DISSERTATION

HORIZONTAL AND VERTICAL FOREST COMPLEXITY INTERACT TO INFLUENCE POTENTIAL FIRE BEHAVIOR

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In partial fulfillment of the requirements
For the Degree Doctor of Philosophy
Colorado State University
Fort Collins, Colorado
Spring 2022

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ABSTRACT

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Wildland fire behavior is a dynamic process controlled by complex interactions among fuels, weather, and topography. There is significant need to better understand the role of fuels and, particularly, complex arrangements of fuels, on potential fire behavior and effects as a there is a growing emphasis on forest treatments that emulate the heterogenous structures of historical forest ecosystems. Ideally such treatments are intended to reduce fire hazard while concurrently improving resilience to a wide range of disturbance agents and restoring the natural ecosystem dynamics that maintained these forest structures. One way to evaluate how the complex forest structures created by these treatments will influence fire behavior are modeling approaches that account for dynamic interactions between fire, fuels, and wind. These physical fire models build from computational fluid dynamics methods to include processes of heat transfer, vegetative fuel dehydration and pyrolysis, and gas phase ignition and combustion. In this work, several aspects of horizontal and vertical forest structure were evaluated to understand how spatial complexity influences fire behavior, with a particular emphasis on the transition of a surface fire into tree crowns. I used a combination of spatially explicit field data and a physics-based wildfire model, the Wildland-Urban Interface Fire Dynamics Simulator (WFDS), to deepen our fundamental understanding of fire behavior, inform the design of forest treatments that aim to achieve a variety of ecological and social objectives, and develop hypotheses related to the pattern-process feedbacks that contributed to the maintenance of resilient forests across millennia.

Chapter 2 presents a simulation study focused on the relationship between horizontal forest structure and surface to crown heat transfer and crown fire initiation. The results indicated that relative to larger 7- and 19-tree groups, isolated individual trees and 3-tree groups had greater convective cooling and reduced canopy heat flux. Because isolated individuals and 3-tree groups were exposed to less thermal energy, they required a greater surface fireline intensity to initiate torching and had less crown consumption than trees within larger groups. Similarly, I found that increased crown separation distance between trees reduced the net heat flux leading to reduced ignition potential. These findings identify the potential physical mechanisms responsible for supporting the complex forest structures typical of high-frequency fire regimes and may be useful for managers designing fuel hazard reduction and ecological restoration treatments.

Chapter 3 extends chapter 2 by investigating how different levels and types of vertical heterogeneity influence crown fire transition and canopy consumption within tree groups. These results show the importance of fuel stratum gap (or canopy base height) on vertical fire propagation, however vertical fire propagation was mediated by the level of horizontal connectivity in the upper crown layers. This suggests that the fuel stratum gap cannot fully characterize the torching hazard. The results also indicate that as the surface fire line intensity increases, the influence of horizontal connectivity on canopy consumption is amplified. At the scale of individual tree groups, the perceived hazard of small, understory trees and vertical fuel continuity may be offset by lower horizontal continuity (or canopy bulk density) within the midstory and overstory crown layers.

Chapter 4 compares outcomes from four real-world forest treatments that cover a range of potential treatment approaches to evaluate their impacts of forest spatial pattern and potential fire behavior. My results indicate that restoration treatments created greater vertical and horizontal structural complexity than the fuel hazard reduction treatments but resulted in similar reductions to potential fire severity. However, the restoration treatments did increase the surface fire rate of spread which suggests some potential fire behavior tradeoffs among treatment approaches. Overall, these results suggest the utility of restoration treatments in achieving a wide range of management objectives, including fire hazard reduction, and that they can be used in concert with traditional fuel hazard reduction treatments to reduce landscape scale fire risk.

Together this work shows that tree spatial pattern can significantly influence crown fire initiation and canopy consumption through alterations to net heat transfer and feedbacks among closely spaced trees. At the scale of the tree group these results suggest that larger tree groups may sustain higher levels of canopy consumption and mortality as they are easier to ignite and, in cases with small separation between crowns, can sustain horizontal spread resulting in density-depended crown damage. These findings carry over to vertically complex groups where the spatial relationship between small, understory trees and larger, overstory trees has a large impact on the ability of fire to be carried vertically. Further, in these vertically complex groups reducing the density (and/or increasing the horizontal separation) of the overstory trees, resulted in lower rates of crown fuel consumption, therefore, mitigating some of the “laddering” effect caused by the presence of small understory trees. These complex interactions between vertical and horizontal aspects of stand structure were born out in my evaluation of the measured forest treatments, where similar crown fire behavior reductions were observed across various stand structures. Overall, this work shows that forest managers can apply treatments to achieve a wide range of ecological benefits while simultaneously increasing fire resistance and resilience.

ACKNOWLEDGEMENTS

This work would not have been possible without the support, effort, and guidance of a number of people. Most importantly, my wife Emilee whose constant support and cheerleading kept me focused and pushing forward, as well as our son Harris who has added some much need joy and balance. It also goes without saying that this project would have never come to fruition without my advisor Chad Hoffman. He has been instrumental in my development as a scientist, has supported me throughout my graduate studies, and has always made himself available to my questions and need for critical feedback. Mike Battaglia has also provided immense support through project development, identification of our field research sites, and as a constant sounding board who ensured some of my more theoretical thinking could be translated into relevant guidance to forest managers. Similarly, my conversations with Seth Ex focused on operational relevance and he was always quick to highlight the limitations and simplifications of my modeling approaches. Ruddy Mell provided me with invaluable support in learning WFDS and pushed me deeper into the science of combustion, heat transfer, and fire modeling. Outside of my committee, I also benefited greatly from conversations with Camille Stevens-Rumann around the intersection of my work and forest ecology, and with Terrie Jain whose deep roots in operational forestry substantially improved the larger relevance of this work. I also must recognize the amazing field crew members I've had over the years whose hard work and independence made our intensive stem-mapping a breeze. Within the department I have made many great connections with my fellow graduate students, some of whom have developed into lifelong friends. Finally, I recognize the funding support provided by the USDA Forest Service, Rocky Mountain Research Station, the National Fire Plan.

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CHAPTER 1: INTRODUCTION

Over the past century, the combination of wildfire suppression, livestock grazing, and forest management practices have substantially altered the structure and composition of many fire-prone conifer forest ecosystems across the Western United States (Brown et al. 2015, Franklin et al. 2013, Hessburg et al. 2005, Reynolds et al. 2013). In general, these factors have increased tree densities, shifted species compositions towards more shade tolerant tree species, and increased the loading of surface and canopy fuel (Brown et al. 2015, Hessburg et al. 2005, Reynolds et al. 2013). In combination with anthropogenic climate change, these alterations to forest structure are resulting in wildfires whose scale, intensity, and severity are far outside the historical range of variability of these forest types (Miller et al. 2009, Dennison et al. 2014, Barbero et al. 2015). The annual area burned by wildfire across the Western US has been increasing steadily during the past three decades, resulting in mounting fire suppression costs, increased structure loss, and alterations to forest structure and successional pathways (Savage and Mast 2005, Miller et al. 2009, Dennison et al. 2014, Millar and Stephenson 2015).

In response to growing negative impacts resulting from these uncharacteristically severe wildfire events, forest treatments are often implemented with a stated primary goal of reducing fire behavior by modifying the forest fuels complex (Stephens et al 2021). These fuel reduction treatments have primarily targeted dry pine and mixed conifer forest types. Treatment prescriptions often call for reducing the surface fuel load, raising the canopy base height, reducing the canopy fuel load and bulk density, and retaining large trees of fire-resistant species (Agee and Skinner 2005). This approach commonly results in homogenous stand structures comprised of evenly spaced residual trees and limited vertical heterogeneity. Though these alterations reduce expected fire behavior, the resulting horizontally and vertically homogeneous stands do not emulate the historical forest structure in dry fire-prone conifer forests, which were highly heterogeneous both horizontally and vertically and consisted of a matrix of isolated trees, patches or groups of trees, and non-treed openings (Harrod et al 1999, Abella and Denton 2009, Larson and Churchill 2012, Lyderson et al. 2013, Brown et al. 2015, Clyatt et al. 2016). Therefore, restoring dry forest ecosystems requires silvicultural prescriptions that enhance structural diversity in place of more traditional approaches that generate highly simplified stand structures.

Fuel reduction and forest restoration treatments that create high levels of horizontal and vertical heterogeneity recreate historical stand structures and produce stands that are highly resilient to a range of disturbance agents including fire, drought, and tree-damaging insects (Churchill et al. 2013, Franklin et al. 2007, Larson and Churchill 2012). As a result of this understanding, there is a strong push for forest managers to design treatments that will increase heterogeneity at multiple scales from the stand to the landscape (Churchill et al. 2013, Hessburg et al. 2015, Larson and Churchill 2012, North et al. 2009, Reynolds et al. 2013, Underhill et al. 2014, Stephens et al. 2021). Therefore, there is a need to develop a better mechanistic understanding of how vertical and horizontal heterogeneity influences potential fire behavior. Though numerous studies have shown that fuel reduction treatments can significantly reduce wildfire behavior and increase forest resilience to fire (e.g., Cram et al. 2006, Cram et al. 2015, Pollet and Omi 2002, Stafford et al. 2009, Stafford et al. 2012, Stevens et al. 2014), these studies rarely consider variations in fire behavior and effects due to fine-scale fuel heterogeneity. Similarly, several studies have utilized fire simulation modeling to show that fuel reduction treatments are effective in reducing potential fire behavior (e.g., Stephens and Moghaddas 2005, Roccaforte et al. 2008, Schmidt et al. 2008, Stephens et al. 2009, Valliant et al. 2009, Agee and Lolley 2006, Moghaddas et al. 2010, Reinhardt et al. 2010). However, the non-spatial, semi-empirical fire models used in these studies rely on stand level averages of the surface and canopy fuel complexes and are therefore unable to account for the influence of fine-scale heterogeneity in forest structure on fire behavior.

Recently, a growing body of research utilizing spatially explicit, physics-based fire modeling programs (e.g., FIRETEC, Linn et al. 2005; WFDS, Mell et al. 2007) has shown that fuel heterogeneity is important to fire behavior prediction at scales from the individual tree crown to the stand (Contreras et al. 2012, Pimont et al. 2009, Pimont et al. 2011, Linn et al. 2013, Parsons et al. 2017, Ziegler et al. 2017, Ritter et al. 2020, Ziegler et al. 2021). To support the development of forest restoration and fuel reduction treatments that achieve the simultaneous goals of restoring historical forest structure and reducing potential fire behavior, there is a clear need to better understand the implications of increased structural heterogeneity on wildfire behavior. Significant questions remain surrounding the interaction between horizontal and vertical heterogeneity at the stand and sub-stand scale. For example, the creation of discrete groups of uneven-sized trees can improve wildlife habitat and restores a key component of historical forest structure (Larson and Churchill 2012, Reynolds et al. 2013). However, groups of trees are generally assumed to be at risk of increased tree torching and fire induced mortality. Similarly, models of surface to crown fire transition are often based on the mean surface fire intensity and canopy base height without regard to within stand variability in canopy fuels. Not only is spatial variability in the vertical arrangement of crown fuel likely to influence fire behavior, but the horizontal arrangement or level of fuel aggregation may alter the ease with which a surface fire can transition into the canopy (Ritter et al. 2020).

To better understand the interactions between horizontal and vertical heterogeneity on potential fire behavior, I utilized a combination of three-dimensional fire behavior modeling and spatially explicit field measurements. Three-dimensional, physics-based fire models present a path forward to address these complex, multi-scale questions by allowing for detailed control over burning conditions and the fine-scale spatial distribution of fuel (Morvan et al. 2011, Hoffman et al. 2018, Yedinak et al. 2018). In chapter two, I present the results of a simulation study that focused on the role of horizontal pattern on heat transfer and ease of surface to crown fire transition. Given the functional importance of tree groups and the growing emphasis on their deliberate creation in restoration treatments, this work compares the ignition potential of isolated trees to trees located in groups of various sizes and inter-tree spacings. By assessing the relative differences in surface fire to crown heat transfer between different group sizes and horizontal structures, I provided an increased understanding of crown fire transition and how the position of a tree in a stand alters its relative torching risk. In chapter three, I seek to extend these findings to trees in groups with varying levels of vertical heterogeneity and horizontal fuel connectivity. In this simulation experiment, eight different groups were created to represent a large range of vertical and horizontal distributions of crown fuel by altering the mixture of tree sizes within the groups. I then simulated a spreading surface fire at five different intensities to understand how these tree mixtures influenced the level of vertical fire propagation. This work shows important interactions between the horizontal and vertical components of group structure such that the horizontal arrangement of tree crowns mediates the effect of mean crown base height on crown fire transition. Finally, in chapter four, I compare the outcomes of a range of forest treatment prescriptions on both spatial patterns of trees, levels of vertical heterogeneity, and potential fire behavior. By installing eleven 1-ha stem maps across these different treatments, I was able to precisely evaluate their horizontal and vertical structure and simulate fire through them in three-dimensions using the Wildland Urban Interface Fire Dynamics Simulator (Mell et al. 2007, 2009). These results showed that treatments were successful in moving stand structures towards the objectives of each treatment. However, more explicit targets were needed to create both large aggregations of trees and large non-treed openings. Overall, there were limited differences in simulated fire behavior among the treatments, suggesting that high levels of horizontal and vertical heterogeneity do not result in greater crown fire hazard than treatments more closely following the guidelines of Agee and Skinner (2005).

This work directly addresses the perceived tension between silvicultural treatments that modify stands to optimally reduce potential fire behavior (fuel hazard reduction) versus those that aim to emulate historical forest structures and create structurally complex stands (restoration). Together these chapters enhance our understanding of spatial aspects of fire behavior and ecosystem dynamics. The results from chapters 2-4 indicate that land managers can implement a variety of stand level silvicultural approaches that simultaneously achieve ecological and social objectives while reducing fire behavior. This work provides some guidance on ways to balance potential tradeoffs between heterogeneity and potential fire behavior while showing that forest treatments which create complex forest structures can be used to significantly reduce crown fire hazard.

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CHAPTER 2: FINE-SCALE FIRE PATTERNS MEDIATE FOREST STRUCTURE IN FREQUENT-FIRE ECOSYSTEMS

2.1 Introduction

In fire-prone, conifer forests of western North America, recurrent fires act as a stabilizing negative feedback mechanism, where prior burned areas influence fire spread and severity (Parks et al. 2015) and greater mortality rates of small trees maintain lower density stands dominated by large trees (Larson and Churchill 2012, Larson et al. 2013, Hagmann et al. 2013, Battaglia et al. 2018). Observations from frequent-fire forests with natural or restored fire regimes and dendrochronological reconstructions of historical stand structure prior to Euro-American settlement have shown strong agreement that this feedback process resulted in structurally variable forests comprised of scattered, large individual trees, variously sized groups of trees and non-treed openings (Sánchez Meador et al. 2011, Larson and Churchill 2012, Larson et al. 2013, Fry et al. 2014, Brown et al. 2015, Clyatt et al. 2016, Jeronimo et al. 2019). Furthermore, forests that support this pattern-process feedback are believed to be more resistant and resilient to wildfires and other forest disturbances (Larson and Churchill 2012, Reynolds et al. 2013, Fry et al. 2014, Hessburg et al. 2015).

Forest resilience is the capacity for a system to regain its structure, function, and feedbacks following a disturbance (Holling 1973, Hessburg et al. 2019). Forest resistance is often considered a core part of resilient systems (Ingrisch and Bahn 2018) and is defined as the difficulty or ease of changing the state, function, and pattern-process linkages of an ecosystem (Holling 1973). Here forest resistance is defined as the capacity of an individual tree, or group of trees to withstand crown ignition, canopy consumption, and mortality due to a wildfire.

Alterations to resistance and resilience in frequent-fire forests have occurred due to land management policies, including grazing and fire suppression across the western US throughout the 20th century which, in combination with increased temperatures and more frequent droughts, have impacted the characteristic structure and pattern-process feedbacks that historically drove ecosystem function in these forests (Hessburg et al. 2005, Collins et al. 2011, Brown et al. 2015). Consequently, these forests increasingly experience uncharacteristic wildfires, the loss of critical functional components of the biota (i.e., large fire-resistant trees) and ecosystem goods and services all of which interact to increase the risk of ecosystem collapse and transformation (Covington and Moore 1994, Keith et al. 2013, Seidl et al. 2016). To minimize the occurrence and negative impacts of uncharacteristic fires, managers are increasingly emphasizing the use of variable retention harvesting to restore both the complex forest structures and pattern-process linkages associated with more resilient historical forests (e.g. Underhill et al. 2014, Hessburg et al. 2016, Knapp et al. 2017, Addington et al. 2018). Although a number of recent research projects have provided quantitative data on the historical patterns that can be used to guide the design of forest restoration treatments (e.g. Sanchez Meador et al. 2011, Lydersen et al. 2013, Brown et al. 2015, Clyatt et al. 2016, Rodman et al. 2016, Wiggins et al. 2019), empirical evidence explicitly linking fine-scale forest pattern to self-regulation is limited and questions remain around the scale of structural variability that most affects forest resilience (Parks et al. 2015, Koontz et al. 2020).

Patterns of fire severity at a relatively broad scale (i.e., 10’s to 1000’s of ha) are an emergent property of local interactions between the forest structure and fire behavior (Harris and Taylor 2017, Koontz et al. 2020) which in turn arise from finer-scale, fire-fuel-atmospheric interactions. These fire-fuel-atmospheric interactions are believed to influence heat transfer processes directly and therefore the occurrence of individual tree and group level torching which are responsible for variations in fire severity at broader scales (Pimont et al. 2011, Hoffman et al. 2012, Linn et al. 2013, Ziegler et al. 2016, Parsons et al. 2017, Sieg et al. 2017). Individual tree and group level torching occurs when sufficient convective and radiative energy is transferred from the surface fire to heat the crown fuels to the ignition temperature (Weise et al. 2018). In practice, surface to crown fire transition is assessed based on comparisons between the surface fireline intensity and a critical value which depends only upon the average crown base height and the foliar moisture content of the crown fuels (i.e., Van Wagner 1977). However, this approach does not account for the local arrangement of crown fuels, which could influence convective and radiative heat transfer and therefore the potential for surface to crown fire transition (Pimont et al. 2006, Hoffman et al. 2012).

There are various mechanisms through which the local crown fuel arrangement could potentially influence heat transfer from the surface fire to individual tree crowns and ultimately crown ignition and consumption. For example, as the size of a tree group increases, the corresponding drag forces will result in a decrease in the wind velocity through the canopy of the group. As a result, for a given surface fireline intensity the likelihood for the surface fire to transition into the crowns may increase due to both a reduction in convective cooling within the canopy and by allowing the fire plume to travel more vertically through the canopy space thereby increasing the gas temperatures at a given height above the fireline. The separation distance between crowns within the group may also alter heat transfer and therefore play a significant role in determining thresholds for crown fire ignition and canopy consumption. As crown separation distance increases, localized reductions in crown fuel density and void spaces form within the canopy. These void spaces have the potential to influence convective heating and reduce the likelihood of ignition if they allow increased mixing of cooler ambient air into the fire plume and reduce the residence time of convective heating (Tachajapong et al. 2009). Although there is increasing evidence of significant interactions between fine-scale vegetation structure and wildfire behavior, several studies have suggested that these effects are conditional upon a host of fine- and broad-scale factors that directly or indirectly affect the surface fireline intensity and therefore influence the likelihood of crown fire ignition (Hoffman et al. 2012, Lydersen et al. 2014, Parsons 2017, Sieg et al. 2017).

To improve our understanding of the linkage between fine-scale forest pattern and self-regulation in frequent-fire forests of the western US I used a physics-based fire model, the Wildland-Urban Interface Fire Dynamics Simulator, to address two interrelated questions: 1) How does group size influence the surface fireline intensity required for tree torching (hereafter, torching threshold) and crown fuel consumption? 2) What effect does crown separation distance have on torching thresholds and crown fuel consumption? I will then assess the model predictions to identify critical physical mechanisms driving differences in fire behavior related to the local arrangement of canopy fuels. Finally, I will discuss the findings in terms of pattern-process feedbacks in forests with active fire regimes, implications for fire refugia following higher-severity fire events, and the development of silvicultural prescriptions that seek to both restore heterogeneous forest structures and reduce crown fire activity.

2.2 Methods

2.2.1 Overview of the Wildland Fire Model

Fire simulations were conducted using the physics-based Wildland-Urban Interface Fire Dynamics Simulator (WFDS-PB, Mell et al. 2009). WFDS-PB (version 9977) is an extension of the Fire Dynamics Simulator, developed at the National Institute of Standards and Technology, to predict fire spread and smoke transport within structures (McGrattan et al. 2013a). WFDS-PB is a physics-based model that simulates fire dynamics by explicitly representing the known and assumed processes and their interactions with each other and the environment (Hoffman et al. 2018). Physics-based models, such as WFDS-PB, play a particularly important role in advancing our understanding by allowing researchers to conduct virtual experiments that would otherwise be impossible, too costly, time-consuming, or risky and by inspiring new experiments, observational studies, and analyses to assess model-driven hypotheses (Linn et al. 2013, Hoffman et al. 2018). In WFDS-PB, computational fluid dynamics methods and the large eddy simulation approach are used to solve for conservation of momentum, total mass, and energy. Models for radiative and convective heat transfer, thermal degradation of vegetation, and gas-phase combustion are coupled with the conservation equations to predict the spatial and temporal evolution of various physical quantities associated with the evolution of the fire's flaming front such as gas temperature and velocity. Wildland vegetation is represented as a porous media consisting of thermally-thin, solid fuels described by their bulk quantities (e.g., bulk density, fuel moisture content, and surface area to volume ratio). The thermal degradation of solid fuel is modeled using a two-step process where the fuel must first be dehydrated before subsequently undergoing pyrolysis (Morvan and Dupuy 2004). Gas-phase combustion is simulated using a mixing-limited, infinitely-fast reaction model. For the simulations presented here, convective heat transfer was modeled based on either forced or free convection to an isothermal cylinder where the forced convection coefficient is calculated using the Hilpert correlation and the free convection coefficient is calculated based on the Morgan correlation (Incropera et al. 2007). The larger of these two calculated convection coefficients are then multiplied by the temperature difference between the solid fuel and surrounding gas to determine convective heat transfer at each simulation time step. Thermal radiation transport is solved using a non-scattering, grey gas assumption with solid fuel particles that are modeled as discrete, thermally thin, optically black vegetation elements.

A more detailed description of the model formulation is provided by Mell et al. (2007) and Mell et al. (2009). Verification and validation of the Fire Dynamics Simulator are presented in McGrattan et al. (2013b, 2013c). Further evaluation of the use of WFDS-PB for vegetative fuels can be found in Mell et al. (2007, 2009), Castle et al. (2013), Mueller et al. (2014), Overholt et al. (2014), Hoffman et al. (2016), Perez-Ramirez et al. (2017), and Sánchez-Monrory et al. (2019).

2.2.2 Simulation Domain and Experimental Set-Up

The model domain was 250m, 100m, and 100m in the x (windward), y, and z (vertical) directions, respectively, with varying spatial resolution depending on the location within the domain (Figure 2.1). In the center of the domain, a fine resolution subdomain (denoted by darker shading in Figure 2.1) was created with dimensions of 40m x 40m x 30m and a grid cell size of 25 cm x 25 cm x 25 cm. The resolution surrounding this subdomain is first increased to 50 cm x 50 cm x 50 cm and then to 1 m x 1 m x 1 m across the rest of the domain. At the upwind end of the domain, the ambient flow was introduced using a standard logarithmic wind profile with the mid-flame (z = 2 m) windspeed set to 2 m/s. The bottom of the domain was modeled as an inert boundary, the top and downwind boundaries were simulated with open boundary conditions, and domain sides were simulated as no flux, no slip surfaces.

To evaluate the role of group size and separation distance on crown ignition and fuel consumption, individual trees and three group sizes (3, 7, and 19 trees) were tested across five different crown separation distances and four surface fireline intensities resulting in a total of 88 simulations. All simulations were run in parallel on 16, 2.2 GHz Intel Xeon processors, and took an average CPU time of ~66 hours each to complete. In each simulation, individual trees or regularly spaced groups of trees were placed within the center of the high-resolution domain area (Figure 2.1). The five crown separation distances were 0, 0.75, 1.5, 3, and 6 meters between the outer edge of the crown base which corresponded to 3, 3.75, 4.5, 6, and 9 meters between tree boles. These separation distances were selected to encompass a range of separation distances across which trees might be defined as a group (Graham et al. 2006, Churchill et al. 2013). For the individual tree tests, replication was created by completing one simulation with the isolated tree in the center of the high-resolution subdomain ($x = 0$, $y = 0$) and then running replicate simulations where the isolated tree was placed at six random x, y locations within a 6 m radius of the subdomain center.

All trees were simulated as right, rectilinear cones, with a tree height of 14 m, a width at crown base of 3 m, and a crown base height of 7 m. Within each cone, 0.82 kg/m^3 of foliage and 0.06 kg/m^3 of fine branchwood (< 6 mm in diameter) was simulated with a surface area to volume ratio of 4000 m^{-1} and 2667 m^{-1}, respectively, resulting in a total crown mass of 15.35 kg per tree. These dimensions approximate the red pine (*Pinus resinosa*) trees in the Van Wagner (1968) crown fire experiment. A complete list of tree dimensions and crown fuel parameters are listed in Table 2.1.

Rather than simulating a free spreading surface fire, the surface fire was modeled as a spreading burner with prescribed dimensions and heat output. This assumption ensured consistent, steady-state surface fire behavior within and across each simulation. Using this method, a range of surface fireline intensities, 3000 kW/m, 3250 kW/m, 3500 kW/m, 3750 kW/m, were tested with the rate of spread fixed at 0.25 m/s, a fire depth of 6 m and a residence time of 24 seconds. The prescribed surface fireline intensities (FLI) result in heat release rates per unit area of 500 kW/m^2, 541.7 kW/m^2, 583.3 kW/m^2, and 625 kW/m^2, and theoretical total surface fuel consumptions of 0.68 kg/m^2, 0.73 kg/m^2, 0.79 kg/m^2, and 0.85 kg/m^2, respectively, based on a 17,700 J/kg heat of combustion for woody fuel. The surface fireline intensities were chosen to capture a range of outcomes from the total absence of crown ignition to complete ignition and canopy consumption, and incorporate the critical surface FLI (3134 kW/m) needed to ignite crowns as predicted by the Van Wagner (1977) equation for a stand with the same canopy base height and crown fuel moistures used in the simulation. The surface fire rate of spread, depth and residence time were selected as they closely match the descriptions of the Van Wagner (1968) crown fire experiments on which the tree-level properties and mid-flame wind speed were based.

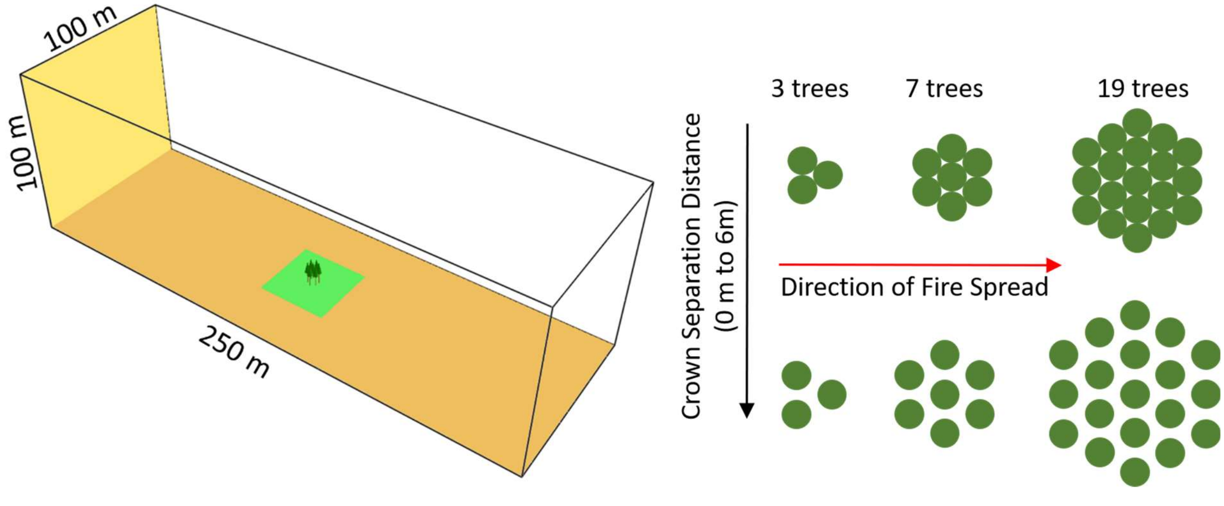

Figure 2.1. Example of the simulation domain and the regular tree arrangements used.

Table 2.1. Tree dimensions and crown fuel parameters used for each simulation.

Parameter	**Value**
Tree DBH	0.25 m
Tree Height	14 m
Tree CBH	7 m
Crown Width	3 m
Foliage Mass	14.3 kg
Foliage SAV	4000 m^{-1}
Foliage Bulk Density	0.82 kg/m^3
Fine Mass	1.05 kg
Fine SAV	2667 m^{-1}
Fine Bulk Density	0.06 kg/m^3
Vegetation Temperature	20 ^oC
Vegetation Moisture (%)	100
Vegetation Density	520 kg/m^3
Vegetation Char Fraction	0.25
Vegetation Heat of Combustion	17700 J/kg
Vegetation Drag Coefficient	0.25

2.2.3 Analysis

To evaluate the influence of the local canopy fuel pattern on tree torching the percent fuel consumption for each simulated tree was calculated on a dry mass basis where C is percent crown fuel consumption, M_i is initial dry mass, and M_e is the ending dry mass:

$$1)\quad C = \frac{M_i - M_e}{M_i} * 100$$

Ignition was considered to have occurred for any given tree when crown fuel consumption exceeded 5% as this value has been used as the lower detection limit in measurements of crown consumption in the field (Sieg et al. 2006, Fowler et al. 2010). To identify significant effects of group size and crown separation distance on the mean crown fuel consumption, analysis of variance and Tukey adjusted pairwise comparisons were conducted using the R software for statistical computing (R Core Team 2019). For the group size analysis, results from the isolated tree tests and the 3, 7, and 19 tree group tests were considered where crown separation distance was equal to zero and surface FLI was included as a fixed effect. Differences related to separation distance were identified by pooling the results from the 3, 7, and 19 tree group simulations and considering crown separation distance and surface FLI as fixed effects.

The effects of fine-scale fuel arrangement on radiative, convective, and total net heat transfer were assessed by comparing changes in the cumulative sum of each term through time. The analysis was restricted to the center tree (located at $x = 0$ m, $y = 0$ m) and to simulations with the lowest FLI considered of 3000 kW/m (no tree-ignition occurred at this FLI), as this allowed for consistent comparisons regardless of group size and without the confounding influence of heat transfer from adjacent torching trees. The radiative or convective flux was calculated throughout a tree crown at time t by the sum of divergence of the heat flux q_f (where the subscript f denotes either the convective or radiative heat flux):

2) $Q_f(t) = \frac{1}{N}\sum_{n=1}^{N}(\nabla \cdot \mathrm{q_f})_n\, V_n$

where the units of Q_f is kW, N is the total number of grid cells in the tree crown, V_n is the volume of grid cell n. The quantity Q_f is computed every time step, Δt, during the simulation. To assess the change in the heat exposure of a tree crown, I plot the running sum of Q_f. At time $t_M = M\Delta t$ this sum is:

3) $S_f(t_M) = \sum_{m=0}^{M} Q_f(t_m)$

Where M is the current total number of time steps. In WFDS, the divergence of the radiation flux, ($\nabla \cdot q_r$), for a given grid cell is computed as:

4) $< \nabla \cdot q_r > = k_b[4\pi I_b * (T_e) - U]$

Where <()> denotes the explicit box filter of WFDS-PB, U is the integrated radiation intensity, I_b is the black body radiation intensity and k_b is the radiation absorption coefficient which is a function of the surface area to volume ratio and packing ration of the vegetation (Perez-Ramirez et al. 2017). The divergence of the convective heat flux for a grid cell is computed as:

5) $< \nabla \cdot q_c > = \beta_e \sigma_e h_{c,e}(T_e - T_g)$

Where βe is the packing ratio, σ_e is the surface area to volume ratio of the vegetation, T_g is the gas phase temperature and $h_{c,e}$ is the Reynolds number dependent convective heat transfer coefficient (Porterie et al 2005, Perez-Ramirez et al. 2017).

2.3 Results

2.3.1 Group Size

The results indicated that isolated, individual trees require higher surface FLI to ignite than any given tree in a group with interlocking crowns (crown separation distance = 0 m) and that both FLI and the number of trees in the group had a significant effect on percent crown fuel consumed (Table 2.2 and Figure 2.2). Tukey adjusted pairwise comparisons show that trees in all group sizes had greater consumption than individual trees and that trees in groups of 7 and 19 had greater consumption than those in the smaller 3 tree groups (Figure 2.2b). A strong influence of FLI on tree ignition was detected with pairwise comparisons showing significant differences between each FLI level. At the lowest surface FLI I tested (3000 kW/m) none of the trees ignited in any simulation (Figure 2.3a), and as FLI is progressively increased more trees ignited (Figure 2.3). At 3250 kW/m the only trees that ignited were in the larger 7 and 19 tree groups (Figure 2.3b), at 3500 kW/m trees ignited sporadically in all group sizes (Figure 2.3c), but none of the isolated trees ignited. At the highest surface FLI I tested (3750 kW/m), all trees within groups ignited while the isolated, individual tree ignited in only 3 out of 7 cases (Table 2.2, Figure 2.3d).

Analysis of the total net heat transfer to the center tree for each group size revealed the significant differences that are driving the observed impacts on tree torching and crown consumption (Figure 2.4). Radiative net heat transfer was tightly linked to group size as there are more obstructed view paths to the interior of a group with increasing group size and, therefore, a continuous decrease in radiative pre-heating of the center tree was observed when group size increased from one to nineteen trees (Figure 2.4b). Convective net heat transfer (Figure 2.4a) was greatest for the center tree in the nineteen-tree group (max = 23.3 kJ/m^3) which was followed closely by the seven-tree group (max = 21.9 kJ/m^3). The isolated tree and the tree at x =

0 m, *y* = 0 m in the three-tree group (the downwind tree, Figure 1) received similar maximum convective heating (16.5 kJ/m^3 vs. 16.3 kJ/m^3). The combined effects of the two modes of net heat transfer (Figure 2.4c) resulted in the greatest total net heat transfer to the nineteen-tree group (27.6 kJ/m^3), followed by the seven-tree group (26.4 kJ/m^3), followed by the isolated tree (24.1 kJ/m^3), with the smallest net total heat transferred to the three-tree group (21.5 kJ/m^3).

Table 2.2. Mean percent crown fuel consumptions (PFC) on a dry mass basis for every simulation. Values for the isolated tree tests (group size = 1) represent the mean consumption across the seven replicated simulations. Sep is the separation distance between the base of adjacent tree crowns in meters.

Group Size	Sep	PFC @ 3000	PFC @ 3250	PFC @ 3500	PFC @ 3750
1	NA	0.0	0.1	0.3	26.9
3	0	0.0	0.0	26.7	96.1
3	0.75	0.0	0.1	24.5	64.1
3	1.5	0.0	0.1	0.1	49.7
3	3	0.0	0.2	0.1	18.3
3	6	0.0	0.0	4.2	32.1
7	0	0.0	23.4	96.2	98.0
7	0.75	0.0	0.2	14.7	82.6
7	1.5	0.0	0.1	10.5	55.0
7	3	0.0	0.0	13.4	41.5
7	6	0.0	0.0	0.5	44.8
19	0	0.0	15.8	84.7	98.7
19	0.75	0.0	6.4	28.4	52.2
19	1.5	0.0	4.9	7.1	38.8
19	3	0.0	0.5	13.3	50.0
19	6	0.1	2.9	21.6	51.0

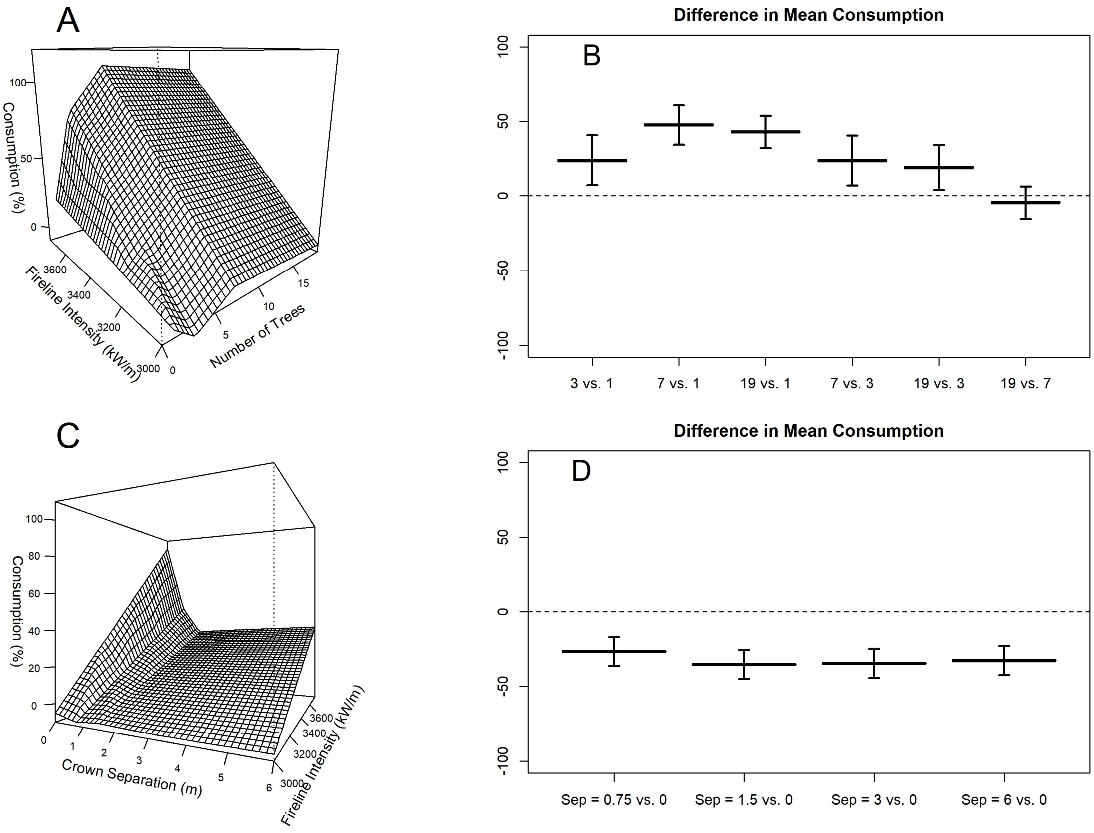

Figure 2.2. Effect of crown separation, group size and fireline intensity on the mean percent dry mass loss (fuel consumption). Perspective plots and pairwise differences in mean fuel consumption between each group size (A and B) and crown separation (C and D). Top row represents effects of group size when crowns are interlocking (Sep = 0 m) while the bottom row represent results when the cases with a single isolated tree are dropped from the analysis and comparisons are made across crown separation distance for the multi-tree groups. Comparisons where 95% Tukey confidence bars do not cross zero indicate a significant difference in mean consumption based on the Tukey test. Sep is the number of meters between adjacent tree crowns.

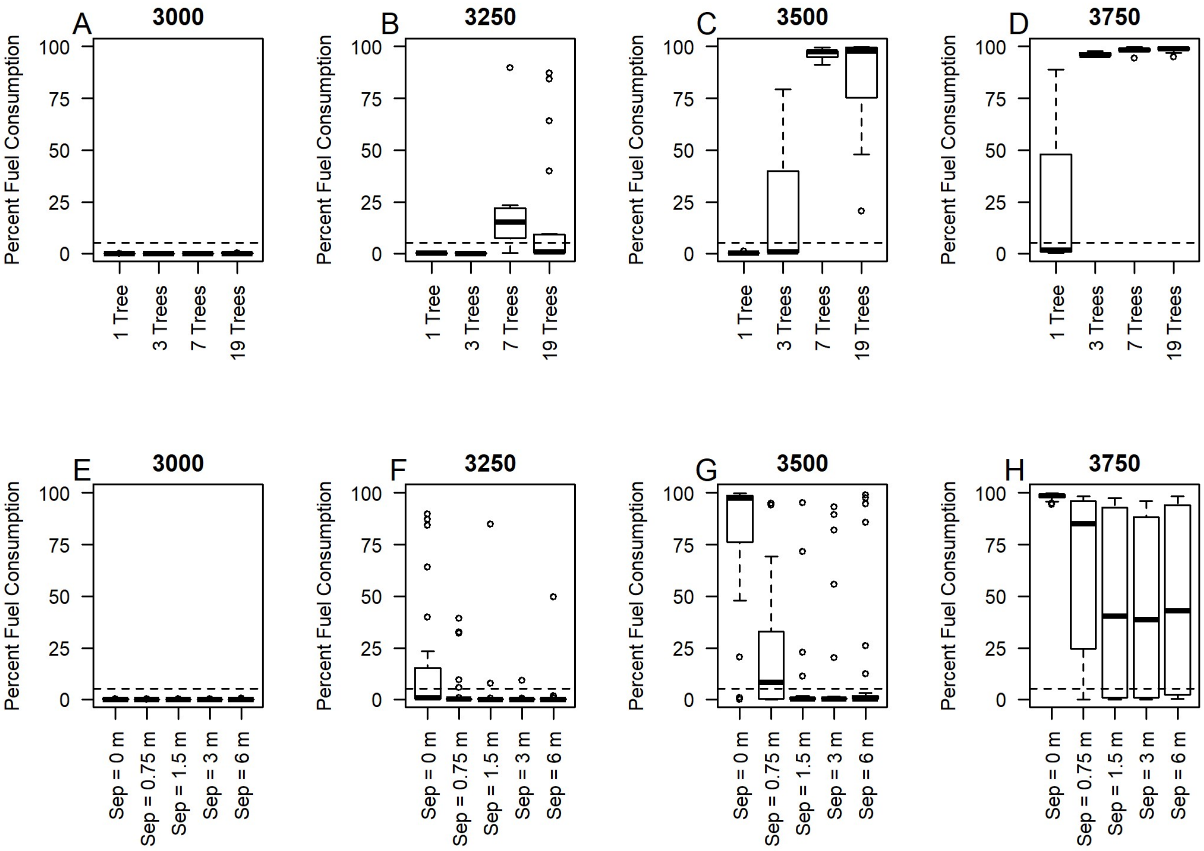

Figure 2.3. Box plots of percent crown fuel consumption for each group size when crowns are interlocking (A to D) and across each crown separation distance for the multi-tree group simulations (E to H). Each point represents the percent dry mass consumption of the crown fuel for one tree. Plots are split by intensity level to show the interactive effect of FLI. Sep is the number of meters between adjacent tree crowns. The dotted horizontal lines represent a 5% ignition criterion.

2.3.2 Separation Distance

The results indicated that increasing separation distance had a significant negative effect on crown ignition and fuel consumption. Based on Tukey adjusted pairwise comparisons all crown separation distances greater than 0 meters had reduced crown fuel consumption when compared to the interlocking crown cases (Figure 2.2d). There were no further significant pairwise differences when the crown separation was increased from 0.75 m to 6 m (Figure 2.2d). Once again, FLI had a clear influence on crown ignition, with no tree ignitions occurring at 3000 kW/m and numerous ignitions at 3750 kW/m (Figure 2.3). The influence of separation distance was apparent with greater mean consumption at 0 m crown separation for all intensities at which crown ignition occurred (3250 kW/m to 3750 kw/m). There was however a significant interaction between FLI and separation distance as the local spatial pattern has no effect when FLI is low (3000 kW/m) and no ignitions occurred. A large amount of variability was observed for the interlocking crown cases at 3500 kW/m and all crown separation cases at 3750 kW/m, suggesting that these intensities are at or near the torching threshold for interlocking trees and separated trees, respectively (Figure 3 g-h, Table 2.2).

Comparisons between the total net heat transfer to the center tree in the seven-tree group across all separation distances clearly illustrate the importance of convective heating as the primary mechanism driving these results (Figure 2.5 a-c). The center tree in the interlocked seven-tree group received the greatest total net heat transfer, while the four other separation distances all received similar, but substantially lower, amounts of total heating (Figure 2.5c). Interestingly, the center tree in the most widely spaced seven-tree group (6 m crown separation distance) received slightly greater total net heat transfer due to increased radiative pre-heating in comparison to the intermediate separation cases (crown separation = 0.75 m, 1.5 m, and 3 m; Figure 2.5c).

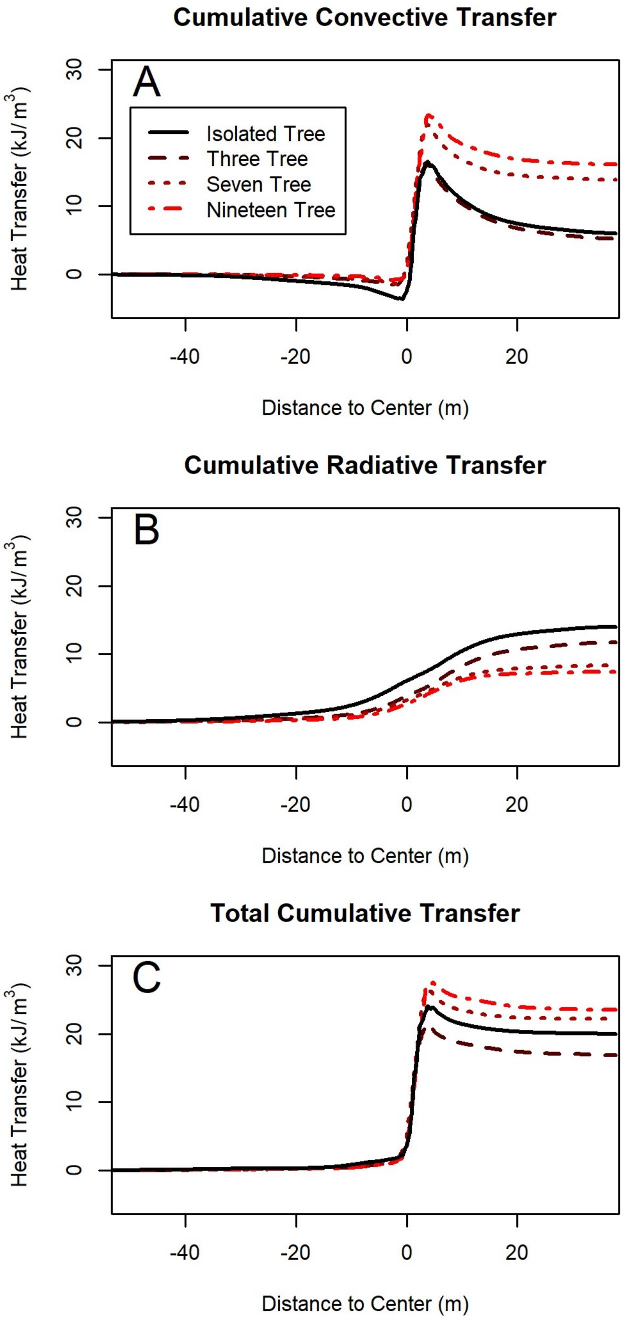

Figure 2.4. Cumulative radiative (A), convective (B), and total (C) heat transfer for the isolated tree case and the center tree in each of the interlocking crown cases. Cumulative heat transfer, S_f, is defined in equation 3 and represents the running sum of the heat transfer in the volume of the tree's crown. The Distance to Center is the distance in meters from the leading edge of the fireline to the center of the tree group (i.e., at location $x = 0$ and $y = 0$).

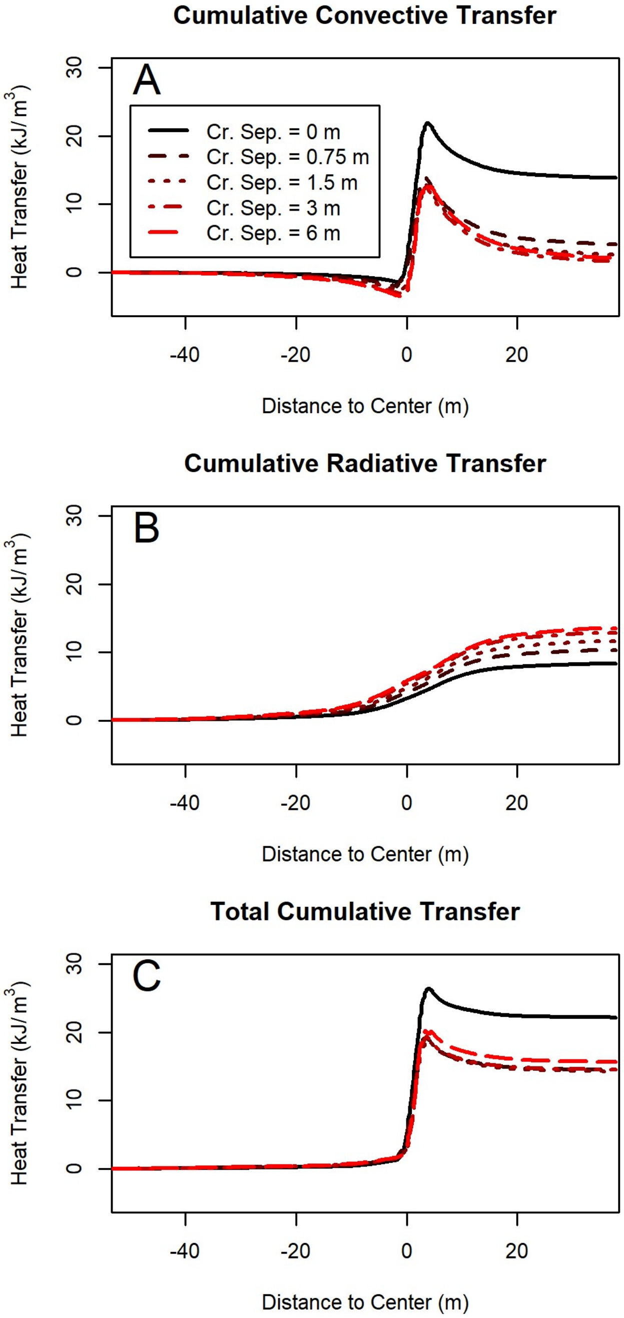

Figure 2.5. Cumulative radiative (A), convective (B), and total (C) heat transfer for the center tree in the seven-tree group cases at each crown separation distance. Cumulative heat transfer, S_f, is defined in equation 3 and represents the running sum of the heat transfer in the volume of the tree's crown. Cr. Sep. = The distance in meters between the base of adjacent tree crowns. The Distance to Center is the distance in meters from the front of the fireline to the group center (x = 0 and y = 0).

2.4 Discussion

Using a process-based approach, these results show how fine-scale forest structure and resistance to crown fire are tightly linked through the effects of the local arrangement of crown fuels on convective and radiative net heat transfer. These results suggest that isolated trees and, to a lesser extent, small groups of trees (3-tree groups) have higher torching thresholds and reduced consumption compared to trees within larger groups (7 or 19 trees), and therefore trees in larger groups would be expected to suffer increased rates of mortality for a given surface FLI. Similar to other studies, isolated trees and trees in small groups had increased radiative heating due to longer, obstruction-free view paths (Linn et al. 2005, Pimont et al. 2009). However, increased net radiative heating did not translate to increased ignition potential or crown fuel consumption due to the tree's exposure to the ambient wind field, which increased convective cooling and ultimately resulted in a reduction in net heat transfer (Figure 2.4a-c). Increased canopy drag within denser and large groups is the likely mechanism driving decreased convective cooling as it limits the ability of cooler ambient air to flow through the canopy of the group. This will also have the add on effect of increasing the plume temperature as mixing will be limited and therefore, convective heating (particularly in the lower crowns) will be enhanced. These results suggest that isolated trees and small groups may act as predictable fire refugia (*sensu* Meddens et al. 2018) whose increased resistance represents an important pattern-process feedback in frequent-fire forests. This could be one of several pattern-process feedbacks that explain why studies in forests with an active fire regime have generally found small mean group sizes (<5 trees) and that a large proportion of trees and basal area occurred as isolated trees and small groups rather than larger sized groups (e.g., Sanchez Meador et al. 2011, Brown et al. 2015, Tuten et al. 2015, Clyatt et al. 2016, Rodman et al. 2016, Wiggins et al. 2019).

Although the results provide evidence that isolated trees and trees located in small groups are more resistant to fire under a given fire environment (surface fuels, weather, topography), the increased resistance associated with these forest structures was conditional upon the surface fireline intensity. As surface FLI increased, binary fire behavior was observed where there was either no crown ignition or a large proportion of trees ignite and ultimately consume. This binary fire behavior has been reported for marginal burning conditions where threshold effects drive the behavior of the system and whether burning will or will not occur is stochastic (Wilson 1985, Weise et al. 2005). Therefore, when the surface FLI is near this threshold, fire behavior will be responsive to the local canopy fuel arrangement. However, in situations where the surface FLI is either far below or significantly greater than the threshold for crown ignition the local fuel arrangement will have no effect. This is evident, as simulations where the surface FLI was far below this threshold resulted in no tree ignitions regardless of group size or crown separation distance. Low intensity wildfire scenarios where there is no canopy ignition represent the lower bound of conditions under which one would expect differences in fire resistance to occur due to fine-scale forest structure. Conversely, in scenarios where the surface FLI is much greater than the ignition threshold, the increased convective cooling associated with isolated and trees in small groups is overwhelmed by the surface FLI and all trees can ignite and consume readily regardless of the local fuel pattern. Therefore, scenarios in which the surface FLI is much greater than the ignition threshold represent the upper bound of conditions under which differences in fire resistance occur due to the fine-scale forest structure. These results are similar to those from Hoffman et al. (2012) who found that the effect of changes in fine-scale fuel during the red-phase of a bark beetle outbreak on fire behavior was reduced under relatively low and high surface FLI. Other studies have found that the influence forest structure on fire behavior is dependent upon the burning conditions and in particular, the ambient wind velocity, fuel moisture, and surface fuel loads which all influence the surface FLI (Beaty and Taylor 2001, Pimont et al. 2011, Krawchuk et al. 2016, Parsons et al. 2017). Given the highly stochastic nature of surface fireline intensity during actual wildfire events due to complex topography and spatial and temporal variability in ambient wind flow and fuel moistures, individual trees and small groups are likely best thought of as having conditional resistance or as acting as predictable, but ephemeral, refugia (*sensu* Meddens et al. 2018).

Not only does enhanced resistance for isolated trees and small groups of trees have implications for reinforcing spatial patterns and self-regulation in frequent-fire ecosystems, the role of these structures as predictable refugia is important for post-fire trajectories following higher severity fire events. For tree species whose post-fire recovery strategies are reliant on seeds from mature, surviving trees (e.g., Ponderosa pine (*Pinus ponderosa*) or Douglas-fir (*Pseudotsuga menziesii*)), distance to live seed sources is essential for post-fire regeneration (Chambers et al. 2016, Owen et al. 2017) and therefore tree refugia have very large impacts on recovery trajectories (Meddens et al. 2018). Additionally, refugia size is an important factor as small refugia have a far greater impact on fire recovery when compared to a similar number of surviving trees that are aggregated in larger patches (Coop et al. 2019). Due to the finding that isolated trees and small groups of trees may be preferentially retained and the demonstrated importance of small tree refugia on forest recovery, management actions that promote these structures across the landscape are likely to create forests that are both more resistant to fire and better able to recover following higher severity events. These structural features likely contributed to crown fire resistance in historical forests and will be increasingly important in contemporary forest landscapes that are and will continue to experience more fires burning under extreme weather conditions due to climate change (Abatzoglou et al. 2019).

While trees in larger groups (7 and 19 tree groups) were more likely to ignite and consume, the results indicate that their fate was also conditional upon the surface fireline intensity. Similar to individual trees and smaller groups of trees, crown fuel consumption generally increased within the larger groups as the thermal energy transferred from the fire to the crowns increased. At moderate levels of surface fireline intensity, the crown fuel consumption primarily occurred within the interior portions of the group resulting in the fragmentation of the large group into either smaller sized groups or individual trees. Comparison of net heat transfer between the various trees within these groups suggests that differential heat transfer processes between the interior and edge trees are likely responsible for this phenomenon. Specifically, trees in exterior group positions were less likely to torch as they received greater convective cooling due to increased exposure to the ambient wind field while the sheltered interior trees were exposed to less ambient flow. Similar to the findings of Kane et al. (2014), these results suggest that fires occurring under low to moderate severity conditions are likely to favor the retention and creation of isolated trees and small groups of trees. However, under more extreme burning conditions, these results show that larger groups are likely to experience almost complete combustion and thus result in the creation or expansion of non-treed openings. Together these processes will contribute to self-regulation as fire events will increase the proportion of isolated trees and small groups (features which have increased resistance), therefore creating stand structures that will be more resistant to the next fire event. However, self-regulation is certainly not a guarantee as fires or portions of fires burning under extreme conditions can overwhelm resistance mechanisms and result in the transition to an alternative stable state (Lauvaux et al. 2016, Stevens-Rumann et al. 2018).

This assessment of forest resistance is based on the assumption that the relative risk of tree mortality can be evaluated using crown consumption alone. While several studies (e.g., Sieg et al. 2006, Hood et al. 2008) have found that crown fuel consumption is a strong predictor of tree mortality, the reality is far more complicated. The risk of any given tree suffering fire mortality depends on not only the consumption of plant material but also necrosis of tissues, cavitation and deformation of xylem and a host of post-fire plant stressors (Hood et al. 2018, O'Brien et al. 2018). Although this study did not investigate tree tissue damage, the results do indicate that trees in large groups are exposed to greater amounts of thermal energy which is an indicator of crown damage. This means that under moderate to low burning conditions where crown consumption was zero, trees in large groups are likely to experience greater levels of tissue damage due to increased convective heat transfer to their crowns. Furthermore, the interior trees of large groups are likely to experience greater competition relative to isolated trees or trees in small groups and previous research has shown that higher levels of pre-fire competition are associated with increased mortality risk at a given level of crown tissue damage (van Mantgem et al. 2018). Taken together the increased heating and greater level of competition in large groups suggests that the simulations likely underestimated the actual differences in resistance between isolated trees, small groups, and larger groups. Future research that evaluates the potential interactions between forest structure and heat transfer on tree injury, function and mortality are needed to develop better mechanistic models of fire effects (Hood et al. 2018, O'Brien et al. 2018, Yedinak et al. 2018).

To limit some of the complexity inherent in modeling spatially explicitly fire behavior, several simplifying assumptions were made. A steady-state spreading line-burner was used to represent the surface fire rather than including heterogeneous surface fuels in the model and simulating dynamic surface fire spread. While simulating a free-spreading surface fire through spatially heterogeneous fuels is possible in WFDS-PB, this simplification allowed us to assess the effect of group size and tree separation distance under consistent heat exposure conditions and to replicate the surface fires reported in Van Wagner (1968). The ability to isolate the effects of specific variables or processes on ignition and consumption represents a significant benefit of using a physical model like WFDS-PB as it would be physically impossible to separate variables like surface and canopy fuels in the real world (Hoffman et al. 2018). Although surface fire intensity, spread rate, and depth were held consistent throughout a simulation, it’s important to note that the fire plume, which is the source of a tree's heat flux exposure, was not constrained, and evolved according to the interactions among the buoyant flow, the tree crown(s) and ambient wind. If a freely evolving surface fire has been simulated through heterogeneous fuels, one might expect a local increase or decrease in surface fireline intensity as the fire burns across different fuel types. Since crown ignition is a local effect driven by the surface FLI, which is captured in the simulations, the reported relative effect of group size and crown separation distance on the surface FLI required for torching would remain unchanged regardless of the particular mixture of surface fuels. Though it would be expected that the observed trends between group size, tree spacing, and ignition would be consistent across a range of conditions, the high levels of surface fuel variability that exist both within and across ecosystems suggest future research that investigates a wide gradient in fuel types and ecosystems. As an additional simplification, the role of horizontal pattern on crown fire transition was evaluated without consideration for the interacting role of vertical complexity, or so-called ‘ladder fuels’, on this process. Though the vertical distribution of fuels certainly plays a role in crown fire behavior, simple group structures where used as they make comparisons with previous crown fire initiation models possible, are representative of the types of groups created when homogeneous stands are treated using restoration principles, and because the concept of ‘ladder fuels’ is poorly defined and quantified across the literature. The influence of vertical complexity and heterogeneous surface fuels on crown fire behavior across a range of environmental conditions represent future research needs.

Although the primary goal in this study was not to perform a model evaluation, the simulated trees, ambient wind velocity, and fire rate of spread were based on those reported in Van Wagner (1968, 1977) which allowed us to provide some level of model assessment. Overall, it was found that the critical surface fireline intensity associated with surface to crown fire transition was approximately 4 to 12% greater for WFDS-PB to ignite trees in the largest group relative to those predicted by VW77 for trees of identical dimensions located within a closed canopy plantation (3250 to 3500 kW/m for the 19-tree group with inter-locking crowns in WFDS-PB versus 3134 kW/m based on VW77). I report a range rather than a single critical torching threshold as it is unclear from Van Wagner (1968, 1977) what proportion of trees ignited or what level of crown consumption qualified as surface to crown fire transition. In the 19-tree group with inter-locking crowns, some sporadic tree ignitions occurred at 3250 kW/m (6 of 19 trees ignited) while all trees ignited and group level crown consumption was 84.7% at 3500 kW/m. Though the predictions for large interlocking groups were similar to VW77, the fact that torching thresholds were dependent on the local fuel arrangement also suggests that non-spatial crown fire transition models such as VW77 are not suitable for forests with complex spatial structures that share little resemblance to the dense, uniform plantations in which VW77 was developed. Although comparisons such as the present one help establish both the acceptable uses and limitations of WFDS-PB, it is also important to recognize the need for continued verification, validation and uncertainty quantification efforts (Hoffman et al. 2018).

2.4.1 Implications for Forest Management

The influence of the local arrangement of crown fuels on heat transfer, torching thresholds, and crown consumption have several implications for the design of fuel hazard reduction and restoration treatments. This analysis suggests that mechanical thinning operations that favor the creation of small groups and isolated individuals will result in greater crown fire resistance than treatments that favor the creation of large continuous groups. Furthermore, the results indicate that crown separation distances as small as 0.75 meters can increase the torching threshold and reduce crown consumption. This suggests that by relaxing the inter-tree spacing guidelines such that trees within a group do not need to have an interlocking crown, managers can significantly increase crown fire resistance while potentially not changing the overall ecological function of the group.

These results also highlight two important ways in which fire burning under low to moderate conditions can be used by managers to support the creation and maintenance of forests that resemble historical conditions. First, fires burning under these conditions can reinforce and maintain historical spatial patterns by favoring the survival of individuals and small clumps. Second, the results suggest that fire burning under these conditions can convert larger tree groups to isolated individuals and small groups that dominate historic forest structure. The role of prescribed fires and wildfires burning under moderate conditions in reducing fuel loading is well understood, and this work lends further support that they can also restore the structures and complex spatial patterns that existed in these forests historically (Holden et al. 2007, Battaglia et al. 2008, Larson et al. 2013, Lyderson 2013, Kane et al. 2019, Brown et al. 2019, Pawlikowski et al. 2019, Walker et al. 2019). Forest restoration through the use of fire is an important management tool given the reality that mechanical treatments alone cannot achieve forest restoration goals across the vast areas in need of treatment (North et al. 2012, 2015, Schoennagel et al. 2017). Although these results indicate several ways in which managers can utilize low to moderate severity fire to maintain and create forest structures and pattern-process relationships that mimic historical conditions, more extreme burning conditions, which are expected to increase under a changing climate (Abatzoglou et al. 2019), may significantly reduce the likelihood that isolated trees and small tree groups survive future fires and can act as refugia.

2.5 Conclusion

Plant tissue damage and mortality are the direct result of complex, three-dimensional heat transfer processes the quantification of which represents an important frontier in the understanding and prediction of fire effects on plant and ecosystems (O'Brien et al. 2018). Spatially explicit, physical models such as the one used here are powerful tools that will play an integral role in progress on this frontier (Hoffman et al. 2018, Yedinak et al. 2018). Through a detailed analysis of the interactions between spatial pattern and heat transfer, this work shows fine-scale pattern-process linkages whereby the local arrangement canopy fuel surrounding a tree alters its risk of torching and consumption due to changes to net convective and radiative heating. Evaluating how these fine-scale fuel patterns impact torching thresholds contributes to a mechanistic understanding of spatial pattern development in historical forests and show how silvicultural thinning treatments that seek to restore these historical forest structures can increase stand-level resistance to crown fire. Particularly, the results suggest that treatments that increase the stand-level proportion of isolated trees and small tree groups will have the greatest benefits for forest resistance to crown fire as the results indicate that tree spatial patterns at very-fine scales contribute to self-regulation in fire-prone, forested ecosystems.

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CHAPTER 3: VERTICAL AND HORIZONTAL CROWN FUEL CONTINUITY INFLUENCES GROUP-SCALE IGNITION AND FUEL CONSUMPTION

3.1 Introduction

Sustained concern over the increased occurrence of large high severity fires across the forested ecosystems of the western US has prompted calls for action in the form of fuel hazard reduction and forest restoration treatments, increased number and scale of prescribed and managed wildland fires, and the need to adapt to the inevitability of increased wildfire activity considering climate change (North et al. 2012, North et al. 2015, Stephens et al. 2016, Schoennagel et al 2017). At the core of all these challenges is the physical process of fire propagation through wildland vegetation. Though our understand of these processes has grown extensively over the past century of wildland fire science, there are still many questions surrounding fire spread through the inherently heterogenous and discontinuous fuel complexes that characterize natural ecosystems. In the context of both the social and ecological impacts of wildland fire, understanding crown fire transition and propagation is of particular importance as these behaviors are associated with large increases in fire rate of spread, fire intensity, tree mortality, ecological impacts, difficulty of suppression, and risks to human lives and infrastructure.

As such, the physical processes involved with the transition of fire from the surface into tree canopies has received a large amount of attention. This research has led to the development of a host of fire models to predict crown fire transition to aid fire management decision-making, suppression efforts, and fuel treatment design (e.g. Van Wagner 1977, Xanthopoulos 1991, Alexander 1998, Cruz et al. 2006). These crown fire transition models make predictions based on a limited set of inputs including the surface fire intensity and the distance from the surface to canopy fuels. Though these modeling approaches have demonstrated their utility in fire operations, fuel treatment design and evaluation, and wildfire risk assessment, they do not account for fine-scale fuel heterogeneity which may influence crown fire transition and spread (Loudermilk et al. 2012, Ziegler et al. 2017, Parsons et al. 2017, Ritter et al. 2020). Enhanced understanding of interactions between fire behavior and fine-scale fuel heterogeneity is increasingly relevant as there is a growing emphasis on forest treatments that deliberately enhance within stand structural heterogeneity for combined ecological restoration and fire hazard reduction goals (Stephens et al. 2021).

Such forest management approaches center around quantifying and creating the structural features that comprise a heterogenous forest canopy, specifically, individual trees, groups of trees and non-treed openings (Larson and Churchill 2012). Attention to these features, particularly the tree groups, forms the basis of forest treatments to restore historical structure and function (e.g. Churchill et al. 2013). However, from a fire behavior standpoint, tree groups represent local aggregations of fuel and have the potential to modify potential fire behavior (crown ignition and consumption) through several factors. For example, theoretical work has shown that trees within groups ignite more easily than isolated, individual trees (Ritter et al. 2020) and that the contagion effect due to crown-to-crown heat transfer can cause density dependent crown damage (Ziegler et al. 2021) and horizontal crown fire propagation (Kim et al. 2016, Atchley et al. 2021). In addition to differences between tree groups and isolated individuals, the influence of the horizonal and vertical distribution of fuels within the group is needed to inform forest treatments that create highly heterogenous structures and understand how fire in historical forests may have acted to shape forest structure and stand dynamics.

In terms of within group vertical fuel distribution the importance of distance from the forest floor to the lowest canopy fuel (canopy base height or fuel stratum gap) is clear, and, therefore, is the primary input in many crown fire transition models (e.g. Van Wagner 1977, Cruz et al. 2006). However, if one is concerned with the consumption of overstory trees, as is the case in many fuel hazard reduction and forest restoration treatments, it is also necessary to consider the continuity of fuels along the entire vertical canopy space (Menning and Stephens 2007, Marino et al. 2018). For example, a group containing small understory trees whose crowns are vertically separated from the crowns of the overstory trees may not pose the same risk of vertical fire propagation as a group whose understory trees create vertical fuel continuity into the overstory. In addition to vertical fuel continuity, the horizontal continuity of crown fuels is highly influential on both the vertical propagation of fire and the rate of fuel consumption. Closer tree spacing (and/or higher fuel bulk density) allows for easier ignition (Tachajapong et al. 2009, Ritter et al. 2020) and energy feedbacks among adjacent burning crowns can enhance the rate of fuel consumption (Padhi et al. 2017, Shannon et al. 2020) and crown damage (Ziegler et al. 2021). Tree spacing, or horizontal continuity, is only characterized in traditional wildfire modeling through its influence on canopy bulk density which is used as an input in many crown fire propagation models (e.g. Van Wagner 1993, Cruz et al. 2005), but is not considered in crown fire initiation despite its potential importance (Ritter et al. 2020). Crown fire initiation is also likely influenced by the interaction between the vertical arrangement and horizontal spacing of trees within the group. For example, small and medium sized trees may be clustered together but are unable to act as a vertical fire ladder as they are horizontally separated from larger canopy trees. A more complete picture of how vertical and horizontal continuity work together to influence potential fire behavior will aid forest and fire management as treatment objectives often include the dual goals of fire hazard reduction and structural complexity enhancement.

This work sought to better understand how the interaction between the height to crown fuel, vertical fuel continuity, and horizontal fuel continuity influences the vertical propagation of fire and the consumption of overstory trees at the scale of individual tree groups. I hypothesized that height to crown fuel would have a pronounced effect on vertical fire propagation, but that the relative importance of the variables would change at different levels of surface fireline intensity. To address these questions, a physical fire model was used to simulate a free spreading surface fire with a range of fireline intensities beneath discrete tree groups. Within these groups the mixture of tree sizes was varied to represent a wide range of minimum height to crown fuel and combinations of vertical and horizontal fuel continuity (Figure 3.1). This work has direct implications to our understanding of crown fire transition and behavior, can directly inform forest treatment design and longevity, and develops hypotheses on the dynamics of crown damage and patterns of tree mortality under natural wildfire regimes.

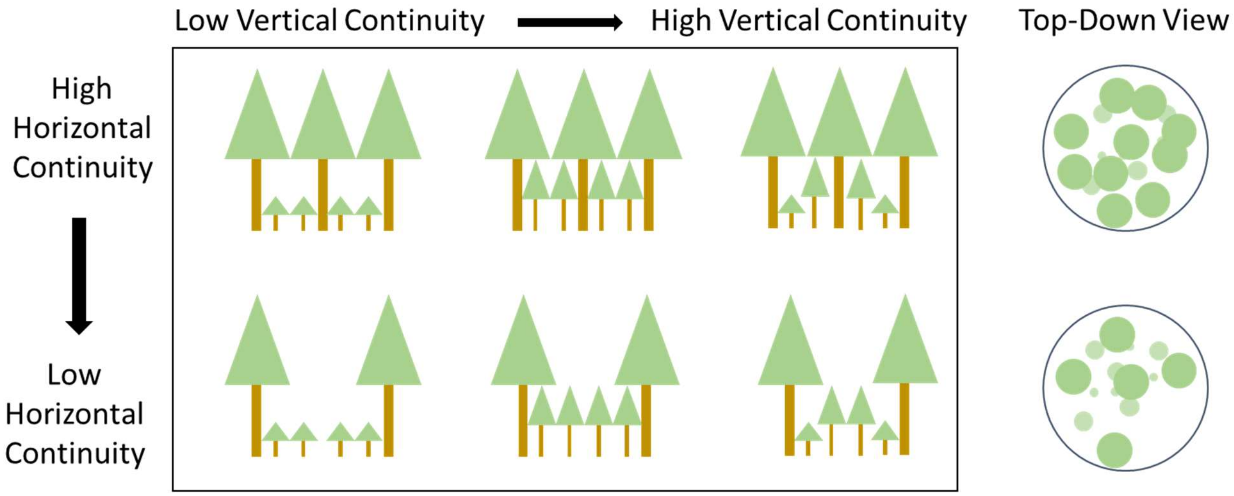

Figure 3.1. Conceptual diagram visualizing different aspects of vertical and horizontal heterogeneity within tree groups.

3.2 Methods

3.2.1 Fire Model

Fire behavior simulations were performed using the Wildland Urban Interface Fire Dynamics Simulator version 9977 (WFDS; Mell et al. 2009). WFDS is a physics-based model that simulates fire behavior through a three-dimensional domain. By linking a large eddy computational fluid dynamics model to sub-models for radiative and convective heat transfer and vegetation ignition and combustion, WFDS simulates three-dimensional fire behavior and captures the complex interactions between heterogenous fuel structures, wind flow, and fire behavior. Within the model domain, vegetative fuels are represented based on their bulk properties (e.g., bulk density, fuel moisture content, and surface area to volume ratio) and are modeled as a thermally thin, porous media. Fuel degradation is modeled as a two-step process described by Morvan and Dupoy (2004) wherein fuel must be dehydrated prior to undergoing pyrolysis. A more detail description of WFDS can be found in Mell et al. (2007) and Mell et al. (2009) and discussion of model formulation, verification, and validation of FDS are provided in McGrattan et al. (2013a-c). WFDS has been evaluated for combustion and fire spread through vegetative fuels in Mell et al. (2007, 2009), Castle et al. (2013), Mueller et al. (2014), Overholt et al. (2014), Hoffman et al. (2016), Perez-Ramirez et al. (2017), Sánchez-Monrory et al. (2019), and Ritter et al. (2020).

3.2.2 Fire Simulations and Domain

In WFDS, simulations were conducted using 8 tree mixtures (i.e., varied vertical and horizontal arrangements) and 5 fuel loads for a total of 40 fire simulations. Simulations were run in parallel on 21, 2.2 GHz Intel Xeon processors with a simulation times ranging from 265 to

328 CPU hours. The domain was 750 m in length, 240 m wide, and 100 m tall (Figure 3.2). The boundary conditions for the lateral edges were simulated as periodic, the top boundary was simulated as a no-flux, no-slip boundary, the leeward boundary was open, and the windward boundary was set to a prescribed inflow velocity. Inflow was set to follow a standard logarithmic vertical wind profile based on a steady, 4 m/s open (20 m) windspeed. Domain resolution varied from 1 m x 1 m x 1 m to 0.5 m x 0.5 m x 0.5 m in the x, y, and z dimensions. The finer grid resolution was only used in the portion of the domain containing the test groups (Figure 3.2). This allowed for increased simulation speed while having a well resolved area surrounding the primary interests. This high-resolution area was placed from 370 m to 620 m downwind from the inflow boundary, extended across the entire y direction and was 30 m meters in height (Figure 3.2). The surface fire was ignited at 330 m downwind from the inlet as a continuous line across the y direction. This allowed the surface fire to achieve steady-state behavior prior to entering the higher-resolution area of interest.

To generate a wind field and fire behavior representative of real interior forest conditions, the domain was populated with randomly located trees at a density of 250 trees/ha and a mix of the small, medium, and large trees whose properties and dimensions are described below (Table 3.1). The density of trees and their size distribution was selected based on observations of forest restoration treatments in the Black Hills, South Dakota, USA (described in Chapter 4). This resulted in 75 small trees, 100 medium trees and 100 large trees per hectare and a spatially random pattern. Within this random forest, 7 openings were created in which the test groups were placed. These openings had a radius of 20 m and were located at 420 m downwind at y = 80 and 160, 500 m downwind at y = 40, 120, 200, and at 580 m downwind at y = 80 and 160.

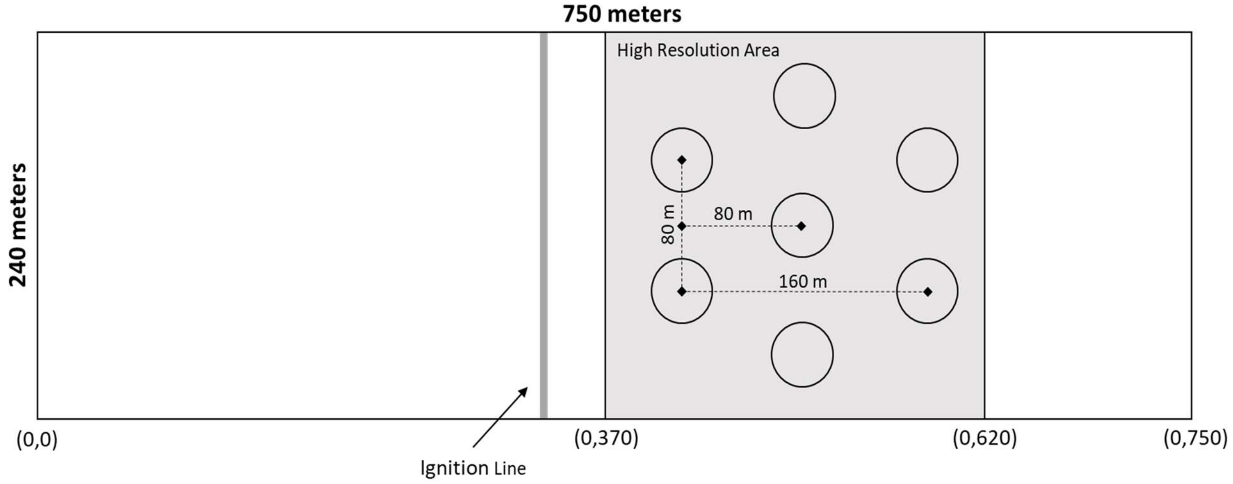

Figure 3.2. Example of the simulation domain. Group mixtures were placed at the center of each circle in the high resolution area. All surrounding areas were populated with randomly located trees. Wind flow and fire spread were from left to right. Coordinates are given in meters.

3.2.3 Tree Dimensions and Parameters

Tree crowns were simulated as right, rectilinear cones within which foliage was homogenously distributed with a bulk density of 0.7 kg/m^3. This bulk density was selected as it resulted in crown fuel loads that matched well with values calculated using allometries derived for Black Hills ponderosa pine by Keyser and Smith (2010). Foliage surface area to volume ratio was set to 5808 m^{-1} (Brown 1970).

Three tree sizes were selected for the sake of simplicity and comparability between groups and simulations. Diameters at breast height (DBH) of 40, 25, and 10 cm were chosen to represent small, medium, and large trees. The tree height, crown base height, and crown width for each tree size were then calculated based on the simple equations for Black Hills ponderosa pine developed in Chapter 4. This resulted in tree heights of 19, 12.5, and 6 m, crown base heights of 10, 6.5, and 3 m and crown widths of 5, 3.5, and 2 m for the large, medium, and small trees respectively (Table 3.1).

Table 3.1. Dimensions of the three tree sizes used in the simulations. DBH is diameter at breast height, HT is the tree height, CBH is crown base height, and CW is crown width.

Size	**DBH (cm)**	**HT (m)**	**CBH (m)**	**CW (m)**
Large	40	19	10	5
Medium	25	12.5	6.5	3.5
Small	10	6	3	2

3.2.4 Tree Mixtures

Eight different tree groups were created using a range of tree size mixtures to capture a wide combination of group scale horizontal and vertical continuity (Figure 3.1; Table 3.2). Each simulation contained 7 groups with the same tree mixture which served as replicates and allowed for some variability in the horizontal arrangement of trees. Within these groups tree locations were randomly assigned, but crowns were not allowed to overlap by more than 25% of their width. This resulted in groups with a small amount of horizontal separation between some crowns but overall tight tree spacing.

Table 3.2. Description of group mixtures including number of trees of each size and the fuel stratum gap (or distance from the surface to the lowest canopy fuel).

Mixture	**Number of Trees**			**Fuel Stratum Gap (m)**
	Large	**Medium**	**Small**	
L10	10	0	0	10
L4_M3_S3	4	3	3	3
L5_M5	5	5	0	6.5
L6_S4	6	0	4	3
L10_M3_S3	10	3	3	3
L10_M10_S10	10	10	10	3
L10_M10	10	10	10	6.5
L10_S10	10	0	10	3

3.2.5 Surface Fuels

Surface fuels were simulated as homogenous across the entire simulation domain using the WFDS boundary model and were parameterized as long-needle conifer litter based on Brown (1970, 1981). The surface area to volume ratio was fixed at 5760 m^{-1} and the bulk density of the surface fuel layer was 13.1 kg/m^3. To achieve a range of surface fireline intensities simulations were run with surface fuel loads of 0.8, 0.9, 1, 1.2 and 1.4 kg/m^2. In all cases bulk density was held constant while the fuel load and depth were increased proportionally giving fuel heights of 6.1, 6.8, 7.6, 9.2, and 10.6 cm.

The intention in varying the surface fuel load was to expose the groups to a range of surface fireline intensities (FLI). This was successful and FLI increased non-linearly with progressively greater surface fuel load (Figure 3.3). For surface fuel loads of 0.8, 0.9, 1, 1.2 and 1.4 kg/m^2 the resultant mean FLI were 967, 1,415, 1,930, 3,495, and 6367 kW/m, respectively. These intensities correspond to flame lengths of 1.8, 2.2, 2.5, 3.3, and 4.4 meters, respectively, based on the Bryam (1559) flame length equation. The observed non-linear increase in FLI was the result of the greater amounts of surface fuel consumption and progressively faster rates of spread (Figure 3.3). Overall, the variability in FLI within each fuel load category was fairly low but it did slightly increase with FLI. This variance highlights the dynamic nature of WFDS as variations in the overstory structure, fire-atmosphere interactions, and turbulence result in slight differences in surface fire behavior across simulations. Despite these dynamics, the overall variance in FLI was low and each surface fuel load resulted in reasonably narrow range of FLI and rate of spread.

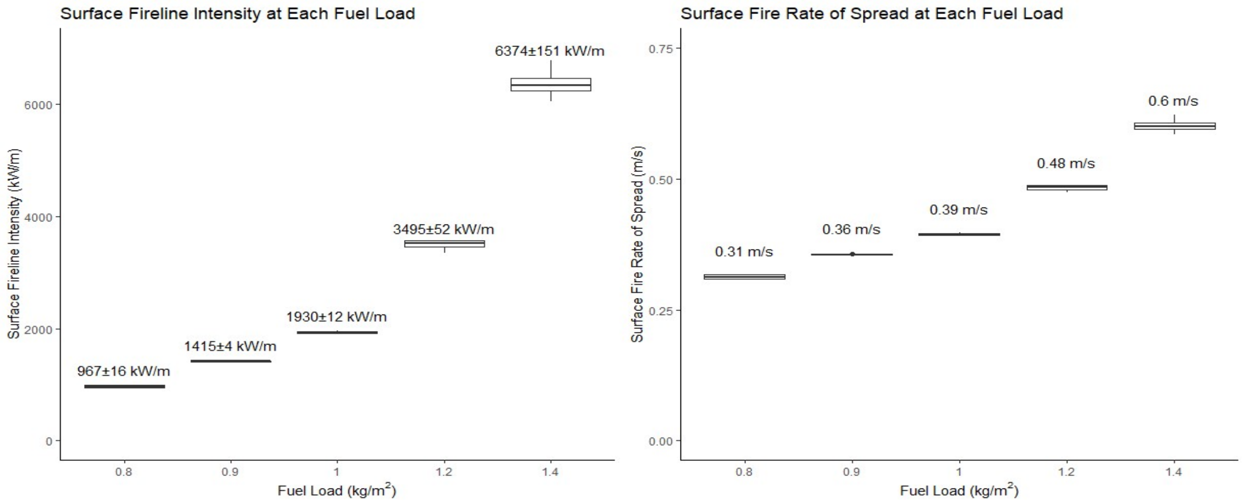

Figure 3.3. Mean surface fireline intensities (± standard error) and rates of spread associated with each surface fuel load. Values were calculated based on the mean behavior through the high resolution portion of the domain.

3.2.6 Data Analysis

Group-scale canopy bulk density was calculated to quantify the density of canopy fuels within each fuel layer. In this case the total fuel mass in a given 1-m vertical segment was divided by the group area to give a bulk density in kg/m^3. Group area was calculated as a circle whose diameter was defined based on the maximum edge to edge crown distance in the group.

This method essentially allows for normalization of the values from groups with different diameters and, thus, enables comparison of the relative differences in local fuel density among the groups. Finally, canopy bulk density was calculated for the understory, midstory and overstory layers by taking the mean bulk density from 3 to 6 meters, 6 to 10 meters, and 10 to 19 meters, respectively.

Surface fireline intensity and fire rate of spread were both calculated as their mean values within the high-resolution area of the domain (Figure 3.3). Surface FLI was calculated based on the rate of fuel consumption and a 17,770 kJ/kg heat of combustion for woody fuel. Though there were some slight variations in the surface fire behavior within simulations due to variability in the wind field, the overall behavior was relatively homogenous and a straight fireline was maintained from domain edge to edge.

The level of crown fire transition was quantified based on the mean crown consumption of large trees for each tree group (7 groups per simulation). The effect of group composition on large tree consumption was evaluated by calculating Tukey's Honest Significant difference among mixtures at each fuel load. A small effect of group location was identified and was therefore included as a random effect in the calculation of Tukey's Honest Significant difference. In addition, generalized linear models using a quasibinomial log link were calculated at each surface fuel load to characterize which aspects of group structure were most influential on the amount of large tree crown fuel consumption. Predictor variables were normalized as z-scores to produce comparable beta coefficients in the final models. The full initial model included fuel stratum gap, understory bulk density, midstory bulk density, and overstory bulk density as predictor variables. Models were selected using backwards selection while maintaining group location as a random effect.

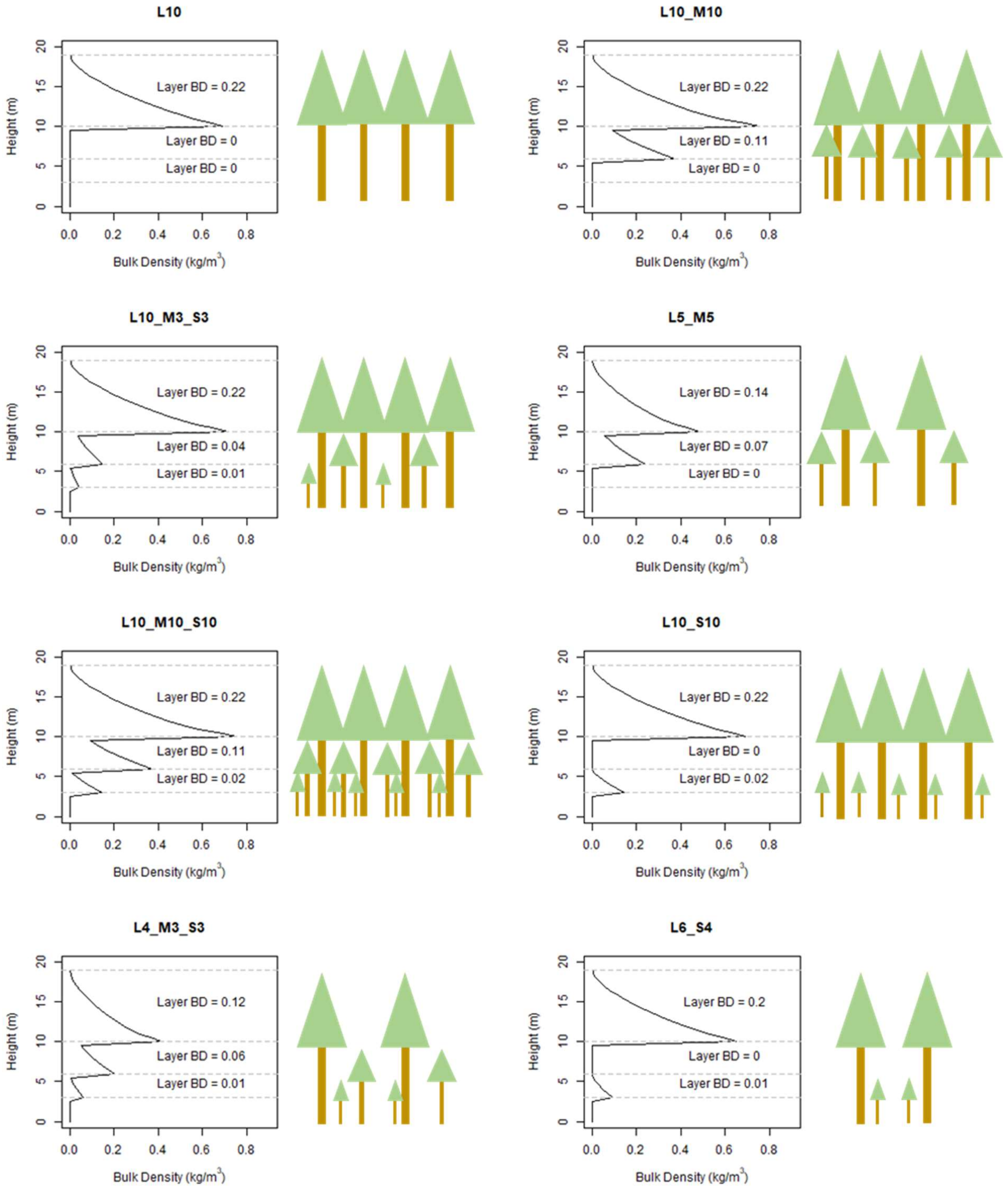

Figure 3.4. Vertical crown fuel profiles for all group mixtures at 0.5 meter vertical height intervals. Layer BD is the mean bulk density within 3 crown layers split based on the crown base height of the small, medium, and large trees (3, 6.5, and 10 meters). Images are intended to generally represent the horizontal and vertical distribution of trees to enhance clarity but are not exact replications of the simulated arrangements.

3.3 Results and Discussion

3.3.1 Horizontal and Vertical Continuity

Crown fuel bulk density profiles were used to visualize and compare the horizontal and vertical continuity of fuels across the different group mixtures (Figure 3.4). Greater bulk density within a particular layer indicates more horizontal connectivity in that canopy layer while the quantity of fuel across multiple layers reflects the level of vertical continuity. For example, the groups containing 10 large trees (L10, L10_M3_S4, L10_M10_S10, L10_M10, and L10_S10) all have similar levels of horizontal connectivity in the upper canopy, but differ in their vertical continuity with L10 having a large fuel gap from the surface to the overstory layer, L10_M3_S4 and L10_M10_S10 having vertically continuous fuels, L10_S10 having fuel near the surface but a discontinuity between the low canopy and the upper canopy, and, finally, L10_M10 having a gap between the surface and midstory. The L4_M3_S3 mixture also resulted in vertically continuous fuel but had lower horizontal continuity in the overstory layer compared to L10_M3_S4. L5_M5 resulted in similar horizontal continuity in the overstory as L10_M3_S4 but has a large gap from the surface to the lowest crown fuel. L6_S4 resulted in greater overstory continuity than L5_M5, as the large trees were closer to one another on average but had a discontinuous vertical profile.

These different mixtures capture a wide range of possible combinations of group-scale vertical and horizontal connectivity. Based on the typical understanding and characterization of crown fire transition the canopy variable of primary importance should be the fuel stratum gap or the distance from the surface fuel to the canopy fuel layer. This conceptual understanding would suggest similar risk of crown fire transition and large tree torching between L4_M3_S3 and L10_M3_S3 as both of these group mixtures have canopy fuel close to the surface and vertical connectivity of fuel throughout the canopy layer. Similarly, one would expect similar behavior between L10_M10 and L5_M5 given the comparable shapes of their vertical canopy fuel profiles.

Table 3.3. Percent large tree (40 cm DBH) consumption in the tested group mixtures and each surface fireline intensity.

Mix	**Surface Fireline Intensity (kW/m)**				
	967	**1,415**	**1,930**	**3,495**	**6,374**
L10	0.0	5.4	36.9	46.7	64.3
L4_M3_S3	0.0	16.9	24.3	32.6	38.0
L10_M10_S10	17.7	28.7	35.8	67.1	71.8
L10_M3_S3	2.9	25.7	33.4	59.0	62.7
L10_M10	9.3	21.1	42.1	67.8	74.2
L5_M5	4.7	10.6	15.8	30.9	64.6
L10_S10	0.1	8.4	37.0	45.1	64.7
L6_S4	0.0	10.5	34.0	42.7	62.7

3.3.2 Large Tree Consumption

Evaluation of large tree crown fuel consumption across a range of surface FLI confirmed some of the well-established notions of crown fire transition, but also suggested a need for a more nuanced understanding of this process. There was a clear independent effect of the vertical fuel arrangement on large tree consumption at the two lowest surface FLI (967 and 1,415 kW/m; Table 3.3, Figure 3.5). At 967 kW/m (0.8 kg/m^2 of surface fuel), both L10_M10_S10 and L4_M3_S3 resulted in significantly greater consumption of large trees than L10 due to their low fuel stratum gap and vertically continuous fuel. Similarly, L10_M3_S3 and L5_M5 supported a small amount of crown fire transition, though the difference was not statistically significant from L10. Interestingly, L4_M3_S3, L10_S10, and L6_S4 all resulted in zero or near zero large tree consumption, likely due to the limited (in the case of L4_M3_S3) to non-existent (L10_S10 and L6_S4) horizontal connectivity in the midstory layer which prevented sufficient vertical fire propagation. These trends were also corroborated by the selected GLM model for this fuel load which indicated the importance of both fuel stratum gap and the density of fuel in the midstory and overstory layers (Table 3.4). In fact, the midstory bulk density had the largest effect on large tree consumption which indicates the importance of midstory fuels in carrying fire vertically from the understory to the overstory layer at low surface FLI.

These effects were even more pronounced at 1,415 kW/m (0.9 kg/m^2) where all mixtures resulted in greater large tree consumption than the homogenous large tree only group (L10; Figure 3.5). The group with vertically continuous fuels and high bulk density in every layer (L10_M10_S10) resulted in significantly greater large tree consumption than L5_M5, L10_S10, and L6_S4. Though the difference was not significant, it is also notable that L10_M10_S10 sustained greater large tree consumption than L4_M3_S3 as both groups had low fuel stratum gap and vertically continuous fuels but L10_M10_S10 had more horizontal continuity of the large, overstory trees which allowed more vertical heat transfer and crown ignition, as was seen by Ritter et al. (2020). Additionally, horizontal heat feedbacks among these large adjacent trees likely contributed to fuel consumption and horizontal fire propagation in the canopy once ignition had occurred (Padhi et al. 2017, Shannon et al. 2020). In contrast, S10_L10 had a large amount of horizontal continuity in the overstory and understory, however the vertical discontinuity between the small and large trees did not allow for as much vertical fire propagation. The L6_S4 and L5_M5 groups both had similarly low consumption owing to their vertical discontinuity as L6_S4 had fuel close to the surface but a gap between the under and overstory, while L5_M5 has a larger gap between the surface and the bottom of the canopy (Figure 3.3). Once again, these patterns are largely seen in the GLM analysis with the model for 1,415 kW/m identifying fuel stratum gap as the more influential variable followed by the midstory bulk density (Table 3.4). Interestingly this model also suggests a slight negative relationship with the understory bulk density.

As surface FLI increased to 1,930 kW/m (1 kg/m^2), the effect of vertical continuity (or 'ladder fuels') lost importance and the role of horizontal continuity in the overstory became the primary driver of large tree consumption (Figure 3.5). The lowest large tree consumption occurred in the L5_M5, and while one interpretation could be that the FLI was insufficient to ignite many medium trees, the greater consumption seen in both the L10 mixture and the L10_M10 suggests that this was not the case. Rather, when large tree ignition did occur, the reduced midstory and overstory horizontal continuity limited crown fuel consumption and vertical fire spread. This is also highlighted by the slightly lower consumption of large trees in the L4_M3_S3 group. Clearly this group has vertically continuous fuel, but the low overstory horizontal continuity in each canopy layer limited combustion. Addition support for this interpretation was the fact that the distinct vertical discontinuity in the L6_S4 group did not impede large tree consumption. The combined energy from the surface fire and combusting small trees was enough to bridge the vertical gap in L6_S4 and the greater bulk density in the upper crown layer then enabled heat feedback and greater combustion among large trees (Figure 3, Figure 3.5).

A key finding in this group of simulations was that the FLI produced by 1,930 kW/m (1 kg/m^2 of surface fuel) was sufficient to ignite trees in the L10 group and, ultimately, the high level of horizontal continuity in this group resulted in more large tree fuel consumption than either L5_M5 or L4_M3_S3. This effect of horizontal fuel continuity overriding the effect of 'ladder fuels' is distinctly different from classical views of crown fire transition and behavior (Van Wagner 1977, Cruz et al. 2006) and suggests a need for a more complex view of crown fire behavior in vertically and horizontally heterogenous stands. The fact that the overstory bulk density was the only significant predictor in the GLM model highlights this surface fuel load (and the associated surface FLI) as a transition point where the role of ladder fuels is superseded by the bulk density in the overstory layer (Table 3.4).

At the next level up 3,495 kW/m (1.2 kg/m^2), this transition has clearly been crossed and the level of large tree torching and consumption are largely being driven by the bulk density in the midstory and overstory. The L10_M10_S10 and L10_M10 groups sustained the greatest large tree consumption owing to their high levels of both vertical and horizontal connectivity and were both significantly greater than their structural counterparts (L4_M3_S3 and L5_M5, respectively). These two contrasts provide a good comparison point as they had similar vertical distributions of fuel to their structural counterparts, but with lower bulk densities in each layer. The fact that L10 sustained similar consumption to both L10_S10 and L6_S4 also suggests that the presence of fuels low in the canopy is no longer an important driver of vertical fire propagation or crown fire transition. With that said, the higher levels of consumption in L10_M10_S10 and L10_M10 does show that burning in the midstory plays a supporting role in enhancing the consumption of the largest trees in the group. The GLM model also supports this with overstory and midstory bulk density having an equal effect on large tree consumption.

Finally, at 6,374 kW/m (1.4 kg/m^2) significant levels of large tree consumption (> 60%) occurred in all groups other than L4_M3_S3. Despite the small fuel stratum gap and vertically continuous fuels in this group, it sustained significantly lower levels of large tree consumption due to low crown fuel bulk density and horizontal discontinuities across all canopy layers (Figure 3.3). The fact that consumption for L10 was on par with all groups (other than L4_M3_S3) indicates that the surface FLI was great enough to bridge the large fuel stratum gap and therefore differences in consumptions are the result of variations in bulk density within the upper canopy layers. The GLM model for this surface FLI indicates a high level of significance and similarly large effects of both overstory and midstory bulk density on large the consumption (Table 3.4).

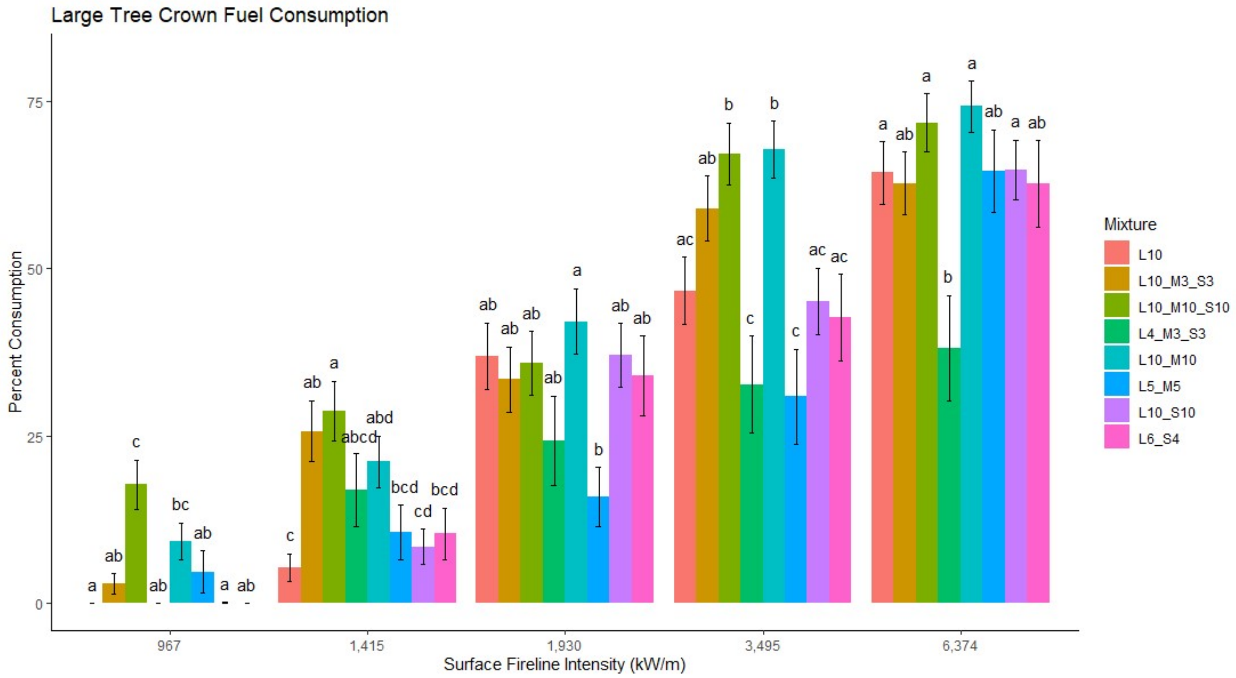

Figure 3.5. Mean consumption of large tree crowns for each mixture and fuel load. Standard error bars are provided, and letters indicate pairwise significant differences ($p < 0.05$).

Table 3.4. Selected GLM models to predict the proportion of crown consumed for large trees across all surface fuel loads and split by each surface fireline intensity level. Beta coefficients represent direction and relative magnitude of the predictor variable effect size.

Model	Predictors	B	p value
All Fuel Loads	FLI	0.99	< 0.0000
	Overstory Bulk Density	0.39	< 0.0000
	Midstory Bulk Density	0.32	< 0.0000
967 kW/m	Overstory Bulk Density	0.68	< 0.0000
	Midstory Bulk Density	2.09	0.0003
	Fuel Stratum Gap	-0.61	< 0.0000
1,415 kW/m	Midstory Bulk Density	0.53	< 0.0000
	Understory Bulk Density	-0.38	0.0041
	Fuel Stratum Gap	-0.75	< 0.0000
1,930 kW/m	Overstory Bulk Density	0.35	0.0006
3,495 kW/m	Overstory Bulk Density	0.09	< 0.0000
	Midstory Bulk Density	0.09	< 0.0000
6,374 kW/m	Overstory Bulk Density	1.50	< 0.0000
	Midstory Bulk Density	1.71	< 0.0000

3.4 Conclusion

Taken together these results highlight the complexities involved with predicting crown fire transition and behavior and the need to consider both horizontal and vertical aspects of heterogeneity simultaneously. Based on traditional understandings of crown fire transition, it would be expected that the groups with crown fuels closest to the surface would always result in greater levels of overstory consumption and those with crown fuels further from the surface would always result in the least. This was clearly not the case as one of the mixtures with crown fuels closest to the surface (L4_M3_S3) also had a vertically continuous crown fuel profile but resulted in the some of the lowest large tree consumption once the surface FLI was greater than

1,930 kW/m. This result was due to the horizontal continuity in the overstory layer as L10_M3_S3 had the same amount of fuel in the understory and midstory as L4_M3_S3 but resulted in significantly greater large tree consumption. Additionally, the mixture with the greatest distance from the surface to the lowest crown fuel (L10) resulted in the nearly the same or more consumption than vertically heterogenous groups with mixed tree sizes for surface FLI greater than 1,930 kW/m due to horizontal continuity in the overstory layer. The only exception to this trend was at 3,495 kW/m where L10_M10_S10 and L10_M10 both resulted in greater large tree consumption than L10. This result is not unexpected based on the important influence of the midstory and overstory bulk density as both of these groups had the same bulk density in the overstory as L10 while also having high bulk density within lower canopy layers. Note that this effect seems to be more related to the midstory bulk density as L10_M10 has no small trees but resulted in equal large tree consumption as L10_M10_S10. Interestingly, these same group mixtures suggest that at surface FLI well below the large tree torching threshold, understory trees or vertical heterogeneity is required for propagation into the upper canopy. Therefore, the results suggest that when surface FLI is low the 'ladder fuels' are necessary to sustain crown fire transition, however, at higher surface FLI group-scale horizontal continuity plays an important role in the total consumption of large, overstory trees. It should be emphasized that these interpretations are not intended to suggest that particular structures are resistant to crown fire transition or that large tree consumption can be wholly mitigated under a given set of circumstances. Rather, the interpretation is that relative torching hazard differed as a result of the horizontal and vertical fuel continuity and the results suggest that, on average, groups with less horizontal connectivity among overstory trees will sustain less large tree torching (and therefore mortality).

Though these results add some nuance to the typical understanding of crown fire initiation and propagation, they do generally align with long held characterizations of the relevant structural parameters. The importance of canopy bulk density on crown fire spread has been recognized since the inception of crown fire modeling (Van Wagner 1977). Specifically, this view of active crown fire spread recognizes that under a given scenario there is a minimum canopy bulk density to maintain tree crown to tree crown fire spread. If the canopy bulk density (or horizontal continuity) is too low to maintain active crown fire spread, the surface fire may still be intense enough to torch individual trees, but horizontal spread within the canopy will not be possible. The results presented here align with this model but add some additional fine scale nuance. That is, not only is the canopy bulk density important for canopy consumption and horizontal crown fire spread, but it also influences the role of so-called 'ladder fuels' in carrying fire into the overstory. It appears that by reducing canopy bulk density at the group scale, overstory tree torching (and potential mortality) can be reduced independently of the group's fuel stratum gap.

Large tree torching and consumption was the primary result of interest in this study for several reasons. For one, the process of vertical fire propagation as mediated by 'ladder fuels' is most relevant to trees in larger size classes as these trees generally have higher crown base heights and are more difficult to sustain crown ignition and torching than smaller trees. Therefore, in the context of vertical fire propagation it makes sense to view outcomes based on large (or overstory) trees. In addition, the largest trees in a stand represent a disproportionate amount of total biomass and therefore fire-caused mortality of these trees has amplified impacts on fuel loads, carbon sequestration, and the behavior of subsequent fires (Lutz et al. 2018, Lutz et al. 2021). Further, in many cases, very large, and/or old, trees are locally rare and therefore have increased ecological and/or cultural significance which increases the desire to protect these individuals (Mobley and Eldridge 1992, Brown et al. 2019, Flanary and Keane 2020). The thicker bark and, typically, greater crown base height of large trees also make them more likely to survive a fire event and therefore their presence and persistence is an important resilience mechanism in fire prone forests that depend on living trees as a seed source and can serve as a proxy for a system's ability to recover following significant disturbance. Therefore, the fact that these results show how different group mixtures and levels of horizontal continuity influence large tree crown consumption (and therefore potential mortality) has wide ranging implications for forest ecology and management.

In the context of contemporary forest management, and specifically forest restoration, the creation of highly heterogenous stands with a mixture of tree sizes and vertically complex groups is often desirable to improve wildlife habitat and forest resilience to a host of disturbance agents (Larson and Churchill 2012, O'Hara 2014, Stephens et al. 2014). However, concerns over the fire hazard associated with the mixed sized groups, and their effect on stand level mean crown base height, can lead forest managers to create more simplified stand structures with homogenous tree size distributions. Such structures (as described by Agee and Skinner 2005) certainly enhance crown fire resistance, however this emphasis on the creation of homogenous structure for fire hazard reduction may not be entirely necessary as the results presented here show that groups with a variety of tree sizes can be made more fire resistant by limiting the horizontally connectivity of the overstory, or large tree, component. This discontinuous overstory layer will allow heated air to move between overstory tree crowns rather than through them (Tachajapong et al. 2009, Ritter et al. 2020) and when overstory ignitions do occur there is less opportunity for horizontal heat feedback and fire propagation. Essentially, this means that treatments can create complex vertical structures through the retention of a variety of tree sizes while simultaneously mitigating the potential crown fire hazard through overstory density reduction. Overall, these findings suggest that forest managers have a good deal of flexibility in designing forest treatments to reduce fire hazard and therefore can integrate a wider range of management objectives including the restoration of historical stand structures, enhancing heterogeneity across scales, and creating stands that are resilient to a wide range of disturbances.

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CHAPTER 4: RESTORATION AND FUEL HAZARD REDUCTION RESULT IN EQUIVALENT REDUCTIONS IN CROWN FIRE BEHAVIOR

4.1 Introduction

Dry pine and mixed-conifer forests represent extensive and diverse ecosystems in which historically frequent fires created complex forest structures and promoted diverse understory plant communities (Hessburg et al. 2019). Fire, recognized as a keystone disturbance process, in conjunction with local climate, soils, and topography, influenced tree density and spatial pattern, and species composition in these ecosystems (Lydersen and North 2012, Hessburg et al. 2015, Hessburg et al. 2019, Jaquette et al. 2021). However, wildfire suppression and unregulated and unmanaged grazing practices following Euro-American colonization altered the structure and function of these fire-adapted ecosystems across the western U.S. (Borman 2005, Hagmann et al. 2021). This legacy has resulted in significant increases to tree densities, enhanced dominance of shade-tolerant tree species, and generated more homogenous tree spatial patterns (e.g., Brown and Cook 2006, Larson and Churchill 2012, Reynolds et al. 2013, Hessburg et al. 2015, Battaglia et al. 2018, Hessburg et al. 2019, Knight et al. 2020). Climate change presents an additional risk to the continued ecological function of these ecosystems by enhancing tree stress and sensitivity to biotic disturbances (Weed et al. 2013), increasing the potential for wildfires to occur under extreme weather conditions resulting in more severe fires (Abatzoglou and Williams 2016, Westerling 2016, Khorshidi et al. 2020, Parks and Abatzolgou 2020), and limiting the opportunity for post-fire fire regeneration and recovery (Haffey et al. 2018, Stevens-Rumann et al. 2018, Rodman et al. 2020, Coop et al. 2020). These changes to forest structures and climate are not only associated with reductions to biodiversity and ecosystem resistance and resilience

(Graham et al. 2019, Hessburg et al. 2019, Latif et al. 2020, van Mantgem et al. 2020), but contribute to highly visible societal and economic costs in the form of smoke impacts on human health and the loss of life and property due to uncontrolled wildfire occurring in areas that are increasingly urbanized (Radeloff et al. 2018, Schweizer et al. 2019, Caggiano et al. 2020).

A major management strategy used to address the linked ecological and social concerns associated with altered forest structure, wildfire behavior, and an actively changing climate is tree density reduction through mechanical treatments or silvicultural practices (Peterson et al. 2005, Kalies and Yoccom Kent 2016, Stephens et al. 2021). Although the primary objective of such treatments is typically the reduction of potential fire behavior, additional considerations include the reduction of drought stress, harvesting of commercial products, shifting stands and landscapes towards the historical range of variability, improving wildlife habitat, and increasing resistance and resilience to disturbance (Reynolds et al. 2013, Hessburg et al. 2015, Addington et al. 2018, Crotteau and Keyes 2020, van Mantgem et al. 2020). The scientific basis for reducing potential fire behavior through the direct manipulation of the fuel complex derives from a basic understanding of the biophysical factors that, in conjunction with fire weather and topography, influence fire behavior (Graham et al. 2004). Fuels are the only aspect of the fire environment that land managers can directly modify (Keane 2015). One of the primary fire behavior concerns addressed by treatment is the potential for surface to crown fire transition and active crown fire spread. Crown fire transition occurs when there is adequate surface fire intensity and/or vertical continuity of aerial fuels to enable tree crown ignition (Van Wagner 1977) and when combined with high canopy bulk density this behavior can further transition into the development of an active crown fire (Van Wagner 1977, Agee 1996). Crown fires are of particular concern as they are associated with substantial increases in rate of spread, ember production, tree mortality, and present a serious danger to wildland firefighters and the public.

This understanding suggests that the greatest reductions of potential crown fire behavior would be achieved through treatments that reduce surface fuel loads and remove understory trees to increase canopy base heights therefore reducing the potential for crown fire transition, as well as thinning the remaining overstory trees to reduce active crown fire spread potential (see Agee and Skinner 2005). Though not explicit in the recommendations of Agee and Skinner (2005), thinning treatments that create uniform spacing between tree crowns have been increasingly recommended (Dennis 2005, Colorado State Forest Service 2012, Jones et al. 2016, Alexander and Cruz 2020). As a result of such recommendations, treatments designed to achieve maximum reduction to potential fire behavior often tend toward spaced-based, thin-from-below approaches that uniformly increase canopy base height and separate overstory tree crowns from one another, with the aim of hampering surface to crown fire transition and limiting the potential for tree-to-tree fire spread (i.e., active crown fire). However, the uniform stand conditions created starkly contrast the historical structure of dry conifer forests and, in doing so, such treatments fail to capture the overall ecological resilience associated with complex, heterogenous forest structures or meet other management objectives such as creating goshawk (*Accipiter gentilis atricapillus*) habitat or promoting variable light conditions that enhance understory biodiversity and create diverse regeneration niches (Larson and Churchill 2012, Reynolds et al. 2013, Graham et al. 2015, Cannon et al. 2019). Although our basic understanding of crown fire behavior and fuels management suggests that fuel treatments that generate homogenous forest structures will optimize the reduction of fire behavior, it may be the case that emulating historical heterogenous forest structures can achieve similar results while simultaneously benefiting other aspects of ecosystem function.

Though concern exists that the multi-aged structures and vertically continuous tree groups created by treatments that enhance structural complexity may not result in equal reductions in crown fire hazard as traditional fuel hazard reduction treatments it is not clear that such concerns are borne out. For example, measurements of post-fire dynamics in dry conifer forests have suggested strong associations between structural heterogeneity and resilience to fire (Jeronimo et al. 2020, Koontz et al. 2020) and stand-scale simulation studies that account for spatial arrangement of fuels have shown that reductions to potential fire behavior and effects are more closely related to the total amount of available fuel and the environmental burning conditions than the spatial arrangement of that fuel (Parsons et al. 2017, Ziegler et al. 2017, Atchley et al. 2021). These findings suggest that treatments creating complex forest structures may result in similar effects on fire hazard as more traditional, space-based treatments. However, the existing research has focused on larger scale measures of heterogeneity (e.g., Koontz et al. 2020, Jeronimo et al. 2020, Cannon et al. 2020) or only considered the within-stand impacts of heterogenous tree patterns on fire behavior without direct comparison to outcomes of space-based fuel hazard reduction (e.g., Parsons et al. 2017, Ziegler et al. 2017). If restoration treatments have similar efficacy in reducing fire behavior as space-based fuel hazard reduction treatments, this suggests that land managers can reduce fire hazard to ecosystems and communities, while simultaneously achieving the broader suite of objectives realized through ecologically based silvicultural systems such as variable density thinning (Carey 2003), free selection (Graham et al. 2007), or Individuals Clumps and Openings (ICO; Churchill et al. 2013).

Though there are differences in ecological responses between treatments that reduce heterogeneity and those that enhance it, any form of tree density reduction is commonly referred to as restoration regardless of the resultant spatial pattern and structure (e.g., Crotteau and Keyes 2020). The lack of distinction among different silvicultural treatments can lead to confusion and potential disagreements between stakeholders, managers, and scientists (Stephens et al. 2021). Therefore, it may be better to think of treatment approaches falling along a continuum from fuel hazard reduction to ecological restoration, depending on the explicit goals and management objectives that guide silvicultural prescriptions (Stephens et al. 2021). Management objectives aimed at restoring historical forest structures are typically concerned with a broad suite of ecological considerations and intend to create stands that closely approximate the spatially complex forest structures which existed historically under intact fire regimes (North et al. 2009, Reynolds et al. 2013, Addington et al. 2018). Restoration treatments specifically aim to retain trees of all sizes arranged in a complex matrix of canopy openings, tree groups and isolated individual trees (e.g., ICO; Larson and Churchill 2012, Churchill et al. 2013). In contrast, fuel hazard reduction treatments primarily focus on reducing potential fire behavior to protect human resources and infrastructure through spaced-based, thin-from-below prescriptions (Agee and Skinner 2005, Peterson et al. 2005). These disparate structural outcomes are the direct result of the differing primary objectives driving the treatment prescriptions, and, as a result, there is a perceived tension between active management approaches that are primarily focused on reducing fire behavior with those that include a wide variety of other ecological considerations (Stevens et al. 2016, Stephens et al. 2021).

In this work, I utilized spatially explicit measurements of forest structure within four different silvicultural treatments on the Black Hills National Forest in conjunction with 3D physics-based fire behavior modeling to assess the potential difference in fire behavior resulting from different levels of structural complexity. Treatments were selected to represent a range of possible structural outcomes ranging from a highly complex treatment implemented to create favorable Norther Goshawk habitat (*Accipiter gentilis atricapillus*), to two slightly different treatments that used free selection to create heterogenous stands, all the way to a traditional space-based, thin-from-below treatment implemented to reduce fire hazard and enhance timber volume production. I sought to characterize the differences between the structural outcomes of the prescriptions in terms of 1) non-spatial structural metrics, 2) horizontal spatial patterns including measures of tree aggregation and the distribution of group sizes, 3) and the interaction between vertical and horizontal complexity. Finally, I evaluated the impact of treatments with differing objectives on 4) potential fire behavior. These results will provide a better understanding of how particular prescriptions alter spatial aspects of forest structure, but, most importantly, investigate whether fire behavior tradeoffs truly exist when implementing treatments that create complex forest structures.

4.2 Methods

4.2.1 Study Area and Treatment Description

This study took place in ponderosa pine (*Pinus ponderosa* var. *scopulorum*) dominated forests of the Black Hills, U. S. The Black Hills are a geologic uplift in southwestern South Dakota and northeastern Wyoming that forms a forested island rising from the Great Plains. The study occurred on the United States Forest Service (USFS) Black Hills Experimental Forest (BHEF). The BHEF is in the central Black Hills which is primarily underlain by granites and is the most productive area of the Black Hills uplift (Sheppard and Battaglia 2002). Typical site index (base age 100) ranges from 36 to 75 feet (Myers and Van Deusen 1960), and the site index for the BHEF specifically has been estimated at 55 feet (Graham et al. 2019). Between 1981-2010 annual precipitation for the BHEF averaged 49 cm, which peaks in the spring with 32% falling in just May and June (Prism Climate Group 2021). This early season moisture combined with consistent summer rains, warm growing season temperatures, and periodic cone crops results in prolific natural ponderosa pine regeneration (Sheppard and Battaglia 2002).

Like many other frequent-fire forest ecosystems, the ponderosa pine forests of the Black Hills are characterized with increased tree densities and a loss of stand and landscape scale structural heterogeneity compared to their pre-European settlement structures (Grafe and Horsted 2002; Brown and Cook 2006) due to the legacy of wildfire suppression and timber-based forest management practices (Naficy et al. 2010, Collins et al. 2017). The region has a long history of timber production as the primary management objective leading to the popular use of the multi-step shelterwood silvicultural system which provides consistent timber yields and abundant natural regeneration (Shepperd and Battaglia 2002, Freeman 2015, Graham et al. 2019). The high regeneration rates have both advantages and disadvantages, as securing post-treatment regeneration is rarely problematic, however, without active management of this regeneration the dense layer of understory trees can further exacerbate susceptibility to fire and mountain pine beetles (*Dendroctonus ponderosae;* Lentile et al. 2006, Graham et al. 2016, Mullen et al. 2018). This silvicultural system results in predominantly two-aged stand structures with a continuous, uniform overstory and a single cohort of understory trees. In contrast, the historical fire regime in the Black Hills, in combination with other disturbances (e.g., wind, endemic *Dendroctonus ponderosae*, and diseases) and the biophysical setting (soils, topography, and geology), created a variety of stand structures and age classes across the landscape including complex multi-aged stands, dense one and two-aged stands, low-density pine savanna, and large, open meadows (Graves 1899, Grafe and Horsted 2002, Brown and Cook 2006, Brown et al. 2008).

Within the BHEF and the Black Hills National Forest immediately to the north of the BHEF four different mechanical forest thinning treatments were sampled that represented a wide range of management activities to characterize their differences across several forestry and fire behavior metrics. These treatments included a silviculture prescription designed to meet habitat restoration objectives by utilizing small group retention, two similar prescriptions that follow concepts associated with the free selection silvicultural system (Graham et al. 2007), and finally a commercial thinning treatment. The small group retention prescription (hereafter, SGR) was implemented to reduce the susceptibility and severity of mountain pine beetle infestation and provide wildlife habitat for the Northern Goshawk and its prey. For trees ≥ 22.9 cm diameter at breast height (DBH) the SGR prescription called for the retention of groups of 15-20 trees with interlocking or nearly interlocking crowns and thinning commercial trees to a basal area of ~2.3 m^2/ha (10 ft^2/ac) between groups. The retained groups emphasized large trees but could include trees of different sizes. In addition, pre-commercial understory trees (< 22.9 cm DBH) were retained in large patches beneath the retained tree groups of large trees. The two free selection (FS) prescriptions were designed to address management objectives that required multi-aged complex forest conditions and met integrated management objectives like timber products and wildlife habitat; yet also maintain healthy and vigorous growing trees of all sizes spatially dispersed to favor the regeneration of early-seral tree species. The marking guide for both FS treatments used vigor selection criteria to select leave trees of ponderosa pine ≥ 22.9 cm DBH where trees were retained if they had high crown vigor (i.e., a crown ratio greater than 40% and more than three years of needle retention; Hornbrook 1939, Jain et al. 2012). A target density was not dictated during marking; however, the basal area after harvest resulted in 9.2 to 13.8 m^2/ha (40 to 60 ft^2/ac). Within the FS treatments, two different pre-commercial thinnings were applied to trees < 22.9 cm DBH. On half the stands overstory trees were excluded from the spacing guidelines and only pre-commercial trees were considered. Pre-commercial trees were spaced evenly using ~4.3 m (14 ft) spacing across the stand even if the small tree was growing underneath the crown of an overstory tree (FS-On). Within the other half of the stands (FS-Off), large trees were included in the spacing guidelines; thus, pre-commercial trees were spaced a minimum of 4.3 m from all neighboring trees including the overstory trees. This created conditions where advanced regeneration was spatially separate from the overstory. In theory, the FS-On treatment should create greater vertical heterogeneity as pre-commercial trees could be retained directly adjacent to commercial trees, while in FS-Off pre-commercial trees could never occur within 4.3 m of a commercial tree. FS-On is also likely to result in slightly greater retention of pre-commercial trees as their spacing was independent of the commercial tree locations. The final prescription evaluated was a simple commercial thinning treatment (CT) where the stands were thinned from below to 9.2 to 13.8 m^2/ha (40 to 60 ft^2/ac), and trees were spaced a minimum of ~4.9 m (16 ft) apart. Trees smaller than 22.9 cm DBH were only retained when a gap in the fixed tree spacing would have occurred.

4.2.2 Field Sampling

Eleven, 100 m by 100 m (1-ha), permanently monumented plots were established within the treatment units. These plots were randomly located within each unit boundary such that roads and powerline corridors did not fall within the plot boundary. Three plots were installed in the CT treatment and each of the two FS treatments. However only two plots were installed in the

SGR treatment as it was smaller in area and was bisected by a powerline corridor which precluded the placement of more than two non-overlapping plots.

Each plot was subdivided into sixteen, 25 m by 25 m quadrats within which all live trees greater than 1.37 m tall had their x, y locations recorded. In addition to mapping their x, y location, all live trees were tagged and had their DBH, tree height (TH), compacted crown base height (CBH), crown width (CW), and species recorded. The grid was first established and monumented using a Pentax PCS-515 laser total station that is accurate to 0.001 m and 0.005°. All live trees in each quadrat were then mapped relative to the monumented points by recording distance to the 0.1 m and azimuth to the 0.1° using a TruePulse™ 360R laser range finder. Before converting azimuth and distance to x, y locations, each distance was corrected based on stem radius. The precise grid installed with the total station prevented the propagation of spatial error that can occur when grids are laid out successively using handheld range finders. Rather than being additive, any measurement errors will be contained to a particular quadrat and not propagated across the entire plot.

To reconstruct the pre-treatment forest, I mapped and recorded diameter at stump height (DSH) for all stumps >12.7 cm. Simple linear regressions were then developed to predict DBH from the measured DSH based on 200 randomly sampled ponderosa pine trees located outside the plots in the BHEF. Using the predicted DBH for each stump it was then possible to predict TH, CW and CBH from simple linear regressions derived from all live trees measured in the mapped plots. The calculated taper equation to adjust measured diameter at stump height to DBH had an adjusted R^2 of 0.98 and is as follows:

1) $\text{DBH} = -0.69 + 0.85 * \text{DSH}$

with DBH and DSH in centimeters. The simple linear regressions to convert the calculated DBH to TH, CW, CBH had adjusted R^2 values of 0.92, 0.84, and 0.77, respectively:

2) $HT = 1.41 + 0.45 * DBH$

3) $CW = 0.54 + 0.12 * DBH$

4) $CBH = 0.43 + 0.24 * DBH$

with HT, CW, and CBH in meters and DBH in centimeters.

To estimate the density of pre-commercial trees (<12.7 cm DBH) prior to treatment, three control (untreated) plots were established in adjacent stands whose productivity and management history mirrored the treated stands. In these untreated stands, randomly located, one-hectare square plots were installed. Each one-hectare plot was subdivided into sixteen 25 m by 25 m quadrats, and in each quadrat, five 1 m diameter subplots were randomly located. This gave a total of 80 subplots within which the number of live trees >1.37 m tall was recorded in each DBH class (0 to 2.54, >2.54 to 5.08, >5.08 to 7.62, >7.62 to 10.16, >10.16 to 12.7 cm). In each subplot, the first tree encountered in each size class was tagged, and its height, crown width, and crown base height were recorded. This data allowed us to estimate the pre-treatment density of the small tree cohort in the treated plots by averaging the number of trees in each 2.54-cm diameter class found within the control plots. Tree dimensions for these small trees were calculated by averaging the dimensions of all measured trees in each diameter class.

4.2.3 Stand Structure Analysis

4.2.3.1 Tree Groups and Horizontal Pattern

Several metrics were calculated to evaluate the effect of treatment on horizontal forest structure. Changes to the proportion of the stand area comprised of isolated trees, tree groups of various sizes, and non-treed openings were characterized by identifying tree groups based on crown interlock and calculating the percent crown cover attributable to each of these structural features post-treatment. Based on these identified groups, the proportion of the stand area occurring in isolated trees and small (2-4 trees), medium (5-9 trees), large (10-19 trees), and very large groups (20+ trees) was calculated. These proportions could not be calculated for the pre-treatment stands as pre-treatment tree location data was only available for trees > 12.7 cm DBH. I also calculated the amount of stand area >9 m away from another tree bole as larger openings provide different functional attributes than smaller openings (Matonis and Binkley 2017). To further characterize the spatial stand structure, density distribution curves were generated for the distance from any point in the plot to the nearest tree bole and the distribution of tree bole to tree bole nearest neighbor distances. The distance to the nearest live tree (DTL) showed the distribution of opening sizes by plotting distances from all points within the plot to the nearest tree. The nearest neighbor distance (NND) distribution is reflective of tree aggregation by plotting the distribution of distances between each tree and its closest neighbor.

Using the spatstat R package (Baddeley et al. 2015) the pair-correlation function was calculated for all post-treatment trees taller than 1.37 m and for post-treatment commercial-sized trees to understand the spatial pattern of both all retained trees in the stand as well as for just the commercial-sized trees. It was important to characterize both of these spatial patterns as the SGR and FS treatments specifically sought to create aggregation among trees in the commercial size class. In addition, the marked pair correlation was used to evaluate the spatial relationship between pre-commercial and commercial-sized trees in the post-treatment stands. Finally, the change in the pattern of commercial-sized trees was assessed by subtracting the pre-treatment pair correlation function for commercial-sized trees from the post-treatment pair correlation function. Comparing pre-and post-treatment patterns of commercial-sized trees indicates how the horizontal pattern these trees were altered by each treatment. A significant departure (using an alpha level of 0.05) from a random pattern was assessed by using a pointwise Monte Carlo test to generate a 95% confidence interval (Baddeley et al. 2015). The global spatial pattern was also evaluated using the Clark-Evans index of aggregation (Clark and Evans 1954).

4.2.3.2 Vertical Heterogeneity

To quantify the impacts of each treatment on vertical structural complexity, I used the stand level height differentiation index (HDI) as well as the group-scale coefficient of variation of tree height (grpCOV). The HDI is calculated by finding the dissimilarity between each tree's height and its three nearest neighbors and then taking the mean dissimilarity value of all trees in the stand. This calculation results in values that range from 0 to 1, with higher values representing greater dissimilarity (Kint et al. 2000). The grpCOV is found by calculating the coefficient of variation in tree heights for each group (defined by crown interlock) in a stand and then finding the mean value across all groups. Lower grpCOV values represent less mean variation in tree heights within groups.

4.2.3.3 Canopy Fuels

The canopy fuel load (CFL), canopy bulk density (CBD), and canopy base height (CBH) were calculated at the plot scale following the methods of the Forest Vegetation Simulator – Fire and Fuels Extension (FVS-FFE; Rebain 2015). To do this, the total mass of available fuel (foliage mass plus ½ the mass in twigs < 0.635 cm in diameter) was calculated for each live tree using the allometric equations developed for ponderosa pine in the Black Hills by Keyser and

Smith (2010). The CFL is simply the sum of all the available crown fuels divided by the plot area in square meters. As is done in FVS-FFE, this available fuel mass was assumed to be homogeneously distributed along the length of the live crown. These individual tree crown profiles were then summed across the plot to develop a canopy fuel profile. Finally, CBD was calculated from the canopy fuel profile by finding the maximum of the three-meter running mean bulk density and the CBH was calculated as the lowest height at which >0.011 kg/m^3 of available fuel is present (Rebain 2015). These calculations were completed for the post-treatment stands based on the measured live trees and for the pre-treatment stands by combining the live tree values with those of the pre-treatment trees reconstructed from their stumps and the small tree cohort characterized by the control plots.

4.2.4 Fire Simulation

4.2.4.1 Wildland Urban Interface Fire Dynamics Simulator Background

Fire behavior simulations were conducted using the Wildland Urban Interface Fire Dynamics Simulator version 9977 (WFDS; Mell et al. 2007), which is based on the Fire Dynamics Simulator (FDS) version 6 developed by the National Institute of Standards and Technology (McGrattan et al. 2013a). WFDS is a spatially explicit, physics-based model that simulates fire behavior by linking a large eddy computational fluid dynamics model that solves the governing equations for the conservation of momentum, total mass, and energy with sub-models that calculate radiative and convective heat transfer, thermal degradation of vegetation, and gas-phase combustion. Wildland vegetation (fuels) are represented within a 3-dimensional computational grid as a porous media based on their bulk properties (e.g., bulk density, fuel moisture content, and surface area to volume ratio). These fuels are treated as thermally thin, optically black elements whose thermal degradation is modeled as a two-step process where the fuel is first dehydrated before undergoing pyrolysis (Morvan and Dupuy 2004). The combustion of this gaseous fuel is then modeled as a mixing-limited, infinitely fast reaction. WFDS is a dynamic model, accounting for interactions between the ambient wind flow, fire plume, and vegetation elements and therefore is well suited to capture the complex interactions between heterogenous fuel elements and fire behavior (Hoffman et al. 2018, Yedinak et al. 2018). Further description of WFDS can be found in Mell et al. (2007) and Mell et al. (2009). Additional details about the formulation, verification, and validation of FDS are provided in McGrattan et al. (2013a-c). Evaluation of WFDS for the simulation of the combustion and fire spread through vegetative fuels is presented by Mell et al. (2007, 2009), Castle et al. (2013), Mueller et al. (2014), Overholt et al. (2014), Hoffman et al. (2016), Perez-Ramirez et al. (2017), Sánchez-Monrory et al. (2019), and Ritter et al. (2020).

4.2.4.2 WFDS Simulation Setup

To simulate fire behavior through each 1-ha plot, a simulation domain 100 meters tall with an area of 10.5 ha (750m long and 140m wide, Figure 4.1) was used. The stem mapped plot data was then placed within a 100m by 100m area of interest that extended from x = 450 to 550 and y = 20 to 120. The stem map was placed with north in the positive y direction and therefore fire spread, and wind direction was from west to east across the plots. The resolution within the domain varied to reduce computational demand while achieving suitably fine resolution within the area of primary interest. The upwind area from x = 0 to 370, the downwind area from x = 560 to 750, and the entire area above the canopy (z > 30m) had a resolution of 1m by 1m by 1m in the x, y, and z dimensions. The volume bounded by x = 370 to 560, y = 0 to 140, z = 0 to 30 was simulated at a resolution of 0.5m by 0.5m by 0.5m so that fire behavior, and the surface and canopy fuel complex surrounding the area of interest could be more fully resolved. Boundary conditions for the lateral edges were simulated as periodic, the top boundary was simulated as a no-flux, no-slip boundary, the leeward edge was open, and the windward edge was set to a prescribed inflow velocity. Inflow was set to follow a standard logarithmic vertical wind profile with a neutral atmosphere with a prescribed open (20 m) windspeed. Simulations were conducted with the open wind speed at 4 levels: 2 m/s, 3.5 m/s, 5 m/s, and 10 m/s. Surface fire was ignited simultaneously across the entire width of the domain 70 meters upwind from the area of interest. This allowed the surface fire spread to reach semi-steady-state behavior prior to encountering the stem mapped area where fire behavior metrics were calculated.

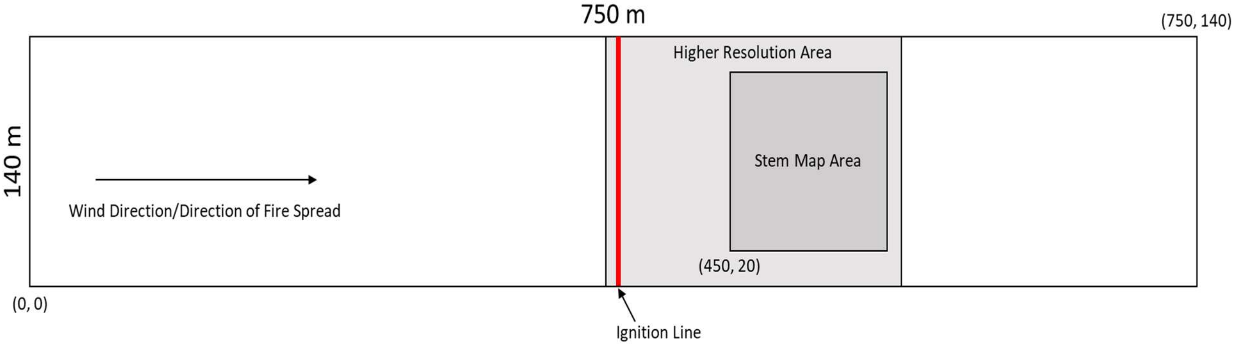

Figure 4.1. Layout of the 140 m by 750 m WFDS simulation domain. Fire spread and wind direction was left to right. The white area was simulated at 1m resolution while the shaded area was simulated at 0.5 m resolution. The darkest shading is the location of the 100 m by 100 m stem mapped data for a particular simulation. The surrounding area was filled with trees by randomly rotating and mirroring the stem mapped plot. Coordinates in parenthesis are the x, y coordinates in meters based on a lower left origin. Lateral boundaries were periodic, the domain top was a no-flux, no-slip boundary, the leeward edge was open, and the upwind edge was set to a fixed inflow velocity.

4.2.4.3 Simulated Surface Fuel and Canopy Fuel

To account for spatial variability in the type and loading of fine surface fuels a simple model was developed to estimate the loading of either 1-hr surface fuels consisting of litter and fine woody debris or grass fuel based on the cumulative tree basal area within a 5 m radius of each 0.25 m^2 area on the ground. This model assumes that greater local basal area will increase fine woody fuels and decrease the loading of grass. The model construction follows a similar form to the surface fuel model utilized in Linn et al. (2005) to generate a spatially heterogenous surface fuel bed. The surface fuel loading of fine woody fuels and grass was calculated at 0.25 m^2 resolution using the equation:

$$5)\quad M_{ground} = m_{grass}^{-C*BaR} + m_{litter}(1-e^{-C*BaR})$$

In this equation, the values of m_{grass} and m_{litter} were set to 0.35 kg/m^2 and 1.4 kg/m^2, respectively, and represent the maximum loading of either fine woody fuels or grass. C is a non-dimensional proportionality constant and was set to 5 kg following Linn et al. (2005). BaR was calculated by relativizing the total BA within 5m of pixel by the highest local (5 m) basal area found in any of the field plots.

Tree crowns were simulated as right, rectilinear cones based on their measured or allometrically derived crown measurements. Foliage was then homogenously distributed within each crown volume with a bulk density of 0.7 kg/m^3. This bulk density was selected as it resulted in canopy fuel loads that matched the values calculated using the local allometries derived by Keyser and Smith (2010). Foliage surface area to volume ratio was set to 5808 m^{-1} (Brown 1970).

4.2.4.4 *Analysis of the WFDS Simulations*

Stand scale fire behavior statistics were calculated from the WFDS simulations to allow comparisons between treatments. The mean rate of spread (ROS) was estimated for each simulation by averaging the instantaneous rate of spread at 2 second intervals for each 0.5 m segment of the fireline within the 100 m by 100 m area of interest. The mean fireline intensity was similarly calculated at 2 second intervals by adding the surface fuel consumed per second in each 0.5 m section across the fireline to the mass of canopy fuels consumed during the time step. This combined mass was then multiplied by the low heat of combustion (17,770 kW/kg) and the ROS for the time period to find the instantaneous fireline intensity (FLI). The instantaneous FLIs were averaged across the entire period of fire spread through the area of interest to generate a mean FLI. The percent canopy fuel consumed was estimated as the difference in dry mass before and after the simulated fire within the area of interest.

In addition to these fire behavior metrics, vertical u-velocity profiles were generated prior to the ignition of the simulated fires for the pre- and post-treatment conditions when the open wind speed was 10 m s^{-1}. This allowed for the characterization of the influence of stand structure on wind velocity at different heights through the canopy. To calculate the wind profiles, the averaged the streamwise velocity was calculated during the 120 seconds immediately before ignition at 1-m height intervals along three lengthwise y-slices at y = -25, y = 0, and y = 25. The time-averaged profiles at each y-slice were averaged to generate the plot level wind profiles. The treatment level mean was then found by averaging these plot level profiles. To allow easier comparison between treatments the mean profiles were normalized by the mean wind speed at 25 m above the ground. This approach allowed us to average out the effects of variation in the wind field due to transient gusts and downdrafts, as well as the plot differences and the horizontally heterogenous distributions of fuel (i.e., drag) within each plot.

4.3 Results

4.3.1 Stand Structure

Prior to treatment, sapling (<12.7 cm DBH) densities exceeded 16,000 TPH, while pole (12.7 – 22.9 cm DBH) and sawtimber (>22.9 cm DBH) densities ranged from 220 to 584 TPH (Table 4.1). All treatments significantly reduced the density of saplings. However, the SGR prescription retained more of the sapling size class, 386 TPH, as compared to the FS-Off, FS-On, and CT treatment means of 77, 117, and 22 TPH, respectively (Table 4.1). Treatments also significantly reduced basal area (BA) with the SGR treatments resulting in the lowest post-treatment BA of 6.3 m^2/ha compared to 12.8, 11.0, and 12.4 m^2/ha for the FS-Off, FS-On, and CT treatments, respectively (Table 4.1). Quadratic mean diameter (QMD) for all trees >1.37 m tall was increased following all treatments, with the SGR treatment having the lowest QMD at 13.7 cm, in comparison to 23.2 and 21.0 cm for the FS-Off and FS-On treatments and 30.0 cm for the CT treatment (Table 4.1). Similarly, the mean tree height was the lowest in SGR at 5.2 m, versus 9.0 and 10.6 m for FS-Off and FS-On, respectively, and 14.3 m for CT (Table 4.1). Differences in QMD and mean tree height among the treatments was due to greater retention of saplings in SGR and lower retention of both saplings and pole sized trees in CT.

Visual comparisons of the DBH distributions reveal a reverse-J shaped distribution typical of balanced, uneven-aged stands for SGR (Figure 4.2). In comparison, both FS treatments generated distributions that are multi-cohort and reflective of an irregular uneven-aged structure. Finally, CT resulted in a bi-modal distribution with a small peak in density between 5 - 10 cm and a larger peak at 25 – 30 cm, which is characteristic of a two-aged (or two-sized) structure.

The mean HDI increased compared to pre-treatment in all cases except for CT (Figure 4.3a). The post-treatment HDI was greater in the FS-On and FS-Off treatments than CT. There was no difference in HDI between either FS treatment and SGR or between SGR and CT (Figure 4.3a). Differences in HDI were driven by a combination of the retention of small diameter trees in the SGR and FS treatments, and the proximity of these small trees to larger trees. The grpCOV also indicates that SGR, FS-Off, and FS-On resulted in similar levels of within-group height variability, which were significantly greater than that in the CT (Figure 4.3b). Overall, every treatment resulted in greater vertical heterogeneity relative to the pre-treatment conditions, however, the CT treatments generated stands with significantly less vertical complexity than the other treatments.

Table 4.1. Pre and post-treatment stand structure, canopy fuel, and simulated fire behavior data. Densities of trees in seedling (<1.47 m tall), sapling (< 12.7 cm DBH), pole (12.7 – 22.9 cm DBH), and sawtimber (>22.9 cm DBH) size class and diameter at breast height (DBH), quadratic mean diameter (QMD), tree height (TH), canopy base height (CBH), canopy fuel load (CFL), and canopy bulk density (CBD) are all presented as treatment level means. Fire behavior metrics including rate of spread (ROS), fireline intensity(FLI), and percent canopy fuel consumption represent the mean values from all tested wind speeds. Pre represents the pre-treatment pole and sawtimber densities that were estimated from the stump data in the treated plots. Pre-treatment sapling data were based on the measurements from the three untreated control plots. Post is the post-treatment means for each treatment prescription. Seedling densities are not available for the pre-treatment stands and are only available post-treatment. Canopy fuel metrics (CBH, CFL, and CBD) were calculated following the FVS-FFE approach described in the methods. SGR is the small group retention treatment, FS-On and FS-Off are the free selection ghost on and free selection ghost off treatments, and the CT is the commercial thinning treatment.

		SGR		FS - Off		FS - On		CT	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post
Tree Density* (#/ha)	Sapling	16484	386	16194	77	16225	117	16177	22
	Pole	66	53	147	60	90	51	46	10
	Sawtimber	215	42	196	120	284	99	244	139
	Total	16765	481	16537	257	16599	267	16467	171
Basal Area (m^2/ha)	Sapling	6.7	0.5	6.7	0.3	6.6	0.3	6.9	0.1
	Pole	1.9	1.4	3.9	1.7	2.5	1.4	1.2	0.3
	Sawtimber	19.5	4.4	24.5	10.8	31.1	9.3	26.7	12.0
	Total	28.0	6.3	35.1	12.8	40.2	11.0	34.7	12.4
	Seedlings (#/ha)	NA	7305	NA	1791	NA	1831	NA	1592
	Mean DBH (cm)	1.0	3.3	1.0	8.0	1.0	6.6	1.0	11.1
	QMD (cm)	4.6	13.7	4.3	23.2	4.9	21.0	4.5	30.0
	Mean Height (m)	2.2	5.2	2.2	10.6	2.2	9.0	2.2	14.3
	Mean CBH (m)	2.0	10.0	2.0	4.0	2.0	6.7	2.0	8.3
	Mean CFL (kg/m^2)	0.95	0.19	0.85	0.38	1.05	0.34	0.91	0.37
	Mean CBD (kg/m^3)	0.09	0.02	0.09	0.04	0.10	0.03	0.08	0.04
	Mean ROS (m/s)	0.70	0.64	0.71	0.47	0.71	0.49	0.71	0.48
	Mean FLI (kW/m)	17624	6624	15655	3504	18676	3866	18145	3773
Canopy Consumed (%)	Trees < 22.9 cm DBH	99.6	29.7	99.4	44.2	99.8	36.8	99.9	39.4
	Trees ≥ 22.9 cm DBH	94.7	16.5	90.1	14.3	95.3	15.3	93.9	16.2
	Total	95.5	19.3	93.0	19.3	96.4	17.7	95.0	16.8

* More than 99% of the trees were Ponderosa pine.

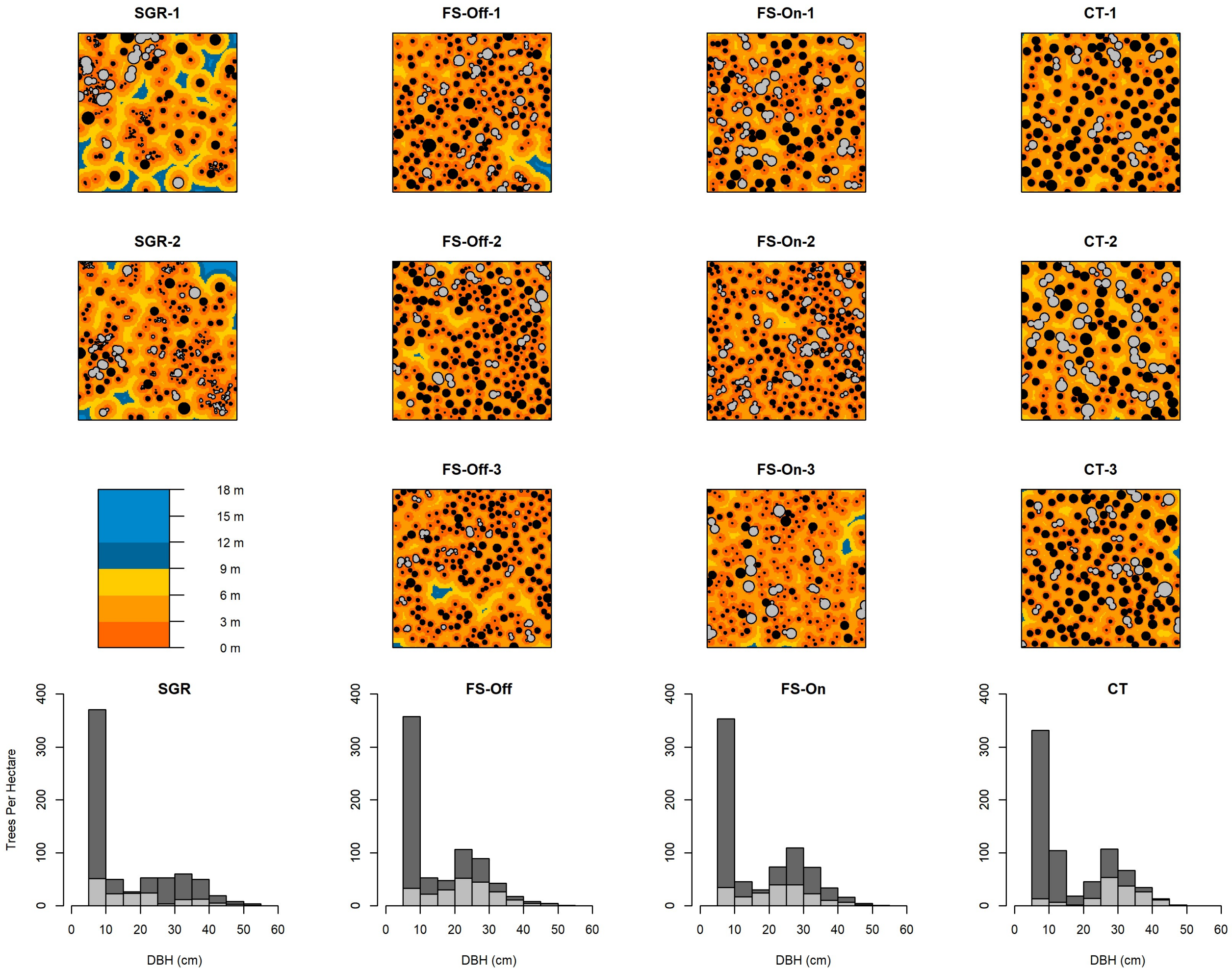

Figure 4.2. Post-treatment plot maps for all trees taller than 1.4 m and DBH distributions with the pretreatment represented by the darker grey. Only tree >5 cm DBH are included as pre-treatment densities of trees in this size class exceeded 16,000 stems per hectare. In the plot maps, each circle represents a tree crown and grey circles represent the crown of trees that are located within groups based on crown-interlock while black circles represent isolated trees. The background color is the distance to the nearest tree in meters with large gaps (>9 m from nearest tree) highlighted in shades of blue. SGR is the small group retention treatment, FS-On and FS-Off are the free selection ghost on and free selection ghost off treatments, and the CT is the commercial thinning treatment.

4.3.2 Isolated Trees, Tree Groups and Non-Treed Openings

Treatments resulted in different proportions of the stand area in isolated trees, openings, and groups, with SGR resulting in 87.5% of the stand area in openings, followed by FS-On and FS-Off with 82% and 81.5%, respectively, and finally CT with 75% (Table 4.2; Figure 4.3c).

The stand area in "large" openings (defined here are >9 m from the nearest tree bole), varied among the treatment types with SGR creating the most area with large openings (535 m^2/ha) relative to all other treatment types (70.7, 29, and 23 m^2/ha for FS-Off, FS-On, and CT, respectively; Table 4.2). Similarly, SGR had greater mean and max group sizes, followed, in decreasing order, by FS-On, FS-Off, and CT. When the distribution of group sizes is considered in terms of the percentage of trees in each group, there is a large difference between SGR and the other treatments. Not only did SGR have a much smaller proportion of isolated trees (30.7% vs 77.5%, 76.7%, and 68.9% for FS-Off, CT, and FS-On, respectively), but it also had a much greater proportion of trees in large (10-19 trees) and very large groups (20+ trees) with 9.4 % and 26.6%, respectively. None of the other treatments had groups in either of these two size classes and therefore their structures were only comprised of isolated trees or small to medium sized groups while SGR created a full range of tree group sizes (Table 4.2; Figure 4.3d).

Table 4.2. Post-treatment percentage of total stand area occupied by isolated trees, groups and opening, mean and max groups sizes in each treatment. The distribution of group sizes is given as a percentage of the total number of tree. SGR is the small group retention treatment, FS-On and FS-Off are the free selection ghost on and free selection ghost off treatments, and the CT is the commercial thinning treatment.

	SGR	FS - Off	FS - On	CT
Stand Area - Isolated Trees (%)	6.3	13.4	9.9	17.3
Stand Area - Groups (%)	6.2	5.1	8.2	7.7
Stand Area - Openings (%)	87.5	81.5	82.0	75.0
Stand Area >9 m From a Tree (m^2/ha)	535.5	70.7	29.0	23.0
Mean Group Size (# of trees)	14.9	2.6	2.8	2.3
Max Group Size (# of trees)	52.0	6.0	9.0	4.0
Percent of trees				
Isolated Trees (%)	30.7	77.5	68.9	76.7
Small Groups 2-4 (%)	22.6	21.8	27.7	23.3
Medium Groups 5-9 (%)	10.6	0.8	3.3	0.0
Large Groups 10-19 (%)	9.4	0.0	0.0	0.0
Very Large Groups 20+ (%)	26.6	0.0	0.0	0.0

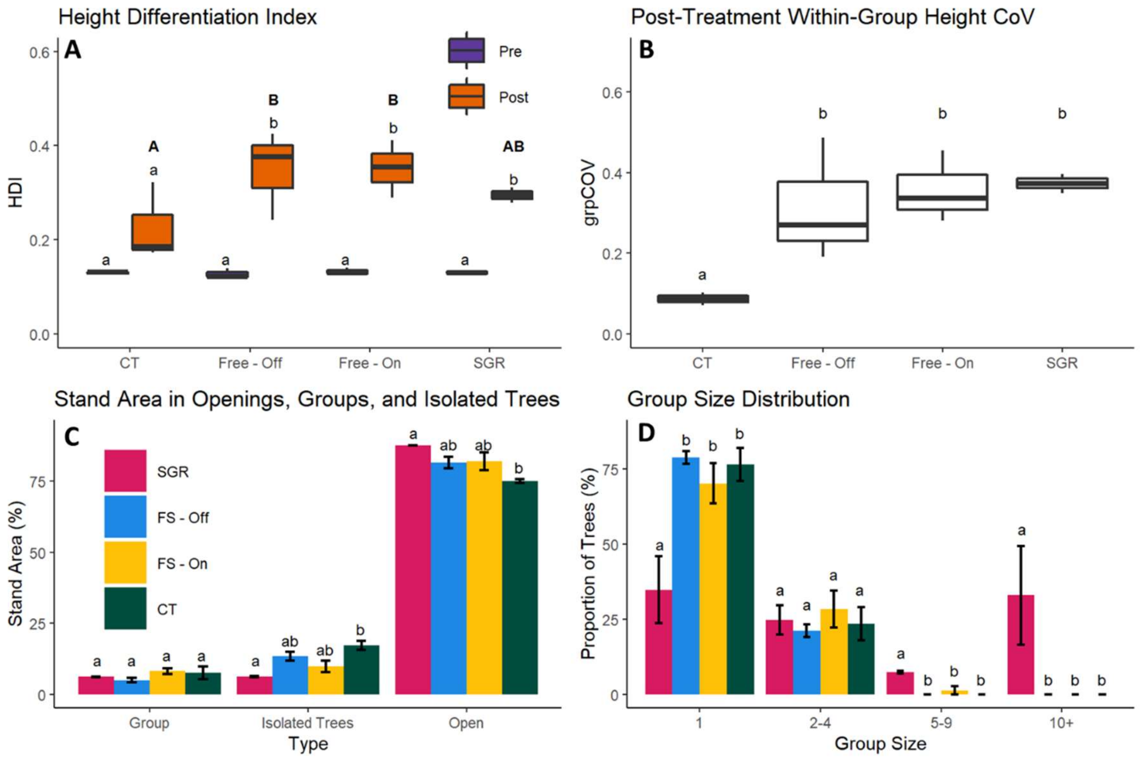

Figure 4.3. A) Mean height differentiation index (HDI) for each plot split by treatment and time. Large HDI values indicate greater height variability between a tree and it's three nearest neighbors. Lower case letters indicate significant differences between pre and post-treatment while uppercase letters indicate significant differences between prescriptions post-treatment. B) Tree height coefficient of variation within groups (grpCOV) for each post-treatment plot. This plot level value was calculated by averaging the values of each unique group with the plot and larger values indicated a greater coefficient of variation in height among trees in a group. Letters indicate significant differences between treatments C) Post-treatment stand area occupied by groups, isolated trees, and non-treed openings. Letters indicate significant differences between treatments. D) Post-treatment proportion of trees found as isolated individuals and small, medium, and large groups. Letters indicate significant differences between treatments. SGR is the small group retention treatment, FS-On and FS-Off are the free selection ghost on and free selection ghost off treatments, and the CT is the commercial thinning treatment.

4.3.3 Tree Spatial Patterns

Following treatment, the SGR plots had a clustered spatial pattern while the two FS treatments and the CT treatment had dispersed spatial patterns based on the Clark-Evans test. Post-treatment pair correlation functions show that SGR resulted in significant aggregation of live trees across all lag distances (0 to 25 m), while the CT treatment resulted in dispersion up to ~5m and a random pattern thereafter (Figure 4.4a). The FS-Off treatment also resulted in dispersion up to ~4m, but the FS-On treatment resulted in a random pattern at lag distances <1m, a dispersed pattern from 1 to 4m, and a random pattern thereafter. Looking at the pattern of only commercial sized trees (Figure 4.4b), the SGR treatment created aggregation from 5 to 15 m lag distances suggesting that the aggregation seen from 0 to 5 m and from 15 to 25 m for all live trees (Figure 4.4a) is driven by the aggregated retention of smaller, pre-commercial sized trees. Commercial trees in CT were dispersed up to about 4m and were random thereafter, while those in FS-On and FS-Off were randomly located at all analyzed scales (Figure 4.4b).

The pooled multitype pair correlation function between pre-commercial (< 22.9 cm DBH) and commercial trees showed that SGR resulted in significant aggregation between commercial and pre-commercial trees from 3 to 14 m (Figure 4.4c). In contrast, both the CT and FS-Off caused dispersion up to ~4 m. In the FS-On treatment, the spatial relationship between retained pre-commercial and commercial trees was random at all tested scales.

Subtracting the pooled, commercial tree pair correlation function post-treatment from the pre-treatment showed that both FS treatments fall within the Monte Carlo simulation envelope at all scales. This indicates that the spatial selection of which commercial trees to retain and which to harvest was random and, therefore, aggregation of commercial-sized trees was not increased. Similarly, the CT treatment fell within the simulation envelope at all lag distances other than 3 to 4 m, which reflects increased dispersion resulting from the space-based prescription. In contrast, the SGR treatment significantly increased commercial tree aggregation at intermediate lag distances (5 to 14 m; Figure 4.4d).

To further understand the treatment effect on the spatial pattern, the distributions of distance to the nearest live tree (DTL; Figure 4.4e) and the nearest neighbor distance (NND; Figure 4.4f) were evaluated. The DTL distribution was nearly identical between the two FS treatments while the distribution for the CT treatment is slightly shifted, indicating a slightly greater mean spacing between trees. The peak of the CT curve is ~5.5 m which is very close to the 4.9 m spacing specified in the prescription. The lower peak and long tail for the SGR DTL distribution shows that this treatment was successful in generating larger openings and more area further than 5 m from a tree than the other treatments. The NND distribution shows a sharp peak at ~1m in the SGR treatment due to large groups of very closely spaced saplings that are dominating the spatial pattern. Once again, the two FS treatments have similar left skewed distributions and peaks around 4 m, however the fact that FS-On curve is above the FS-Off curve at low distances (<4 m) is reflective of greater fine-scale aggregation of trees. Finally, the CT distribution is approximately normal with a peak around 5.5 m confirming a highly uniform spatial pattern.

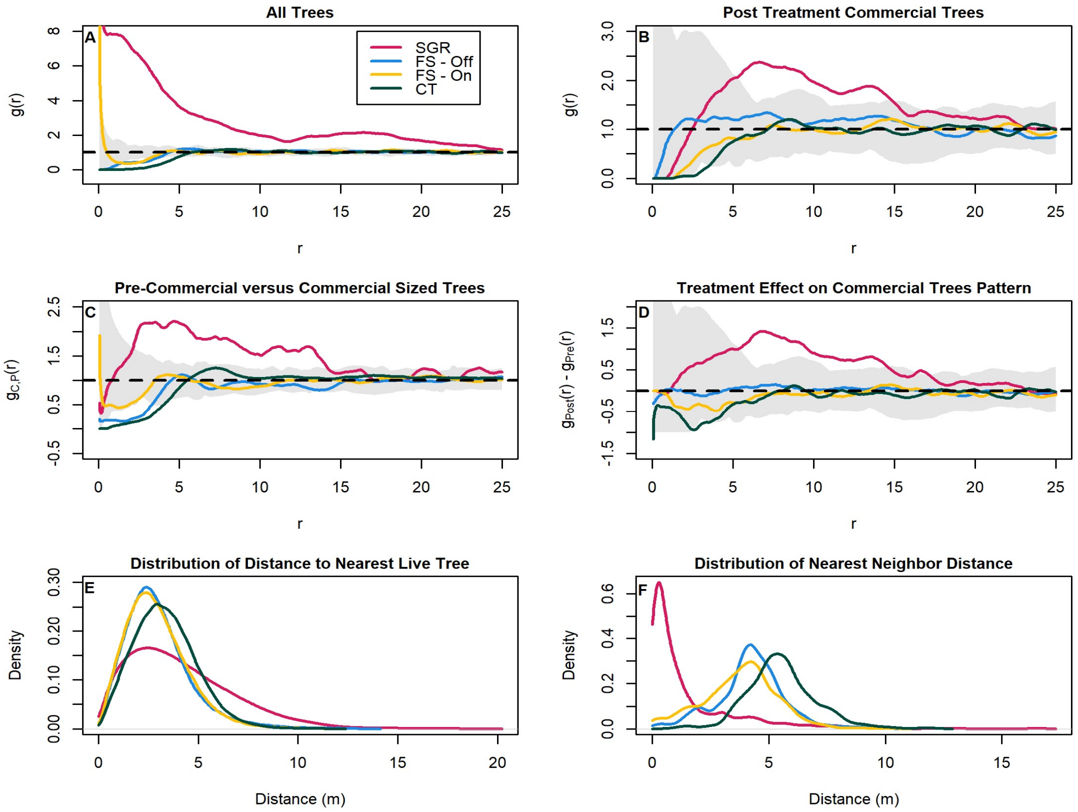

Figure 4.4. Pooled-point pattern statistics for each treatment. Combined pair-correlation function for all post-treatment live trees (A) and post-treatment commercial sized (>22.9 cm dbh) trees (B). Pooled multi-type pair correlation function showing the level of aggregation or dispersion between post-treatment pre-commercial and commercial sized trees (C) and the treatment effect on the spatial pattern of commercial trees pre and post-treatment (D). When the colored line is not contained within the grey shading this is evidence of either clustering or dispersion based on the 95% confidence interval generated by a pointwise Monte Carlo test. For plots A-C g(r) > 1 indicates aggregations and g(r) < 1 indicates dispersion, but for panel D the cutoff for either increased or decreased aggregation is 0 as the plot is the post-treatment commercial tree pair correlation function subtracted by the pre-treatment commercial tree pair correlation function. Post-treatment distribution of the distance to nearest live tree (E) and the nearest neighbor distance (F) for all live trees are also shown. SGR is the small group retention treatment, FS-On and FS-Off are the free selection ghost on and free selection ghost off treatments, and the CT is the commercial thinning treatment.

4.3.4 Crown Fuels, Winds, and Potential Fire Behavior

All treatments resulted in significant reductions to canopy fuel load (CFL) and canopy bulk density (CBD) while increasing canopy base height (CBH; Table 4.1). The SGR treatment resulted in the greatest reduction in the CFL and CBD and had the lowest post-treatment BA

(Table 4.1). The two FS treatments and the CT treatment retained similar BA and had similar CFL and CBD following treatment. The SGR treatment also resulted in the greatest increase to the CBH which was raised from 2 m up to 10 m (Table 4.1). In comparison, FS-Off increased CBH from 2 to 4 m, FS-On from 2 to 6.7 m, and finally, CT increased CBH from 2 m to 8.3 m (Table 4.1).

Simulated vertical wind profiles were substantially altered by the structural changes associated with the treatments. Pre-treatment wind profiles were similar across treatments and showed a moderate increase in velocity through the mid-canopy space (Figure 4.5d). Post-treatment the U-velocity increased throughout the vertical profile compared to pre-treatment and differences between treatments were evident (Figure 4.5d-e). In particular, wind speeds at all heights were greater in the SGR treatment due to its lower BA, CFL, and larger opening sizes. The wind profiles for the two FS treatment were similar in shape but FS-On resulted in greater velocities. The shape of the CT treatment showed a greater difference between the velocity in the upper and lower canopy space with is indicative of stronger sub-canopy winds caused by lower drag near the surface. The reduction in drag is due to the lower number of sapling and pole sized trees retained in this treatment.

Each treatment modified fire behavior by significantly reducing simulated canopy fuel consumption and mean fireline intensity as compared to pre-treatment (Table 4.1; Figure 4.5b - c), however there were no significant differences in fire behavior among the treatments. Pre-treatment simulations resulted in 85 to 100% crown fuel consumption (Table 4.1; Figure 4.5c). In contrast, the thinning treatments resulted in stand level mean canopy consumption from 16.8 to 19.3% (Figure 4.1). Visual inspection of simulations indicates that the reduction in canopy consumption was associated with a switch from an active crown fire to the individual tree and small group torching. Large tree (≥ 22.9 cm DBH) canopy consumption was reduced from 29.7% to 44.2% in the pretreatment stands to 14.3% to 16.5% in the post-treatment stands (Table 4.1). Fire rate of spread (ROS) was also reduced by treatment for all simulations with open wind speeds >2 m/s. At the lowest open wind speed, predicted ROS was similar pre- and post-treatment however, mean FLI and canopy fuel consumption were substantially reduced following treatment.

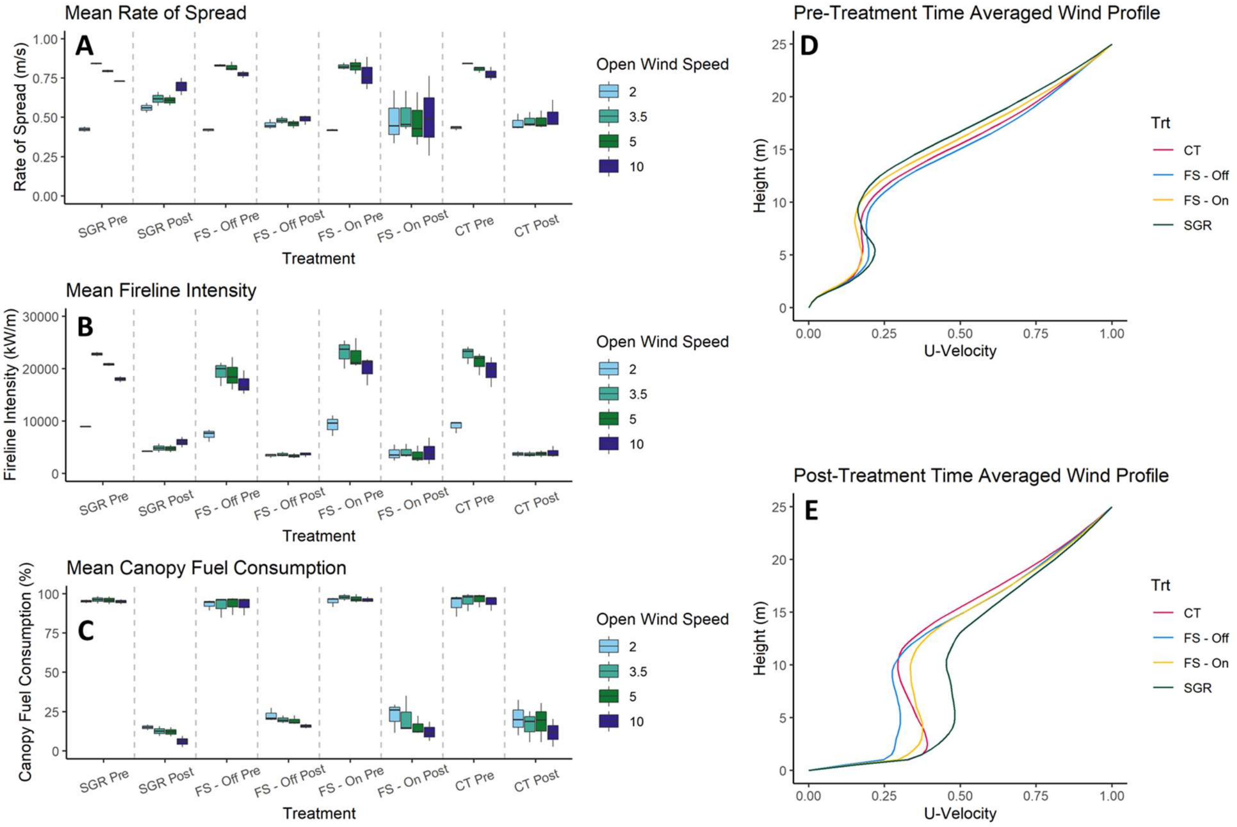

Figure 4.5. Boxplots showing the mean rate of spread (A), mean fireline intentity (B), and mean canopy fuel consumption (C). Within each treament group wind speed increased from 2-10 m/s as you move left to right. Pre (D) and post-treatment (E) time averaged vertical profiles of the normalized horizontal wind velocity (U-velocity) just prior to fire ignition. SGR is the small group retention treatment, FS-On and FS-Off are the free selection ghost on and free selection ghost off treatments, and the CT is the commercial thinning treatment.

4.4 Discussion

This work indicates that similar reductions in stand-level crown fire behavior are achieved regardless of the specific spatial pattern of retained trees. This suggests that forest managers have significant flexibility in the design of treatments which seek to simultaneously reduce crown fire hazard while meeting other land management objectives. Such flexibility is critical as managers are increasingly interested in the use of forest treatments to enhance forest resilience through increased structural complexity and the promotion of old growth structures, and the results show there are opportunities to balance multiple, potentially disparate, objectives such as wildlife habitat improvement, timber production, and the reduction of wildfire hazard (Reynolds et al. 2013, Underhill et al. 2014, Graham et al. 2015, Hessburg et al. 2015, Addington et al. 2018, Stephens et al. 2021). Despite concerns that conflicts may exist between some of these objectives (Stephens et al. 2021), this work found support for the idea that treatments that create horizontally and vertically complex forests (e.g., FS-off, FS-on, and SGR) result in reductions in crown consumption, which are comparable to reductions observed in traditional fuel hazard reduction treatments (CT). It should be noted, however, that the simulations did predict greater post-treatment ROS and FLI for the SGR treatment as compared to both CT and the two FS treatments. This difference was driven by both faster midflame windspeeds and the enhanced proportion of grass fuels in SGR due to the more open forest structure. The potential for tree thinning to increase ROS has been frequently noted (e.g., Agee et al. 2000, Reinhardt et al. 2008), however these changes did not translate to increased mean canopy consumption (a proxy for fire resistance).

These results suggest that under a given set of environmental conditions, stand level canopy fuel load is a primary driver of crown fire behavior and that the fine-scale, spatial arrangement of this fuel is of secondary importance in terms of driving fire behavior. This has been shown in a previous simulation study where spatially heterogenous ponderosa pine restoration treatments reduced potential fire behavior (Zeigler et al. 2017) as well as empirical work that has found a variety of treatment approaches result in significant reductions to fire severity due to reduced surface and canopy fuel loads (e.g. Waltz et al. 2014, Kalies and Yocum Kent 2016, Dodge et al. 2019, Johnson and Kennedy 2019, Jain et al. 2020a). However, there are certainly potential physical mechanisms by which the spatial arrangement of canopy fuels could influence potential crown fire behavior and effects. Groups containing a mixture of tree sizes can enable vertical fire spread (Johnson and Kennedy 2019) and larger and denser groups may be more susceptible to surface to crown fire transition (Ritter et al. 2020). In the present work these finer scale effects did not significantly impact the mean stand level canopy consumption as their effects were evidently overshadowed by reduced CFL and CBD, increased stand level CBH, and greater horizontal complexity that limited active crown fire potential. It is particularly notable that similar fire behavior was observed between the FS-Off and FS-On treatments, given that these stands differed in their spatial relationship between sapling/pole sized trees and commercial sized trees and their mean CBH (4 m vs. 6.7 m, respectively). Further, in the SGR treatment large groups of saplings were retained beneath commercial-sized trees but mean large tree crown consumptions remained similar to all other treatments. The fact that this increased co-mingling of different tree sizes (i.e., greater vertical fuel continuity) did not increase mean crown fire behavior suggests that land managers may be able to realize the habitat and ecological benefits associated with vertical heterogeneity without increasing stand level crown fire hazard. Though this finding is a direct contrast to the typical understanding that vertically continuous fuels (‘ladder’ fuels) increase crown fire behavior by enabling surface to crown fire transition, it may be the case that when large horizontal discontinuities exist between tree groups this increased risk of surface to crown transition does not result in increased stand level canopy fuel consumption.

Though large tree (>22.9 cm DBH) canopy fuel consumption did not change across treatments, the potential for localized large tree torching may warrant management attention in certain situations. For example, in situations where large trees are locally rare, or of high ecological or cultural significance (Brown et al. 2019, Flanary and Keane 2020, Mobley and Eldridge 1992), additional steps can be taken to protect individuals. By removing adjacent and subordinate trees around these highly valued trees so that they are retained as isolated individuals, crown torching will be less likely due to increased convective cooling (Ritter et al. 2020). In other cases, land managers may want to leverage natural disturbance dynamics (i.e., fire caused mortality) to accelerate the restoration of historical forest structure and pattern (Larson et al. 2013, Huffman et al. 2020). In this context, the potential for fine-scale group torching may be an acceptable, or even desirable, treatment outcome as patchy overstory mortality will enhance structural complexity, create snags that provide valuable wildlife habitat, and generate non-treed openings that will enhance understory plant diversity and provide favorable regeneration sites for shade-intolerant tree species (Bigelow et al. 2011, Matonis and Binkley 2018, Jain et al. 2020b).

4.4.1 Treatment Effects on Spatial Stand Structure

The common structural goal of the SGR, FS-On, and FS-Off treatments was to increase horizontal heterogeneity through the deliberate creation of distinct groups of trees to restore elements of historical structure, improve wildlife habitat, and enhance resilience to fire and mountain pine beetle. In contrast, the CT treatment typifies treatments intended to increase timber volume production and reduce fire hazard by introducing regular spacing trees of trees and preferentially removing smaller, non-dominant trees. The studied treatments were generally successful in moving the stands towards each of their structural objectives and the structures created by each treatment were distinctly different from one another. However, the FS treatments did not fully meet their objective for spatial aggregation and the creation of large canopy openings. This suggests that these prescriptions needed to be more explicit in their creation of large tree groups and openings. This need to write explicit instructions on how, and potentially where, large groups and openings should be created has been observed in other studies in spatially complex forest treatments (Churchill et al. 2013, Maher et al. 2019).

Though the FS treatments resulted in an overall random pattern rather than an aggregated pattern, it is important to consider that spatial aggregation is just one potential measure of heterogeneity, and failure to create statistically significant tree aggregation does not necessarily mean that a treatment has failed to enhance resilience or restore elements of historical structure. In fact, spatial reconstructions have shown that historical horizontal spatial patterns in dry conifer forests were not always aggregated and had spatial patterns ranging from highly aggregated to random (e.g., Abella and Denton 2009, Sanchez Meador et al. 2011, Clyatt et al. 2016). Furthermore, the often-described historical pattern of isolated trees, tree groups and openings (Larson and Churchill 2012) does not preclude a spatially random distribution of trees, particularly when the mean group size is small (i.e., 2-4 trees). This was the case in CT and both FS treatments which created stands with small mean group sizes, a spatial pattern which aligns with many observations of natural spatial patterns in dry conifer forests in the southern Rockies

(Sanchez Meador et al. 2011, Brown et al. 2015, Rodman et al. 2016), northern Rockies (Clyatt et al. 2016,), the Sierra Nevada Mountains (Jeronimo et al. 2019), and eastern Oregon (Churchill et al. 2017). Given the wide range of spatial patterns associated with historical/resilient forests, I suggest that ‘horizontal heterogeneity’ need not be conflated with ‘statistically significant evidence of spatial aggregation’. Rather, metrics such as distribution of groups sizes, the proportion of the stand in isolated trees, groups and openings, and the size distribution of openings are better suited to evaluate the success of a prescription in creating structural heterogeneity, enhancing resilience, and/or emulating historical forest patterns. Not only are these metrics directly tied to the ecological functioning of a stand, but they can also be tabulated in real time by marking crews allowing treatment outcomes to match objectives more closely (Maher et al. 2019).

It is important to consider that the findings reflect the short-term impacts of these treatments, and forest structure will change through time as trees grow and stand development progresses. For example, the growth of smaller understory trees can increase vertical fuel continuity. This may be particularly important in the future for the FS-On treatment as there was significantly greater spatial co-mingling of pre-commercial and commercial-sized trees when compared to the FS-Off treatment and, therefore, a disproportionate increase in crown fire hazard may occur as these smaller trees grow. In addition, increasing horizontal connectivity between trees as their crown elongate laterally will not only increase the number and size of groups, but will potentially increase them to greater torching risks as large tree groups may be more susceptible to surface to crown transition than small groups or isolated individuals (Ritter et al. 2020). Further changes in forest structure and fire hazard among the treatments may also occur due to differences in both the quantity and spatial distribution of regeneration as the stands develop. Though some variability in the spatial pattern and density of regeneration is likely due to variation in grass cover (Pearson 1942, Abella and Denton 2009) and heterogeneity of the light environment (Cannon et al. 2019), overall regeneration densities are expected to be high across all treatments as early season moisture and warm growing season temperatures in the Black Hills generate conditions highly suitable to Ponderosa pine regeneration (Sheppard and Battaglia 2002). Therefore, like treatments in other dry conifer systems, subsequent mechanical treatment or prescribed fire/managed wildfire will be necessary to maintain treatment effectiveness (Battaglia et al. 2008, Jain et al. 2012, Tinkham et al. 2016). Future research on these plots will monitor tree growth, regeneration, and fuel dynamics to assess treatment longevity as well as the tradeoffs for timber volume production and fire behavior.

4.4.2 Implications for Silviculture and Forest Management

Generally speaking, traditional silviculture treats stands as discrete units with a uniform set of characteristics as this is operationally efficient and is well suited to managing for the optimal utilization of growing space to maximize volume accumulation in future crop trees (Puettmann et al. 2012, O'Hara and Nagel 2013, Fahey et al. 2018). In shifting the focus from production and consistent, predictable yield towards management for ecological function and ecosystem resilience, there is a new paradigm in forestry (Palik et al 2020) that seeks to enhance with-in stand variability and to create particular structural features (e.g., isolated trees, groups of trees, stand openings) that are defined based on their spatial location. The SGR and FS treatments evaluated in this work represent this ongoing shift towards an ecological approach to silviculture based on the creation and maintenance of spatial complexity forest structure while managing for other resources. Under this paradigm, land managers must consider many factors, such as the spatial aspects of tree growth and regeneration, as well as the spatial aspects of potential fire behavior considered in this work. For example, certain wildlife species prefer the continuous vertical foliage created by tree groups with a multi-layered canopy and mixture of tree sizes (Reynolds et al. 1992, Stephens et al. 2014), while such groups may be viewed as hazardous from a fire behavior perspective due to the vertical continuity of crown fuels (Graham et al. 2004, Johnson and Kennedy 2019). Similarly, large groups of trees were a key component in some historical forest structures (Ng et al. 2020) but may also increase the risk of MPB mortality (Buonanduci et al. 2020, Negron 2020), drought stress (van Mantgem et al. 2020), and torching potential (Ritter et al. 2020). These conflicting considerations speak to the complexity associated with the implementation of these approaches and suggest the need to carefully consider the various tradeoffs.

This work fits well into the context of these shifting paradigms in forest management and provides some additional confidence that a variety of stand level treatment approaches can be used to achieve fire hazard reduction and ecological restoration. The fact that low canopy consumption was observed for all treatments shows that they all significantly increased stand level resistance and resilience to fire. However, the fact that greater ROS and FLI were seen in the SGR treatment underscores the idea that land managers need to consider the spatial context of treatments when deciding which treatment approach is best. For example, when implementing treatments near the wildland-urban interface or other values-at-risk it may be desirable to utilize treatments that promote fire behavior that is more amenable to fire suppression (lower ROS and FLI). In contrast, treatments in areas further from the wildland-urban interface or other values-at-risk could shift more towards the restoration end of the continuum in order to capture some enhanced ecological benefits and move ecosystems towards historical structure and dynamics. It is also important to recognize that historically a wide variety of stand structures existed within frequent-fire landscapes because of the interaction between complex fire regimes and environmental factors (Graves 1899, Brown and Cook 2006, Brown et al. 2008, Reynolds et al 2013, Brown et al. 2015, Hessburg et al. 2015, Churchill et al. 2017, Addington et al. 2018, Battaglia et al. 2018). Therefore, restoration of landscape-scale structural heterogeneity may be best achieved through the application of a large range of prescriptions that generate a variety of stand structures across landscapes. Overall, this work supports the idea that using different treatment approaches in concert can achieve numerous ecological and societal objectives and suggests that potential differences in fire behavior may be useful to guide spatial decision-making (Stephens et al. 2021).

4.5 Conclusion

These results indicate that the FS and SGR forest treatments that were designed to create spatially complex, multi-aged stands provided similar reductions to wildfire hazard as the space-based, thin-from-below CT treatments which created a more regular forest structure. These findings suggest minimal fire behavior tradeoffs between treatments that create significant heterogeneity and treatments that create uniform structures which is extremely relevant given the increasing promotion of ecologically based silvicultural systems (Larson and Churchill 2012, Reynolds et al. 2013, Addington et al. 2018, Cannon et al. 2020, Stephens et al. 2021). Such systems (e.g., variable density thinning, Carey 2000; free selection, Graham et al. 2007; ICO, Churchill et al. 2013) aim to generate forests with heterogenous tree spatial patterns that will emulate historical forest structures, promote habitat complexity, generate multi-aged structures, and enhance recovery pathways following disturbance (O’Hara 2014). Owing to the potentially negative ecological effects and risks to human lives and property of high severity fire in dry conifer ecosystems the identification of silvicultural systems which can simultaneously achieve social and ecological benefits is extremely relevant to forest management (Stephens et al. 2021). Though these findings suggest that some minor tradeoffs may exist, treatment effects differed more greatly between metrics of fire behavior that relate to fire suppression efforts (i.e., ROS, FLI, flame length) rather than ecological concerns (i.e., canopy consumption). Together, these findings point to the utility of thinning treatments that enhance structural complexity in reducing potential stand-scale fire behavior while simultaneously achieving a host of other ecological benefits.

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CHAPTER 5: CONCLUSION

The preceding chapters utilized a scale-based approach to evaluate how the horizontal and vertical spatial arrangement of trees influences potential fire behavior, crown fire transition, and canopy fuel consumption. Chapter two focused on changes in fire behavior associated with group-scale variability, while chapters three and four evaluated fire behavior at larger scales and in forests with greater horizontal and vertical complexity. By progressively increasing in both scale and level of structural complexity, these studies aimed to disentangle the mechanisms driving crown fire behavior and understand how these mechanisms influence the outcomes of real-world silvicultural treatments. The study presented in chapter two clearly showed that both smaller horizontal separation distances between tree crowns and increasing group size substantially impacted the amount of heat transferred from a spreading surface fire into the canopy. This altered vertical heat transfer resulted in marked changes to the surface fireline intensity (FLI) required to ignite tree crowns and showed how fine scale spatial structure alters crown fire hazard. Chapter three then extended these findings to evaluate the interactive effects of vertical and horizontal fuel arrangement on crown fire transition and overstory tree consumption. These findings confirmed the influence of canopy base height on crown fire transition at low surface FLI, but there was an interactive effect between vertical and horizontal fuel continuity in the overstory at higher surface FLI. This meant that at moderate to high surface FLI groups with low canopy base height and vertically continuous fuel but less horizontal continuity sustained less consumption than groups with lower vertical continuity but high horizontal continuity. Finally, in chapter four, stand scale impacts of the vertical and horizontal arrangement of trees were evaluated based on real treatments implemented on the Black Hills

Experimental Forest. Overall, this study showed that greater levels of complexity and tree aggregation did not result in increased crown fire hazard, despite the presence of vertically continuous fuels and so-called ladder fuels.

Though aspects of forest structure like canopy base height and canopy bulk density have long been understood as primary drivers of crown fire behavior, there has been less attention given to the influence of fine-scale spatial structure and interactions between the horizontal and vertical distributions of fuel. The general framework used to determine crown fire transition was described by Van Wagner (1977) and is based on the idea that fire spread from the surface into tree crowns (crown fire transition) be predicted based on a simple, aspatial characterization of the fuels complex where mean canopy base height is the key determinate of transition potential. The results presented in chapter two and three highlight limitations of aspatial approach, particularly under moderate fire conditions. Though the Van Wagner (1977) model has driven decades of empirical fire modeling and has clear merits and demonstrated utility, chapters 2 and 3 show physical mechanisms that lead to its breakdown under heterogeneous canopy fuel conditions. This breakdown has major implications for the design of forest treatments for multiple objectives as the traditional understanding of crown fire transition would suggest that vertically complex tree groups and stands represent greater fire hazard. Additionally, this more nuanced understanding of interactions between canopy structure and crown fire transition is important to our knowledge the mechanisms driving fire behavior, severity, and, ultimately, forest structure in fire-prone ecosystems.

5.1 Traditional Models of Crown Fire Transition

Though this work shows additional nuance is required in our understanding of crown fire behavior in highly heterogenous stands, it also supports the utility of traditional empirical models that have long been used to support fire management and assess fire hazard reduction treatments. Similar to previous empirical and semi-empirical frameworks these results highlight the importance of parameters like canopy base height surface FLI on crown fire transition. However, the results also indicate that the influence of these parameters may be altered when comparing between stands with very different horizontal fuel distributions, especially at fine scales. As shown in chapter 2, torching thresholds are expected to change depending on the local fuel conditions around a particular tree such that isolated individuals are more difficult to ignite than trees within groups of any size, and this effect is amplified as group size increases. Further nuance was added in chapter 3, where canopy base height (or 'ladder fuels') was important at low FLI, but as surface FLI increased the effects of canopy base height and vertical fuel continuity were mediated by the horizontal connectivity of the overstory fuel.

A direct comparison was made in chapter 2 between the simulated torching threshold in WFDS and the predicted torching threshold based on the Van Wanger (1977) equations. This comparison was made based on results from the 19-tree groups with overlapping crowns as these groups were most similar in structure to the tree plantations used to develop the Van Wagner (1977) model. This comparison showed that in WFDS the surface FLI require for tree torching was about 4 to 12 % greater than the predicted surface FLI from Van Wagner (1977). Given the inherent complexities in predicting fire behavior and the significant differences in methodologies between the two models, this suggests very good agreement between the two approaches in the case of simplistic canopy fuel structures. While this was far from a complete model validation effort, it provides additional confidence in the ability of WFDS to independently predict surface to crown heat transfer and crown ignition processes in alignment with empirical observations.

5.2 Group-Scale Mechanisms Driving Fire Transition and Canopy Consumption

The work herein shows that the spatial aspects of the canopy fuel complex, including horizontal continuity (or tree spacing), are important in predicting crown fire transition, particularly in cases of complex forest structure and moderate surface FLI. Some of the potential mechanisms responsible for canopy fuel structure modifying crown fire transition have been identified in previous theoretical work. For example, as was observed in chapter three, greater canopy bulk densities are associated greater ease of fuel ignition due to alterations to convective heating that occur because of less convective cooling within the canopy space and greater plume temperatures due to reduced mixing of cooler, ambient air (Tachajapong et al. 2009, Ritter et al. 2020). Once ignition occurs, the presence of densely packed trees also allows for increased fire-fire interactions in the form of radiation feedback among the adjacent crowns. This feedback has been shown to increase both the rate and total amount of fuel consumption in lab experiments using wood cribs (Kamikawa et al. 2005) and burning pools of volatile, flammable gases (Liu et al. 2007, 2009, 2013), as well as modeling studies on the porous, elevated fuels of simulated wildland shrubs (Dahale et al. 2015, Pahdi et al. 2017). The findings of chapters three and four support these experimental results by highlighting the role of closely spaced overstory trees on both crown fire transition and total canopy fuel consumption. Together these findings suggest that local aggregation of trees can result in greater heat transfer from a surface fire to tree crowns and increase the rate and amount of fuel combustion once ignition occurs.

The results presented in Chapter 2 suggest that increases in net energy transfer from the surface fire into tree crowns and the effects of fire-fire interactions did increase crown ignition and crown fuel consumption. However, they also suggested that these factors can be mitigated with relatively small gaps (0.5 to 1 m) between tree crowns. On the one hand, these results highlight the importance of tree spacing on crown fire initiation. On the other hand, they also suggest that either small amounts of natural variation in tree spacing or the deliberate retention of trees with non-overlapping crowns can result in notable changes in fine-scale crown fire behavior. Though present, these effects of crown spacing on surface to crown heat transfer are only relevant at low to moderate surface FLI as high FLI quickly overwhelms the effects of fine scale structure once the flames from the surface fire fully impinge into tree crowns. These findings have clear implications for efforts for managing forest complexity and the utilization of fire to achieve ecological goals like restoring historical forest structure and function.

5.3 Managing for Forest Complexity

Understanding the interactions between three-dimensional forest structure and potential wildfire behavior is important for developing fuel hazard reduction and forest restoration treatments. Not only do the present challenges of increasing wildfire activity and severity demand informed action but shifting paradigms in forest management underscore the need to balance multiple ecological and social objectives in forest planning and treatment design (Stephens et al. 2021). At the project scale, factors such as the spatial pattern of trees (i.e., level of aggregation, number and size of tree groups, and opening sizes and distributions) impact outcomes including wildlife habitat, tree regeneration, understory plant diversity, tree growth rates, disturbance resistance and resilience, and timber production (Bigelow et al. 2011, Reynolds et al. 2013, Larson and Churchill 2012, Matonis and Binkley 2018, Jain et al. 2020). The findings of this work generally show that the perceived tradeoffs between forest treatments that restore the complex spatial structures associated with historical forests (Stephens et al. 2021) can be mitigated, and multiple objectives can be achieved simultaneously. Not only does this give forest managers great flexibility in selecting a particular treatment approach, but it also suggests that drawing a distinct dichotomy between fuel hazard reduction and forest restoration may not be necessary as there is a great deal of overlap between these approaches from a fire behavior perspective.

Looking at the findings of each chapter together, there are several unifying concepts that can drive prescription development depending on specific project goals. For example, individual trees well separated from nearby crowns have lower torching hazard than trees within groups of any size. Therefore, in cases where high value individual trees exist, removing trees from around the individual can provide the greatest possible fire protection. Similarly, in cases where structurally complex tree groups are desirable for habitat benefits or the restoration of historical forest structure, the overall hazard associated with that group can be mitigated by reducing horizontal connectivity among the overstory trees in the group. One additional consideration is that horizontal crown expansion following treatment will quickly reduce the distance between adjacent tree crowns so creating larger separation distances will likely increase treatment longevity. Further, the differences in torching thresholds among groups comprised of different numbers of trees suggest that forest treatments that create a diversity of tree group sizes are more likely to sustain heterogenous fire effects than either homogenous stands or stands comprised of a single type of group. This type of pattern-process feedback whereby heterogeneity begets heterogeneity may help explain some of the mechanisms that lead to the maintenance of complex forest structures and aggregated tree patterns in historical frequent-fire forests (Ritter et al. 2020). Further, these feedbacks underscore the use of prescribed and managed fire in either maintaining or accelerating the development of spatial heterogeneity associated with historical forest structure.

In addition to supporting management for forest heterogeneity and the use of prescribed and managed fire, chapter four presents spatially explicit measurements of forest structure that provide some additional guidance in the development of marking guides to ensure treatment outcomes match treatment objectives. Specifically, when large openings and/or large aggregations of trees are desired, explicit instructions should be provided to marking crews to achieve these structures. The tendency for tree markers to hesitate to create these structures was also observed by Churchill et al. (2013) and Maher et al. (2019). Therefore, targets in the form of group size distributions combined with clearly marked areas for large openings are needed to meet objectives. An additional advantage is that methods have been developed for tree markers to track these aspects of spatial stand structure in real time (Maher et al. 2019). This contrasts with more ambiguous objectives like ‘create aggregated tree patterns’ which are difficult to implement without more explicit guidance and cannot be assessed statistically without mapping the locations all trees in the post-treatment stand.

5.4 Limited Fire Behavior Tradeoffs with Heterogeneous Forest Structures

Though chapter four showed similar reductions in canopy consumption between treatments that created disparate forest structures, there were important differences in the simulated fire rate of spread (ROS) and FLI. Stands with aggregated structures, large openings, and higher proportions of grass fuels resulted in increased ROS and FLI compared to treatments with less heterogeneous structures. Although these alterations did not increase canopy consumption, greater ROS and FLI are both associated with fire suppression difficulty. Given that heterogeneous treatments can result in increased ROS forest managers should consider their location during the planning phase. For example, near wildland-urban interface areas where facilitating fire suppression is a major objective, treatment approaches likely to mitigate ROS and FLI are likely more appropriate. In contrast, areas where management goals are more aligned with restoring ecological dynamics and pattern-process feedbacks, are better suited for treatments that recreate complex historical forest structures at the expense of potential increases to ROS and FLI.

Despite the potential need to consider the context-dependent implications of increased ROS and FLI, the overall results of these studies illustrate that treatments that create complex forest structures (particularly vertical heterogeneity) do not come with profoundly different risks of tree torching. Not only does this suggest their utility in achieving ecological goals like habitat restoration and increased forest resilience, but it also suggests that they don't result in the enhanced risks associated with crown fire, such as increased ember production. This increased operational flexibility for forest managers significantly enhances potential treatment options without concerns about substantial differences in potential fire behavior.

5.5 Final Thoughts

Overall, this work suggests that there are limited fire behavior tradeoffs when creating complex forest structures rather than more simple, uniform stand structures. Therefore, forest managers planning treatments have a good deal of flexibility in achieving multiple objectives. Though there were increased ROS and FLI in the treatments that created higher levels of tree aggregation these treatments did not sustain higher levels of canopy consumption and therefore achieved similar reductions in crown fire hazard and potential fire severity as the other treatment approaches. The results presented in chapters 2 and 3 suggest several ways in which crown fire behavior can be mitigated by limiting crown interlock within tree groups. Inter-crown spacing allows for convective cooling, reduced plume temperatures, and limits fire-fire feedbacks that occur when numerous trees combust in close proximity. As these mechanisms are not considered in operational crown fire transition models, such models cannot fully characterize torching potential in complex forests. This is not to say these models are not useful in assessing fire hazard and potential treatment effectiveness, but these results suggest that care should be taken when non-spatial models are used to compare relative changes to potential fire behavior between stands with very different spatial structures. In particular, the results in chapter 3 suggest that the effect of canopy base height on the potential for tree ignition and consumption in the upper canopy is modified based on the density (or inter-tree spacing) within that upper canopy space. Therefore, traditional crown fire initiation models would overpredict the risk of large tree torching and consumption in cases with low canopy continuity. It should still be noted, however, that while aspects of the fuel complex such as load and arrangement are primary drivers of fire behavior and effects, in each of the simulation studies presented here, it was clear that under high flame lengths and extreme fire weather conditions the effect of the fine scale fuel arrangement was substantially diminished.

Greater attention to the role of complex fuel arrangements on crown fire behavior is needed to fully understand the implications of treatments that create these heterogenous forest structures as well as the processes that led to the maintenance of relatively stable forest structure and cover under historical frequent-fire regimes. Continued research utilizing spatial explicit, physics-based models such as WFDS (and FIRETEC; Linn et al. 2002) are useful for further hypothesis development and identification of physical mechanisms controlling fine-scale fire behavior. These modeling approaches account for complex interactions between the fire, fuels and atmosphere and allow for a level of control over the relevant variables that is impossible in the real world. Therefore, they can be used to carefully assess the relative influence of each variable driving fire behavior and conduct experiments that would not be operationally possible due to costs and risks. Despite the promise of these models, research must also continue utilizing precise measurements of wildland fires to both validate model predictions and understand how the physical mechanisms identified in simulation studies play out in the field.

While WFDS, FRETEC, and similar models have been frequently used for such hypothesis development it is important to recognize that these models and the components are in various stages of development and validation. Further comparisons between simulation outputs and well documented wildfires and prescribed fires are one avenue of field scale model validation (Hiers et al. 2020, Gallagher et al. 2021, Mueller et al. 2021). In addition, remote sensing approaches like LIDAR (Jeronimo et al. 2020) and unmanned aerial vehicles (Moran et al. 2019) could be used to test hypotheses like those suggested in the proceeding chapters. These approaches allow for fine-scale quantification of fire effects and therefore could be used to evaluate the impacts of tree arrangement and pattern on potential fire behavior and effects under a range of conditions. Such evaluation has the potential to not only increase confidence in the physics-based fire modeling frameworks, but also serve to greatly enhance understanding of fire patterns and vegetation feedbacks that are highly relevant to forest ecology and wildfire management. With continued investment in projects wherein prescribed fires are carefully documented and highly instrumented (e.g., Stocks et al. 2004, Clements et al. 2007, O'Brien et al. 2015, Hiers et al. 2020, Mueller et al. 2021), the utilization of remote sensing techniques to understand fine-scale patterns of fire effects, as well as the chance of wildfires burning through the increasingly large network of permanently monumented, spatially explicit plots (e.g., Anderson-Teixeira et al. 2015, Lutz et al. 2018), there will be greater opportunities to evaluate spatial fire models and enhance understanding of the complex, fine-scale processes driving wildfire outcomes.

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