THESIS

INVESTIGATING THE RELATIONSHIP BETWEEN HORIZONTAL FOREST STRUCTURE AND FIRE BEHAVIOR USING A PHYSICS-BASED FIRE MODEL

Submitted by

Conamara S. Burke

Department of Forest and Rangeland Stewardship

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2017

Master's Committee:

Advisor: Chad Hoffman

William Mell
Timothy Amidon

ABSTRACT

INVESTIGATING THE RELATIONSHIP BETWEEN HORIZONTAL FOREST STRUCTURE AND FIRE BEHAVIOR USING A PHYSICS-BASED FIRE MODEL

Silvicultural treatments are increasingly being implemented across the Western US in fire-prone forests as a way to simultaneously reduce fire hazard while also increasing horizontal structural heterogeneity (tree spatial patterns). However, it is poorly understood how fire behavior is impacted by treatment designs that incorporate tree clumping spatial configurations that mimic patterns found within the historic structural ranges of forests frequented by low to mixed severity fire. The Wildland Urban-Interface Fire Dynamics Simulator (WFDS), a physics-based fire behavior model, was used to better understand the effect that heterogeneous horizontal forest structure has on fire behavior. Fire behavior across seven treated ponderosa pine forests with different spatial patterns were simulated and compared to each other, and to an untreated scenario. All forest simulations were also burned under three different wind speeds and two surface fuel loading levels to better evaluate fuel treatment effectiveness across a range of conditions. Results indicate that the removal of surface fuels in treated stands was the most effective method for reducing the percent of canopy consumption and rates of fire spread, especially under high wind velocity conditions. This study found that variations in horizontal forest structure between treated forest scenarios had a minimal effect on driving differences in fire behavior, thus forest managers should be more concerned with increasing horizontal structural heterogeneity for ecological objectives rather than

implementing such treatments to reduce the potential for hazardous fire behavior. Future research should focus on determining how vertical structural complexity interacts with horizontal structure to influence fire behavior.

ACKNOWLEDGEMENTS

I would like to extend thanks to my family, friends, colleagues, committee, and advisor for their support during my academic and research pursuits. The daunting technical and modeling aspects of this project would have been impossible for me to complete without extensive assistance from my advisor Chad Hoffman, colleague Justin Ziegler, and committee member Ruddy Mell. Ideas for the concentration and application of this research, as well my perspective on research were further developed by conversations with my committee member Tim Amidon, as well as with research lab members: Dani Steger, Jared Scott, Scott Ritter, Wade Tinkam, and Mike Caggiano. Daily encouragements from my family, and friends no doubt allowed me to persevere during this process. Lastly, funding for this project from the Joint Fire Science Program provided me with the financial opportunity to live, work, and attend school in Fort Collins, and pursue an advanced degree at Colorado State University.

TABLE OF CONTENTS

1 INTRODUCTION

Throughout the 20th century a combination of fire exclusion, livestock grazing patterns, and timber management practices have altered forest structure, composition and function particularly in forests that were historically characterized as having low or mixed severity frequent fire regimes (Savage and Swetnam, 1990; Covington and Moore, 1994; Hessburg et al., 2005; Naifcy et al., 2010). These shifts have led to greater surface and canopy fuel loads, reduced structural heterogeneity, and a greater potential for severe stand-replacing wildfires (Kaufmann et al., 2000; Keane et al., 2004; Schoennagel et al., 2004; Jenkins et al., 2008). To reduce the potential for extensive uncharacteristic fires, and reestablish forest structure more in line with historical ranges, managers are increasingly implementing silvicultural treatments to a meet a range of management objectives including reducing current fuel loads, and reestablishing historic forest structural characteristics (Kaufmann et al., 2000; Agee and Skinner, 2005; Noss et al., 2006; Graham et al., 2005; North et al., 2009; Naifcy et al., 2010; Evans et al., 2011; Churchill et al., 2013). While forest management strategies increasingly incorporate multiple objectives that can take place across a range of scales (O'Neill 1986; Wu and David, 2002; Falk, 2007; Hessburg et al., 2015), most forest treatments are designed and implemented at the stand scale (e.g between 10 and 100 hectares) (Barnett et al., 2016).

A number of previous studies have concluded that stand scale fuel reduction treatments that decrease surface and canopy fuel loads are successful at moderating potential fire behavior, and can reduce the potential for further uncharacteristic fires (Stephens and Moghaddas, 2005; Hudak et al., 2011; Fulé et al., 2012; Safford et al., 2012; Martinson and Omi, 2013; Kalies and Kent, 2016). However, a number of factors including the intensity of surface and canopy fuel reduction, and the environmental and fuel conditions present during a fire (e.g. wind speed and fuel moisture) play an important role in determining overall treatment effectiveness (Fulé et al., 2001a; Hudak et al., 2001; Batagglia et al., 2008). For example, fuel treatments that do not sufficiently reduce canopy or surface fuels may result in minimal reductions in fire behavior relative to untreated forest stands (Graham et al., 1999; Reinhardt et al., 2008; Hudak et al., 2011; Fulé et al., 2012). Alternatively, even when treatments significantly reduce surface and canopy fuels, extreme fire behavior may still occur under severe weather conditions such as high wind velocities, and low moisture levels (Bessie and Johnson, 1995; Martinson et al., 2003). In addition to these factors, several researchers have suggested that the spatial pattern or arrangement of the canopy fuels may also play a role in determining treatment efficacy (Fulé et al., 2001b; Larson and Churchill, 2012; Dickenson et al., 2014; Omi 2015; Ziegler et al., 2017).

Although the potential effect of fuel pattern on fire behavior has long been recognized (Turner and Romme, 1994; Hargrove et al., 2000; Miller and Urban, 2000), developing a greater understanding of this relationship is becoming increasingly important as managers incorporate explicit spatial objectives into treatment design. For example, a number of recent treatment strategies have suggested utilizing principles from variable retention harvests to reduce fire behavior while meeting other resource objectives such as improving wildlife habitat or restoring historical forest structural dynamics (Graham et al., 2005; Youtz et al., 2008; Larson and Churchill, 2012; Lynderson and North, 2012; Reynolds et al., 2013). An emerging approach to implementing such treatments is to incorporate mosaics of individual trees, clumps of trees and openings (ICO structure) commonly found in historic stands with intact fire regimes into treatment designs (Larson and Churchill, 2012; Churchill et al., 2013; Lydersen et al., 2013). While previous studies have investigated the impacts of treatments on potential fire behavior using non-spatial fire models, an understanding of the relationship between forest structure and fire behavior could be improved by explicitly accounting for the heterogeneous nature of forest structure (Fulé et al.,2001a; Parsons et al., 2011; Hoffman et al., 2016).

Recently several studies have utilized three-dimensional physics-based fire models, such as the Wildland Urban Interface Fire Dynamics Simulator (WFDS) (Parson et al., 2010a; Contreras et al., 2012; Hoffman et al., 2012, 2013; Ziegler et al., 2017) and FIRETEC (Pimont et al., 2009, 2011; Parson et al., 2010b; Linn et al., 2012) to explore the effect of fuel heterogeneity on fire behavior at multiple scales. At fine scales, Parsons et al. (2011) found that the spatial variability within a tree crown influences the timing, magnitude, and dynamics of combustion. At larger scales, several studies have suggested that the within-stand fuel heterogeneity influences fire behavior by altering the characteristic wind flow driving fire behavior and by modifying the interactions among the fire, fuels, and atmosphere (Pimont et al., 2011, Hoffman et al., 2012, Linn et al., 2013, Hoffman et al., 2016, Ziegler et al., 2017). Although there is a growing body of literature on the effects of fuel spatial pattern on fire behavior, only two papers have directly considered the spatial pattern of fuel formed after silvicultural activities (Pimont et al., 2011; Ziegler et al., 2017). These studies both found that reductions in canopy fuel load due to forest treatments resulted in greater within-canopy wind flow and reduced fire behavior relative to untreated forests, thus providing increasing evidence that treatments are effective at reducing potential fire behavior despite concerns over increased within-stand wind velocities. In addition, Pimont et al., (2011) found differences in fire behavior between heterogeneous and homogenous canopy fuel patterns, but this effect was dependent upon the surface fuel load. Overall these simulation studies suggest that the interaction between environmental conditions, surface and canopy fuel loads, and the spatial arrangement of fuels drive differences in fire behavior, and ultimately influence treatment efficacy.

The overall goal of this study is to improve an understanding of how various post-treatment fuel spatial patterns influence fire behavior, and to explore the potential roles that surface fuel load and burning conditions may play in determining treatment effects on fire behavior. To meet research goals, a set of analogous forests were developed that cover a range of post-treatment canopy spatial patterns representing typical pre-treatment and post-treatment fuel loadings commonly found within ponderosa pine *(Pinus ponderosa)* dominated forests in the southern Rocky Mountains. Using the Wildland-Urban Interface Fire Dynamics Simulator (WFDS), 8 variations of horizontal forest structure (1 hypothetical untreated forest scenario and 7 treated forest scenarios), with 2 different surface fuel loads and 3 wind velocities were simulated. The trees used to build these forests all have the same characteristics. Using this set of simulations, three questions were investigated: First, do fuel treatments result in reduced fire behavior relative to untreated forests? Second, does fire behavior differ across different post-treatment spatial patterns? Third, does the influence of post-treatment spatial pattern on fire behavior depend significantly upon the surface fuel load and/or wind velocity?

2 METHODS

Model Description

The Wildland-Urban Interface Dynamics Simulator (WFDS) is a physics-based fire behavior model that seeks to capture the physical processes governing fire behavior in vegetative fuels, or a mix of vegetative and urban fuels (Figure 1). The model was developed through a partnership between the US Forest Service Pacific Northwest Research Station and the National Institute for Science and Technology (NIST) (McGrattan et al., 2010), and is largely based on the Fire Dynamics Simulator (FDS) developed by NIST. The WFDS model uses a set of partial differential equations along with computational fluid dynamic and large eddy simulation methods to solve three-dimensionally equations governing the conservation of momentum, total mass and energy. WFDS simulates thermal degradation using either an Arrhenius kinetics scheme or a simplified linear thermal decomposition model (water evaporation and solid fuel pyrolysis) with or without char oxidation (Mell et al., 2007 and 2009). This study utilized the simpler linear thermal decomposition model without char oxidation following (Mell et al., 2013). The products of thermal degradation are linked to gas phase reactions through an oxygen mixing equation. Radiation transport from and to heated objects employs a finite volume method (within a fixed volume, discrete angles calculate heat transfer) (Mell et al., 2007, 2009; McGrattan et al., 2010). More detailed descriptions of the mathematical and physical equations used in WFDS can be found in McGrattan et al. (2004), Mell et al. (2007, 2009), and McGrattan et al. (2010). Verification and validation studies of FDS and WFDS have found simulated fire behavior comparable to other model and field observations, and details of these studies can be found in Mell et al. (2007, 2009), McDermott et al. (2010), Mueller et al. (2012), and Hoffman et al. (2016).

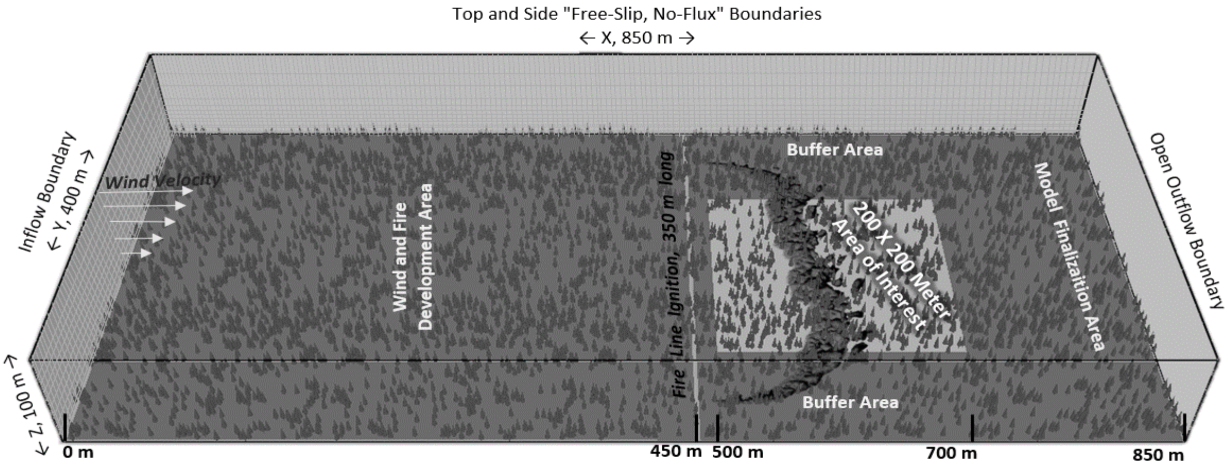


Figure 1. The WFDS domain is 850 meters long (x), 400 meters wide (y), and 100 meters high (z). The 200 X 200 meter area of interest is located between 500 and 700 (x), 100 and 300 (y), and 0 and 100 m (z). Fire behavior outputs were derived from the area of interest. The 350 m long fire line was ignited at x=450 meters. The remaining space served as a wind and fire development area, buffer area, and model finalization area. Boundaries were either open (in and outflow), or free-flux, no slip (top and sides). The grids or meshes were made up of 3D voxels with dimensions of 1 m wide by 1 m long by 0.5 – 2 high (increasing in size with height above the ground).

WFDS Simulation Domain Setup

All WFDS simulations developed to address research questions were performed using identical, level, spatial domains measuring 850 x 400 x 100 meters along the x, y, and z-axes respectively (Figure 1). All domains were discretized using a rectilinear grid with cell dimensions of 1 m in the x- and y-axis and a non-uniform resolution in the z-axis that ranged from 0.5 m at the bottom of the domain to 2 m at the top of the domain. Similar to Ziegler et al. (2017) and Hoffman et al. (2012) the overall domain consisted of five parts (Figure 1). The boundaries at x = 0m and x = 850m represent the inflow and outflow boundaries respectively. The wind entering the domain through the inflow boundary was simulated following a power-law profile with a natural atmosphere (Hoffman et al., 2016; Mell et al., 2007; Morvan and

Dupuy, 2001). The outflow boundary (x = 850 m) was prescribed as an open boundary where heat, smoke and wind are allowed to freely move into and out of the simulation domain. The boundaries along the x = 0, y =400m and z = 100 axis were simulated as free-slip, no flux boundaries following Ziegler et al. (2017). The interior of the simulation domain where trees were populated consisted of three areas: an upwind fire and wind development zone, an area of interest, and a pre-boundary outflow zone (Figure 1).

Developing the Simulated Forests

A total of eight theoretical 4-hectare forests including: 1 untreated forest and 7 treated forests, each with different spatial configurations of trees, were simulated within the area of interest. To represent typical contemporary ponderosa pine forests in the southern Rocky Mountains, untreated forest scenarios were assigned a stand density of 413 trees per hectare (TPH), a basal area of 25.30 m^2 ha^{-1} (Table 1) and a random spatial pattern, (Ziegler et al., 2017). Individual tree spatial locations within untreated forests were located using a Poisson point process whereby locations are independently and identically distributed (Diggle et al. 1984). A random spatial pattern was chosen to represent untreated forests because it is unbiased, and is a typical structural pattern found within contemporary ponderosa pine stands (Bonnicksen and Stone, 1981; Gardner et al., 1987; North et al., 2007; Getzin et al., 2008).

Table 1. Forest or stand characteristics used in all WFDS simulations

Stand Attributes	*Value:*	*Based on:*
UNTREATED		
Basal area:	25.3 m^2/hectare	
Trees per hectare (TPH):	413	*Ziegler et al., 2017*
TREATED		
Basal area:	9.18 m^2/hectare	
Trees per hectare (TPH):	153	

To evaluate the effects of forest treatments on fire behavior, seven theoretical treated forests with different spatial configurations of trees were developed. Each treated forest scenario was simulated with an approximate density of 153 TPH, and basal area of 9.18 m^2ha^{-1} (Table 1). To provide a direct unbiased comparison with the untreated forest, a treated forest scenario with a random spatial pattern of trees was developed following the same approach as the untreated forest. Next, a treated forest with a uniform spatial pattern of trees was developed using a simple sequential inhibition process (Diggle, 2003) to imitate the horizontal forest structural patterns commonly found within traditional fuel-reduction treatments that follow minimum tree spacing guidelines (Hunter et al., 2007). All trees within the treated forest scenarios with uniform structure were independently located, and tree stems were separated by at least 6 meters (radius). Four of the seven treated forest scenarios were developed to represent silvicultural treatments that use principles from variable retention harvesting (VRH), and incorporate historic heterogeneous tree clumping spatial configurations. Treated scenarios with horizontal forest structure based on VRH principles were specifically designed to mimic the dominant tree clumping spatial patterns described by Churchill et al. (2013), and Larson and Churchill (2012). The last treated forest scenario was developed to highlight potential effects of extreme clumping on wildfire behavior even though this spatial pattern does not typically exist in contemporary treatment designs.

Treatment scenarios with clumped tree spatial configurations were developed using a custom Python script (Tinkham et al., 2017). The script was developed to act like a real harvest, where a high-density untreated stand (413 TPH) was thinned down (153 TPH) to meet a set of prescription objectives within a 4 hectare area. After setting the target basal area (9.18 m^2ha^{-1})

for the treatment, the script then proportionally allocated trees to different clump sizes determined by the user by setting a maximum distance of 6 meters or less (radius from stem center) between all trees in a clump. Given the stated objectives, the script then simulated a treatment by locating existing clumps of trees and removing nearby trees around the clump perimeters. If a clump did not exist, the script would randomly select a focal tree, and then search for nearby neighbors until the clump size requirements are met. In this study there were six user defined clump sizes: small tree clumps (2-4 trees), medium clumps (5-9 trees), intermediate clumps (10-15 trees), large clumps (16-20 trees) and extra-large tree clumps (>50 trees). The custom script ultimately produced the spatial location for each tree in the treated stands based on the proportion of trees that were assigned to each of the six clump categories (Figure 2).

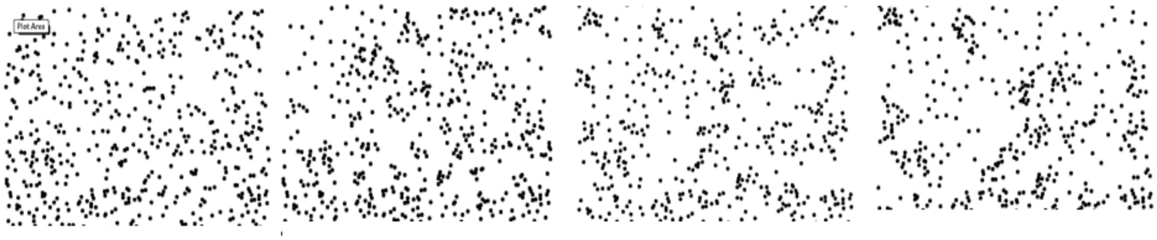
The mostly small (SM), medium (MD), intermediate (IN), and large (LG) clump scenarios were simulated such that 20% of all trees in the stand were classified as isolated individuals, 50% of all trees were in the dominant clump size and the remaining 30% of trees were spread evenly among other clump sizes. For example, the small clump scenario has 20% of all trees classified as isolated individuals, 50% of all trees classified as being a member of a small clump (2-4 trees per clump), and 10% of all trees in the medium, intermediate and large clump. Figure 2 shows an example of simulated horizontal patterns for each scenario. It is important to note that for these four scenarios, extra-large (XL) clumps were not present. An extreme clumping treatment was also developed where 20% of all trees within the stand were classified as isolated individuals and the remaining 80% of trees were placed in XL clumps.

Untreated--**Random Structure**

Treated--**Random Structure**

Treated--**Uniform Structure**

Treated-- **All XL (50 trees) Clumps**



Treated--**Mostly SM (2-4 trees) Clumps**

Treated--**Mostly MD (5-9 trees) Clumps**

Treated--**Mostly IN (10-15 trees) Clumps**

Treated--**Mostly LG (16-20 trees) Clumps**

Figure 2. The eight tree spatial patterns within a 4-hectare area burned/tested in WFDS. The one untreated scenario had a random tree spatial pattern. The treated scenarios were chosen to test non-heterogeneous horizontal structural patterns (random and uniform), and tree clumping spatial patterns (SM, MD, IN, LG, and XL). “Mostly” indicated that 50% of the trees within a stand were part of a particular clump size (SM, MD, IN, LG), and the remaining trees were either single (20%) or part of another clump size (30%). “All” indicated that 80% of the trees in the stand were part of extra-large (XL) clumps.

Individual tree crowns within all forest simulations were represented as circular cones consisting of homogenous, thermally thin, highly porous media, characterized by the bulk qualities of the fuel (e.g. foliar moisture content, load, crown bulk density, surface area to volume ratio) (Table 2). Physical attributes of trees including height, crown base height, crown width, and stem diameter were constant across all individuals, and were based on typical tree dimensions found in post-treated ponderosa pine stands in central Colorado (Ziegler et al., 2017) (Table 2). Maintaining constant individual tree characteristics across all simulations minimized potential effects of vertical heterogeneity on fire behavior, and kept focus on the main research question of this study regarding the relationship between horizontal forest fuel structure and fire behavior.

Table 2. Tree characteristics used in all WFDS simulations

Tree Attributes	*Value:*	*Based on:*
Height:	16 m	Ziegler et al., 2017
Crown Base Height:	4 m	
Crown Width:	3.8 m	
Stem Diameter	.28 m	
Crown Bulk Density	.52 kg/m^2	Brown, 1978
Surface-Area-Volume	5710 m^{-1}	Brown, 1970; Catchpole et al., 1998
Particle density	520 kg/m^3	Ritchie et al., 1997

To evaluate the potential effects of surface fuel load and burning conditions on the relationship between spatial pattern and fire behavior, each forest scenario was simulated with 2 levels of surface fuel load and 3 wind velocities. Surface fuels were represented as a pine needle dominated fuel bed with either 1.86 or 0.5 kg m^{-2} load, with a characteristic surface area to volume ratio of 5808 m^{-1}, and a dead fuel moisture content of 5% (Table 3). To simulate a range of burning conditions, each combination of surface fuel load and horizontal forest structure was simulated across three different wind velocities: 3 ms^{-1} (slow), 6 ms^{-1} (moderate), and 13 ms^{-1} (fast) at 10m above the canopy. In all simulations, a wildfire was initiated as a 350 m long 3 meter wide fireline, 50 meters upwind of the area of interest, and was allowed to burn across the remainder of the domain (Figure 2).

Table 3. Surface fuel attributes and wind velocities tested in different WFDS simulations

Surface Fuel Attributes	*Values:*	*Based on:*
High		
Loading:	1.86 kg/m^2	
Height of fuel:	0.09 meters	
Moisture content:	0.05	Scott and Burgan, 2005
Surface-area-volume:	5808 m^{-1}	
Particle density:	510 kg/m^3	
Low		
Loading:	0.5 kg/m^2	
Height of fuel:	0.05 meters	
Moisture content:	0.05	Scott and Burgan, 2005
Surface-area-volume:	5808 m^{-1}	
Particle density:	510 kg/m^3	
Wind Velocities		
Fast	13 m/s	
Moderate	6 m/s	Bradshaw and Brittain, 1999
Slow	3 m/s	

WFDS Simulation Outputs and Analysis Description

To assess changes in potential fire behavior, fire rate of spread and percent canopy fuels consumed within the 200 x 200m area of interest was estimated for each simulation. Percent canopy consumption was calculated by dividing the sum of each tree's biomass after the fire had passed through the simulation domain by the sum of all trees' biomass at the start of the simulation (Hoffman et al., 2012). Rate of fire spread was estimated by calculating the forward propagation distance every second within the area of interest as the farthest downwind distance where solid fuel was being converted to gas (Ziegler et al., 2017). The mean rate of fire spread was estimated as a slope of a least squares fit to the propagation distance vs. time.

An Analysis of Variance (ANOVA) tested the main effects of, and interactions between, horizontal structural scenarios, wind velocity, and surface fuel. A beta regression with a logit link was used to assess differences in canopy consumption across each factor. The beta regression has the following form:

$$CC\% = \beta_0 + (\beta_1 Horizontal\ Forest\ Structure + \beta_2 Surface\ Load + \beta_3 Wind\ Velocity)^2$$

Where βo is the intercept term, and β1, β2, and β3 are estimated parameters for each of the predictor variables (Horizontal Forest Structure, Surface Fuel load, and Wind Velocity). This model form was chosen in part because measurements such as fraction of canopy consumption (reported as a percentage) take on values within the open interval (0,1) and the influence of explanatory variables on the response are continuous and bounded within this interval (Ferrari and Cribari-Neto, 2004). A generalized linear model (GLM) with a log link was used to assess potential differences in rate of fire spread across each factor. The GLM used for rate of fire spread had a similar form to the beta regression model used for percent canopy consumption with βo representing the intercept term, and β1, β2, and β3 are estimated parameters for each of the predictor variables. This model form was chosen because the distribution of rate of fire spread values were concentrated between 0 and 3 meters per second (values were infinite, and not bounded) (Bolker et al., 2009). The Least Squared (LS) means method in R evaluated pairwise differences from the ANOVA test for canopy consumption and rate of fire spread between various horizontal structural scenarios, wind velocities, and surface fuel loads. Significant differences between canopy consumptions and fire rates of spread were determined using an alpha value of 0.05 (p-value < alpha was significant).

3 RESULTS

Simulation results suggest fire behavior was significantly impacted by most of the factors and interactions between the factors tested in this study (Figure 3 and 4). Canopy consumption was significantly impacted by horizontal forest structure (HS) ($p < 2.2e-16$), surface fuel load (SF) ($p < 2.2e-6$), and wind velocity (WV) ($p = 1.8e-5$), and the two way interactions between HS and SF ($p = 2.6e-7$), and HS and WV ($p = 1.1e-7$) (Figure 3). Rate of fire spread was significantly impacted by HS, SF, WV, (all with p-values < 2e-16) as well as the interaction between HS and WV ($p < 2e-16$) but not between HS and SF ($p = 0.18$).

Fire Behavior between Untreated and Treated Stands

When addressing the first research question of this study, %CC was significantly reduced ($p < 0.0001$) in all treated forest scenarios compared to untreated forest scenarios regardless of wind velocity or surface fuel load (Figure 3). The average reduction in %CC from untreated to treated stands was more pronounced in low SF scenarios than high SF scenarios (Figure 3A). For low SF scenarios, the average drop in %CC between untreated and treated scenarios was 36.7 % (SE +/- .008), while the average drop in %CC for high SF between untreated and treated was only 5.0% (SE +/- .007). Comparisons between untreated and treated scenarios by wind velocities indicate that differences in %CC between the two forest stand densities increased with escalating WV (Figure 3). The average decrease in %CC between untreated and treated scenarios for slow WV was 12.5% (SE +/- .005), for moderate WV 21.0% (SE +/-.007), and for fast WV 28.9% (SE +/- .004). With escalating wind velocities, %CC increased in untreated forest scenarios, but remained relatively unchanged across treated forest scenarios (Figure 3B).

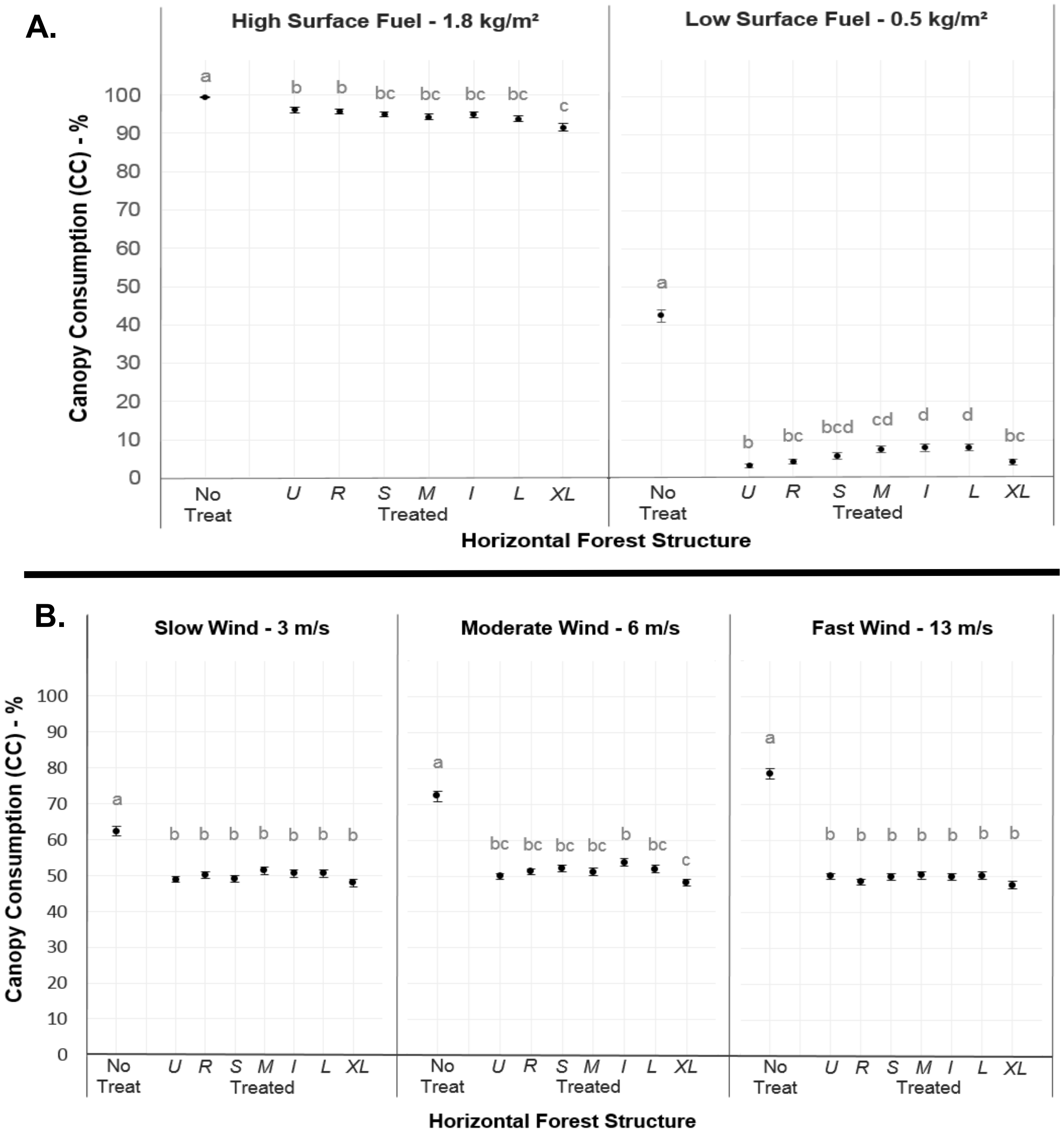


Figure 3. Canopy consumption (%) across horizontal forest structures by treatment spatial pattern, grouped by surface fuel load level (high and low) (averaged across all winds) in plot A, and grouped by wind velocity (slow, moderate and fast) (averaged across surface fuel loads) in plot B. Along the x axis treated (153 TPH) scenarios (uniform, random, small clumps, medium clumps, intermediate clumps, large clumps, and extra-large clumps) are respectively represented as “U,” “R,” “S,” “M,” “I,” “L,” “XL”. “No Treat” scenarios represent high stand density scenario (413 TPH). Lower case alphabetical letters denote significant differences (p value < 0.05) in horizontal forest structural scenarios by surface fuel load level or wind velocity. Standard error bars are represented.

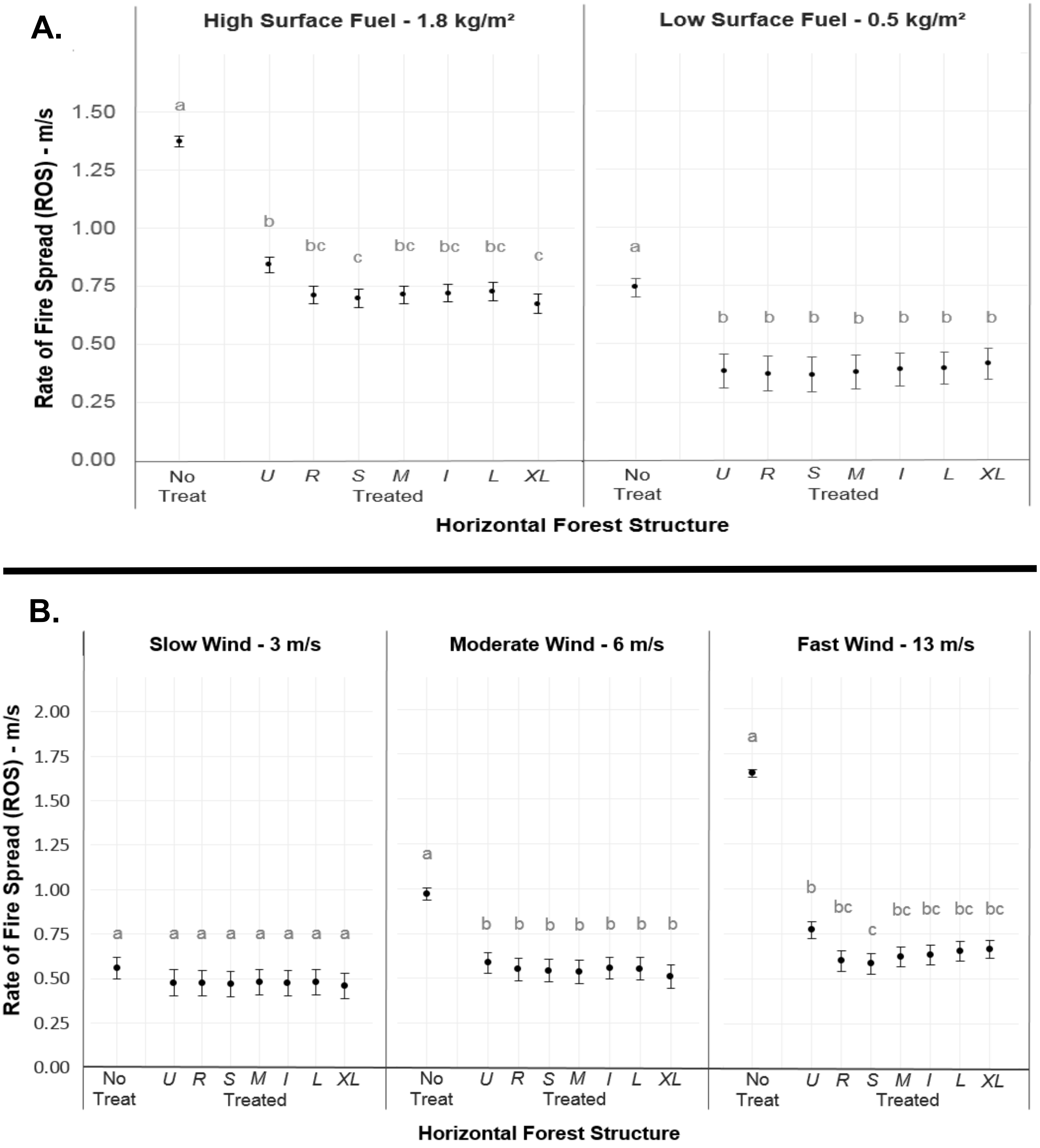


Figure 4. Rate of fire spread (m/s) across horizontal forest structures by treatment spatial pattern, grouped by surface fuel load level (high and low) (averaged across all winds)in plot A, and grouped by wind velocity (slow, moderate and fast) (averaged across surface fuel loads) in plot B. Along the x axis treated (153 TPH) scenarios (uniform, random, small clumps, medium clumps, intermediate clumps, large clumps, and extra-large clumps) are respectively represented as “U,” “R,” “S,” “M,” “I,” “L,” “XL”. “No Treat” scenarios represent high stand density scenario (413 TPH). Lower case alphabetical letters denote significant differences (p value < 0.05) in horizontal forest structural scenarios by surface fuel load level or wind velocity. Standard error bars are represented.

When considering fire rate of spread between untreated and treated scenarios, results suggest lower stand densities did not necessarily lead to reductions in ROS. For low wind velocity (WV), there was not a significant difference in the ROS (reduction of 0.09 m/s or 15%, SE +/- .003m/s) between untreated and treated scenarios ($p > 0.30$) (Figure 4B). However, with moderate and fast WV there was an average reduction in ROS between untreated and treated scenarios of 0.42 m/s (44%) (SE +/- .009m/s), and 0.99 m/s (61%) (SE +/- .023m/s), respectively. Similar to %CC, ROS in untreated scenarios significantly increased with escalating WV, while ROS in treated scenarios between different WV remained relatively unchanged (Figure 4B). Rate of fire spread across both untreated and treated scenarios was significantly lower in low SF than high SF scenarios ($p < 0.0001$ for both). Additionally, the mean reduction in ROS between untreated and treated scenarios for low SF was 0.36 m/s (48%) (SE +/- .01m/s), and high SF was 0.65 m/s (47%) (SE +/- .02m/s).

Fire Behavior between Treated Stands with Different Horizontal Forest Structures

When addressing the second research question of this study, significant differences in both %CC and ROS existed between the various horizontal forest structures within treated stands across different levels of surface fuel load and wind velocity (Figures 3 and 4). Although results indicate that %CC and ROS were significantly impacted by various configurations of trees tested within the model (pairwise comparisons resulted in p values between .0002 and .999), the overall effect of horizontal forest structure within treated scenarios was minimal. Canopy consumption did vary by treatment scenario across both SF, however the average difference in %CC between different treatment scenarios was only 1.7% (SE +/- .003) for high SF, and 2.4% (SE +/- .003) for low SF (Figure 5). Differences in %CC between treated scenarios across different WV were only significant for moderate WV, and only between two of the tested tree spatial configurations: mostly intermediate clumps, and mostly extra-large clumps (p = 0.002) (Figure 3). In contrast to %CC, ROS was only affected by various treatment scenarios with high SF (avg. diff. in ROS was .055 m/s (6.8%), SE +/- .010 m/s), and fast WV (avg. diff. in ROS was .069 m/s (9.7%) SE +/- .010 m/s) (Figures 4 and 5). There were no significant differences in ROS present between treated scenarios for low SF, or slow and moderate WV (Figure 4).

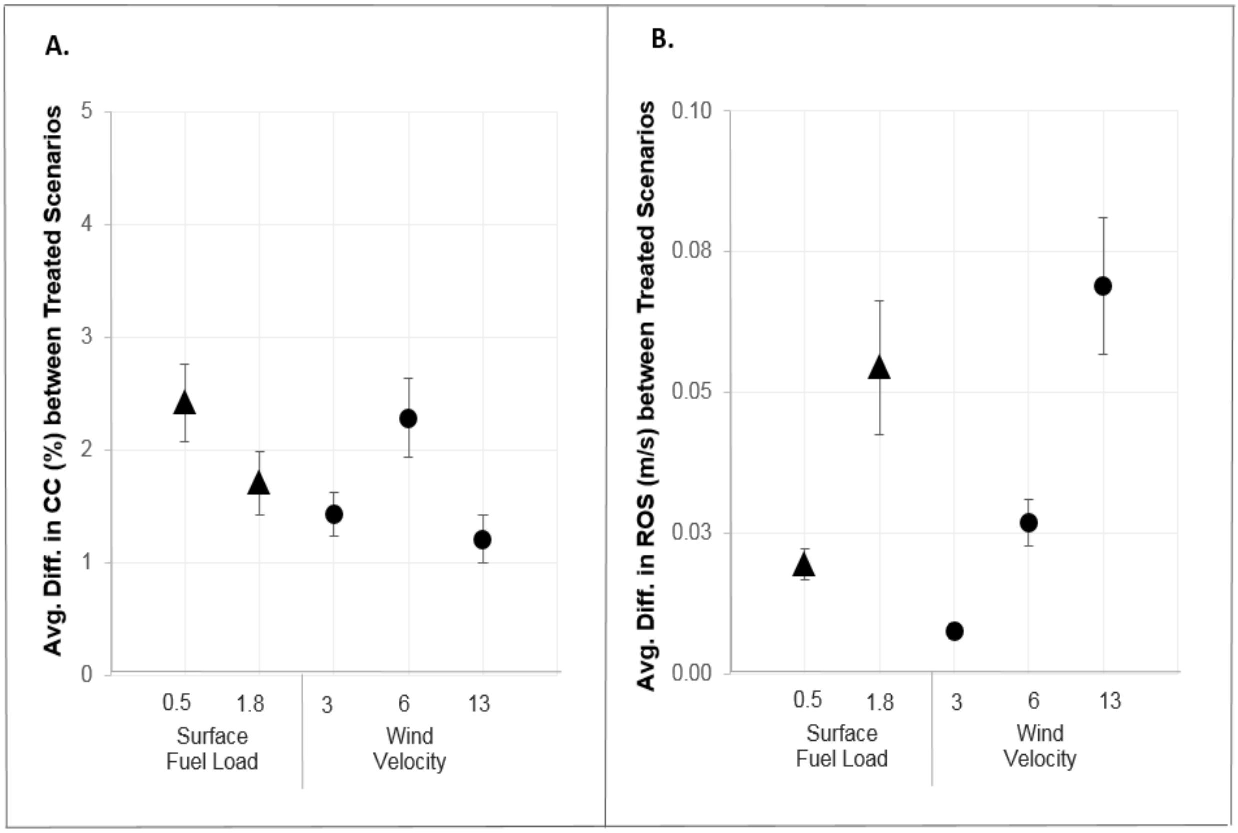


Figure 5. Plot A. represents average difference in canopy consumption (%), and plot B. represents average difference in forward rate of fire spread (m/s) between treated scenarios by surface fuel load (triangle) and wind velocity (circles) (x axis). Standard error bars are represented.

Overall, the maximum difference in % CC between all treated scenarios (accounting for the fixed effects of SF and WV) was 10.48%, and the maximum difference in ROS between all treated scenarios was .56 m/s (51%). Although fire behavior results indicate that there were significant differences among the treated scenarios, the overall effect of applying different tree spatial patterns to treatment designs was minimal (and likely unimportant form a managerial stand point) for both %CC and ROS.

Fire Behavior between Forests with Different Surface Fuel Loads and Wind Velocities

As highlighted above, results associated with the third research question of this study found that surface fuel load level (0.5 and 1.8 kg/m^2) had the most dramatic effect on fire behavior. Low SF produced lower severity fires (CC <60%, ROS < 0.5 m/s), and high SF produced higher severity fires (CC > 90%, ROS > 0.5 m/s), regardless of WV or horizontal forest structure. Wind velocities also produced significant differences in CC and ROS, but to a lesser extent than surface fuel load. Faster WV led to faster rates of fire spread, and moderate WV produced the highest levels of canopy consumption. Because of the strong effect of surface fuel load on fire behavior, treatment designs should consider surface fuel removal during treatment operations.

4 DISCUSSION

Results from WFDS simulations indicated that in most cases, potential fire behavior (percent of canopy consumption and rate of spread) was significantly reduced in treated stands compared to untreated stands. These findings are similar to findings from several previous studies that evaluated treatment effectiveness (Age and Skinner, 2005; Stephen et al., 2009; Safford et al., 2012). Decreasing stand densities makes tree-to-tree crown ignition less likely as the average distance between all trees in the stand increases (Van Wagner, 1977; Agee et al., 2000). However, simulation results from this study also indicated that the level of treatment effectiveness in reducing potential fire behavior depended on surface fuel load level and wind velocity. Compared to untreated forests, treating stands was more effective for decreasing %CC in low surface fuel loads, and decreasing ROS in high surface fuel loads; both %CC and ROS experienced greater reductions under fast wind velocity conditions in the treated stands.

The finding that treatments with lower surface fuel loads were more effective in reducing potentially hazardous wildfire behavior is in line with previous research that evaluated fire behavior response in post-treated stands that had received different surface fuel load prescriptions (Stephens, 1998; Graham et al., 1999; Reinhardt et al., 2008; Stephens et al., 2009; Hudak et al., 2011; Pimont et al., 2011; Fulé et al., 2012). For example, a study by Raymond and Peterson (2005) found that during the 2002 Biscuit Wildfire in Southwestern, Oregon, treatments that included both mechanical thinning and surface fuel removal had tree mortality levels of only 5%, while mechanically thinned-only treatments had mortalities of 80 to 100%. A fire simulation study by Pimont et al., (2011), which assessed changes in fire behavior across forest stands with different tree spatial patterns, found a dramatic effect of surface fuel load on driving significant differences in fire behavior regardless of changes to the over-story structure. Reducing surface fuels during treatment operations decreases surface fire intensities and potential flame lengths which in turn decreases the likelihood for active crown fire conditions (Rothermel, 1972; Wagner, 1977; Scott and Reinhardt, 2001). Results from this study, as well as previous studies evaluating treatment effectiveness, support literature that suggests forest treatments are more effective in reducing potential hazardous fire behavior when understory vegetation buildup is periodically removed by prescribed burn operations (Stephens, 1998; Fule et al., 2001; Pollet and Omi, 2002; Fernandes and Botelho, 2003; Agee and Skinner, 2005).

Fulé et al. (2001), Martinson and Omi (2002), and Ziegler et al. (2017) found that treating stands led to reductions in fire behavior regardless of ambient wind conditions; similarly, this study found that %CC in treated stands signficantly decreased from %CC in untreated stands across slow, moderate and fast wind velocities. However in this study, the magnitude of reduction in %CC between untreated and treated stands increased as wind velocities were elevated. One explanation why untreated stands were more impacted by elevated wind velocities than treated stands is that faster winds increase flame lengths, which in turn increseases the likelihood for tree-to-tree ignition, and is then further exaggerated in dense forests with high fuel continuity and loading (Wagner, 1977, Rothermel, 1972, 1983, 1991; Scott and Reinhardt, 2001)

Although %CC in the treated scenarios was significantly lower than untreated scenarios for all simulated wind velocities, ROS did not significantly decrease between untreated and treated scenarios for slow wind conditions. This finding highlights the complex set of interactions and feedbacks that exist between fuels, fire, and the atmosphere. Forests with higher levels of %CC will also experience higher levels of ROS as indrafts and flow dynamics generated by burning trees, reduced wind resistance (drag), increased preheating of fuel, and faster heat transfer processes interact with each other to “push” fire through the stand faster (Morvan and Dupuy, 2004; Fernando, 2012; Linn and Cunningham, 2013). For this study, the simulated comparison between untreated and treated forest scenarios under slow wind velocities, which resulted in no significant decrease of ROS, was likely because canopy consumption and the fuel-fire-atmospheric interactions between untreated and treated stands were not dissimilar enough to drive significant differences.

Even though ROS was not found to be significantly different between untreated and treated scenarios for slow wind velocities, ROS did generally increase with elevated wind velocities, especially for untreated forest scenarios. The finding that faster winds lead to faster rates of fire spread is similar to findings from past studies (Cheney et al., 1993; Rothermel, 1991; Linn and Cunningham, 2003; Hoffman et al., 2015). With faster wind velocities, radiative and convective heat transfer from burning fuels to unburned fuels increases as fire line depths increase, flames elongate, plume angle decreases, and overall fire intensity increases (Rothermel, 1972; Linn and Cunningham, 2003). Therefore, as heat is more effectively transferred from unburned fuels to burned fuels with faster winds, rates of fire spread increase (Rothermel, 1972).

When addressing the primary research focus of this study, results suggest that differences in fire behavior between various tree spatial patterns within treated stands were significant for both %CC and ROS (p values < .05); however the magnitude of that effect was minimal from a managerial standpoint. The handful of observed differences between treated scenarios was small, regardless of whether the tree spatial pattern was uniform, random, mostly small clumps, mostly medium clumps, mostly intermediate clumps, mostly large clumps, or all extra-large clumps. The observed differences between treated scenarios was likely due to stochastic processes, therefore it is more constructive to consider and discuss why larger differences in %CC and ROS between treated scenarios were not observed. In this study, horizontal forest structure was manipulated while vertical forest structure was held constant. All of the trees in tested simulations had identical physical properties (equal height, crown base height, crown width etc.); thus the ignition requirements for a surface fire to transition to a crown fire were for the most part uniform across scenarios. With similar crown fire ignition requirements, differences in surface fire intensites generated from different surface fuel loads acted as an "on/off" switch for inititating crown fires. High surface fuel load produced high severity crown fires while low surface fuel loads produced significantly less severe fire behavior, thus overpowering potential effects of horizontal forest structure on fire behavior in the modeled scenarios.

The finding that horizontal forest structure had a limited effect on fire behavior is in line with findings by Pimont et al. (2011), who also investigated variations in fire behavior between different spatial arrangements using a physics-based fire behavior model (FIRETEC). In contrast, Hoffman et al. (2015) found that heterogeneous forest structure did drive significant differences in fire behavior, with higher severity crown fires occurring in areas where canopy fuels were more aggregated. The difference between this study's results, which found a minimal effect of tree spatial patterns on fire behavior, and Hoffman et al. (2015), could potentially be attributed to the fact that simulated forests in Hoffman et al. (2015) had variations in vertical structural complexity, whereas this study did not.

Analyzing fire behavior across forest stands with vertical structural heterogeneity in addition to horizontal structural heterogeneity is an opportunity for future investigation. Vertical structure in this study was kept constant to maintain focus on understanding the relationship of fire behavior between different tree spatial patterns within a forest. As mentioned above, maintaining homogeneous vertical structure led to similar crown fire ignition requirements across the stand. Therefore, introducing some vertical complexity in future studies may determine that there is interaction with horizontal tree spatial patterns to generate different fire behavior results, as crown fire ignition requirements vary depending on tree crown height and height to live crown (Scott and Reinhardt, 2001). Future modeling studies should also consider introducing heterogeneity in surface fuel loads into study designs as variability in fuels below the forest canopy can also alter heat transfer processes. In real forests, the gaps or breaks in canopy fuels associated with heterogeneous horizontal forest structural patterns often drive variable patterns and loadings in understory vegetation as different grasses, forbs and shrubs establish in between and under tree clumps (Carey, 1999; Thysell and Carey, 2001). This study attempted to isolate the effect of horizontal stand structure on fire behavior under a limited set of conditions; together, heterogeneous surface fuel loads and variations in vertical canopy structure could interact with horizontal forest structure to drive differences in fire behavior, and should be investigated in future studies.

5 CONCLUSION

The Wildland Urban-Interface Fire Dynamics Simulator (WFDS) provided a practical way to investigate how tree spatial patterns within different horizontal forest structures affect fire rates of spread and canopy consumption in treated and untreated forest stands. Although the modeled forests can never truly incorporate all of the complex environmental and physical interactions that occur during a real wildfire, WFDS can be used as a tool to help fire behavior researchers and forest managers consider the influence that forest horizontal structure has on wildfire behavior. Results from this study serve to remind the research and management communities that models do not produce precise predictions, but rather frameworks for what may occur during fire events. Additional physics-based modeling studies are needed to determine how vertical heterogeneous structure, variable surface fuels, and other diverse horizontal structural properties (clump shape, orientation, and density etc.) interact with each other to drive potential differences in wildfire behavior.

Overall, this modeling study has determined that removing surface fuels and reducing stand densities are the most important factors to consider for designing forest treatments with regard to fire behavior activity. If the surface fuel load is high enough to cause a surface fire intense enough to allow for canopy ignition, then the spatial arrangement of trees within the stand is only of minor relevance--most of the stand will burn regardless even in treated stands. As silvicultural treatments are implemented, forest managers should be concerned with increasing horizontal structural heterogeneity for ecological purposes, and be reassured (from this study's results) that manipulating tree spatial patterns has minimal effect on fire behavior.

LITERATURE CITED

Agee, J. K., & Skinner, C. N. (2005). Basic principles of forest fuel reduction treatments. *Forest Ecology and Management*, *211*(1), 83-96.

Agee, J. K. (1998). The landscape ecology of western forest fire regimes. Northwest. *Science*, 72, 24.

Allen, C. D., Savage, M., Falk, D. A., Suckling, K. F., Swetnam, T. W., Schulke, T., ... & Klingel, J. T. (2002). Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. *Ecological applications*, *12*(5), 1418-1433.

Barnett, K., Parks, S. A., Miller, C., & Naughton, H. T. (2016). Beyond Fuel Treatment Effectiveness: Characterizing Interactions between Fire and Treatments in the US. *Forests*, *7*(10), 237.

Battaglia, M. A., Smith, F.W., Shepperd, W.D., (2008). Can prescribed fire be used to maintain fuel treatment effectiveness over time in Black Hills ponderosa pine forests? *Forest Ecology and Management* 256, 2029–2038.

Bessie, W. C., & Johnson, E. A. (1995). The relative importance of fuels and weather on fire behavior in subalpine forests. *Ecology,* 76(3), 747-762.

Bolker, B. M., Brooks, M. E., Clark, C. J., Geange, S. W., Poulsen, J. R., Stevens, M. H. H., & White, J. S. S. (2009). Generalized linear mixed models: a practical guide for ecology and evolution*. Trends in ecology & evolution*, 24(3), 127-135.

Bonnicksen, T. M., & Stone, E. C. (1980). The giant sequoia—mixed conifer forest community characterized through pattern analysis as a mosaic of aggregations. *Forest Ecology and Management*, *3*, 307-328.

Brown, J.K. (1970). Physical fuel properties of ponderosa pine forest floors and cheatgrass. USDA *Forest Service Research Paper,* INT-74. 16 p

Brown, T. J., Hall, B. L., & Westerling, A. L. (2004). The impact of twenty-first century climate change on wildland fire danger in the western United States: an applications perspective. *Climatic change*, *62*(1), 365-388.

Carey, A. B., Kershner, J., Biswell, B., & de Toledo, L. D. (1999). Ecological scale and forest development: squirrels, dietary fungi, and vascular plants in managed and unmanaged forests. *Wildlife Monographs*, 3-71.

Catchpole, W. R., Catchpole, E. A., Butler, B. W., Rothermel, R. C., Morris, G. A., & Latham, D. J. (1998). Rate of spread of free-burning fires in woody fuels in a wind tunnel. *Combustion Science and Technology*, *131*(1-6), 1-37.

Cheney, N. P., Gould, J. S., & Catchpole, W. R. (1993). The influence of fuel, weather and fire shape variables on fire-spread in grasslands. *International Journal of Wildland Fire*, *3*(1), 31-44.

Churchill, D. J., Larson, A. J., Dahlgreen, M. C., Franklin, J. F., Hessburg, P. F., & Lutz, J. A. (2013). Restoring forest resilience: from reference spatial patterns to silvicultural prescriptions and monitoring. *Forest Ecology and Management*, *291*, 442-457.

Contreras, M. A., Parsons, R. A., & Chung, W. (2012). Modeling tree-level fuel connectivity to evaluate the effectiveness of thinning treatments for reducing crown fire potential. *Forest Ecology and Management*, *264*, 134-149.

Cooper, C. F. (1960). Changes in vegetation, structure, and growth of southwestern pine forests since white settlement. *Ecological Monographs*, *30*(2), 129-164.

Covington, W. W., & Moore, M. M. (1994). Post-settlement changes in natural fire regimes and forest structure: ecological restoration of old-growth ponderosa pine forests. *Journal of Sustainable Forestry*, *2*(1-2), 153-181.

Deardorff, J. W, (1980), Stratocumulus-Topped Mixed Layers Derived from a Three-Dimensional Model, *Boundary-Layer Meteorology. 18*, 495–527.

Diggle, P. (2003). Statistical analysis of spatial point patterns. Arnold, London, UK.

Diggle, P. J., & Gratton, R. J. (1984). Monte Carlo methods of inference for implicit statistical models. *Journal of the Royal Statistical Society. Series B (Methodological)*, 193-227.

Dunn, O.J., and Clark, V.A. (1987). Applied Statistics: Analysis of Variance and Regression, Second ed. John Wiley, New York, NY.

Evans, A.M.; Everett, R.G.; Stephens, S.L.; Youtz, J.A. (2011). Comprehensive fuels treatment practices guide for mixed conifer forests: California, Central and Southern Rockies, and the Southwest. *USDA Forest Service, Southwestern Region and The Forest Guild*, Albuquerque, NM. 106 pp.

Falk, D. A., Miller, C., McKenzie, D., & Black, A. E. (2007). Cross-scale analysis of fire regimes. *Ecosystems*, *10*(5), 809-823.

Fernandes, P. M., & Botelho, H. S. (2003). A review of prescribed burning effectiveness in fire hazard reduction. *International Journal of wildland fire*, *12*(2), 117-128.

Fernando, H. J. (2012). Handbook of Environmental Fluid Dynamics, Volume One: Overview and Fundamentals. CRC press. 116-117

Ferrari, S., & Cribari-Neto, F., (2004). Beta regression for modelling rates and proportions. *Journal of Applied Statistics*, 31(7), 799-815.

Finnigan, J. (2000). Turbulence in plant canopies. *Annual review of fluid mechanics*, *32*(1), 519-571.

Franklin, J. F., Spies, T. A., Van Pelt, R., Carey, A. B., Thornburgh, D. A., Berg, D. R., ... & Bible, K. (2002). Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. *Forest Ecology and Management*, *155*(1), 399-423.

Fulé, P.Z., Crouse, J. E., Roccaforte, J. P., & Kalies, E. L. (2012). Do thinning and/or burning treatments in western USA ponderosa or Jeffrey pine-dominated forests help restore natural fire behavior? *Forest Ecology and Management*, *269*, 68-81.

Fulé, P.Z., McHugh, C., Heinlein, T.A., Covington, W.W. (2001, a). Potential fire behavior is reduced following forest restoration treatments. In: Vance, R.K., Covington, W.W., Edminster, C.B., Blake, J. (Eds.), Ponderosa Pine Ecosystems Restoration and Conservation, Steps Toward Stewardship. *USDA Forest Service Proceedings RMRSP-22*. Rocky Mountain Research Station, Ogden, UT, 28–35.Fulé, P. Z., Waltz, A. E., Covington, W. W., & Heinlein, T. A. (2001, b). Measuring forest restoration effectiveness in reducing hazardous fuels. *Journal of Forestry*, *99*(11), 24-29.

Gardner, R. H., Milne, B. T., Turnei, M. G., & O'Neill, R. V. (1987). Neutral models for the analysis of broad-scale landscape pattern. *Landscape ecology*, *1*(1), 19-28.

Getzin, S., Wiegand, K., Schumacher, J., & Gougeon, F. A. (2008). Scale-dependent competition at the stand level assessed from crown areas. *Forest Ecology and Management*, *255*(7), 2478-2485.

Graham R.T., McCaffrey S, Jain T.B. (2004). Science basis for changing forest structure to modify wildfire behavior and severity. USDA Forest Service, Rocky Mountain Research Station, *General Technical Report RMRS-GTR-120*, 43 pp.

Graham, R. T., A. E. Harvey, T. B. Jain, and J. R. Tonn. (1999). The effects of thinning and similar stand treatments on fire behavior in western forests. USDA Forest Service General Technical Report PNW-GTR-463, 27 pp.

Graham, R. T., Jain, T. B., & Sandquist, J. (2005). Free selection: a silvicultural option. In *2005 national silviculture workshop: restoring fire-adapted ecosystems.* Albany, CA: US Department of Agriculture, Forest Service, Pacific Southwest Research Station. 121-156.

Hann, W. J., & Bunnell, D. L. (2001). Fire and land management planning and implementation across multiple scales. *International Journal of Wildland Fire*, *10*(4), 389-403.

Hargrove, W. W., Gardner, R. H., Turner, M. G., Romme, W. H., & Despain, D. G. (2000). Simulating fire patterns in heterogeneous landscapes. *Ecological modelling*, *135*(2), 243-263.

Hessburg, P. F., Agee, J. K., & Franklin, J. F. (2005). Dry forests and wildland fires of the inland Northwest USA: contrasting the landscape ecology of the pre-settlement and modern eras. *Forest Ecology and Management*, *211*(1), 117-139.

Hessburg, P. F., Churchill, D. J., Larson, A. J., Haugo, R. D., Miller, C., Spies, T. A., ... & Gaines, W. L. (2015). Restoring fire-prone Inland Pacific landscapes: seven core principles. *Landscape Ecology*, *30*(10), 1805-1835.

Hoffman, C. M., Canfield, J., Linn, R. R., Mell, W., Sieg, C. H., Pimont, F., & Ziegler, J. (2016). Evaluating crown fire rate of spread predictions from physics-based models. *Fire Technology*, *52*(1), 221-237.

Hoffman, C. M., Linn, R., Parsons, R., Sieg, C., & Winterkamp, J. (2015). Modeling spatial and temporal dynamics of wind flow and potential fire behavior following a mountain pine beetle outbreak in a lodgepole pine forest. *Agricultural and Forest Meteorology*, 204, 79-93.

Hoffman, C. M., Morgan, P., Mell, W., Parsons, R., Strand, E., & Cook, S. (2013). Surface fire intensity influences simulated crown fire behavior in lodgepole pine forests with recent mountain pine beetle-caused tree mortality. *Forest Science*, *59*(4), 390-399.

Hoffman, C., Morgan, P., Mell, W., Parsons, R., Strand, E. K., & Cook, S. (2012). Numerical simulation of crown fire hazard immediately after bark beetle-caused mortality in lodgepole pine forests. *Forest Science*, *58*(2), 178-188.

Hudak, A.T., Rickert I, Morgan P, Strand E, Lewis SA, Robichaud PR, Hoffman C, Holden Z.A., (2011). Review of fuel treatment effectiveness in forest and rangelands and a case study from the 2007 megafires in central Idaho, USA. USDA Forest Service, Rocky Mountain Research Station, *General Technical Report RMRS-GTR-252*.

Hunter, M.E., Shepperd, W.D., Lentile, L.B., Lundquist, J.E., Adreu, M.G., Butler, J.L., Smith, F.W., (2007). A comprehensive guide to fuels treatment practices for ponderosa pine in the

Black Hills, Colorado Front Range, and Southwest, USDA Forest Service, Rocky Mountain Research Station. *General Technical Report RMRS-GTR-198*.

Jenkins, M. J., Hebertson, E., Page, W., & Jorgensen, C. A. (2008). Bark beetles, fuels, fires and implications for forest management in the Intermountain West. *Forest Ecology and Management*, *254*(1), 16-34.

Jenkins, M. J., Hebertson, E., Page, W., & Jorgensen, C. A. (2008). Bark beetles, fuels, fires and implications for forest management in the Intermountain West. *Forest Ecology and Management*, *254*(1), 16-34.

Kalies, E. L., & Kent, L. L. Y. (2016). Tamm Review: Are fuel treatments effective at achieving ecological and social objectives? A systematic review. *Forest Ecology and Management*, *375*, 84-95.

Kaufmann, M. R., Regan, C. M., & Brown, P. M. (2000). Heterogeneity in ponderosa pine/Douglas-fir forests: age and size structure in unlogged and logged landscapes of central Colorado. *Canadian Journal of Forest Research*, *30*(5), 698-711.

Keane, R. E., Ryan, K. C., Veblen, T. T., Allen, C. D., Logan, J. A., Hawkes, B., & Barron, J. (2002). The cascading effects of fire exclusion in Rocky Mountain ecosystems. *Rocky Mountain futures: an ecological perspective*, 133-152.

Kennedy, M. C., & Johnson, M. C. (2014). Fuel treatment prescriptions alter spatial patterns of fire severity around the wildland–urban interface during the Wallow Fire, Arizona, USA. *Forest Ecology and Management*, *318*, 122-132.

Larson, A. J., & Churchill, D. (2012). Tree spatial patterns in fire-frequent forests of western North America, including mechanisms of pattern formation and implications for designing fuel reduction and restoration treatments. *Forest Ecology and Management*, *267*, 74-92.

Linn, R. R., & Cunningham, P. (2005). Numerical simulations of grass fires using a coupled atmosphere–fire model: basic fire behavior and dependence on wind speed. *Journal of Geophysical Research: Atmospheres*, *110*(D13).

Linn, R. R., Sieg, C. H., Hoffman, C. M., Winterkamp, J. L., & McMillin, J. D. (2013). Modeling wind fields and fire propagation following bark beetle outbreaks in spatially-heterogeneous pinyon-juniper woodland fuel complexes. *Agricultural and Forest Meteorology*, *173*, 139-153.

Lydersen, J. M., North, M. P., Knapp, E. E., & Collins, B. M. (2013). Quantifying spatial patterns of tree groups and gaps in mixed-conifer forests: reference conditions and long-term changes following fire suppression and logging. *Forest Ecology and Management*, *304*, 370-382.

Martinson E.J., Omi P.N. (2003). Performance of fuel treatments subjected to wildfires. In 'Fire, Fuel Treatments, and Ecological Restoration: Conference Proceedings', 16–18 April 2002, Fort Collins, CO. (Tech. Eds PN Omi, LA Joyce) USDA Forest Service, Rocky Mountain Research Station. *Proceedings RMRS-P29*, 7–14.

Martinson, E. J., & Omi, P. N. (2013). Fuel treatments and fire severity: a meta-analysis. *USDA Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-103WWW,* 1-41.

McDermott, R., Forney, G., McGrattan, K., & Mell, W. (2010). Fire dynamics simulator 6: complex geometry, embedded meshes, and quality assessment. In *V European Conference on Computational Fluid Dynamics, Lisbon, Portugal*.

McGrattan, K., Hostikka, S., & Floyd, J. E. (2010). Fire dynamics simulator (version 5), user's guide. *NIST special publication*, *1019*(5), 1-186.

McGrattan, K., Hostikka, S., Floyd, J., Baum, H. R., Rehm, R. G., Mell, W., & McDermott, R. (2004). Fire dynamics simulator (version 5), technical reference guide. *NIST special publication*, *1018*(5).

Mell, W. E., McDermott, R. J., & Forney, G. P. (2010, October). Wildland fire behavior modeling: perspectives, new approaches and applications. In *Proceedings of 3rd Fire Behavior and Fuels Conference, Spokane, Washington, USA*, 45-62.

Mell, W., Charney, J., Jenkins, M. A., Cheney, P., & Gould, J. (2013). Numerical simulations of grassland fire behavior from the LANL-FIRETEC and NIST-WFDS models. In *Remote Sensing and Modeling Applications to Wildland Fires*,209-225.

Mell, W., Jenkins, M. A., Gould, J., & Cheney, P. (2007). A physics-based approach to modelling grassland fires. International Journal of Wildland Fire, 16(1), 1-22.

Mell, W., Maranghides, A., McDermott, R., & Manzello, S. L. (2009). Numerical simulation and experiments of burning douglas fir trees. *Combustion and Flame*, *156*(10), 2023-2041.

Morvan, D. (2011). Physical phenomena and length scales governing the behaviour of wildfires: a case for physical modelling. *Fire technology*, *47*(2), 437-460.

Morvan, D., & Dupuy, J. L. (2001). Modeling of fire spread through a forest fuel bed using a multiphase formulation. *Combustion and flame*, *127*(1), 1981-1994.

Morvan, D., & Dupuy, J. L. (2004). Modeling the propagation of a wildfire through a Mediterranean shrub using a multiphase formulation. *Combustion and Flame*, 138(3), 199-210.

Mueller, E., Mell, W., & Simeoni, A. (2014). Large eddy simulation of forest canopy flow for wildland fire modeling. *Canadian Journal of Forest Research*, *44*(12), 1534-1544.

Naficy, C., Sala, A., Keeling, E. G., Graham, J., & DeLuca, T. H. (2010). Interactive effects of historical logging and fire exclusion on ponderosa pine forest structure in the northern Rockies. *Ecological Applications*, *20*(7), 1851-1864.

North, M., Innes, J., & Zald, H. (2007). Comparison of thinning and prescribed fire restoration treatments to Sierran mixed-conifer historic conditions. *Canadian Journal of Forest Research*, *37*(2), 331-342.

North, M., P. A. Stine, K. L. O'Hara, W. J. Zielinski, and S. L. Stephens. 2009. An ecosystems management strategy for Sierra mixed-conifer forests, with addendum. USDA Forest Service, Pacific Southwest Research Station, *General Technical Report PSW-GTR-220*.

Noss, R. F., Franklin, J. F., Baker, W. L., Schoennagel, T., & Moyle, P. B. (2006). Managing fire-prone forests in the western United States. *Frontiers in Ecology and the Environment*, *4*(9), 481-487.

Omi, P. N. (2015). Theory and practice of wildland fuels management. *Current Forestry Reports*, *1*(2), 100-117.

O'Neill, R. V. (1986). *A hierarchical concept of ecosystems* (Vol. 23). Princeton University Press.

Parsons, R. A., Mell, W. E., & McCauley, P. (2011). Linking 3D spatial models of fuels and fire: Effects of spatial heterogeneity on fire behavior. *Ecological Modelling*, *222*(3), 679-691.

Parsons, R. A., Sauer, J., & Linn, R. R. (2010, a). Crown fuel spatial variability and predictability of fire spread. In *Proceedings of the VI International Conference on Forest Fire Research* (pp. 15-18).

Parsons, R.A., Mell, W. & McCauley, P. (2010, b) Modeling the spatial distribution of forest crown biomass and effects on fire behaviour with FUEL2D and WFDS. In Viegas, D.X. (ed.), *Proceedings of VI International Conference on Forest Fire Research*, Coimbra, 13–18.

Pimont, F., Dupuy, J. L., Caraglio, Y., & Morvan, D. (2009). Effect of vegetation heterogeneity on radiative transfer in forest fires. *International journal of wildland fire*, *18*(5), 536-553.

Pimont, F., Dupuy, J. L., Linn, R. R., & Dupont, S. (2011). Impacts of tree canopy structure on wind flows and fire propagation simulated with FIRETEC. *Annals of Forest Science*, *68*(3), 523.

Pollet, J., & Omi, P. N. (2002). Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *International Journal of Wildland Fire*, *11*(1), 1-10.

Raymond, C. L., and D. L. Peterson. (2005). Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon, USA. *Canadian Journal of Forest Research* 35: 2981-2995.

Reinhardt, E. D., Keane, R. E., Calkin, D. E., & Cohen, J. D. (2008). Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. *Forest Ecology and Management*, *256*(12), 1997-2006.

Reynolds, R.T., Sánchez Meador, A.J., Youtz, J.A., Nicolet, T., Matonis, M.S., Jackson, P.L., DeLorenzo, D.G., Graves, A.D. (2013). Restoring composition and structure in southwestern frequent-fire forests: a science-based framework for improving ecosystem resiliency. USDA Forest Service, Rocky Mountain Research Station, *General Technical Report RMRS-GTR-310. 76 pp.* .

Ritchie, J.R., Steckler, K.D., Hamins, A., Cleary, T.G., Yang, J.C., Kashiwagi, T. (1997) The effect of sample size on the heat release rate of charring materials. In *Proceedings 5th International Association Fire Safety Science.* 177-188 pp. 177- 188.

Rothermel, R. C. (1972). A mathematical model for predicting fire spread in wildland fuels. *USDA Forest Service Research Paper INT-115. 40 pp*.

Rothermel, R. C. (1983). How to predict the spread and intensity of forest and range fires. *The Bark Beetles, Fuels, and Fire Bibliography*, 70.

Rothermel, R.C. (1991). Predicting behavior and size of crown fires in the northern Rocky Mountains. *USDA Forest Service Research Paper INT-438.*

Safford, H. D., Stevens, J. T., Merriam, K., Meyer, M. D., & Latimer, A. M. (2012). Fuel treatment effectiveness in California yellow pine and mixed conifer forests. *Forest Ecology and Management*, *274*, 17-28.

Savage, M., & Swetnam, T. W. (1990). Early 19th-Century Fire Decline Following Sheep Pasturing in a Navajo Ponderosa Pine Forest. *Ecology*, *71*(6), 2374-2378.

Schoennagel, T., Veblen, T. T., & Romme, W. H. (2004). The interaction of fire, fuels, and climate across Rocky Mountain forests. *BioScience*, *54*(7), 661-676.

Scott, J. H., & Burgan, R. E. (2005). Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. *The Bark Beetles, Fuels, and Fire Bibliography*, 66.

Scott, J.H., Reinhardt, E.D., (2001). Assessing crown fire potential by linking models of surface and crown fire behavior. *USDA Forest Service Research Paper RMRS-RP-29*.

Shaw, R. H., & Schumann, U. (1992). Large-eddy simulation of turbulent flow above and within a forest. *Boundary-Layer Meteorology*, *61*(1-2), 47-64.

Stephens, S. L. (1998). Evaluation of the effects of silvicultural and fuels treatments on potential fire behaviour in Sierra Nevada mixed-conifer forests. *Forest Ecology and Management*, 105(1), 21-35.

Stephens, S. L., & Moghaddas, J. J. (2005). Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. *Forest Ecology and Management*, *215*(1), 21-36.

Stephens, S. L., Moghaddas, J. J., Edminster, C., Fiedler, C. E., Haase, S., Harrington, M., ... & Skinner, C. N. (2009). Fire treatment effects on vegetation structure, fuels, and potential fire severity in western US forests. *Ecological Applications*, *19*(2), 305-320.

Thysell, D. R., & Carey, A. B. (2001). Manipulation of density of Pseudotsuga menziesii canopies: preliminary effects on understory vegetation. *Canadian Journal of Forest Research*, *31*(9), 1513-1525.

Tinkham, W. T, Dickinson, Y., Hoffman, C., Battaglia, A, M., Ex, S., Underhill, J., (2017). Visualization guide to heterogeneous forest structures following treatment in southern Rocky Mountains. Unpublished manuscript. Colorado State University, Fort Collins CO. pp 64.

Turner, M. G., & Romme, W. H. (1994). Landscape dynamics in crown fire ecosystems. *Landscape ecology*, *9*(1), 59-77.

Underhill, J. L., Dickinson, Y., Rudney, A., & Thinnes, J. (2014). Silviculture of the Colorado Front Range landscape restoration initiative. *Journal of Forestry*, *112*(5), 484-493.

Veblen, T. T., Kitzberger, T., & Donnegan, J. (2000). Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado Front Range. *Ecological Applications*, *10*(4), 1178-1195.

Wagner, C. V. (1977). Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research*, *7*(1), 23-34.

Waring, R. H., & Running, S. W. (2010). *Forest ecosystems: analysis at multiple scales*. Elsevier.

Westerling, A. L., Hidalgo, H. G., Cayan, D. R., & Swetnam, T. W. (2006). Warming and earlier spring increase western US forest wildfire activity. *Science*, *313*(5789), 940-943.

Wu, J., & David, J. L. (2002). A spatially explicit hierarchical approach to modeling complex ecological systems: theory and applications. *Ecological Modelling*, *153*(1), 7-26.

Youtz, J.A., Graham, R.T., Reynolds, R.T., Simon, J., (2007). Implementing northern goshawk habitat management in southwestern forests: a template for restoring fire-adapted forest ecosystems in Integrated Restoration of Forested Ecosystems to Achieve Multi-Resource Benefits. In: Deal, R.L. (Ed.), Proc. of the 2007 National Silviculture Workshop, *USDA Forest Service General Technical Report PNWGTR-733*, p. 19.

Ziegler, J. P., Hoffman, C., Battaglia, M., & Mell, W. (2017). Spatially explicit measurements of forest structure and fire behavior following restoration treatments in dry forests. *Forest Ecology and Management*, 386, 1-12.

APPENDIX

Below is a text file containing typical input parameters for WFDS to perform simulations across the 48 scenarios tested in this study. Parameters that changed were the XY locations of trees, surface fuel characteristics, and wind velocities.

```
EXAMPLE WFDS INPUT FILE:

&HEAD CHID='80_20_TL8low_mostly_md_6'
    TITLE='80_20_TL8low_mostly_md_6_850x400' /

-- Atmos inflow, This is 850x400 mirror on sides and on top. dz is changed to a finer
resolution.  Fireline mlr max is .35

-- Specify number of grid cells (IJK) and domain size (XB) in x,y,z directions

&MESH ID='MESH1', IJK=225,25,100, XB=0,450,0,50,0,100 /
&MESH ID='MESH2', IJK=225,25,100, XB=0,450,50,100,0,100 /
&MESH ID='MESH3', IJK=225,25,100, XB=0,450,100,150,0,100 /
&MESH ID='MESH4', IJK=225,25,100, XB=0,450,150,200,0,100 /
&MESH ID='MESH5', IJK=225,25,100, XB=0,450,200,250,0,100 /
&MESH ID='MESH6', IJK=225,25,100, XB=0,450,250,300,0,100 /
&MESH ID='MESH7', IJK=225,25,100, XB=0,450,300,350,0,100 /
&MESH ID='MESH8', IJK=225,25,100, XB=0,450,350,400,0,100 /

&MESH ID='MESH9', IJK=300,20,100, XB=450,750,0,20,0,100 /
&MESH ID='MESH10', IJK=300,20,100, XB=450,750,20,40,0,100 /
&MESH ID='MESH11', IJK=300,20,100, XB=450,750,40,60,0,100 /
&MESH ID='MESH12', IJK=300,20,100, XB=450,750,60,80,0,100 /
&MESH ID='MESH13', IJK=300,20,100, XB=450,750,80,100,0,100 /
&MESH ID='MESH14', IJK=300,20,100, XB=450,750,100,120,0,100 /
&MESH ID='MESH15', IJK=300,20,100, XB=450,750,120,140,0,100 /
&MESH ID='MESH16', IJK=300,20,100, XB=450,750,140,160,0,100 /
&MESH ID='MESH17', IJK=300,20,100, XB=450,750,160,180,0,100 /
&MESH ID='MESH18', IJK=300,20,100, XB=450,750,180,200,0,100 /
&MESH ID='MESH19', IJK=300,20,100, XB=450,750,200,220,0,100 /
```

```
&MESH ID='MESH20', IJK=300,20,100, XB=450,750,220,240,0,100 /
&MESH ID='MESH21', IJK=300,20,100, XB=450,750,240,260,0,100 /
&MESH ID='MESH22', IJK=300,20,100, XB=450,750,260,280,0,100 /
&MESH ID='MESH23', IJK=300,20,100, XB=450,750,280,300,0,100 /
&MESH ID='MESH24', IJK=300,20,100, XB=450,750,300,320,0,100 /
&MESH ID='MESH25', IJK=300,20,100, XB=450,750,320,340,0,100 /
&MESH ID='MESH26', IJK=300,20,100, XB=450,750,340,360,0,100 /
&MESH ID='MESH27', IJK=300,20,100, XB=450,750,360,380,0,100 /
&MESH ID='MESH28', IJK=300,20,100, XB=450,750,380,400,0,100 /

&MESH ID='MESH29', IJK=100,200,100, XB=750,850,0,200,0,100 /
&MESH ID='MESH30', IJK=100,200,100, XB=750,850,200,400,0,100 /

&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=1 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=2 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=3 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=4 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=5 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=6 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=7 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=8 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=9 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=10 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=11 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=12 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=13 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=14 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=15 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=16 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=17 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=18 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=19 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=20 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=21 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=22 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=23 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=24 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=25 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=26 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=27 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=28 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=29 /
&TRNZ IDERIV=1,CC=0.,PC=0.5,MESH_NUMBER=30 /
```

```
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=1 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=2 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=3 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=4 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=5 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=6 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=7 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=8 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=9 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=10 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=11 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=12 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=13 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=14 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=15 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=16 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=17 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=18 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=19 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=20 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=21 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=22 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=23 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=24 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=25 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=26 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=27 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=28 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=29 /
&TRNZ IDERIV=2,CC=0.,PC=0.0,MESH_NUMBER=30 /

- Account for water vapor from drying vegetation
&SPEC ID='WATER VAPOR' /

&TIME TWFIN=2500. /

- initialize domain with the 20 m input wind speed (Uo=U20), no negative number in
front of wind speed on misc line
&MISC
RADIATION=.TRUE.,BAROCLINIC=.TRUE.,TERRAIN_CASE=.FALSE.,WIND_ONLY=.FALSE.,
PROJECTION=.TRUE.,U0=6 /

- Specify parameters for combustion of fuel gases from pyrolysis of the solid fuel(s)
&REAC ID='WOOD'
```

```
    FYI='Ritchie, et al., 5th IAFSS, C_3.4 H_6.2 O_2.5'
    SOOT_YIELD = 0.02
    O        = 2.5
    C        = 3.4
    H        = 6.2
    HEAT_OF_COMBUSTION = 17700 /

- Ground fuel elements Based on TL8,
&SURF ID = 'GROUND VEG1'
    VEGETATION = .TRUE.
    VEG_DRAG_COEFFICIENT    = 0.125
    VEG_MOISTURE = 0.05
    VEG_SV  = 5808
    VEG_CHAR_FRACTION  = 0.265
    VEG_LOAD     = .5
    VEG_HEIGHT   = 0.05
    VEG_DENSITY= 510
    FIRELINE_MLR_MAX = 0.35
    RGB       = 252,252,120
&VENT XB=500,700,100,300,0,0,SURF_ID='GROUND VEG1'

&SURF ID = 'GROUND VEG2'
    VEGETATION = .TRUE.
    VEG_DRAG_COEFFICIENT    = 0.125
    VEG_MOISTURE = .05
    VEG_SV  = 5808
    VEG_CHAR_FRACTION  = 0.265
    VEG_LOAD     = .5
    VEG_HEIGHT   = 0.05
    VEG_DENSITY= 510
    FIRELINE_MLR_MAX = 0.35
    RGB       = 122,117,48 /
&VENT XB=483,500,1,399,0,0,SURF_ID='GROUND VEG2' /
&VENT XB=500,849,1,100,0,0,SURF_ID='GROUND VEG2' /
&VENT XB=500,849,300,399,0,0,SURF_ID='GROUND VEG2' /
&VENT XB=700,849,100,300,0,0,SURF_ID='GROUND VEG2' /

&SURF ID = 'GROUND VEG3'
    VEGETATION = .TRUE.
    VEG_DRAG_COEFFICIENT    = 0.125
    VEG_MOISTURE = 2.00
    VEG_SV  = 5808
    VEG_CHAR_FRACTION  = 0.265
    VEG_LOAD     = .5
```

```
     VEG_HEIGHT   = 0.05
     VEG_DENSITY= 510
     FIRELINE_MLR_MAX = 0.35
     RGB       = 122,117,48 /
&VENT XB=1,480,1,399,0,0,SURF_ID='GROUND VEG3' /


- Ponderosa pine elements, SAV based on Catchpole, Canopy Bulk Density based on
Brown 1978
&PART ID='PIPO',TREE=.TRUE.,QUANTITIES='VEG_TEMPERATURE',
     VEG_INITIAL_TEMPERATURE=20.,
     VEG_SV=5710.,VEG_MOISTURE=1.0,VEG_CHAR_FRACTION=0.25,
     VEG_DRAG_COEFFICIENT=0.125,VEG_DENSITY=520.,VEG_BULK_DENSITY=0.52,
     VEG_BURNING_RATE_MAX=0.4,VEG_DEHYDRATION_RATE_MAX=0.4,
     VEG_REMOVE_CHARRED=.TRUE. /

- Tree stem elements
&PART ID='TRUNK1',TREE=.TRUE.,QUANTITIES='VEG_TEMPERATURE',
     VEG_SV=3.,VEG_MOISTURE=1.0,
     VEG_DRAG_COEFFICIENT=0.125,VEG_DENSITY=520.,
     VEG_BULK_DENSITY=520 /


-Area of InterestTree list
-- Area of Interest forest was based on X 0-200 Y 0-200, then the original 4ha AOI tree
quadrant 'A,B,C,D' was shifted and divided to fill excess area (900(X), 400(Y), 100(Z))

-- Area of interest TREES: X 500-700  Y 100-300 Z 0-100
&TREE
XYZ=541.8,118.1,0,PART_ID="PIPO",FUEL_GEOM="CONE",CROWN_WIDTH=3.8,CROWN
_BASE_HEIGHT=4,TREE_HEIGHT=16,OUTPUT_TREE=.TRUE.,LABEL="TREE1" /
&TREE
XYZ=538.7,136.2,0,PART_ID="PIPO",FUEL_GEOM="CONE",CROWN_WIDTH=3.8,CROWN
_BASE_HEIGHT=4,TREE_HEIGHT=16,OUTPUT_TREE=.TRUE.,LABEL="TREE2" /
&TREE
#…………………………….All tree canopies in stand within area of interest

-- Area of interest TRUNKS: X 500-700  Y 100-300 Z 0-100
&TREE
XYZ=541.8,118.1,0,PART_ID="TRUNK1",FUEL_GEOM="CYLINDER",CROWN_WIDTH=0.28
,CROWN_BASE_HEIGHT=0,TREE_HEIGHT=4 /
&TREE
XYZ=538.7,136.2,0,PART_ID="TRUNK1",FUEL_GEOM="CYLINDER",CROWN_WIDTH=0.28
,CROWN_BASE_HEIGHT=0,TREE_HEIGHT=4 /
```

```
          &TREE
          #……………………………….All trucks in in stand within area of interest.




          -- Buffer area TREES:
          &TREE XYZ=41.8,18.1,0,PART_ID="PIPO",FUEL_GEOM="CONE",CROWN_WIDTH=3.8,CROWN_BASE_HEIGHT=4,TREE_HEIGHT=16,OUTPUT_TREE=.TRUE.,LABEL="TREE1" /
          &TREE XYZ=38.7,36.2,0,PART_ID="PIPO",FUEL_GEOM="CONE",CROWN_WIDTH=3.8,CROWN_BASE_HEIGHT=4,TREE_HEIGHT=16,OUTPUT_TREE=.TRUE.,LABEL="TREE2" /
          &TREE
          #……………………………….All tree canopies in stand in buffer areas

          -- Buffer area TRUNKS:
          &TREE XYZ=41.8,18.1,0,PART_ID="TRUNK1",FUEL_GEOM="CYLINDER",CROWN_WIDTH=0.28,CROWN_BASE_HEIGHT=0,TREE_HEIGHT=4 /
          &TREE XYZ=38.7,36.2,0,PART_ID="TRUNK1",FUEL_GEOM="CYLINDER",CROWN_WIDTH=0.28,CROWN_BASE_HEIGHT=0,TREE_HEIGHT=4 /
          &TREE
          #……………………………….All trucks in in stand in buffer areas


-Igniter fire
&SURF ID='IGN FIRE', HRRPUA=500.,RAMP_Q='RAMPFIRE' /
&RAMP ID='RAMPFIRE',T=0.0,F=0.0 /
&RAMP ID='RAMPFIRE',T=200.0,F=0.0 /
&RAMP ID='RAMPFIRE',T=216.0,F=0.5 /
&RAMP ID='RAMPFIRE',T=222.0,F=1.0 /
&RAMP ID='RAMPFIRE',T=252.0,F=1.0 /
&RAMP ID='RAMPFIRE',T=256.0,F=0.5 /
&RAMP ID='RAMPFIRE',T=260.0,F=0.0 /
&VENT XB=480,483,50,350,0,0, SURF_ID='IGN FIRE'/


- Inflow
&SURF ID='INFLOW',VEL=-6, RAMP_V='RAMPVEL', PROFILE='ATMOSPHERIC', Z0=20.,PLE=0.143 /
&RAMP ID='RAMPVEL',T=0.0,F=0.0 /
&RAMP ID='RAMPVEL',T=1.0,F=0.5 /
```

```
&RAMP ID='RAMPVEL',T=2.0,F=0.6 /
&RAMP ID='RAMPVEL',T=3.0,F=0.7 /
&RAMP ID='RAMPVEL',T=4.0,F=0.8 /
&RAMP ID='RAMPVEL',T=5.0,F=0.9 /
&RAMP ID='RAMPVEL',T=6.0,F=1.0 /
```

- Domain-Boundary conditions

```
&VENT MB='XMIN', SURF_ID='INFLOW' /
&VENT MB='XMAX', SURF_ID='OPEN' /
&VENT MB='YMIN', SURF_ID='MIRROR' /
&VENT MB='YMAX', SURF_ID='MIRROR' /
&VENT MB='ZMAX', SURF_ID='MIRROR' /
```

- Output data to be viewed by Smokeview
-- time intervals at which various quantities are written

```
&DUMP DT_DEVC=2, DT_SLCF=01, DT_PART=01, DT_BNDF=01. /
```

-- two-dimensional slice files

```
&SLCF XB=500,700,100,300,1,1, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,2,2, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,3,3, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,4,4, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,5,5, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,6,6, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,7,7, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,8,8, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,9,9, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,10,10, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,11,11, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,12,12, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,13,13, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,16,16, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,20,20, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,25,25, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,30,30, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,40,40, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,50,50, QUANTITY='U-VELOCITY' /
&SLCF XB=500,700,100,300,60,60, QUANTITY='U-VELOCITY' /

&SLCF XB=500,700,100,300,1,1, QUANTITY='V-VELOCITY' /
```

```
&SLCF XB=500,700,100,300,2,2, QUANTITY='V-VELOCITY' /
&SLCF XB=500,700,100,300,3,3, QUANTITY='V-VELOCITY' /
&SLCF XB=500,700,100,300,4,4, QUANTITY='V-VELOCITY' /
&SLCF XB=500,700,100,300,5,5, QUANTITY='V-VELOCITY' /
&SLCF XB=500,700,100,300,6,6, QUANTITY='V-VELOCITY' /
&SLCF XB=500,700,100,300,7,7, QUANTITY='V-VELOCITY' /
&SLCF XB=500,700,100,300,8,8, QUANTITY='V-VELOCITY' /
&SLCF XB=500,700,100,300,9,9, QUANTITY='V-VELOCITY' /
&SLCF XB=500,700,100,300,10,10, QUANTITY='V-VELOCITY' /
&SLCF XB=500,700,100,300,11,11, QUANTITY='V-VELOCITY' /
&SLCF XB=500,700,100,300,12,12, QUANTITY='V-VELOCITY' /
&SLCF XB=500,700,100,300,13,13, QUANTITY='V-VELOCITY' /
&SLCF XB=500,700,100,300,16,16, QUANTITY='V-VELOCITY' /
&SLCF XB=500,700,100,300,20,20, QUANTITY='V-VELOCITY' /
&SLCF XB=500,700,100,300,25,25, QUANTITY='V-VELOCITY' /
&SLCF XB=500,700,100,300,30,30, QUANTITY='V-VELOCITY' /
&SLCF XB=500,700,100,300,40,40, QUANTITY='V-VELOCITY' /
&SLCF XB=500,700,100,300,50,50, QUANTITY='V-VELOCITY' /
&SLCF XB=500,700,100,300,60,60, QUANTITY='V-VELOCITY' /

&SLCF XB=500,700,100,300,1,1, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,2,2, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,3,3, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,4,4, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,5,5, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,6,6, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,7,7, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,8,8, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,9,9, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,10,10, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,11,11, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,12,12, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,13,13, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,16,16, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,20,20, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,25,25, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,30,30, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,40,40, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,50,50, QUANTITY='W-VELOCITY' /
&SLCF XB=500,700,100,300,60,60, QUANTITY='W-VELOCITY' /

--This will be used to calculate rate of spread.
&SLCF XB=500,700,110,110,0,60, QUANTITY='HRRPUV' /
&SLCF XB=500,700,130,130,0,60, QUANTITY='HRRPUV' /
```

```
&SLCF XB=500,700,150,150,0,60, QUANTITY='HRRPUV' /
&SLCF XB=500,700,170,170,0,60, QUANTITY='HRRPUV' /
&SLCF XB=500,700,190,190,0,60, QUANTITY='HRRPUV' /
&SLCF XB=500,700,210,210,0,60, QUANTITY='HRRPUV' /
&SLCF XB=500,700,230,230,0,60, QUANTITY='HRRPUV' /
&SLCF XB=500,700,250,250,0,60, QUANTITY='HRRPUV' /
&SLCF XB=500,700,270,270,0,60, QUANTITY='HRRPUV' /
&SLCF XB=500,700,290,290,0,60, QUANTITY='HRRPUV' /

&SLCF PBZ=8, QUANTITY='U-VELOCITY', VECTOR=.TRUE. /
&SLCF PBZ=8, QUANTITY='W-VELOCITY' /
&SLCF PBZ=8, QUANTITY='V-VELOCITY' /

&SLCF PBY=200, QUANTITY='U-VELOCITY' /
&SLCF PBY=200, QUANTITY='V-VELOCITY' /
&SLCF PBY=200, QUANTITY='W-VELOCITY' /

&BNDF QUANTITY='HEAT_FLUX' /
&BNDF QUANTITY='RADIATIVE HEAT FLUX' /
&BNDF QUANTITY='CONVECTIVE HEAT FLUX' /

-- Burning Rate will be used to quanitfy surface rate of spread
&BNDF QUANTITY='BURNING RATE' /

--Comparing Wall thickness at start and finish can give an idea of how much surface fuel was
consumed.
&BNDF QUANTITY='WALL THICKNESS' /
&BNDF QUANTITY='WALL TEMPERATURE' /

-For use in quantifying the HRR in just the volume of interest
&DEVC XB=500,700,100,300,0,100, QUANTITY='HRRPUV', ID='IntegratedHRRPUV',
STATISTICS='VOLUME INTEGRAL' /

- Declare end of input file
&TAIL /
```