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Article

Development of Vegetation and Surface Fuels Following Fire Hazard Reduction Treatment

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Abstract: In dry western Unites States forests where past resource management has altered the ecological role of fire and stand characteristics alike, mechanical thinning and prescribed burning are commonly applied in wildfire hazard abatement. The reduced surface fuel loads and stand structures resulting from fuels modifications are temporary, yet few studies have assessed the lifespan of treatment effects. We sampled forest fuels and vegetation following fuels reduction in a chronosequence of time since treatment in the northern Sierra Nevada and southern Cascade regions of California. Treatments altered overstory characteristics including stand density, basal area, and species composition. These effects were still present on the oldest treatment sites (8–15 years post-treatment). Other stand characteristics, particularly timelag fuel loads, seedling density, and shrub cover, exhibited substantial variability, and differences between treatment age classes and between treatment and control groups were not statistically significant.

Keywords: eastside pine; fire hazard; fuel break; fuel treatment longevity; Jeffrey pine; mixed conifer; prescribed fire; Sierra Nevada; thinning

1. Introduction

The disturbance role of wildfire in many dry, temperate western United States forests has been altered through fire exclusion, timber harvesting, and livestock grazing. These land-use practices have affected forest structure and species composition, increasing surface fuel loads, tree density, dominance of shade-tolerant tree species, and forest homogeneity [1–3]. As a consequence, many historically fire-frequent forests are now vulnerable to spatially extensive high-severity wildfire [4]. A primary focus of contemporary management in these forests is the treatment of fuels and vegetation to address wildfire hazards.

Fuels reduction treatments are intended to reduce the potential for high-intensity, high-severity wildfire by reducing the quantity and continuity of forest fuels. A number of techniques are employed to meet these fuels reduction objectives, and each method has associated effects on forest structure. Mechanical thinning reduces stand density, basal area, and canopy fuels [5–7]. To reduce accumulated surface fuel loads and offset the activity fuels produced during harvest operations, prescribed fire is often coupled to forest thinning. Broadcast burning can also be expected to reduce ladder fuels and elevate canopy base height [8,9]. Research generally supports the ability of such treatments to alter potential fire behavior and impacts [5,8,10–14].

Though the immediate effects of treatment on forest fuels and stand structure are relatively well known, the long-term consequences remain poorly understood. Post-treatment conditions are impermanent: after treatment, the overstory responds to take advantage of newly available growing space, filling the canopy space vacated by thinned trees; the canopy base falls in height as new regeneration joins the overstory; and surface fuels accumulate as the canopy deposits leaves, cones, and branches. Some treatment techniques may actually enhance post-treatment vegetation growth, effectively shortening the lifespan of low fire hazard conditions. Reducing overstory density has long been recognized to promote regeneration [15] and increase understory growth [16,17]. Additionally, the exposure of mineral soil by prescribed burning fosters seed germination [18]. In order to retain low fire hazard conditions, areas that have been treated must be maintained following their initial establishment. However, few management tools exist to guide the division of resources between establishment of new treatments and maintenance of existing treatments.

In this study, we assessed dead fuel loads, shrub cover, regeneration, and overstory characteristics in a chronosequence of sites treated for fuels reduction in the northern Sierra Nevada and southern Cascade regions of California. Sampling sites were stratified on the basis of forest type: Sierra mixed conifer and eastside pine forests are present in the study region. Our hypothesis anticipated differences in fuel development and vegetation regrowth between the two forest types, with slower accumulation of surface fuels and development of understory and ladder fuels predicted in the xeric eastern slope pine forests. This work should inform resource allocation between fuel treatment implementation and future maintenance.

These management considerations are of particular interest in the study region due to the influence of the Herger-Feinstein Quincy Library Group Pilot Project and prior fuels reduction work enabled by a developing biomass industrial infrastructure. The Project was established in 1998 to promote hazardous fuels reduction in the region, aiming to treat ~16–24,000 ha (40–60,000 acres) per year within a strategic network of fuel breaks [19]. Support from the local community and relatively abundant economic resources dedicated to fuel treatment implementation have generated many potential sampling sites established over the years since the Project's creation, making this region exceptionally suited for a chronosequence study of fuels reduction. Most of the treatment areas sampled in this study are shaded fuel breaks *sensu* Agee *et al.* [10], *i.e.*, areas in which fuels have been modified in order to moderate fire hazard while maintaining some forested cover. Supporting fire suppression activities is an explicit goal of fuel breaks, which are often strategically situated along roads and ridgetops and near communities and other high-value resources. Nonetheless, we expect our findings will be applicable to the broader category of fuel treatments, which include treatments intended to reduce the likelihood of wildfire ignition and/or mitigate potential fire effects and resistance to control [20].

2. Methods

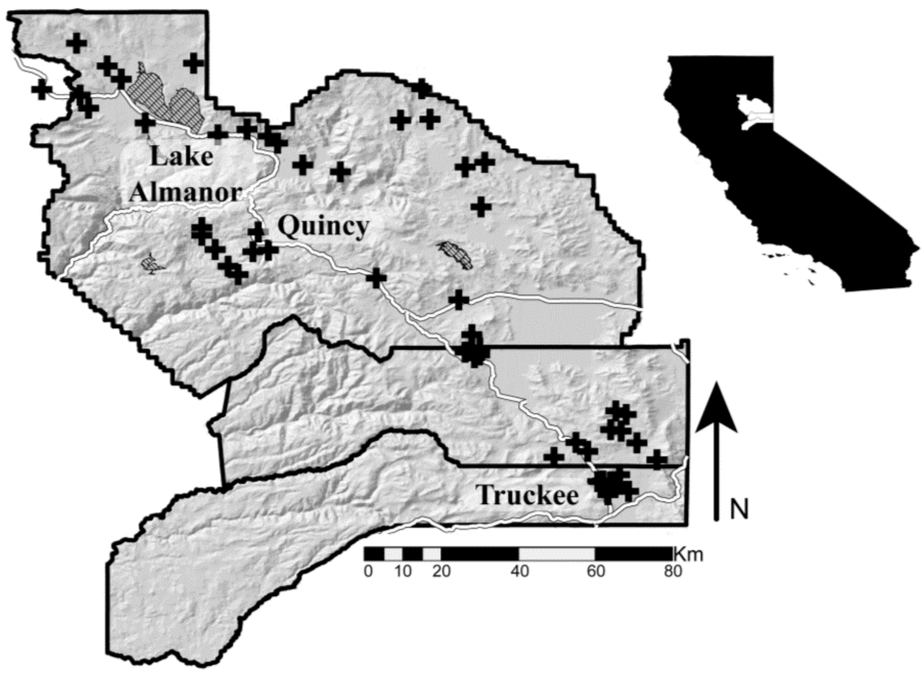
2.1. Study Area

This study was conducted in Nevada, Sierra, and Plumas Counties in the northern Sierra Nevada and southern Cascade regions of California (Figure 1). Historically, low- to moderate-severity fires here were frequent: a study of fire history in similar forests found a pre-Euro-American settlement mean composite fire return interval of 6–18 years (for fires scarring more than 10% of samples) [21]. The climate west of the Sierra Nevada crest is Mediterranean with warm, dry summers and cold, wet winters. To the east, the continental pattern is prevalent, and is characterized by more extreme daily and seasonal temperature shifts and lower precipitation. Most precipitation falls as snow during the winter months, and annual precipitation ranges from 38 cm on the east side to nearly 230 cm on the west [22]. The geologic and climatic diversity of this portion of the Sierra Nevada range have produced an equally diverse soil mosaic that includes granitic, volcanic, and serpentine soils. The west side is characterized by relatively deep and productive soils while those of the cool and dry east side are shallow and less productive [22]. Study site elevations range from 1100 to 2150 m.

The Sierra mixed conifer forest type is dominated by sugar pine (*Pinus lambertiana* Dougl.), ponderosa pine (*P. ponderosa* Dougl.), white fir (*Abies concolor* (Gord. and Glend.)), incense-cedar (*Calocedrus decurrens* [Torr.] Florin.), Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco), and California black oak (*Quercus kelloggii* Newb.) [23] while the colder and drier lower montane eastside pine type is dominated by Jeffrey pine (*Pinus jeffreyi* Grev. and Balf.) and white fir.

Downed fuels and understory and overstory vegetation were sampled within 51 treatment sites 2–15 years following initial treatment and 13 untreated sites. Local forest managers helped identify treatment projects suitable for sampling. Sampling sites had been treated with mechanical thinning alone or in combination with broadcast or pile burning. If applicable, follow-up burning was to occur within three years of the thinning treatment. All treatment projects fitting the study design requirements were sampled. A single treatment *project* often included multiple units treated over a period of several years. In order to avoid possible pseudoreplication arising from adjacent unit locations and identical timber operators, a single unit was randomly selected to represent each individual project.

Figure 1. Study area in the northern Sierra Nevada and southern Cascades, CA. Black crosses indicate study site locations.



The mechanical thinning treatments sampled in this study included some prescriptions that were not explicitly designed for hazardous fuels reduction. These included single-tree selection harvests and understory thinning to improve the vigor of residual trees. Incorporating thinning treatments not necessarily intended as fuel treatments in this exhaustive sampling effort permitted a larger sample size. In practice, the stand structures produced by all mechanical thinning types were similar and included reduced ladder fuels and reduced density of small- and mid-diameter trees. To limit variability in post-thinning conditions, hand-thinning and mastication treatments were not included in this study. While most stand treatments (40 of 51) were located on land managed by the US Forest Service, nine sites belonged to the Collins Pine Company, a private forest products company, and two fuel treatments had been implemented by Fire Safe Councils on privately owned land.

Untreated control sites were established in stands adjacent to treatment areas. Control sites were defined as having overstory species composition and slope steepness comparable to those of the adjacent treated unit, without evidence of recent (within ~25 years) wildfire or management. Because mechanical thinning equipment is generally restricted to slopes of less than 30 percent grade, no prospective control site with a slope exceeding 30 percent was sampled. In many cases, potential control sites were deemed unsuitable for sampling because there was evidence of recent thinning or fire, such as intact stumps or char, or because the slope or dominant vegetation differed substantially from that of the adjacent treated area.

2.2. Field Sampling

Downed woody fuels, understory composition, and overstory characteristics were sampled using a systematic sampling design with a random starting point. Three circular plots, 50 m apart, were established in each treatment unit and placed parallel to the treatment boundary, typically a road. This choice of plot number and spacing represents a compromise between minimizing potential spatial autocorrelation between plots while ensuring that most treatment units could accommodate the sampling design. A fixed number of plots were selected because while treatments varied in areal extent, georeferenced treatment maps were often unavailable. To minimize boundary effects, plots were placed 30 m from the nearest treatment boundary. When gaps in the treatment were encountered during plot placement (e.g., a group selection unit) subsequent plots were placed on the opposite side of the treatment gap with a 30 m buffer from the gap edge.

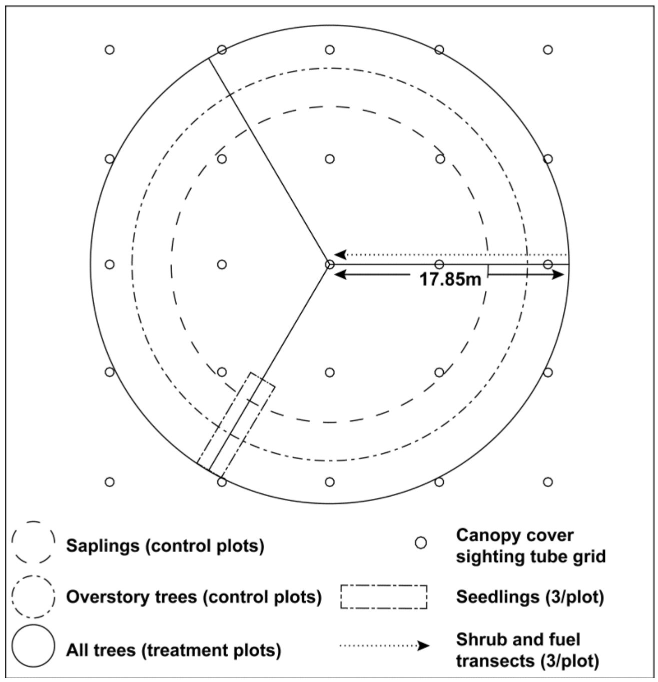
The elevation, aspect, slope, and slope position for each plot were recorded. Plot centers were permanently marked with wooden stakes and witness trees marked with aluminum tags. Three 17.85 m transects were established within each circular plot (Figure 2). The azimuth of the first transect was chosen randomly while the second and third transects were placed with headings of 120° and 240° greater than the first. Surface and ground fuels were sampled using the planar-intercept method [24,25]. Beginning at the transect end farthest from plot center, 1 h (≤0.64 cm diameter) and 10 h timelag fuels (>0.64 cm to ≤2.54 cm diameter) were tallied from 0 to 2 m and 100 h timelag fuels (>2.54 cm to ≤7.62 cm diameter) were tallied from 0 to 3 m. The number and diameter of 1000 h timelag (>7.62 cm) and larger fuels were recorded along the full length of the transect, and fuels were categorized according to condition (sound or rotten). Duff and litter depths were measured at 2.85 and 12.85 m. Total surface fuel depth was recorded at three points along each transect. Fuel loads were calculated using Sierra Nevada tree species-specific estimates [26,27], weighted by the contribution of each species to plot-level basal area [28].

Shrub measurements including species, average height, and status (live or dead) were taken along each linear transect. Shrub cover was calculated as the transect length occupied by shrub divided by the total transect length. The height, caliper at base, and species of all seedlings (trees <2.5 cm dbh) were recorded in three 2 m × 7 m plots, each centered on a transect and positioned at the end farthest from plot center (Figure 2). Within each plot, overstory canopy cover was sampled with a densitometer (sighting tube) on a 25-point, 8 m × 8 m grid oriented north–south and east–west [29]. Percent canopy cover was estimated as the number of canopy "hits" divided by the total number of sampling points.

Sampling of treated and untreated plots was identical except with regard to tree sampling. In treatment plots, the total height, height to live crown base, diameter at breast height (dbh), crown class, and species were recorded for all trees ≥2.5 cm dbh within 17.85-m radius. Because stand density on the untreated control sites was greater than for treatment sites, overstory trees (≥7.6 cm dbh) and saplings (2.5–7.6 cm dbh) were sampled in nested subplots 0.075 and 0.05 ha in size, respectively.

Treatment history records associated with two of the oldest sites were incomplete. Using standard dendrochronological techniques [30,31], the year of thinning in these sites was verified using evidence from tree rings contained in stumps of small- to intermediate-diameter trees and visible logging scars on live trees presumed to have resulted from mechanical thinning operations. Stump cross-sections distributed over the sampling area were removed with a chainsaw; increment cores were removed from trees with visible logging scars. Each cross-section or core was sanded to a high polish to allow rings and scars to be viewed clearly under a microscope. The year of thinning was determined by cross-dating tree rings against a master tree-ring chronology.

Figure 2. Illustration of sampling plot layout. Three sampling plots were placed in each treatment site to investigate patterns of fuel, vegetation, and stand development after treatment. Sampling did not vary between control and treatment sites with the exception of tree data collection.



2.3. Canopy Fuel Calculations and Statistical Analysis

The Crown Mass program (version 3.0.49) within the Fuels Management Analyst Plus (FMAPlus) suite was used to estimate canopy bulk density and canopy base height [32]. FMAPlus uses modified allometric equations to estimate average canopy profile characteristics from field-derived inputs including tree species, dbh, tree crown ratio, and canopy class. Canopy base height is defined in FMAPlus as the height above the ground of the first canopy layer with sufficient density of canopy fuels to carry fire vertically. The canopy bulk density is the maximum value of a running mean of vertically oriented one-foot (30.5-cm) canopy layers.

The effects of treatment and differences between time-since-treatment groups were examined by analysis of variance. Data were log-transformed when necessary to meet the assumptions of statistical tests. Where significant differences occurred ($p < 0.05$), comparisons between means were performed using Tukey's HSD multiple comparison test. Due to limited sample sizes, data representing both methods of active treatment and major slope aspects (north and south) were combined for these analyses.

An analysis of covariance (ANCOVA) was performed to examine the relationship between stand density and site factors, including stand productivity measures (combined average height of dominant and codominant trees and site index [33], estimated from average dominant tree height at a specified base age), forest type, slope aspect, and treatment factors, including method of fuel treatment and ownership.

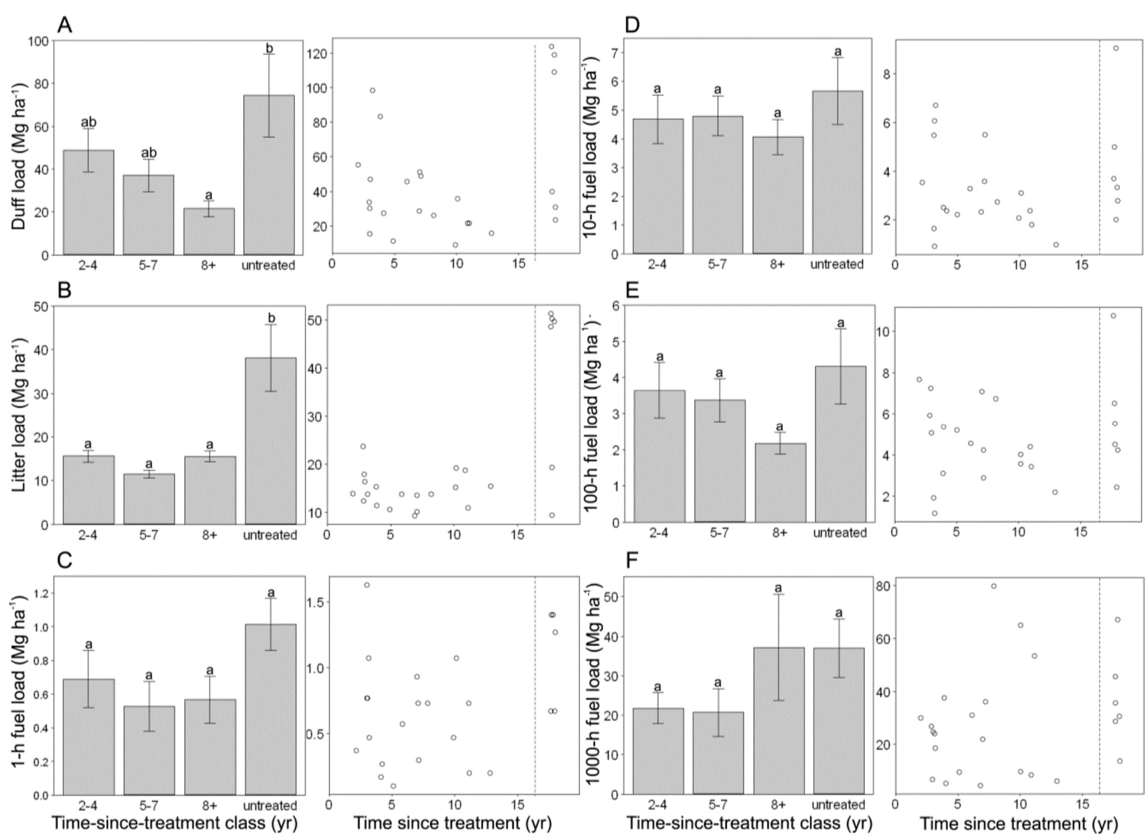
All statistical analyses were performed in the statistical software package *R* version 2.10.1 [34].

3. Results

3.1. Fuel Characteristics

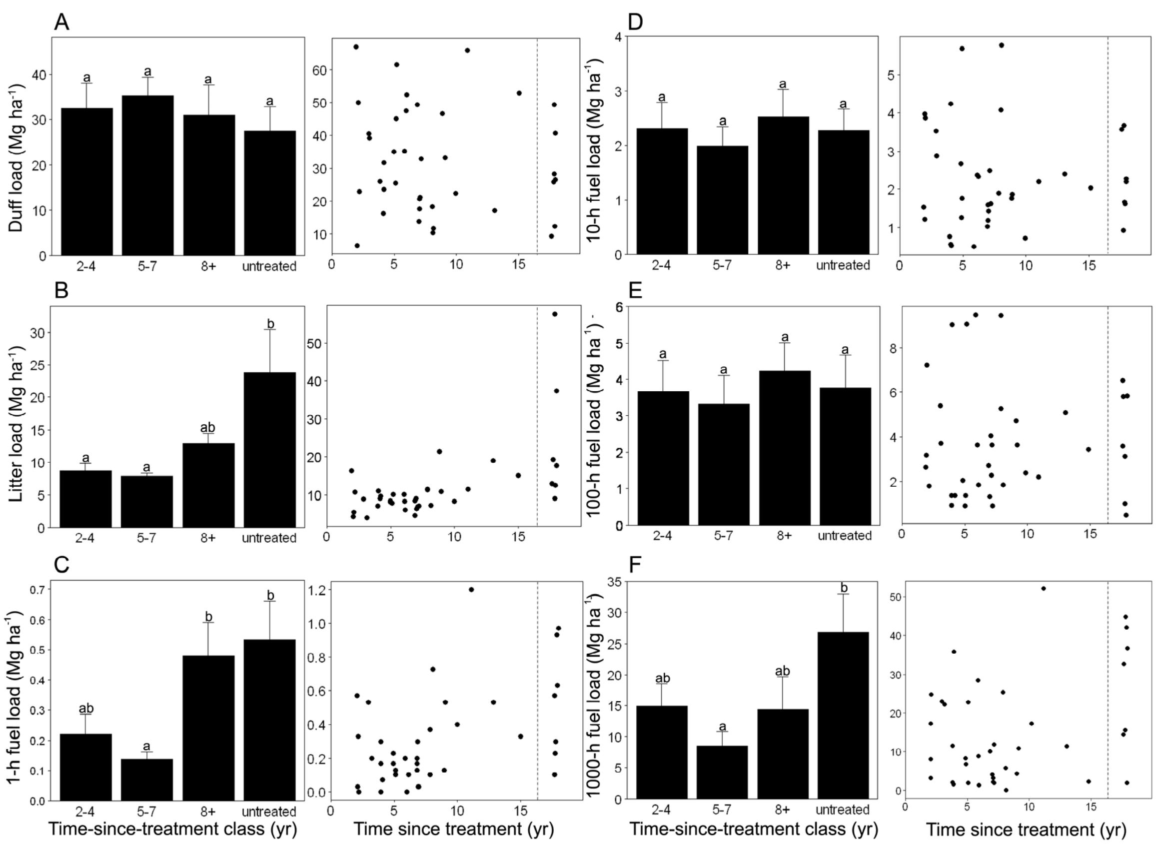
Mixed Conifer.—With the exception of leaf litter, surface fuel loads in the mixed conifer forest type did not differ significantly between any of the age classes or between the treated and untreated sites (Figure 3). Mean 1-, 10-, and 100-h fuel loads were respectively 78%, 98%, and 40% greater in the untreated sites relative to the oldest treatment class, but high variation led to insignificant differences between groups. Control litter loads were nearly double those of the treatment age classes, which were very similar. Mean ground (duff) fuel loads for the untreated sites was ~1.5–3.5 times treated site levels, though this difference was significant only for the oldest time-since-treatment class.

Figure 3. Dead surface fuel load by category in the mixed conifer chronosequence (n = 19) and control (n = 6) sites. Fuel load in the (**A**) duff layer; (**B**) litter layer; and the (**C**) 1-h; (**D**) 10-h; (**E**) 100-h; and (**F**) 1000-h timelag categories. Left-hand panels show means ± SE for the three age class groups and the control group. Different letters above each bar indicate significant difference in means between groups (Tukey's HSD multiple comparison test, p < 0.05). Right-hand panels show the relationship between time since treatment and each fuel category. Vertical dashed lines separate treated and untreated study sites.



Eastside pine.—For the eastside pine forest type, there was no significant difference in duff or 10- and 100-h fuel loads over time following treatment and no difference between any time-since-treatment class and the untreated group (Figure 4A,D,E). Litter loads were significantly greater in the untreated sites than for the two youngest age classes (*i.e.*, sites treated 2–7 years prior to sampling), but not for the oldest class (8–15 years since treatment). While 10- and 100-h fuel loads exhibited no trend over time since treatment, 1-h fuel loads were significantly lower in the mid-range treatment age class (5–7 years since treatment) than the oldest class and the untreated group. A similar trend was observed for 1000-h fuel loads (Figure 4F).

Figure 4. Dead surface fuel load by category in the eastside pine chronosequence (n = 32) and control (n = 7) sites. Fuel load in the (**A**) duff layer; (**B**) litter layer; and the (**C**) 1-h; (**D**) 10-h; (**E**) 100-h; and (**F**) 1000-h timelag categories. Left-hand panels show means ± SE for the three age class groups and the control group. Different letters above each bar indicate significant difference in means between groups (Tukey's HSD multiple comparison test, p < 0.05). Right-hand panels show the relationship between time since treatment and each fuel category. Vertical dashed lines separate treated and untreated study sites.



3.2. Vegetation Characteristics

Mixed conifer.—Mean stand basal area (50.3 m^2 ha^{-1}) for untreated stands was double that of treated stands, and this difference was significant across time-since-treatment classes (Figure 5A). Treatment also significantly reduced stand density (Table 1). The combined contribution of

Abies concolor and *A. magnifica* to density (Table 1), though not basal area (Table 2), was reduced, which reflects the preferential removal of small-diameter trees. Likewise, treatment increased quadratic mean diameter (QMD) by 49.5% (Table 2). Control canopy base height (mean = 1 m) was significantly lower than for any of the treatment groups (overall treatment mean = 4.3 m) (Figure 5B). Control canopy bulk density was approximately double that of treated sites, and exhibited no trend over time following treatment (Figure 5C). Overstory canopy cover for the two most recent treatment classes (46% and 48%) was intermediate between the oldest time-since-treatment class (41%) and the control (67%). Treatment age classes did not differ significantly from one another with respect to canopy cover, but the 2–4 and 8–15 years-since-treatment groups each had significantly lower percent cover than the untreated control (Figure 5D).

Figure 5. Vegetation characteristics in the mixed conifer chronosequence (n = 19) and control (n = 6) sites. (**A**) basal area; (**B**) canopy base height; (**C**) canopy bulk density; (**D**) canopy cover; (**E**) shrub cover; and (**F**) seedling density (all trees <2.5 cm dbh). Left-hand panels show means ± SE for the three age class groups and the control group. Different letters above each bar indicate significant difference in means between groups (Tukey's HSD multiple comparison test, p < 0.05). Right-hand panels show the relationship between time since treatment and each stand characteristic. Vertical dashed lines separate treated and untreated study sites.

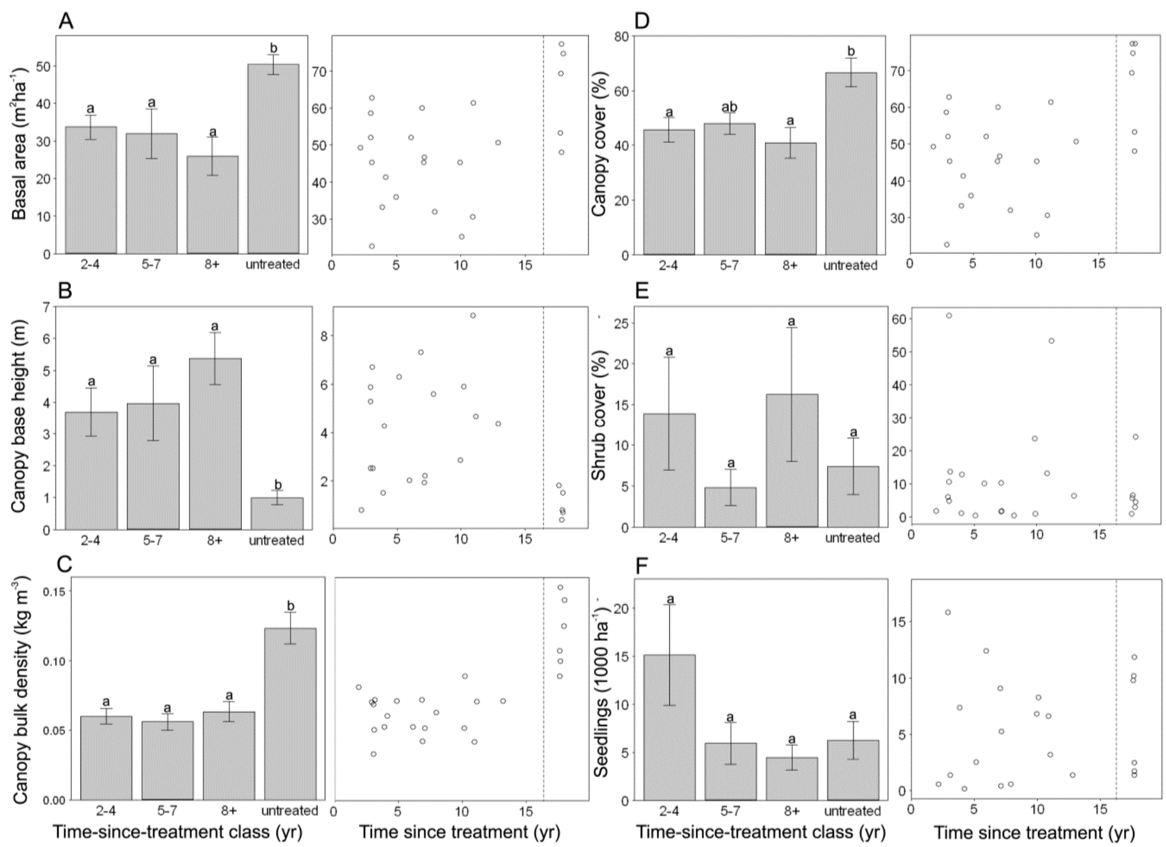


Table 1. Mixed conifer mean stand density (standard error), quadratic mean diameter (QMD), and mean contribution of each tree species to total density for each time-since-treatment category. Different letters indicate significant difference in means between groups (Tukey's HSD multiple comparison test, $p < 0.05$). Calculations include all trees with diameter at breast height ≥2.5 cm. Tree species codes are *ABSP*: *Abies concolor* and *A. magnifica* (combined); *CADE*: *Calocedrus decurrens*; *PIJE*: *Pinus jeffreyi*, *PILA*: *P. lambertiana*; *PIPO*: *P. ponderosa*; *PSME*: *Pseudotsuga menziesii*; *QUKE*: *Quercus kelloggii*. Species composing less than 1% of total density are not included in % density calculations.

Time since treatment (years)	**Mean density (stems ha^{-1})**	**QMD (cm)**	**% Density by species**						
			ABSP	*CADE*	*PIJE*	*PILA*	*PIPO*	*PSME*	*QUKE*
2–4 (n = 8)	372(47) a	33.7	26	21	12	7	7	14	13
5–7 (n = 5)	336(62) a	32.0	32	11	12	11	12	15	8
8+ (n = 7)	388(55) a	30.2	13	6	11	4	15	25	26
Untreated (n = 6)	1406(119) b	21.4	57	17	1	5	9	9	2

Table 2. Mixed conifer mean basal area (standard error) and mean contribution of each tree species to total basal area for each time-since-treatment category. Different letters indicate significant difference in means between groups (Tukey's HSD multiple comparison test, $p < 0.05$). Calculations include all trees with diameter at breast height ≥2.5 cm. Species composing less than 1% of basal area are not included in % basal area calculations. See Table 1 for explanation of species codes.

Time since treatment (years)	**Mean basal area (m^2 ha^{-1})**	**% Basal area by species**						
		ABSP	*CADE*	*PIJE*	*PILA*	*PIPO*	*PSME*	*QUKE*
2–4	33.7(3.2) a	21	18	15	15	8	18	5
5–7	32.0(6.6) a	34	7	11	22	15	12	0
8+	27.7(4.7) a	28	5	10	6	22	27	3
Untreated	50.3(2.7) b	33	10	2	15	20	17	3

A high degree of variability in understory vegetation characteristics contributed to a lack of significant differences between the treatment age classes and between the treatment and control groups. Tree regeneration was especially variable in the youngest time-since-treatment age class. Though mean seedling density in the youngest class was ~2.5 times greater than that of the next age class, mean densities did not differ at a significance level of 0.05 (Figure 5F). This short-lived peak in seedling density following treatment was apparent for sites treated with mechanical thinning alone as well as those in which thinning was followed by burning (not shown). Shrub cover was generally low, and exhibited no trend over time following treatment (Figure 5E). Shrub cover was >20% in only 4 of 26 mixed conifer sites, and >30% in only 2 sites.

Eastside pine.—Overstory characteristics generally did not vary between time-since-treatment classes, but were significantly affected by treatment. Control basal area and canopy bulk density were significantly greater than for any treatment age class (Figure 6A,C). Basal area of the untreated sites was double that of the oldest time-since-treatment class, while control canopy bulk density was ~4 times that of the oldest treatment class. Likewise, at nearly 50%, mean control canopy cover was 39%–82% greater than for treated sites (Figure 6D). Mean canopy base height in the control sites was 1 m compared with 2.5–3.7 m in the treatment units (Figure 6C). In terms of stand density, treatment favored Jeffrey pine over true fir (Table 3). As thinning prescriptions generally targeted the smallest-diameter trees, QMD was increased by 55.5% (Table 4).

Figure 6. Eastside pine vegetation characteristics. (**A**) basal area; (**B**) canopy base height; (**C**) canopy bulk density; (**D**) canopy cover; (**E**) shrub cover; and (**F**) seedling density (all trees <2.5 cm dbh) in the eastside pine chronosequence (n = 32) and control (n = 7) sites. Left-hand panels show means ± SE for the three age class groups and the control group. Different letters above each bar indicate significant difference in means between groups (Tukey's HSD multiple comparison test, p < 0.05). Right-hand panels show the relationship between time since treatment and each stand characteristic. Vertical dashed lines separate treated and untreated study sites.

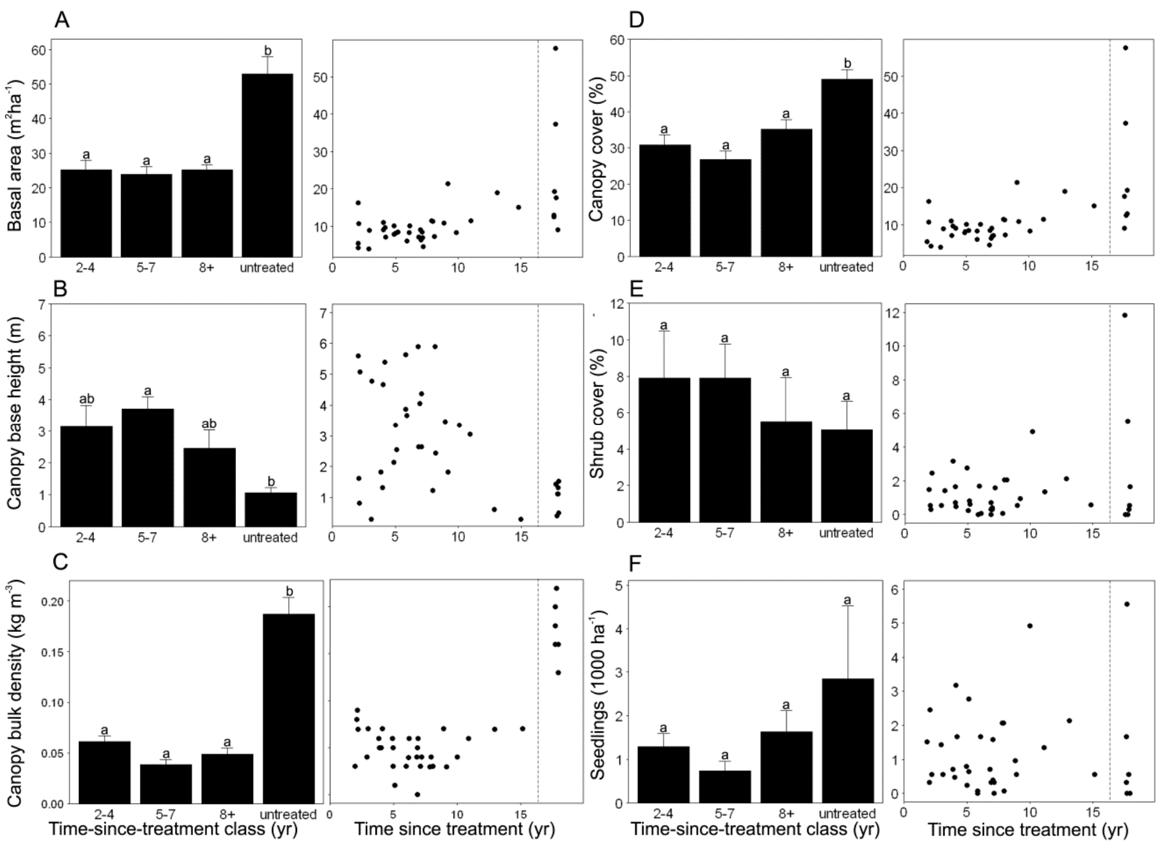


Table 3. Eastside pine mean stand density (standard error), quadratic mean diameter (QMD), and mean contribution of each tree species to total density for each time-since-treatment category. Different letters indicate significant difference in means between groups (Tukey's HSD multiple comparison test, $p < 0.05$). Calculations include all trees with diameter at breast height ≥2.5 cm. Tree species codes are *ABSP*: *Abies* concolor and *A. magnifica* (combined); *CADE*: *Calocedrus decurrens*; *JUOC*: *Juniperus occidentalis*; *PIJE*: *Pinus jeffreyi*; *PIPO*: *P. ponderosa*. Species composing less than 1% of total density are not included in % density calculations.

Time since treatment (years)	Mean density (stems ha^{-1})	QMD (cm)	% Density by species				
			ABSP	*CADE*	*JUOC*	*PIJE*	*PIPO*
2–4 (*n* = 10)	258(31.6) a	35.3	34	1	0	64	0
5–7 (*n* = 13)	181.5(12.9) a	41.0	16	0	0	83	0
8+ (*n* = 9)	345.6(90.94) a	30.5	16	0	0	83	0
Untreated (*n* = 7)	1283.5(162.1) b	22.9	42	5	1	52	1

Table 4. Eastside pine mean basal area (standard error), and mean contribution of each tree species to total basal area for each time-since-treatment category. Different letters indicate significant difference in means between groups (Tukey's HSD multiple comparison test, $p < 0.05$). Calculations include all trees with diameter at breast height ≥2.5 cm. The "*Abies sp.*" category includes combined contributions of *Abies concolor* and *A. magnifica*. Species composing less than 1% of basal area are not included in % basal area calculations.

Time since treatment (years)	Mean basal area (m^2 ha^{-1})	% Basal area by species					
		ABSP	*CADE*	*PIJE*	*PILA*	*PIPO*	*PSME*
2–4	25.2(2.8) a	18	1	80	0	0	0
5–7	23.9(2.3) a	8	0	92	0	0	0
8+	25.3(1.4) a	38	3	46	1	8	4
Untreated	53.0(4.9) b	26	11	61	0	2	0

Shrub cover and seedling regeneration did not exhibit the high degree of variability observed for the mixed conifer forest type. Shrub cover was low overall, from 8% in the youngest treatment group to 5% in the untreated group, and did not significantly vary between control and treatment groups. Though mean control seedling density was ~2–4 times treatment group levels, this difference was not significant at $p < 0.05$.

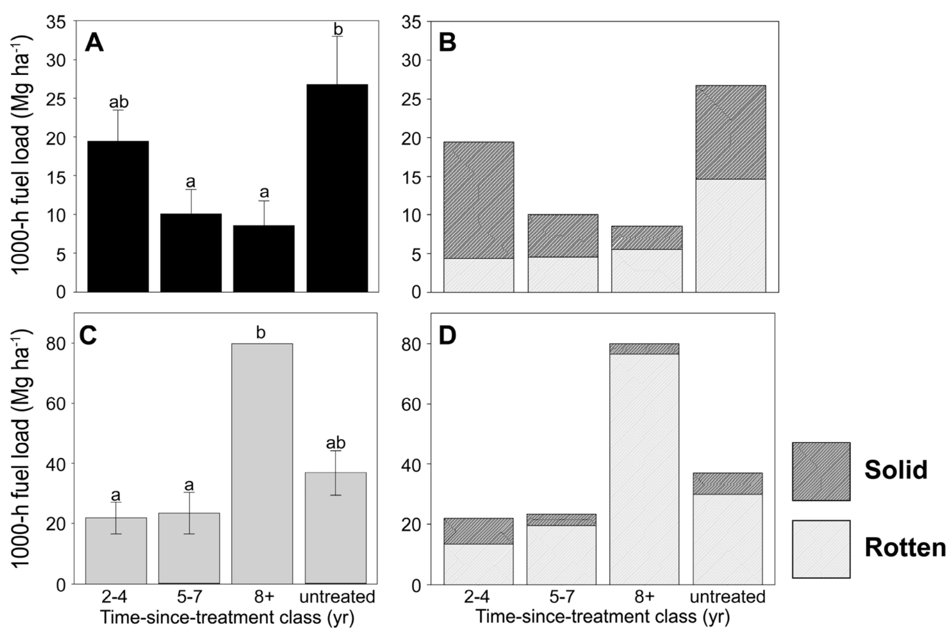
4. Discussion

4.1. Ground and Surface Fuels

Downed coarse wood, often defined as material larger than 7.6 cm (3 in) in diameter [35], is a focus of habitat management, as it is required by many wildlife species for foraging, cover, and substrate [36]. It is also important with regard to ecosystem structure and function (e.g., maintenance of site productivity, protection of soils from compaction and erosion). Yet given the frequent fire regime characteristic of the study area and the high consumption of decomposed coarse wood during burning in low-moisture conditions [37], historic levels of large-diameter surface fuels were likely lower than at present [38,39]. Reducing pretreatment levels and ameliorating additions produced during fuels manipulation is a management concern, as large quantities of coarse woody fuels can influence potential fire behavior [5,10,40].

For the eastside pine forest type, loads of large-diameter fuels were significantly higher in the untreated sites than in unburned sites that had been thinned 5–15 years earlier, but they were not significantly different from loads on sites treated 2–4 years prior to sampling (Figure 4F). In the xeric environment characteristic of the eastern Sierra Nevada, large-diameter woody fuels may remain on site for many years without follow-up treatment of activity fuels produced during thinning [41]. Some sites were treated with prescribed fire after thinning, but while broadcast burning effectively reduces loads of small-diameter fuels and rotten large-diameter fuels [42,43], it may have less influence on sound logs [44]. The initial post-harvest peak in 1000-h loads is particularly clear in Figure 7, which shows coarse woody fuel loads in eastside pine sites treated with mechanical thinning alone. The relatively high proportion of solid coarse fuels in the most recently treated sites is likely due to additions produced during harvest. The rapid decline in solid 1000-h fuels is surprising given the expected slow rate of decomposition. Follow-up surface fuel treatment was planned but not yet completed on some sampled sites, and it may be the case that by chance such sites were overrepresented in the first time-since-treatment age class.

Figure 7. Thousand-hour timelag class (diameter >7.62 cm) fuel load in eastside pine (**A**,**B**) and mixed conifer (**C**,**D**) sites treated with mechanical thinning alone or untreated. **A**,**C**: Different letters above each bar indicate significant difference in means between groups (Tukey's HSD multiple comparison test, $p < 0.05$); **B**,**D**: Total thousand-hour fuels by decomposition class.



The early pulse in coarse fuels was not observed in mixed conifer stands and in general, clear temporal trends among the woody timelag fuel categories were not detectable (Figures 3 and 4).

Because of limited availability of treatment sites, sites with varying methods of post-thinning surface fuel treatment were grouped for the analyses shown in Figures 3–6. While harvest activities transfer woody fuels from the canopy to the surface [9], several prescriptions included in the present study utilized whole-tree yarding, biomass removal, and/or grapple piling, each of which effectively reduce the activity fuels remaining onsite after treatment. Thirty-three percent of sites were treated with either pile or broadcast burning after harvesting in order to address natural and activity fuels. Burning reduces surface fuels but also produces direct and indirect tree mortality [44–46]; over time, fire-killed snags enter the surface fuel pool. Indeed, in burned sites, the number of snags in the most recently treated stands was 1.4–6.7 times that of the next age class, indicating that some trees killed during burning and still standing 2–4 years after treatment will become part of the surface fuel pool in the coming years. Combining sites treated with burning, which experience additions to the surface fuel pool in years after treatment, with those on which activity fuels were treated mechanically or left untreated would likely have the effect of masking trends in woody fuel loads over time.

Though some studies have assessed long-term dynamics of large-diameter woody fuels [38,47], few have looked beyond the initial impacts of treatment with respect to small-diameter woody fuels and the litter layer, which have the greatest influence on surface fire spread. Litter loads in stands belonging to every treatment age class were substantially lower than in untreated stands, and remained at low levels throughout the chronosequence. It appeared that duff loads were not affected by treatment, as they generally did not vary between treated and untreated stands (Figures 3A,4A).

Broadcast burning often reduces both ground and surface fuels [48–50], though these effects may not be long-lived. Keifer *et al.* [48] found that surface fuels reached approximately 85 percent of pre-fire levels within 10 years after prescribed burning in ponderosa pine and white fir-mixed conifer forests in Sequoia and Kings Canyon National Parks in the southern Sierra Nevada. In the present study, litter loads in the mixed conifer and eastside pine sites reached only 47% and 54% of untreated levels, respectively, within 8–15 years of treatment. This may indicate that surface fuels in the study area accumulate more slowly than in the southern Sierra, but may also reflect differences in litter deposition between thinned and unthinned sites, as Keifer *et al.* [48] did not include mechanical tree-removal in their study. Thinning reduces litter fall [51] since canopy cover is strongly linked to foliage production and litter accumulation [52].

As a general rule, burning reduces surface fuel loads while mechanical treatments tend to increase them [6], yet it appears that the post-treatment reductions in litter loads observed here are not solely the result of burning. When sites treated with mechanical thinning alone (34 of 51 treatment sites) were analyzed separately, mean litter loads for every forest type/age class combination were at least 40% less than for comparable untreated sites. As a result of the reduced sample size, however, this difference was significant at $p < 0.05$ for only the 2–4 and 5–7 year (mixed conifer) and 5–7 year (eastside pine) time-since-treatment classes.

Others have found reduced duff or litter layer depths after mechanical harvesting. Stephens and Moghaddas [7] saw reduced litter depth after removal of chainsaw-thinned trees with rubber-tired and tracked skidders. Fulé *et al.* [5] found reduced average duff loads following both mechanical felling with broadcasting of activity fuels and whole-tree harvesting combined with slash piling. Stephens and Moghaddas [53] found that combined duff and litter loads following overstory removal and clear-cutting were reduced relative to young- and old-growth reserves, though loads following thin from below and individual tree selection treatments did not differ significantly from the reserves. Harvesting machinery can displace surface and ground fuel layers within a site, though it is not clear by what mechanism this should reduce ground and litter fuel mass. Alternatively, since fuel loads are typically estimated from measurements of fuel depth, compaction of the litter layer by harvesting equipment could produce an apparent reduction in loads. It is unclear whether this influence might be significant, as it has not been addressed in the literature.

4.2. Tree Regeneration

The lack of clear trends in tree seedling density over time was not unexpected. Mechanical thinning and thinning with prescribed fire tend to increase tree seedling density, but high variability among sites is common [6]. Species respond to post-treatment conditions independently [54,55], and regeneration has been linked to stand density, light levels, soil moisture and disturbance, variation in seed production (masting), and site productivity [6,17,54,56]. Interannual climate variation has also been shown to significantly influence recruitment [57,58].

The early peak in seedling density in the mixed conifer treatments was not observed in the eastside forest. The relatively productive mixed conifer forest would be expected to promote higher levels of regeneration. In addition, mechanical thinning may have relatively little influence on the light environment in the eastside forest, where canopy cover in untreated stands is relatively low (~50%). Jeffrey pine, a dominant overstory species of the eastside, is associated with indirect radiation, and white and red fir are associated negatively with direct solar radiation and positively with soil moisture [56]. Irregularity in Jeffrey pine seed crops has also been reported [59].

Chronosequence studies rely on the assumption that time since treatment is the primary explanatory variable. Variation in conditions at the time of treatment can make this assumption untenable. This shortcoming is particularly relevant with respect to regeneration, which is known to exhibit a high degree of spatial and temporal variation.

4.3. Shrubs

Some have suggested that reducing canopy cover during thinning may promote shrub growth [6,60], thereby shortening the longevity of fuel treatment effectiveness. In the short-term, fuels treatment is expected to reduce shrub cover through mechanical damage [6,61,62] and consumption during burning [6,62,63]. Beyond these initial impacts, thinning could potentially promote shrub growth through reduced overstory competition. Campbell *et al.* [64] found live shrub cover increased from 9% in unthinned controls to 32% and 22%, 3 and 16 years, respectively, after thinning-from-below in northern Sierra Nevada ponderosa pine plantations. Many shrubs in the study region are vigorous resprouters, and prescribed fire stimulates seed germination in some species [63]. However, potential increases in shrub growth as a result of reduced canopy cover and increased microsite availability may be limited. In the Teakettle Experimental Forest, a southern Sierra Nevada site, North *et al.* [65] determined that mixed conifer shrubs were associated with diffuse light and low soil moisture levels. Cover was reduced in both closed canopy and canopy gaps with shrubs preferentially occupying an ecotone between the two cover types.

The lack of clear trends in shrub development in the years following treatment may reflect variability in pre-treatment conditions. Dodson *et al.* [66] found that pre-treatment shrub cover was much more influential than treatment with respect to changes in shrub cover over time. Although the high variability in post-treatment shrub cover precluded clear findings with respect to development over time, the hypothesis that thinning and prescribed fire treatments would promote shrub growth, exacerbating potential fire hazards, is not supported by these data, as total shrub cover was nearly always low (<20%) in control and treatment sites alike. Similarly low levels of shrub cover have been observed in other dry western forests following treatment [16,67].

4.4. Stand Characteristics

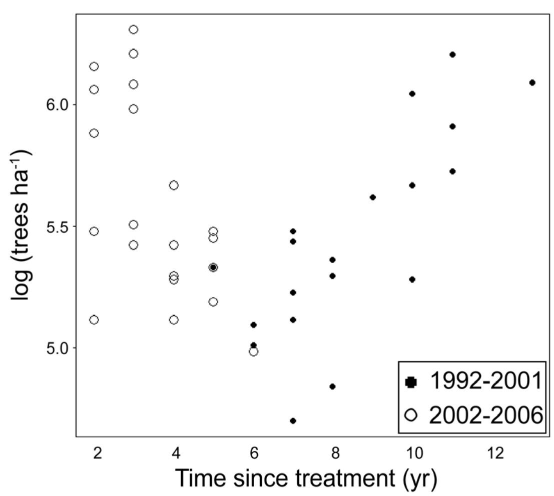
Treatments for fuels reduction are often intended to achieve multiple objectives. Apart from fire hazard reduction, the restoration of pre-Euro-American settlement (hereafter "pre-settlement") conditions is a common goal of treatment. Some goals of restoration align with those of hazard reduction: a focus on recreating the conditions associated with pre-settlement can also be expected to reduce fire hazards, as manipulations for restoration typically involve reducing surface fuels and the density of small-diameter trees. While many of the treatments sampled here did not include restoration as an explicit goal, and fuel treatments cannot in general be assumed to achieve restoration, they did move stands toward the structure of pre-settlement forests by some measures.

The abundance of shade-tolerant fir species is a concern from a restoration standpoint as a well as a fire hazard perspective. Shade-tolerant conifers are characterized by vertically continuous crowns that can convey surface fire into the forest canopy. In mixed conifer stands in a Sierra Nevada old growth reserve (Teakettle Experimental Forest), North *et al.* [68] compared stand conditions before and after understory thinning with and without prescribed fire to stand reconstructions of 1865. As in their study, treatment in the present study increased QMD and reduced stand density. However, while North *et al.* found that treatment did not significantly reduce pre-treatment contributions of *Abies* species (red and white fir) to stand density (65.3%–71.9%), the contribution of true fir to mixed conifer stand composition in this study was reduced from 57.2% in untreated stands to <26% in treated stands. By comparison, North *et al.* estimated that true fir composed 36.6% of stand density in their 1865 reconstruction, similar to an estimate of 42% by volume in a 1913 Plumas National Forest survey [69]. Though treatments in the present study reduced the contribution of true fir to stand density, its contribution to stand basal area was not altered, reflecting preferential removal of small-diameter individuals during mechanical thinning. The same pattern was observed in the eastside pine forest type, where treatment favored Jeffrey pine over true fir with respect to density but not basal area.

The structural changes created by fuels management were still evident in the oldest chronosequence class. In both forest types, with respect to stand characteristics, the oldest treated units were statistically indistinguishable from more recently treated stands but were clearly distinct from untreated sites. Treatment effects included reduced vertical and horizontal fuel continuity and a higher proportion of large-diameter, fire-resistant trees. These changes indicate that treated stands are less vulnerable to high-severity fire even 8–15 years after treatment [11].

One limitation of the chronosequence approach is that variation at the time of treatment can easily be attributed to variation over time since treatment. The changes in stand structure over time may be somewhat confounded with changing mechanical thinning prescriptions over time. Changing forest management over time has frustrated other chronosequence studies [70]. Figure 8 illustrates the challenge. Stand density appears to exhibit a *u*-shaped relationship with time following treatment, which likely reflects changes in mechanical treatment prescriptions over time rather than a real trend in stand development. ANCOVA results indicated a significant interaction between treatment age and the period in which thinning occurred. The pre-2002 and post-2002 (inclusive) division was chosen to represent the period before and after the 2001 Sierra Forest Plan Amendment Record of Decision [71], which had the effect of reducing harvest levels in fuel treatments through canopy cover targets, diameter limits, and an emphasis on creating stand heterogeneity. While a number of other management directives certainly affected treatment implementation, notably the California Spotted Owl interim guidelines [72] and the Herger-Feinstein Quincy Library Group (HFQLG) Forest Recovery Act of 1998 [73], the 2001 split best described the pattern in stand density based on R^2 and *p*-values (not reported). Only treatments completed on federal forest land are included in the analysis of density reported in Figure 8. The larger chronosequence study includes a significant number of privately managed stands which would not be expected to be influenced by changing federal policies.

Figure 8. Stand density at the time of sampling for treatments sampled in both forest types. Figure includes data from sites located on land managed by the US Forest Service only. Symbol color represents the period in which forest thinning occurred.



Apart from historical changes in mechanical thinning prescriptions over time, we were unable to account for other probable sources of variation, including the seasons of thinning and burning, annual climatic variability, and prescribed burn intensity and fuel consumption. This variation likely contributed to the lack of significant differences between time-since-treatment groups and between treatment and control groups.

5. Conclusions

Many have noted the need for future maintenance of post-treatment conditions in order to retain low fire hazard [10,74,75], yet little research exists to guide management planning beyond initial treatment establishment. This chronosequence study indicates that some treatment effects are long-lived in the mixed conifer and eastside pine forests typical of the northern Sierra Nevada and southern Cascade regions of California. Metrics of overstory structure in treated stands were significantly different from those of untreated stands even 8–15 years after treatment implementation. The lack of significant differences between the youngest post-treatment class and the oldest class is further evidence of the longevity of structural changes produced by mechanical thinning alone and in combination with burning. Other effects of treatment, namely on tree seedling regeneration, shrub cover, and most surface fuel categories, were highly variable among sites. Patterns of post-treatment recovery were difficult to discern as a result. As shrub cover across both treated and untreated sites was low (generally <20%), our findings did not validate past concerns that treatment activities could enhance shrub growth, thereby exacerbating wildfire hazards and shortening the lifespan of fuel treatment effectiveness. This work could be used to plan additional fuel treatments and schedule maintenance of existing treatments. A recent analysis of the spatial scale of Sierra Nevada fuel treatments revealed that the current rate of treatment is insufficient to significantly advance restoration goals [76], which emphasizes the need for continued and accelerated fire hazard reduction on large forested areas.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. Scholl, A.E.; Taylor, A.H. Fire regimes, forest change, and self-organization in an old-growth mixed-conifer forest, Yosemite National Park, USA. *Ecol. Appl.* **2010**, *20*, 362–380.
2. Covington, W.W.; Moore, M.M. Postsettlement changes in natural fire regimes and forest structure. *J. Sustain. For.* **1994**, *2*, 153–181.
3. Naficy, C.; Sala, A.; Keeling, E.G.; Graham, J.; DeLuca, T.H. Interactive effects of historical logging and fire exclusion on ponderosa pine forest structure in the northern Rockies. *Ecol. Appl.* **2010**, *20*, 1851–1864.

4. Skinner, C.N.; Chang, C. Fire Regimes, Past and Present. In *Sierra Nevada Ecosystem Project: Final Report to Congress*; University of California, Davis, Centers for Water and Wildland Resources: Davis, CA, USA, 1996; Volume 2, pp. 1041–1069.
5. Fulé, P.Z.; McHugh, C.W.; Heinlein, T.A.; Covington, W.W. *Potential Fire Behavior is Reduced Following Forest Restoration Treatments*; USDA Forest Service, Rocky Mountain Research Station: Ogden, UT, USA, 2001; pp. 22–28.
6. Schwilk, D.W.; Keeley, J.E.; Knapp, E.E.; McIver, J.; Bailey, J.D.; Fettig, C.J.; Fiedler, C.E.; Harrod, R.J.; Moghaddas, J.J.; Outcalt, K.W.; *et al.* The national fire and fire surrogate study: Effects of fuel reduction methods on forest vegetation structure and fuels. *Ecol. Appl.* **2009**, *19*, 285–304.
7. Stephens, S.L.; Moghaddas, J.J. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. *For. Ecol. Manag.* **2005**, *215*, 21–36.
8. Stephens, S.L.; Moghaddas, J.J.; Edminster, C.; Fiedler, C.E.; Haase, S.; Harrington, M.; Keeley, J.E.; Knapp, E.E.; McIver, J.D.; Metlen, K.; *et al.* Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forests. *Ecol. Appl.* **2009**, *19*, 305–320.
9. Raymond, C.L.; Peterson, D.L. Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon, USA. *Can. J. For. Res.* **2005**, *35*, 2981–2995.
10. Agee, J.K.; Bahro, B.; Finney, M.A.; Omi, P.N.; Sapsis, D.B.; Skinner, C.N.; van Wagtendonk, J.W.; Phillip Weatherspoon, C. The use of shaded fuelbreaks in landscape fire management. *For. Ecol. Manag.* **2000**, *127*, 55–66.
11. Agee, J.K.; Skinner, C.N. Basic principles of forest fuel reduction treatments. *For. Ecol. Manag.* **2005**, *211*, 83–96.
12. Strom, B.A.; Fulé, P.Z. Pre-wildfire fuel treatments affect long-term ponderosa pine forest dynamics. *Int. J. Wildland Fire* **2007**, *16*, 128–138.
13. Ritchie, M.W.; Skinner, C.N.; Hamilton, T.A. Probability of tree survival after wildfire in an interior pine forest of northern California: Effects of thinning and prescribed fire. *For. Ecol. Manag.* **2007**, *247*, 200–208.
14. Stephens, S.L.; McIver, J.D.; Boerner, R.E.J.; Fettig, C.J.; Fontaine, J.B.; Hartsough, B.R.; Kennedy, P.; Schwilk, D.W. Effects of forest fuel reduction treatments in the United States. *Bioscience* **2012**, *62*, 549–560.
15. Smith, D.; Larson, B.; Kelty, M.J.; Ashton, P.M.S. *The Practice of Silviculture: Applied Forest Ecology*, 9th ed.; John Wiley & Sons, Inc.: New York, NY, USA, 1997.
16. McConnell, B.R.; Smith, J.G. Response of understory vegetation to ponderosa pine thinning in eastern Washington. *J. Range Manag.* **1970**, *23*, 208–212.
17. Bailey, J.D.; Tappeiner, J.C. Effects of thinning on structural development in 40- to 100-year-old Douglas-fir stands in western Oregon. *For. Ecol. Manag.* **1998**, *108*, 99–113.
18. Haase, S.M. *Effects of Prescribed Burning on Soil Moisture and Germination of Southwestern Ponderosa Pine Seed on Basaltic Soils*; Research Note RM-462; USDA Forest Service, Rocky Mountain Forest and Range Experiment Station: Fort Collins, CO, USA, 1986; p. 6.
19. Moghaddas, J.J.; Craggs, L. A fuel treatment reduces fire severity and increases suppression efficiency in a mixed conifer forest. *Int. J. Wildland Fire* **2007**, *16*, 673–678.

20. National Wildfire Coordinating Group (NWCG); Glossary of Wildland Fire Terminology, 2011. Available online: http://www.nwcg.gov/pms/pubs/glossary/index.htm (accessed on 1 May 2012)
21. Moody, T.J.; Fites-Kaufman, J.; Stephens, S.L. Fire history and climate influences from forests in the northern Sierra Nevada, USA. *Fire Ecol.* **2006**, *2*, 115–141.
22. USDA Forest Service. *Plumas National Forest Land and Resource Management Plan*; USDA Forest Service, Pacific Southwest Region: Quincy, CA, USA, 1988.
23. Barbour, M.; Minnich, R. Californian upland forests and woodlands. In *North American Terrestrial Vegetation*; Barbour, M., Billings, W., Eds.; Cambridge University Press: Cambridge, UK, 2000; pp. 131–164.
24. Van Wagner, C.E. The line intercept method in forest fuel sampling. *For. Sci.* **1968**, *14*, 20–26.
25. Brown, J.K. *Handbook for Inventorying Downed Woody Material*; General Technical Report INT-16; USDA Forest Service: Ogden, UT, USA, 1974; p. 32.
26. Van Wagtendonk, J.W.; Benedict, J.M.; Sydoriak, W.M. Physical properties of woody fuel particles of Sierra Nevada conifers. *Int. J. Wildland Fire* **1996**, *6*, 117–123.
27. Van Wagtendonk, J.W.; Benedict, J.M.; Sydoriak, W.M. Fuel bed characteristics of Sierra Nevada conifers. *West. J. Appl. For.* **1998**, *13*, 73–84.
28. Stephens, S.L. Fire history differences in adjacent Jeffrey pine and upper montane forests in the eastern Sierra Nevada. *Int. J. Wildland Fire* **2001**, *10*, 161–167.
29. Jennings, S.; Brown, N.; Sheil, D. Assessing forest canopies and understorey illumination: Canopy closure, canopy cover and other measures. *Forestry* **1999**, *72*, 59–74.
30. Swetnam, T.; Thompson, M.; Sutherland, E. *Spruce Budworm Handbook: Using Dendrochronology to Measure Radial Growth of Defoliated Trees*; Agriculture Handbook 639; USDA Forest Service: Washington, DC, USA, 1985.
31. Stokes, M.; Smiley, T.L. *An Introduction to Tree-Ring Dating*; University of Chicago Press: Chicago, IL, USA, 1977.
32. Carlton, D. *Fuels Management Analyst Plus, User's Guide to Using the CrownMass and Fuel Model Manager Programs*, Version 3; Fire Program Solutions LLC: Sandy, OR, USA, 2005.
33. Dunning, D. *A Site Classification for the Mixed-Conifer Selection Forests for the Sierra Nevada*; Research Note 28; USDA Forest Service, California Forest and Range Experiment Station: Berkeley, CA, USA, 1942; p. 21.
34. R Development Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2011.
35. Harmon, M.E.; Franklin, J.F.; Swanson, F.J.; Sollins, P.; Gregory, S.V.; Lattin, J.D.; Anderson, N.H.; Cline, S.P.; Aumen, N.G.; Sedell, J.R.; *et al.* Ecology of coarse woody debris in temperate ecosystems. *Adv. Ecol. Res.* **1986**, *15*, 133–302.
36. Bunnell, F.L.; Houde, I.; Johnston, B.; Wind, E. How Dead Trees Sustain Live Organisms in Western Forests. In *Proceedings of the Symposium on the Ecology and Management of Dead Wood in Western Forests*; General Technical Report PSW-GTR-181; Laudenslayer, W.F., Jr., Shea, P.J., Valentine, B.E., Weatherspoon, P.C., Lisle, T.E., Eds.; USDA Forest Service: Albany, CA, USA, 2002; pp. 291–318.

37. Kauffman, J.B.; Martin, R.E. Fire behavior, fuel consumption, and forest-floor changes following prescribed understory fires in Sierra Nevada mixed conifer forests. *Can. J. For. Res.* **1989**, *19*, 455–462.
38. Brown, J.K.; Reinhardt, E.D.; Kramer, K.A. *Coarse Woody Debris: Managing Benefits and Fire Hazard in the Recovering Forest*; General Technical Report RMRS GTR-105; USDA Forest Service, Rocky Mountain Research Station: Ogden, UT, USA, 2003; p. 16.
39. Stephens, S.L.; Fry, D.L.; Franco-Vizcaíno, E.; Collins, B.M.; Moghaddas, J.M. Coarse woody debris and canopy cover in an old-growth Jeffrey pine-mixed conifer forest from the Sierra San Pedro Martir, Mexico. *For. Ecol. Manag.* **2007**, *240*, 87–95.
40. Van Wagtendonk, J.W. *Use of a Deterministic Fire Growth Model to Test Fuel Treatments*; In Sierra Nevada Ecosystem Project: Final report to Congress, Volume II; Centers for Water and Wildland Resources, University of California, Davis: Davis, CA, USA, 1996; pp. 1155–1165.
41. Laiho, R.; Prescott, C.E. Decay and nutrient dynamics of coarse woody debris in northern coniferous forests: A synthesis. *Can. J. For. Res.* **2004**, *34*, 763–777.
42. Covington, W.W.; Sackett, S.S. The effect of a prescribed burn in southwestern ponderosa pine on organic matter and nutrients in woody debris and forest floor. *For. Sci.* **1984**, *30*, 183–192.
43. Stephens, S.L.; Finney, M.A. Prescribed fire mortality of Sierra Nevada mixed conifer tree species: Effects of crown damage and forest floor combustion. *For. Ecol. Manage.* **2002**, *162*, 261–271.
44. Stephens, S.L.; Moghaddas, J.J. Fuel treatment effects on snags and coarse woody debris in a Sierra Nevada mixed conifer forest. *For. Ecol. Manag.* **2005**, *214*, 53–64.
45. Mutch, L.S.; Parsons, D.J. Mixed conifer forest mortality and establishment before and after prescribed fire in Sequoia National Park, California. *For. Sci.* **1998**, *44*, 341–355.
46. Youngblood, A.; Grace, J.B.; McIver, J.D. Delayed conifer mortality after fuel reduction treatments: Interactive effects of fuel, fire intensity, and bark beetles. *Ecol. Appl.* **2009**, *19*, 321–337.
47. Duvall, M.D.; Grigal, D.F. Effects of timber harvesting on coarse woody debris in red pine forests across the Great Lakes states, U.S.A. *Can. J. For. Res.* **1999**, *29*, 1926–1934.
48. Keifer, M.; van Wagtendonk, J.W.; Buhler, M. Long-term surface fuel accumulation in burned and unburned mixed-conifer forests of the central and southern Sierra Nevada, CA (USA). *Fire Ecol.* **2006**, *2*, 53–72.
49. Kobziar, L.N.; McBride, J.R.; Stephens, S.L. The efficacy of fire and fuels reduction treatments in a Sierra Nevada pine plantation. *Int. J. Wildland Fire* **2009**, *18*, 791–801.
50. Vaillant, N.M.; Fites-Kaufman, J.; Reiner, A.L.; Noonan-Wright, E.K.; Daily, S.N. Effect of fuel treatments on fuels and potential fire behavior in California, USA, national forests. *Fire Ecol.* **2009**, *5*, 14–29.
51. Trofymow, J.A.; Barclay, H.J.; McCullough, K.M. Annual rates and elemental concentrations of litter fall in thinned and fertilized Douglas-fir. *Can. J. For. Res.* **1991**, *21*, 1601–1615.
52. Hall, S.A.; Burke, I.C.; Hobbs, N.T. Litter and dead woody dynamics in ponderosa pine forests along a 160-year chronosequence. *Ecol. Appl.* **2006**, *16*, 2344–2355.

53. Stephens, S.L.; Moghaddas, J.J. Silvicultural and reserve impacts on potential fire behavior and forest conservation: Twenty-five years of experience from Sierra Nevada mixed conifer forests. *Biol. Conserv.* **2005**, *125*, 369–379.
54. Zald, H.S.J.; Gray, A.N.; North, M.; Kern, R.A. Initial tree regeneration responses to fire and thinning treatments in a Sierra Nevada mixed-conifer forest, USA. *For. Ecol. Manag.* **2008**, *256*, 168–179.
55. Moghaddas, J.J.; York, R.A.; Stephens, S.L. Initial response of conifer and California black oak seedlings following fuel reduction activities in a Sierra Nevada mixed conifer forest. *For. Ecol. Manag.* **2008**, *255*, 3141–3150.
56. Gray, A.N.; Zald, H.S.J.; Kern, R.A.; North, M. Stand conditions associated with tree regeneration in Sierran mixed-conifer forests. *For. Sci.* **2005**, *51*, 198–210.
57. League, K.; Veblen, T. Climatic variability and episodic *Pinus ponderosa* establishment along the forest-grassland ecotones of Colorado. *For. Ecol. Manag.* **2006**, *228*, 98–107.
58. Van Mantgem, P.J.; Stephenson, N.L.; Keeley, J.E. Forest reproduction along a climatic gradient in the Sierra Nevada, California. *For. Ecol. Manag.* **2006**, *225*, 391–399.
59. Hallin, W.E. *The Application of Unit Area Control in the Management of Ponderosa-Jeffrey Pine at Blacks Mountain Experimental Forest*; Technical Bulletin 1191; United States Department of Agriculture: Washington, WA, USA, 1959.
60. Vaillant, N.M. Sagehen Experimental Forest Past, Present, and Future: An Evaluation of the Fireshed Assessment Process. Ph.D. Thesis, University of California, Berkeley, CA, USA, 2008.
61. Collins, B.M.; Moghaddas, J.J.; Stephens, S.L. Initial changes in forest structure and understory plant communities following fuel reduction activities in a Sierra Nevada mixed conifer forest. *For. Ecol. Manag.* **2007**, *239*, 102–111.
62. Wayman, R.B.; North, M. Initial response of a mixed-conifer understory plant community to burning and thinning restoration treatments. *For. Ecol. Manag.* **2007**, *239*, 32–44.
63. Knapp, E.E.; Schwilk, D.W.; Kane, J.M.; Keeley, J.E. Role of burning season on initial understory vegetation response to prescribed fire in a mixed conifer forest. *Can. J. For. Res.* **2006**, *37*, 11–22.
64. Campbell, J.; Alberti, G.; Martin, J.; Law, B.E. Carbon dynamics of a ponderosa pine plantation following a thinning treatment in the northern Sierra Nevada. *For. Ecol. Manag.* **2009**, *257*, 453–463.
65. North, M.; Oakley, B.; Fiegener, R.; Gray, A.; Barbour, M. Influence of light and soil moisture on Sierran mixed-conifer understory communities. *Plant Ecol.* **2005**, *177*, 13–24.
66. Dodson, E.K.; Peterson, D.W.; Harrod, R.J. Understory vegetation response to thinning and burning restoration treatments in dry conifer forests of the eastern Cascades, USA. *For. Ecol. Manag.* **2008**, *255*, 3130–3140.
67. Perchemlides, K.A.; Muir, P.S.; Hosten, P.E. Responses of chaparral and oak woodland plant communities to fuel-reduction thinning in southwestern Oregon. *Rangel. Ecol. Manag.* **2008**, *61*, 98–109.
68. North, M.; Innes, J.; Zald, H. Comparison of thinning and prescribed fire restoration treatments to Sierran mixed-conifer historic conditions. *Can. J. For. Res.* **2007**, *37*, 331–342.

69. McKelvey, K.S.; Johnston, J.D. Historical Perspectives on Forests of the Sierra Nevada and the Transverse Ranges of Southern California: Forest Conditions at the Turn of the Century. In *The California Spotted Owl: A Technical Assessment of Its Current Status*; General Technical Report GTR-PSW-133; Verner, J., McKelvey, K.S., Noon, B.R., Gutierrez, R.J., Gould, G.I., Jr., Beck, T.W., Eds.; USDA Forest Service, Pacific Southwest Research Station: Albany, CA, USA, 1992; pp. 225–246.
70. Yanai, R.D.; Arthur, M.A.; Siccama, T.G.; Federer, C.A. Challenges of measuring forest floor organic matter dynamics: Repeated measures from a chronosequence. *For. Ecol. Manag.* **2000**, *138*, 273–283.
71. *USDA Forest Service Sierra Nevada Forest Plan Amendment: Final Environmental Impact Statement*; USDA Forest Service, Pacific Southwest Region: Vallejo, CA, USA, 2001.
72. USDA Forest Service. *California Spotted Owl Sierran Province Interim Guidelines and Environmental Assessment*; USDA Forest Service, Pacific Southwest Region: San Francisco, CA, USA, 1993.
73. Herger, W.; Feinstein, D. *Herger-Feinstein Quincy Library Group Forest Recovery Act*. Department of the Interior and Related Agencies Appropriations Act, Section 401; U.S. Congress: Washington, DC, USA, 1998.
74. Reinhardt, E.D.; Keane, R.E.; Calkin, D.E.; Cohen, J.D. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. *For. Ecol. Manag.* **2008**, *256*, 1997–2006.
75. Peterson, D.L.; Johnson, M.C.; Agee, J.K.; Jain, T.B.; McKenzie, D.; Reinhardt, E.D. *Forest Structure and Fire Hazard in Dry Forests of the Western United States*; General Technical Report PNW-GTR-628; USDA Forest Service, Pacific Northwest Research Station: Portland, OR, USA, 2005; p. 30.
76. North, M.; Collins, B.M.; Stephens, S.L. Using fire to increase the scale, benefits and future maintenance of fuel treatments. *J. For.* **2012**, in press.