THESIS

SIMULATING CUT TO LENGTH FOREST TREATMENT EFFECTS ON FIRE BEHAVIOR OVER STEEP SLOPES

Submitted by

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ABSTRACT

SIMULATING CUT TO LENGTH FOREST TREATMENT'S EFFECTS ON FIRE BEHAVIOR OVER STEEP SLOPES

The increase of wildfire size and behavior in many western U.S. forests is due to increased fuel loads resulting from the past century's fire suppression, logging, and grazing policies of the 20th century, along with compounding climactic changes including increased drought and temperatures. Fuel hazard treatments are the key land management tool used to reduce fire intensity and severity however these treatments are often not possible on steep terrain of over 30% slope. Cable tethered cut to length machinery opens new avenues for managers to treat forests in steep slopes, but there is limited data on how effective the treatments will be. I conducted a numerical experiment using the wildfire model, FIRETEC, coupled with the atmospheric dynamics model, HIGRAD, to understand the complex interactions of wind, topography, and fire behaviors of two cut to length forest treatments on slopes of up to 60%. Results show that treatments can effectively reduce some fire behaviors such as heat release and canopy consumption when compared to untreated forests on slopes. However, increased sub canopy wind penetration along the slopes following treatments results in marginal fire severity reduction regarding biomass consumption and variable results on rates of spread. The results of these numerical experiments indicate that CTL treatment can effectively reduce some fire behavior and severity, however the effects were marginal and additional research is needed to better understand treatment's effects.

ACKNOWLEDGEMENTS

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CHAPTER 1

1.1- INTRODUCTION

Wildfires have increased in size and severity in recent decades (Dennison et al. 2014), raising concerns over increasing socioeconomic costs and the resistance and resilience of forested ecosystems to future disturbances. The increase in fire behavior and effects in western US coniferous forests are due to climatic changes that are tending towards warmer and dryer burning conditions and longer fire seasons, and a legacy of fire suppression, logging, and grazing policies in the 20th century that increased fuel loadings (Covington 2000; Rocca et al. 2014; Jolly et al. 2015; Kalies and Kent 2016; Buotte et al. 2019; Hessburg et al. 2019). Climatic change and past management practices have not only increased the risk of uncharacteristic wildfires, but have altered plant and animal species compositions resulting in reduced biodiversity, created forest structures that are less resistant to insect and pathogen epidemics, and negatively impact a number of ecosystem goods and services (Jain et al. 2012; Battaglia et al. 2018; Pereira et al. 2021). Fuel hazard reduction treatments are one of the principal tools available to land managers to limit the occurrence of large high severity fires, ensure resilient ecosystems and communities, and reduce fire's smoke impacts on human health and loss of life and property (Radeloff et al. 2018; Schweizer et al. 2019).

Fuel reduction treatments utilize silvicultural methods to alter a forest's fuels complex with the ultimate goal of modifying fire behavior to minimize unwanted effects of fires on ecological goods and services, infrastructure, and human health (Stephens et al. 2009; Jain et al. 2012; Martinson and Omi 2013; Kalies and Kent 2016). Fuel reduction treatments can be accomplished through various management activities including managed and prescribed burning, mechanical and hand thinning, grazing and herbicides, or a combination of these (Stephens et al. 2009; Kalies and Kent 2016; Stevens et al. 2016). The concepts governing fuel reduction treatment design were primarily developed at the stand scale [e.g., 10s-100s hectares] and consists of four overarching principles (Agee and Skinner 2005). The first two principles seek to reduce the risk of surface to crown fire transition by increasing the crown base height and reducing surface fuel load. The next principle focuses on reducing the crown fuel load which in turn limits the potential for active crown fire spread. When taken together these first three principles act to reduce the risk of crown fire initiation and spread (Hoffman et al. 2020). The final principle focuses on increasing resistance to future fires by limiting tree mortality through the preservation of large trees of fire-resistant species which can also provide a seed source for post-fire recovery. Although a number of active management approaches can be used to support these principles, they have traditionally been accomplished through the targeted removal of small, shade-tolerant trees, followed by thinning to evenly space the residual overstory trees to a target density, along with prescribed burning to remove surface fuels. Recently, land managers have utilized more flexible treatment designs that do not strictly adhere to the principles of fuel hazard reduction, and instead focus on creating forests that simultaneously seek to restore heterogeneous forest structures while reducing fuel hazards and resulting fire behavior and effects (Millar et al. 2007; Underhill et al. 2014; Tinkham et al. 2017; Ziegler et al. 2017; Ritter et al. 2022). Over the past 20 years, there has been a considerable number of studies that have evaluated fuel hazard reduction treatment efficacy across the western U.S. (e.g., Fernandes and Botelho 2003; Stephens and Moghaddas 2005; Agee and Lolley 2006; Hudak et al. 2011; Safford et al. 2012; Ex et al. 2019; Prichard et al. 2020) using simulation studies or data following wildfire events. Meta-analysis and reviews of fuel hazard treatment efficacy indicate that these treatments can be effective at reducing fire behavior and severity at the stand scale, across a range of ecosystems and treatments (Stephens et al. 2009; Fule et al. 2012; Martinson and Omi 2013; Kalies and Kent 2016). These studies further suggest that fuel treatment effectiveness is greatest for areas that combine thinning and burning, followed by thinning alone, and finally prescribed fire as the sole treatment.

Although fuel treatments have been shown to be effective at reducing fire behavior and severity at stand scales, the size of wildfires often warrants treatment networks that extend the principles of individual stand scale treatments across landscape scales [100's-1000s ha] (Finney et al. 2007; Collins et al. 2013). In theory, extending stand scale treatments to an entire landscape would be effective at reducing landscape fire severity, however, treatments at this scale are not realistic due to physical, managerial, and socioeconomic constraints (North et al. 2015). Previous studies have provided some evidence that networks of landscape treatments can reduce fire severity and improve fire suppression capabilities, however these benefits depend on the proportion of landscape treated and the placement of those treatments (Finney 2001; Kennedy and Johnson 2014; Lydersen et al. 2017). While treatment efficacy can be dependent on topography, weather conditions, scale of analysis, and whether treatments are randomly or optimally placed, studies have found that 10-57% of a landscape requires treatment in order to reduce fire severity and spread (Finney et al. 2007; Cochrane et al. 2012; Lydersen et al. 2017). In the western US, meeting these targets can be especially difficult in mountainous areas which would require treatments to be located on slopes above 30% which are too steep for many traditional treatment methods (Safford et al. 2009; Loudermilk et al. 2014; North et al. 2015). Although there are options for treating on steep slopes such as helicopter thinning, cable logging, or hand thinning, these are often cost-prohibitive at landscape scales, thus hampering a manager's ability to meet landscape fuel reduction targets in many areas (Dow et al. 2016).

In several locations across the western US, land managers are beginning to explore the use of cable-tethered cut-to-length (CTL) approaches to implement fuel treatments on steep slopes which can be applied on slopes up to 60% (Stampfer 2016). These CTL systems operate by tethering harvester and forwarder machinery via cables at the top of the hill such that it is secured to travel a path up and down the hillslope (Figure 1.1). The harvester has a pendulum arm capable of extending to either side to select, cut, and stack trees that are later loaded on a forwarder and removed to a landing. In most systems, the harvested tree is delimbed and the branches are placed in front of the harvester to reduce erosion and soil impacts (Brame et al. 2019). Treatments from CTL result in increased localized surface fuel loads in the harvest roads, so they do not strictly adhere to the principles of fuel hazard treatment design, raising concerns of the treatment's overall efficacy. Yet CTL approaches are appealing for fuel hazard reduction because they effectively increase the proportion of the landscape over which treatments can be implemented, thus allowing managers to meet landscape treatment goals.

Figure 1.1: Images taken of experimental CTL treatment on landscape utilized at Monarch pass, CO. Left image is looking up a path which a harvester traversed, right image is taken from highway allowing visualization of paths cut up the hill and thinning in between paths.

Given the lack of treatments on steep slopes across the western US, there is a paucity of empirical data on how treatment methods on sloped areas might affect wildfire behaviors and effects relative to untreated forests (Pollet and Omi 2002; Loudermilk et al. 2014; Krofcheck et al. 2018). Conceptually, treatment efficacy should be reduced on steep slopes due to the effects of slope to increase fire spread and heat transfer as well as complex interactions between the wind, topography, and vegetation (Anderson 1969; Albini 1985; Dupuy 1995; Finney 2001; Linn et al. 2007; Zardi and Whiteman 2013; Povak et al. 2018; Atchley et al. 2021). It has long been known that fire rates of spread (ROS) are increased on slopes (Rothermel 1972, 1983, 1991; Dupuy 1995; Viegas 2004). This increase in ROS is due to alterations in convective heat transfer by a process called flame attachment whereby the flame front engulfs the unburned fuel, resulting in increased fire spread rates and intensities (Tang et al. 2017). Flame attachment associated with fire spread on slopes can also cause exponential increases in ROS and energy release called "eruptive" or "blow up" fires (Viegas 2006; Viegas and Simeoni 2011; Xie et al. 2017). Another potential cause of reduced treatment efficacy on slopes is through interactions among wind, vegetation, and slope position. As a fire spreads up a slope it will experience greater wind speeds due to the relationship between elevation and wind velocity and decreased drag effects of vegetation leading to increased rates of spread and fire line intensity. Though there are conceptual rationale for reduced treatment efficacy on slopes, there have not been many studies that have assessed this problem. Some exceptions to the lack of studies on treatment effectiveness on slopes are Safford et al. (2009, 2012), finding that treatments on steep slopes were effective at reducing fire severity relative to untreated areas in mixed-conifer forests of California. However, treatments on slopes were less effective than those on flat ground, but it was unclear if this difference was due to the effect of slope on fire behavior alone or because of differences in residual forest structure caused by sloped treatments. Given the interest in utilizing CTL technology for implementing fuel hazard treatments and the lack of empirical data on treatment efficacy on slopes, there is a need to better understand treatment effects on fire behavior across a range of sloped conditions.

In this study, we used the physics-based atmospheric transport/wildfire model FIRETEC to evaluate CTL treatment effects on wind dynamics and fire behavior across a range of slopes. FIRETEC is a coupled fire atmospheric model that allows us to capture the complex interactions between the fuel complex, topography, and the atmosphere that drive fire behavior and effects and represent the heterogeneous nature of the fuels complex associated with various treatments. We simulated CTL treatments and fire behavior in a dry mixed conifer forest, as these ecosystems provide a number of challenges to fire and fuels managers (Agee 1993; Jain et al. 2012; Abella and Springer 2015) and are of great ecological and management interest within the southern Rocky Mountains and across the western US (Addington et al. 2018). The CTL treatments were modeled to mimic recent silvicultural treatments in mixed conifer forests within Colorado. Fire behavior simulations were performed with fuel moisture and wind conditions that represent extreme summer fire weather, with slope and wind aligned to represent a worst-case scenario in terms of potential fire behavior.

1.2- METHODS

1.2.1- Wildfire Model: FIRETEC

All simulations were done using the physics-based model FIRETEC that is coupled with the computational fluid dynamics model HIGRAD to acceptably approximate fire dynamic physics in an Eulerian terrain following coordinate method. The FIRETEC modeling system is a multi-phase 3D transport model that simulates the critical processes thought to control the behavior of wildland fire by predictively solving a coupled set of partial differential equations for the conservation of mass, momentum, energy, and chemical species. The model is designed for high-resolution simulation of atmospheric flows and is based in terms of potential temperatures as a conserved quantity closely related to temperature. FIRETEC is based on a fully explicit, fully compressible atmospheric dynamics model. The turbulence model uses transport equations for turbulent kinetic energy at multiple length scales with a Boussinesq approximation to estimate the Reynolds stresses associated with each length scale, and the Reynolds stress terms are used to close momentum equations. The conservation equations are solved similar to a large eddy simulation, where eddies larger than twice the grid mesh are explicitly solved in a calculation and sub grid-scale eddies are implicitly modeled. This modeling approach allows for understanding the temporal and 3D-spacial evolution of temperatures, velocities, and species' mass.

Detailed physics-based modeling approaches are involved to account for the mesh resolution being designed to capture stand and landscape scale behaviors. Some approximations must be made considering the space and time scales associated with the physics of turbulent combustion, couple heat transfer, and thermal degradation of biomass via drying, pyrolysis, and char oxidation. The variability in the fine fuels complex, for example the needles on a tree, are too fine a scale to be explicitly resolved. Vegetation is instead treated as a highly-porous medium within the 3D numerical grid involving drag-forces of pressure and viscosity for the wind momentum equations and are characterized by mean or bulk properties (e.g. surface area to volume ratio, moisture content, and bulk density). Combustion approximations are made in FIRETEC to represent combustion through a mixing-limited single-step model. Fire is only able to manifest with sufficient quantities of fuel, oxygen, and heat. The method also accounts for numerical cell's mean temperature not being adequate to determine if fuel in the cell is hot enough to burn by using a probability distribution function for the fraction of fuel at sufficiently high temperatures. Radiation heat transfer is a Monte-Carlo algorithm which randomly emits packets of photons from a hot cell to be absorbed by nearby cells, until the spatial distribution of absorbed energy from a given point in time converges.

Although evaluation of FIRETEC is ongoing, there have been a number of efforts in assessing its ability to capture wind flow and fire behavior. FIRETEC has been validated against key fire behavior metrics like ROS for both surface and crown fires, where FIRETEC simulations have been conducted and successfully compared to empirical data of real burns. Experimental surface fires in Florida were performed with pre-fuel sampling conducted and aerial spread rate and intensity data collected during burns to support FIRETEC validation (Bossert et al. 1998). In addition, experimental fires in Australia where spread rate and wind data was collected and compared to simulations which FIRETEC has been shown to be able to accurately capture wind effects on fire ROS (Linn et al. 2005). A large set of experimental fires known as the International Crown Fire Modeling Experiment set has been conducted, and validation has been done against the empirical crown fire data to again demonstrate FIRETEC's ability to accurately capture critical components of wind dynamics and the coupled fire behavior interactions in crown fires (Linn et al. 2012). Crown fire behavior has further been validated using empirical data of measurements from a large set of crown fires in Canada and the U.S. (Hoffman et al. 2015) and another set of crown fires from British Columbia Canada (Hoffman et al. 2016), providing a qualitative check that FIRETEC simulation's ROS behavior consistently falls within expectations of real-world systems across a range of wind behaviors. FIRETEC has been shown to be capable of capturing all essential features of turbulent wind flows for fire propagation over varying forest structures (Pimont 2009), and previous studies have shown the validity of FIRETEC in investigating the impact of fuel structure on wind and fire behavior (Linn et al. 2005; Pimont et al. 2006). Some sensitivity analysis has also been done by Jonko et al. (2021) on FIRETEC simulations to look at simulation's ability to demonstrate fire behavior responses to small variations in atmospheric turbulence.

1.2.1.2- FIRETEC Domain

All simulations used a consistent computational domain of 2400m (x) by 800m (y) by 1200m (z). The computational domain was meshed with a horizontal grid cell resolution of 2m and a vertical resolution that varied from 1.5 meters at the surface stretched to 30m at the top of the domain. The vertical grid allows for high resolution in the bottom of the domain where fire, fuel, and turbulence are most critical to fire behavior while saving on computational resources at the top. All simulations were set up to use a time step of 0.0005s, and set the radiation heat transfer to be calculated 400 times per second.

The domain was divided up into several areas (Figure 1.2). A 400 m flat region at the front of the hill allows for winds a "run up" to the hill, followed by an 800 m sloped region leading up to the hill crest. The back 1200 m of the domain is mirrored with the front. In the middle of the sloped region, from dx=600m to 1000 m, is a constant slope angle defined as the area of interest (AOI). An ignition region 8 m deep and 400 m wide is ignited just before the AOI. Fire simulations were run for up to 500s to allow fires to travel through AOI, and wind simulations were run for 1000s to allow stabilized turbulent winds in and around the fuels. Simulations were done using 1200 processor nodes, where each processor calculated 20 x and y cells, and all z cells associated.

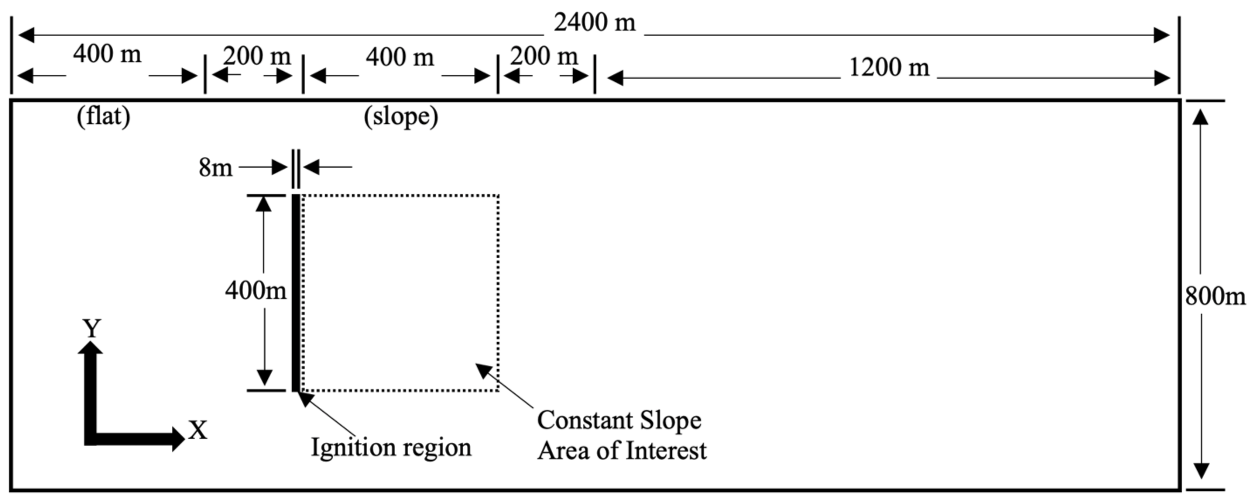

Figure 1.2: Basic layout of the simulations at time of ignition. There is a 400 m flat inlet, 200 m section increasing from flat to desired slope grade, 400 m of constant slope grade, 200 m decreasing from slope to the hill crest, and then the back 1200 m of the domain is a mirror of the front 1200 m.

1.2.2- Developing Slopes and Winds

To assess treatment effectiveness, untreated and two treatment scenarios were simulated across four different slope conditions: 0%, 30%, 45%, and 60% (Figure 1.3). These slopes were selected to represent a control and the lower, median, and upper bound of slopes where CTL treatments can be performed. A transition for slopes occurred from x=400 to 600 following a quadratic function to increases from 0% to reaching the desired angle. A similar transition occurred after the AOI from x=1000 to 1200, this time going from slope angle back to 0% at the crest. The back end of the domain is mirrored, ending in another flat region to allow a cyclic domain for winds.

To capture topographically influenced winds across the range of slopes we initiated each simulation using 10m open canopy winds as 12 m/s wind speed at approximately 22 m on flat ground, which is considered a moderate to strong ambient wind for fire behavior. Winds were allowed to cyclically spin-up through the entire domain for 10 minutes in order to reach stable turbulent flow in and around the tree canopy, using a lateral cyclic x-boundary condition for the wind regime so winds flow through the domain outlet and can re-enter the domain inlet until stable in time. A set of stable inlet cell's wind vectors three cells deep called "ghost" or "halo" cells were saved to be used as a starting profile for fire simulations. The horizonal y-boundary was set to open to allow winds to freely flow for both wind and fire simulations, and the outlet x-boundary was also set to open during fire simulations.

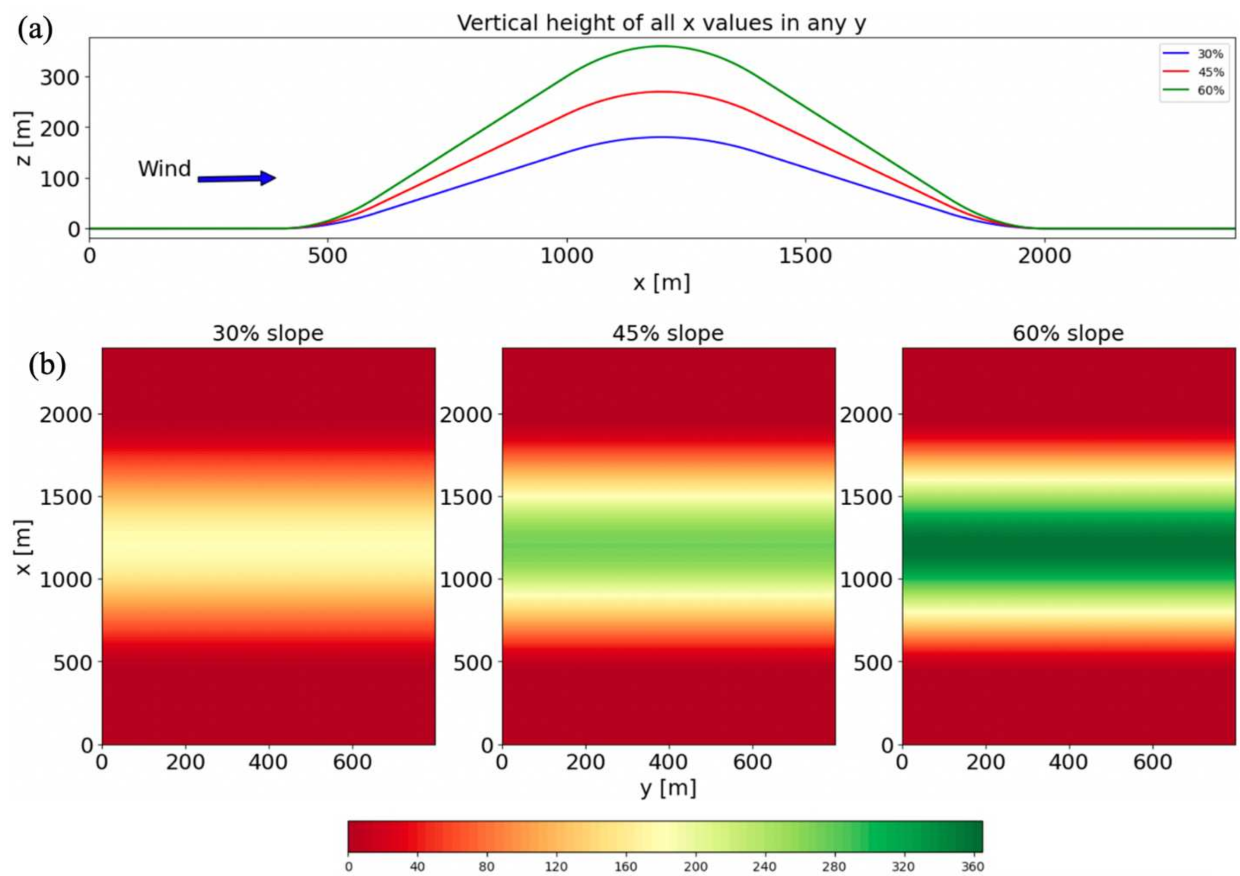

Figure 1.3: Vertical slope profiles on domain. 1.2a (top) are cross sections showing the profile of each of the slopes tested, representing a slice showing all x,z values for a single y slice at each of the three slopes. 1.2b (bottom plots) are op-down views of the non-zero slopes as colormap, where x and z are constant for all y cells. Wind orientation is marked as a blue arrow, and the color bar is showing vertical heights z for all x and y cells as a colormap.

1.2.3- Generating Synthetic Forest

The simulations for this study used real world data from the United States Forest Service (USFS) Forest Inventory and Analysis (FIA) program which maintain an inventory of forests across the US and associated territories (Tinkham et al. 2018). The FIA inventory was created with a sampling scheme that involves the tessellation of hexagons superimposed across the nation, with one field plot per 2428 ha hexagon. Each field plot is 0.4047 ha in size and is comprised of four nested subplots for sampling trees (USDA Forest Service, 2005).

All FIA plots for the state of Colorado were acquired from the FIA DataMartData (Forest Inventory and Analysis Database 2023). The database was filtered to include the most recent inventory of 2010 through 2019 data available, and these plots were filtered to include 40-80% Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) by the number of stems. This filtering resulted in a database of 72 FIA subplots that contained 689 trees. The resulting tree list was further filtered by removing any tree that was not characterized with a diameter at breast height (DBH; 1.37 m above ground), crown diameter, or total height to allow attribution of each tree in FIRETEC. Missing crown widths were calculated using species-specific allometric equations (Bechtold 2003) and the FIA crown ratio and tree heights. Plots averaged 570 trees hectare^{-1} (TPH) with 25.2 m^2 hectare^{-1} of basal area. From the FIA tree list, a synthetic forest was generated to have the same average TPH as the FIA plots for the 192-hectare domain. Trees were placed in the domain by first randomly selecting a coordinate then randomly assigning a tree to that coordinate, while ensuring no tree was within 2 m of another tree to avoid overlapping tree centers. The untreated synthetic forest's stem density averaged 64% Douglas-fir, 20% ponderosa pine (*Pinus ponderosa* var. *scopulorum*), 6% aspen (*Populus tremuloides*), and <5% limber pine (*Pinus flexilis*), Engelmann spruce (*Picea engelmannii* var. *engelmannii*), and blue spruce (*Picea pungens*). The untreated forest had a mean tree height of 11.4 m and a mean crown base height of 6.8 m. Figure 1.4a shows the entire simulation domain containing all the trees and their locations.

All simulations parameterized surface fuels assuming that grass was the dominant fuel between trees, and litter accumulates beneath trees while also diminishing grass loads. The spatial distribution of grass and litter were therefore functions of overstory canopy with the greatest amount of litter beneath canopy and the greatest amount of grass in areas between trees. Fuel loads were based on Brown site MC 04 of the Digital Photo Series database (Brown 1981). Fine surface fuels assumed a surface area to volume of 4000 m^2/m^3. Simulations used a grass fuel density of 1 kg m^{-3} which had a maximum height of 30 cm and a litter fuel density of 7 kg m^{-3} at a maximum height of 5 cm.

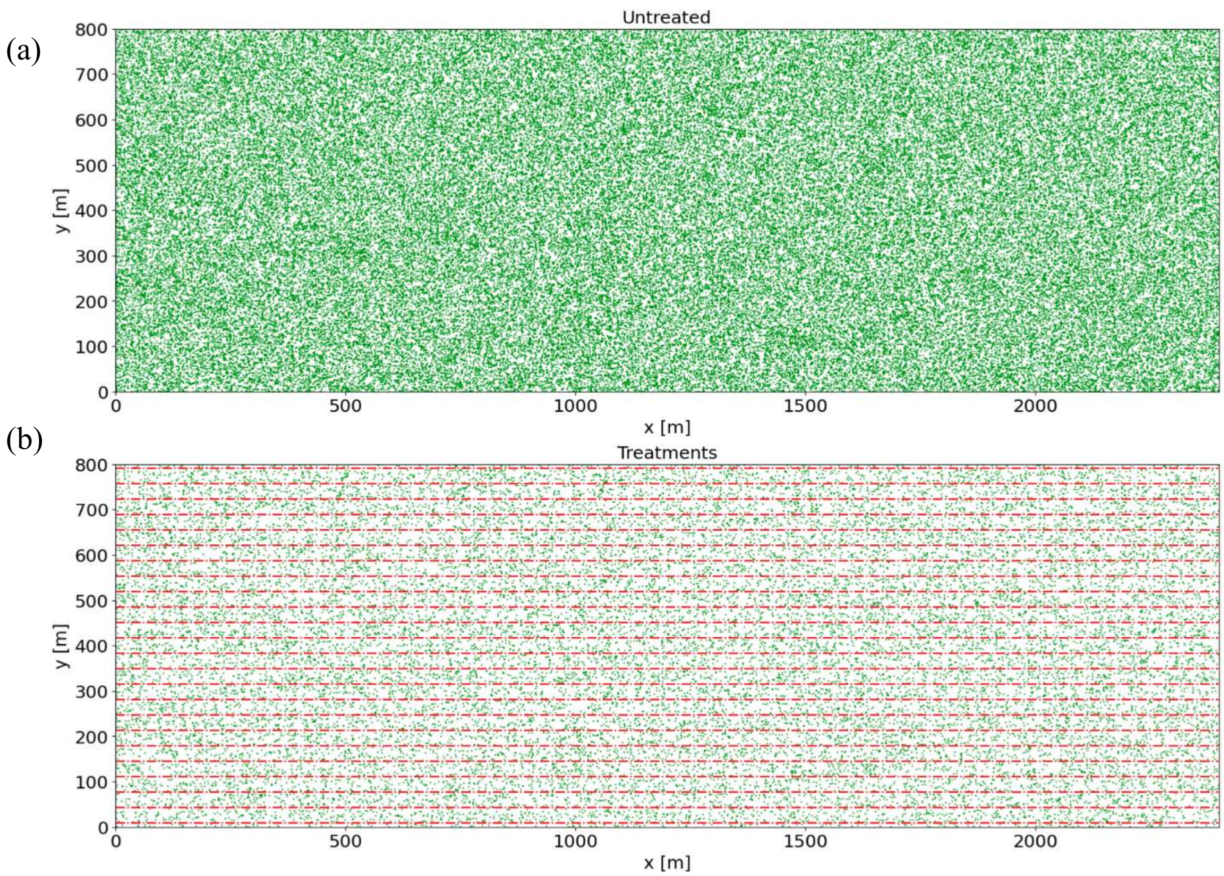

Figure 1.4: Treated and untreated domain tree locations. 1.3a (top) showing a top-down view of the whole domain with each tree location marked with a green dot, 1.3b (bottom) showing the same view but of the treated domains and marking cleared harvester roads as red dashed lines. Upslope winds used for simulations are u-vectored progressing from x=0 to x=2400.

1.2.4- Simulating CTL Treatments

CTL treatments were simulated by first cutting roads as 4 m wide paths placed 30 m apart across the domain. Paths were cut wide enough for the harvesting equipment to travel, while separated enough to allow the harvester's pendulum arm to thin to the center point 15m away between the paths on either side. For the two treatments, overstory trees were thinned to a target 120 TPH, selected based on similar CTL treatment thinning regimes. Regions between the roads were thinned by first having all very small trees of under 15 cm DBH removed and removing all shade-tolerant species of Engelmann and blue spruce. Thinning was then done by randomly selecting a tree in the list and removing it so long as it had a DBH less than 40 cm, and was not an aspen. After each tree was removed the current tree density was checked and thinning was completed once below the target. The treated forests ended up with a mean tree height of 13.4 m for almost 2 m higher than untreated, and a mean crown base height of 7.8 m for about 1 m higher than untreated.

Residues from the cut-to-length processing of trees were varied between the two treated scenarios. The no slash scenario assumed that the residue of the tree processing was removed from the site, similar to how a whole tree harvest operation would be conducted. For the scenario with slash, the removed tree's fine canopy biomass fuels called slash were placed in the roads where the harvesters traverse to simulate CTL modified surface fuels. The grass and litter surface fuels are otherwise unchanged. The added slash modified the surface fuel load, density, and depths in the road areas. This simulation represents an active area of investigation of how erosion from cable tethered harvesting equipment can be mitigated by using the slash material as a buffer between the equipment and soil.

Table 1.1: Mean surface and canopy fuel characteristics for the untreated and two treated scenarios.

	Untreated	Treatment no slash	Treatment with slash
Trees per hectare	570	120	120
Basal Area [$m^2 \cdot ha^{-1}$]	20.0	5.7	5.7
Tree fuel load [$kg \cdot m^{-2}$]	1.10	0.37	0.37
Surface fuel load [$kg \cdot m^{-2}$]			
Forest area	0.4	0.4	0.4
Road area	0.4	0.4	5.2
Surface fuel depth [m]			
Forest area	0.30	0.30	0.30
Road area	0.30	0.30	0.30 (0.05)*
Surface fuel density [$kg \cdot m^{-3}$]			
Forest area	8.1	8.1	8.1
Road area	8.1	8.1	17.2

* Slash treatment contain two surface depths, with additional slash at 0.05 m

1.2.5- Analysis Methods

Fire behavior parameter comparisons are made for all simulations by analyzing key fire metrics that are often used by managers like ROS, fire depths, energy release, and fuel consumption. The ROS is calculated as the shortest time the fire front took to travel through the AOI. Each row of y cells has a calculated fire front as the furthest x cell where the temperature was greater than 700 °C at each time step to allow calculating a ROS from ignition to exiting the AOI. The depth of the fire can be shown in two ways to consider different effects: a fire front flaming depth is represented as an average in the AOI of all y row's distance between the forward and backward most x locations where a cell is reaching active flaming temperatures of at least 700 °C, and a total fire depth that represents the average distance between the same flaming fire front but then considers the back of the flaming front to include cells which are down to 400°C as a lower temperature which is still consuming fuels. In addition, we estimated the heat release per unit area by calculating how much fuel is consumed and taking into account stoichiometric coefficients and low heat of combustion values for the fuel for all cells in the AOI which consume, then normalized the total heat released by the area of these cells (reference appendix A for more detail on FIRETEC.) Consumption of surface and canopy fuels was estimated as the difference in pre- and post-fire mass within the AOI. We estimated post-fire biomass when the fire had traveled 50 m out of the area of interest.

1.3- RESULTS

1.3.1- Wind Behavior

The treatments had a considerable impact on increasing pre ignition sub canopy wind profiles when compared to untreated winds. The normalized streamwise wind profiles help demonstrate the differences between canopy structure and slope angle, having a characteristic inflection point at the normalized height of 22 m (Figure 1.5). The greatest differences in the shape of the wind profile occurs between the flat treated and untreated scenarios, where for example sub canopy winds at around 5m in the untreated scenario is only 14% that of the open wind speed, where the treatments are at 48%. The treatment removed many of the small lower canopied trees and raised the crown base height, allowing winds to better penetrate into the sub canopy. All simulations still experience winds slowing down near the surface due to surface fuels and ground interaction, although the treatment is still increasing in winds right up to these surface fuels as canopy reduces.

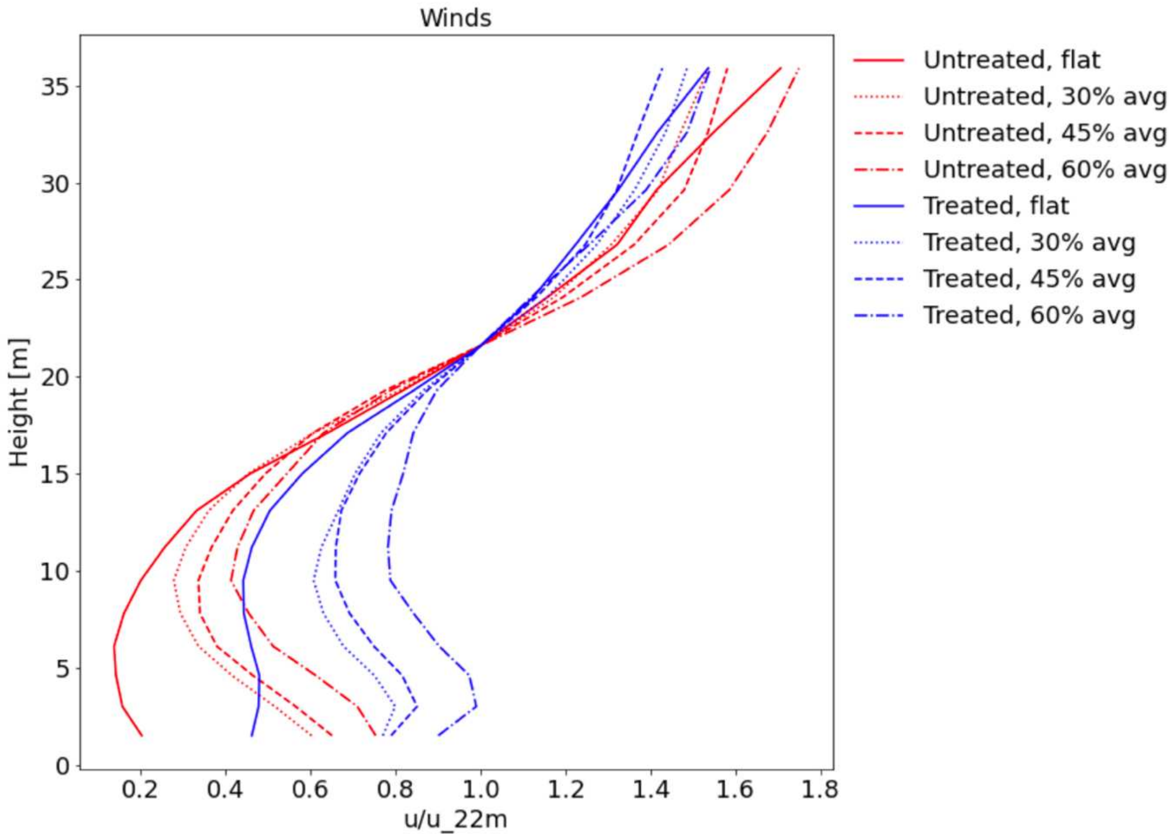

Figure 1.5: Averaged winds vertically for simulation area of interests, of streamwise wind velocity (u) normalized to the open wind speed at approximately 22 m as x axis, and the height above the ground and going up to 35m and starting with the average of ground to 1.5 shown at 1.5 m. The treated with no slash is shown and winds do not vary largely from the treatment with slash.

As the simulations go from flat to 30% slope, the sub canopy winds begin increasing to be closer to the open winds. The slopes have a strong effect on the untreated simulations where the 5 m normalized wind velocity increases from 2.6 to 3.2 times greater than flat ground, while the treated simulations only have a 1.5 to 1.6-fold increase. For the 60% slope scenarios we see similar behavior as the untreated increase by 3.6 to 4.9 times, and the treated have a 1.7 to 2.3-fold increase, a near doubling on all slopes for sub canopies and even more extreme on flat. The increase in slopes has a more drastic impact on untreated simulation streamwise winds than on the treatments, as seen by the nearly 5-fold increase when going from flat to 60% for untreated versus the approximately 2-fold increase the 5m sub treated canopy winds experience. The difference is largely due to the amount of penetration the treated runs already experience even when on flat simulations.

A sub canopy jet also forms within the treated runs at high slopes, as there is a vertical tunneling effect allowing free flow between the fuels that otherwise slow down the winds, which are above as canopy and below as surface. The increased penetrability of the canopy also modifies crossflow winds, which affects lateral fire expansion which can be seen readily at the lower slopes (Figure 1.6). The untreated fuels are more restricted due to added canopy drag, and considering the vertical wind and plume dynamics, untreated simulations are less able to spread horizontally by flanking fire while more laterally constrained. From the ground to canopy base height the treatments experience much higher streamwise wind magnitudes in the more open understory, while the untreated case in contrast gradually increases all the way to the ground level and have a noticeably smaller drag effect due to canopy.

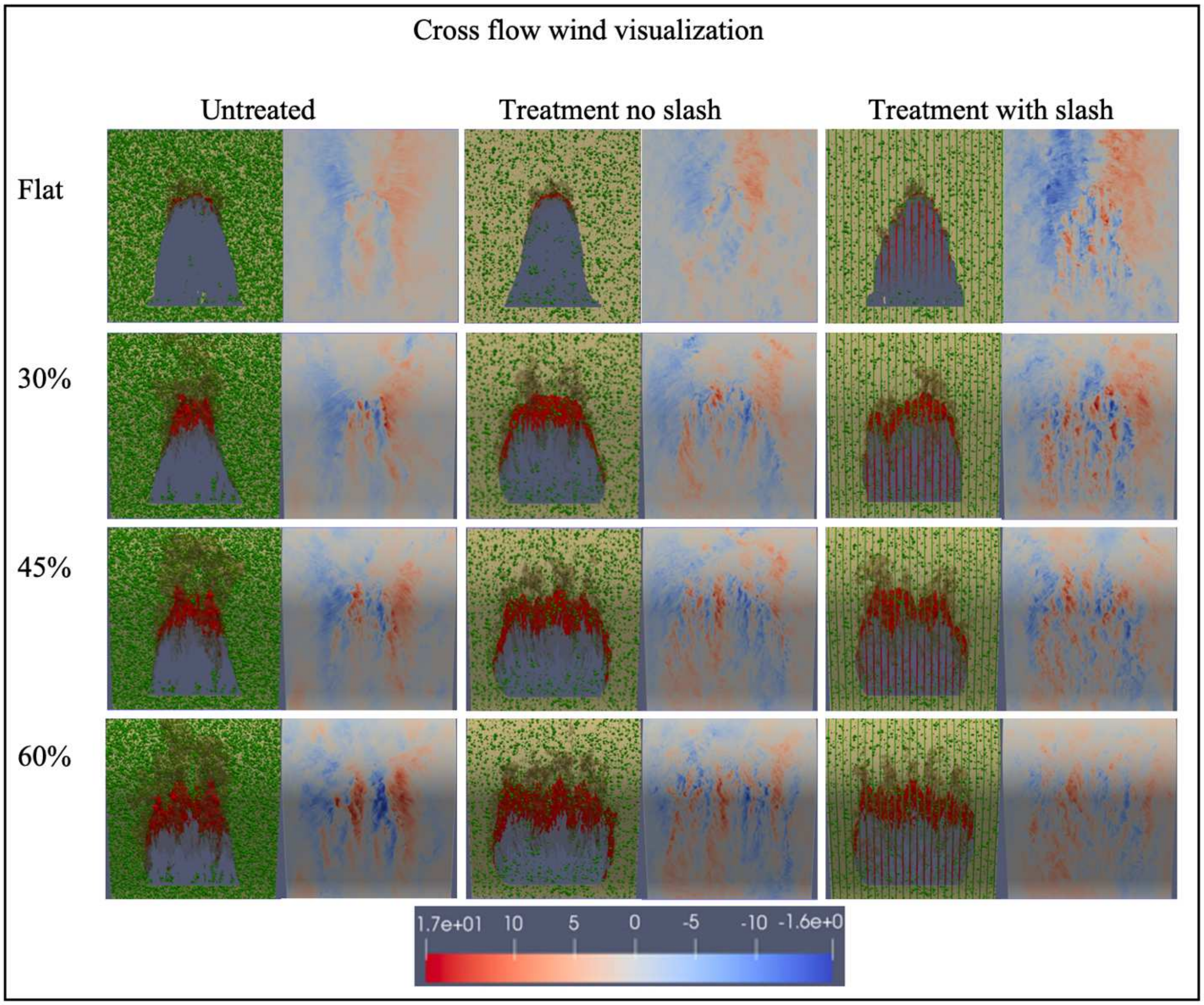

Figure 1.6: Simulation stills comparing crossflow wind behaviors. Each simulation is show as two images; on the left a still with tree fuel represented as green, surface fuel as yellow, and fire/smoke as red/grey; on the right is a colormap showing cross flow winds at the same timestep. The domain is x along the vertical and y along the horizontal. Note untreated spread constrained by winds and the lack of vertical spread especially at lower slopes, and lower canopy survival compared to treatments. Also note the fire and flame size, illuminating intensity and heat release. All images are taken as the fire front approaches the same point exiting the constant sloped area of interest, before it approaches the crest. Each panel shows all four slopes for a given treatment scenario. Panels allow comparison of cross flow v-winds at time as each simulation makes the same approach, allowing visualization of the size of the fire as well as the flanking fire spread while providing active fire cross wind behavior that is contributing.

1.3.2- Simulation Fire Behavior

Key fire behavior metrics for all simulations are compared and summarized in Table 1.2. Figure 1.7 provides an oblique view to give a visual insight into these behaviors. The image stills are of each run as the simulations exit the primary AOI, visually highlighting heat release values, canopy consumption, and fire depths.

Table 1.2: Summary table of average values for simulations as progressed through area of interest, including key variables for each simulation. Consumption values are taken after fire back exits the area of interest.

	ROS $[m \cdot s^{-1}]$	Depth [m] Flaming front	Depth [m] Total fire	Heat Release per Area $[kW \cdot m^{-2}]$	Fuel Consumption [%] Canopy	Fuel Consumption [%] Surface
untreated, flat	1.4	11	32	5.1	79%	71%
treated no slash, flat	1.6	15	40	2.6	56%	77%
treated with slash, flat	1.5	33	89	4.7	73%	61%
untreated, 30%	4.3	65	100	11.8	77%	77%
treated no slash, 30%	4.7	77	172	5.1	63%	73%
treated with slash, 30%	4.1	72	209	5.3	73%	47%
untreated, 45%	5.4	81	148	15.6	80%	75%
treated no slash, 45%	5.5	95	202	7.7	64%	76%
treated with slash, 45%	4.4	82	234	7.1	74%	56%
untreated, 60%	5.8	96	205	15.8	82%	80%
treated no slash, 60%	5.9	105	233	6.7	65%	81%
treated with slash, 60%	5.0	93	260	6.8	72%	53%

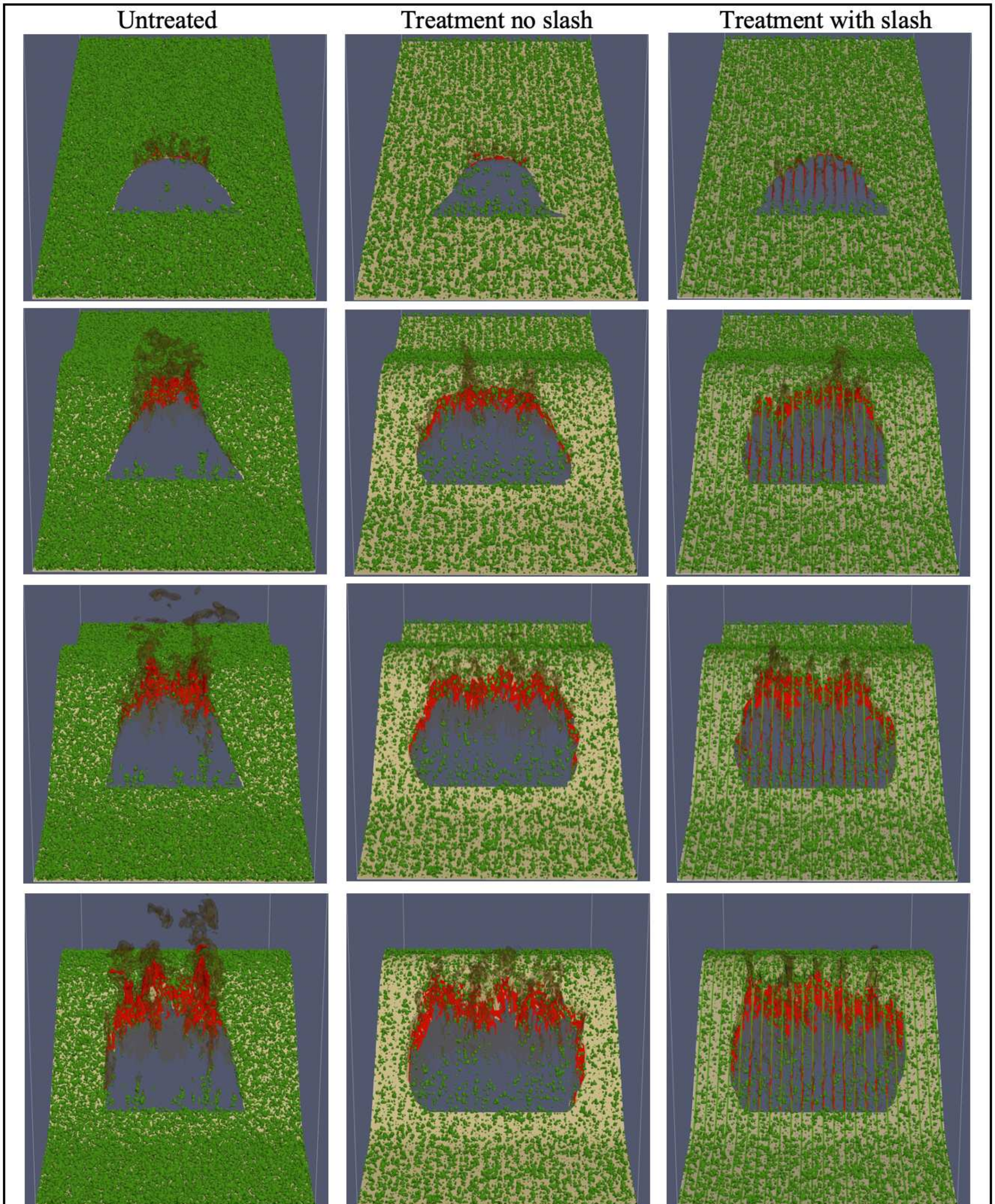

Figure 1.7: Oblique view looking towards hill as fire exits AOI, giving a good visualization for shape, canopy remaining, and heat release via flames/smoke contours. Domain is shown as y along the horizontal and x into the page. Each image is a still at same fire front point.

Results show that both treatments lowered heat release per unit area across slopes compared to untreated scenarios. The treatments with no slash generally have lower heat release per unit area than treatments with slash corresponding to the lower overall fuel available in the fire path, but the differences reduce on slopes. On flat simulations the treatment with slash was <10% lower than untreated scenario's heat release per unit area, while the treatment with no slash was approximately 50% that of untreated. Going from a flat to 30% slope the untreated and treatment with no slash each approximately double in heat release per unit area, while the treatment with no slash only increases by about 13%. For all slopes, both treatments had <50% the heat release per unit area as untreated scenarios. Heat release per area for both treatments on slopes begin to have similar behavior compared to untreated, and while generally increasing with increasing slopes they do not have the same magnitude increase that can be seen with the untreated runs. Canopy consumption is also consistently lower for both treatments compared to untreated. On flat simulations the treatment with no slash had approximately 70% canopy consumption as the untreated, while the extra surface fuel in the treatment with slash led to a <10% difference of canopy consumed vs untreated. Canopy consumption increased the most for the treatment with no slash once slopes were introduced but remained consistently the lowest. ROS responded similarly for treatments and untreated as slopes were introduced, although treatment with no slash responded the least increasing by about 3.3-fold when going from flat to 60%, while the treatments with slash increased by about 3.7-fold and the untreated increased by around 4.1-fold.

The treatment fire behaviors differed from each other the most on flat but began to converge in several behaviors as the slopes were introduced. Heat release of the treatment with slash on flat simulations was 1.8-fold the treatment without slash, but dropped down to being within 10% of each other over slopes. On the flat simulations the surface fuel in the treatment with slash was significantly higher than on slopes which contributed to heat release. On sloped simulations the ROS increased corresponding to winds and topography meaning the extra slash surface fuels not consuming as much as untreated on flat, decreasing by 10-20% across introduced slopes while canopy was a little more variable but overall similar. The treatment with no slash had faster ROS across all simulations especially on flat at almost 15% faster than untreated compared to less than 10% faster for treatment with slash, corresponding to the increased wind penetration both treatments experienced.

The treatment with slash simulations had notably higher total fire depth than other simulations due to the slow burning slash in the roads especially on the flat simulation. The treatment with no slash and the untreated simulations total depth increases over hills substantially more by increasing by 5.8-fold and 6.4-fold respectably once at 60% slope compared to flat, while the slash treatment increased by less than 3-fold already having a large total fire depth. The total flaming depth is similar for all simulations across slopes being within 20% of each other except on flat where the treatment with slash had 3 times the untreated depth and the treatment with no slash was approximately 40% more. The treatment without slash had a slightly increased flame depth corresponding to the slightly faster fire front spread.

1.4- DISCUSSION

The findings of this study indicate that CTL treatments are effective at reducing several aspects of fire behavior such as heat release and canopy consumption relative to untreated forests, but have some marginal results with ROS and allowing increased sub canopy winds. The results generally agreeing with models and previous literature on stand scale treatment behaviors (Finney 2001; Finney et al. 2007; Jain et al. 2012; Martinson and Omi 2013). The treatments reduced heat release per unit area by 10 to 50% relative to the untreated scenarios. On flat slopes the no slash treatment had half the heat release per unit area as the untreated simulation, while the treatment with slash was within 10% of heat release compared to untreated. Given how retaining fuels via slash opposes general fuel reduction principles, it makes sense that the treatment with slash was less effective by retaining the additional biomass to be consumed and could potentially benefit from some form of controlled burning. These findings are similar to previous studies that also show increased surface fuel loads are not as effective at reducing fire severity as fuel removal or reduction (Agee and Lolley 2006; Stephens et al. 2009; Fule et al. 2012). The reduced effectiveness highlights the consensus in previous reviews that treatments achieve partial effectiveness by removing trees, but ultimately work best by ensuring added surface fuels are also managed with prescribed burning to achieve “thin and burn” treatments (Martinson and Omi 2013; Kalies and Kent 2016).

Canopy consumption results also reveals treatment effectiveness, where untreated canopy consumed was consistently higher than both the treatment. The treatment with no slash ranged from over 40% higher consumption on flat to about 25% on each slope, and the treatment with slash ranged from around 5-15% higher across all simulations. It's worth noting that the treatment with slash always had higher canopy consumption than the treatment with no slash, ranging from 30% more on flat to 10-15% across slopes, which suggests that the added surface fuels contributed to consumed canopy and again that the slash treatments may benefit from some form of controlled fire following thinning. Although both treatments did have lower canopy consumption relative to the untreated control, it's worth noting they overall had relatively minor effects and only reduced fire severity from high to moderate regarding empirical biomass consumption (Miller and Thode 2007; Keeley 2009).

The treatments had a considerable impact on canopy and sub canopy winds which aligns well with literature (Finnigan 2000; Linn et al. 2002, 2007; Pimont et al. 2009, 2011), where treatments allowed winds to penetrate through the canopy and a sub canopy wind jet forms for treatments on slopes. The compounding effects of winds and slope cause all simulations to experience some degree of eruptive/blow up fire behavior regarding ROS, likely associated with flame attachment from winds and slope that allows for more effective heat transfer to downstream fuels. These finding agree with Finney's (2001) results that show treatments are expected to increase spread rates, but could still have benefits of reduced fire damage and improved controllability. While on flat the untreated control had lower ROS than both the treatment with slash and the treatment with no slash at 13% and 7% respectively. An interesting result can be seen on slopes where the treatment with slash began having 5-20% lower ROS compared to untreated while the treatment with no slash maintained a 2-10% higher ROS. The reduced ROS for the treatment with slash could be due to the added drag of the surface fuels and may be an important metric to consider for fire behavior, although the increase in canopy consumption should also be kept in mind.

Wind dynamics contributed to additional fire behavior effects such as increased lateral spread and deeper fires. The reduction in canopy allowed winds to be less constrained and treatments experienced more laterally spreading fire fronts than the untreated, particularly on lower slopes. Stream wise winds also allowed both treatments to have greater fire depths than untreated scenarios, especially on flat simulations. The total fire depth was higher versus untreated for the treatment with no slash (ranging from 25% on flat to 14-70% on slopes) as well as the treatment with slash (ranging from almost 200% on flat to 27-110% on slopes). The fire depth could have implications toward surface effects and sub litter soil behavior especially for the treatment with slash. Higher surface intensities resulting from the additional slash fuels could contribute to hydrophobic soils that impact future erosion and water retention (DeBano 2000), potentially producing results counter to the goal of placing the slash for erosion control if a fire does hit the treated areas.

This study had some limitations, and future work could be performed to further the understandings of CTL treatment's effects of fire behavior. Alternate treatment profiles for simulations would be informative, such as modifying thinning to be a bottom to top treatment profile, utilizing more heterogeneous patchy treatments of different orientations, simply doing more or less thinning, or strategically creating treatment patterns could all generate different fire behavior as literature suggests (Finney 2001; Collins et al. 2010; Larson and Churchill 2012; Hoffman et al. 2020; Urza et al. 2023). Treatment longevity has also been shown to have some impact on fire behavior (Finney et al. 2007; Kalies and Kent 2016; Martinson and Omi 2013), so studying treatment maintenance and successive year's post-treatment grown could help further understanding. This study chose to focus on the most severe fire behavior scenario of upslope winds with moderately high wind speeds, so investigating alternate angles of wind attack, different wind profiles, and various sets of weather conditions could be informative. The assumption that all parts of the hill were homogeneous and contained the same moisture content for this study could also be expanded on. In reality moisture content can be a function of conditions such as slope aspect where southern slopes are more dry than northern ones. Moisture content can also be a function of valley location where lower in the valley has more terrain shading and generally higher moistures (Pavok et al. 2018), and topography and tree interactions have been shown to impact special heterogeneity patterns including moisture (Ziegler et al. 2017; Ex et al. 2019). In addition to more simulations, continued effort is needed in sampling and gathering data methods to allow better correlating simulations to.

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APPENDIX A: FIRETEC

FIRETEC simulates the dynamic processes that are occurring in the fire and the compounding effects these processes have on one and other. This type of physics-based model works to resolve the actual physics occurring within the fire taking into account the environment around it, rather than being empirically derived. This allows for predicting fire behavior is specific conditions given known properties including topography, wind conditions, weather, and fuel conditions like fuel load, location, density, heat of reaction, heat capacities, fuel shape, and fuel moisture. FIRETEC is coupled with a computational fluid dynamics (CFD) model called HIGRAD, which resolves airflow based on the topography, vegetation, and turbulence from and around the fire's dynamics. Together HIGRAD/FIRETEC are able to simulate the constantly changing interactions occurring in wildfires between the atmosphere, topography, vegetation, and the fire itself on a landscape scale of hundreds or thousands of meters.

For a detailed description of all source equations and background for the model, refer to Linn (1997). To gain some better insight into FIRETEC, some of the critical equations can be reviewed. Combustion chemistry for wildfires is going to involve extremely complex equations with lots of intermediate steps of transient species, requiring precrisis knowledge of local variables including fuel composition and atmospheric conditions. These complex and very large sets of equations were simplified to a small set of wood pyrolysis, solid-gas, and gas-gas reaction equations, and can further be simplified into the following single solid-gas reaction:

$$N_{wood}(fuel) + N_{O_2}(oxygen) \rightarrow (products) + (heat) \qquad (1)$$

N_{wood} and N_{O2} are the stoichiometric coefficients that describe the net amount of consumed fuel and oxygen during pyrolysis and the resultant 'inert' products and heat produced by combustion of pyrolysis-gas. Along with the simplified chemical reaction (1), a similarly extreme reaction rate simplification can be expressed as the following equation:

$$F_{wood} = \rho_{wood}\rho_{O_2}\sigma\Pi \qquad (2)$$

Equation (2) allows for the extreme simplification resulting in a model which is representing pyrolysis as being ultimately related to the heat flux of solid wood being tied to nearby gaseous reaction which are oxygen limited, so that the chemical chain reaction breaks if either there is not enough oxygen or fuel pyrolysis present. F_{wood} represents the rate of change of wood within a given resolved volume; ρ variables represent the density of given species in the resolved volume; σ represents the turbulent diffusion coefficient, taking into account length scales based on vegetation geometry and turbulent kinetic energy; and Π represents the coefficient for fuel rate of change, taking into account stoichiometry terms and a temperature probability distribution function. These simplifications assume active burning exothermic reactions are dominated by fire involving oxygen and hydrocarbon oxidization, which are each rate, or mixing, limited in the resolved volume. The production of carbon monoxide, soot, and other incomplete combustion products result due to lack of a proper oxygen ratio. In tandem with above equations, conservation equations (3) and (4) and a solid temperature equation (5) are used in order to track average fuel properties in the resolved volume, along with the fuel's associated moisture, as described by the following equations:

$$\frac{\partial \rho_{wood}}{\partial t} = -N_{wood}F_{wood} \qquad (3)$$

$$\frac{\partial \rho_{water}}{\partial t} = -F_{water} \qquad (4)$$

$$\left(C_{P_{water}}\rho_{water} + C_{P_{wood}}\rho_{water}\right)\frac{\partial T_s}{\partial t} = \dot{Q}_{rad} + ha_v\left(T_{gas} - T_s\right) - F_{water}\left(H_{water} + C_{P_{water}}T_{boil}\right) + F_{wood}\left(\Theta H_{wood} - C_{P_{wood}}T_{wood}N_{wood}\right) \qquad (5)$$

Equation (5) represents the change in specific energy of the solid over time in terms of related temperatures and densities. C_{p_x} variables represent the isobaric heat capacities of species x; ρ again represent species densities in the resolved volume; T_x variables represent the temperature of species x in resolved volume; $\dot{Q}_{rad}$ represents the net thermal radiation heat flux to the solid at the given location; h is the coefficient of convective heat exchange; a_v is the contact area between the gas and solid per unit volume; F_x variables again represent the rate of change of species x within the resolved volume; H_x variables represent the heat energy per unit mass associated with a flux in species x; N_x again represent the ratio of the mass of species x to the total mass of the combined product; and Θ represents the average potential temperature of the combined gas at a given location, such that Θ increases as the fraction of consumed fuel increases in order to crudely represent the increase in temperature returned to the solid as combustion changes from flaming to smoldering with the buildup of char and ash which act as insulators to retain more heat and release less heat with gases as occurs in flaming combustion.

In order to be able to resolve the fire physics at landscape scales even with the computation costs, the model has to resolve variables that capture the essence of the physics without explicitly describing every process in detail. Physical effects such as a flame's whipping dynamics or the solid fuel's chemical structure change while undergoing pyrolysis and then combustion are not attempted to be resolved; they are subscale of the resolution in the meshed cells, shaped at about two by two meters. Another example is that locations of individual branches and leaves are not known and are therefore represented as average fuel within cells based on tree characteristics. Fuel has inputs of size, densities, and moisture for mass, and a representative size scale which is used for resolving how winds and energies will interact with the fuel within a cell. FIRETEC is run by determining the key variables that are required to understand the conservation of mass, momentum, and energy, and then iterates through time to solve these variables as a mean and a fluctuating part with ensemble averages of the equations. These variables are used to understand how pyrolysis and combustion will occur with the given fuel and atmospheric properties within the cell. Primarily convective and radiative energies are given off during combustion, and will transfer to nearby cells. This energy is used to burn off vegetative moisture, heat up fuel to pyrolysis temperatures, and then take into account how much oxygen is present in the cell. If there is enough oxygen and pyrolyzing fuel then combustion is able to occur and keep a fire going, and if not, then combustion is not sustainable. Simplified solid-gas and gas-gas chemical reactions are used that allow for capturing of the key combustion behaviors without excessive computing of less dominant behaviors.