessed in UGPs (understory groundcover plots). Total cover of any species that made up ≥10% of each plot was estimated visually and recorded in 10% cover increments. Non-palatable, less-preferred, or otherwise noxious species in the study area such as bull thistle, chinquapin, cheatgrass and bracken fern were screened from the data and not included in analyses (these constituted a very small proportion of observations). Average cover per life form in each sampling unit was calculated by dividing the sum of cover by 15 (i.e., the number of subplots per plot).

Distribution of forbs and graminoids was highly patchy and many plots were entirely lacking in these life life-forms. The patchiness was manifested in a right-skewed frequency distribution, and we therefore used a negative binomial mixed model with log link (as described above for snags and down wood) for forbs and graminoids implemented in the statistical package *glmmADMB* in *R* (Fournier *et al.*, 2012). Cover estimates were rounded to integers for statistical analysis. Shrub distributions were normal and we therefore used a mixed model with normal error distribution in the *nlme* statistical package (Fournier *et al.*, 2012).The statistical model was

the same as the one for canopy cover, except that a likelihood ratio test indicated the need for a term for interaction between exam and ecological zone.

Fire Behavior Modeling

Fire behavior was simulated under moderate (90th percentile) and severe (97th percentile) weather conditions with the fire and fuels extension to the forest vegetation simulator (Rebain *et al.*, 2011). The fire and fuels extension uses physically based equations to estimate fire intensity from wind speed, air temperature, plot slope, and fuel amounts, surface area, and moisture (Rothermel, 1972). Fire intensity has both vertical (flame length) and horizontal (rate of spread) components. The estimated fire intensity is combined with information on tree density, species composition, size distribution, and crown depth to predict how a fire would behave if ignited in that stand. Fires are classified according to whether torching (crowns of large trees being ignited by surface fire)and/or crowning (fire passing from crown to crown of large trees) are predicted to occur. A surface fire has neither torching nor crowning, a passive crown fire has torching but not crowning, a conditional crown fire has crowning but not torching, and an active crown fire has both torching and crowning.

Weather and fuel moisture conditions for the simulations were obtained from nine remote access weather stations near the study plots. Wind speed, air temperature, and live and dead fuel moistures were calculated for 90th and 97th percentile conditions for the period 1998-2008; each plot was assigned weather conditions from the nearest station. Surface fuels (those within 6 feet of the ground) were estimated visually in the UTPs with the photo series method. A local fuels expert used these measurements and plot photographs, along with information on shrubs and herbs (see earlier sections), and stand type to select among a limited number of fuel models

(Table 2) to characterize fuel bed depth, and surface fuel loads and surface-to-volume ratios within each surface fuel size class(Anderson, 1982).

Table 2. Characteristics of fuel models (FM) used for fire behavior simulations.

FM	Description	Fuel loads (tons/acre)				Fuel bed depth (ft)
		1 hr	10 hr	100 hr	Live	
2	Timber (grass & understory)	2	1	0.5	0.5	1
5	Brush	1	0.5	0	2	2
8	Closed timber litter	1.5	1	2.5	0	0.2
9	Hardwood litter	2.9	0.4	4.5	0	0.2
10	Timber (litter & understory)	3	2	5	2	1
11	Light logging slash	1.5	4.5	5.5	0	1

Results

Canopy Cover and Basal Area

Mean canopy cover decreased by an average 15 percent canopy cover (e.g. 45%canopy cover reduced to 30% canopy cover) after treatment ($p < 0.001$), and did not change significantly between 1 and 5 years after treatment ($p = 0.56$; Table 3).Despite the lack of change in the mean, the canopy cover of individual units often changed substantially; standard deviation of the change in canopy cover between 1 and 5 years post treatment was 8.4 canopy cover. Mean pretreatment canopy cover in east side forests was 47%, and mean difference between canopy

cover in west side and east side forests, averaged across exams, was 6 percent canopy cover (west > east, marginally significant at $p = 0.07$).

Prior to treatment, canopy cover was within the target range in 21% of the 53 stands with specified targets (Table 4); most of the remaining stands had canopy cover higher than the target range. One year after treatment, 36% of stands met canopy objectives, a marginally significant increase ($p = 0.08$, McNemar's test). Many of the stands that were above the target range before treatment were below the target range at 1 year after treatment. By five years after treatment, the proportion of units in attainment had dropped to 32% because increases in canopy cover had put some stands out of their target range.

Table 3—Canopy cover, basal area (live trees ≥ 6 inches DBH) and quadratic mean diameter (live trees ≥ 5 inches DBH; means and standard deviations) pre-, 1 year after, and 5 years after treatment by ecological zone; Plumas, Lassen and Tahoe (Sierraville ranger district) national forests

Zone		Canopy Cover (%)			Basal area (ft^2/acre)			Quadratic mean diameter (inches)		
	n	*Pre**	*Post 1*	*Post 5*	*Pre**	*Post 1*	*Post 5*	*Pre*	*Post 1*	*Post 5*
West	21	49^a(16)	38^b(17)	37^b(14)	162 $(75)^a$	133 $(67)^b$	134 $(66)^b$	13.3 $(3.2)^a$	16.0 $(4.6)^b$	16.4 $(4.7)^b$
East	43	47^a(15)	29^b(9)	31^b(10)	125 $(53)^a$	85 $(30)^b$	89 $(31)^b$	12.0 $(2.1)^a$	14.5 $(2.8)^b$	15 $(2.9)^b$

* Means with different superscripts within a line differ with a type-1 error probability of $p<0.05$

The influence of treatment and ecological zone on basal area changed strikingly across DBH classes: in the smaller size classes, treatment had a strong effect and ecological zone did not, and in the larger size classes the opposite was true. In the 6–11.9 inch class, mean pre-treatment basal area varied from 33.6 ft^2/acre in the east to 37.8 in the west (not significantly different; $p = 0.36$), decreasing by 17.8 ft^2/acre after treatment ($p < 0.001$) and remaining unchanged four years later. In the 12–23.9 inch DBH classes, mean pre-treatment basal area varied from 69.9 ft^2/acre in the east to 76.3 in the west ($p = 0.38$), decreasing by 15.0 ft^2/acre after treatment ($p < 0.001$). By four years after treatment a statistically significant increase of basal area from tree growth of 4 ft^2/acre had occurred ($p < 0.001$). Pre-treatment basal area of the 24–29.9 inch DBH class differed strongly from east side (8.1 ft^2/acre)to west side (22.4 ft^2/acre; $p < 0.001$). Mean basal area in this size class did not decrease significantly 1 year after treatment, and had increased by 1.9 ft^2/acre by 5 years after treatment ($p = 0.02$).For the largest trees (≥30 inches DBH) the east side stands had basal area 2.5 ft^2/acre compared to 16.7 ft^2/acre in west side stands (different at $p = 0.0001$). At the 1-yr post-treatment census mean basal had increased by 2.0 ft^2/acre ($p = 0.08$), but did not increase further at the 5 year post-treatment census.

Mean total basal area before treatment (i.e., basal area of all trees ≥6 inches DBH) was 125ft^2/acre in east-side and 162 ft^2/acre in west side stands ($p < 0.001$; Fig. 3). As might be expected from the basal area findings separated by size class, total basal area decreased after treatment (average decrease of 33.3 ft^2/acre) but did not change significantly between the 1-yr and 5-yr exams. Quadratic mean diameter (QMD) differed only slightly between ecological zones (12 inches in the east side, and 13.4 inches in the west side; $p = 0.08$). As expected from treatments that mainly remove smaller trees, QMD increased significantly on average 2.6 inches

at the 1 year post-treatment exam ($p < 0.0001$). QMD had increased slightly further (0.4 inches) at the 5-yr exam ($p = 0.08$).

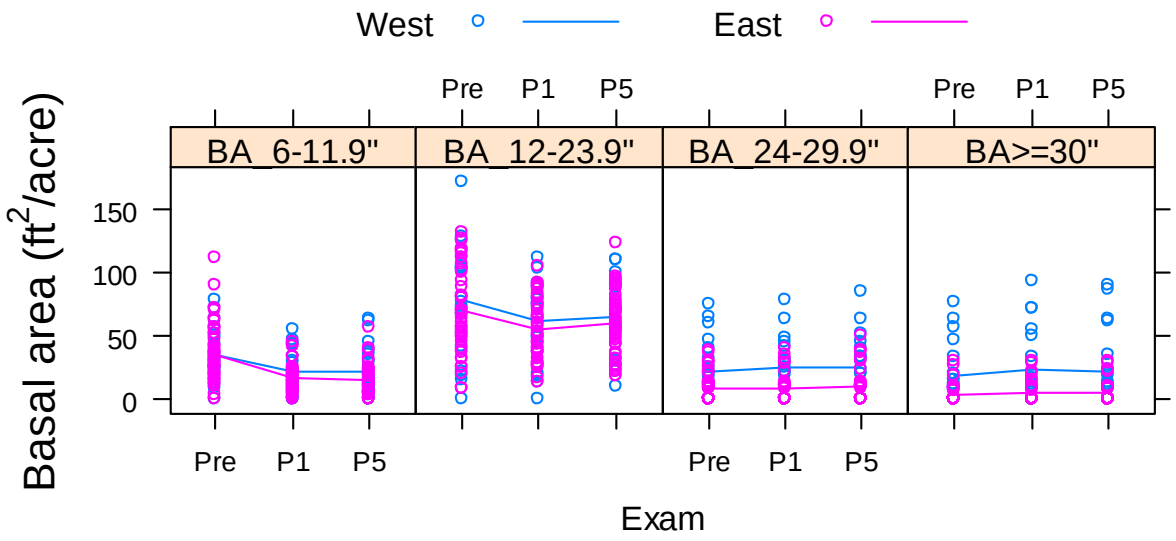

Figure 3. Live tree basal area by diameter size class and ecological zone before (Pre), one year after (P1), and 5 years (P5) after treatment, lines connect statistical means.

Snags

Density of snags ≥15 inches(38 cm) DBH declined by 45% after treatment ($p = 0.002$), remaining unchanged from 1 yr to 5 yr after treatment. Snag density differed significantly among the two ecological zones ($p = 0.008$;Fig. 4): the west side forests had an average pre-treatment snag density of 4.6 per acre (11.4 per ha); the east side, 2.2 per acre (5.4 per ha).

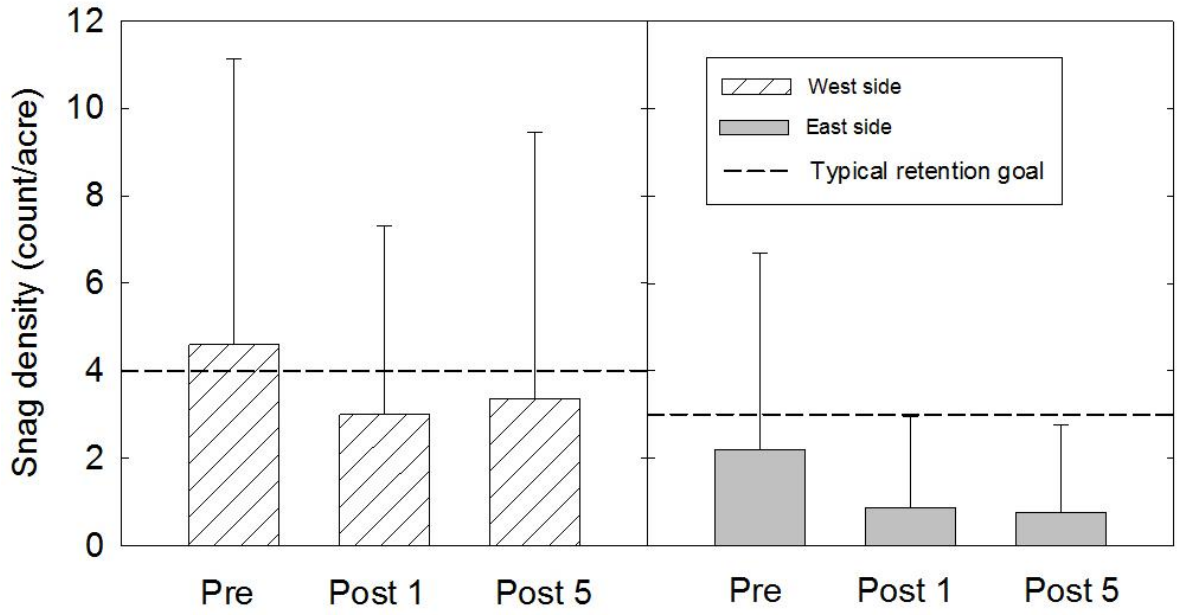

Figure 4. Snag density by ecological zone (i.e, west side and east side)before, 1 year after, and 5 years after treatment. Wide bars are means, and narrow bars are standard deviations based on the negative binomial distribution.

The number of plots in which snag retention objectives were met decreased immediately after treatment but recovered to pre-treatment levels within five years. Prior to treatment, 28% of plots had snag densities at least as high as the target density, but one year after treatment only 14% of plots had target densities(different at $p < 0.01$; McNemar's test). At five years after treatment, the proportion of plots in attainment with snag retention objectives (25%) did not differ significantly from before treatment ($p = 0.72$, McNemar's test) even though mean snag density remained much lower.

Table 4. Proportion of plots in west and east side conifer forest attaining recommended target objectives for canopy cover, large snag count, and large log weights before, one year after and five years after treatment.

Attribute	n	Pre (%)	Post-1 (%)	Post-5 (%)
Canopy Cover*	53	21^{a}	36^{b}	32^{ab}
Large (≥ 15 inch DBH) snag count**	64	28^{a}	14^{b}	25^{a}
Large (≥ 20 inch diameter) log weight**	64	38^{a}	17^{b}	11^{b}

* Values within a horizontal line possessing different alphabetic superscripts differ at $p<0.10$

** Percentages within a line having different alphabetic superscripts differ at $p<0.05$

Down Wood

Mean pretreatment loads, 1.1 and 1.7tons/acre for small (9-19.9" large-end diameter) logs, and 4.2 and 1.4 tons/acre for large (≥20 inch large-end diameter)logs (west and east side respectively), were low compared to suggested targets. Before treatment, west side log loads were similar to east side loads in the small log size class (p=0.61) but greater than east side loads in the large size class (p = 0.04). At one year after treatment, both west and east side large and small log loads were significantly lower than pretreatment (p< 0.01; Table 5). Mean small log load did not change significantly between 1 year and 5 years after treatment (p= 0.31). The pattern of large log biomass accrual diverged on west and east side by 5 years after treatment; east side log loads continued to decline (to 0.2 tons/acre), but west side large log loads recovered to 3.4 tons/acre, a level between the pre-treatment high and 1-year post-treatment low.

Table 5—Down log loads (tons/acre) before, one year, and 5 years after treatment in west and east side ecological zones in Plumas, Lassen, and Tahoe (Sierraville ranger district) national forests.

Zone*	9–19.9 inches**			Zone		≥20 inches		
	Pre	*Post 1*	*Post 5*		*n*	*Pre*	*Post 1*	*Post 5*
West+East	1.5^{a} (2.1)	0.9^{b} (1.4)	1.0^{b} (1.6)	West	21	4.2^{a} (6.1)	2.2^{b} (3.6)	3.4^{ab} (5.7)
				East	43	1.4^{a} (2.1)	0.7^{b} (1.3)	0.2^{c} (0.5)

^{b}means within a line with differing alphabetic superscripts are different at $p<0.1$

Prior to treatment, 24 of 64 plots (38%) had estimates of large log weight that were equal to or greater than the recommended retention target (Table 4). Targets varied from 0.6 tons per acre in east side stands to 6 tons per acre in west side stands; these targets were modified from those recommended in the forest management plan (USDA Forest Service, 2004) to reflect our sampling protocol, which underestimated log weight contributed by severely decayed logs. At one year after treatment, only 11 plots (17%) had large log loads greater than or equal to the target value, a significant change from pre-treatment (p=0.008, McNemar's test) . Five years after treatment there were seven plots meeting target log weights, but this did not represent a significant change from one year post-treatment (p=0.34).

Understory Plants

Treatments more than doubled forb cover in eastside treatment units (Fig. 5). Graminoid cover increased significantly, by more than 50%, in both east side and west side units after treatment. There was a slight decrease in shrub cover in west side units after treatment, which was statistically significant (p = 0.011). Pre-treatment forb and shrub cover were higher on the

west side than the east side (3.3% vs. 1.8 %, and 18.7% vs. 12.5%, respectively). There was little difference in grass cover 3.2% vs. 4.4%, west side vs. east side.

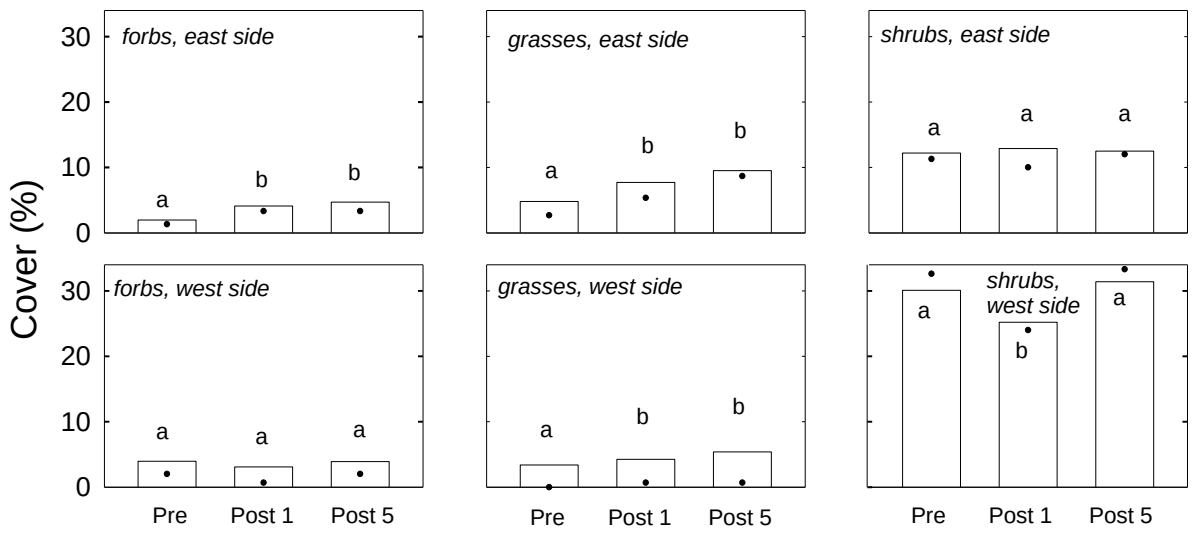

Figure 5.Mean (boxes) and median (dots) cover of forbs, grasses/graminoids and shrubs in east side and west side forest, before and 1 year and 5 years after silvicultural treatment. Columns with different letter superscripts differ at *p*< 0.05.

Fire Behavior Modeling

Fire behavior modeling indicated that treatments changed fire behavior significantly (Fig. 6). The proportion of stands predicted to have active or conditional crown fire if ignited under 90th percentile weather conditions dropped from 34% of stands before treatment to 9% one year after treatment (p = 0.004,χ^2 test of proportions); the change in predicted fire type between 1 year and 5 years post treatment was not significant (p = 0.86, χ^2). Under 97th percentile weather conditions, 45%of stands were predicted to have active or conditional crown fire before

treatment, dropping to 20% one year after treatment ($p = 0.01$, χ^2) and remaining statistically unchanged between one and five years after treatment ($p = 0.79$, χ^2). Most of these stands were converted to a predicted regime of surface fires.

Changes in fire type were driven by characteristics of aerial rather than surface fuels. Estimated crown bulk density decreased significantly with treatment, and estimated canopy base height, an important factor in conveying fire from the forest floor to the canopy, increased significantly (Fig. 7). In contrast, surface flame lengths did not change significantly with treatment, despite significantly increased mid-flame wind spreads (estimated as a function of canopy cover). Increased estimated surface winds may have been mitigated by surface fuel models, many of which were reassigned after treatment. Model 10 (Timber: litter and understory) was used for 45% of pre-treatment stands, but only 12% to 17% of post-1 and post-5 treatment stands, respectively. Model 9 (named ‘Hardwood litter’ but which also has terms for conifer litter) was used for only 39% of pre-treatment stands, increasing to 59% to 55% post-1 and post-5 treatment stands.

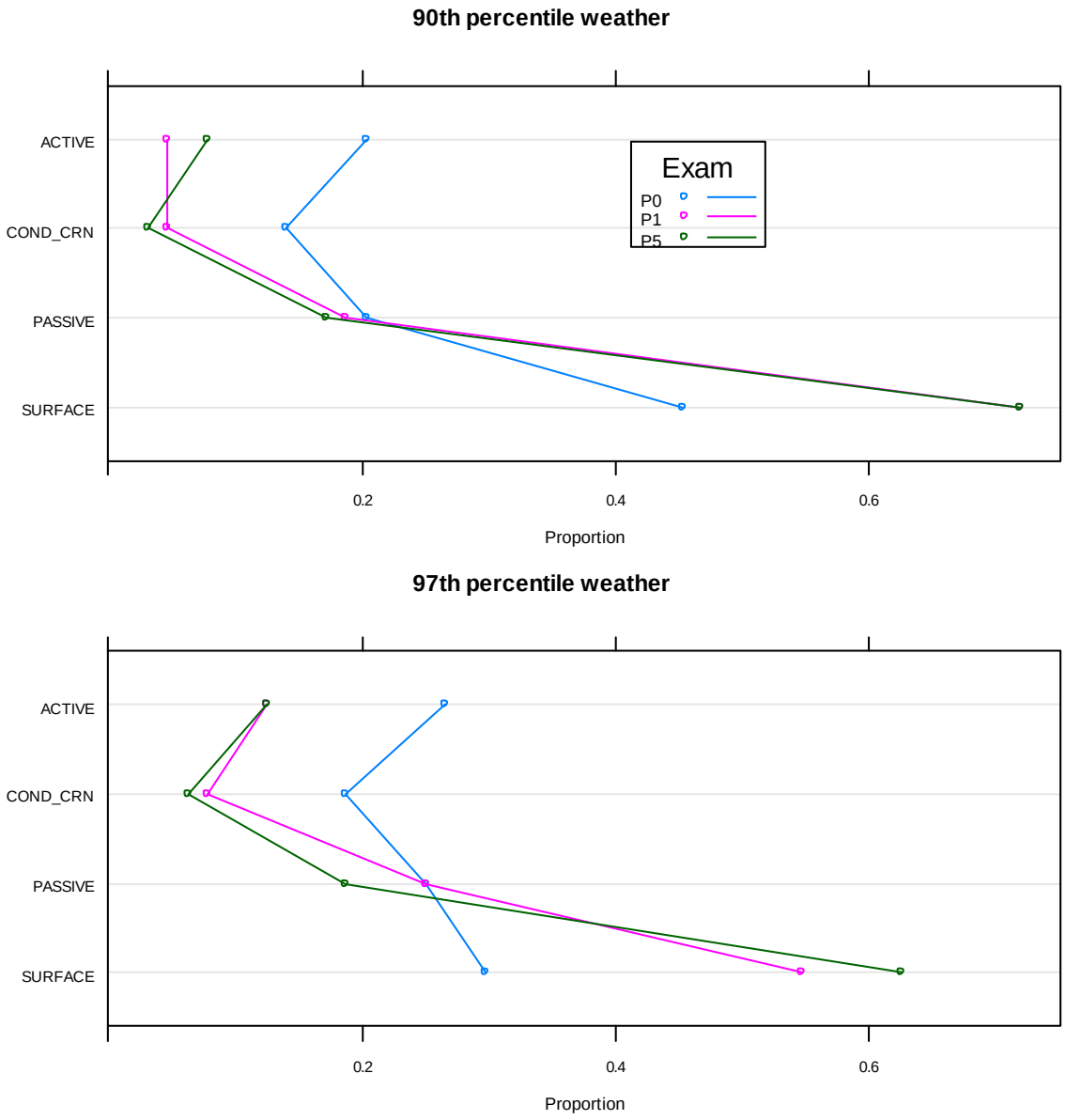

Figure 6. Proportion of predicted fire types (surface, passive crown, conditional crown, or active crown fire) simulated for 64 stands before, one year after, and 5 years after silvicultural treatment; 90thand 97th percentile weather conditions.

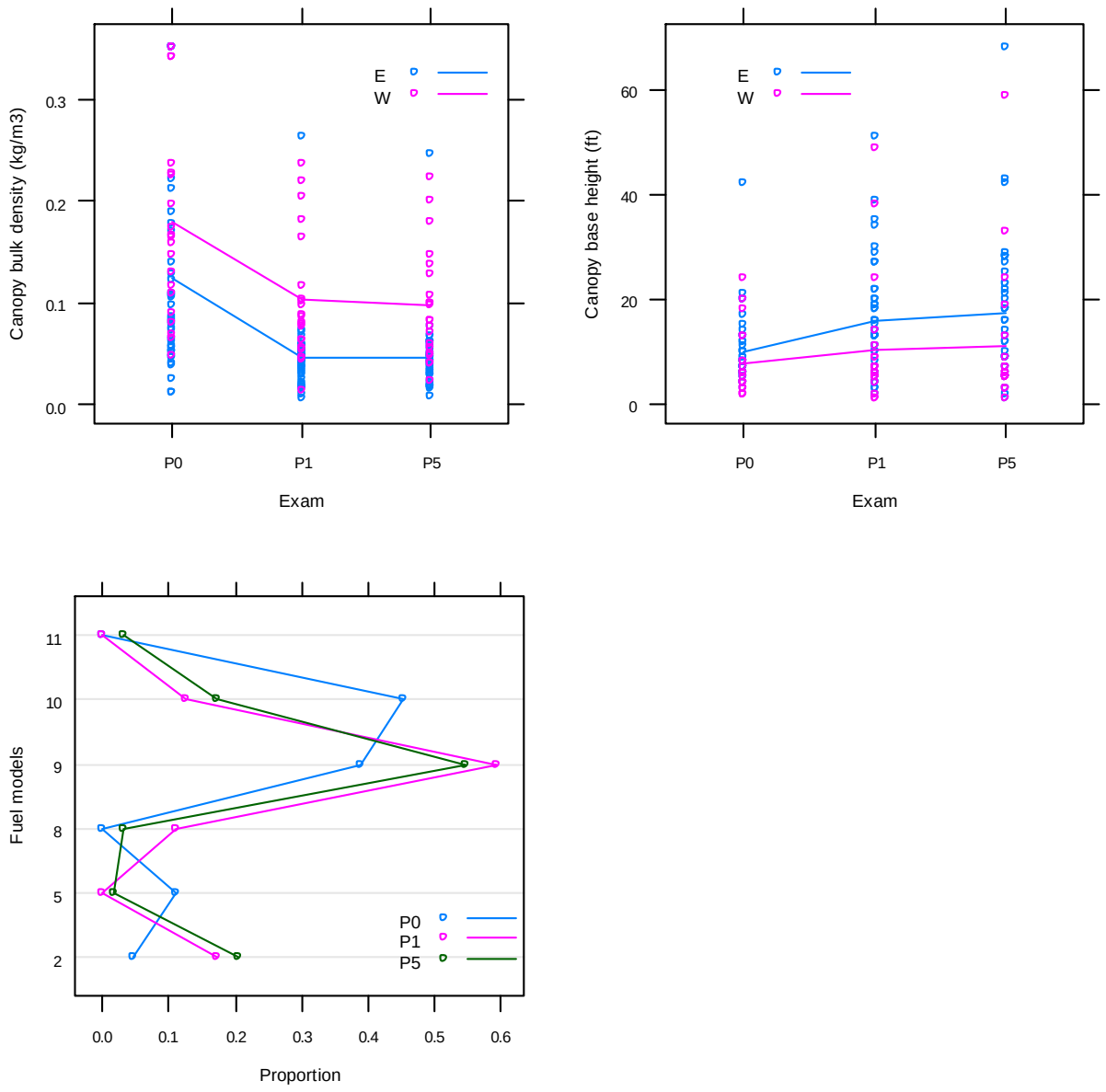

Figure 7. Canopy bulk density, canopy base height, and fuel models used in fire behavior simulations of 64 plots before, one year after, and five years after silvicultural treatment (see Table 2 for fuel model definitions).

Discussion

The untreated forest

Quantitative estimates of pre-treatment forest attributes were similar in most respects to those from similar untreated forests nearby. Mean canopy cover in untreated stands, about 49% in west-side stands and 47% in east side stands, was lower than some published estimates of canopy cover in untreated, fire-suppressed mixed conifer stands (e.g., 63-69% canopy cover in untreated stands at a productive site in the central Sierra Nevada; Stephens and Moghaddas, 2005).Mean pre-treatment large-log loads however, 3.2 tons/acre (≥ 20 inches diameter and≥ 10 feet long), was somewhat low. For comparison, the weight of dead fuels (≥ 6 inches diameter and≥ 3.3 feet long)in untreated forest was 7.4 tons/acre at Blodgett Forest in the central Sierra Nevada, and 19.3 tons/acre (≥ 24 inches diameter and≥ 6 feet long) at Teakettle Experimental Forest in the southern Sierra Nevada. This study excluded a portion of the large-log load that was included in the other studies.

Because of the century and a half-long history of intensive resource extraction from the forest, and what is generally conceded to have been a misguided fire suppression policy (Stephens and Ruth, 2005), pre-treatment data reflect a forest that is degraded compared to the pre-European condition. This degradation is manifested as high density and canopy cover of small-diameter trees, few large trees, low understory plant cover and diversity, low numbers of snags and large down logs, and volatile fire behavior under moderate to extreme weather conditions. Pre-settlement reference conditions for down dead wood in frequent-fire dry forest are uncertain particularly because the accumulation of large-diameter down wood would have been limited by the low-intensity fires that formerly burned at 8-22 year intervals over much of the area now making up Plumas and Lassen national forests (Moody *et al.*, 2006). Still, given the

formerly much higher density of large trees on the landscape, it may be reasonably assumed that large wood loads were considerably greater than under present conditions despite the legacy of a century of fire suppression management. The Pilot Project has sought to restore forest structure and function to pre-European-settlement conditions, while increasing commercial resource extraction beyond the very low levels of the early 1990's (Bernard, 2010). Monitoring of the short-term effects of the Pilot Project implementation shows areas both of improvement and of further degradation in forest condition. It also documents the ability of managers to achieve management targets and suggests some areas in which current practice may be modified to enhance management outcomes.

The monitoring scheme in the present report departs from standard research designs in that there are no controls, only measurements before and after treatments. Therefore, measurements reflect not only the effects of management treatments, but also changes taking place naturally over time. In general, the factors measured change slowly over time (e.g., canopy cover; Bigelow and North, 2012), and we have assumed that the changes detected have been due to management treatments. The monitoring scheme did not readily allow estimation of effects of different practices (e.g., fuels-reduction-thinning vs. group selection), and there has been no attempt to do so in the present analysis. An additional caveat is that many of the post-treatment measurements were done on plots in which treatment was incomplete, insofar as the application of prescribed fire for surface treatment of fuels has lagged far behind the mechanical treatment of fuels. Post-treatment monitoring data reflect treatments as implemented rather than as planned.

Treatment effects on the landscape

The mean level of canopy cover reduction, 15% canopy cover, suggests that treatments did not have a drastic effect on the forest ecosystem. Mean residual canopy cover in east side

stands, 29-31%, was at the upper end of the range of a historical reconstruction of stands in a mixed conifer forest under a natural fire regime, (Collins et al., 2011), and as such does not appear excessively low. The rather low attainment rate of canopy cover objectives (36% at one year post-treatment) was primarily due to stands that fell below the targeted canopy cover range. The lack of change in mean canopy cover in the present study between one and five years post-treatment would seem to imply that the canopy will re-grow only slowly, but the considerable dynamism in canopy cover of individual stands shows that canopy cover can potentially increase rapidly. Causes of the counterbalancing decreases in canopy cover between one and five years after treatment were not investigated but if due to transiently elevated post-treatment tree mortality then mean canopy cover could increase rapidly in the future. The trend in the proportion of stands meeting canopy cover target guidelines (36%at one year post-treatment, but down to 32% at 5 years post-treatment) was due primarily to canopies growing out of the target attainment range.

The lack of decrease, and indeed marginally significant increase, in basal area of the largest trees (≥30 inches breast-height diameter) implies that these trees were adequately protected during forest operations, which was an important treatment goal. The diameter class analysis indicated that treatments succeeded in making the diameter-class distribution flatter by removing many small and small-to-intermediate diameter trees while retaining intermediate-to-large and large ones. Although making the diameter distribution flatter was not a specific goal of the treatments, it is consistent with the Quincy Library Group vision of approximating the pre-settlement landscape (Yost, 1994; North *et al.*, 2007).

Snag retention guidelines represent a compromise between preserving habitat values and protecting firefighters; notably, managers were not directed to maintain current levels of snags in

project areas but simply to consider large snag retention guidelines during project planning (USDA Forest Service, 2004, p.69).Given that the proportion of stands in attainment with snag retention objectives was no different before and five years after pre-treatment, implementation should be considered successful with respect to snag objectives. Nevertheless, from a habitat perspective the snag trends are troubling because of the substantial decline in mean snag density relative to pre-treatment. Indeed, the low proportion (28%) of pre-treatment stands in attainment with snag retention objectives suggests that there is a landscape-level snag deficit, at least in the treated portion of the landscape, that may limit the habitat available for certain wildlife species (Bull, 2002; Bunnell *et al.*, 2002; Innes *et al.*, 2008).

Just as with snags an initial scarcity of medium and large-sized logs on the landscape was exacerbated by treatment, causing mean loads to drop by one third (9-19.9 inch large-end diameter logs)to one half (≥ 20 inch large-end diameter logs) of pretreatment levels. The initial scarcity is reflected in the modest proportion of plots (38%) that had loads at least as high as the target level. Most of the plots that were initially above target were in the east side, which was a reflection of the rather low east side target levels, i.e., 0.6 tons/acre of sound wood. The longer term trend, from one to five years post-treatment, is mixed in that responses varied from stable (medium logs) to further drop (large logs on the east side) to slight recovery (large logs, west side). Treatments should be viewed as having failed at the objective of producing ‘the desired abundance and distribution’ of logs.

The life-form spectrum, or relative abundance of plant life-forms, is a reflection of climate, topography, disturbance regime, and competition from neighboring vegetation (Raunkiaer, 1934). Abundant shrub cover is common in forests of Mediterranean climates, and shrub cover in the present study, with mean 10% (east side) to 30%(west side), exemplified this

trend. The proportion of understory cover contributed by grasses relative to shrubs typically increases as environmental conditions become more demanding, e.g., drier, more exposed, or at higher elevation (Abella and Covington, 2004; Gracia *et al.*, 2007; Coll, 2011), and our study area displayed this trend from west to east. Although forest treatments led to increased cover of graminoid(east and west sides) and forb (west side only) lifeforms, the increases were small compared to those seen in other manipulative studies in mixed-conifer forest. For example, thinning and burning treatments in the southern Sierra Nevada caused a shift from shrub-dominated to herb-dominated communities, with herb cover increasing by a factor >10 (Wayman and North, 2007). In our study, a post-treatment decrease in west side shrub cover proved to be transient, indicating that on the whole the treatments can be viewed as having fulfilled the goal of increasing the amount of vegetation available for wildlife species that rely on early seral stage habitat.

The predicted decrease in conditional and active crown fire behaviors under moderate and extreme weather conditions up to five years after treatment suggests that this vital function of the treatments has been properly fulfilled. Elsewhere within the larger study area fuels treatments have been empirically demonstrated to be effective against high-intensity fire (Moghaddas and Craggs, 2007; Safford *et al.*, 2012), which lends credence to the prediction that most of the treated stands would not support a crown fire under the foreseeable range of weather conditions. Despite these encouraging results, limitations of models prediction must be borne in mind given that fire spread simulation models based on the Rothermel equations may substantially under-predict conditions under which the transition from surface to crown fire will occur (Cruz and Alexander, 2010; Moghaddas *et al.*, 2010). A further important factor is that treatments did not decrease predicted surface fire behavior, possibly because any decreases in

surface fuels (as estimated visually in photo-series, and reflected in choice of fuel models) may have been counterbalanced by increases in predicted understory wind velocity.

Conclusions

The HFQLG 'Pilot Project' program (1999-2012) featured fuels-reduction thinning of northern California mixed-conifer forest in a system of defensible fuel profile zones, and area-regulated group selection with reserves. Short- and medium-term monitoring examined treatment effects on forest structure and function and has tested the ability of treatments both to achieve explicit quantitative management targets, and the implicit goal of moving the landscape closer to a pre-settlement reference structure. Achieving specified canopy cover targets proved difficult and canopy cover was frequently reduced to below the target range although the mean canopy cover reduction, 15%, was not excessive. For canopy cover, as for most metrics, there was no significant change from one year to five years post-treatment. Management targets for snags and large down logs proved unrealistic in the heavily exploited Plumas-Lassen-Tahoe forests, instructing foresters to "retain" these at levels that usually exceeded the quantities present before treatment. After the inevitable treatment-induced attrition of snags and dead logs, the small amounts remaining on the landscape are cause for concern. Other wildlife habitat elements fared better: large trees, also a key element for wildfire fire resilience, were successfully avoided and growth of understory forage (grasses, forbs) was increased. The *sine qua non* of the HFQLG program, protection from high-severity wildfire, was significantly enhanced by the treatments although fire behavior simulations indicated that under extreme weather conditions roughly 30% of stands remain susceptible to crown fire. Time will be the ultimate arbiter of the HFQLG treatments, but given the increasing onslaught of vast high-severity wildfires in the western USA they may prove to have been a sound investment in the forest's future.

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