

ARTICLE

Restoration and fuel hazard reduction result in equivalent reductions in crown fire behavior in dry conifer forests

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Abstract

Over the past several decades, the management of historically frequent-fire forests in the western United States has received significant attention due to the linked ecological and social risks posed by the increased occurrence of large, contiguous patches of high-severity fire. As a result, efforts are underway to simultaneously reduce potential fire and fuel hazards and restore characteristics indicative of historical forest structures and ecological processes that enhance the diversity and quality of wildlife habitat across landscapes. Despite widespread agreement on the need for action, there is a perceived tension among scientists concerning silvicultural treatments that modify stands to optimally reduce potential fire behavior (fuel hazard reduction) versus those that aim to emulate historical forest structures and create structurally complex stands (restoration). In this work, we evaluated thinning treatments in the Black Hills National Forest that exemplify the extremes of a treatment continuum that ranges from fuel hazard reduction to restoration. The goal of this work was to understand how the differing three-dimensional stand structures created by these treatment approaches altered potential fire behavior. Our results indicate that restoration treatments created higher levels of vertical and horizontal structural complexity than the fuel hazard reduction treatments but resulted in similar reductions to potential crown fire behavior. There were some trade-offs identified as the restoration treatments created larger openings, which generated faster mean rates of fire spread; however, these increased spread rates did not translate to higher levels of canopy consumption. Overall, our results suggest that treatments can create vertical and horizontal complexity desired for restoration and wildlife habitat management while reducing fire hazard and that they can be used in concert with traditional fuel hazard reduction treatments to reduce landscape scale fire risk. We also provide some suggestions to land managers seeking to design and implement prescriptions that emulate historical structures and enhance forest complexity.

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KEYWORDS

Black Hills, crown fire, ecology, fire behavior, fuel hazard reduction, ponderosa pine, restoration, silviculture, Wildland Urban Interface Fire Dynamics Simulator, wildfire

INTRODUCTION

Dry pine and mixed-conifer forests represent extensive and diverse ecosystems in which historically frequent fires created complex forest structures and promoted diverse understory plant communities (Hessburg et al., 2019). Fire, recognized as a keystone disturbance process, in conjunction with local climate, soils, and topography, influenced tree density and spatial pattern, and species composition in these ecosystems (Hessburg et al., 2015, 2019; Jaquette et al., 2021; Lydersen & North, 2012). However, wildfire suppression, cessation of indigenous burning practices, and unregulated and unmanaged grazing practices following Euro-American colonization altered the structure and function of these fire-adapted ecosystems across the western United States (Borman, 2005; Hagmann et al., 2021). This legacy has resulted in significant increases to tree densities, enhanced dominance of shade-tolerant tree species, and generated more homogenous tree spatial patterns (e.g., Battaglia et al., 2018; Brown & Cook, 2006; Hessburg et al., 2015, 2019; Knight et al., 2020; Larson & Churchill, 2012; Reynolds et al., 2013). Climate change presents an additional risk to the continued ecological function of these ecosystems by enhancing tree stress and sensitivity to biotic disturbances (Weed et al., 2013), increasing the potential for wildfires to occur under extreme weather conditions resulting in more severe fires (Abatzoglou & Williams, 2016; Khorshidi et al., 2020; Parks & Abatzoglou, 2020; Westerling, 2016), and limiting the opportunity for post-fire fire regeneration and recovery (Coop et al., 2020; Haffey et al., 2018; Rodman, Veblen, Battaglia, et al., 2020; Rodman, Veblen, Chapman, et al., 2020; Stevens-Rumann et al., 2018). These changes to forest structures and climate are not only associated with reductions to biodiversity and ecosystem resistance and resilience (Graham et al., 2019; Hessburg et al., 2019; Latif et al., 2020; van Mantgem et al., 2020), but contribute to highly visible societal and economic costs in the form of smoke impacts on human health and the loss of life and property due to uncontrolled wildfire occurring in areas that are increasingly urbanized (Caggiano et al., 2020; Radeloff et al., 2018; Schweizer et al., 2019).

Tree density reduction through mechanical treatments or silvicultural practices is a major management strategy used to address the linked ecological and social

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

This understanding suggests that the greatest reductions of potential crown fire behavior would be achieved through treatments that reduce surface fuel loads and remove understory trees to increase canopy base heights therefore reducing the potential for crown fire transition, as well as thinning the remaining overstory trees to reduce active crown fire spread potential (see Agee & Skinner, 2005). Given the strong relationship between surface fuel loading and fire behavior, it is unsurprising that studies of fuel treatment effectiveness have highlighted the importance of reducing surface fuel loads and have shown that mechanical treatment followed by prescribed burning confer the greatest reduction in potential fire behavior (Kalies & Yocom Kent, 2016). Though not explicit in the recommendations of Agee and

Skinner (2005), thinning treatments that create uniform spacing between tree crowns have been increasingly recommended (Alexander & Cruz, 2020; Colorado State Forest Service, 2012; Dennis, 2005; Jones et al., 2016). As a result of such recommendations, treatments designed to achieve maximum reduction to potential fire behavior often tend towards spaced-based, thin-from-below approaches that uniformly increase canopy base height and separate overstory tree crowns from one another, with the aim of hampering surface to crown-fire transition and limiting the potential for tree-to-tree fire spread (i.e., active crown fire). However, the uniform stand conditions created starkly contrast the historical structure of dry conifer forests and, in doing so, such treatments fail to capture the overall ecological resilience associated with complex, heterogenous forest structures or meet other management objectives such as creating northern goshawk (*Accipiter gentilis atricapillus*) habitat or promoting variable light conditions that enhance understory biodiversity and create diverse regeneration niches (Cannon et al., 2019; Graham et al., 2015; Larson & Churchill, 2012; Reynolds et al., 2013). Although our basic understanding of crown fire behavior and fuels management suggests that fuel treatments that generate low-density, vertically homogenous forest structures will optimize the reduction of fire behavior, it may be the case that emulating historical heterogenous forest structures can achieve similar results while simultaneously benefiting other aspects of ecosystem function.

Previous empirical work has suggested that the multi-aged structures and vertically continuous tree groups created by treatments that enhance structural complexity may not effectively mitigate crown fire hazard and fire severity (Johnson & Kennedy, 2019), however other studies suggest these concerns may not be born out. For example, measurements of post-fire dynamics in dry conifer forests have suggested strong associations between structural heterogeneity and resilience to fire (Jeronimo et al., 2020; Koontz et al., 2020) and stand-scale simulation studies that account for spatial arrangement of fuels have shown that reductions to potential fire behavior and effects are more closely related to the total amount of available fuel and the environmental burning conditions than the spatial arrangement of that fuel (Atchley et al., 2021; Parsons et al., 2017; Ziegler et al., 2017). These findings suggest that treatments creating complex forest structures may result in similar effects on fire hazard as more traditional, space-based treatments. However, the existing research has focused on larger scale measures of heterogeneity (e.g., Cannon et al., 2020; Jeronimo et al., 2020; Koontz et al., 2020) or only considered the within-stand impacts of heterogenous tree patterns on fire behavior without direct

comparison to outcomes of space-based fuel hazard reduction (e.g., Parsons et al., 2017; Ziegler et al., 2017). If restoration treatments have similar efficacy in reducing fire behavior as space-based fuel hazard reduction treatments, this suggests that land managers can reduce fire hazard to ecosystems and communities, while simultaneously achieving the broader suite of objectives realized through ecologically based silvicultural systems such as variable-density thinning (Carey, 2003), free selection (Graham et al., 2007), or individuals clumps and openings (ICO; Churchill et al., 2013).

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

In this work, we utilized spatially explicit measurements of forest structure within four different silvicultural treatments on the Black Hills National Forest in conjunction with three-dimensional physics-based fire-behavior modeling to assess the potential difference in fire behavior resulting from different levels of structural

complexity. Treatments were selected to represent a range of possible structural outcomes ranging from a highly complex treatment implemented to create favorable Northern Goshawk habitat (*Accipiter gentilis atricapillus*), to two slightly different treatments that used free selection to create heterogenous stands, all the way to a traditional space-based, thin-from-below treatment implemented to reduce fire hazard and enhance timber volume production. We sought to characterize the differences between the structural outcomes of the prescriptions in terms of (1) nonspatial structural metrics (e.g., basal area, quadratic mean diameter, canopy bulk density), (2) horizontal spatial patterns including measures of tree aggregation and the distribution of group sizes, and (3) the interaction between vertical and horizontal complexity. Finally, we evaluated the impact of treatments with differing objectives on potential fire behavior. These results will provide a better understanding of how particular prescriptions alter spatial aspects of forest structure, but most importantly investigate whether fire-behavior trade-offs truly exist when implementing treatments that create complex forest structures.

METHODS

Study area and treatment description

This study took place in ponderosa pine (*Pinus ponderosa* var. *scopulorum*) dominated forests of the Black Hills. The Black Hills are a geologic uplift in southwestern South Dakota and northeastern Wyoming, USA that forms a forested island rising from the Great Plains. Our study occurred on the United States Forest Service (USFS) Black Hills Experimental Forest (BHEF). The BHEF is in the central Black Hills, which is primarily underlain by granites and is the most productive area of the Black Hills uplift (Shepperd & Battaglia, 2002). Typical site index (base age 100) ranges from 36 to 75 feet (1 foot = 0.30 m; Myers & Van Deusen, 1960), and the site index for the BHEF specifically has been estimated at 55 feet (Graham et al., 2019). Between 1981 and 2010, annual precipitation for the BHEF averaged 49 cm, which peaks in the spring with 32% falling in just May and June (PRISM Climate Group, 2021). This early-season moisture combined with consistent summer rains, warm growing-season temperatures, and periodic cone crops results in prolific natural ponderosa pine regeneration (Shepperd & Battaglia, 2002).

Like many other frequent-fire forest ecosystems, the ponderosa pine forests of the Black Hills are characterized with increased tree densities and a loss of stand- and

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

Within the BHEF and the Black Hills National Forest immediately to the north of the BHEF, we sampled four different mechanical forest-thinning treatments that represented a wide range of management activities to characterize their differences across several forestry and fire-behavior metrics. These treatments included a silviculture prescription designed to meet habitat restoration objectives by utilizing small group retention, two similar prescriptions that follow concepts associated with the free selection silvicultural system (Graham et al., 2007), and finally a commercial thinning treatment. The small group retention prescription (hereafter, SGR) was implemented to reduce the susceptibility and severity of mountain pine beetle infestation and provide wildlife habitat for the Northern Goshawk and its prey. For trees ≥ 22.9 cm diameter at breast height (DBH), the SGR prescription called for the retention of groups of 15–20 trees with interlocking or nearly interlocking crowns and thinning commercial trees to a basal area of ~ 2.3 m²/ha (10 square feet per acre) between groups. The retained groups emphasized large trees but could include trees of different sizes. In addition, pre-commercial understory trees (< 22.9 cm DBH) were retained in large patches beneath

the retained tree groups of large trees. The two free selection (FS) prescriptions were designed to address management objectives that required multi-aged complex forest conditions and met integrated management objectives like timber products and wildlife habitat; yet also maintain healthy and vigorously growing trees of all sizes spatially dispersed to favor the regeneration of early-seral tree species. The marking guide for both FS treatments used vigor selection criteria to select leave trees of ponderosa pine ≥ 22.9 cm DBH where trees were retained if they had high crown vigor (i.e., a crown ratio greater than 40% and more than 3 years of needle retention; Jain et al., 2012; Hornibrook, 1939). A target density was not dictated during marking; however, the basal area after harvest resulted in 9.2–13.8 m²/ha (40–60 square feet per acre). Within the FS treatments, two different pre-commercial thinnings were applied to trees <22.9 cm DBH. On one-half of the stands, overstory trees were excluded from the spacing guidelines and only pre-commercial trees were considered. Pre-commercial trees were spaced evenly using ~4.3 m (14 feet) spacing across the stand even if the small tree was growing underneath the crown of an overstory tree (FS-On). Within the other half of the stands (FS-Off), large trees were included in the spacing guidelines; thus, pre-commercial trees were spaced a minimum of 4.3 m from all neighboring trees including the overstory trees. This created conditions where advanced regeneration was spatially separate from the overstory. In theory, the FS-On treatment should create greater vertical heterogeneity as pre-commercial trees could be retained directly adjacent to commercial trees, while in FS-Off pre-commercial trees could never occur within 4.3 m of a commercial tree. FS-On is also likely to result in slightly greater retention of pre-commercial trees as their spacing was independent of the commercial tree locations. The final prescription we evaluated was a simple commercial thinning treatment (CT) where the stands were thinned from below to 9.2 to 13.8 m²/ha (40 to 60 square feet per acre), and trees were spaced a minimum of ~4.9 m (16 feet) apart. Trees smaller than 22.9 cm DBH were only retained when a gap in the fixed tree spacing would have occurred.

Field sampling

We established 11, 100 × 100 m (1-ha), permanently monumented plots within the treatment units. Measurements occurred during the summer of 2017, which represented 3 years post-treatment for SGR and 4 years post-treatment for FS-Off, FS-On, and CT. The plots were randomly located within each unit boundary such that roads and powerline corridors did not fall within the plot

boundary. Three plots were installed in the CT treatment and each of the two FS treatments. However only two plots were installed in the SGR treatment as it was smaller in area and was bisected by a powerline corridor that precluded the placement of more than two non-overlapping plots.

Each plot was subdivided into 16 25 × 25 m quadrats within which all live trees >1.37 m tall had their *x*, *y* locations recorded. In addition to mapping their *x*, *y* location, all live trees were tagged and had their DBH, tree height (TH), compacted crown base height (CBH), crown width (CW), and species recorded. The grid was first established and monumented using a Pentax PCS-515 laser total station that is accurate to 0.001 m and 0.005°. All live trees in each quadrat were then mapped relative to the monumented points by recording distance to the 0.1 m and azimuth to the 0.1° using a TruePulse 360R laser range finder. Before we converted azimuth and distance to *x*, *y* locations, we corrected each distance based on stem radius. The precise grid installed with the total station prevented the propagation of spatial error that can occur when grids are laid out successively using handheld range finders. Rather than being additive, any measurement errors will be contained to a particular quadrat and not propagated across the entire plot.

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

$$DBH = -0.69 + 0.85 \times DSH \quad (1)$$

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

$$HT = 1.41 + 0.45 \times DBH \quad (2)$$

$$CW = 0.54 + 0.12 \times DBH \quad (3)$$

$$CBH = 0.43 + 0.24 \times DBH \quad (4)$$

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

To estimate the density of pre-commercial trees (<12.7 cm DBH) prior to treatment, we establish three control (untreated) plots in adjacent stands whose productivity and management history mirrored the treated stands. In these untreated stands, randomly located, 1-ha² plots were installed within which we estimated the number of trees <12.7 cm DBH. Each 1-ha plot was subdivided into 16 25 × 25 m quadrats and, in each quadrat, we randomly located five 1 m diameter circular subplots. This gave us a total of 80 subplots within which we recorded the number of live trees >1.37 m tall in each DBH class (0–2.54, >2.54–5.08, >5.08–7.62, >7.62–10.16, >10.16–12.7 cm). In each subplot, the first tree encountered in each size class was tagged, and its height, crown width, and crown base height were recorded. This data allowed us to estimate the pre-treatment density of the small tree cohort in our treated plots by averaging the number of trees in each 2.54-cm diameter class found within our control plots. Tree dimensions for these small trees were calculated by averaging the dimensions of all measured trees in each diameter class. All tree and stump data is available in a public Dryad repository (Ritter et al., 2022).

Stand structure analysis

Tree groups and horizontal pattern

We calculated several metrics to evaluate the effect of treatment on horizontal forest structure. We characterized changes to the proportion of the stand area comprised of isolated trees, tree groups of various sizes, and non-treed openings by identifying tree groups based on crown interlock and calculating the percent crown cover attributable to each of these structural features post-treatment. Based on these identified groups, we calculated the proportion of the stand area occurring in isolated trees and small (2–4 trees), medium (5–9 trees), large (10–19 trees), and very large groups (20+ trees). These proportions could not be calculated for the pre-treatment stands as pre-treatment tree location data was only available for trees >12.7 cm DBH. We also calculated the amount of stand area >9 m away from another tree bole as larger openings provide different functional attributes than smaller openings (Matonis & Binkley, 2018). To further characterize the spatial stand structure, we generated density distribution curves for the distance from any point in the plot to the nearest tree bole and the distribution of tree bole to tree bole nearest-neighbor distances. The distance to the nearest live tree (DTL) showed the distribution of opening sizes by plotting distances from all points within the plot to the nearest tree. The nearest-

neighbor distance (NND) distribution is reflective of tree aggregation by plotting the distribution of distances between each tree and its closest neighbor.

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

Vertical heterogeneity

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

Canopy fuels

We calculated the canopy fuel load (CFL), canopy bulk density (CBD), and canopy base height (CBH) at the plot scale following the methods of the Forest Vegetation Simulator – Fire and Fuels Extension (FVS-FFE; Rebain, 2010). To do this, we first calculated the total mass of available fuel (foliage mass plus one-half the mass in twigs <0.635 cm in diameter) for each live tree using the allometric equations developed for ponderosa pine in the Black Hills by Keyser and Smith (2010). The CFL is simply the sum of all the available crown fuels divided by the plot area in square meters. As is done in FVS-FFE, this available fuel mass was assumed to be homogeneously distributed along the length of the live crown. These individual tree crown profiles were then summed across the plot to develop a canopy fuel profile. Finally, CBD was calculated from the canopy fuel profile by finding the maximum of the 3-m running mean bulk density and the CBH was calculated as the lowest height at which $>0.011 \text{ kg/m}^3$ of available fuel is present (Rebain, 2010). These calculations were completed for the post-treatment stands based on the measured live trees and for the pre-treatment stands by combining the live tree values with those of the pre-treatment trees reconstructed from their stumps and the small tree cohort characterized by the control plots.

Fire simulation

Wildland urban interface fire dynamics simulator background

We conducted fire-behavior simulations using the Wildland Urban Interface Fire Dynamics Simulator version 9977 (WFDS; Mell et al., 2007), which is based on the Fire Dynamics Simulator (FDS) version 6 developed by the National Institute of Standards and Technology (McGrattan et al., 2013a). WFDS is a spatially explicit, physics-based model that simulates fire behavior by linking a large eddy computational fluid dynamics model that solves the governing equations for the conservation of momentum, total mass, and energy with sub-models that calculate radiative and convective heat transfer, thermal degradation of vegetation, and gas-phase combustion. Wildland vegetation (fuels) are represented within a three-dimensional computational grid as a porous media based on their bulk properties (e.g., bulk density, fuel moisture content, and surface area to volume ratio). These fuels are treated as thermally thin, optically black elements whose thermal degradation is modeled as a two-step process where the fuel is first dehydrated before undergoing pyrolysis (Morvan & Dupuy, 2004). The combustion of this gaseous fuel is then

modeled as a mixing-limited, infinitely fast reaction. WFDS is a dynamic model, accounting for interactions between the ambient wind flow, fire plume, and vegetation elements and therefore is well suited to capture the complex interactions between heterogeneous fuel elements and fire behavior (Hoffman et al., 2018; Yedinak et al., 2018). Further description of WFDS can be found in Mell et al. (2007, 2009). Additional details about the formulation, verification, and validation of FDS are provided in McGrattan et al. (2013a, 2013b, 2013c). Evaluation of WFDS for the simulation of the combustion and fire spread through vegetative fuels is presented by Castle et al. (2013), Hoffman et al. (2016), Mell et al. (2007, 2009), Mueller et al. (2014), Overholt et al. (2014), Perez-Ramirez et al. (2017), Ritter et al. (2020), and Sánchez-Monroy et al. (2019).

WFDS simulation set-up

To simulate fire behavior through each 1-ha plot, we created a simulation domain 100 m tall with an area of 10.5 ha (750 m long and 140 m wide, Figure 1). We placed our stem mapped plot data within a 100 m by 100 m area of interest that extended from $x = 450$ to 550 and $y = 20$ to 120 . The stem map was placed with north in the positive y direction and therefore fire spread and wind direction was from west to east across the plots. The rest of the simulation domain was filled with random rotations of the stem map to generate realistic, interior forest wind-flow regimes within the area of interest. The resolution within the domain varied to reduce computational demand while achieving suitably fine resolution within the area of primary interest. The upwind area from $x = 0$ to 370 , the downwind area from $x = 560$ to 750 , and the entire area above the canopy ($z > 30$ m) had a resolution of $1 \times 1 \times 1$ m in the x , y , and z dimensions. The volume bounded by $x = 370$ to 560 , $y = 0$ to 140 , $z = 0$ to 30 was simulated at a resolution of $0.5 \times 0.5 \times 0.5$ m so that fire behavior, and the surface and canopy fuel complex surrounding the area of interest could be more fully resolved. Boundary conditions for the lateral edges were simulated as periodic, the top boundary was simulated as a no-flux, no-slip boundary, the leeward edge was open, and the windward edge was set to a prescribed inflow velocity. Inflow was set to follow a standard logarithmic vertical wind profile with a neutral atmosphere with a prescribed open (20 m) windspeed. We conducted simulations with the open wind speed at four levels: 2.0, 3.5, 5.0, and 10.0 m/s. Surface fire was ignited simultaneously across the entire width of the domain 70 m upwind from the area of interest. This allowed the surface fire spread to reach semi-steady-state behavior prior to encountering the stem mapped area where fire-behavior metrics were calculated.

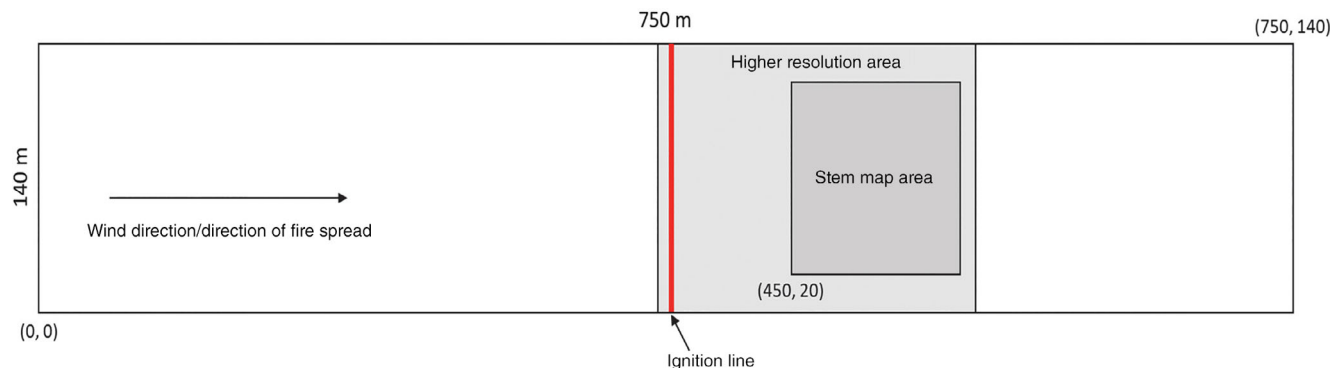


FIGURE 1 Layout of the 140×750 m Wildland Urban Interface Fire Dynamics Simulator (WFDS) simulation domain. Fire spread and wind direction was left to right. The white area was simulated at 1-m resolution while the shaded area was simulated at 0.5-m resolution. The darkest shading is the location of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

Simulated surface fuel and canopy fuel

Given that our study relied on post-treatment reconstructions, we were not able to directly utilize measured surface fuel data in our fire-behavior modeling. Instead, we modeled spatially explicit loading of fine surface fuels (i.e., herbaceous and litter) as a function of the local forest structure. This approach allowed us to incorporate spatial variability in both the type of surface fuel (litter vs. herbaceous) as well as the load. Our model construction follows a similar form to the surface fuel model utilized in Linn et al. (2005) where the presence and load of either the litter layer, which consists of both litter and 1-h dead down woody fuels, or herbaceous fuels depends upon the cumulative tree basal area within a 5 m radius of any location. The surface fuel loading of litter and herbaceous fuels was simulated at 0.25-m^2 resolution using the equation

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

In this equation, the values of m_{grass} and m_{litter} were set to 0.35 and 1.4 kg/m^2 , respectively, and represent the maximum loading of either fine woody fuels and litter (Reich et al., 2004) or grass (Uresk & Benzon, 2007). C is a non-dimensional proportionality constant and was set to 5 kg following Linn et al. (2005). BaR was calculated by relativizing the total BA within 5 m of pixel by the highest local (5 m) basal area found in any of the field plots. Fine woody fuels and litter were simulated with a fuel moisture of 5% and the grass fuels were simulated at 15% moisture on a dry mass basis.

Tree crowns were simulated as right, rectilinear cones based on their measured or allometrically derived crown measurements. Foliage was then homogeneously distributed within each crown volume with a bulk density of 0.7 kg/m^3 . This bulk density was selected as it resulted in canopy fuel loads that matched the values calculated using the local allometries derived by Keyser and Smith (2010). Foliage surface area to volume ratio was set to 5808 m^{-1} (Brown, 1970). Live canopy fuel moisture was 100% to represent an average value for live tree crowns.

Analysis of the WFDS simulations

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

In addition to these fire-behavior metrics, we also calculated vertical U-velocity profiles prior to the ignition of

our simulated fires for the pre- and post-treatment conditions when the open wind speed was 10 m/s. This allowed us to characterize the influence of stand structure on wind velocity at different heights through the canopy. To calculate the wind profiles, in each plot, we averaged the streamwise velocity during the 120 s immediately before ignition at 1-m height intervals along three lengthwise y-slices at $y = -25$, $y = 0$, and $y = 25$. The time-averaged profiles at each y-slice were averaged to generate the plot-level wind profiles. We then found the treatment mean by averaging these plot-level profiles. To allow easier comparison between treatments, the mean profiles were normalized by the mean wind speed at 25 m above the ground. This approach allowed us to

average out the effects of variation in the wind field due to transient gusts and downdrafts, as well as the plot differences and the horizontally heterogenous distributions of fuel (i.e., drag) within each plot.

RESULTS

Stand structure

Prior to treatment, sapling (<12.7 cm DBH) densities exceeded 16,000 TPH, while pole (12.7–22.9 cm DBH) and saw timber (>22.9 cm DBH) densities ranged from 220 to 584 TPH (Table 1). All treatments significantly

TABLE 1 Pre- and post-treatment stand structure, canopy fuel, and simulated fire-behavior data.

Metric	SGR		FS-Off		FS-On		CT	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Tree density ^a (no./ha)								
Sapling	16,484	386	16,194	77	16,225	117	16,177	22
Pole	66	53	147	60	90	51	46	10
Saw timber	215	42	196	120	284	99	244	139
Total	16,765	481	16,537	257	16,599	267	16,467	171
Basal area (m ² /ha)								
Sapling	6.7	0.5	6.7	0.3	6.6	0.3	6.9	0.1
Pole	1.9	1.4	3.9	1.7	2.5	1.4	1.2	0.3
Saw timber	19.5	4.4	24.5	10.8	31.1	9.3	26.7	12.0
Total	28.0	6.3	35.1	12.8	40.2	11.0	34.7	12.4
Mean DBH (cm)	1.0	3.3	1.0	8.0	1.0	6.6	1.0	11.1
QMD (cm)	4.6	13.7	4.3	23.2	4.9	21.0	4.5	30.0
Mean height (m)	2.2	5.2	2.2	10.6	2.2	9.0	2.2	14.3
Mean CBH (m)	2.0	10.0	2.0	4.0	2.0	6.7	2.0	8.3
Mean CFL (kg/m ²)	0.95	0.19	0.85	0.38	1.05	0.34	0.91	0.37
Mean CBD (kg/m ³)	0.09	0.02	0.09	0.04	0.10	0.03	0.08	0.04
Mean ROS (m/s)	0.70	0.64	0.71	0.47	0.71	0.49	0.71	0.48
Mean FLI (kW/m)	17,624	6624	15,655	3504	18,676	3866	18,145	3773
Canopy consumption (%)								
Trees < 22.9 cm DBH	99.6	29.7	99.4	44.2	99.8	36.8	99.9	39.4
Trees ≥ 22.9 cm DBH	94.7	16.5	90.1	14.3	95.3	15.3	93.9	16.2
Total	95.5	19.3	93.0	19.3	96.4	17.7	95.0	16.8

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

^aMore than 99% of the trees were ponderosa pine.

reduced the density of saplings. However, the SGR prescription retained more of the sapling size class, 386 TPH, as compared to the FS-Off, FS-On, and CT treatment means of 77, 117, and 22 TPH, respectively (Table 1). Treatments also significantly reduced basal area (BA) with the SGR treatments resulting in the lowest post-treatment BA of 6.3 m²/ha compared to 12.8, 11.0, and 12.4 m²/ha for the FS-Off, FS-On, and CT treatments, respectively (Table 1). Quadratic mean diameter (QMD) for all trees >1.37 m tall was increased following all treatments, with the SGR treatment having the lowest QMD at 13.7 cm, in comparison to 23.2 and 21.0 cm for the FS-Off and FS-On treatments and 30.0 cm for the CT treatment (Table 1). Similarly, the

mean tree height was the lowest in SGR at 5.2 m, versus 9.0 and 10.6 m for FS-Off and FS-On, respectively, and 14.3 m for CT (Table 1). Differences in QMD and mean tree height among the treatments was due to greater retention of saplings and lower retention of saw timber in SGR and lower retention of both saplings and pole-sized trees in CT.

Visual comparisons of the DBH distributions reveal a reverse-J-shaped distribution typical of balanced, uneven-aged stands for SGR (Figure 2). In comparison, both FS treatments generated distributions that are multi-cohort and reflective of an irregular uneven-aged structure. Finally, CT resulted in a bimodal distribution with a small peak in density between 5 and 10 cm and a larger

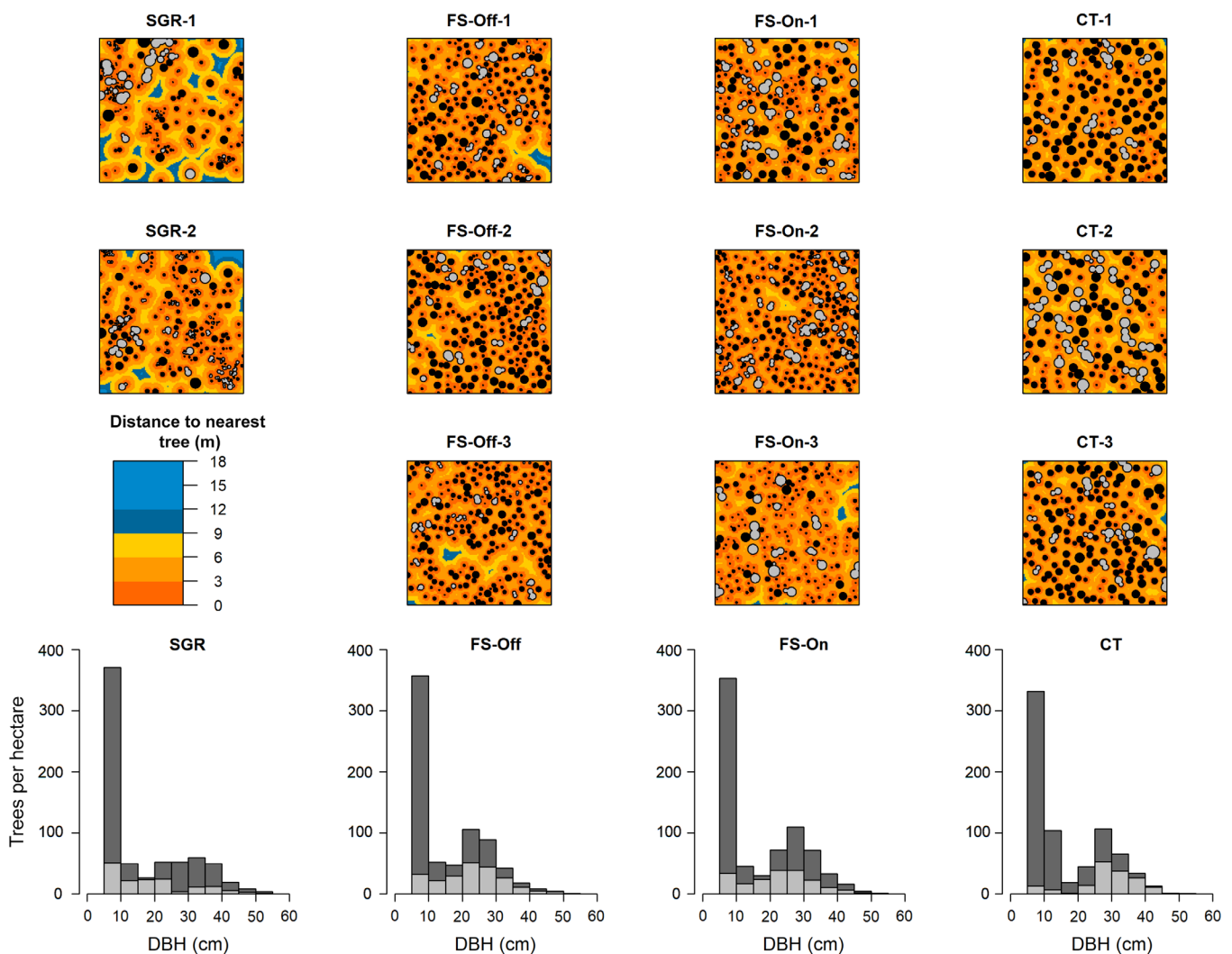


FIGURE 2 Post-treatment plot maps for all trees taller than 1.4 m and diameter at breast height (DBH) distributions with the pre-treatment represented by the darker gray. Only trees >5 cm DBH are included as pre-treatment densities of trees in this size class exceeded 16,000 stems per hectare. In the plot maps, each circle represents a tree crown and gray circles represent the crowns of trees that are located within groups based on crown interlock while black circles represent isolated trees. The background color is the distance to the nearest tree in meters with large gaps (>9 m from nearest tree) highlighted in shades of blue. SGR is the small group retention treatment, FS-On and FS-Off are the two free selection treatments, and CT is the commercial thinning treatment.

peak at 25–30 cm, which is characteristic of a two-aged (or two-sized) structure.

The mean HDI increased compared to pre-treatment in all cases except for CT (Figure 3a). The post-treatment HDI was greater in the FS-On and FS-Off treatments than CT. There was no difference in HDI between either FS treatment and SGR or between SGR and CT (Figure 3a). Differences in HDI were driven by a combination of the retention of small diameter trees in the SGR and FS treatments, and the proximity of these small trees to larger trees. The grpCOV also indicates that SGR, FS-Off, and FS-On resulted in similar levels of within-group height variability, which were significantly greater than that in the CT (Figure 3b). Overall, every treatment resulted in greater vertical heterogeneity relative to the pre-treatment conditions, however, the CT treatments

generated stands with significantly less vertical complexity than the other treatments.

Isolated trees, tree groups and non-treed openings

Treatments resulted in different proportions of the stand area in isolated trees, openings, and groups, with SGR resulting in 87.5% of the stand area in openings, followed by FS-On and FS-Off with 82% and 81.5%, respectively, and finally CT with 75% (Table 2 and Figure 3c). The stand area in “large” openings (defined here as >9 m from the nearest tree bole), varied among the treatment types with SGR creating the most area with large openings (535 m²/ha) relative to all other treatment types

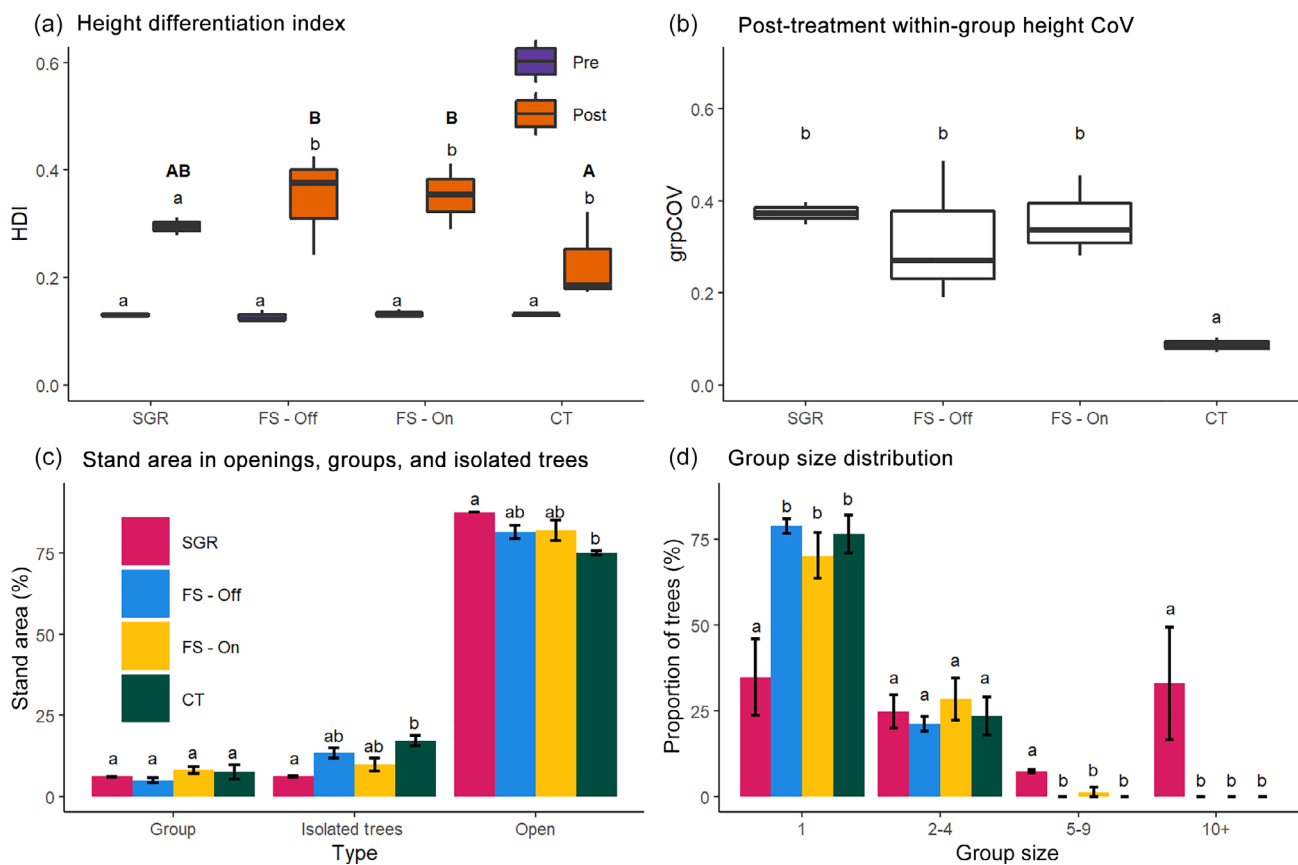


FIGURE 3 (a) Mean height differentiation index (HDI) for each plot split by treatment and time. Large HDI values indicate greater height variability between a tree and its three nearest neighbors. Lowercase letters indicate significant differences between pre- and post-treatment while uppercase letters indicate significant differences between prescriptions post-treatment. (b) Tree height coefficient of variation within groups (grpCOV) for each post-treatment plot. This plot-level value was calculated by averaging the values of each unique group with the plot and larger values indicated a greater coefficient of variation in height among trees in a group. Letters indicate significant differences between treatments. Box plot components are mid line, median; box edges, 25th and 75th percentiles; and whiskers, extreme values. (c) Post-treatment stand area occupied by groups, isolated trees, and non-treed openings. Letters indicate significant differences between treatments. Values are mean ± standard error. (d) Post-treatment proportion of trees found as isolated individuals and small, medium, and large groups. Letters indicate significant differences between treatments. SGR is the small group retention treatment, FS-On and FS-Off are the free selection ghost-on and free selection ghost-off treatments, and CT is the commercial thinning treatment

(70.7, 29, and 23 m²/ha for FS-Off, FS-On, and CT, respectively; Table 2). Similarly, SGR had greater mean and max group sizes, followed, in decreasing order, by FS-On, FS-Off, and CT. When the distribution of group sizes is considered in terms of the percentage of trees in each group, we see a large difference between SGR and the other treatments. Not only did SGR have a much smaller proportion of isolated trees (30.7% vs. 77.5%, 76.7%, and 68.9% for FS-Off, CT, and FS-On, respectively), but it also had a much greater proportion of trees in large (10–19 trees) and very large groups (20+ trees) with 9.4% and 26.6%, respectively. None of the other treatments had groups in either of these two size classes and therefore their structures were only comprised of isolated trees or small to medium-sized groups while SGR created a full range of tree group sizes (Table 2 and Figure 3d).

Tree spatial patterns

Following treatment, the SGR plots had a clustered spatial pattern while the two FS treatments and the CT treatment had dispersed spatial patterns based on the Clark-Evans test. Post-treatment pair correlation functions show that SGR resulted in significant aggregation of live trees across all lag distances (0–25 m), while the CT treatment resulted in dispersion up to ~5 m and a random pattern thereafter (Figure 4a). The FS-Off treatment also resulted in dispersion up to ~4 m, but the FS-On treatment resulted in a random pattern at lag distances <1 m,

a dispersed pattern from 1 to 4 m, and a random pattern thereafter. Looking at the pattern of only commercial-sized trees (Figure 4b), the SGR treatment created aggregation from 5 to 15 m lag distances suggesting that the aggregation seen from 0 to 5 m and from 15 to 25 m for all live trees (Figure 4a) is driven by the aggregated retention of smaller, pre-commercial-sized trees. Commercial trees in CT were dispersed up to about 4 m and were random thereafter, while those in FS-On and FS-Off were randomly located at all analyzed scales (Figure 4b).

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

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

TABLE 2 Post-treatment percentage of total stand area occupied by isolated trees, groups, and opening and mean and maximum group sizes in each treatment.

Metric	SGR	FS-Off	FS-On	CT
Stand area				
Isolated trees (%)	6.3	13.4	9.9	17.3
Groups (%)	6.2	5.1	8.2	7.7
Openings (%)	87.5	81.5	82.0	75.0
Stand area >9 m from a tree (m ² /ha)	535.5	70.7	29.0	23.0
Mean group size (no. trees)	14.9	2.6	2.8	2.3
Maximum group size (no. trees)	52.0	6.0	9.0	4.0
Percentage of trees				
Isolated trees (%)	30.7	77.5	68.9	76.7
Small groups, 2–4 (%)	22.6	21.8	27.7	23.3
Medium groups, 5–9 (%)	10.6	0.8	3.3	0.0
Large groups, 10–19 (%)	9.4	0.0	0.0	0.0
Very large groups, 20+ (%)	26.6	0.0	0.0	0.0

Notes: The distribution of group sizes is given as a percentage of the total number of trees. SGR is the small group retention treatment, FS-On and FS-Off are the free selection ghost-on and free selection ghost-off treatments, and CT is the commercial-thinning treatment.

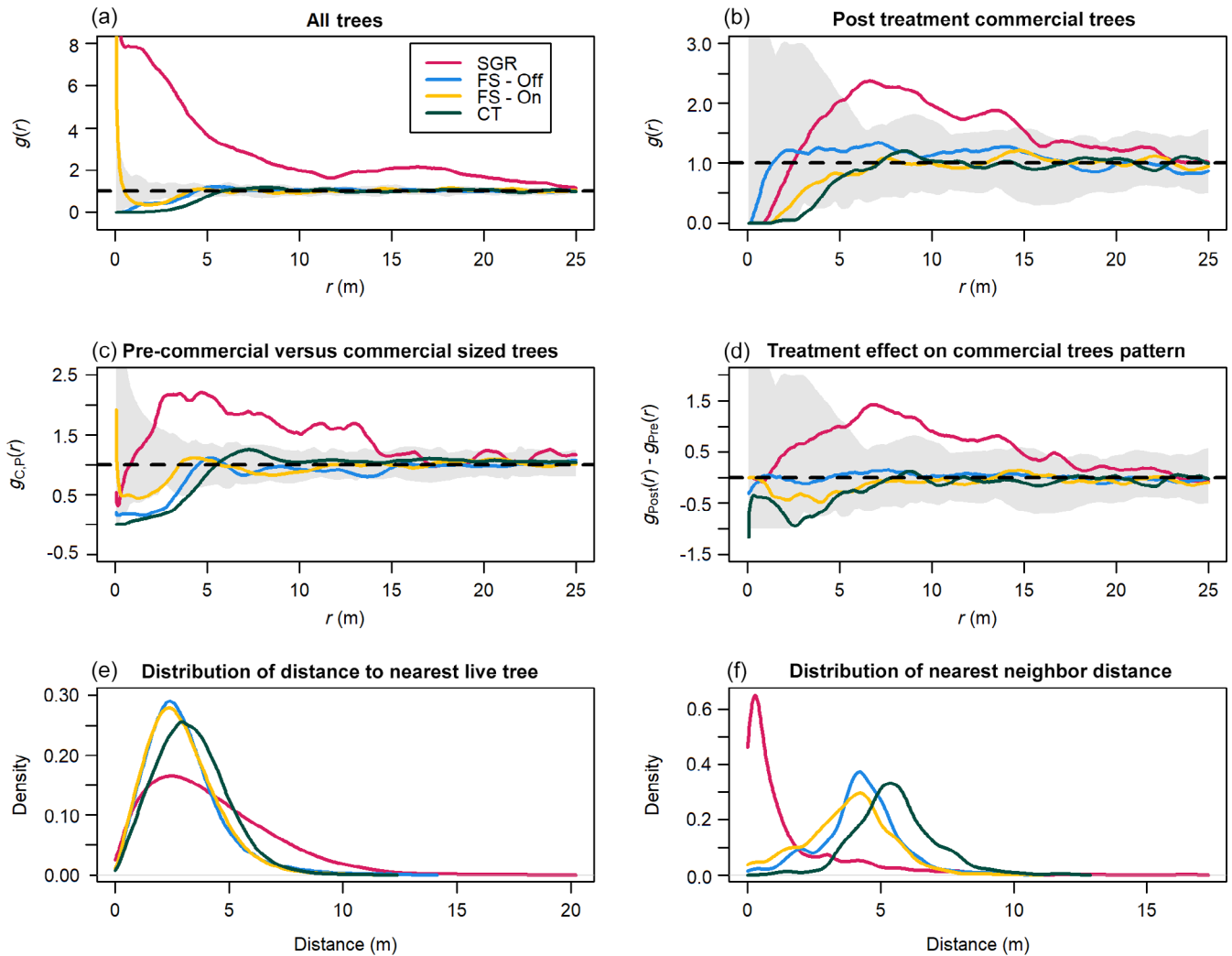


FIGURE 4 Pooled-point pattern statistics for each treatment. Combined pair-correlation function for (a) all post-treatment live trees and (b) post-treatment commercial-sized (>22.9 cm dbh) trees. Pooled multi-type pair correlation function showing (c) the level of aggregation or dispersion between post-treatment pre-commercial and commercial-sized trees and (d) the treatment effect on the spatial pattern of commercial trees pre and post-treatment. When the colored line is not contained within the gray shading, this is evidence of either clustering or dispersion at a particular lag distance based on the 95% confidence interval generated by a pointwise Monte Carlo test. For panels (a)–(c), $g(r) > 1$ indicates aggregations and $g(r) < 1$ indicates dispersion but, for panel (d) the cutoff for either increased or decreased aggregation is 0 as the plot is the post-treatment commercial tree pair correlation function subtracted by the pre-treatment commercial tree pair correlation function. Post-treatment distribution of (e) the distance to nearest live tree and (f) the nearest-neighbor distance for all live trees are also shown. SGR is the small group retention treatment, FS-On and FS-Off are the free selection ghost-on and free selection ghost-off treatments, and CT is the commercial thinning treatment.

To further understand the treatment effect on the spatial pattern, we evaluated the distributions of distance to the nearest live tree (DTL; Figure 4e) and the nearest neighbor distance (NND; Figure 4f). The DTL distribution was nearly identical between the two FS treatments while the distribution for the CT treatment is slightly shifted, indicating a slightly greater mean spacing between trees. The peak of the CT curve is ~5.5 m, which is very close to the 4.9 m spacing specified in the prescription. The lower peak and long tail for the SGR DTL distribution shows that this treatment was successful in generating larger

openings and more area further than 5 m from a tree than the other treatments. The NND distribution shows a sharp peak at ~1 m in the SGR treatment due to large groups of very closely spaced saplings that are dominating the spatial pattern. Once again, the two FS treatments have similar left skewed distributions and peaks around 4 m, however the fact that FS-On curve is above the FS-Off curve at low distances (<4 m) is reflective of greater fine-scale aggregation of trees. Finally, the CT distribution is approximately normal with a peak around 5.5 m confirming a highly uniform spatial pattern.

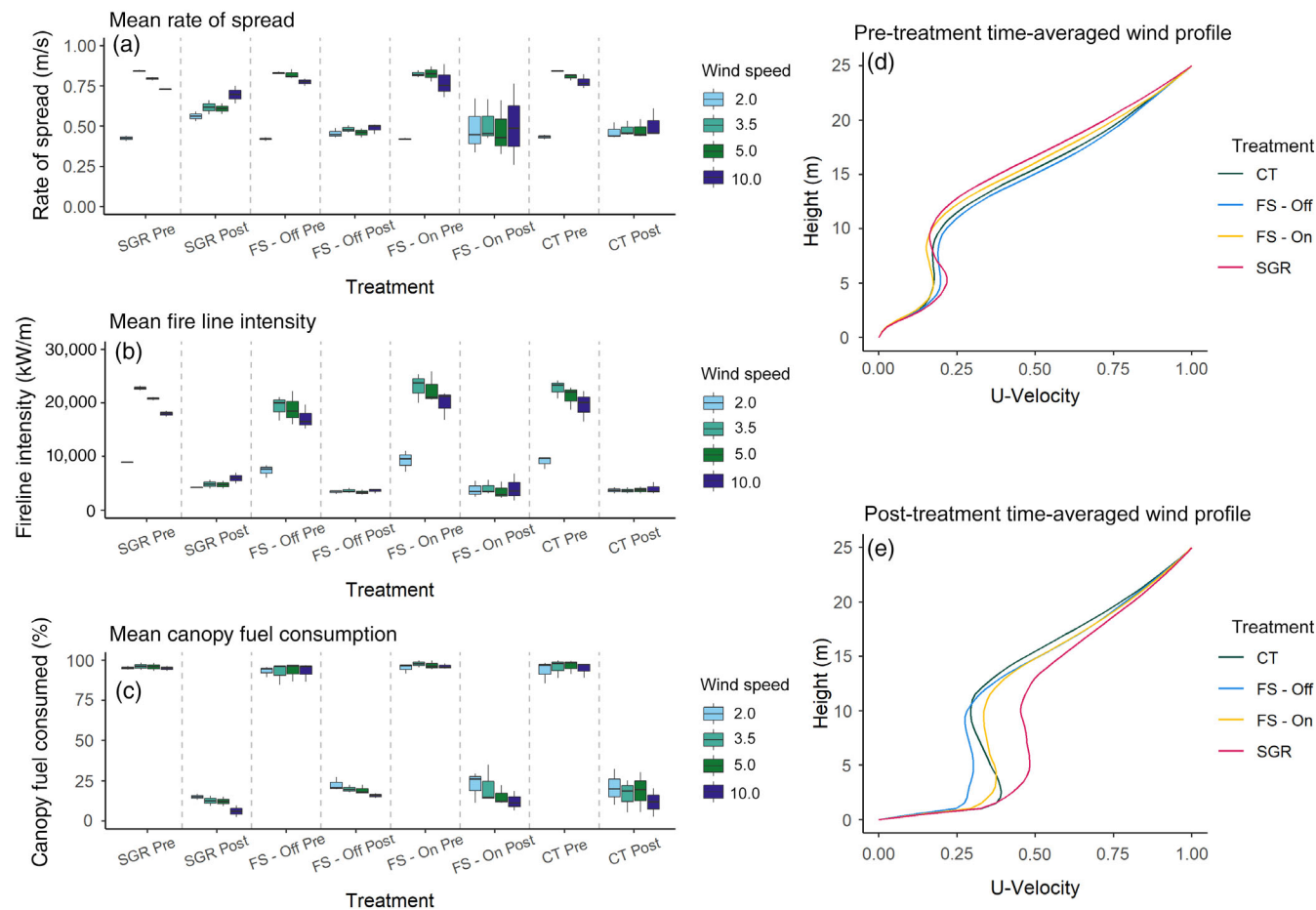


FIGURE 5 Box plots showing the (a) mean rate of spread, (b) mean fire-line intensity, and (c) mean canopy fuel consumption. Within each treatment group, wind speed increased from 2 to 10 m/s from left to right. (d) Pre- and (e) post-treatment time-averaged vertical profiles of the normalized horizontal wind velocity (U-velocity) just prior to fire ignition. SGR is the small group retention treatment, FS-On and FS-Off are the free selection ghost-on and free selection ghost-off treatments, and CT is the commercial thinning treatment.

Crown fuels, winds, and potential fire behavior

All treatments resulted in significant reductions to canopy fuel load (CFL) and canopy bulk density (CBD) while increasing canopy base height (CBH; Table 1). The SGR treatment resulted in the greatest reduction in the CFL and CBD and had the lowest post-treatment BA (Table 1). The two FS treatments and the CT treatment retained similar BA and had similar CFL and CBD following treatment. The SGR treatment also resulted in the greatest increase to the CBH, which was raised from 2 m up to 10 m (Table 1). In comparison, FS-Off increased CBH from 2 to 4 m, FS-On from 2 to 6.7 m, and finally, CT increased CBH from 2 to 8.3 m (Table 1).

Simulated vertical wind profiles were substantially altered by the structural changes associated with the treatments. Pre-treatment wind profiles were similar across treatments and showed a moderate increase in velocity through the mid-canopy space (Figure 5d). Post-

treatment, the U-velocity increased throughout the vertical profile compared to pre-treatment and differences between treatments were evident (Figure 5d,e). In particular, wind speeds at all heights were greater in the SGR treatment due to its lower BA, CFL, and larger opening sizes. The wind profiles for the two FS treatments were similar in shape but FS-On resulted in greater velocities. The shape of the CT treatment showed a greater difference between the velocity in the upper and lower canopy space with is indicative of stronger sub-canopy winds caused by lower drag near the surface. The reduction in drag is due to the lower number of sapling and pole-sized trees retained in this treatment.

Each treatment modified fire behavior by significantly reducing simulated canopy fuel consumption and mean fire-line intensity as compared to pre-treatment (Table 1 and Figure 5b,c); however, there were no significant differences in fire behavior among the treatments. Pre-treatment simulations resulted in 85–100% crown fuel consumption (Table 1 and Figure 5c). In contrast, the

thinning treatments resulted in stand-level mean canopy consumption from 16.8% to 19.3% (Figure 1). Large tree (≥ 22.9 cm DBH) canopy consumption was reduced from 29.7% to 44.2% in the pre-treatment stands to 14.3% to 16.5% in the post-treatment stands (Table 1). Fire rate of spread (ROS) was also reduced by treatment for all simulations with open wind speeds >2 m/s. At the lowest open wind speed, predicted ROS was similar pre- and post-treatment; however, mean FLI and canopy fuel consumption were substantially reduced following treatment.

DISCUSSION

Our work indicates that similar reductions in stand-level crown fire behavior are achieved regardless of the specific spatial pattern of retained trees. This suggests that forest managers have significant flexibility in the design of treatments that seek to simultaneously reduce crown fire hazard while meeting other land management objectives. Such flexibility is critical as managers are increasingly interested in the use of forest treatments to enhance forest resilience through increased structural complexity and the promotion of old-growth structures, and our results show there are opportunities to balance multiple, potentially disparate, objectives such as wildlife habitat improvement, timber production, and the reduction of wildfire hazard (Addington et al., 2018, Graham et al., 2015, Hessburg et al., 2015, Reynolds et al., 2013, Stephens et al., 2021, Underhill et al., 2014). Despite concerns that conflicts may exist between some of these objectives (Stephens et al., 2021), our work found support for the idea that treatments that create horizontally and vertically complex forests (e.g., FS-Off, FS-On, and SGR) result in reductions in crown consumption, which are comparable to reductions observed in traditional fuel hazard reduction treatments (CT). Importantly, these reductions occurred under dry simulation scenarios and were consistently observed across wind speeds ranging from mild fire conditions (2 m/s open winds) to more hazardous, wildfire conditions (10 m/s open wind speed). It should be noted, however, that our simulations did predict greater post-treatment ROS and FLI for the SGR treatment as compared to both CT and the two FS treatments. This difference was driven by both faster midflame windspeeds and the enhanced proportion of grass fuels in SGR due to the more open forest structure. The potential for tree thinning to increase ROS has been frequently noted (e.g., Agee et al., 2000; Reinhardt et al., 2008), however these changes did not translate to increased mean canopy consumption (a proxy for fire resistance). Overall, these results suggest that, under a given set of environmental conditions, stand-level canopy fuel load is a primary driver of crown fire behavior and that the fine-

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

It must be recognized that the reduction of surface fuel loading through broadcast burning, pile burning, or removal off-site is an essential part of any management action intended to reduce potential fire behavior. In this work, we quantified and distributed surface fuels within our simulated stands using a spatial model that assumes pre-treatment fuels and post-treatment slash management were equal across treatments. This approach was utilized as our study did not have pre-treatment surface fuels measurements and therefore, we could not account for changes to the surface fuel complex owing to

differences in slash management. Further, this approach allowed us better experimental control by isolating the effects of overstory management on potential fire behavior rather than the interactions between overstory and slash management. Future research into interactions between complex canopy structure, surface fuel complexes, and potential fire behavior should leverage methods to acquire spatially explicit pre- and post-treatment surface fuel data. One avenue for such research will be understanding surface fuel changes and accumulations through time in response to disparate canopy structures including differences between small and very large stand openings. This work help understand the complexities in developing treatment approaches for multiple land management objectives. Though more research is needed in these areas, the overall relationships identified between overstory structure and canopy fuel consumption shown here support the idea that multiple treatment approaches can effectively reduce stand-level crown fire potential assuming comparable actions are taken to manage surface fuels.

Though large tree (>22.9 cm DBH) canopy fuel consumption did not change across treatments, the potential for localized large-tree torching may warrant management attention in certain situations. For example, in situations where large trees are locally rare or of high ecological or cultural significance (Brown et al., 2019; Flanary & Keane, 2020; Mobley & Eldridge, 1992), additional steps can be taken to protect individuals. By removing adjacent and subordinate trees around these highly valued trees so that they are retained as isolated individuals, crown torching will be less likely due to increased convective cooling (Ritter et al., 2020). In other cases, land managers may want to leverage natural disturbance dynamics (i.e., fire caused mortality) to accelerate the restoration of historical forest structure and pattern (Cannon et al., 2021; Huffman et al., 2020; Larson et al., 2013). In this context, the potential for fine-scale group torching may be an acceptable, or even desirable, treatment outcome as patchy overstory mortality will enhance structural complexity, create snags that provide valuable wildlife habitat, and generate non-treed openings that will enhance understory plant diversity and provide favorable regeneration sites for shade-intolerant tree species (Bigelow et al., 2011; Jain et al., 2020; Matonis & Binkley, 2018).

Treatment effects on spatial stand structure

The common structural goal of the SGR, FS-On, and FS-Off treatments was to increase horizontal heterogeneity

through the deliberate creation of distinct groups of trees to restore elements of historical structure, improve wild-life habitat, and enhance resilience to fire and mountain pine beetle. In contrast, the CT treatment typifies treatments intended to increase timber volume production and reduce fire hazard by introducing regular spacing trees of trees and preferentially removing smaller, non-dominant trees. The studied treatments were generally successful in moving the stands towards each of their structural objectives and the structures created by each treatment were distinctly different from one another. However, the FS treatments did not fully meet their objective for spatial aggregation and the creation of large canopy openings. This finding suggests that these prescriptions needed to provide more explicit instructions on how marking crews should create the desired numbers and size of tree groups and non-treed openings. Failure to create large groups of trees and non-treed openings has been observed in other studies on spatially complex forest treatments (Cannon et al., 2021; Churchill et al., 2013; Maher et al., 2019).

Though the FS treatments resulted in an overall random pattern rather than an aggregated pattern, it is important to consider that spatial aggregation is just one potential measure of heterogeneity, and failure to create statistically significant tree aggregation does not necessarily mean that a treatment has failed to enhance resilience or restore elements of historical structure. In fact, spatial reconstructions have shown that historical horizontal spatial patterns in dry conifer forests were not always aggregated and had spatial patterns ranging from highly aggregated to random (e.g., Abella & Denton, 2009; Clyatt et al., 2016; Sánchez Meador et al., 2011). Furthermore, the often-described historical pattern of isolated trees, tree groups, and openings (Larson & Churchill, 2012) does not preclude a spatially random distribution of trees, particularly when the mean group size is small (i.e., two to four trees). This was the case in CT and both FS treatments, which created stands with small mean group sizes, a spatial pattern that aligns with many observations of natural spatial patterns in dry conifer forests in the southern Rockies (Brown et al., 2015, Rodman et al., 2016; Sánchez Meador et al., 2011), northern Rockies (Clyatt et al., 2016), the Sierra Nevada Mountains (Jeronimo et al., 2019), and eastern Oregon (Churchill et al., 2017). Observations of historical forest patterns are commonly used as treatment targets or markers of stand-scale forest resilience as the patterns were formed and persisted under frequent-fire disturbance regimes. Given the wide range of spatial patterns associated with historical/resilient forests, we suggest that “horizontal heterogeneity” need not be conflated with “statistically significant evidence of spatial aggregation.” Rather, metrics such as distribution of groups sizes, the

proportion of the stand in isolated trees, groups and openings, and the size distribution of openings are better suited to evaluate the success of a prescription in creating structural heterogeneity, enhancing resilience, and/or emulating historical forest patterns. Not only are these metrics directly tied to the ecological functioning of a stand, but they can also be tabulated in real time by marking crews allowing treatment outcomes to match objectives more closely (Maher et al., 2019).

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

Implications for silviculture and forest management

Traditional silviculture treats forests as discrete units (i.e., stands) with a uniform set of characteristics as this is operationally efficient and is well suited to managing for

the optimal utilization of growing space to maximize volume accumulation in future crop trees (Fahey et al., 2018; O'Hara & Nagel, 2013; Puettmann et al., 2012). In shifting the focus from production and consistent, predictable yield towards management for ecological function and ecosystem resilience, there is a new paradigm in forestry (Palik et al., 2020) that seeks to enhance within-stand variability and to create particular structural features (e.g., isolated trees, groups of trees, stand openings) that are defined based on their spatial location. The SGR and FS treatments evaluated in this work represent this ongoing shift towards an ecological approach to silviculture based on the creation and maintenance of spatial complexity forest structure while managing for other resources. Under this paradigm, land managers must consider many factors, such as the spatial aspects of tree growth and regeneration, as well as the spatial aspects of potential fire behavior considered in this work. For example, certain wildlife species prefer the continuous vertical foliage created by tree groups with a multi-layered canopy and mixture of tree sizes (Reynolds et al., 1992; Stephens et al., 2014), while such groups may be viewed as hazardous from a fire behavior perspective due to the vertical continuity of crown fuels (Graham et al., 2004; Johnson & Kennedy, 2019). Similarly, large groups of trees were a common component in some historical forest structures (Clyatt et al., 2016) but may also increase the risk of MPB mortality (Buonanduci et al., 2020, Negrón, 2020), drought stress (van Mantgem et al., 2020), and torching potential (Ritter et al., 2020). These conflicting considerations speak to the complexity associated with the implementation of these approaches and suggest the need to carefully consider the various trade-offs.

Our work fits well into the context of these shifting paradigms in forest management and provides some additional confidence that a variety of stand-level treatment approaches can be used to achieve fire hazard reduction and ecological restoration. The fact that low canopy consumption was observed for all treatments shows that they all significantly increased stand-level resistance and resilience to fire. However, the fact that greater ROS and FLI were seen in the SGR treatment underscores the idea that land managers need to consider the spatial context of treatments when deciding which treatment approach is best. For example, when implementing treatments near the wildland–urban interface or other values at risk, it may be desirable to utilize treatments that promote fire behavior that is more amenable to fire suppression (lower ROS and FLI). In contrast, treatments in areas further from the wildland–urban interface or other values at risk could shift more towards the restoration end of the continuum in order to capture some enhanced ecological benefits and move ecosystems towards historical structure and

dynamics. It is also important to recognize that historically a wide variety of stand structures existed within frequent-fire landscapes because of the interaction between complex fire regimes and environmental factors (Addington et al., 2018; Battaglia et al., 2018; Brown et al., 2008, 2015; Brown & Cook, 2006; Churchill et al., 2017; Graves, 1899; Hessburg et al., 2015; Reynolds et al., 2013). Therefore, restoration of landscape-scale structural heterogeneity may be best achieved through the application of a large range of prescriptions that generate a variety of stand structures across landscapes. Additionally, these treatments and diverse stand structures can enhance ecological outcomes following unplanned wildfire and therefore can be leveraged to achieve broader scale restoration of structural heterogeneity and ecological processes (North et al., 2021). Overall, our work supports the idea that using different treatment approaches in concert can achieve numerous ecological and societal objectives and suggests that potential differences in fire behavior may be useful to guide spatial decision-making (Stephens et al., 2021).

CONCLUSION

Our results indicate that the FS and SGR forest treatments that were designed to create spatially complex, multi-aged stands provided similar reductions to wildfire hazard as the space-based, thin-from-below CT treatments that created a more regular forest structure. These findings suggest minimal fire-behavior trade-offs between treatments that create significant heterogeneity and treatments that create uniform structures, which is extremely relevant given the increasing promotion of ecologically based silvicultural systems (Addington et al., 2018; Cannon et al., 2020; Larson & Churchill, 2012; Reynolds et al., 2013; Stephens et al., 2021). Such systems (e.g., variable density thinning [Carey, 2003]; free selection [Graham et al., 2007]; ICO [Churchill et al., 2013]) aim to generate forests with heterogeneous tree spatial patterns that will emulate historical forest structures, promote habitat complexity, generate multi-aged structures, and enhance recovery pathways following disturbance (O'Hara, 2014). Owing to the potentially negative ecological effects and risks to human lives and property of high-severity fire in dry conifer ecosystems, the identification of silvicultural systems that can simultaneously achieve social and ecological benefits is extremely relevant to forest management (Stephens et al., 2021). Though we suggest that some minor trade-offs may exist, we found treatment effects differed more greatly between metrics of fire behavior that relate to fire suppression efforts (i.e., ROS, FLI, flame length) rather than ecological concerns (i.e., canopy consumption). Together, these findings

point to the utility of thinning treatments that enhance structural complexity in reducing potential stand-scale fire behavior while simultaneously achieving a host of other ecological benefits.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data (Ritter et al., 2022) are available from Dryad at <https://doi.org/10.5061/dryad.2jm63xsr2>.

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