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Long-Term Effects of Fuel Reduction Treatments on Surface Fuel Loading in the Blue Mountains of Oregon

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Abstract: Fire exclusion and a lengthening fire season has resulted in an era of megafires. Fuel reduction treatments in forested ecosystems are designed to guard against future extreme wildfire behavior. Treatments create a heterogenous landscape and facilitate ecosystem function and resilience in fire-adapted forests of the western United States. Despite widespread recognition that repeated fuel treatments are needed to maintain desired stand characteristics over time, few field studies have evaluated treatment longevity. The Blue Mountains Fire and Fire Surrogate site in northeastern Oregon presented an opportunity to investigate woody fuel loading 15–17 years after four treatments: mechanical thin, prescribed burn, both thin and burn, and no treatment control. The principal findings were: (1) fine fuel load 15 years post-burn remained slightly below pre-treatment values; (2) rotten coarse fuel load was reduced post-burn, but sound coarse fuel was not altered by any active treatment; and (3) total woody fuel load 15–17 years post-treatment was similar to pre-treatment values. Understanding surface fuel loading is essential for predicting fire behavior. Overall, the effects of fuel reduction treatments on woody surface fuels were transitory in dry mixed conifer forests. Frequent maintenance treatments are recommended to protect values at risk in areas with high fire hazards. Quantifying the persistence of changes in forest conditions aids in the planning and analysis of future fuel treatments, along with scheduling maintenance of existing treated areas.

Keywords: fuel treatment; woody fuel; ponderosa pine; Douglas-fir; fire hazard; forest management; Fire and Fire Surrogate

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1. Introduction

Dry forests of the western United States co-evolved with fire, a disturbance that alters plant communities through successional processes. In return, vegetation impacts fire spread and behavior. The interaction of fire with fuels, weather, and topography creates a range of fire intensities, giving rise to a heterogeneous landscape. Plant and animal communities depend on fire as an essential disturbance for the structural diversity it generates [1]. A forest that supports a mix of successional stages is predicted to be more resilient to future disturbance [2].

Recent management practices have directly and indirectly homogenized the structure and composition of many dry forests in the western United States, prompting concerns about wildfire and sparking debate over future management [3–5]. In addition, human-induced climate change has been linked to longer fire seasons and increased frequency of large fires [6,7]. The cost of fighting wildland fire is rising quickly, and is likely to continue with increasing human encroachment into the wildland–urban interface, rising mid-summer temperatures in the western United States, and lengthening fire seasons [6]. Attempting to use suppression as the primary method to deal with wildfires is a reactive approach which is not always effective, and if successful, compounds the hazard posed by fire over time.

Forests characterized by frequent, predominantly low-severity fire regimes prior to Euro-American settlement currently support unusually high stand densities and fuel accumulations, which were created by a century of fire exclusion along with grazing and timber-harvesting practices [3,8]. These forests are good candidates for fuel reduction treatments, although forests with predominately infrequent, high-severity fire regimes may not realize such ecological benefits [9]. Increasing attention is being focused on historical reconstructions of mixed-severity fire regimes that have been found across the range of dry to moist mixed-conifer forest types and may be equally qualified candidates for fuel reduction treatments [10,11]. Forest fuels are categorized as canopy, ladder, surface, and ground fuels, ranging from the tops of overstory trees, vegetation between the canopy and the surface, organic matter and woody debris on the ground, and subsurface organic material [12]. Ladder fuels, such as tall shrubs and understory trees, create vertical continuity capable of carrying fire from the forest surface into the canopy, which is considered severe fire behavior. High surface fuel loading can increase flame lengths and promote crown fire activity. Most fuel treatments aim to reduce surface fuels, create gaps in the canopy, and break up ladder fuels [13,14]. These modifications decrease the likelihood of fire spreading into the crowns of trees.

Dry ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) and mixed-conifer forests in the western United States are commonly targeted for fuel reduction treatments which are designed to reduce future extreme fire behavior, promote resilient forest structure and composition, and facilitate wildfire management/suppression efforts [15]. Treating stands with mechanical thinning, prescribed fire, or a combination of both reduces stand density and alters fuel loading [13]. As a result, recently treated stands with low surface fuel accumulations that subsequently experience wildfire often support increased tree survival compared to neighboring untreated stands [16–18]. The effectiveness of fuel reduction treatments varies based on many factors, including forest type, the specific treatment implemented, weather and fuel moisture conditions; however, a common theme is the importance of slash management and time elapsed since treatment.

Not all harvesting activities qualify as fuel reduction treatments. Any desired reduction in wildfire severity can be negated by residual slash left on-site after mechanical thinning [19,20]. Furthermore, applying low-intensity prescribed fire may result in little change to fuels, whereas using prescribed fire alone to reduce tree density can result in fire-killed trees that eventually fall and increase surface fuel loading over time [21]. In western dry forests, using mechanical thinning to reduce stand density followed by prescribed fire to consume surface fuels and increase crown base height provides the greatest reduction in fire hazard and movement towards historical stand structure [22,23].

Few field studies have examined the length of time that treatments remain effective, and empirical research on treatment longevity has been identified as a knowledge gap [24]. The effect of single-entry fuel reduction treatments diminishes with time as gaps created by thinning and burning fill in with trees and understory vegetation. Additionally, dead woody debris re-accumulates on the forest floor post-burn and slash decomposes post-thin. Several studies from California provide insight into mid- and long-term changes in fuel loading following fuel reduction treatments, generally finding that fuel loads return to pre-treatment levels within a decade after treatment [25–27]. Investigating temporal changes in stand structure and fuel loading provides insight into treatment longevity, which is critical for understanding how both fire intensity and the rate of spread may change post-treatment. Fire intensity, or energy released per second per unit of fire edge, is largely affected by the total amount of fuel that is available to burn; the rate of spread, or speed of forward fire movement, is primarily driven by fine fuel loading [28]. Changes in surface fuel loading can have a substantial impact on wildfire behavior and are the focus of this paper.

The Fire and Fire Surrogate (FFS) study network, funded by the Joint Fire Science Program, includes 13 sites across the United States that examine the economic and ecological effects of common fuel reduction treatments across many forest types, as well as the applicability of using mechanical thinning as a surrogate for fire [29]. The Blue Mountains FFS study site in northeastern Oregon is a prime location to evaluate the lasting effects of mechanical thinning and prescribed fire 15–17 years after treatment [30]. We used this site to ask: (1) What are the differences between pre-treatment and post-treatment woody fuel loading 4–6 years post-treatment; and (2) Do differences between pre-treatment and post-treatment woody fuel loading persist over longer post-treatment time periods (15–17 years)? These questions were investigated for thinning and burning, singly and in combination.

2. Materials and Methods

2.1. Study Site

The Blue Mountains FFS study area is located within the Wallowa-Whitman National Forest in northeastern Oregon. Study units were spread across 50 km^2, but limited to elevations between 1040 m and 1480 m [30]. Between 1981 and 2010, the average annual precipitation was 483 mm, average wintertime low temperature was −8 °C, and average summertime high temperature was 30 °C [31]. The dominant tree species is ponderosa pine, with Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) secondary and intermittent grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), lodgepole pine (*Pinus contorta* Dougl. ex Loud.), and western larch (*Larix occidentalis* Nutt.). Some stands were partially cut within the several decades prior to treatment and the study area was affected by high levels of bark beetle activity in the 1990s [32]. Fire history reconstructions from similar ponderosa-pine-dominated forest in the neighboring Malheur National Forest estimate a pre-1900 fire return interval of 11–18 years [33]. A study of dry forests in the Imnaha watershed, where the study site is located, found fire scar evidence for 46 fires between 1687 and 1900, suggesting that frequent, low-severity fire characterized the historical fire regime [34]. Timber harvesting, grazing, and fire exclusion have altered the historical fire regime for over a century, contributing to a denser forest with a higher proportion of shade-tolerant species than found in the era prior to Euro-American settlement [10,35].

2.2. Treatment Implementation

The Blue Mountains FFS site contains sixteen treatment units, ranging in size from 8 to 20 hectares [30]. Units were randomly assigned to one of four treatments, for a total of four replications of each treatment. Treatments included mechanical thinning, prescribed burning, a combination of thinning and burning, and a no-treatment control (Figure 1). The target basal area (BA) was 16 m^2 ha^{-1}, and the fine fuel loading target was $\leq$4.5 Mg ha^{-1} [32]. Thinning treatments took place after the initial measurement in 1998, consisting of a thin from below, with a preference for retaining large trees or snags and fire-tolerant species, specifically ponderosa pine. Residue from thinning remained on site. Units were broadcast-burned in the fall of 2000; weather and fuel conditions during ignition are described in Youngblood et al. [32]. Overall, fire effects were low to moderate, with flame lengths averaging <0.3 m. Thin and burn units tended to support more intense fire than burn-only units due to residual slash from thinning.

Figure 1. Photographs depicting the range of conditions found within each treatment at the Blue Mountains FFS site. Photographs taken by Kat Morici, 2015.

2.3. Field Sampling

Depending on the size and shape of the unit, approximately 25 grid points on a 50 m spacing were located as sampling plots, for a total of 380 plots within 16 units [30]. At each plot, researchers measured trees and woody fuels. Data were collected pre-treatment in 1998 (1999 for three of the burn-only units) and post-treatment in 2001 (trees only), 2004 and 2015. The 2015 measurement undertaken by this study consisted of eight of the original plots within each unit, selected at random from all plots in a unit, for a total of 128 plots. This number of plots was feasible within the time and budgetary constraints given the intensity of measurement.

To quantify woody fuels, three 20 m Brown's transects [36] were measured at each plot. Fine fuels are usually defined as dead woody material on the forest floor with a diameter of less than 7.6 cm; in this study, the diameter of fine fuels ranged from 0.64 cm to 7.6 cm. Field sampling methods between 1998 and 2004 did not include tallying 1 h fuels (<0.64 cm) because the study organizers at that time did not believe 1 h fuels to be a large contributor to fire behavior. On a 3 m section of each transect, 10 h (0.64–2.5 cm) fuels were tallied. Along the entire transect, 100 h fuels (2.5–7.6 cm) and 1000 h fuels (>7.6 cm) were counted. For 1000 h fuels, also known as coarse woody debris, diameter and decay class were recorded. The 2015 sampling effort measured 1 h fuels along the same length of transect as 10 h fuels. Data showing the minimal contribution of 1 h fuels to total woody fuel loading are presented in Figure 2; however, 1 h fuels could not be included in analyses comparing between years.

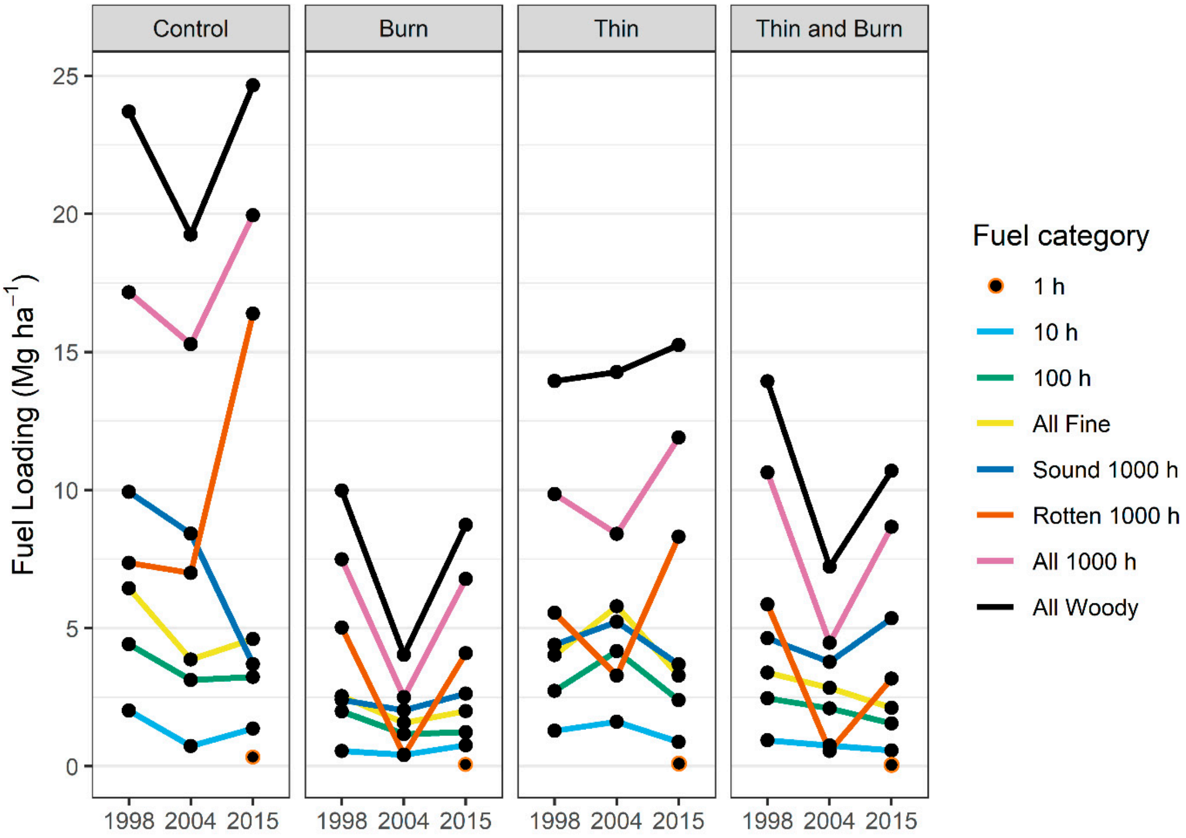

Figure 2. Estimated mean fuel loading by treatment and year. Line color indicates fuel loading category. The All Fine fuel category does not include 1 h fuels, which were only collected in 2015 and are shown here to be a minor component of overall fuel loading.

Fuel loading was calculated for each treatment unit as the mean loading of all plots measured in that unit for a given measurement year. As suggested in Brown's Handbook [36], inputs to the fine fuel calculations were adjusted by the presence of slash and proportion of dominant tree species. Tree species, diameter at breast height, height, and height to live crown was recorded for every tree, sapling, and seedling at each plot in 400 m^2 circular plots. McCaskill [37] examined long-term tree responses to treatment at the Blue Mountains FFS study site.

2.4. Data Analysis

The starting condition of each unit varied due to site differences and past management. Consequently, we used a repeated measures study design to compare the change in fine and coarse woody fuel loadings from the initial measurement to the post-treatment measurements. Each treatment was applied to four units, allowing for analyses of changes in fuel loading within the treatments over time. In 2015, a subset of 128 plots were measured, but analyses of previous years included all 380 plots.

As mentioned in Hungerford et al. [38], site productivity influences fuel loading. To obtain a surrogate for differences in productivity between units, the 30-year monthly averages of the daily maximum vapor pressure deficit (VPD) was gathered for June, July, and August [39]. VPD has a negative relationship with vegetation growth [40]. Each plot was assigned a summer average VPD value based on its spatial location, and plot values were averaged to the unit level.

Linear mixed effects models in R [41,42] were created to investigate the long-term effect of mechanical thinning, prescribed burning, and a combination treatment on fuel loading while allowing for different starting conditions and variances among each treatment and year. Fixed effects included VPD, treatment, year, and the interaction of treatment and year. Unit was included as a random effect, with four replicates per treatment. We used BIC model selection to choose a model with an appropriate correlation structure for each response variable (Table A1 in Appendix A). The selection process included first-order autoregressive, compound symmetry, and general correlation models. To examine differences in size and decay classes, separate models were built for 10 h, 100 h, combined fine fuel, sound 1000 h, rotten 1000 h, and total woody fuel loading (Table A2).

To determine how woody fuel loading changed over time within each treatment, we estimated differences between average fuel loading pre-treatment in 1998 and average fuel loading post-treatment in both 2004 and 2015, resulting in two time period comparisons for each of the four treatments (Table A3). A 95% Bonferroni correction was used to adjust for the eight comparisons of interest (adjusted confidence intervals 99.38%). Due to inherent site differences, such as the initial basal area, species composition, and soil type, the treatments were not directly compared to the no action control.

3. Results

Overall, treatment effects were subtle, with little alteration of forest structure and composition or fuel loading. The post-treatment basal area (BA) target was 16 m^2 ha^{-1}, and the desired fine fuel loading was $\leq$4.5 Mg ha^{-1}. Five of the sixteen units met the BA target pre-treatment, and all treatments except the control met fine fuel target pre-treatment (Figures 2 and 3). At the end of the study, only the thin and burn treatment remained below the target BA, and all active treatments remained below the target fine fuel loading.

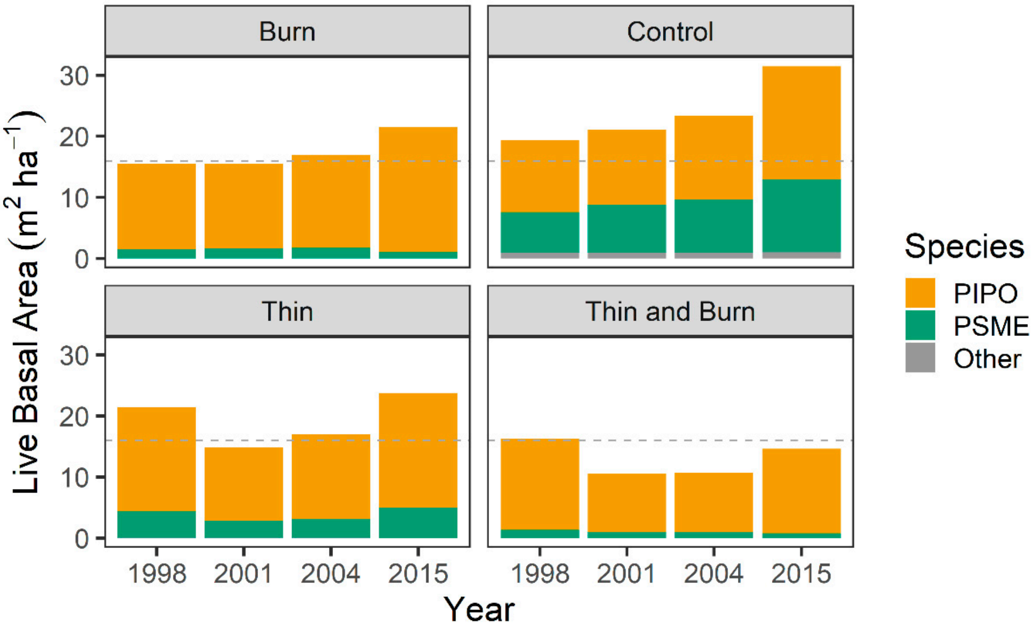

Figure 3. Change in tree species basal area by treatment over time. PIPO is ponderosa pine, PSME is Douglas-fir, and Other includes grand fir, larch, lodgepole pine, and Engelmann spruce. Each treatment is the average of 4 treatment units. The dashed line represents the target BA of 16 m^2 ha^{-1}. Thinning took place in 1998 after the initial measurement, and burning occurred in 2000.

Fuels were highly variable across all treatments, resulting in few statistically significant differences between pre- and post-treatment values in 2004 or 2015 (Figure 4, Table A3). Estimates of differences in fuel loading between years were derived from the selected mixed model. Total woody fuel loading 4–6 years post-treatment was significantly lower than pre-treatment values in the burn-only treatment, an estimated decrease of 6 Mg ha^{-1} (Figure 4). Thinning followed by burning appears to have a similar effect, although it was not statistically detectable. Total woody fuel loading six years following mechanical thinning was estimated to be similar to pre-treatment values (Figure 4). The no-treatment control also did not display a statistically significant difference in mean woody fuel loading over the course of the study. However, fluctuations in mean fuel loading in the control between 1998 and 2004 were comparable to fuel loading changes in active treatments (Figure 4).

Fine fuel loading was examined as a combination of 10 h and 100 h fuel loading. The burn-only treatment showed an estimated 0.96 Mg ha^{-1} reduction in mean fine fuel loading between 1998 and 2004 (Table A3, Figure 4). Sound 1000 h fuel loading did not display a statistically significant change in any of the treatments 4–6 years post-treatment (Figure 4). Although all active treatments showed decreases in mean rotten 1000 h fuel loading 4–6 years post-treatment, only the thin and burn combination reached statistical significance, with a decrease of 5.31 Mg ha^{-1} (Table A3).

There is no evidence that thinning, burning, or a combination of the two had a statistically significant effect on total woody fuel loading 15–17 years post-treatment. A long-term reduction in fine fuel loading is evident in the burn-only treatment, mainly due to the drop in 100 h fuels, which were estimated to be 0.74 Mg ha^{-1} less than the 1998 measurement (Table A3). Mechanical thinning with and without burning did not result in statistically detectable shifts in fine fuel loading during any time period comparison.

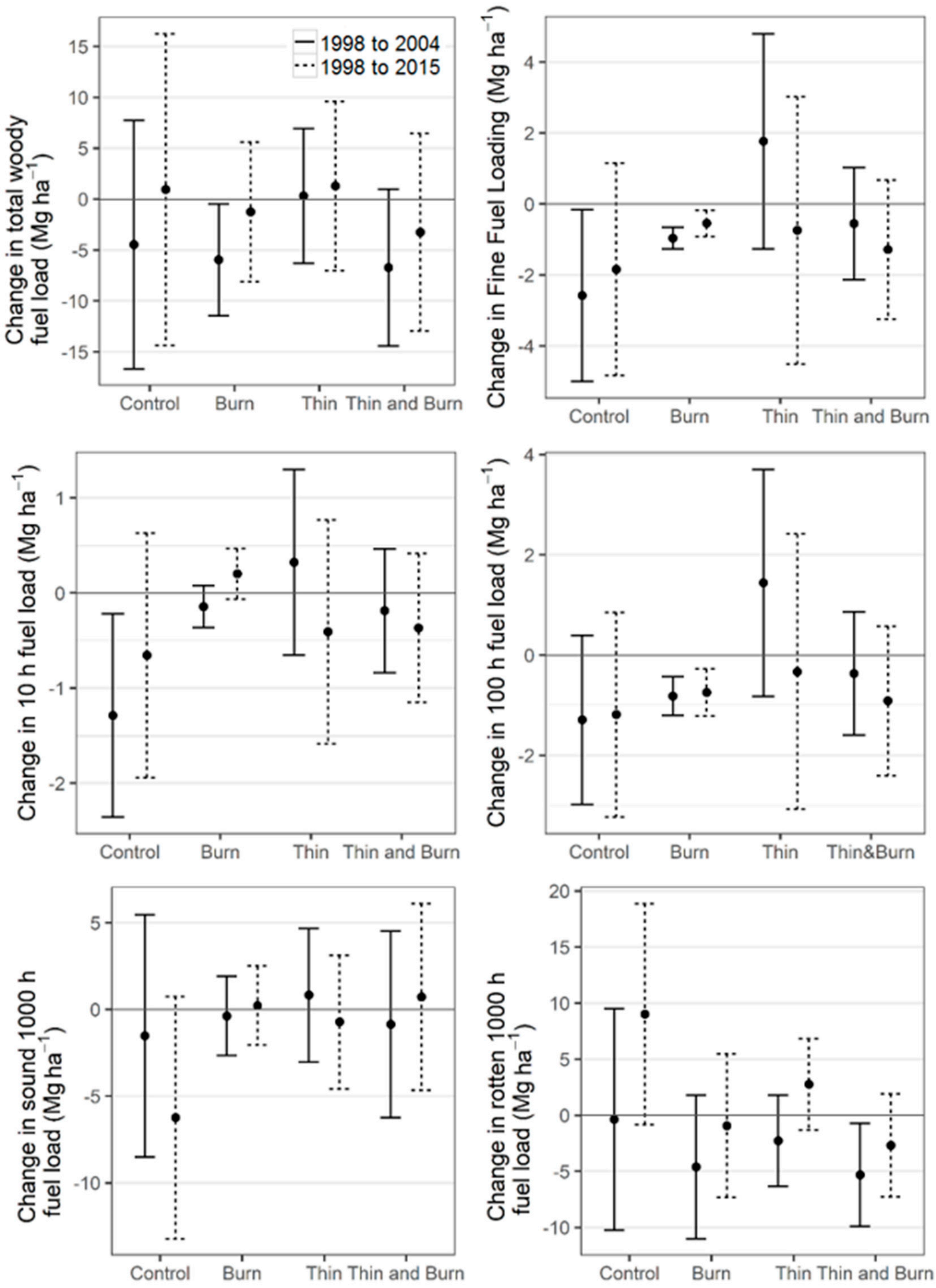

Figure 4. Plots displaying the differences in mean average fuel loading between the initial and post-treatment measurements for each treatment. Error bars represent the 99.38% adjusted confidence interval for the differences. Comparisons where error bars intersect the line at 0 are not statistically significant.

None of the treatments showed a statistically significant change in sound 1000 h fuel loading (Table A3, Figure 4). However, the reduction in mean sound 1000 h loading was estimated to be 6.23 Mg ha^{-1} in the no-treatment control between 1998 and 2015. The corresponding increase, estimated to be 9.02 Mg ha^{-1}, in rotten 1000 h loading indicates that a major portion of the large sound fuels are decaying. After adjusting for multiple comparisons, evidence for these changes is not statistically significant, but presents a reasonable interpretation for the movement in both sound and rotten coarse fuel loading. In the thin and burn treatment, a reduction in rotten 1000 h fuel loading was not statistically detectable 15–17 years post-treatment, although the estimated loading remained 2.69 Mg ha^{-1} below pre-treatment values (Table A3).

4. Discussion

In this study, we examined woody surface fuel loading changes over time following common fuel treatments. Although all active treatments met the management goal for fine fuel loading of less than 4.5 Mg ha^{-1}, both pre-treatment and 15–17 years post-treatment, there were differences in the trajectory towards pre-treatment values. However, total woody fuel loading did not exhibit a long-term detectable difference for any fuel reduction treatment.

4.1. Fuels Trajectories

Total woody fuel loading was reduced in the near term by the burn-only treatment, but returned to pre-treatment levels over the course of the study. This finding is in line with other studies tracking woody surface fuels over time following treatment. An investigation of prescribed fire and mechanical thinning treatments across California's coniferous forests found the total woody fuel load 8 years post-treatment to be 67–79% of the initial loading for the burn-only treatment [26]. The reduction in woody fuel found in California for the burn-only treatment largely fell between the 4-year and 15-year post-burn measurements in our Blue Mountains study, estimated to be 40% and 87% in the burn-only and 52% and 77% in the thin and burn, respectively. In some areas, the effect of burning is more transitory. For example, both fine and coarse woody fuels returned to pre-treatment loading 7 years following prescribed fires in California mixed conifer forests as well as ponderosa pine forests in California and the Colorado Plateau [43]. Woody surface fuels did not exhibit strong trends between immediately post-treatment and 22–23 years following a thin and burn in a mixed conifer forest in Montana [44]. High levels of consumption combined with minimal tree mortality promote larger treatment effects and greater longevity. Westlind and Kerns [45] suggest an initial low-intensity burn to reduce surface and ground fuels while limiting tree mortality, followed by a more intense reburn to maintain low surface fuels and address ladder fuels such as lower tree branches, regeneration, and tall shrubs.

Temporary decreases in fine fuels are expected after prescribed fire, because fine fuels are primary carriers of fire, and are consumed in the process [19]. Fine woody fuels in the burn-only treatment remained slightly below pre-treatment levels fifteen years post-fire in our Blue Mountains site, although initial fuel loading and tree BA were also lowest in the burn-only units. This is most notable when comparing against control units, where the starting fuel loading was more than twice the burn-only units. The burn-only and combined thin and burn units tended to be in less productive sites; factors such as basal area, trees per hectare, species composition, soils, and aspect suggest that the control was skewed towards more productive sites. As such, direct comparison with actively treated units would be problematic. We attempted to capture the influence of the productivity on fuel loading with the inclusion of VPD in the mixed models, but finding more representative controls would be warranted for future studies.

Thinning alone is expected to increase woody fuel loading due to residual slash, "activity fuels," but this effect was not statistically significant 6 years post-treatment in the Blue Mountains thin-only treatment. The whole tree harvest used during the thin likely limited the initial increase in woody fuel loading. In addition, studies from similar forest types confirm that the input of thinning slash dissipates in that approximate timeframe. Thin-only treatments across California's conifer forests were found to have 55–103% of the initial total woody fuel load 8 years post-treatment [26]. The thin-only estimates in this study skewed towards the upper end of the range found in California, estimated to be 102% of initial loading 6 years post-thin, and 109% of initial loading 17 years post-thin.

Fine woody fuels measured at both time periods post-thin remained similar to pre-treatment values. Mixed-conifer forests in the north-central Sierra Nevada experienced a significant increase in fine fuel loading measured 1 year post-thin and decreased to pre-treatment levels by 7 years post-thin [12]. A chronosequence study of mechanical fuel treatments in the eastern Sierras showed that 1 h fuel loading reached a low 5–7 years post-treatment, and returned to untreated levels after 8 or more years [27]. Although the first complete re-measurement of the Blue Mountains study site took place 4–6 years after treatment, Youngblood et al. [32] collected woody fuel data one year post-thin and found an increase in fine woody fuels. This increase was no longer evident after 6 years, indicating that moderate inputs of fine fuels decay or are integrated into litter and duff layers within several years following thinning.

A significant decrease in fine fuel loading in the control between 1998 and 2004 was unexpected and could be due to a microclimate better suited to rapid decomposition. Ponderosa pine and Douglas-fir roots have been found to decompose faster with higher moisture levels [46], and the same trend may hold for fine fuels on the forest surface. Generally, the rate of decay in fine fuels has not been well studied. Sampling and measurement error are also possible causes of the abrupt decline found in these data. Regardless, fine fuel loading in control units was similar in 1998 and 2015. The high variability of fuel loading across landscapes makes the use of experimental controls somewhat speculative in all but the most homogenous study areas [21].

4.2. Restoring Forest Condition

Thinning and prescribed burning treatments are typically designed to restore resilient forest conditions without removing all coarse woody fuels, which are important habitats for a variety of wildlife species [47]. Sound 1000 h fuel loading was not significantly affected by active treatments. The possibility that sound logs were consumed in the prescribed fire and replaced with fire-killed trees is unlikely, given that the total basal area increased over the same period. The lack of effect of prescribed fire on sound fuels is consistent with observations made in Hyde et al. [48]. Sound fuels were noticeably reduced in the control, where they appeared to transition into coarse rotten fuels over the 17-year study. The evident reduction in rotten 1000 h fuels post-burn was also found in other studies [19,49]. Rotten large fuels were likely cured when prescribed burning took place in the fall, which, along with their reduced density and higher surface area to volume ratio, increased their flammability and consumption. Many studies of fuel reduction treatments consider all coarse fuels as a single response variable. However, the differing responses of sound and rotten coarse woody fuels in this study demonstrate a need to examine them separately.

One possible explanation for the lack of a middle-term effect of treatment on total woody loading in our Blue Mountains study is that treatments were designed to have a light touch overall. A portion of the sixteen units met basal area and fine fuel loading targets pre-treatment, reducing the need for a more intense prescribed fire. Additionally, a full re-measurement was not completed until 4 years post-burn and 6 years post-thin. Partial measurements took place one year post-thin and immediately post-burn, but were not considered in this paper due to a lack of corresponding tree data. The effects, especially on fine fuels, were too transitory to be captured in the 4–6-year time frame. Finally, high variability of fuels across the landscape may obscure trends in surface fuel loading with the number of plots measured in this study. However, the similar range of variance between the 2015 measurement of 128 plots and the previous years' 380 plots provides evidence against this line of reasoning.

Downed woody fuel dynamics have not been well studied in these systems, and current fire models are not precise enough to address definitive changes in fuel loading that would substantially impact fire behavior in complex forested systems [50]. Compound disturbances, such as bark beetle attack, have been shown to impact woody surface fuel trajectories in treated stands. An FFS study site in Montana found that both fine and coarse woody fuel were lower in thinned stands than in burned or control stands $\geq$4 years following a mountain pine beetle (*Dendroctonus ponderosae* Hopkins) outbreak due to increased tree survival in thinned areas [51]. Fuel loading is highly variable across forested landscapes; however, estimates of biologically significant changes can be refined by more accurate fire behavior models and additional empirical data. Surface fuels alone do not paint a complete picture of fire hazards; examining changes in canopy and ladder fuels is an important consideration to assess treatment effectiveness over time.

5. Conclusions

It is critically important for humans to coexist with wildfire, a primary disturbance in dry forested landscapes [52]. The current trajectory of increasingly frequent severe fire and rising spending on wildfire suppression efforts is not sustainable [9]. Fuel treatments, such as mechanical thinning and prescribed fire, are tools used to create fire-resilient landscapes through the alteration of live and dead fuel beds. However, fuel reduction treatments do not have a lasting impact on most categories of dead woody fuel loading, highlighting the need for maintenance treatments in areas where surface fuels are a concern. The combination of thinning and burning has consistently been highlighted as the most effective method to accomplish forest restoration, fuel reduction, and resilience to disturbances [21,44,51]. To re-create the heterogeneity produced by a patchwork of fires across the historical dry forest landscape, treatments could be applied every 5–25 years, with more intense treatments following longer treatment-free intervals. Continued monitoring of a range of treated areas, treatment types and intensities will supply a broader picture of fuel loading dynamics across a range of treatments and ecosystems and promote long-term, sustainable and adaptive management.

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Data Availability Statement: Publicly available datasets were analyzed in this study. Historical data were obtained from Jim McIver (https://www.frames.gov/ffs, accessed on 15 January 2015). Data collected in 2015 can be found here: [link/accession number will be provided during review].

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Appendix A

Table A1. Results of model selection for each fuel variable. Bold names indicate low BIC values and acceptable residual plots. cshet uses compound symmetry correlation structure, genhet uses general correlation structure, and arhet uses first-order autoregressive correlation. All models allow for variance heterogeneity among years.

All Fine			**All Wood**		
Model	**DF**	**BIC**	**Model**	**DF**	**BIC**
cshet	19	180.56	cshet	19	299.33
genhet	21	182.68	genhet	21	304.35
arhet	19	**177.38**	**arhet**	19	**297.30**
10 h			**Sound 1000 h**		
cshet	19	119.65	**cshet**	19	**254.92**
genhet	21	124.70	genhet	21	260.64
arhet	19	**118.01**	arhet	19	257.27
100 h			**Rotten 1000 h**		
cshet	19	163.95	cshet	19	259.90
genhet	21	169.34	genhet	21	266.29
arhet	19	**162.51**	**arhet**	19	**259.62**

Table A2. Summary of overall F-tests model fixed effects using the selected model. Results are presented for each fuel variable, bold indicates significance (p-value $\leq$ 0.05).

All Fine				**All Wood**			
Predictor	**DF**	**F-Value**	***p*-Value**	**Predictor**	**DF**	**F-Value**	***p*-Value**
treatment	**3.11**	**9.32**	**0.002**	**treatment**	**3.11**	**5.49**	**0.015**
year	2.24	3.21	0.058	**year**	**2.24**	**6.48**	**0.006**
VPD	1.11	0.41	0.533	VPD	1.11	0.56	0.469
treat * year	**6.24**	**3.52**	**0.012**	treat * year	6.24	1.18	0.351
10 h				**Sound 1000 h**			
treatment	**3.11**	**5.35**	**0.016**	treatment	3.11	2.19	0.146
year	2.24	3.08	0.065	year	2.24	1.72	0.200
VPD	1.11	1.31	0.277	VPD	1.11	2.09	0.176
treat * year	**6.24**	**4.34**	**0.004**	treat * year	6.24	1.71	0.161
100 h				**Rotten 1000 h**			
treatment	**3.11**	**10.79**	**0.001**	**treatment**	**3.11**	**6.89**	**0.007**
year	**2.24**	**3.42**	**0.049**	**year**	**2.24**	**13.90**	**<0.001**
VPD	1.11	0.04	0.851	VPD	1.11	0.06	0.817
treat * year	6.24	2.44	0.055	treat * year	6.24	2.33	0.065

Table A3. Estimated differences in mean average fuel loading (Mg ha^{-1}) between initial and post-treatment measurements for each treatment. Bold indicates statistical significance (p-value ≤ 0.006).

Treatment	Comparison	Estimate	t_{24} Value	p-Value	99.4% Confidence Interval
All Wood					
Control	2004 vs. 1998	−4.46	−1.09	0.285	(−16.67, 7.76)
	2015 vs. 1998	0.95	0.19	0.854	(−14.37, 16.26)
Burn	2004 vs. 1998	−5.95	−3.25	**0.003**	(−11.43, −0.47)
	2015 vs. 1998	−1.25	−0.55	0.591	(−8.12, 5.62)
Thin	2004 vs. 1998	0.33	0.15	0.884	(−6.29, 6.94)
	2015 vs. 1998	1.31	0.47	0.641	(−6.99, 9.6)
Thin and Burn	2004 vs. 1998	−6.71	−2.61	0.015	(−14.43, 1.01)
	2015 vs. 1998	−3.24	−1.00	0.325	(−12.92, 6.44)
All Fine					
Control	2004 vs. 1998	−2.58	−3.20	**0.004**	(−4.99, −0.16)
	2015 vs. 1998	−1.84	−1.84	0.078	(−4.84, 1.16)
Burn	2004 vs. 1998	−0.96	−9.49	**<0.001**	(−1.27, −0.66)
	2015 vs. 1998	−0.54	−4.31	**<0.001**	(−0.92, −0.16)
Thin	2004 vs. 1998	1.77	1.74	0.094	(−1.27, 4.8)
	2015 vs. 1998	−0.74	−0.59	0.563	(−4.51, 3.03)
Thin and Burn	2004 vs. 1998	−0.55	−1.05	0.304	(−2.13, 1.03)
	2015 vs. 1998	−1.28	−1.96	0.062	(−3.24, 0.68)
10 h					
Control	2004 vs. 1998	−1.29	−3.61	**0.001**	(−2.35, −0.22)
	2015 vs. 1998	−0.65	−1.52	0.141	(−1.94, 0.63)
Burn	2004 vs. 1998	−0.14	−1.94	0.064	(−0.36, 0.08)
	2015 vs. 1998	0.20	2.29	0.031	(−0.06, 0.47)
Thin	2004 vs. 1998	0.32	0.99	0.331	(−0.65, 1.3)
	2015 vs. 1998	−0.41	−1.04	0.310	(−1.59, 0.77)
Thin and Burn	2004 vs. 1998	−0.19	−0.86	0.400	(−0.84, 0.46)
	2015 vs. 1998	−0.37	−1.41	0.172	(−1.15, 0.41)
100 h					
Control	2004 vs. 1998	−1.29	−2.30	0.030	(−2.97, 0.39)
	2015 vs. 1998	−1.19	−1.74	0.094	(−3.23, 0.85)
Burn	2004 vs. 1998	−0.82	−6.34	**<0.001**	(−1.21, −0.43)
	2015 vs. 1998	−0.74	−4.75	**<0.001**	(−1.21, −0.28)
Thin	2004 vs. 1998	1.44	1.91	0.068	(−0.82, 3.71)
	2015 vs. 1998	−0.33	−0.36	0.721	(−3.08, 2.42)
Thin and Burn	2004 vs. 1998	−0.37	−0.89	0.380	(−1.6, 0.86)
	2015 vs. 1998	−0.91	−1.83	0.080	(−2.41, 0.58)
Sound 1000 h					
Control	2004 vs. 1998	−1.51	−0.65	0.522	(−8.5, 5.47)
	2015 vs. 1998	−6.23	−2.67	0.013	(−13.22, 0.75)
Burn	2004 vs. 1998	−0.38	−0.50	0.624	(−2.66, 1.9)
	2015 vs. 1998	0.22	0.29	0.772	(−2.06, 2.51)
Thin	2004 vs. 1998	0.83	0.65	0.523	(−3.02, 4.68)
	2015 vs. 1998	−0.71	−0.56	0.583	(−4.57, 3.14)
Thin and Burn	2004 vs. 1998	−0.85	−0.48	0.639	(−6.25, 4.54)
	2015 vs. 1998	0.72	0.40	0.691	(−4.67, 6.11)

Table A3. *Cont.*

Treatment	Comparison	Estimate	t_{24} Value	*p*-Value	99.4% Confidence Interval
Rotten 1000 h					
Control	2004 vs. 1998	−0.37	−0.13	0.900	(−9.05, 8.32)
	2015 vs. 1998	9.02	2.88	0.008	(−0.35, 18.4)
Burn	2004 vs. 1998	−4.61	−2.43	0.023	(−10.3, 1.08)
	2015 vs. 1998	−0.93	−0.45	0.654	(−7.08, 5.22)
Thin	2004 vs. 1998	−2.27	−1.80	0.084	(−6.06, 1.51)
	2015 vs. 1998	2.76	2.02	0.054	(−1.33, 6.85)
Thin and Burn	2004 vs. 1998	−5.31	−3.34	**0.003**	(−10.07, −0.55)
	2015 vs. 1998	−2.69	−1.57	0.130	(−7.83, 2.45)

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