Assessing Fuel Treatment Strategies for Decreasing Fire Risk in Sonoma County, CA

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ABSTRACT

The western United States has experienced an increase in forest fire activity over the past few decades, with record-breaking wildfires becoming more frequent and intense. Climate change, drought conditions, and human activities such as land-use changes and fire suppression are some of the factors contributing to this trend. To address this issue, forest managers and policymakers are working to develop strategies to reduce the risk of catastrophic wildfires and promote the resilience of forest ecosystems. In this study, I assessed how three different management treatments change fuel loading, fire behavior, mortality, and consumption via a modeling analysis using BehavePlus5 and First-Order Fire Effects Modeling. I found notable differences across measured variables including fuel loading, rate of spread, and mortality. In all modeled scenarios, treatment greatly reduced the intensity and severity of wildfire behavior and fire effects. My results demonstrate the need for forests to undergo management treatments to decrease fuel loading and increase resiliency to fire and other disturbance effects.

KEYWORDS

Mechanical thinning, pile burning, prescribed fire, BehavePlus5, First-Order Fire Effects Modeling

INTRODUCTION

Wildland fire is an important ecosystem component of terrestrial ecosystems in the western United States and is a critical driver of biodiversity, nutrient cycling, and plant succession (Chuvieco and Argoneses 2021). With the growing severity and extent of fire activity in recent decades, there has been an increasing pressure on public land managers to plan and implement wildfire mitigation activities such as fuels reduction and ecological restoration (Coppoletta et al. 2016). Strategic fuels treatment projects have been implemented in many areas in the western United States to mitigate fire risk and improve the emergency response. One area that has implemented several hazardous fuels reduction treatments is Sonoma County, CA. In the past decade, there has been a massive increase in the size and destruction left behind by catastrophic wildfires in Sonoma County. At the time in 2017, the Tubbs fire was the most destructive wildfire in California history. It burned in Sonoma, Napa, and Lake counties and inflicted the greatest losses in the city of Santa Rosa (California Department of Forestry and Fire Protection 2018). In order to mitigate the destructive effects of these catastrophic wildfires, fuel reduction treatments are increasingly important on both public and private lands, particularly in residential communities that have expanded into areas of heavier vegetation known as the wildland urban interface (WUI).

Sonoma County has extensive topographic diversity which supports a wide variety of vegetation types (Howlett 2018). Vegetation, which is also known as fuel, plays a major role in fire behavior and potential fire hazards. Environmental factors such as temperature, precipitation, aspect, slope, soil-type, and land use history also play a role in determining the existing vegetation at any location (Graham et al. 2004). The degree of flammability of a fuel depends on its composition which includes density, moisture level, and chemical make-up (Graham et al. 2004). Fuel moisture is generally the most important consideration in determining the flammability of a fuel and defines how hot a fire will burn and how quickly it will spread. In addition to fuel moisture, a fuel’s chemical make-up also contributes to how easily it will burn (Graham et al. 2004). Lastly, the density of a fuel influences its flammability. When fuels are close together, they will easily ignite one another, causing fire to spread rapidly (Anderson 1982). There are several areas in Sonoma County that have extremely high fuel loading and are extremely susceptible to wildfires under the right conditions, making the area ideal for fuel reduction treatments.

An example of an area with dense vegetation and high fire risk is Santa Rosa Junior College's Shone Farm, a 365-acre agriculture site located in the town of Forestville in northern Sonoma County. Shone Farm has 120 acres of coniferous, oak woodland, and manzanita forest that has been unmanaged and unburned for decades. As a result, there are extremely high levels of fuel loading throughout the forest, making the area a prime candidate for fuel reduction treatments. I have chosen the Shone Farm Forest as my study site due to my participation as an intern with the Santa Rosa Junior College's Wildfire Resilience Program. I have been an intern with the program since the fall of 2022 and have learned valuable hands-on skills in hazardous fuel reduction and land stewardship. I have been an active participant in several fuel reduction treatments throughout the forest and saw this project as an opportunity to quantify the effectiveness of specific fuel reduction treatments in reducing fire behavior. There are several different fuel treatment sites within the Shone Farm Forest that I have selected to gather surface fuel loading data from. This study aims to address the knowledge gap within Sonoma County of how different levels of fuel treatments impact modeled fire behavior.

The first question aims to address is what is the difference in fuel loading between control conditions (C), mechanical thinning and pile burning (M + P), and mechanical thinning, pile burning, and broadcast burning (M + P + B)? I expect that the findings will show that the (M + P + B) treated experimental unit has much less fuel accumulation compared to the untreated control unit. The second question that this study will address is what is the difference in fire behavior between the three treatment sites when modeled using BehavePlus5 and First-Order Fire Effects Modeling (FOFEM) programs? I hypothesize that the untreated control unit will demonstrate significantly more severe and more intense fire behavior compared to the two treated units. The final question that the study will aim to address is what is the predicted mortality and consumption of trees within the three treatment sites when modeled using BehavePlus5 and FOFEM modeling programs? I predict that the BehavePlus5 and FOFEM models will show significantly higher tree mortality and consumption for the untreated control unit compared to the two treated units.

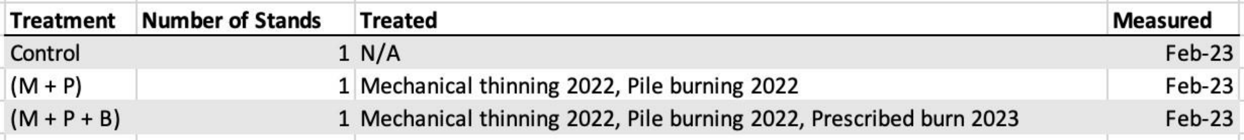
METHODS

Study Site

This study took place at Santa Rosa Junior College's Shone Farm (38°30'31.0"N 122°52'13.6"W), located in northern Sonoma County in the town of Forestville. Shone Farm ranges from 330 to 500 feet in elevation and receives an average yearly rainfall of 30" (UC ANR 2023). The vegetation in the Shone Farm Forest is a mix of coniferous forest, oak woodlands, and manzanita groves. The most dominant tree species include Douglas fir (*Pseudotsuga menziesii*), California bay laurel (*Umbellularia californica*), Pacific madrone (*Arbutus menziesii*), and California black oak (*Quercus kelloggii*). Summer temperatures range from 54°F to 83°F, while winter temperatures range from 39°F to 56°F (UC ANR 2023). The historical fire regime of Sonoma County includes frequent, low-severity fires set by Indigenous Peoples as a way of maintaining healthy and vibrant ecosystems. As a result of these frequent fires, the native trees and vegetation possess qualities such as thick bark and fire-simulated flowering, seed release, and germination (Sonoma County Regional Parks).

The data for this study was collected in February of 2023 across areas of the forest that have received varying levels of fuel treatment. The fuel treatment efforts at the selected study sites began in the fall of 2022 and have been ongoing. The study area for each fuel treatment site was approximately one acre in size. Each selected study site was managed with one of three treatments: (1) control unit (C), (2) mechanical thinning with pile burning unit (M + P), mechanical thinning, pile burning, and (3) broadcast burning unit (M + P + B). The control treatment site has been left untouched by fuel reduction crews and is representative of the unmanaged areas of land within the forest. The (M + P) treatment unit was treated with a variety of mechanical tools such as chainsaws, brush cutters, and woodchippers. The resulting downed trees and vegetation were then made into burn piles and burned during the winter of 2022 when conditions allowed. The same mechanical fuel reduction and pile burning occurred at the (M + P + B) study site, but a prescribed broadcast burn in February of 2023 was the final fuel treatment applied to the land.

Table 1. Breakdown and timeline of study design from 2022 to 2023



Treatment	Number of Stands	Treated	Measured
Control	1	N/A	Feb-23
(M + P)	1	Mechanical thinning 2022, Pile burning 2022	Feb-23
(M + P + B)	1	Mechanical thinning 2022, Pile burning 2022, Prescribed burn 2023	Feb-23

Figure 1. Left: prescribed broadcast burn at (M + P + B) treatment site. Right: an active pile burn at the (M + P) treatment site.

Data Collection

The field data for this study was collected in February of 2023 using the Brown-Planar Intercept method (Brown 1974). Thirty plots were established overall, with 10 plots in each treatment site. Fuel transects plots measured 35’ long and were spaced 60° apart. The cardinal direction of the plot was determined by a random compass spin. The measured fuels were dead, downed, and woody. Material that was alive and downed, dead but suspended at an angle, or herbaceous was not measured. The 1-hour and 10-hour fuels that crossed the transect were counted to 6 ft from the plot center. The 100-hour fuels that crossed the transect were counted to 10 ft from the plot center. The intersecting 1000-hour fuels were counted over the length of the transect and were classified as either sound or rotten. The vertical depth of duff and litter was measured in 5-foot intervals (5 ft, 10 ft, 15 ft, etc.).

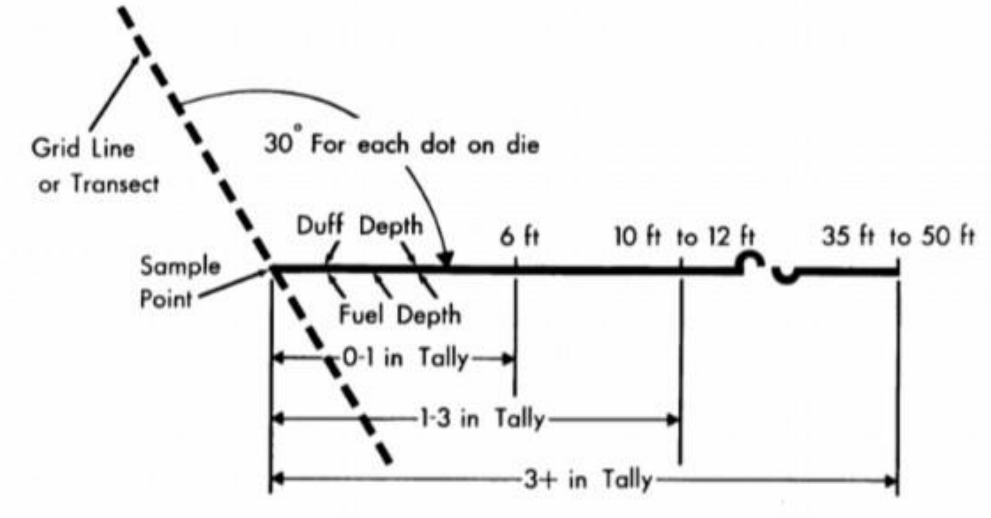


Figure 2.--Top view of sampling plane and location of fuel depth measurements.

Figure 2. Top view of a Brown's transects sampling plane with location of fuel depth measurements.

Figure 3. Map of Shone Farm Forest

Fuel Loading

Fuel treatments have been found to create significant differences in fuel loading (Valliant et al. 2009). I used descriptive and inferential statistics to analyze the differences in fuel loading between the treatment sites and the eight different fuel classes: duff, litter. 1-hour, 10-hour, 100-hour, 1000-hour (sound and rotten). Fuel loading calculations were run for all fuel types but the focus was put on fine fuels, 1000 hour fuels, and fuel bed depth because they serve as parameters for BehavePlus and FOFEM modeling inputs (Reinhardt et al. 2002).

Model Assumptions and Simulations

Fuel data collected from the transects was entered, organized, and converted into tons per acre using equations provided by the Brown Planar Intercept method (Table 2) (Brown 1974). Descriptive statistics of BehavePlus5 and FOFEM model outputs and collected fuel data were produced for each category by treatment area in Microsoft Excel (Andrews 2009).

Table 2: Table showing mean values of fuels in tons per acre by fuel type.

Fuel Type	Control	(M + P)	(M + P + B)
1 hour	1.86	1.54	0.79
10 hour	3.05	2.17	1.47
100 hour	4.12	2.08	1.21
Total fine fuel load	9.03	5.79	3.47
1000 hour (sound)	2.03	1.32	0.63
1000 hour (rotten)	1.63	1.15	0.52
Total 1000 hour	3.66	2.47	1.15
Total woody fuel load	12.69	8.26	4.62
Litter	3.39	4.94	2.01
Duff	2.71	4.14	3.98
Total fuel load	18.79	17.34	10.61

BehavePlus5

Fire behavior for each of the three treatment scenarios was simulated using BehavePlus5, a product of the US Forest Service. Real data collected in February of 2023 was used as input values for fine fuel loading and fuel bed depth, and slope steepness was averaged across each treatment unit. Weather data was accessed from the Fire Behavior Field Reference Guide (FBFRG) provided by the National Wildfire Coordinating Group (NWCG). Weather data was ranked as “low”, “moderate”, “high”, and “extreme” based on its effects on fire behavior.

A surface fire spread simulation provided four basic outputs: rate of spread (ROS), heat per unit area, fire line intensity, and flame length. These variables are commonly used for their effective description of potential surface fire behavior.

First-Order Fire Effects Modeling

Fire effect predictions were made by conducting model simulations in the First-Order Fire Effects Modeling (FOFEM) for all three treatment types (Reinhardt et al. 2002). The field data collected in February of 2023 was used as the input values into the FOFEM model to predict consumption fire effects (Table 2). Flame length in the FOFEM mortality simulations was determined by the flame length outputs of the BehavePlus5 fire behavior model for moderate weather conditions and wind speeds of 5, 10, 15, and 20 mph.

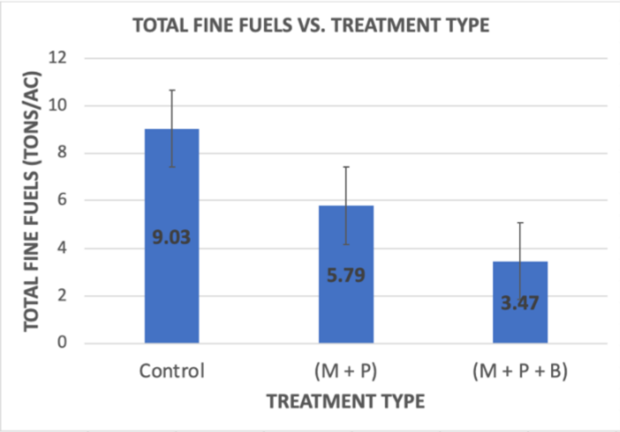
RESULTS

Fuel loading

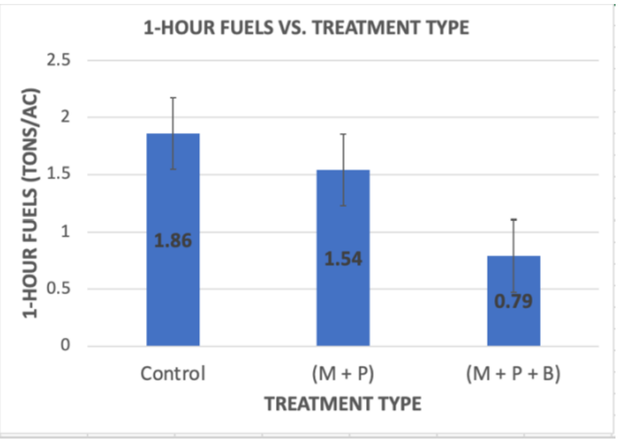
Comparisons in fuel loading were analyzed after descriptive and inferential statistics had been run. Fuel loading calculations were run for all fuel types. The focus was put on fine fuels, 1000-hour fuels, and fuel bed depth since they serve as parameters for BehavePlus5 and FOFEM modeling inputs.

Fuel loading across treatments

Treatment type is clearly the most significant factor when determining differences in fuel loading values. The fuel loading across all three treatment types was the highest in the untreated control area. The (M+P) treatment area had the second highest fuel loading, and the (M+P+B) treatment area had the least amount. The largest amount of sound 1000-hour fuels occurred in the untreated control area, followed by the (M+P) treatment area, and then the (M+P+B) treatment area with the least amount. Rotten 1000-hour fuels were also highest in the untreated control area, followed by the (M+P) treatment area, and then the (M+P+B) treatment area with the least amount.



(a)



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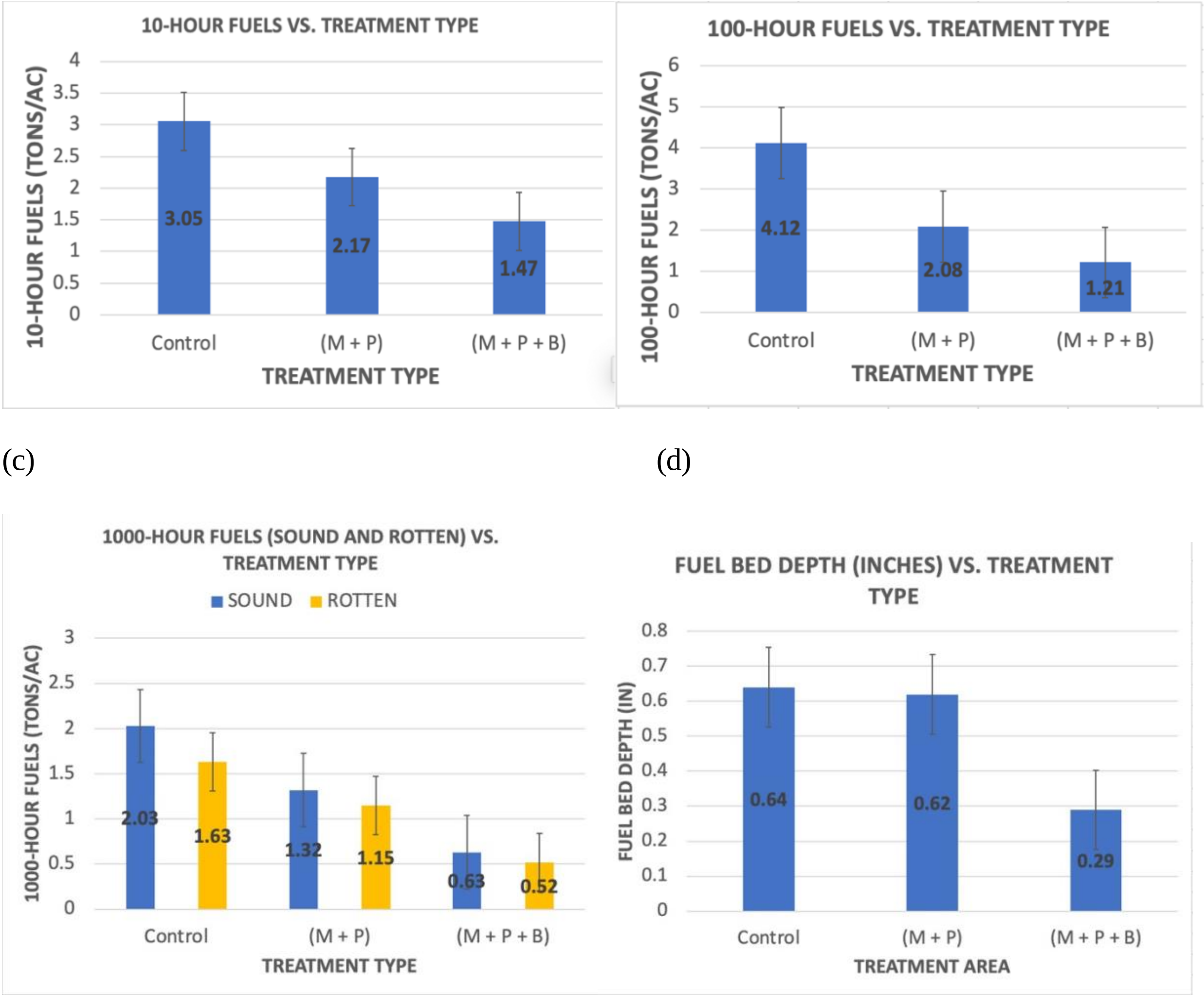


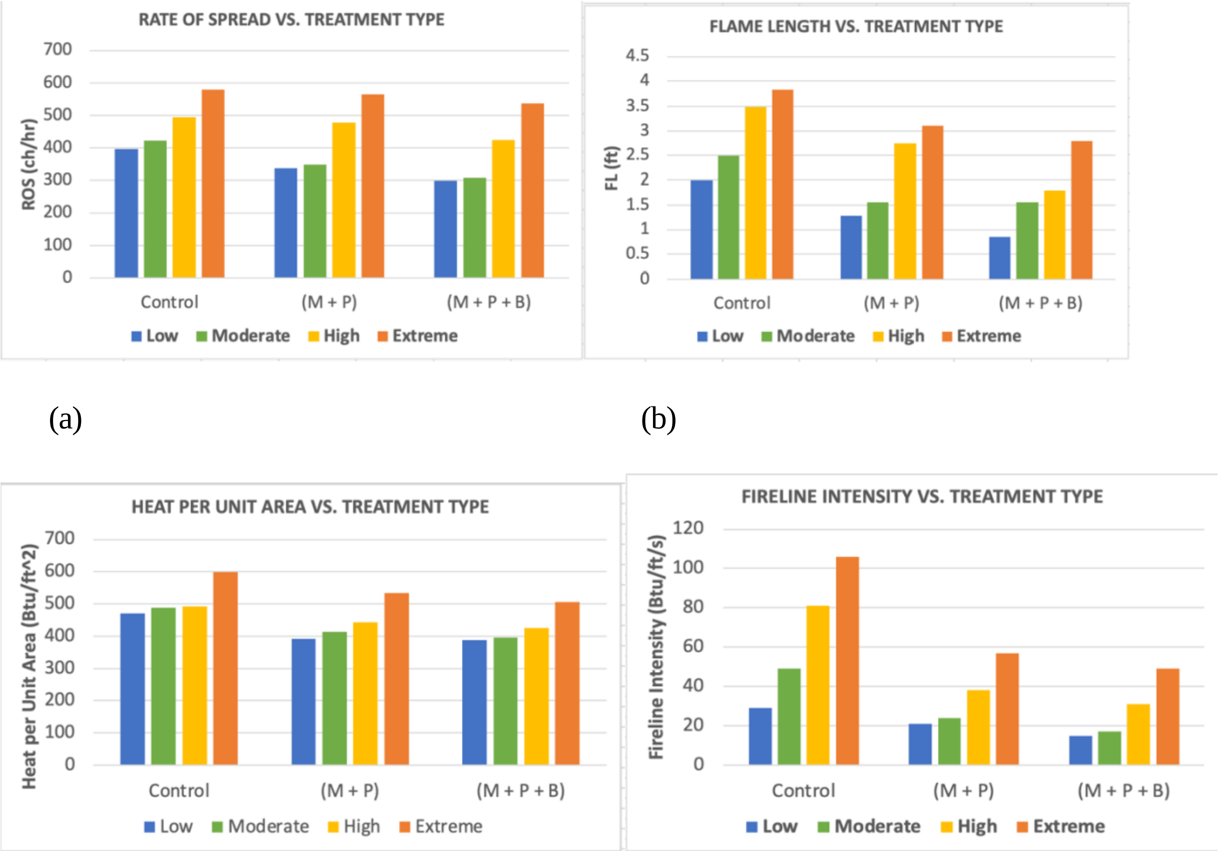
(c) (d)

(e) (f)

Figure 3: Fine fuel loading in tons/acre across the three treatment areas for (a) total fine fuels, (b) 1-hour fuels, (c) 10-hour fuels, (d) 100-hour fuels, (e) 1000-hour fuels (sound and rotten), (f) fuel bed depth (inches)

Fire behavior

For this analysis, only surface fire outputs were chosen to represent the hypothetical fire's spread across the forest floor. Four descriptive metrics were used to illustrate basic characteristics of fire spread. As expected, all metrics have a staircase increase in value as the weather scenario changes from low to extreme. There is a consistent pattern of comparably high outputs in the control and (M + P) treatment sites, with noticeably lower values for the (M + P + B) treatment site. The higher fire behavior metrics for the control site can be attributed to the higher fuel loading values of 10-hour and 100-hour fuels. This explanation is reinforced by the rapid rate of spread (ROS) (a) and the high measurement of heat at the flaming front in this treatment area. These metrics exemplify a rapidly moving surface fire with most of the energy at the flaming front.



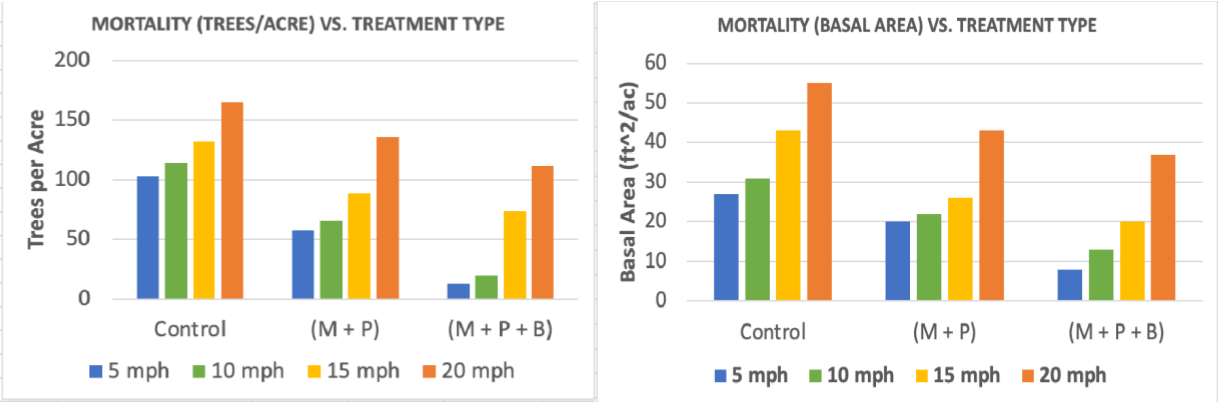
(a) (b)

(c) (d)

Figure 4: Comparison of four fire behavior metrics between treatments and across time depicting the outputs of models created in BehavePlus5. (a) ROS (ch/hr), (b) FL (ft), (c) Heat per unit area (Btu/ft^2), (d) Fireline intensity (Btu/ft/s)

Mortality

Mortality predictions for the stand in each treatment area were made in trees per acre and basal area. The scenarios were modeled with 5,10, 15, and 20 mph relative wind speeds and moderate weather conditions. The highest mortality in trees per acre and basal area was predicted for fires with a 20-mph relative wind speed. Mortality in the number of trees per acre was highest in the untreated control area and lowest in the (M + P + B) treatment area. The mortality in basal areas differed among different wind speeds.



(a) (b)

Figure 6: Mortality of (a) trees per acre and by (b) basal area in the control, (M + P), and (M + P + B) with 5, 10, 15, and 20 mph wind speeds.

Consumption

Across all treatment types, 100% of fine fuels, litter, and 100-hour fuels were consumed for all treatment types. A general decrease in fuel consumption was observed from the untreated control to the (M + P + B) for 1000-hour sound, 1000-hour rotten, and duff fuel types.

Table 4: Percent of fuels consumed in different treatments by fuel type for each of the three treatment areas.

	Control	**(M + P)**	**(M + P + B)**
1-hour	100	100	100
10-hour	100	100	100
100-hour	100	100	100
1000 hour-sound	58	37.3	23.7
1000 hour-rotten	75	52	36.7
Litter	100	100	100
Duff	73.1	66.4	51.8

DISCUSSION

The results demonstrate the effects of three different management strategies on fuel loading, fire behavior, and predicted mortality and consumption in the event of a wildfire in the Shone Farm Forest. It is critical to understand fire behavior as a result of fuel loading in order to effectively implement management practices such as mechanical thinning and prescribed burning (Howlett 2018). The results indicate that differences in management among treatment areas are the best way to create actual detectable changes in fuel loading. It is important to take into consideration more factors that might affect fuel loading like tree density, canopy cover, weather patterns, and the influence of disturbance on the different treatment sites (Graham 2004).

Fuel loading between treatment sites

Fuel loading is a critical aspect of wildfire management, and it can vary greatly depending on the type of management practices employed in a particular area. In the case of this study, the control site had the highest amount of fuel loading since no active management practices had been implemented at the time of data collection. In contrast, the (M + P) management site had the second to least amount of fuel loading. The mechanical thinning process removed some of the biomass, and the pile burning burned the remaining biomass, reducing the overall fuel load. Additionally, the mechanical thinning and pile burning created fuel breaks throughout the forest which helps to reduce the risk of a wildfire spreading (Stephens 2005). However, the mechanical thinning and pile burning treatment alone may not be sufficient to reduce the fuel loading in areas with a history of wildfire suppression, such as the Shone Farm Forest. In this case, the (M + P + B) treatment was the most effective in reducing the fuel load. The prescribed burning that followed the mechanical thinning and pile burning treatments helped to consume the fine fuels that pile burning may have not completely removed, reducing the potential for wildfires to ignite and spread. Furthermore, prescribed burning can promote forest health by reducing competition for resources among trees, increasing biodiversity, and promoting nutrient cycling (Collins et al. 2017). Therefore, a combination of mechanical thinning, pile burning, and prescribed burning can be an effective strategy for reducing fuel loading and promoting forest health.

BehavePlus5: Fire Behavior

Fire behavior is influenced by a variety of different factors such as fuel load, topography, weather, and vegetation structures (Stephens et al. 2012). The use of three different forest management techniques in this study demonstrated that there was a significant impact on fire behavior between the three different study sites. The control treatment site had no forest management intervention whatsoever at the time of data collection. In this case, there was a very high fuel load which resulted in very high intensity fire behavior as demonstrated by the statistics produced by BehavePlus5. As expected, the control site had the highest outputs across all metrics (rate of spread, flame length, heat per unit area, and fire line intensity). Additionally, the metrics across the control site demonstrated a staircase increase in value as modeled weather conditions moved from low to extreme. The fire behavior modeled from the control site data demonstrates that when a wildfire occurs in areas with high fuel loading, it can quickly spread and become more intense. Overall, the dense vegetation in the control site led to very dangerous and volatile wildfire conditions when modeled under different weather scenarios.

The mechanical thinning and pile burning site (M + P) still demonstrates intense fire behavior when modeled with BehavePlus5. The rate of spread and flame length outputs under extreme weather conditions for the (M + P) site were like the control site but not quite as intense. This observation can be attributed more to the extreme fire weather conditions rather than the amount of fuel loading at each site. Under the right weather conditions, fire behavior is likely to be extreme regardless of fuel loading (Valliant et al. 2009). Overall, the mechanical thinning and pile burning techniques helped to create a more open forest floor throughout the treatment site, which can decrease the intensity of fire behavior and make fire suppression efforts easier (Knapp et al. 2011). However, the residual fuel on the forest floor can still contribute to fire behavior under the right conditions.

Lastly, the mechanical thinning, pile burning, and prescribed broadcast burning site demonstrated the least intense fire behavior and the lowest outputs across the four chosen BehavePlus5 metrics. It was demonstrated that prescribed burning can be an extremely effective fuel reduction strategy when combined with mechanical thinning and pile burning. In this treatment site, there are much fewer trees and less vegetation than the control site. Additionally, the prescribed fire also helped to consume any remaining fuel on the forest floor, which helped to reduce the intensity of fire behavior. It has also been shown that the use of prescribed fire can promote the growth of fire-adapted plant species and promote forest health (Knapp et al. 2011).

In summary, this study demonstrated that the use of different forest management techniques can significantly impact fire behavior. A control treatment site with a high fuel load can result in high-intensity fires that are difficult to control. Mechanical thinning and pile burning can reduce the fuel load and create a more open forest floor, making fire suppression efforts easier. Adding prescribed burning to the mix can create an even more effective fuel reduction strategy by promoting the growth of fire-adapted plant species and improving overall forest health (Stephens et al. 2012).

First-Order Fire Effects Modeling: Mortality and Consumption

The fire effects regarding fuel consumption coincided with my original hypothesis. As I anticipated, there was 100% consumption of fine fuels across all treatment sites. The fuel consumption of 1000 hour fuels corresponded to the amount of 1000-hour fuel loading which was to be expected. There was 100% consumption of litter across all treatment sites which was to be expected. Lastly, there was a 21.3% drop in duff consumption between the control site and the (M + P + B) site. This change in duff consumption may be attributed to the substantially lower fine fuel loading at the (M + P + B) site. When there is lower fuel loading, there is less energy at the flaming front of the fire and less consumption overall (Stephens et al. 2005).

While the predictions in percent consumption of fine fuels and 1000-hour fuels were reflective of my original hypothesis, the predictions in the mortality of the stand were much more variable. Across all treatment types, wind speeds were the biggest factor in variations in the amount of mortality by trees per acre and basal area in the stand. Although wind speed is shown to cause the greatest variation in mortality amongst the model scenarios, the control was shown to have the highest mortality in trees per acre across all wind speeds. This result is supportive of my original hypothesis because there were significantly more trees located in the control compared to the two other treatment sites. The lower mortality within the (M + P) and (M + P + B) treatment sites indicate that selective tree thinning may be beneficial in reducing fire severity and overall forest restoration objectives (Graham et al. 2004).

Limitations and Future Directions

Overall, my study was valuable for informing localized forest management practices. One major limitation of this study was the fact that I was not able to account for all variables that affect fire behavior and forest resilience. For example, weather conditions, topography, and the presence of invasive species can all have an impact on fire behavior and forest health. These factors are often difficult to quantify and include in a study of this small scale. Furthermore, the results of this study may not be generalizable to all types of forest or geographic regions, as different forest ecosystems have unique characteristics that affect their response to fuel treatments. Another limitation of this study is that it was unable to account for the long-term effects of these forest management practices. The data collected for this study was collected over a short time frame and may not accurately represent the effects of fuel treatments over a longer period. Additionally, the impacts of different fuel treatments on wildlife habitat, water quality, and other ecosystem services may need to be considered in order to make informed management decisions.

Despite these limitations, fuel treatment studies of this nature are an important tool for understanding the effects of different forest management practices on fire behavior and forest resilience. Some potential future directions for these fuel treatment studies include long-term monitoring, multi-scale analysis, and integrating social and economic factors. This study could very easily be conducted over a longer period in order to provide insight into the long-term effects of fuel treatments of fire behavior and forest health. Additionally, studying the effects of fuel treatments at different spatial and temporal scales would be useful in identifying the most effective fuel reduction strategies for different types of forests. Lastly, this study could be modified to consider the variety of social and economic factors that affect forest management practices, such as the availability of funding and public perception of forest management practices such as prescribed burning.

Broader Implications

The results of a fuel treatment study of this nature can have broader implications for forest management policies and practices. By identifying the most effective fuel reduction strategies, similar studies can inform forest management decisions aimed at reducing the risk of catastrophic wildfires and promoting forest health. Additionally, fuel treatment studies of this nature can help to inform the development of policies aimed at incentivizing the use of effective fuel reduction strategies and promoting the use of prescribed fire as a tool for managing forest ecosystems. Overall, the insights gained from this study and ones like it can contribute to the development of more effective and sustainable forest management practices that support the ecological, social and economic values of forest ecosystems.

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