

Fine-scale fire patterns mediate forest structure in frequent-fire ecosystems

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Abstract. In frequent-fire forests, wildland fire acts as a self-regulating process creating forest structures that consist of a fine-grained mosaic of isolated trees, tree groups of various sizes, and non-treed openings. Though the self-regulation of forest structure through repeated fires is acknowledged, few studies have investigated the role that fine-scale pattern-process linkages play in determining fire behavior and effects. To better understand the physical mechanisms driving these pattern-process linkages, we used a three-dimensional, physics-based fire behavior model to investigate how the local arrangement of canopy fuels influences heat transfer from a surface fire to tree crowns and subsequent crown ignition and consumption. In particular, we were interested in the impacts of tree group size and crown separation distance on heat transfer. We found increased convective cooling for isolated individual trees and 3-tree groups as compared to larger 7- and 19-tree groups which resulted in a reduction of the net energy transferred from the surface fire to the tree crowns. Because isolated individuals and 3-tree groups are exposed to less thermal energy, they require a greater surface fireline intensity to initiate torching and have less crown consumption than trees within larger groups. Similarly, we found that increased crown separation distance also reduced heat transfer and crown ignition. However, differences in crown ignition and consumption among various sized groups and separation distances depended upon the surface fireline intensity, suggesting that any change in crown consumption or tree mortality due to pattern-process linkages may be best viewed as a conditional in nature. These findings identify the potential physical mechanisms responsible for supporting the complex forest structures typical of high-frequency fire regimes, and the results may be useful for managers designing fuel hazard reduction and ecological restoration treatments.

Key words: crown fire; crown fire transition; forest ecology; forest management; pattern-process feedback; restoration; self-regulation; spatial pattern; tree torching; wildfire.

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INTRODUCTION

In fire-prone, conifer forests of western North America, recurrent fires act as a stabilizing negative feedback mechanism, where prior burned areas influence fire spread and severity (Parks et al. 2015) and greater mortality rates of small

trees maintain lower density stands dominated by large trees (Larson and Churchill 2012, Larson et al. 2013, Hagmann et al. 2013, Battaglia et al. 2018). Observations from frequent-fire forests with natural or restored fire regimes and dendrochronological reconstructions of historical stand structure prior to Euro-American

settlement have shown strong agreement that this feedback process resulted in structurally variable forests comprised of scattered, large individual trees, variously sized groups of trees and non-treed openings (Sánchez Meador et al. 2011, Larson and Churchill 2012, Larson et al. 2013, Fry et al. 2014, Brown et al. 2015, Clyatt et al. 2016, Jeronimo et al. 2019). Furthermore, forests that support this pattern-process feedback are believed to be more resistant and resilient to wildfires and other forest disturbances (Larson and Churchill 2012, Reynolds et al. 2013, Fry et al. 2014, Hessburg et al. 2015).

Forest resilience is the capacity for a system to regain its structure, function, and feedbacks following a disturbance (Holling 1973, Hessburg et al. 2019). Forest resistance is often considered a core part of resilient systems (Ingrisch and Bahn 2018) and is defined as the difficulty or ease of changing the state, function, and pattern-process linkages of an ecosystem (Holling 1973). Here, we define forest resistance as the capacity of an individual tree, or group of trees to withstand crown ignition, canopy consumption, and mortality due to a wildfire. Alterations to resistance and resilience in frequent-fire forests have occurred due to land management policies, including grazing and fire suppression across the western United States throughout the 20th century which, in combination with increased temperatures and more frequent droughts, have impacted the characteristic structure and pattern-process feedbacks that historically drove ecosystem function in these forests (Hessburg et al. 2005, Collins et al. 2011, Brown et al. 2015). Consequently, these forests increasingly experience uncharacteristic wildfires, the loss of critical functional components of the biota (i.e., large fire-resistant trees) and ecosystem goods and services all of which interact to increase the risk of ecosystem collapse and transformation (Covington and Moore 1994, Keith et al. 2013, Seidl et al. 2016). To minimize the occurrence and negative impacts of uncharacteristic fires, managers are increasingly emphasizing the use of variable retention harvesting to restore both the complex forest structures and pattern-process linkages associated with more resilient historical forests (e.g., Underhill et al. 2014, Hessburg et al. 2016, Knapp et al. 2017, Addington et al. 2018). Although a number of recent research projects

have provided quantitative data on the historical patterns that can be used to guide the design of forest restoration treatments (e.g., Sánchez Meador et al. 2011, Lydersen et al. 2013, Brown et al. 2015, Clyatt et al. 2016, Rodman et al. 2016, Wiggins et al. 2019), empirical evidence explicitly linking fine-scale forest pattern to self-regulation is limited and questions remain around the scale of structural variability that most affects forest resilience (Parks et al. 2015, Koontz et al. 2020).

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

There are various mechanisms through which the local crown fuel arrangement could potentially influence heat transfer from the surface fire to individual tree crowns and ultimately crown ignition and consumption. For example, as the size of a tree group increases, the corresponding drag forces will result in a decrease in the wind velocity through the canopy of the group. As a result, for a given surface fireline intensity the likelihood for the surface fire to transition into the crowns may increase due to both a reduction in convective cooling within the canopy and by allowing the fire plume to travel more vertically through the

canopy space thereby increasing the gas temperatures at a given height above the fireline. The separation distance between crowns within the group may also alter heat transfer and therefore play a significant role in determining thresholds for crown fire ignition and canopy consumption. As crown separation distance increases, localized reductions in crown fuel density and void spaces form within the canopy. These void spaces have the potential to influence convective heating and reduce the likelihood of ignition if they allow increased mixing of cooler ambient air into the fire plume and reduce the residence time of convective heating (Tachajapong et al. 2009). Although there is increasing evidence of significant interactions between fine-scale vegetation structure and wild-fire behavior, several studies have suggested that these effects are conditional upon a host of fine- and broad-scale factors that directly or indirectly affect the surface fireline intensity and therefore influence the likelihood of crown fire ignition (Hoffman et al. 2012, Lydersen et al. 2014, Parsons et al. 2017, Sieg et al. 2017).

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

METHODS

Overview of the wildland fire model

Fire simulations were conducted using the physics-based Wildland-Urban Interface Fire

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

each simulation time step. Thermal radiation transport is solved using a non-scattering, gray gas assumption with solid fuel particles that are modeled as discrete, thermally thin, optically black vegetation elements.

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

Simulation domain and experimental setup

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

To evaluate the role of group size and separation distance on crown ignition and fuel consumption, individual trees and three group sizes (3, 7, and 19 trees) were tested across five different crown separation distances and four surface fire-line intensities resulting in a total of 88 simulations. All simulations were run in parallel on 16, 2.2 GHz Intel Xeon processors, and took an average CPU time of ~66 h each to complete. In each simulation, we placed individual trees or regularly spaced groups of trees within the center of the high-resolution domain area (Fig. 1A, B). The five crown separation distances were 0, 0.75, 1.5, 3, and 6 meters between the outer edge of the crown base which corresponded to 3, 3.75, 4.5, 6, and 9 meters between tree boles. These separation distances were selected to encompass a range of separation distances across which trees might be defined as a group (Graham et al. 2006, Churchill et al. 2013). For the individual tree tests, replication was created by completing one simulation with the isolated tree in the center of the high-resolution subdomain ($x = 0$, $y = 0$) and then running replicate simulations where the isolated tree was placed at six random x , y locations within a 6 m radius of the subdomain center.

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

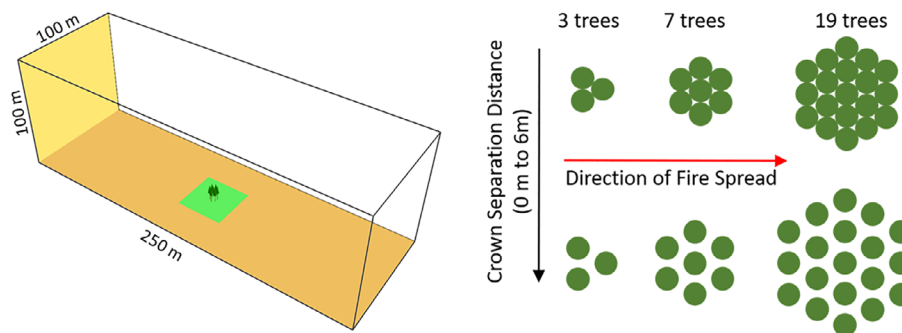


Fig. 1. Example of the simulation domain and the regular tree arrangements used.

Table 1. Tree dimensions and crown fuel parameters used for each simulation.

Parameter	Value
Tree DBH	0.25 m
Tree height	14 m
Tree CBH	7 m
Crown width	3 m
Foliage mass	14.3 kg
Foliage SAV	4000 m ⁻¹
Foliage bulk density	0.82 kg/m ³
Fine mass	1.05 kg
Fine SAV	2667 m ⁻¹
Fine bulk density	0.06 kg/m ³
Vegetation temperature	20°C
Vegetation moisture (%)	100
Vegetation density	520 kg/m ³
Vegetation char fraction	0.25
Vegetation heat of combustion	17,700 J/kg
Vegetation drag coefficient	0.25

dimensions and crown fuel parameters are listed in Table 1.

Rather than simulating a free-spreading surface fire, we choose to model the surface fire as a spreading burner with prescribed dimensions and heat output. This assumption ensured consistent, steady-state surface fire behavior within and across each simulation. Using this method, we tested a range of surface fireline intensities, 3000, 3250, 3500, 3750 kW/m, with the rate of spread fixed at 0.25 m/s, a fire depth of 6 m, and a residence time of 24 s. The prescribed surface fireline intensities (FLI) result in heat release rates per unit area of 500, 541.7, 583.3, and 625 kW/m², and theoretical total surface fuel consumptions of 0.68, 0.73, 0.79, and 0.85 kg/m², respectively, based on a 17,700 J/kg heat of combustion for woody fuel. The surface fireline intensities we simulated were chosen to capture a range of outcomes from the total absence of crown ignition to complete ignition and canopy consumption, and incorporate the critical surface FLI (3134 kW/m) needed to ignite crowns as predicted by the Van Wagner (1977) equation for a stand with the same canopy base height and crown fuel moistures that we used in our simulation. The surface fire rate of spread, depth, and residence time were selected as they closely match the descriptions of the Van Wagner (1968) crown fire experiments on which we based our tree-level properties and mid-flame wind speed.

Analysis

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

$$C = \frac{M_i - M_e}{M_i} \times 100. \quad (1)$$

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

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

$$Q_f(t) = \frac{1}{N} \sum_{n=1}^N \left(\nabla \times q_f \right)_n V_n \quad (2)$$

where the unit of Q_f is kW, N is the total number of grid cells in the tree crown, V_n is the volume of

grid cell n . The quantity Q_f is computed every time step, Δt , during the simulation. To assess the change in the heat exposure of a tree crown, we plot the running sum of Q_f . At time $t_M = M\Delta t$ this sum is:

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

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

$$\langle \nabla \times q_r \rangle = k_b [4\pi I_b(T_e) - U]. \quad (4)$$

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

$$\langle \nabla \times q_c \rangle = \beta_e \sigma_e h_{c,e} (T_e - T_g) \quad (5)$$

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

RESULTS

Group size

Our results indicated that isolated, individual trees require higher surface FLI to ignite than any given tree in a group with interlocking crowns (crown separation distance = 0 m) and that both FLI and the number of trees in the group had a significant effect on percent crown fuel consumed (Table 2 and Fig. 2). Tukey adjusted pairwise comparisons show that trees in all group sizes had greater consumption than individual trees and that trees in groups of 7 and 19 had greater consumption than those in the smaller 3-tree groups (Fig. 2B). A strong influence of FLI on tree ignition was detected with pairwise comparisons showing significant differences between each FLI level. At the lowest

Table 2. Mean percent crown fuel consumptions (PFC) on a dry mass basis for every simulation.

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

Notes: Values for the isolated tree tests (group size = 1) represent the mean consumption across the seven replicated simulations. Sep is the separation distance between the base of adjacent tree crowns in meters.

surface FLI we tested (3000 kW/m), none of the trees ignited in any simulation (Fig. 3A), and as FLI is progressively increased, more trees ignited (Fig. 3). At 3250 kW/m, the only trees that ignited were in the larger 7- and 19-tree groups (Fig. 3B), and at 3500 kW/m, trees ignited sporadically in all group sizes (Fig. 3C), but none of the isolated trees ignited. At the highest surface FLI we tested (3750 kW/m), all trees within groups ignited while the isolated, individual tree ignited in only three out of seven cases (Table 2, Fig. 3D).

Analysis of the total net heat transfer to the center tree for each group size revealed the significant differences that are driving the observed impacts on tree torching and crown consumption (Fig. 4). Radiative net heat transfer was tightly linked to group size as there are more obstructed view paths to the interior of a group with increasing group size, and therefore, a continuous decrease in radiative pre-heating of the center tree was observed when group size increased from one to nineteen trees (Fig. 4B). Convective net heat transfer (Fig. 4A) was greatest for the center tree in the nineteen-tree group (max = 23.3 kJ/m³) which was followed closely by the

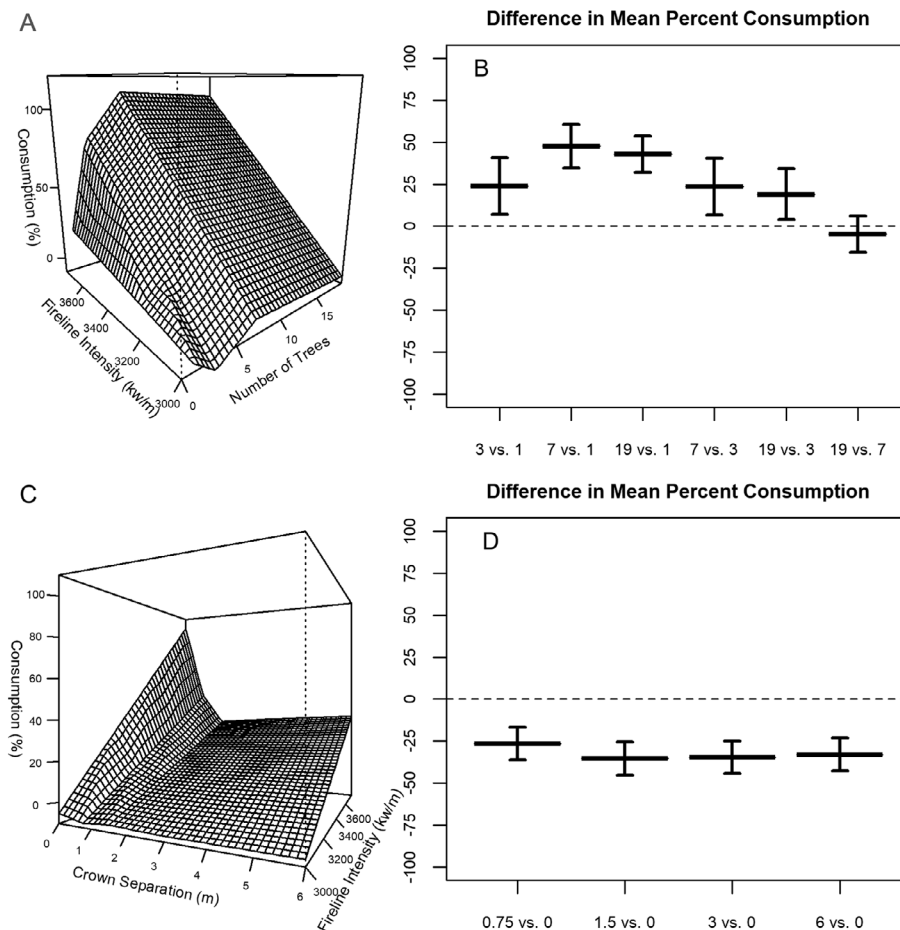


Fig. 2. Effect of crown separation, group size, and fireline intensity on the mean percent dry mass loss (fuel consumption). Perspective plots and pairwise differences in mean fuel consumption between each group size (A and B) and crown separation distance (C and D). Top row represents effects of group size when crowns are interlocking (crown separation distance = 0 m) while the bottom row represents results when the single isolated tree simulation is dropped from the analysis, and comparisons are made across crown separation distance for the multi-tree groups. Comparisons where 95% Tukey confidence bars do not cross zero indicate a significant difference in mean consumption based on the Tukey test.

seven-tree group (max = 21.9 kJ/m³). The isolated tree and the tree at $x = 0$ m, $y = 0$ m in the three-tree group (the downwind tree, Fig. 1) received similar maximum convective heating (16.5 vs. 16.3 kJ/m³). The combined effects of the two modes of net heat transfer (Fig. 4C) resulted in the greatest total net heat transfer to the nineteen-tree group (27.6 kJ/m³), followed by the seven-tree group (26.4 kJ/m³), followed by the isolated tree (24.1 kJ/m³), with the smallest net total heat transferred to the three-tree group (21.5 kJ/m³).

Separation distance

Our results indicated that increasing separation distance had a significant negative effect on crown ignition and fuel consumption. Based on Tukey adjusted pairwise comparisons, all crown separation distances greater than 0 meters had reduced crown fuel consumption when compared to the interlocking crown cases (Fig. 2D). There were no further significant pairwise differences when the crown separation was increased from 0.75 to 6 m (Fig. 2D). Once again, FLI had a clear influence on crown ignition, with no tree

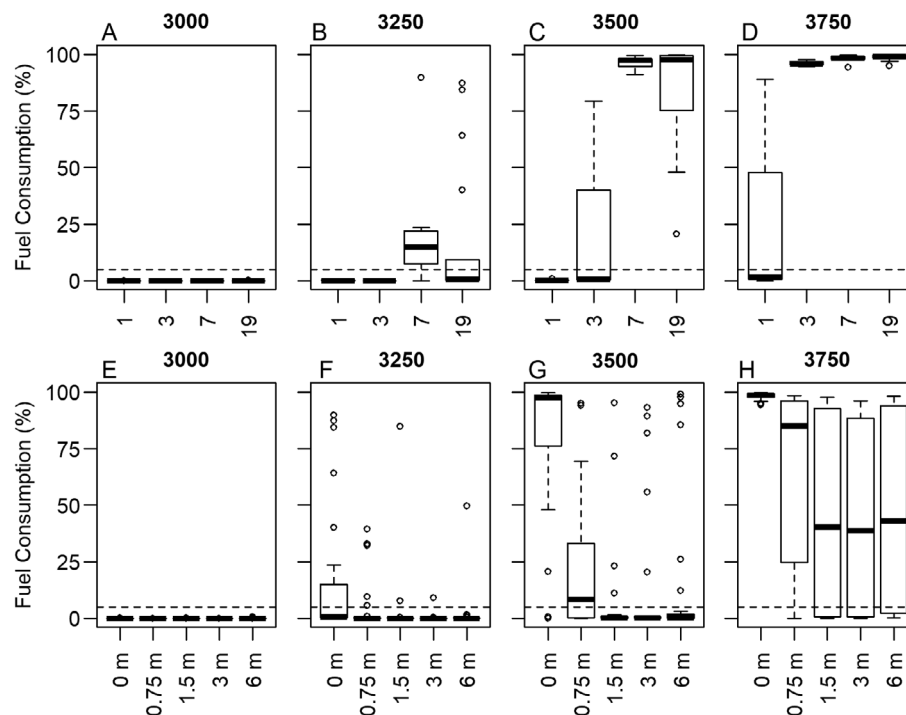


Fig. 3. Box plots of percent crown fuel consumption for each group size when crowns are interlocking (A–D) and across each crown separation distance for the multi-tree group simulations (E–H). Each point represents the percent dry mass consumption of the crown fuel for one tree. Plots are split by intensity level to show the interactive effect of FLI. Sep is the number of meters between adjacent tree crowns. The dotted horizontal lines represent our 5% ignition criterion.

ignitions occurring at 3000 kW/m and numerous ignitions at 3750 kW/m (Fig. 3). The influence of separation distance was apparent with greater mean consumption at 0 m crown separation for all intensities at which crown ignition occurred (3250–3750 kW/m). There was however a significant interaction between FLI and separation distance as the local spatial pattern has no effect when FLI is low (3000 kW/m) and no ignitions occurred. We observed a large amount of variability for the interlocking crown cases at 3500 kW/m and all crown separation cases at 3750 kW/m, suggesting that these intensities are at or near the torching threshold for interlocking trees and separated trees, respectively (Fig. 3G, H, Table 1).

Comparisons between the total net heat transfer to the center tree in the seven-tree group across all our separation distance clearly illustrate the importance of convective heating as the primary mechanism driving these results

(Fig. 5A–C). The center tree in the interlocked seven-tree group receives the greatest total net heat transfer, while the four other separation distances all received similar, but substantially lower, amounts of total heating (Fig. 5C). Interestingly, the center tree in the most widely spaced seven-tree group (6 m crown separation distance) received slightly greater total net heat transfer due to increased radiative pre-heating in comparison with the intermediate separation cases (crown separation = 0.75, 1.5, and 3 m; Fig. 5C).

DISCUSSION

Using a process-based approach, we show how fine-scale forest structure and resistance to crown fire are tightly linked through the effects of the local arrangement of crown fuels on convective and radiative net heat transfer. Our results suggest that isolated trees and, to a lesser

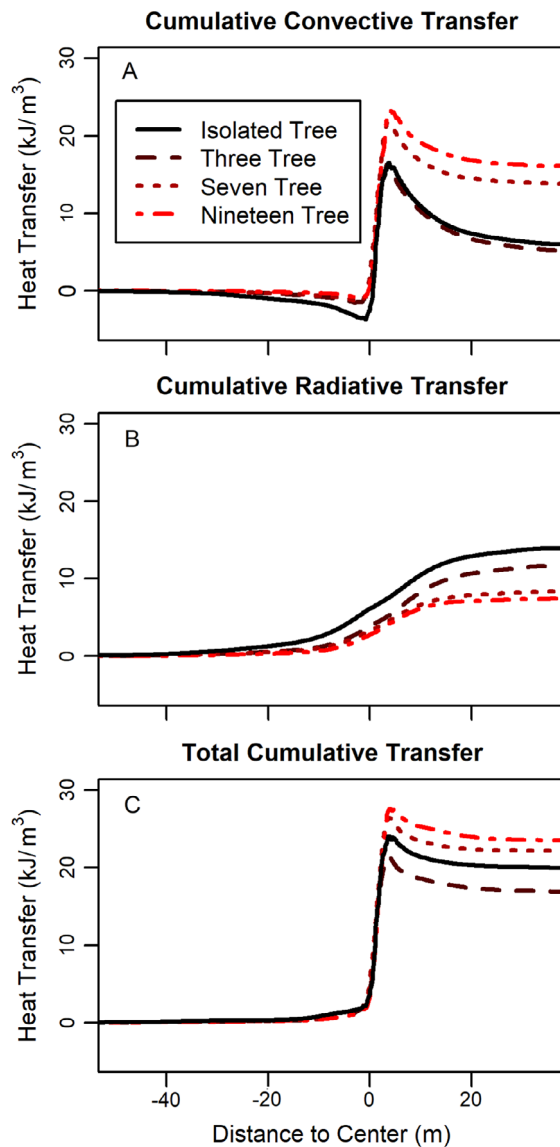


Fig. 4. Cumulative radiative (A), convective (B), and total (C) heat transfer for the isolated tree case and the center tree in each of the interlocking crown cases. Cumulative heat transfer, S_f , is defined in Eq. 3 and represents the running sum of the heat transfer in the volume of the tree's crown. The Distance to Center is the distance in meters from the leading edge of the fireline to the center of the tree group (i.e., at location $x = 0$ and $y = 0$).

extent, small groups of trees (3-tree groups) have higher torching thresholds and reduced consumption compared to trees within larger groups (7 or 19 trees), and therefore, trees in larger

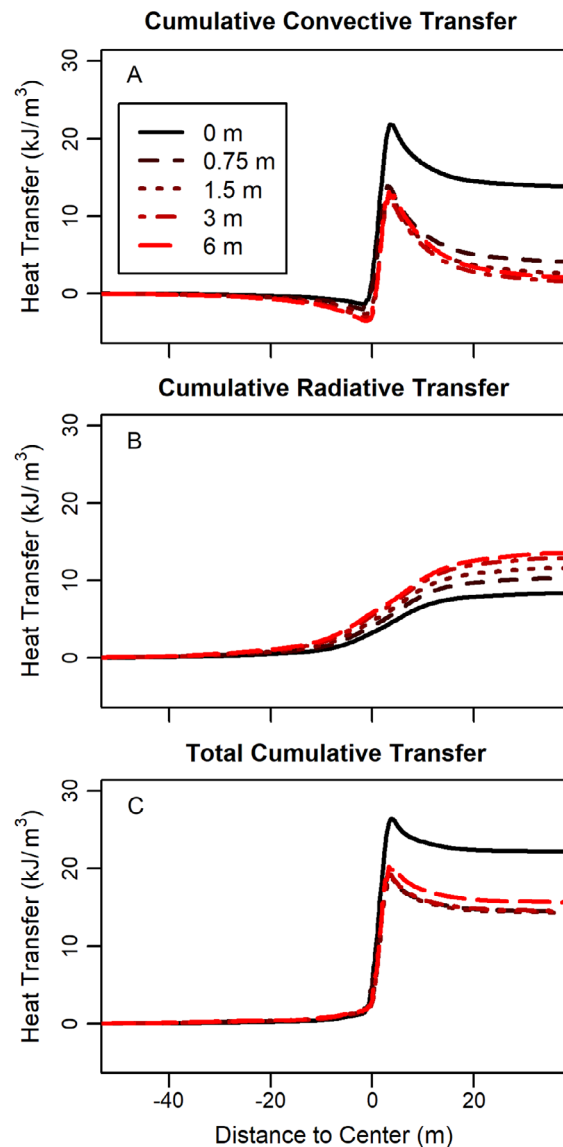


Fig. 5. Cumulative radiative (A), convective (B), and total (C) heat transfer for the center tree in the seven-tree group cases at each crown separation distance. Cumulative heat transfer, S_f , is defined in Eq. 3 and represents the running sum of the heat transfer in the volume of the tree's crown. The Distance to Center is the distance in meters from the front of the fireline to the group center ($x = 0$ and $y = 0$).

groups would be expected to suffer increased rates of mortality for a given surface FLI. Similar to other studies, we found that isolated trees and trees in small groups had increased radiative heating due to longer, obstruction-free view

paths (Linn et al. 2005, Pimont et al. 2009). However, increased net radiative heating did not translate to increased ignition potential or crown fuel consumption due to the tree's exposure to the ambient wind field, which increased convective cooling and ultimately resulted in a reduction in net heat transfer (Fig. 4A–C). Increased canopy drag within denser and large groups is the likely mechanism driving increased convective cooling as it limits the ability of cooler ambient air to flow through the canopy of the group. This will also have the add-on effect of increasing the plume temperature as mixing will be limited, and therefore, convective heating (particularly in the lower crowns) will be enhanced. These results suggest that isolated trees and small groups may act as predictable fire refugia (sensu Meddens et al. 2018) whose increased resistance represents an important pattern-process feedback in frequent-fire forests. This could be one of several pattern-process feedbacks that explain why studies on stand structure in forests with an active fire regime have generally found small mean group sizes (<5 trees) and that a large proportion of trees and basal area occurred as isolated trees and small groups rather than larger sized groups (e.g., Sánchez Meador et al. 2011, Brown et al. 2015, Tuten et al. 2015, Clyatt et al. 2016, Rodman et al. 2016, Wiggins et al. 2019).

Although our results provide evidence that isolated trees and trees located in small groups are more resistant to fire under a given fire environment (surface fuels, weather, topography), we also found that the increased resistance associated with these forest structures is conditional upon the surface fireline intensity. As surface FLI intensity increased, we observed binary fire behavior where there is either no crown ignition or a large proportion of trees ignite and ultimately consume. This binary fire behavior has been reported for marginal burning conditions where threshold effects drive the behavior of the system and whether burning will or will not occur is stochastic (Wilson 1985, Weise et al. 2005). Therefore, when the surface FLI is near this threshold, fire behavior will be responsive to the local canopy fuel arrangement. However, in situations where the surface FLI is either far below or significantly greater than the threshold for crown ignition the local fuel arrangement will have no effect. This is evident in our results, as

simulations where the surface FLI was far below this threshold resulted in no tree ignitions regardless of group size or crown separation distance. Low-intensity wildfire scenarios where there is no canopy ignition represent the lower bound of conditions under which we would expect differences in fire resistance to occur due to fine-scale forest structure. Conversely, in scenarios where the surface FLI is much greater than the ignition threshold, the increased convective cooling associated with isolated and trees in small groups is overwhelmed by the surface FLI and all trees can ignite and consume readily regardless of the local fuel pattern. Therefore, scenarios in which the surface FLI is much greater than the ignition threshold represent the upper bound of conditions under which we expect differences in fire resistance to occur due to the fine-scale forest structure. These results are similar to those from Hoffman et al. (2012) who found that the effect of changes in fine-scale fuel during the red-phase of a bark beetle outbreak on fire behavior was reduced under relatively low and high surface FLI. Other studies have found that the influence forest structure on fire behavior is dependent upon the burning conditions and in particular, the ambient wind velocity, fuel moisture, and surface fuel loads which all influence the surface FLI (Beatty and Taylor 2001, Pimont et al. 2011, Krawchuk et al. 2016, Parsons et al. 2017). Given the highly stochastic nature of surface fireline intensity during actual wildfire events due to complex topography and spatial and temporal variability in ambient wind flow and fuel moistures, individual trees and small groups are likely best thought of as having conditional resistance or as acting as predictable, but ephemeral, refugia (sensu Meddens et al. 2018).

Not only does enhanced resistance for isolated trees and small groups of trees have implications for reinforcing spatial patterns and self-regulation in frequent-fire ecosystems, the role of these structures as predictable refugia is important for post-fire trajectories following higher-severity fire events. For tree species whose post-fire recovery strategies are reliant on seeds from mature, surviving trees (e.g., Ponderosa pine [*Pinus ponderosa*] or Douglas-fir [*Pseudotsuga menziesii*]), distance to live seed sources is essential for post-fire regeneration (Chambers et al. 2016,

Owen et al. 2017), and therefore, tree refugia have very large impacts on recovery trajectories (Meddens et al. 2018). Additionally, refugia size is an important factor as small refugia have a far greater impact on fire recovery when compared to a similar number of surviving trees that are aggregated in larger patches (Coop et al. 2019). Due to our finding that isolated trees and small groups of trees may be preferentially retained and the demonstrated importance of small tree refugia on forest recovery, management actions that promote these structures across the landscape are likely to create forests that are both more resistant to fire and better able to recover following higher-severity events. These structural features likely contributed to crown fire resistance in historical forests and will be increasingly important in contemporary forest landscapes that are and will continue to experience more fires burning under extreme weather conditions due to climate change (Abatzoglou et al. 2019).

While trees in larger groups (7- and 19-tree groups) were more likely to ignite and consume, our results indicate that their fate was also conditional upon the surface fireline intensity. Similar to individual trees and smaller groups of trees, we found that crown fuel consumption generally increased within the larger groups as the thermal energy transferred from the fire to the crowns increased. At moderate levels of surface fireline intensity, the crown fuel consumption primarily occurred within the interior portions of the group resulting in the fragmentation of the large group into either smaller sized groups or individual trees. Comparison of net heat transfer between the various trees within these groups suggests that differential heat transfer processes between the interior and edge trees are likely responsible for this phenomenon. Specifically, trees in exterior group positions were less likely to torch as they received greater convective cooling due to increased exposure to the ambient wind field while the sheltered interior trees were exposed to less ambient flow. Similar to Kane et al. (2014), our results suggest that fires occurring under low to moderate severity conditions are likely to favor the retention and creation of isolated trees and small groups of trees. However, under more extreme burning conditions, our results show that larger groups are likely to

experience almost complete combustion and thus result in the creation or expansion of non-treed openings. Together these processes will contribute to self-regulation as fire events will increase the proportion of isolated trees and small groups (features which we suggest have increased resistance), therefore creating stand structures that will be more resistant to the next fire event. However, self-regulation is certainly not a guarantee as fires or portions of fires burning under extreme conditions can overwhelm resistance mechanisms and result in the transition to an alternative stable state (Lauvaux et al. 2016, Stevens-Rumann et al. 2018).

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

effects (Hood et al. 2018, O'Brien et al. 2018, Yedinak et al. 2018).

To limit some of the complexity inherent in modeling spatially explicitly fire behavior, we made several simplifying assumptions. We used a steady-state spreading line-burner to represent the surface fire rather than including heterogeneous surface fuels in the model and simulating dynamic surface fire spread. While simulating a free-spreading surface fire through spatially heterogeneous fuels is possible in WFDS-PB, this simplification allowed us to assess the effect of group size and tree separation distance under consistent heat exposure conditions and to replicate the surface fires reported in Van Wagner (1968). The ability to isolate the effects of specific variables or processes on ignition and consumption represents a significant benefit of using a physical model like WFDS-PB as it would physically impossible to separate variables like surface and canopy fuels in the real world (Hoffman et al. 2018). Although our surface fire intensity, spread rate, and depth were held consistent throughout a simulation, it is important to note that the fire plume, which is the source of a tree's heat flux exposure, was not constrained and evolved according to the interactions among the buoyant flow, the tree crown(s) and ambient wind. If we had simulated a freely evolving surface fire through heterogeneous fuels, we might expect a local increase or decrease in surface fireline intensity as the fire burns across different fuel types. Since crown ignition is a local effect driven by the surface FLI, which is captured in our simulations, the reported relative effect of group size and crown separation distance on the surface FLI required for torching would remain unchanged regardless of the particular mixture of surface fuels. Though we would expect the observed trends between group size, tree spacing, and ignition to be consistent across a range of conditions, the high levels of surface fuel variability that exist both within and across ecosystems suggest future research that investigates a wide gradient in fuel types and ecosystems. As an additional simplification, we only considered the role of horizontal pattern on crown fire transition and did not consider the interacting role of vertical complexity, or so-called "ladder fuels," on this process. Though the vertical distribution of fuels certainly plays a role in crown fire behavior, we choose to use

simple group structures as they make comparisons with previous crown fire initiation models possible, are representative of the types of groups created when homogeneous stands are treated using restoration principles, and because the concept of ladder fuels is poorly defined and quantified across the literature. The influence of vertical complexity and heterogeneous surface fuels on crown fire behavior across a range of environmental conditions represents future research needs.

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

Implications for forest management

The influence of the local arrangement of crown fuels on heat transfer, torching thresholds,

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

Our results also highlight two important ways in which fire burning under low to moderate conditions can be used by managers to support the creation and maintenance of forests that resemble historical conditions. First, our results indicate that fires burning under these conditions can reinforce and maintain historical spatial patterns by favoring the survival of individuals and small clumps. Second, our results suggest that fire burning under these conditions can convert larger tree groups to isolated individuals and small groups that dominate historic forest structure. The role of prescribed fires and wildfires burning under moderate conditions in reducing fuel loading is well understood, and our results lend further support that they can also restore the structures and complex spatial patterns that existed in these forests historically (Holden et al. 2007, Battaglia et al. 2008, Larson et al. 2013, Lydersen et al. 2013, Kane et al. 2019, Brown et al. 2019, Pawlikowski et al. 2019, Walker et al. 2018). Forest restoration through the use of fire is an important management tool given the reality that mechanical treatments alone cannot achieve forest restoration goals across the vast areas in need of treatment (North et al. 2012, 2015, Schoennagel et al. 2017). Although our results indicate several ways in which managers can utilize low to moderate severity fire to maintain and create forest structures and pattern-process relationships that mimic historical conditions, more extreme burning conditions, which are expected to increase under a changing climate (Abatzoglou et al. 2019), may significantly

reduce the likelihood that isolated trees and small tree groups survive future fires and can act as refugia.

CONCLUSION

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

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