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ORIGINAL ARTICLE

Impact of Thinning Strategy, Surface Fuel Loading and Burning Conditions on Fuel Treatment Efficacy in Ponderosa Pine Dominated Forests of the Southern Rocky Mountains

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Abstract
Managers across the western US seek effective fuel treatment strategies to mitigate hazardous fuel loads and risks of high severity fire in dry conifer forests. Conventional fuel hazard reduction treatments emphasis reducing canopy fuel continuity and surface fuel loading using an even spaced, thin-from-below approach, with pile or broadcast burning of residual surface fuels. Such treatments often result in forest structures that differ from the historical conditions. Ecological restoration treatments emphasize enhancing structural heterogeneity but may produce less fire-resistant stands causing tradeoffs between fuel hazard reduction and restoration objectives. This study explored these tradeoffs by simulating thinning treatments on ponderosa pine sites, spanning several levels of basal areas, horizontal and vertical distributions of canopy fuels, surface fuel loads, fuel moistures and wind speeds. All types of thinning reduced fire behavior and severity relative to untreated forests. Fire rate of spread was slightly increased following variable retention harvests or treatment that included thinning from below. Fire weather, cutting methods, and surface fuel load all influenced potential fire severity. Variable retention thinnings did not reduce severity as much as treatments including a thin-from-below, regardless of the horizontal arrangement of trees. Our results suggest tradeoffs between ecological restoration and hazard reduction could be overcome if restoration treatments incorporate small tree removal. Overstory removal combined with reductions in surface fuel loading, through prescribed fire or other means, were more effective than either overstory or surface fuel reductions alone.

Keywords Forest management · Fire behavior · Forest restoration · Spatial heterogeneity · Fire modeling

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Introduction

Fuel hazard reduction treatments are a key land management practice to reduce fire risk and undesirable fire effects (Vaillant and Reinhardt 2017). In many dry forests of the western US, such fuel treatments aim to enhance wildfire resistance that has deteriorated due to land use practices and widespread suppression of frequent low intensity fires (Covington and Moore 1994; Hessburg et al. 2019). These management decisions have resulted in increased surface and canopy fuel loads, loss of early seral stands, greater abundance of fire sensitive tree species, and alterations to fire regimes (Hagmann et al. 2021). In addition to these effects, climate change has lengthened fire seasons and increased the frequency of severe weather that supports large high severity fire growth (Westerling 2016; Wasserman and Mueller 2023; Coop et al. 2022; Stephens et al. 2018). Changes in the frequency and severity of wildfires have resulted in increased societal and economic costs associated with smoke impacts and loss of life and property (Burke et al. 2021; Caggiano et al. 2020), increased risks of erosion, degradation of water quality and aquatic habitat (Rhoades et al. 2011), and widespread lack of forest recovery where large severely burned patches hinder natural regeneration (Stevens-Rumann et al. 2018). To mitigate these ecological, societal, and economic impacts of large, severe fires, a variety of silvicultural techniques are used to alter the fuel complex to reduce fire behavior and severity to lessen the impacts of future wildfires (Hoffman et al. 2018a; Stephens et al. 2021.

Fuel hazard reduction treatments in dry forests of the western US are accepted as an effective management approach to reduce fire behavior and severity (Fulé et al. 2012; Davis et al. 2024). Such treatments typically focus on four objectives (Agee and Skinner 2005): reduce surface fuel load, increase canopy base height, reduce canopy bulk density, and preserve larger fire-resistant trees. Reducing surface fuel loads and raising canopy base heights work together to reduce the likelihood of fire transition from the forest floor to the canopy. Reducing canopy bulk density decreases the potential for crown fire spread. Retaining large fire-resistant trees helps reduce the loss of forest structure and function post-fire and improves forest recovery. Fire modeling and post-fire case studies demonstrate that such forest management practices effectively reduce fire behavior and effects, especially when treatments combine overstory fuel reduction with prescribed or managed fires to reduce surface fuel loads (Fulé et al. 2012; Agee and Skinner 2005; Davis et al. 2024).

The application of density reduction targets to achieve fuel treatment objectives are often applied uniformly within stands through thinning from below or distance-based thinning (Dennis 1983; Alexander and Cruz 2020). Such applications focus on raising canopy base height by removing smaller trees and reducing canopy bulk density by evenly spacing the residual trees. For example, Peterson et al. (2005) propose that residual trees should be separated by the average crown width of codominant trees in the stand. Even when silvicultural prescriptions for fuel hazard reduction treatments do not explicitly state a target spacing, they still often result in even aged, evenly spaced forest structures due to structural legacies of past density management practices used to optimize timber production (Larson and Churchill 2012; Lefevre et al. 2020; Underhill et al. 2014; Lydersen et al. 2013; Ziegler et al. 2017a).

Interactions among small-scale high fire severity burn patches, climatic events such as drought, forest structure, seed dispersal and zoochotic seed caching are key mechanisms driving growth, regeneration and the self-organization forests into spatially heterogeneous patterns (Larson and Churchill 2012). Canopy openings produced by patchy tree mortality events can promote understory plant and pollinator diversity (Rhoades et al. 2018), or favorable microsite conditions for tree regeneration (North et al. 2004). These processes are exemplified in pre-EuroAmerican settlement dry forests of the western US, where trees were historically arranged in complex mosaics with single, scattered individual trees and tree groups of diverse sizes situated among openings of various sizes (Larson and Churchill 2012; Lydersen et al. 2013). These heterogeneous patterns produced habitats for a variety of wildlife (e.g., northern Goshawk [*Accipiter gentilis*] Reynolds et al. 2013), diverse composition of understory plants (Matonis et al. 2018), and increased soil moisture throughout the annual hydrologic cycle (O'Donnell et al. 2021). As many forest management projects seek to provide multiple ecological benefits and services while concurrently reducing fire hazard, forest restoration treatments at stand scales are increasingly designed to yield spatially complex rather than homogenous forest structures.

Previous studies have suggested that the long-term persistence of relatively sparse heterogeneous forests historically points to their resilience to recurring fires (Hessburg et al. 2015). Fire modeling of a California dry mixed-conifer forest inventoried in 1929 and again in 2008 showed a shift from moderate fire behavior with patchy tree mortality to extreme fire behavior with substantial mortality due to increased tree density (Ziegler et al. 2021). Similar studies have shown that restoration treatments in ponderosa pine dominated forests along the Colorado Front Range and the Black Hills of South Dakota result in substantial decreases in potential fire behavior, largely through reductions in stand density and canopy fuel load (Ziegler et al. 2017a; Ritter et al. 2022). Similar to findings at the stand scale, the likelihood of crown fire initiation and spread is reduced as tree crown base heights and the separation between trees increase (Contreras et al. 2012; Hoffman et al. 2012; Ritter et al. 2023). Despite evidence for reductions in the ignition and spread of crown fires following treatments, there are some concerns that treatments may have minimal reductions or even increases to the surface fire rate of spread, and crown fire ignition due to greater midflame wind speeds (Reinhardt et al. 2008). The potential for increased surface rate of spread is even more likely in sparse heterogenous forests where a pattern of openings and dense clusters of trees can result in localized increases in wind flow beyond those in more evenly spaced forests (Pimont et al. 2009; Hoffman et al. 2015a).

The degree to which forest managers may find a tradeoff between restoration (i.e., spatially heterogeneous) treatments and fuel hazard reduction is an area of active research (Stephens et al. 2021). Ritter et al. (2022) found minor differences in modeled fire behavior and effects between distance-based and heterogeneous fuel hazard reduction treatments suggesting that tradeoffs may be minor or non-existent. However, there were differences in residual treatment forest density which may have masked tradeoffs associated with forest structure, especially given that findings from several previous studies have indicated that density has a larger effect size on fire rate of spread and consumption than forest structure (Atchley et al. 2021; Parsons et al. 2017). Empirical evidence from wildfires in California and Washington state has shown that areas with lower fire severity were correlated with lower canopy and surface fuel loads, variability in forest structure, and lower fuel moistures and wind speeds (Koontz et al. 2020; Prichard et al. 2020). Together these studies indicate that fuel loading, fuel arrangement, and the burning environment (e.g., fuel moisture and wind speed) directly and indirectly impact fire behavior and therefore warrant additional consideration when evaluating treatment efficacy and tradeoffs among treatment types.

This study explores potential tradeoffs in potential fire behavior among different silvicultural treatments using a three-dimensional, physics-based fire behavior model. Thinning strategies span silvicultural methods that resulted in residual forest structures ranging from single storied evenly spaced overstories consistent with conventional fuel hazard treatments to complex multistoried forests consisting of various sized clumps and openings consistent with forest restoration treatments in ponderosa pine (*Pinus ponderosa* ex. Lawson) forests. For each treatment strategy, we simulated three residual basal areas and three surface fuel loads; the inclusion of these two factors allowed us to capture a wide range of post-treatment fuel complexes. Additionally, we simulated fire behavior across three wind speeds and three fuel moistures.

Materials and Methods

Given the range of factors that influence treatment efficacy, we utilized the C-optimized Fedorov's exchange algorithm (Atkinson and Donev 1992) as implemented in the AlgDesign v1.2.0 package (Wheeler 2019) in R v4.1.1 (R Core Team 2016) to maximize the information gained by each fire simulation. Fire behavior was simulated within five pre-treatment stands using six thinning strategies, three residual basal area levels (5, 10, and 15 m^2 ha^{-1}), three residual surface fuel loads (0.4, 0.8, and 1.2 kg m^{-2}), three wind speeds (5, 10, and 15 m s^{-1} at 10 m above ground level), and three surface fuel moistures (5%, 8%, and 11%). Thinning methods (Table 1) included random, thin-from-below (TfB), distance-based, and variable-retention (VRT); we also included a TfB for the distance-based and VRT treatments. This combination of factors would result in 135 possible pre-treatment and 2,430 possible post-treatment simulations, however, implementing Fedorov's exchange algorithm allowed this to be reduced to 39 pre-treatment and 202 post-treatment simulations. The algorithm randomly selects combinations of levels of factors from a full factorial list of combinations to minimize the variance of best linear unbiased estimators. This approach allowed us to incorporate the factors most frequently identified in the literature as influencing fire behavior and treatment efficacy while avoiding the computational demands of a complete factorial design.

Table 1 Implementation and intention behind each of the six tested stand thinning strategies

Thinning Style	Implementation	Intention
Thin-from-Below (TfB)	Sequentially remove the smallest diameter trees until the basal area target is reached	Reduce the vertical continuity of canopy fuels to decrease the probability of crown fire initiation
Random	Randomly thin all tree size classes until desired basal area target is reached	Reduce stand density while retaining initial diameter distribution to promote horizontal and vertical stand heterogeneity
Distance-based	Sequentially remove trees near another tree until a desired spacing was achieved. Spacing was specific to basal area targets	Reduce horizontal continuity of canopy fuels to decrease the probability of crown fire spread
Distance-based with TfB	Trees below 7.5 cm diameter were removed first. Afterwards trees near another tree were systematically removed until a desired spacing was achieved. Spacing was specific to basal area targets	Reduce vertical and horizontal continuity of canopy fuels to decrease the probability of crown fire initiation and spread
Variable Retention Thinning (VRT)	Openings of various sizes were randomly assigned to low density areas of the stand, with identified trees removed. Then tree groups of various sizes were randomly created where trees were within 4 m of enough neighboring trees until the desired basal area was reached, with all remaining trees thinned	Reduce the horizontal continuity of canopy fuels to decrease the probability of crown fire spread, while restoring the distribution of openings and tree groups to pre-European settlement conditions Distributions of openings and tree groups were based on reconstruction of historical forest structure and used to promote vertical and horizontal stand heterogeneity
Variable Retention Thinning with TfB	Trees below 5 cm diameter were removed first and then stand openings and groups were established until the desired basal area was reached, with all remaining trees thinned	Reduce vertical and horizontal continuity of canopy fuels to decrease the probability of crown fire initiation and spread, while also promote horizontal stand heterogeneity reflective of pre-European settlement conditions

Forest Structure Conditions

Pre-treatment forest conditions were based on five stem-mapped ponderosa pine-dominated forests in Colorado Plateau and Southern Rocky Mountains described in Ziegler et al. (2019). The five used in this study were Dowdy Lake, Long John, Lookout Canyon, Messenger Gulch II, and PA5. The sites represent ponderosa pine dominated forests from 1941 to 2490 m within the region. The pre-treatment stands conditions represent typical tree densities in ponderosa pine dominated forests resulting from a century of fire suppression (Battaglia et al. 2018; Reynolds et al. 2013). Overstory composition is dominated by ponderosa pine with other species composing less than 15 percent of total trees. Other overstory species present include Rocky Mountain Juniper (*Juniperus scopulorum*)*,* pinyon pine *(Pinus edulis), trembling aspen (Populus tremuloides*)*, and* Douglas-fir (*Pseudotsuga menziesii*). Pre-European settlement median fire return intervals ranged from 9 to 35 years (Brown et al. 2015; Hunter et. al 2007; Reynolds et al. 2013). The climate of the sites is controlled by their midlatitude and interior continental locations. Thirty-year average temperature ranges from 4.2° to 9.7 °C, with minimum temperature ranging from −4.6° to 2.5 °C and maximum temperature ranging from 12° to 16.9 °C. Thirty-year average precipitation across the sites ranges from 331 to 578 mm characterized by snowy winters and late summer rainfall associated with the North American Monsoon. Sites were located across a range of parent material including granite, limestone, and sandstone. The stem maps were 4 ha (200 m × 200 m) and included the (x, y) locations of live trees and stumps. In addition to their location, all live trees had their diameter at breast height (DBH), crown width, crown base height, tree height, and species recorded. Stumps had their diameter at stump height and species recorded and the DBH, crown radius, height, and crown base height were estimated using previously developed linear regressions (Ziegler et al. 2017a).

Post-treatment conditions were generated by implementing each of the six thinning methods (Table 1). We selected these thinning strategies to capture variation in both the horizontal and vertical forest structure. Each thinning operated by sequentially removing or retaining trees until a basal area target of either 5, 10, or 15 m^2 ha^{-1} was met. We modified an algorithm previously described by Tinkham et al. (2017) to implement (VRT). This algorithm is like the ICO, or individuals, clumps, and openings restoration strategy developed by Churchill et al. (2017). First, half of the basal area was removed by placing openings, eliminating all trees within circles of various sizes. Mimicking Churchill et al. (2017), opening sizes followed a frequency distribution of 24%, 40%, 20%, 10%, 5%, and 1% for openings with radii of 0.75, 2.25, 3.75, 6.75, and 8.25 m, respectively. Openings were placed in areas of low tree density by inverting a Gaussian kernel smoothed map of tree density. Second, groups of trees were designated for retention of various sizes at frequencies like historical ponderosa pine forests, as reported by Clyatt et al. (2016). The desired residual basal area within tree groups of 1, 2 to 4, 5 to 9, 10 to 14, and 15 to 25 trees were set to 30%, 30%, 20%, 10%, and 10%, respectively. Starting with the largest tree group size class, a random tree and its neighboring trees within 4 m were selected to form a group until the desired size was reached. If enough trees were identified to create a group, that group was retained. This happened iteratively until the basal area target was achieved for that group size class and then the next largest group class was identified, progressing until all group size classes and individual trees were identified, with any remaining unassigned trees removed.

Fire Simulations

We simulated fire behavior with the Wildland-Urban Interface Fire Dynamics Simulator v. 9977 (WFDS). This model choice facilitates fire simulation in a spatially complex and temporally dynamic environment (Hoffman et al. 2018b). Using a computational fluid dynamics approach, WFDS solves a coupled set of equations that describe the conservation of mass, momentum, energy, and chemical species. Wildland fuels are represented in 3-D based on their bulk properties (e.g., bulk density, surface area to volume ratio, and fuel moisture). Further description of WFDS and its evaluation can be found in the following references (McGrattan et al. 2020; Mell et al. 2007, 2009; Hoffman et al. 2015a).

All WFDS simulations used an identical domain (Fig. 1). The numerical grid size varied across the 900 m × 400 m × 90 m domain. The area of interest was composed of 1 m^3 voxels while the other areas were represented with a courser 2 m^3 resolution. Wind entered the domain along the x = 0 m boundary, following a power law function, $u(z) = u_{20} \times \frac{z}{20}^{\frac{1}{7}}$, where the open wind speed at 20 m above the ground (u_{20}) was defined either as 5, 10, or 15 m s^{-1}. The lateral sides, $_{y}$ = 0 m, and y = 400 m, and along the top of the domain, z = 90 m, were prescribed as free slip and no flux boundaries. The boundary condition at the outlet, z = 900 m, was set to open. The terrain along the ground, z = 0, was flat. All simulations ran for 2000 s (~ 33.3 min). A line fire at 448 m to 450 m in the x dimension and from 70 to 330 m in the y dimension was ignited at 300 s into the simulation and allowed to freely burn through the 4-ha area of interest. This area of interest spanned from 600 to 800 m in the x dimension and from 100 to 300 m in the y dimension.

The area of interest contained the locations of either pre-treatment or post-treatment trees for one of the five sites. The remaining domain area outside the area of interest was populated using a log-Gaussian Cox Point process model

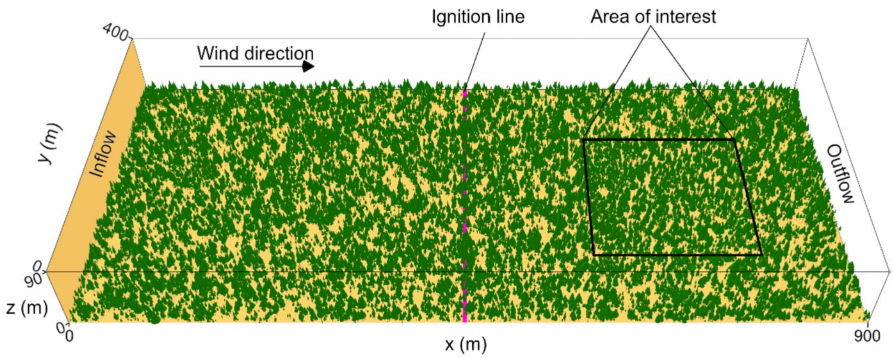


Fig. 1 Features of wildland-urban interface Fire Dynamics Simulator domains used in this study, including overall dimensions, wind direction, location of fire ignition, and area of interest

(Baddeley et al. 2015) fit to mimic the spatial arrangement of trees observed within the area of interest. We randomly sampled trees from the area of interest to attribute heights, crown base heights, and crown widths to these trees outside the area of interest. This process ensured a well-developed wind field representative of a larger interior forest in our area of interest (Fig. 1). Tree crowns were represented as right circular cones defined by the tree height, crown base height, and crown width. The material properties we assigned to tree crowns included a surface to volume ratio of 4000 m^{-2} m^{-3}, drag coefficient of 0.159, bulk density of 0.5 kg m^{-3}, particle density of 520 kg m^{-3}, and foliar moisture content of 100%.

To account for differences in the surface fuel load and the interactions between canopy cover and surface fuels we developed a simplified spatially heterogeneous model of surface fuel type and load. We modeled surface fuels as a heterogeneous layer, that reflects the influence that canopy cover has on the local composition and characteristics of the surface fuelbed. Our process ensured the different thinning methods or residual basal areas had one of three assigned median fuel loads (0.4, 0.8, or 1.2 kg m^{-2}) even though their spatial distributions differed. First, we calculated the distances from any location to a tree using Spatstat (Baddeley and Turner 2005) in R, then inverted these distances, and rescaled these distances using a triangular distribution with a minimum of 0.2, maximum of 3.0, and median of either 0.4, 0.8, or 1.2. We used these values to assign fuel loads, reflecting a tendency for greater fuel loads to be present near trees and lesser fuel loads in openings in our sites (Hoffman et al. 2012; Bonner et al. 2024). Where the surface fuel load was 0.2 kg m^{-2}, we assigned a fuel bulk density of 2 kg m^{-3}, representing a grass-dominated fuelbed. For each surface fuel load increase of 1 kg m^{-2}, we increased fuel bulk density by 6.25 kg m^{-3} to account for a greater relative proportion of conifer needles. Surface fuels had a surface area to volume ratio of 5800 m^{2} m^{-3}, particle density of 510 kg m^{-3}, and drag constant of 0.375. Fuel moistures were assigned as either 5%, 8%, or 11%.

For each of the 241 WFDS simulations, we calculated mean midflame wind speed (u_2), rate of spread (ROS), and canopy consumption (CC). The mean midflame wind speed was calculated by averaging the streamwise wind speed across time in the area of interest at 2 m in height in the x direction for 60 s, from 240 to 300 s before fire line ignition. The fire rate of spread was calculated for the area of interest by averaging the fire's time to travel 10 m in the x direction for each 1 m y position. We calculated canopy consumption on a percentage basis using the dry mass of all tree crowns in the area of interest at the start of the simulation compared to the dry mass at the end.

Analysis

To ensure that our thinning methods produced different arrangements of canopy fuels and forest structure, we examined four attributes, trees per hectare (TPH), quadratic mean diameter of trees' diameter at breast height (QMD), mean tree group size (TPG), and mean opening size (MOS). The size of each tree group was defined as the number of trees where each member tree was within 4 m of another member tree. We calculated the mean opening size by first calculating the area within the 4 ha sites more than 4 m from any trees; then, we identified discrete contiguous openings and measured the area of the opening (m^2). We measured these four attributes after implementing each thinning scenario on each site at each level of residual basal area. We first evaluated whether the average values of these four attributes, per thinning scenario and basal area, differed from pre-thinning using Dunnett's test for comparing several treatments with a control. We used an α of 0.05 for all statistical tests. Second, we applied a Sidak-adjusted pairwise comparisons procedure to assess whether the least-squares means of these four attributes varied between thinning scenarios, at each basal area level. These least-squares means were the values predicted by a mixed-effects model, implemented with nlme v.3–1–152 (Pinheiro et al. 2021) in R to measure the estimators for each variable, (Eq. 1); site was coded as a random effect while basal area (BA) and thinning methods were fixed effects.

$$\{\text{TPH}, \text{QMD}, \text{ TPG}, \text{ MOS }\} = \text{BA} + \text{Thinning} + \text{BA} \times \text{Thinning} + \text{Site} \tag{1}$$

To understand if the thinning scenario impacted the average midflame wind speed (u_2), fire rate of spread (ROS), and percent canopy consumption (CC) compared to pre-treatment we used Dunnett's test for comparing treatments with controls. We developed a mixed-effects model to assess the influence of open wind speed (u_{10}), surface fuel load (SFL), residual basal area, and thinning scenario on midflame wind speed (Eq. 2),

$$u_2 = u_{10} + \text{SFL} + \text{BA} + \text{Thinning} + \text{BA} \times \text{Thinning} + \text{Site} \tag{2}$$

where the fixed effects and site varied by simulation. Site was a random effect. Fire rate of spread (ROS) and percent canopy consumption (CC) were also assessed through mixed-effects models that also included surface fuel moisture (SFM) (Eq. 3),

$$\{\text{ROS}, \text{ CC}\} = u_{10} + \text{SFL} + \text{SFM} + \text{BA} + \text{Thinning} + \text{BA} \times \text{Thinning} + \text{Site} \tag{3}$$

We used a Likelihood Ratio Test to assess statistical significance ($\alpha = 0.05$) of each independent variable. We calculated the marginal effect of each fixed independent variable by averaging over other independent variables. Next, we calculated the effect size of all variables with partial eta squared ($\eta^2{}_p$); partial eta squared measures the proportion of total variance explained by each independent variable after accounting for the variation explained by all other variables. To contextualize the effect sizes, we categorized effect sizes as small, medium, and large when $\eta^2{}_p$ was larger than 0.0099, 0.0588, and 0.1379, respectively (Cohen 2013). Last, we applied Sidak-adjusted pairwise comparison procedures to evaluate whether midflame wind speed, rate of spread, or canopy consumption, significantly differed between thinnings. If the interaction between thinning and basal area was significant, we conducted pairwise comparisons at each level of basal area.

Results

Effects of Thinnings on Forest Structure

The pre-treatment basal areas across sites ranged from 22.6 m^2 ha^{-1} to 30.2 m^2 ha^{-1}, with the treatments representing an average reduction of 43%, 62%, and 82% for our basal area targets of 15, 10, and 5 m^2 ha^{-1}, respectively. The differences in forest structure between thinning scenarios were apparent upon visual inspection (Fig. 2) and reflected in our multiple comparisons.

Regarding non-spatial measures of forest structure, thinnings significantly reduced the average stand's trees per ha (Dunnett's test, all p-values <0.010) from an initial 687 trees ha^{-1} before thinning. Trees per ha averaged 243, 152, and 73 at residual basal areas of 15, 10, and 5 m^2 ha^{-1}, respectively. Multiple comparisons test indicate that trees ha-1 was greatest following random and VRT, and lowest for scenarios incorporating thinning from below (Fig. 3a). Strategies incorporating thin-from-below increased QMD from pre-treatment conditions (Dunnett's test, all p-values >0.001), with no differences among other thinning scenarios (Dunnett's test, all

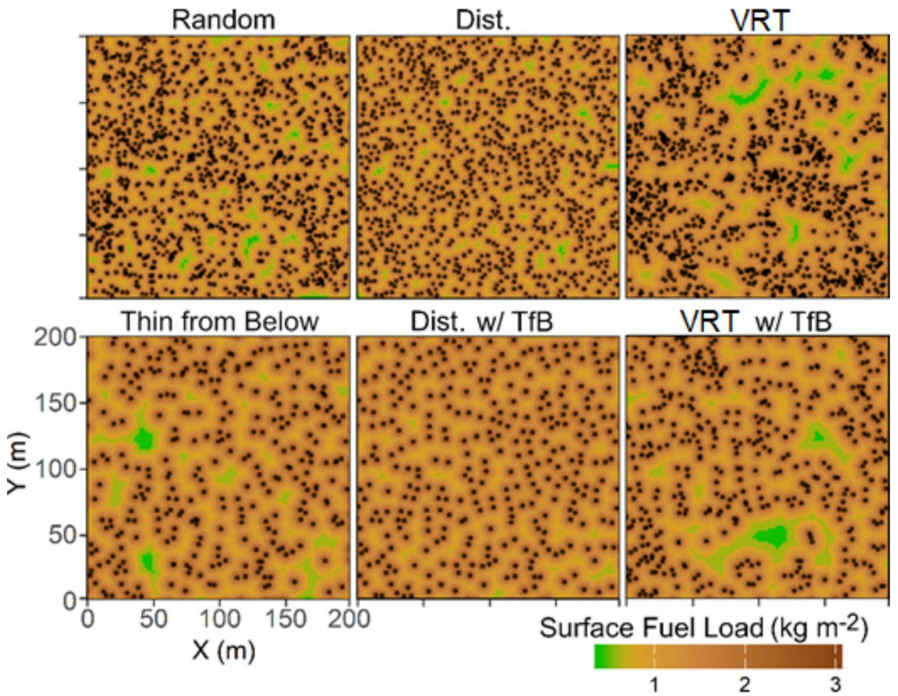
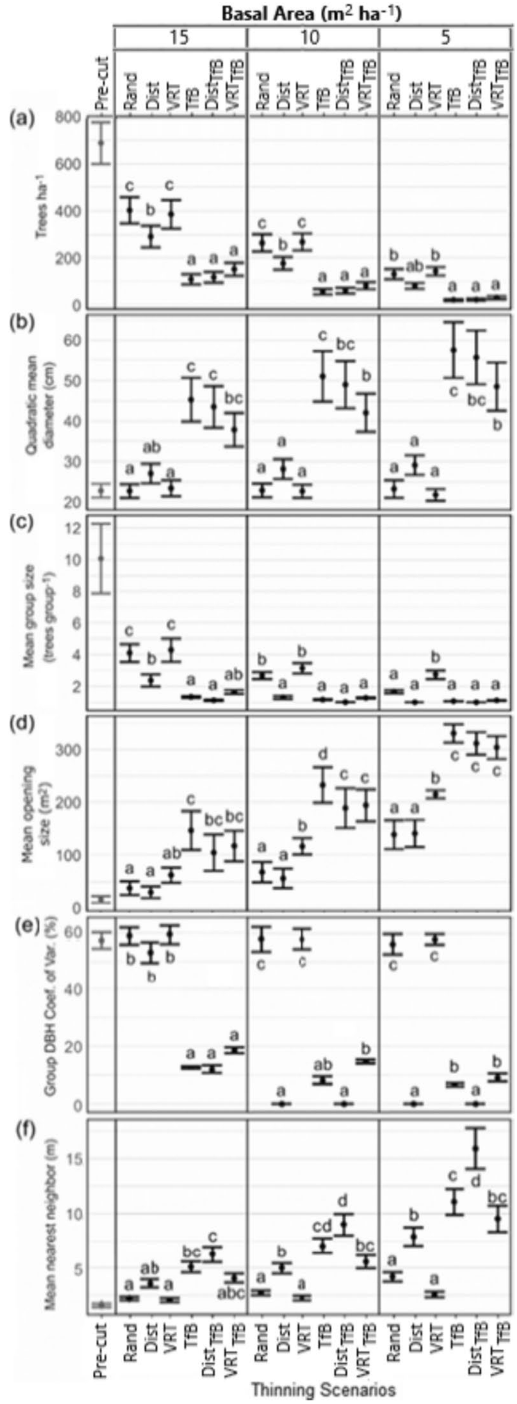


Fig. 2 Maps of tree locations and arrangement of surface fuel loads following each of the six thinning methods on one site, given a target basal area of 10 m^2 ha^{-1} and a spatial median surface fuel load of 1.2 kg m^{-2}. These panels represent six possible WFDS simulation areas of interest. Black dots represent individual trees. Dist. = distance-based thinning; TfB = thin-from-below; VRT = variable retention thinning

Fig. 3 Average and standard error following simulated thinnings, for (**a**) tree density, (**b**) quadratic mean diameter, (**c**) tree group size, (**d**) opening size, (**e**) coefficient of variation of tree diameter at breast height within tree groups, and (**f**) distance between neighbor trees, pre-thinning and at each level of residual basal area. Letters indicate significant differences ($\alpha = 0.05$) of treatments within a residual basal area identified through the multiple comparisons test



p-values <0.646). For the thin-from- below scenarios, QMD increased as less basal area was retained (Fig. 3b).

The mean tree group size was reduced for all thinning scenarios compared to the pre-treatment stand condition (Dunnett's test, all p-values <0.001). The 15 m^2 ha^{-1} residual basal area thinnings left ~4 trees per group after random and VRT, ~2 trees per group after distance-based thinnings, and less than 2 trees per group in all thinnings that incorporated thin-from-below. As less basal area was retained, the average tree group size after any thinning scenario was further reduced relative to the pre-treatment scenario (Fig. 3c). The mean opening size increased following thinnings (Dunnett's test, all p-values <0.034) and with lower residual basal areas. Opening sizes were larger among thinnings incorporating thin-from-below, followed by the VRT, and then the random and distance-based thinnings (Fig. 3d). Random and VRT scenarios maintained similar within tree group DBH variation (Dunnett's test, p-values ≥0.504; Fig. 3e) and average distance between trees (Dunnett's test, p-values ≥0.703; Fig. 3f) as the pre-treatment forest. Treatments that incorporated a thin-from-below resulted in less DBH variation and the largest mean distance between trees.

Effects of Thinnings on Simulated Fire Behavior

All thinning scenarios increased midflame wind speed compared to pre-treatment (Dunnett's test, all p-values <0.010), with increases ranging from 92 to 145%. Following thinning, our results show that increases in midflame wind speed depended upon open wind speed, residual basal area, and thinning method. The open wind speed was the strongest determinant of midflame wind speed (Likelihood Ratio Test, χ^2 (df = 1) = 1468.9, p < 0.001; Fig. 4d). Residual basal area was the second most important variable (Likelihood Ratio Test, χ^2 (df = 1) = 291.6, p < 0.001; Fig. 4b);

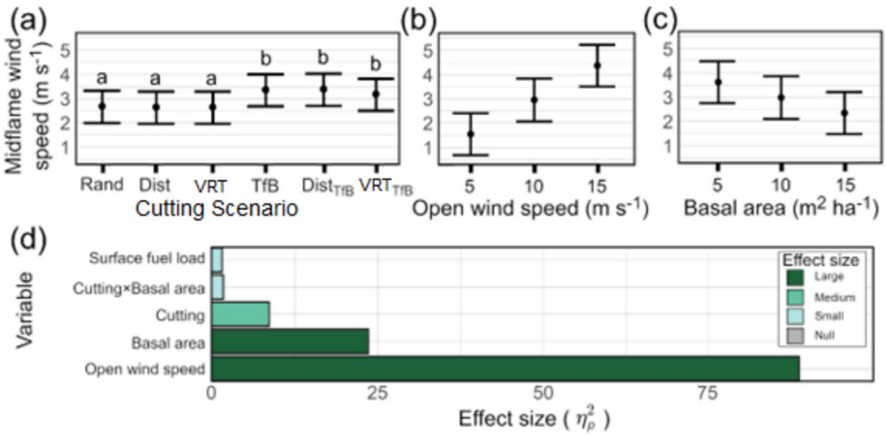


Fig. 4 Marginal effects on midflame wind speed following mixed effects modeling of (**a**) thinning scenario, (**b**) open wind speed, and (**c**) basal area, and (**d**) effect size of variables. Letters indicate significant differences between thinnings using multiple comparison procedures

as residual basal area decreased from 15 m^2 ha^{-1} to 5 m^2 ha^{-1}, mid-flame wind speeds increased from 2.4 m s^{-1} to 3.6 m s^{-1} (Fig. 4c). There were also significant differences between thinnings (Likelihood Ratio Test, χ^2 (df = 5) = 294.2, p < 0.001; Fig. 4a). The thinning scenarios that included thin-from-below were similar with a midflame wind speed averaging 24% faster than for the random, distance-based, and VRT (Fig. 4a). The effect of thinning did not have a significant interaction with residual basal area (Likelihood Ratio Test, χ^2 (df = 5) = 3.3, p = 0.660).

Fire rate of spread (ROS) was reduced after all thinning scenarios relative to pre-treatment (Dunnett's test, all p-values < 0.002), with reductions ranging from 19 to 28% post-treatment. There was a significant main effect between thinnings (Likelihood Ratio Test, χ^2 (df = 5) = 24.6, p < 0.001). Although the effect of residual basal area on the rate of spread was marginal (Likelihood Ratio Test, χ^2 (df = 1) = 3.4, p = 0.064), we found that the differences between thinnings increased with lower residual basal area (Likelihood Ratio Test, χ^2 (df = 5) = 13.9, p = 0.016; Fig. 5a). At the

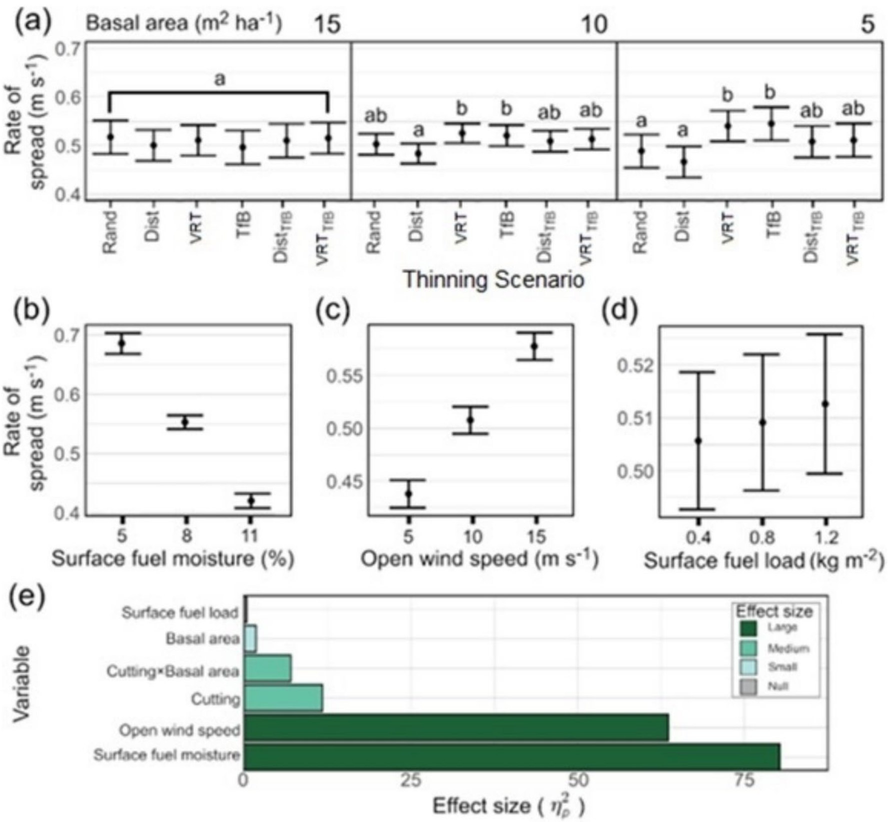


Fig. 5 Marginal effects on Rate of Spread following mixed effects modelling of (**a**) thinning scenario × basal area, (**b**) surface fuel moisture, (**c**) open wind speed, and (**d**) surface fuel load, and (**e**) effect size of variables. Letters indicate significant differences between thinnings at a basal area level using multiple comparison procedures

highest basal area, 15 m^2 ha^{-1}, multiple comparison tests showed that ROS was not different between thinning scenarios, averaging 0.51 m s^{-1}. But when thinning to 5 m^2 ha^{-1}, ROS decreased to 0.47 m s^{-1} within distance-based and random thinnings, but ROS increased to 0.54 m s^{-1} after VRT and thin-from-below thinnings.

Among the independent variables, surface fuel moisture most explained ROS (Likelihood Ratio Test, χ^2 (df = 1) = 759.9, $p < 0.001$; Fig. 5e), with ROS decreasing by 64% from the lowest to the greatest surface fuel moisture assessed (Fig. 5b). As the open wind speed increased from 5 to 15 m s^{-1}, ROS increased ~32% (Likelihood Ratio Test, χ^2 (df = 1) = 323.1, $p < 0.001$; Fig. 5c). Surface fuel load was the only variable that was not a significant explanatory variable for fire ROS (Likelihood Ratio Test, χ^2 (df = 1) = 0.8, $p = 0.381$; Fig. 5d).

Mean percent canopy consumption (CC) decreased for all post-treatment conditions compared to the pre-treatment scenario (Dunnett's test, all p-values < 0.001). Sur-face fuel moisture, surface fuel loading, thinning scenario, and basal area all had large effects on CC (Fig. 6e). Surface fuel moisture had the largest effect (Likelihood Ratio Test, χ^2 (df = 1) = 95.7, $p < 0.001$), with CC increasing from 42 to 56% as surface fuel moisture increased from 5 to 11% (Fig. 6b). As surface fuel loads increased from 0.4 to 1.2 kg m^{-2}, CC increased from 42 to 51% (Likelihood Ratio Test, χ^2 (df = 1) = 56.4, $p < 0.001$; Fig. 6c). Thinning scenario impacted CC (Likelihood Ratio Test, χ^2 (df = 5) = 65.6, $p < 0.001$; Fig. 6a, e), with VRT consistently having the highest amount of CC for a given level of basal area. While CC diminished with lower residual basal areas (Likelihood Ratio Test, χ^2 (df = 1) = 34.5, $p < 0.001$), we identified an interaction with thinning scenarios. Specifically, the differences in CC between thinning scenarios was greater with less residual basal area (Likelihood Ratio Test, χ^2 (df = 5) = 23.3, $p < 0.001$), showing that thinnings that included thin-from-below saw greater CC reductions as residual basal area decreased compared to other treatments. Open wind speed was also a significant predictor of CC (Likelihood Ratio Test, χ^2 (df = 1) = 4.0, $p = 0.045$; Fig. 6d), but had a small effect size (Fig. 5e).

Discussion

Our work shows that fire rate of spread and canopy consumption are reduced following treatment regardless of thinning method, with greater reductions occurring for lower residual basal areas. Furthermore, we found that there were differences in predicted fire rate of spread and canopy consumption among the different thinning methods with the differences becoming increasingly pronounced at lower residual basal areas. More pronounced differences in predicted fire behavior among thinning methods at lower residual basal areas were because the residual forest structures increasingly diverged in terms of tree sizes and arrangement relative to greater residual basal areas.

Forest managers tasked with designing treatments frequently face the difficulty of either maximizing a single objective, such as reducing fire hazard, or balancing multiple objectives, like promoting structural diversity for wildlife while also enhancing resilience to future fires. Although results show that treatments

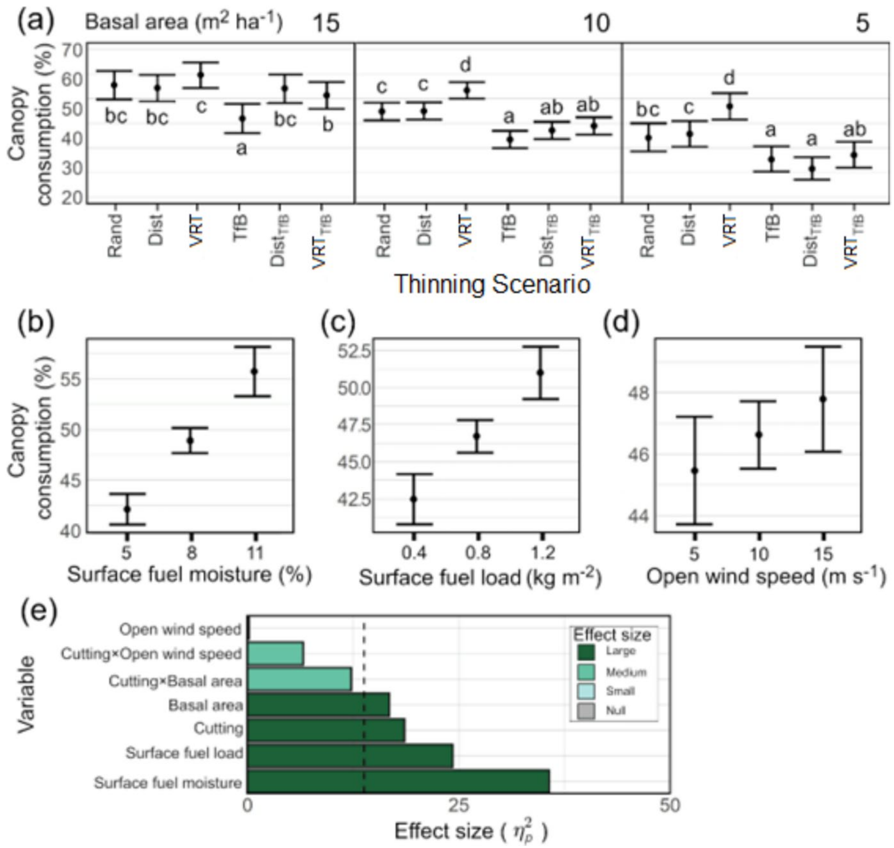


Fig. 6 Marginal effects on canopy consumption for (**a**) thinning scenario ×basal area, (**b**) surface fuel moisture, (**c**) surface fuel load, and **d**) open wind speed following mixed effects modelling on canopy consumption, and (**e**) effect size of variables. Letters indicate significant differences between thinnings using multiple comparison procedures

effectively reduce fire hazards and effects, the differences in rate of spread and canopy consumption among treatments indicate tradeoffs in treatment design. Notably, VRT incorporating thin-from-below produced significantly larger canopy openings. VRT often create openings purposefully (Underhill et al. 2014), while targeted removal of small trees can generate openings because regeneration of shade-intolerant species can cluster in openings between groups of mature trees (Larson and Churchill 2012; Ziegler et al. 2017b; Sánchez et al. 2009). Distance-based thinnings tend to have reduced lateral and greater stream-lined wind flow because the dispersed canopy imposes drag on the wind uniformly (Fig. 7a), while the creation of openings results in increased turbulence and greater variability in mid-flame wind speeds between openings and clumps (Fig. 7b) resulting in localized differences in fire behavior (Fig. 7c and 7 d).

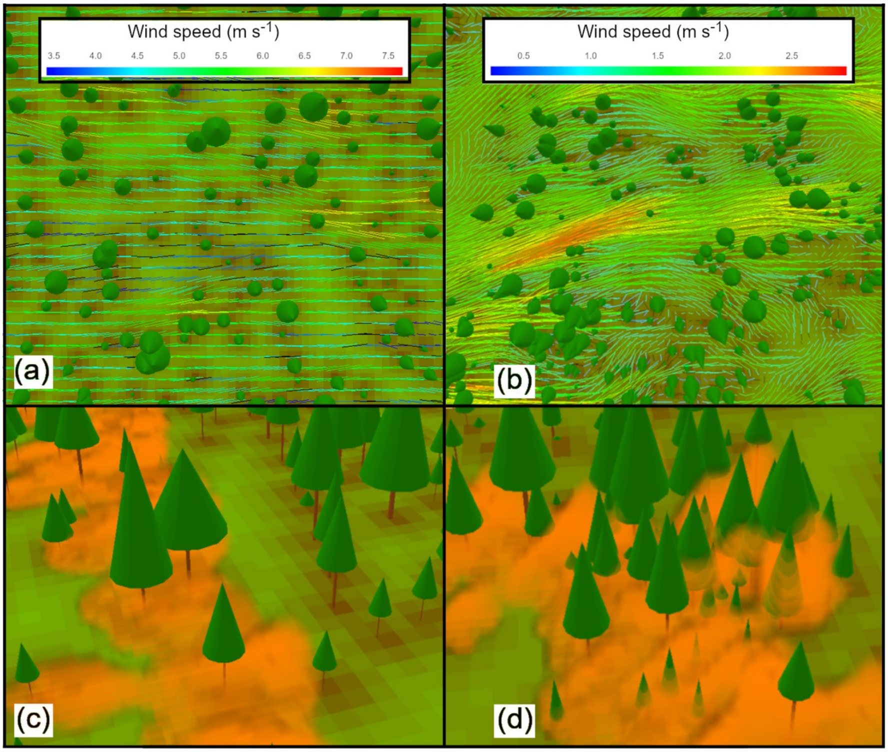


Fig. 7 Variation in wind behavior following thinning, resulting in (**a**) low turbulent flow with distance-based thinnings and (**b**) entrainment of wind following variable retention thinning, with wind vectors at 2 m above ground level flowing from left to right. Subsequent influence on fire spread, (**c**) fire passed under large trees after distance-based thinning, while (**d**) some groups torched after variable retention thinning

Previous research suggests that increases in wind speeds throughout the canopy and near the forest floor may minimize fire behavior reductions from fuels treatment by increasing surface fire rate of spread and intensities and increasing the potential for surface-crown fire transition (Agee and Skinner 2005). In this study, we find that the potential for greater rates of spread due to increased wind flow following treatment is offset by reductions in canopy fuel loading. In addition, our results indicate a correlation between reductions in surface fuel loading and fire rate of spread and canopy consumption; we found that reductions in surface fuels tested in this study (0.4 to 1.2 kg m^{-2}) were not a requirement for the design of effective treatments and that reductions in crown fuels can outweigh increases in surface fire hazard. These results corroborate several previous studies and add to a growing body of literature that indicates a variety of thinning approaches and residual forest structures can effectively reduce potential fire behavior (Stephens et al. 2021; Davis et al. 2024; Ziegler et al. 2021; Ritter et al. 2022; Prichard et al. 2020; McKinney et al. 2022; Ott et al. 2023).

Although all thinning scenarios reduced canopy consumption to acceptable levels, VRT scenarios were slightly less effective at reducing canopy consumption as there were more residual groups of 3 to 5 trees and more vertically continuous crown fuels. While distance-based thinnings reduced the potential for localized tree-to-tree crown fire spread (Contreras et al. 2012), the greater local bulk densities associated with tree groups in VRT can lead to greater localized torching and crown fire initiation (Fig. 7c and d). Despite possible tradeoffs among thinning types, we still observed a significant reduction in fire hazard compared to pre-treatment conditions. Furthermore, our results suggest that thinning scenarios can achieve similar fire hazard reduction depending upon the residual basal area targets, the management of small trees, and the treatment of surface fuels. The VRT strategies commonly implemented for restoration in the ponderosa pine forests modeled in this study have been retaining a basal area of 10 to 20 m^2 ha^{-1} (Lefevre et al. 2020; Ziegler et al. 2017a; Ritter et al. 2022). In contrast, these forests historically averaged basal areas of 6.3 to 9.5 m^2 ha^{-1} and a density of 97 to 163 trees ha^{-1} (Battaglia et al. 2018). We would expect that the removal of additional basal area during VRT to match historical conditions would further reduce potential fire hazard and meet desired conditions for some wildlife. Our results also suggest that the removal of small trees and the reduction of ladder fuels reduces potential differences between thinning strategies, regardless of horizontal tree arrangements. In many contemporary ponderosa pine dominated forests there is an overabundance of small trees providing an opportunity to retain some tree groups with and without ladder fuels, however, additional research is needed to assess the efficacy of such approaches. Other approaches, such as thinning mid- and overstory trees within groups to create discontinuities within group canopies to mitigate fire hazard, but within group thinning can lead to damage in the residual trees, increased windthrow, and move away from desired conditions (Ritter et al. 2023).

Several studies have indicated that there can be tension between meeting objectives that simultaneously seek to retain multiple size classes such as for wildlife versus decreased fire hazard (Stephens et al. 2021; Reynolds et al. 2013). For example, the desired forested conditions to support the food sources of small mammals and birds for the northern goshawk (*Accipiter gentilis*), describes a heterogeneous forested landscape of a mosaic of unforested openings, small groups of trees, and groups of trees with canopy cover $>40\%$ (Reynolds et. al 1992), similar to the outcomes of the VRT treatment. While there were localized torching of tree groups, this outcome still provides additional ecological benefits including snag formation and creation of growing space for a new cohort. Furthermore, multiple tree size classes at low densities provide added resilience to multiple disturbances. For example, the larger ponderosa pine trees are less susceptible to surface fire than the smaller size classes (Battaglia et. al 2009), but the susceptibility is switched when considering mountain pine beetle (*Dendroctonus ponderosae*) attacks (Negrón et. al 2008). This indicates that VRT seeking to maximize structural variation to promote can face tradeoffs between the creation of structural heterogeneity and fire hazard reduction, while still maintaining resilience.

Considerations

Our experimental design allowed us to concentrate on differences between horizontal and vertical arrangements of crown fuels and surface fuel load under a range of typical burning conditions. However, the tradeoffs we identified may be limited in the context of real-world management of forests and fire hazards. First, specific thinning methods, in practice, usually are associated with different levels of residual forest stocking, dictated by desired objectives and conventions. For example, Ritter et al. (2022) found no difference in potential fire severity between fuel hazard reduction treatments designed to support uniform timber production (basal area $= 12.4\ m^2\ ha^{-1}$) and forest restoration treatments designed to provide heterogeneous wildlife habitat (basal area $= 6.3\ m^2\ ha^{-1}$). As our results demonstrate, these differences in forest stocking between different silvicultural methods—as typically implemented—are likely to be as impactful as the arrangement of the residual tree crowns. Fire behavior and effects studies contrasting different silvicultural methods designed to meet various combinations of objectives need to consider how forest stocking, diameter distributions, and fuel loads may differ.

Across the simulations, surface fuel load had a greater effect on canopy consumption than the arrangement of canopy fuels. Our modeling of surface fuels assumed a transition from needle litter to herbaceous fuels at a greater distance from a tree bole into open areas. While this approach allowed us to capture some effects of spatial heterogeneity on fire behavior there has been little research to date that has quantified interactions between surface fuel arrangement and load on fire behavior. Several previous studies have suggested that the use of prescribed fire is a key factor for reducing potential fire behavior and increasing resistance to undesirable fire effects (Kalies et al. 2016; Cansler et al. 2022). In this study, we did not explicitly assess treatments which included prescribed fire, though we did include surface fuel load which is a key metric impacted by prescribed fires. Although our study indicated that reductions in surface fuel loading was not a necessity for effective reduction in potential fire behavior, the loadings modeled were within acceptable and typical loads of ponderosa pine forests. We would expect the effect of prescribed fire to be greater as it also can have impacts on both canopy base height and canopy fuel load. Furthermore, recent research has indicated that forest structure influences prescribed fire effects (Bonner et al. 2024), suggesting the possibility for differential effects of thinning types and prescribed fire combinations on potential fire behavior. Additional research is needed that explores various combinations of prescribed fire and thinning type on fire behavior.

Last, we simulated fires under burning conditions spanning 5% to 11% surface fuel moisture and winds of 5 to 15 $m\ s^{-1}$. We do not expect our findings of fuel reduction effectiveness to hold under more extreme burning conditions. Further research under more extreme conditions is needed given recent research indicating that longer fire season duration and changes in climate patterns are increasing the number of days where extreme fire weather and dry fuels align (Westerling 2016). Furthermore, our study was conducted with an assumption of flat ground, however, interactions between wind flow and terrain can produce atypical fire behavior and influence patterns of fire severity (Sharples et al. 2012). In these conditions we would expect that fuel treatment effectiveness is generally decreased; however, it is unclear if interactions among the terrain, wind flow, and forest structure would impact treatment effects. Further research investigating the interaction between forest canopy fuel arrangement and fire behavior on steep terrain could help develop additional guidance for treatment design in areas with topography.

Conclusion

Our simulations provide evidence that thinnings spanning a range of forest structural arrangements can reduce fire behavior and effects under moderate to high burning conditions. Our results also indicate that treatments that seek to create residual heterogeneous forest structures through retention of tree groups and a wide range of tree size classes are slightly less effective at reducing fire severity than distance-based thin-from-below treatments, though they may meet other land management objectives. Regardless of thinning strategy and residual stocking levels, surface fuel loading had the greatest effect on fire hazard and highlights the need for treatments to directly address the accumulated fuels from a century of fire suppression.

In the context of the landscape planning of treatments, our work supports how treatments that incorporate the removal of small trees (i.e. thin-from-below) can maximize fuel hazard reduction benefits, which is often emphasized within the wildland-urban interface (WUI) where protection of life and property is paramount (Stephens et al. 2021). Prior modeling from Stevens et al. (2016) demonstrated that strategic locations of fuel treatments in the WUI can have an outsized effect on landscape fire behavior; in combination with forest restoration treatments in the wildland, this mix of treatment designs can be more effective than random placements of conventional distance-based fuel treatments alone. Being flexible in the choice of thinning strategy to plan a mixture of treatments in such a way that reflects differences in biophysical settings and values at risk across landscapes could simultaneously accomplish multiple resource management objectives.

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Data Availability Stem mapped data used in this study were published by Ziegler et al. (2019);doi:https://doi.org/10.3390/data4020068. Other data is available upon request.

Declarations

Competing Interests The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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