Assessing Strategies for Decreasing Severe Fire Hazard in Young Plantation Forests in the Sierra Nevada

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ABSTRACT

Since the 1980s, forest fire activity has increased in the western United States, resulting in longer fire seasons, increased number of large fires, more acreage burning at high severity, and larger patch sizes of high severity fire. In an increasing number of scenarios, conifer seedlings fail to reestablish in large, high severity patches due to weather, decreased seed source, and competition from shrubs. Concern over type conversion will likely result in an increase in plantation forestry in the wake of these fires in the coming decades. Plantations possess homogeneous characteristics; even-aged stands planted in grid-like patterns with low species variability create scenarios in which fire can travel with exceptional efficiency throughout a stand. I assessed how four management treatments change stand structure, fuel loading, and predicted tree mortality via a modeling analysis using the Forest Vegetation Simulator (FVS) in young plantations in the Sierra Nevada. I found significant differences across most structural variables as well as fine fuel classes. In all modeled scenarios, treatments reduced predicted mortality relative to a modeled "untreated" control. Predicted mortality was similar across treatments in severe weather but was variable in moderate weather. The greatest reduction from severe to moderate weather was seen in mastication-only stands. My results demonstrate the need for young plantation forests to undergo management treatments to increase heterogeneity and therefore resiliency to fire and other disturbance events, and a framework for interpreting management impacts in FVS.

KEYWORDS

mastication, herbicide, prescribed fire, forest modeling, FFE-FVS, mortality

INTRODUCTION

Since the 1980s, forest fire activity has increased in the western United States, making for longer fire seasons (Westerling et al. 2006), more fires > 400 ha, more area burning at high severity, and increased patch sizes of high severity fire (Miller and Safford 2012). Heightened forest fire activity is attributable to both climate change and a century of forest management centered around fire suppression (Westerling et al. 2006). In the northern Sierra Nevada, the removal of fire from historically frequent-fire forests has led to dense stands and continuous fuels, dramatically increasing the risk of severe fire in any given location (Stephens et al. 2013, Stephens et al. 2007). Furthermore, climate change is causing shifts in ecological processes, including reduced winter precipitation; warmer, earlier springs; and drier vegetation (Kobziar et al. 2009). In some cases, synergistic effects of climate, weather, and management render forests unable to regenerate after high severity events (Collins and Roller 2013); effective reforestation methods are critical if historically forested ecosystems are to be maintained (Kobziar et al. 2009). Plantation forestry is thought to be the most effective reforestation method in areas with historic frequent-fire intervals; however, young plantation forests require management to decrease the risk of another high severity event (Kobziar et al. 2009). We will likely observe an increase in plantation forestry (and plantation management) in the Sierra Nevada in the coming decades (Kobziar et al. 2009).

Plantations are susceptible to an increased risk of fire severity for several reasons. Plantation forests are planted uniformly across a landscape at high density and with low species variability, resulting in homogeneous stand structure characteristics such as trees per acre (TPA), tree height, tree height to live crown base (HTCB), spatial arrangement, and species composition. Ideally, they are periodically treated using herbicides, prescribed fire, mechanical thinning, or combinations thereof in an effort to encourage heterogeneity, decrease fuel loading (Kobziar et al. 2009) and, in an industrial setting, maximize growth of individual trees (Dean and Baldwin 1996). However, thinning and fuel reduction treatments are often inadequate, due to restrictions pertaining to high costs or safety concerns (Donovan and Brown 2005). An ill-managed plantation forest will burn at even higher severity than a naturally occurring forest, due to homogeneous structural characteristics allowing fire to propagate throughout a landscape without interruption (Zald 2018). Consequently, contemporary forest management in the Sierra Nevada requires not only reforestation, but affordable fuel reduction and understory thinning treatments, especially while the stand is still young. However, when considering ecological variability and contemporary anthropogenic impacts, it is often unclear which management strategy will most closely meet objectives (Millar et al. 2007).

Forest modeling can be used as a tool to assess the effects of different management strategies in regard to fire risk. The Forest Vegetation Simulator (FVS) is a widely used individual-tree, distance-independent growth and yield model used to simulate forest stands under a variety of conditions and management treatments (Havis and Crookston 2008). FVS can work in conjunction with the Fire and Fuels Extension (FFE) to combine tree, stand, and fuel information to model potential fire activity (Rebain et al. 2010). Accuracy of the model has been evaluated under many conditions, and simulated results most closely meet real world events when site-specific information overrides default model inputs and is most sensitive to fire weather inputs (Hummel et al. 2013). User inputs to FFE-FVS include tree information; such as species, diameter at breast height (DBH), tree height, age, and crown width; site data, such as site class, slope, site quality, and latitude/longitude; and fuels data such as fuel model, moisture content, wind speed, temperature, and slope (Rebain et al. 2010). FFE-FVS has been used to show differences in predicted fire risk in the western United States post variable treatments (Johnson et al. 2011, Agee et al. 2010).

This study examines how severe fire risk changes in young plantation forests under four different management strategies via a modeling analysis in the Forest Vegetation Simulator. The stands I analyze have undergone one of the following management treatments: prescribed fire, mastication, mastication and herbicide application, and mastication and prescribed burning. I examine how different management treatments have changed stand structure, fuel loading, and predicted tree mortality in FEE-FVS under moderate and severe weather conditions. I expect differences in stand structure, especially trees per acre, specifically between burned and unburned stands. I expect burned stands will have decreased ground fuel loading due to consumption during the fires. I expect the burned stands to have a lower predicted mortality due to decreased fuel loading, especially under moderate weather conditions.

METHODS

Study site

This study took place at UC Berkeley's Blodgett Experimental Forest (Blodgett Forest), located in El Dorado county (38.8863° N, 120.6477° W) in the northern Sierra Nevada. Blodgett Forest ranges from 3,900 to 4,800 feet in elevation and receives an average yearly rainfall of 65" (100" for snow). The vegetation fits the Sierra Nevada Mixed Conifer classification, with white fir (*Abies concolor*), Douglas-fir (*Pseudotsuga menziesii*), incense-cedar (*Calocedrus decurrens*), ponderosa pine (*Pinus ponderosa*), and black oak (*Quercus kelloggii*) as the most dominant tree species (Blodgett). Summer temperatures range from 57 - 80 °F, while winter temperatures range from 32 - 48 °F (Blodgett). The three primary soil types are Holland, Piliken-variant, and Musick, all with granodiorite as parent material (Blodgett). Blodgett has excellent site quality, with conifers growing to be 90-110′ with DBH of 18-26″ after just 50-60 years (Blodgett). The natural disturbance regime of the northern Sierra Nevada includes frequent, low-severity fire - data shows the historic median return interval to be just 13 years (Blodgett).

The data for this study comes from the Treatment Alternatives for Young Stand Resiliency (TAYSR) study, which has examined the effects of a wide variety of management treatments on young stands within Blodgett and analyzed the effects on tree damage and mortality (Bellows et al. 2016). This study is focused on 14 young plantations in Blodgett forest, planted between 1996 and 2000. Stands were around one acre in size, large enough to avoid early height suppression of seedlings (York and Battles, 2008). All stands have been managed with one of four treatments: (1) burn-only (B), (2) masticate-only (M), (3) masticate and burn (M+B), and (4) mastication and herbicide (M+H) (Figure 1). B stands were first treated in 2013 with a pruning treatment and prescribed burn. M+B stands were first treated in 2012 with a pruning and mastication, and received an additional raking fuel modification treatment in 2013 before they were also burned. M+B and B treatments were both reburned in 2017. M and M+H stands were also pruned and masticated in 2012, and herbicide applications were conducted in 2014 for the M+H stands. The most recent measurements were conducted in 2018 (Table 1).

Table 1. Breakdown and timeline of study design from 2012 to 2018.

Treatment	Number of Stands	Treated	Measured
Burn Only	3	Pruned 2013, Burned 2013 and 2017	2018
Masticate and Burn	3	Pruned 2012, Mast 2012, Raked 2013, Burned 2013 and 2017	2018
Masticate and Herbicide	4	Pruned 2012, Mast 2012, Herbicide application 2014	2018
Masticate Only	4	Pruned 2012, Mast 2012	2018

Figure 1. Left: A burn-only stand at Blodgett Forest. Right: A masticate+herbicide stand at Blodgett Forest

Data collection

To collect tree data, the research team at Blodgett Forest measured all trees that fell within 24 ft-wide belt transects running N-S across the stands. They recorded tree height, DBH, HTCB, and species code for all trees which fell within the measurable zone, as well as the distance from the end of the transect. This was to account for differences in the actual area measured in each stand. They also classified trees as being dominant, co-dominant, intermediate, or suppressed.

The research team also measured fuel loading at each stand using two Brown's transects 37.2' long and spaced 60° apart. They counted 1-hour and 10-hour fuels that crossed the transect up to 6 ft from plot center, and 100-hour fuels that crossed the transect up to 10 ft from plot center. They counted intersecting 1000-hour fuels over the entire length of each transect and classified them as either sound or rotten. They took two duff and three litter depth measurements on each transect, and measured shrubs within a 1/1000-acre circle surrounding plot center, recording percent cover and average height for each observable shrub species based on an ocular estimate.

Stand structure

To assess differences in stand structure based on management treatment, I used nonparametric Kruskal-Wallis tests to compare four structural characteristics: tree height, HTCB, DBH, and TPA. Additionally, I plotted percent species composition by treatment to look for trends in the data, although I did not conduct a statistical test. I used the analyses of the structural variables to identify where statistically significant differences occur in the raw data, so that I could have a basis for attributing differences in predicted mortality observed in the modeling portion of the study. I did this under the assumption that the highest degree of differences in structure and fuel loading would correlate to larger differences in predicted fire severity as measured by percent predicted mortality.

Fuel loading

Fuel treatments have been shown to create significant differences in fuel loading (Agee and Lolley 2006, Vaillant et al. 2009). I used a two-component PCA analysis to isolate the highest degrees of variance among the eight measured fuel classes: duff, litter, 1-hour, 10-hour, 100-hour, and 1000-hour (sound and rotten). I also used non-parametric Kruskal-Wallis tests to identify statistical differences between fuel classes in the four treatment groups. My reasoning parallels that of the structural analyses; to understand differences in predicted mortality in FFE-FVS, I needed to identify variance and statistical differences in the fuel distributions based on management treatment in the raw data.

Mortality in FFE-FVS

To assess severe fire risk in stands based on management treatment, I used the Forest Vegetation Simulator with the Fire and Fuels Extension (FFE-FVS) to generate a measurement of predicted mortality in moderate and severe weather conditions for each stand. I input the tree and fuels data for each plot, as well as one of two variations of temperature, fuel moisture, and wind speed. Additionally, I created a modeled "untreated" control stand by taking the stand with the highest total TPA and modeling it 10 years into the future, allowing heavy fuel loading to accumulate.

The Forest Vegetation Simulator is an individual tree, distance-independent growth and yield model, with the ability to simulate forest growth as well as mortality and regeneration. The Fire and Fuels Extension is an addition to FVS, with the ability to simulate fuel accumulation in a stand of trees over time while incorporating various management treatments and natural decay (Rebain et al. 2010). Additionally, FVS-FFE can model predicted fire through intensity, crowning, tree mortality, fuel consumption, and smoke production (Reinhardt and Crookston 2003). Predicted fire intensity is based on Rothermol's fire behavior model (Reinhardt and Crookston 2003). Crowning is based on Van Wagner's (1977) equations and work by Scott and Reinhardt (2001). Models behind tree mortality, fuel consumption, and smoke production are from the First Order Fire Effects Model (FOFEM) (Reinhardt and Crookston 2003).

Model inputs include tree and fuels data, weather data, and management information. Because I was only interested in fire effects in 2018, I chose not to incorporate effects of future treatments. For tree data, I input species codes, tree heights, HTCB, and DBH. For fuel data, I input tons/acre of duff and litter, as well as 1-hour, 10-hour, 100-hour, and 1000-hour fuels (both sound and rotten), as well as dominant shrub cover. For the severe weather conditions, I modeled each stand at 80 degrees F, 50 mph sustained wind speed, and with default values for "Very Dry" fuel moisture. For moderate weather, I ran the model for each stand in 50-degree F weather, 10 mph wind, with "Dry" fuel moisture. I recorded the predicted mortality for each simulation, including for the modeled control stand, and compared between all stand types in both weather conditions.

RESULTS

Stand structure results

Significance testing - structure

Using a non-parametric Kruskal-Wallis test and a p-value cutoff of 0.05, I found that significant differences occurred in stand structure as measured by height (p-value = 0.01759), DBH (p-value = 0.000126), and HTCB (p-value = 0.01129e07). M stands had the lowest average DBH and height, and M+B stands had the highest average DBH and height (Table 2). TPA did not differ significantly between treatments for any tree classification (p-value = 0.054 for all trees, p=0.18 for dominant and codominant trees, and p = 0.27 for suppressed and intermediate trees) (Figure 2). For species composition, differences are illustrated in Figure 3; although the data were insufficient for statistical tests, we can identify trends in some species based on treatment type. For example, burned stands have a higher percentage of pine species, while M stands had the highest percentage of black oak (Figure 3).

Table 2. Average post-treatment tree HTCB, dominant/codominant TPA, height, and DBH by treatment type.

Treatment	avg HTCB (ft)	avg TPA	avg DBH (in)	avg height (ft)
B	6.6	388	6.4	27.4
M+B	3.9	236	8.6	32.4
M+H	4.5	133	7.5	30.5
M	4.3	152	5.9	27.3

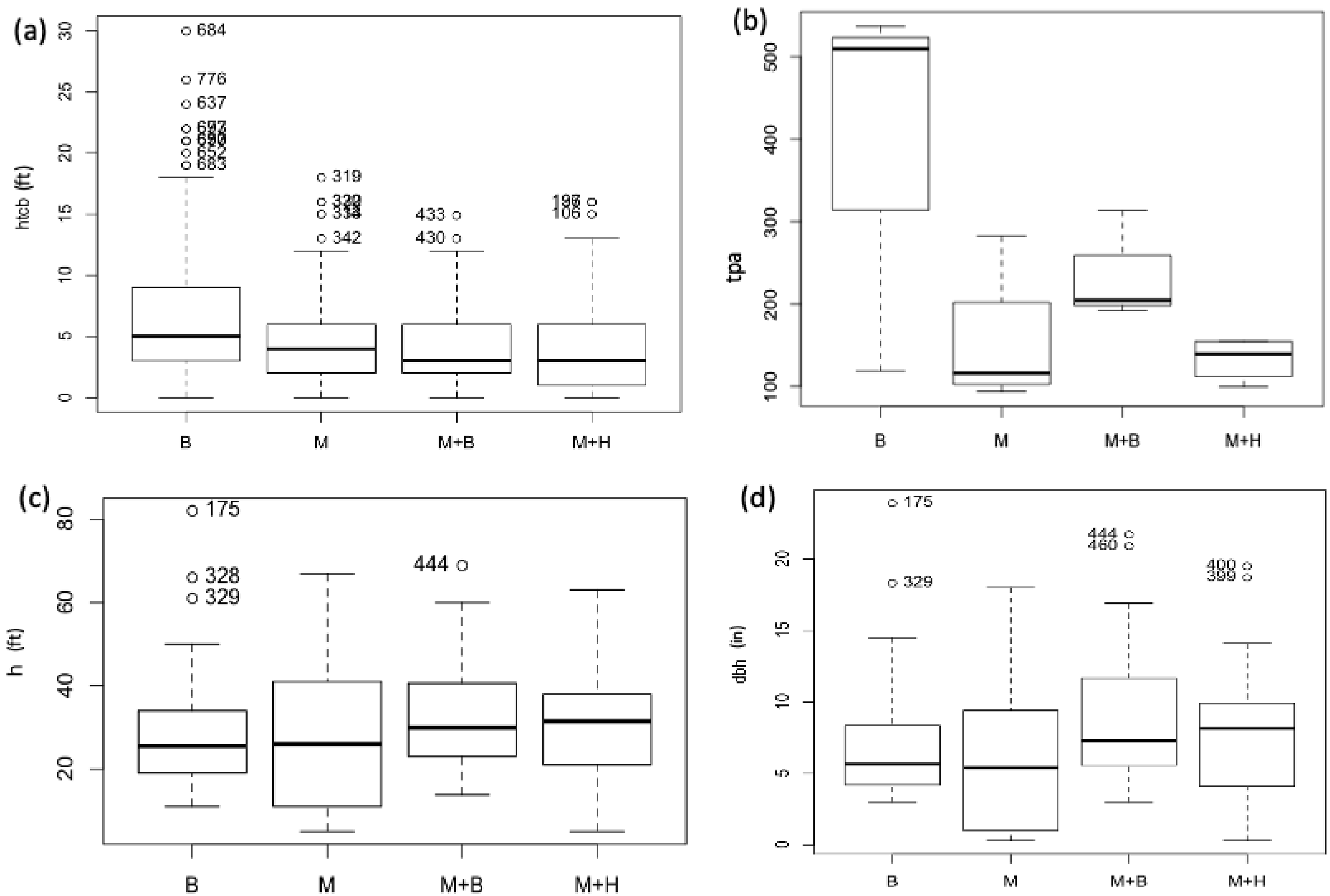

Figure 2. Distributions of post-treatment tree HTCB (a), dominant/codominant TPA (b), height (c), and DBH (d) by treatment type. Highly variable distributions warranted the use of Kruskal-Wallis tests to determine statistical significance.

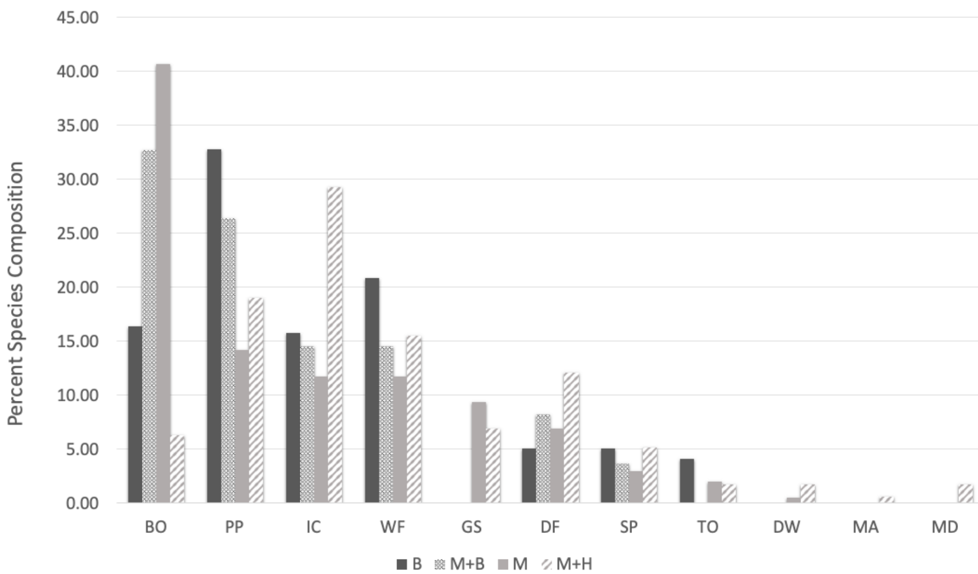

Figure 3. Post-treatment species composition by treatment type. The dominant trees are black oak (Q*uercus kelloggii*), ponderosa pine (*Pinus ponderosa*), incense-cedar (*Calocedrus decurrens*), white fir (*Abies concolor*), giant sequoia *(Sequoiadendron giganteum)*, Douglas-fir *(Pseudotsuga menziesii)*, and sugar pine *(Pinus lambertiana)*. This result is highly variable between treatments.

Fuel Loading Results

Significance testing - fuels

On average, burned sites had a lower total fuel loading than the unburned sites. B sites had the lowest total fuel loading, with a majority of the total tons/acre total attributable to the duff and litter fuel classes. M+B stands had the second lowest total fuel loading. M and M+H stands had similar fuel loading in all fuel categories. The largest difference between burned and unburned stands takes place in the duff and litter categories. All stands had few 1-hour fuels post-treatment, but results were found to be statistically significant for this fuel class (p-value = 0.01189), as well as for the 10-hour fuel class (p-value = 0.03373), the litter fuel class (p-value = 0.01322), and the 1000-hour rotten fuel class (p-value = 0.0122) (Table 4). I did not find the duff, 100-hour, or 1000-hour fuel classes to be statistically different between treatment groups. The 100-hour and 1000-hour fuel classes were highly variable between treatment groups (Figure 4, Table 3).

Table 3. Brown's transect fuel measurements for eight fuel classes. Each plot had two transects for a total of 28.

Treatment	litter	duff	1-hour	10-hour	100-hour	100-hour	1000-hour sound	1000-hour rotten	TOTAL
B	2.13	0	0.09	0.94	6.07	0	0	0	9.23
B	8.5	30.02	0.11	0.71	0	2.96	0	2.96	42.29
B	2.48	0	0.03	0.26	5.07	3.15	0	3.15	10.99
B	0.99	0	0.07	1.04	5.07	0	0	0	7.16
B	0.64	0	0	0.75	0	3.15	0	3.15	4.54
B	0.64	0	0.03	0	1.64	0	0	0	2.31
AVERAGE	2.56	5	0.06	0.62	2.97	1.54	0	1.54	12.75
M+B	10.12	0	0.21	2.45	1.59	2.96	2.86	5.83	20.19
M+B	1.87	0	0	0.98	1.59	2.96	0	2.96	7.4
M+B	4.03	4.29	0.63	2.88	14.4	0	3.73	3.73	29.97
M+B	4.03	4.29	0.8	3.85	8	0	0	0	20.96
M+B	3.89	0	0.19	3.9	14.63	0	6.53	6.53	29.15
M+B	2.59	0	0.19	1.56	3.25	0	7.8	7.8	15.39
AVERAGE	4.42	1.43	0.34	2.6	7.24	0.99	3.49	4.48	20.51
M	5.79	4.56	0.35	4.12	7.79	0	3.28	3.28	25.9
M	19.3	0	0.2	4.35	3.12	4.32	2.9	7.22	34.2
M	3.65	22.75	0.71	5.74	4.59	3.49	0	3.49	40.93
M	2.44	13.65	0.48	2.87	6.12	1.71	2.88	4.59	30.15
M	15.72	18.2	0.07	1.19	0	0	0	0	35.18
M	7.59	0	0	0.71	1.52	0	0	0	9.82
M	10.2	0	0	2.04	0	1.96	0	1.96	14.2
M	8.74	16.34	0	0.77	0	0	0	0	25.85
AVERAGE	9.18	9.44	0.23	2.72	2.89	1.43	1.13	2.57	27.03
M+H	6.03	4.14	0.76	4.15	3.48	0	0	0	18.56
M+H	6.8	8.62	0.25	0.49	3.48	0	0	0	19.64
M+H	4.89	0	1.74	7.77	3.18	0	0	0	17.58
M+H	19.56	17.19	2.72	8.02	6.37	0	0	0	53.85
M+H	5.6	0	0.22	0.72	3.04	0	0	0	9.58
M+H	6.19	15.95	0.15	1.2	4.56	3.32	0	3.32	31.36
M+H	16.48	26.17	0.47	2.37	5.36	2.09	0	2.09	52.95
M+H	8.24	8.72	0.91	1.9	3.57	0	0	0	23.35
AVERAGE	9.22	10.1	0.9	3.33	4.13	0.68	0	0.68	28.36

Table 4. Significance level of post-treatment fuel distributions between treatment types. Significant differences are connoted by *. Significant differences were found in the litter, 1-hour, 10-hour, and 1000-hour rotten fuel classes.

fuel class	p-value
duff	0.161
litter	0.01322 *
1-hour	0.01189 *
10-hour	0.03373 *
100-hour	0.4098
1000-hour sound	0.05159
1000-hour rotten	0.0122 *

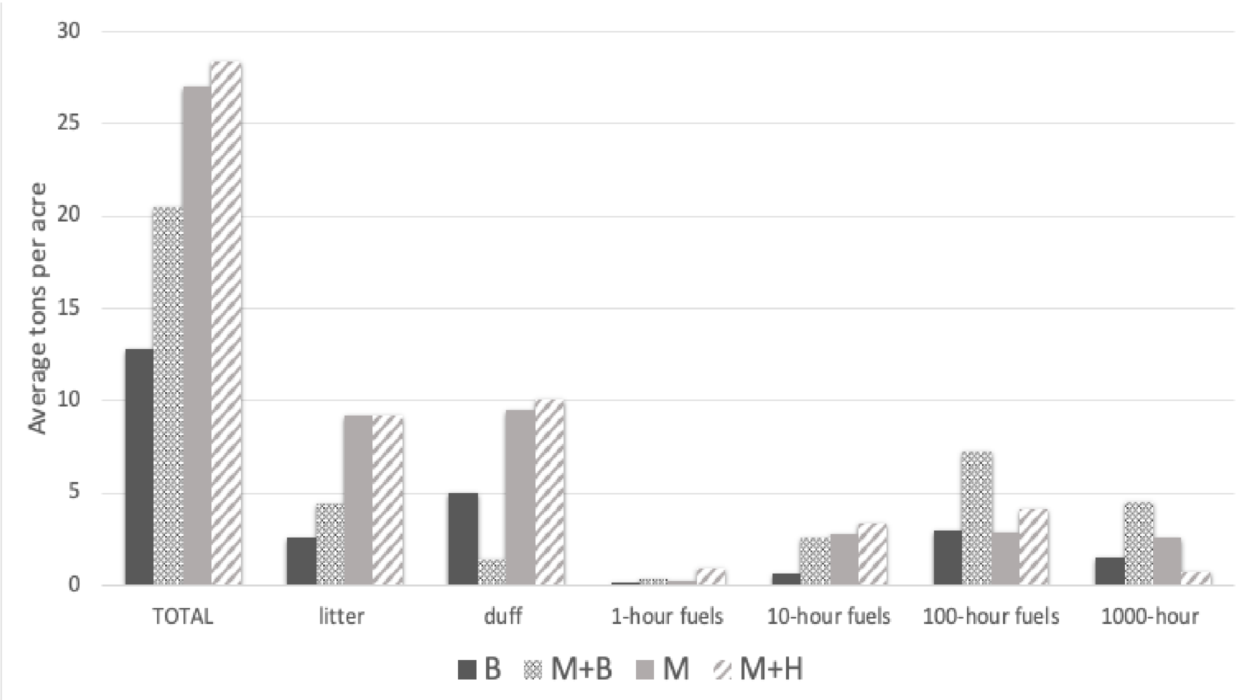

Figure 4: Post-treatment fuel loading by fuel class based on treatment type. B treatments have the lowest fuel loading on average, followed by M+B treatments. Burned stands have less duff and litter than unburned stands. All treatments have few 1-hour fuels. B stands have lower 10-hour fuels. 100 and 1000-hour fuel classes are highly variable.

Principal component analysis results

The PCA analysis accounted for 62% of variance on the first two axes. B stands possess the least amount of overall variation, followed by M+B and M stands. The M+H stands possessed the most diverse fuel loading of any treatment group (Figure 5). The x-axis is most positively correlated with fine fuels (litter, duff, 1-hour, and 10-hour fuel classes), and is negatively correlated with 1000-hour rotten fuels. The y-axis is most positively correlated with 1000-hour rotten and 100-hour fuels, and negatively correlated with duff, litter, and 1000-hour sound fuels (Table 5).

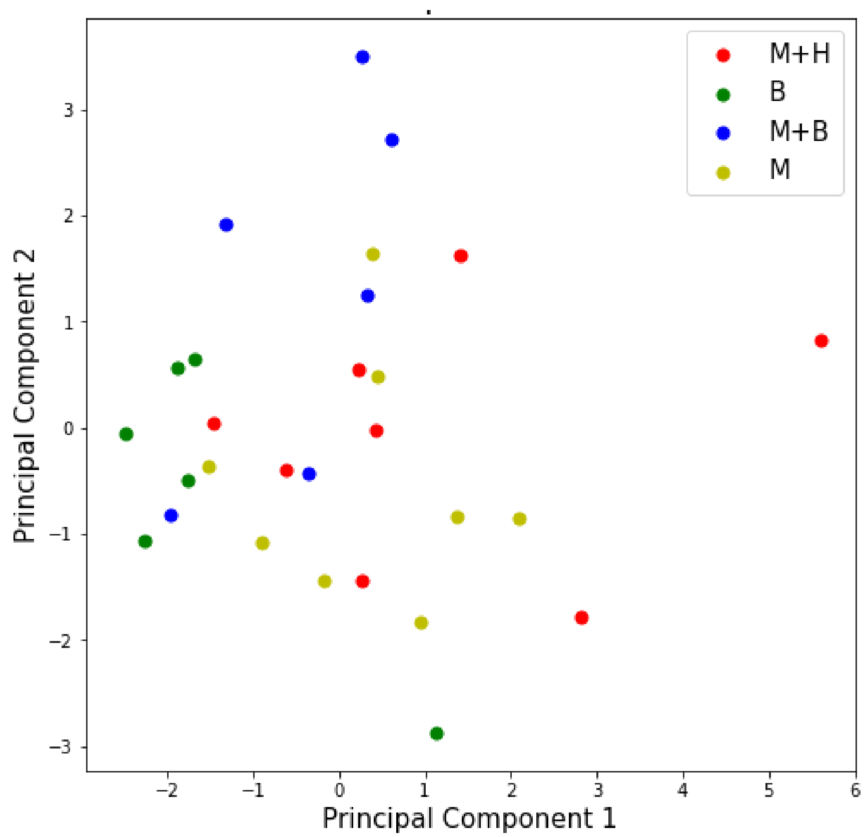

Figure 5. 2-component PCA analysis of fuels data. Burn only treatments are most closely clustered, followed by M+B and M treatments. M+H treatments contain the most variance.

Table 5: Coefficients of variation for each feature of two-component PCA analysis. The x-axis(Principal Component 1) is most positively correlated with fine fuels and is negatively correlated with 1000-hour rotten fuels. The y-axis (Principal Component 2) is most positively correlated with 1000-hour rotten and 100-hour fuels, and negatively correlated with duff, litter, and 1000-hour sound fuels.

component	x-axis coefficient	y-axis coefficient
Litter	0.408301	-0.246162
Duff	0.373904	-0.36893
1-hour	0.440271	0.232238
10-hour	0.43865	0.295978
100-hour	0.145101	0.545528
1000-hour sound	0.0229104	-0.399216
1000-hour rotten	-0.00464664	0.437603

Mortality in FFE-FVS Results

I simulated wildfire events in each stand in FFE-FVS under moderate and severe weather conditions, manipulating wind speed, temperature, and fuel moisture. All stands had lower percent predicted mortality in moderate weather as opposed to severe (Figure 6). Additionally, in both weather conditions, all treatments reduced percent predicted mortality relative to the modeled control. In severe weather, FFE-FVS predicted 100% mortality in the modeled control, but treated stands dropped to a percent predicted mortality rate between 70% and 80% on average. Under moderate weather conditions, M stands exhibited the greatest reduction from severe to moderate weather. This resulted in a lower percent predicted mortality in moderate conditions relative to the M, M+B, and M+H stands, dropping to 36% mortality on average as opposed to 55 - 65% mortality (example in Figure 7).

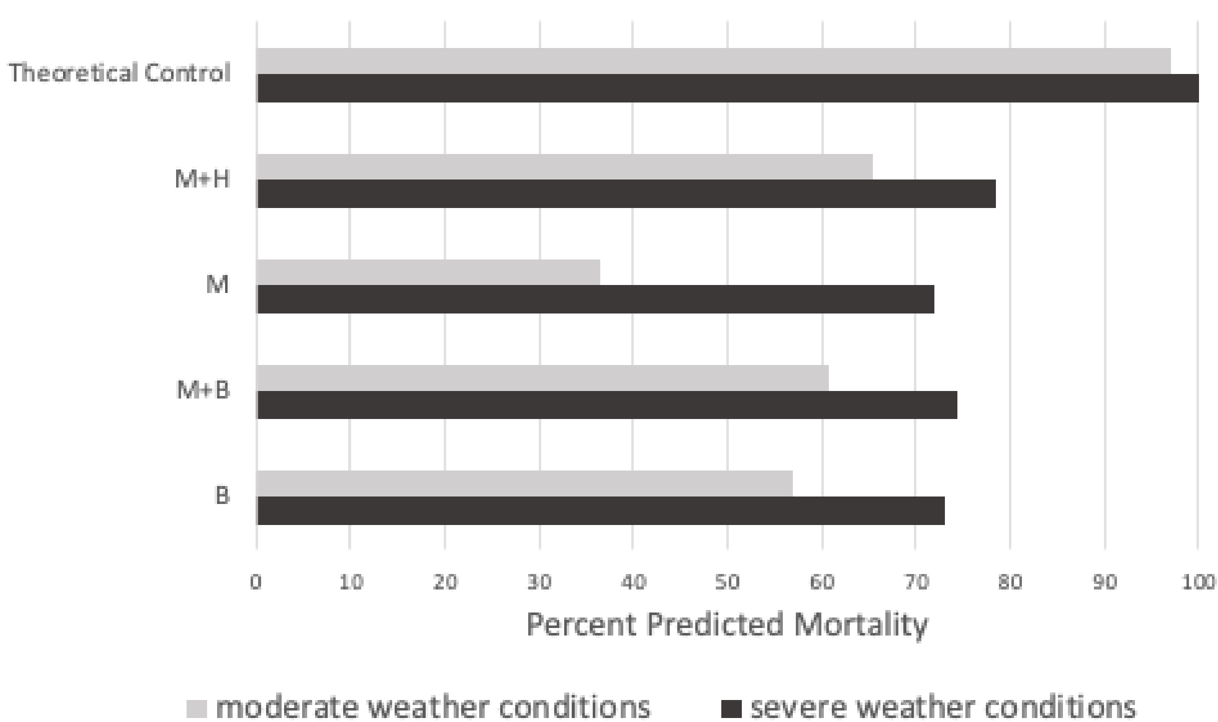

Figure 6. Percent predicted mortality by treatment type under moderate and severe weather conditions. FFE-FVS predicted 100% mortality in modeled control under severe weather conditions, dropping to 96% under moderate weather conditions. All treatments in severe weather average predicted mortality between 70 and 80%. Under moderate conditions, M treatments drop to 36%, while the remaining three stands drop to between 55 and 65%.

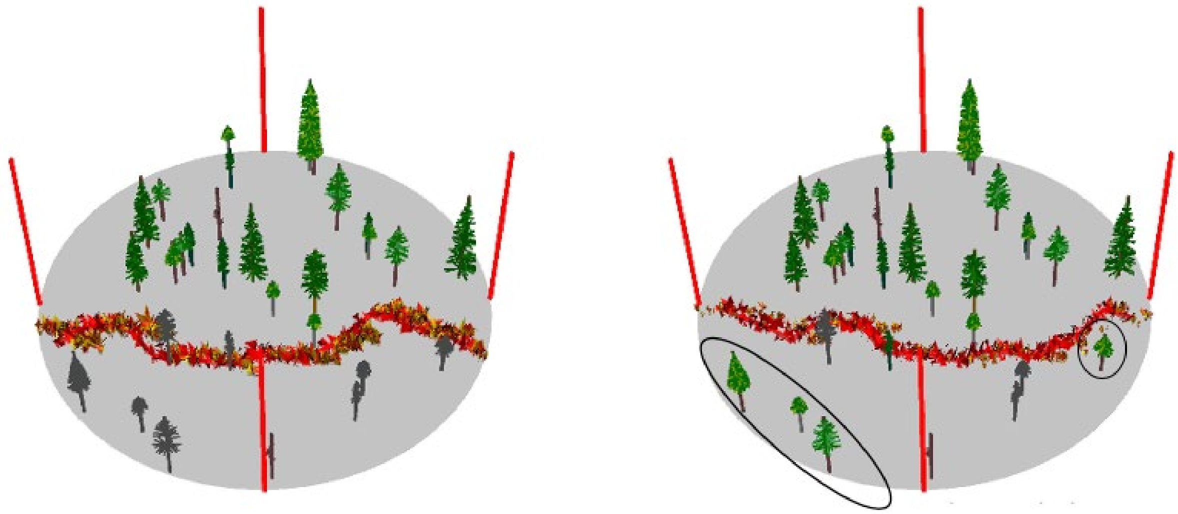

Figure 7: A masticate-only stand in FFE-FVS burning under severe (left) and moderate (right) weather conditions. Circled trees have torched and likely died in severe weather but remain unburned in moderate weather.

DISCUSSION

Results demonstrate the effects of the four forest management strategies on stand structure, fuel loading, and predicted mortality in the event of a severe fire on young plantation forests. Differences in structure and fuels in the data can be linked to differences in percent predicted mortality as measured by FFE-FVS. Non-parametric Kruskal-Wallis tests revealed significant differences in post-treatment tree height, DBH, and HTCB, but did not find significant differences in stand density as measured by TPA (although results were nearly statistically significant). Additionally, also using Kruskal-Wallis tests, I identified significant differences in the litter, 1-hour, 10-hour, and 1000-hour rotten fuel classes. Total fuel loading was lower on average in burned stands, especially when examining litter and other fine fuel classes. Lastly, FFE-FVS simulations predicted lower mortality rates in treated stands than the modeled control stand in all cases. Mortality was similar between treatment types under severe weather conditions (between 70% and 80%). Under moderate conditions, M+B, B, and M+H stands averaged percent predicted mortality between 55% and 65%, but M stands exhibited a large drop to 36%. These findings provide not only information potentially useful to forest managers, but a basis for the use of FFE-FVS to model the effects of forest management strategies in this region, specifically in plantations.

Stand Structure

The differences in DBH and height could be a product of the management treatment. However, due to the lack of comprehensive pre-treatment data, it is difficult to determine causality. Continued measurements of all stands will be necessary to understand long term implications; a 2012 study showed that stands treated with prescribed fires continued to display differences in tree growth up to 7 years post-treatment (Stephens et al. 2012), while burned stands in this study were measured just one year post-treatment.

HTCB in the B treatment was 6.6 ft on average, over 2 ft higher than any other treatment. This result could indicate consumption of the lower branches and canopy in the prescribed burns in the B sites (Fitzgerald and Bennett 2013). However, the same result was not observed in the M+B stands, which had an average HTCB of 4.5 ft. This could be the result of differences in fire behavior between the two sites, or of differences in pruning treatments between the two treatment groups.

As for TPA, if the study design had included more replication of treatments, apparent differences in stand density in the raw data may be present. Specifically, we would observe significantly higher dominant/codominant TPA in B stands. On average B stands had 388 dominant/codominant TPA, 60% more than any other treatment. B stands were the only stands to not receive a mastication treatment, indicating that mastication had an effect on reducing stand density that was not matched by the prescribed fires, which burned at low severity despite the high stand density. Low-intensity burns have been shown to not have a significant impact on forest structure (Schmidt et al. 2006). Instead, the prescribed fires in B stands left most trees living while consuming surface fuels. Additionally, differences in stand density following prescribed burns have been observed up to 8 years post-treatment (van Mantgem et al. 2011), meaning there is also potential for the insignificant finding to be a premature result.

Lastly, slight shifts in tree species composition occurred over the different treatment types. More ponderosa was present in burned stands than unburned, likely a result of the burn prescriptions, and the highest percentage of black oak was in M stands. This difference is likely attributable to oak mortality in burned stands; a 2006 study found that black oak exhibited the highest overall mortality rate during a prescribed fire in the Sierra Nevada (Kobziar et al. 2006).

There is insufficient replication and too short a study period to make conclusions about the impact of treatment on species composition.

Fuels

Principal component analysis

The PCA analysis used each individual plot to visualize the diversity of fuel distributions across treatment groups (similar to Battaglia et al. 2010). The analyses revealed that B stands are the most similar in terms of fuel distributions, indicating the least total variation among the fuels of this treatment group. This difference likely results from the near-total consumption of 1 and 10-hour fuels in all B stands, which was not observed in the other treatment groups. Much of the variation within each treatment group can be accounted for by the 100-hour and 1000-hour fuel classes; for example, in the M+B treatments, one stand had zero tons per acre of 1000 hour fuels, while another stand had nearly 8. It is unclear why high levels of variation were observed in coarse woody debris; this result could also be influenced by differences in prescribed burn severity in individual stands due to factors such as fuel moisture, slope, and wind (Fitzgerald and Bennett 2013)

Differences in Fuels

The significant differences in the litter, 1-hour, and 10-hour fuel classes between treatments is due in part to the consumption of these fuel classes in the B stands (Stephens and Moghaddas 2005). Similar average values occur for 10-hour fuels in the M+B, M+H, and M stands, although the M+B did have the lowest of the three. One explanation for the differences in fine fuels between B and M+B stands is that the mastication treatment in the M+B stands increased the amount of pre-burn fine fuels, which were then only partially consumed (Kobziar et al. 2009). Additionally, the mastication only and mastication and herbicide treatments could have increased the number of fine fuels through pruning treatments which were not followed by a prescribed burn. This is shown to have a significant impact on fire hazard (Kobziar et al. 2009).

Much of the overall difference between burned and unburned stands can be accounted for in the duff and litter fuel classes, which is typical of prescribed burns under fall conditions (Knapp et al. 2005). The decrease in these fuel classes relative to the other treatments indicates partial consumption during prescribed fires, not present in the M or M+H treatments (Although differences in duff were not found to be statistically significant).

Simulating Fire Hazard in FFE-FVS

For all treatments, mortality in moderate weather conditions was lower than mortality in severe weather conditions. Under conditions with decreased temperature, wind speed, and fuel moisture, FFE-FVS anticipated a less severe fire and a higher rate of tree survival. Additionally, in all cases treatments decreased predicted mortality relative to the modeled control, in which 100% mortality was predicted. In severe weather, predicted mortality was between 70% and 80% for all treatment types. This demonstrates that differences in stand structure and fuel loading caused by the different management treatments were able to decrease predicted mortality in all cases relative to the control. This result is supported by Hummel et al. 2013, which found SDI (stand density index) and total fuel loading to be two variables with high mean sensitivity values in FFE-FVS.

Under moderate weather conditions, FFE-FVS predicted more variable mortality, namely a large drop in predicted mortality in M stands. Because of the high fuel loading (average of 27 tons per acre) and low stand density (100 trees per acre on average) in M stands, it is likely that the ease of ground fuel combustion differed widely between the two weather conditions. Under moderate weather conditions, it is likely that fuels were too wet and wind speed was not high enough for torching to occur; however, under severe weather conditions, fuels were dry and the fire was much more severe (Knapp et al. 2005). The modeled control stand had high fuel loads and high tree density, which is why FFE-FVS predicted high mortality rates under both weather conditions (Estes et al. 2017).

Limitations and Future Directions

A future study could expand upon this research to include comprehensive pre-treatment data, which would allow pre and post treatment comparisons of individual treatment types and allow us to conclusively attribute differences in stand characteristics to their respective treatments. Furthermore, a future study could incorporate a true untreated control stand, as opposed to one that existed exclusively in the model.

Potential discrepancy is always inherent whenever a model is used. One way to expand upon this research would be to incorporate real-world data of wildfires burning in these regions under analogous weather conditions. This would allow us to evaluate the accuracy of the mortality estimates generated by FFE-FVS (similar to Hummel et al. 2013). To test the reliability of this model under these circumstances would be valuable to forest managers looking to model the effects of management treatments on plantation forests in the Sierra Nevada. Furthermore, future research could look at longer timeframes and assess the ability of seedlings to reestablish on site in the years succeeding the fire. This could also be done in FFE-FVS, and accuracy could again be compared to a real-world post-fire example.

Lastly, research demonstrates that FFE-FVS is sensitive to the chosen fuel model input (Hummel et al. 2013). This study input on-site fuel information but did not change default fuel model settings as determined by FFE-FVS. A future study could examine on-site fuel configuration in the stands, including live fuels such as shrubs and suppressed/intermediate classified trees, and override the default fuel model settings for a potentially more accurate simulation (Noonan-Wright et al. 2014).

Implications

With this study I have examined the ways in which four management strategies change stand structure and fuel loading, and how changes made influence predicted fire hazard. I was able to identify significant differences in post-treatment stand structure, specifically tree height, HTCB, and DBH, as well as in fine fuel classes and the 1000-hour rotten fuel class. Although changes cannot be attributed to the management treatment itself, understanding the variability between treatment groups indicates which variables are impacting model outputs. The results of the FFE-

FVS simulations revealed all treatments reducing percent predicted mortality relative to the modeled control under both weather conditions. Although percent predicted mortality remained between 70 and 80% under severe weather conditions, we must compare it to the 100% predicted mortality rate in the untreated control. A survival rate of 20% means a stand-replacing event has been avoided, and the presence of a seed source greatly increases the opportunity for seedlings to reestablish on site (Collins and Roller 2013).

This study seeks to assess the impacts of different management treatments on structure and fuel distributions on young plantation forests in the Sierra Nevada and uses FFE-FVS to model wildfire and assess fire severity. This study highlights the advantages of reducing tree density and fuel loading when it comes to decreasing tree mortality under moderate and severe weather conditions, as opposed to leaving plantation forests at high tree density and allowing fuels to accumulate. This study also provides a basis for land managers in the Sierra Nevada to assess fire hazard in plantations post management treatment by using FFE-FVS to simulate wildfire events in different conditions.

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