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Vertical and Horizontal Crown Fuel Continuity Influences Group-Scale Ignition and Fuel Consumption

Scott M. Ritter [1,*], Chad M. Hoffman [2], Mike A. Battaglia [3], Rodman Linn [4] and William E. Mell [5]

[1] Colorado Forest Restoration Institute, Colorado State University, Fort Collins, CO 80523, USA
[2] Department of Forest and Rangeland Stewardship, Warner College of Natural Resources, Colorado State University, Fort Collins, CO 80523, USA; c.hoffman@colostate.edu
[3] USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO 80523, USA; michael.battaglia@usda.gov
[4] Los Alamos National Laboratory, Los Alamos, NM 87545, USA; rrl@lanl.gov
[5] Pacific Northwest Research Station, USDA Forest Service, Seattle, WA 98122, USA; william.mell@usda.gov
* Correspondence: scott.ritter@colostate.edu

Abstract: A deeper understanding of the influence of fine-scale fuel patterns on fire behavior is essential to the design of forest treatments that aim to reduce fire hazard, enhance structural complexity, and increase ecosystem function and resilience. Of particular relevance is the impact of horizontal and vertical forest structure on potential tree torching and large-tree mortality. It may be the case that fire behavior in spatially complex stands differs from predictions based on stand-level descriptors of the fuel distribution and structure. In this work, we used a spatially explicit fire behavior model to evaluate how the vertical and horizontal distribution of fuels influences the potential for fire to travel from the surface into overstory tree crowns. Our results support the understanding that crown fuels (e.g., needles and small-diameter branchwood) close to the surface can aid in this transition; however, we add important nuance by showing the interactive effect of overstory horizontal fuel connectivity. The influence of fuels low in the canopy space was overridden by the effect of horizontal connectivity at surface fire-line intensities greater than 1415 kW/m. For example, tree groups with vertically continuous fuels and limited horizontal connectivity sustained less large-tree consumption than tree groups with a significant vertical gap between the surface and canopy but high-canopy horizontal connectivity. This effect was likely the result of reduced net vertical heat transfer as well as decreased horizontal heat transfer, or crown-to-crown spread, in the upper canopy. These results suggest that the crown fire hazard represented by vertically complex tree groups is strongly mediated by the density, or horizontal connectivity, of the tree crowns within the group, and therefore, managers may be able to mitigate some of the torching hazard associated with vertically heterogenous tree groups.

Keywords: fire behavior; tree torching; crown fire initiation; ladder fuels; fuel continuity; canopy base height

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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 [1–4]. 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., [5–8]). 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 [9–12]. 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 [13].

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 nontreed openings [14]. Attention to these features, particularly the tree groups, forms the basis of forest treatments to restore historical structure and function (e.g., [15]). 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 [12] and that the contagion effect due to crown-to-crown heat transfer can cause density-dependent crown damage [13,16] and horizontal crown fire propagation [17,18]. 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., [5,8]). 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 [19,20]. For example, a group containing small understory trees whose crowns are vertically separated from the crowns of the larger overstory trees may not pose the same risk of vertical fire propagation as a group containing both understory and midstory trees that create vertical fuel continuity into the overstory. The difference between these two vertical fuel distributions is not captured by crown fire initiation models that rely on a simple metric like canopy base height. 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 [12,21], and energy feedback among adjacent burning crowns can enhance the rate of fuel consumption [22,23] and crown damage [16]. 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., [24,25]), but it is not considered in crown fire initiation despite its potential importance [12]. 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. We 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 fire-line intensity. To address these questions, a physical fire model was used to simulate a free-spreading surface fire with a range of fire-line 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 1). These groups were designed to tease apart the factors not captured in traditional crown fire initiation models. This work has direct implications for 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.

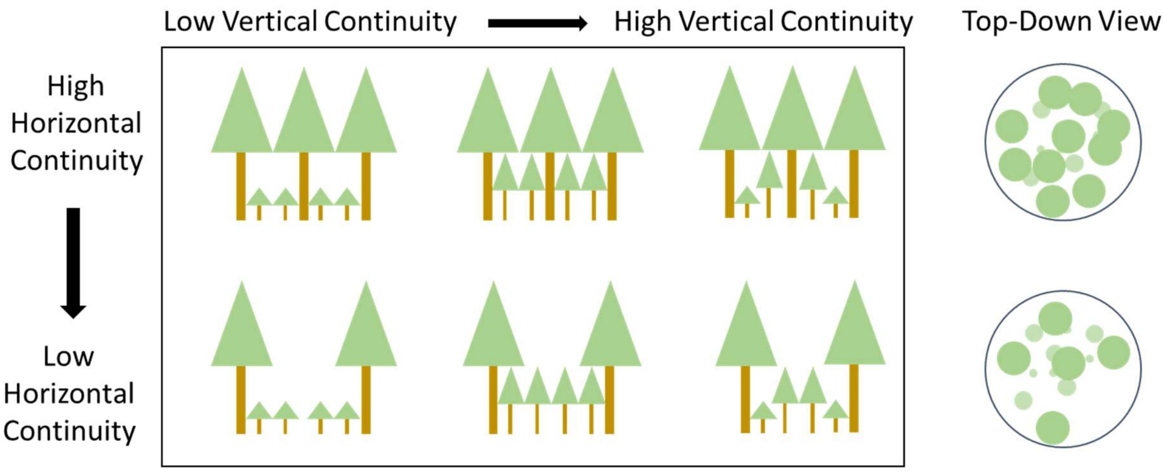

Figure 1. Conceptual diagram visualizing different aspects of vertical and horizontal heterogeneity within tree groups.

2. Materials and Methods

2.1. Fire Model

Fire behavior simulations were performed using the Wildland Urban Interface Fire Dynamics Simulator version 9977 (WFDS) [26]. 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 submodels 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 [27], wherein fuel must be dehydrated prior to undergoing pyrolysis. A more detailed description of WFDS can be found in Mell et al. [26] and Mell et al. [28], and discussion of model formulation, verification, and validation of WFDS are provided in McGrattan et al. [29–31]. WFDS has been evaluated for combustion and fire spread through vegetative fuels in Mell et al. [26,28], Castle et al. [32], Mueller et al. [33], Overholt et al. [34], Hoffman et al. [35], Perez-Ramirez et al. [36], Sánchez-Monrory et al. [37], and Ritter et al. [12].

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 simulation times ranging from 265 to 328 CPU hours. The domain was 750 m in length, 240 m wide, and 100 m tall (Figure 2). This domain height is five times greater than the maximum tree height and was determined to allow for adequate boundary-layer development above the canopy and sufficient advection of the heated plume once the spreading fires were ignited. 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. The inflow was set to follow a standard logarithmic vertical wind profile based on a steady, 4 m/s open (20 m) windspeed. Based on grid resolutions used in previous works which have shown that WFDS can reproduce crown fire ignition [38] and crown fire spread [35], we used a grid resolution that varied from 1 m × 1 m × 1 m to 0.5 m × 0.5 m × 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 2). This allowed for reduced simulation times 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 2). After allowing 300 s for the wind field to develop, the surface fire was ignited at 330 m downwind from the inlet as a continuous line across the y direction. The wind field traveled through 330 m of forest which is approximately 17 times the maximum tree height and allowed equilibrium of the wind field to be achieved prior to ignition of the surface fire. The surface fire was ignited 50 m before the high-resolution area of interest, which allowed it to achieve steady-state behavior prior to entering the area of interest.

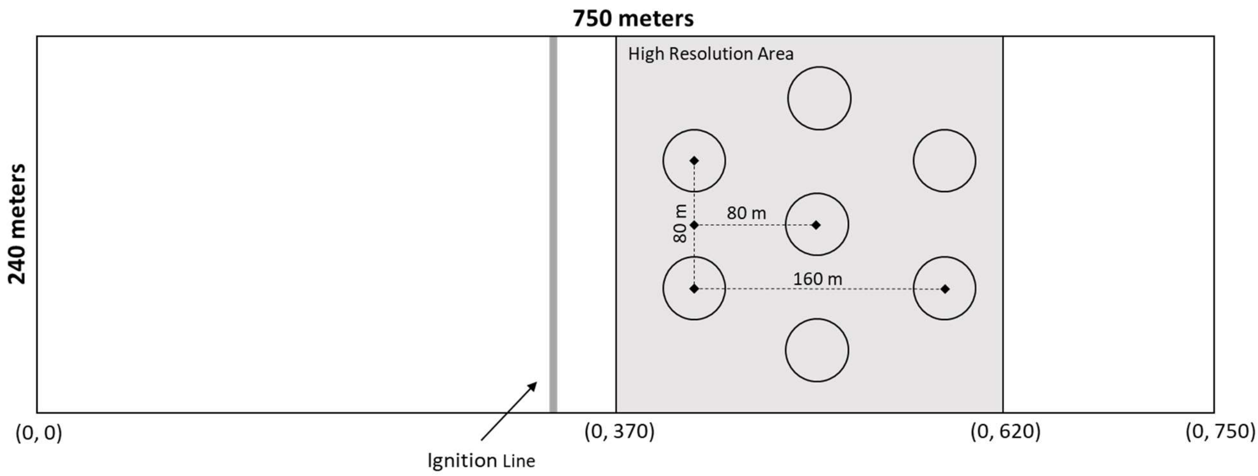

Figure 2. Example of the simulation domain. Group mixtures were placed at the center of each circle in the high-resolution area. All surrounding areas were populated with randomly located trees. Wind flow and fire spread were from left to right. Coordinates are given in meters.

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 275 trees/ha and a mix of the small, medium, and large trees whose properties and dimensions are described below (Table 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, as described in Ritter et al. [38]. 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.

Table 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

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 [39]. The foliage-surface-area-to-volume ratio was set to 5808 m^{-1} [40].

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 large, medium, and small trees, respectively. The tree height, crown base height, and crown width for each tree size were then calculated from DBH based on linear regressions for Black Hills ponderosa pine developed in Ritter et al. [38]. 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 1).

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 1; Table 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 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

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 [40,41]. 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 fire-line 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 fire-line intensities (FLI). This was successful, and FLI increased nonlinearly with progressively greater surface fuel load (Figure 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, 1415, 1930, 3495, and 6367 kW/m, respectively. These intensities correspond to flame lengths of 1.8, 2.2, 2.5, 3.3, and 4.4 m, respectively, based on the Bryam [42] flame length equation. The observed nonlinear increase in FLI was the result of the greater amounts of surface fuel consumption and progressively faster rates of spread (Figure 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 a reasonably narrow range of FLI and rate of spread.

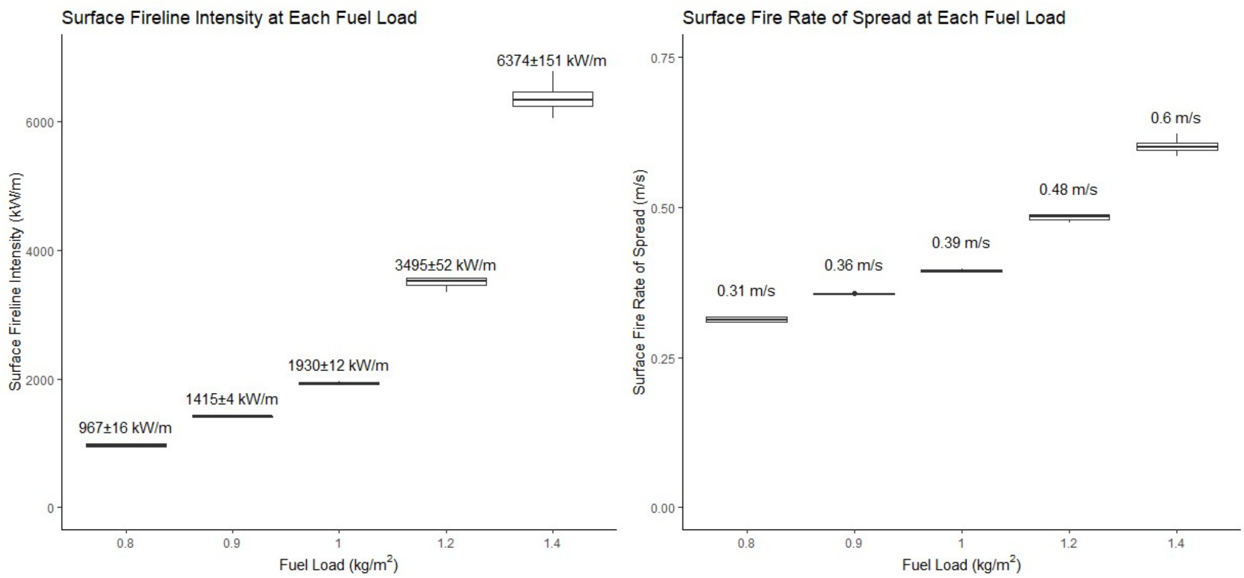

Figure 3. Mean surface fire-line intensities (±standard error) and rates of spread associated with each surface fuel load. Values were calculated based on the mean behavior through the high-resolution portion of the domain.

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. The 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 m, 6 to 10 m, and 10 to 19 m, respectively.

Surface fire-line intensity and fire rate of spread were both calculated as their mean values within the high-resolution area of the domain (Figure 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 fire line 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 Honestly Significant Differences among mixtures at each fuel load by using the TukeyHSD function in R [43]. A small effect of group location was identified and was therefore included as a random effect in the calculation of Tukey's Honestly Significant Differences. In addition, the R glm function was used to generate generalized linear models using a quasibinomial log link, which 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 within the group [43]. Predictor variables were normalized as z-scores to produce comparable beta coefficients in the final models. Models were selected by successively removing nonsignificant predictors using backwards selection while maintaining group location as a random effect. The full initial model included fuel stratum gap, understory bulk density, midstory bulk density, and overstory bulk density as predictor variables. These models were ultimately reduced to the final models presented in Table 3.

Table 3. Selected GLM models to predict the proportion of crown consumed for large trees across all surface fuel loads and split by each surface fire-line intensity level. Beta coefficients represent the 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
1415 kW/m	Midstory Bulk Density	0.53	<0.0000
	Understory Bulk Density	−0.38	0.0041
	Fuel Stratum Gap	−0.75	<0.0000
1930 kW/m	Overstory Bulk Density	0.35	0.0006
3495 kW/m	Overstory Bulk Density	0.09	<0.0000
	Midstory Bulk Density	0.09	<0.0000
6374 kW/m	Overstory Bulk Density	1.50	<0.0000
	Midstory Bulk Density	1.71	<0.0000

3. Results and Discussion

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 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 they 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.

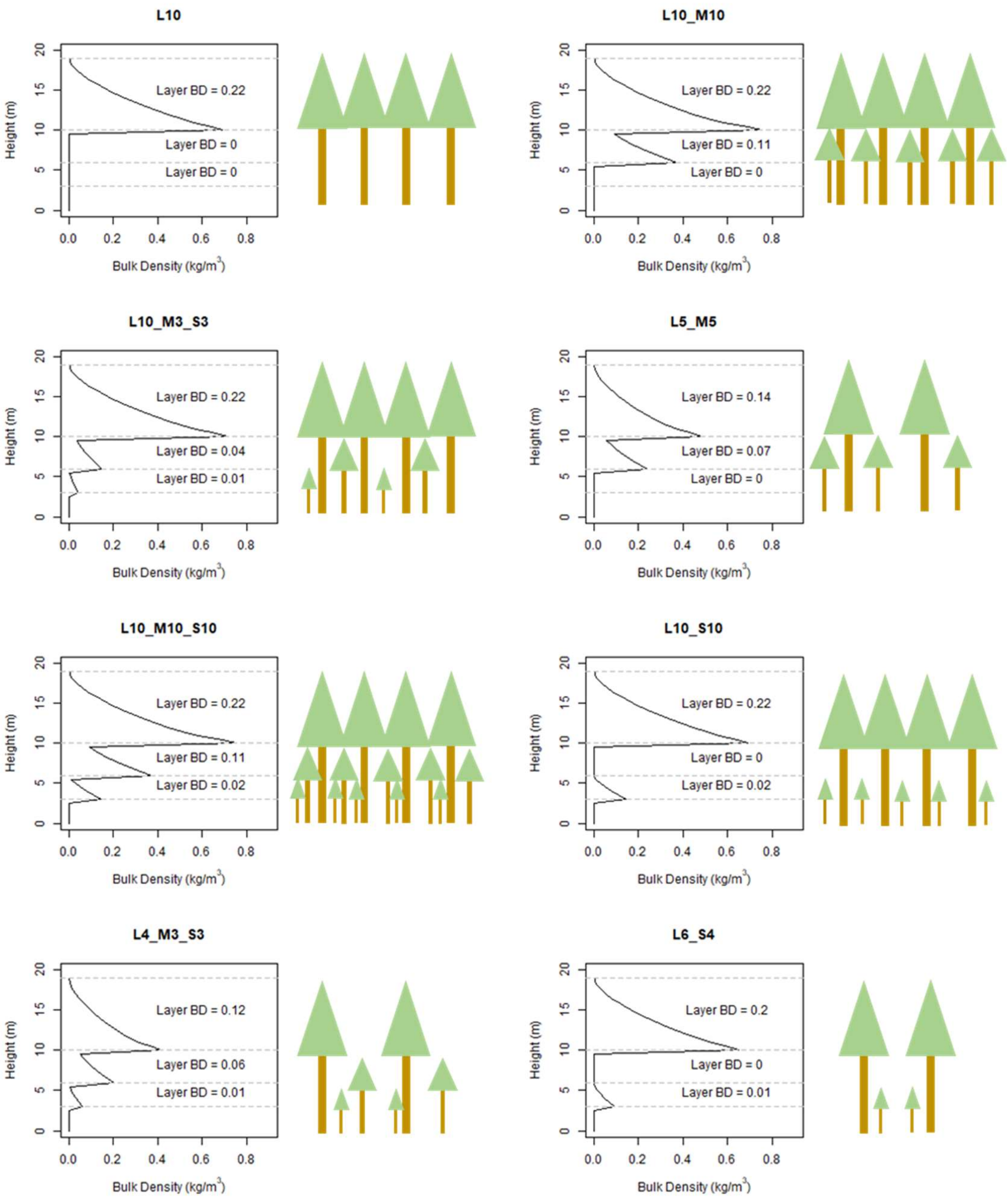

Figure 4. Vertical crown fuel profiles for all group mixtures at 0.5 m vertical height intervals. Layer BD is the mean bulk density within 3 crown layers split based on the crown base height of the small, medium, and large trees (3, 6.5, and 10 m). Images are intended to generally represent the horizontal and vertical distribution of trees to enhance clarity but are not exact replications of the simulated arrangements.

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 a 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.

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 it 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 1415 kW/m; Table 3, Figure 5). At 967 kW/m (0.8 kg/m^2 of surface fuel), both L10_M10_S10 and L10_M10 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, likely due to lower midstory bulk density as compared to L10_M10_S10 and L10_M10. 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 nonexistent (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 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.

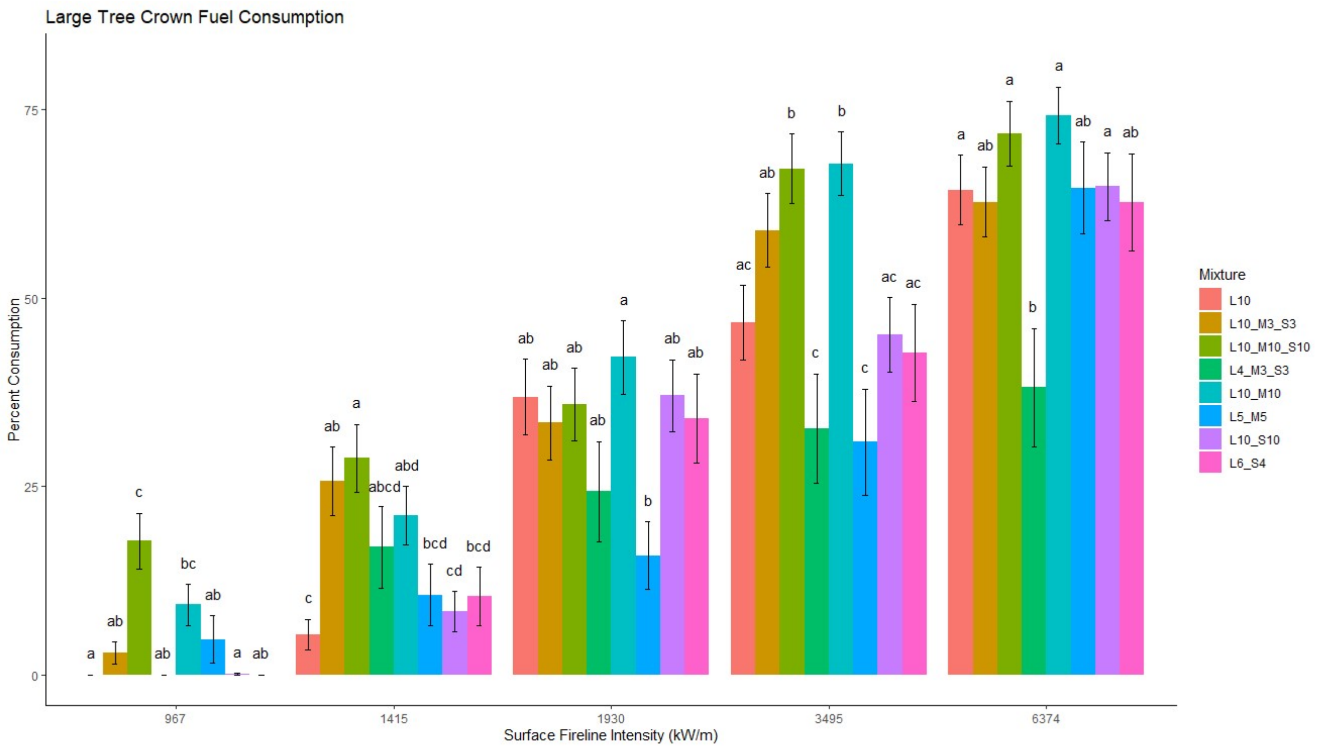

Figure 5. Mean consumption of large-tree crowns for each mixture and fuel load. Standard error bars are provided, and letters indicate pairwise significant differences within each surface fire-line intensity scenario ($p < 0.05$). Within each fire-line intensity scenario, if two groups do not share a letter, they were found to have a pairwise significant difference, and if they do share a letter, no significant statistical difference was detected.

Table 4. Percent large-tree (40 cm DBH) consumption in the tested group mixtures and each surface fire-line intensity.

Mix	Surface Fire-Line Intensity (kW/m)				
	967	**1415**	**1930**	**3495**	**6374**
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

These effects were even more pronounced at 1415 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 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. [12]. Additionally, horizontal heat feedback among these large adjacent trees likely contributed to fuel consumption and horizontal fire propagation in the canopy once ignition had occurred [22,23]. 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 understory and overstory, while L5_M5 had a larger gap between the surface and the bottom of the canopy (Figure 3). Once again, these patterns are largely seen in the GLM analysis with the model for 1415 kW/m identifying fuel stratum gap as the more influential variable followed by the midstory bulk density (Table 4). Interestingly, this model also suggests a slight negative relationship with the understory bulk density.

As surface FLI increased to 1930 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 5). The lowest large-tree consumption occurred in the L5_M5 group, 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. Additional 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 (Figures 3 and 5).

A key finding in this group of simulations was that the FLI produced by 1930 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 [5,8] 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 4).

At the next level up of 3495 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 do 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 6374 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). 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-tree consumption (Table 4).

4. Conclusions

These findings highlight issues with the prevailing concept of ladder fuels and the use of canopy base height as a primary input to traditional crown fire transition models as they only consider the vertical aspects of the canopy fuel distribution. By highlighting the complexities involved with predicting crown fire transition, this work strongly suggests the need to simultaneously consider both horizontal and vertical aspects of heterogeneity. 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. However, these results suggest that this is not always the case and show a decoupling between canopy base height, or ladder fuels, and the potential for surface-to-crown fire transition.

For example, 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 1930 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 nearly the same or more consumption than vertically heterogenous groups with mixed tree sizes for surface FLI greater than 1930 kW/m, due to horizontal continuity in the overstory layer. The only exception to this trend was at 3495 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 in 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) are 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 [5]. 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. One clear avenue for future research is whether the effect of reduced canopy bulk density on crown fire transition holds over a large range of wind speeds where flames may be more able to overcome horizontal discontinuities.

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 [44,45]. 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 [46–48]. 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 comprise 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 [14,49,50]. 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 [51]) 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 horizontal 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 [12,21], 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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