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How are long-term stand structure, fuel profiles, and potential fire behavior affected by fuel treatment type and intensity in Interior Pacific Northwest forests?

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ABSTRACT

Fuel treatments are commonly applied to increase resilience to wildfire in dry and historically frequent-fire forests of western North America. The long-term effects of fuel treatments on forest structure, fuel profiles (amount and configuration of fuels), and potential wildfire behavior are not well known relative to short-term effects. Additionally, long-term treatment effects on the development of stand structure and fuel profiles have rarely been compared to the long-term effects of pre-treatment conditions, treatment intensity, and site productivity. In this study, we addressed these knowledge gaps by resurveying 204 permanent plots at the Northeastern Cascades site of the Fire and Fire Surrogates study 13–18 years ('long-term') after burn-only, thin-only, and thin plus burn treatments, and comparing results to pre-treatment conditions and un-treated controls. Methods included ordinations, generalized linear mixed models, and fire models. All treatments shifted long-term average stand structure toward lower tree density, basal area, and crown fire potential, with thin plus burn treatments showing the highest magnitude of effects for most variables. However, the direction and magnitude of trajectories among plots within treatment types were highly variable. Long-term responses of stand structure, fuel profiles, and modelled fire behavior were positively correlated with their pre-treatment values. Treatment intensity strongly affected long-term stand structure and canopy fuel loads. By ~15 years post-treatment and under 80th percentile fire weather conditions, most plots in all treatments and un-treated controls failed to meet target thresholds for surface flame length, basal area mortality, and torching index, while most plots met thresholds for crowning index. However, live stand structure following wildfire simulated under 80th percentile fire weather conditions was characterized by lower stand density and a shift toward dominance by large-diameter and fire-resistant trees, suggesting that treated stands may be resilient to wildfires occurring under moderate weather. Our study suggests that understanding fuel treatment efficacy and longevity may be improved in future studies by incorporating fine-scale (i.e., plot-level) drivers of variability in stand structure, fuel profiles, and modelled fire behavior, and by using multiple methods of evaluating treatment effectiveness. Thin plus burn treatments and intensely applied burn-only and thin-only treatments can reduce basal area and potential for crown-fire for more than a decade. However, additional maintenance treatments may be needed by 15 years after initial treatment, to further reduce potential for severe surface fire and high tree mortality in subsequent wildfire.

1. Introduction

Ecological and social impacts of wildfires have increased globally in recent decades (Schoennagel et al., 2017; Moreira et al., 2020; Haque et al., 2021). In western North America, many forests that burned frequently before European colonization ('frequent-fire forests') have missed multiple fire cycles since the late 1800s because of fire suppression and exclusion of Indigenous fire (Hessburg and Agee, 2003).

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The resulting fuel accumulation, combined with a warming and drying climate, increases potential for large and severe fires that are likely outside the range of the historical fire regime (Abatzoglou and Williams, 2016; Hagmann et al., 2021). Reducing fuel loads is therefore a major component of many forest management plans to restore low and mixed-severity fire regimes (Hessburg et al., 2021).

Fuel treatment types vary in their effects on stand structure, fuel profiles (amount and configuration of fuels), and potential fire behavior (Schwilk et al., 2009; Stephens et al., 2012b). For example, in the short-term (<5 years post-treatment), prescribed burning ('burn-only' treatment) tends to reduce surface fuel (e.g., dead woody material and leaf litter on the forest floor) but usually has relatively little effect on canopy fuel in the mild weather conditions in which prescribed burning often takes place (Schwilk et al., 2009). Thinning ('thin-only' treatment) often reduces canopy fuel by selectively removing smaller trees, but can increase surface fuel via transport of fuel from the canopy to the forest floor, unless additional fuel management practices such fuel piling, burning, and/or whole tree harvest are implemented (Schwilk et al., 2009). Thinning followed by burning ('thin plus burn' treatment) tends to reduce both surface and canopy fuel profiles (Schwilk et al., 2009, Fulé et al., 2012, Stephens et al., 2012b). Each of the above fuel treatments can reduce wildfire severity, most often measured by tree mortality, though effects are typically strongest in burn-only and especially thin plus burn treatments (Prichard et al., 2010, 2020; Kalies and Yocom Kent, 2016; Cansler et al., 2022).

Vegetation conditions and fuel profiles change with time since treatment, and the long-term dynamics of treatment have been studied less than short-term effects (Kalies and Yocom Kent, 2016; Urza et al., 2023). Vegetation conditions and fuel profiles are often statistically indistinguishable from untreated areas and/or pre-treatment values by 5–15 years after treatment, often with high variability among sample plots and correspondingly low statistical power (Battaglia et al., 2008; Chiono et al., 2012; Stephens et al., 2012a; van Mantgem et al., 2016; Crotteau et al., 2018; Hood et al., 2020; Rossman et al., 2020; Morici and Bailey, 2021). Among treatment types, thin plus burn treatments likely have the strongest long-term effects (Stephens et al., 2012a; Hood et al., 2020; Morici and Bailey, 2021) because of near-simultaneous short-term reductions in surface, ladder, and canopy fuels (Schwilk et al., 2009). However, many key mechanisms affecting treatment longevity are not well understood, including long-term dynamics of tree regeneration (Rossman et al., 2020; Tinkham et al., 2016; Zald et al., 2024), understory vegetation growth (Rossman et al., 2018; Dudney et al., 2021), delayed tree mortality (Hood et al., 2018), surface fuel deposition (Harris et al., 2016), and surface fuel decomposition (Kennedy et al., 2021; Hanan et al., 2022).

Long-term effects of treatments on fuel profiles may be influenced by factors that vary within and among stands, such as pre-treatment stand structure, site productivity, and treatment intensity (Jain et al., 2012). Pre-treatment stand conditions are legacies of past management and disturbance, and constrain potential treatment outcomes (Reinhardt et al., 2008; Zald et al., 2024). For example, stands consisting solely of smaller fire-intolerant trees will take longer to build resistance to fire when treated than stands containing relatively larger, fire-resistant trees (Hessburg et al., 2015). Site productivity drives vegetation growth and decomposition rates, with vegetation in more productive forests likely to grow more rapidly after treatment (Jain et al., 2012; Ex et al., 2019) and activity fuel (i.e., fuel inputs associated with treatment) likely to decompose more rapidly after treatment. However, studies of the effects of productivity on treatment longevity have had variable results (Tinkham et al., 2016; Morici and Bailey, 2021), potentially because of different methods and response variables among studies. For example, Tinkham et al. (2016) analyzed the effect of productivity on longevity through modelling development of canopy and ladder fuel, and Morici and Bailey (2021) analyzed the effects of productivity through field measurements of surface fuel changes over time. Treatment intensity, broadly defined here as the change in vegetation and fuel profiles caused by treatment, varies widely within and among treatments and is likely to affect the duration of fuel treatment effectiveness (Jain et al., 2012). By definition, greater treatment intensity leads to greater short-term reductions in fuel, but long-term effects are less clear. It is plausible that greater treatment intensity may stimulate vegetation development in more productive sites, and thus increase fuel profiles in the long-term (Jain et al., 2012).

We addressed the above knowledge gaps by analyzing long-term (~15-year post-treatment) stand structure and fuel profile responses to control, burn-only, thin-only, and thin plus burn treatments, while accounting for plot-level differences in pre-treatment condition, treatment intensity, and site productivity. We used field data from the Northeastern Cascades site of the US Fire and Fire Surrogates (FFS) study (McIver and Weatherspoon, 2010) to ask:

1) How are long-term stand structure and fuel profiles affected by pre-treatment forest condition, treatment type, treatment intensity, and site productivity?
2) How are expected fire behavior and severity affected by pre-treatment forest condition, treatment type, treatment intensity, and site productivity?
3) Does modelled wildfire behavior meet desired target metrics for surface flame length, basal area mortality, torching index, and crowning index ~15 years after treatment?

2. Methods

2.1. Study area

The Northeastern Cascades site of the FFS study is in central Washington (USA) on the forested mid-slopes between the sagebrush steppe and the alpine crest of the Cascade Mountains, and is characteristic of dry forests of the interior Columbia River basin (Agee and Lehmkuhl, 2009). Forest structure and composition are heavily influenced by moisture dynamics, and therefore, elevation and topographic position (Agee and Lehmkuhl, 2009). The tree layer is dominated by ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*), with much smaller components of western larch (*Larix occidentalis*) and grand fir (*Abies grandis*) (Rossman et al., 2020). The precolonial (before settlement of non-Indigenous peoples, ca. 1850s) fire return interval was between 6 and 21 years (Agee and Lehmkuhl, 2009). In the 20th century, fire suppression and exclusion of Indigenous burning resulted in fuel accumulation and increased density of shade-tolerant, fire-intolerant tree species, and high-grade logging (i.e., selectively cutting the largest trees) caused a deficit of large, fire-resistant trees (Hessburg and Agee, 2003).

2.2. Treatment selection and implementation

The FFS study was a coordinated distributed experiment initiated in the late 1990s and early 2000s across US forests. It was designed to experimentally test the effects of three common fuel treatments (mechanical thinning [thin-only], prescribed burning [burn-only], and mechanical thinning followed by prescribed burning [thin plus burn]) along with an un-treated control. A wide range of response variables were measured, so FFS sites were designed to have fewer and larger experimental units than would generally be used for studies focusing solely on fuel or stand structure (McIver and Weatherspoon, 2010). Treatment implementation details were decided by site managers so that treatments would accurately reflect local ecological conditions and management practices. The common goal of each FFS site was to treat forests so that 80 % of the remaining basal area would survive a fire that occurred during 80th percentile fire weather conditions (McIver and Weatherspoon, 2010).

Planning at the Northeastern Cascades site began in the late 1990s. In accordance with FFS protocols, 30 candidate units of 10 ha or larger were identified. Twelve experimental units were randomly selected from the set of 30 candidates, and three units were randomly assigned to each treatment type. Units were required to be approximately rectangular in shape, have slopes averaging less than 26.5 degrees, and be 90 % forested with the overstory dominated by Douglas-fir and/or ponderosa pine. Thinning was implemented in 2002 and 2003 and was designed to be spatially clumpy, reducing average stand basal area to 10–14 m^2 per hectare. Yarding was done by helicopter, and most snags were felled due to safety concerns (Harrod et al., 2009). Some units were burned in 2004 and others in 2006. Burns implemented in 2004 were of lower intensity and severity than prescribed due to an early spring green up, while those implemented in 2006 met intensity and severity goals but were patchy (Agee and Lehmkuhl, 2009).

In 2012, a wildfire (the Poison Fire, part of the Wenatchee Complex) burned two control units, a thin-only unit, and a burn-only unit (Fig. A1). These four units were omitted from our analyses, along with three wildfire-burned plots in a thin plus burn unit that was otherwise not affected by wildfire (Tripp, the unit immediately north of the wildfire in Fig. A1). As a result, the long-term experimental design consists of three thin plus burn units, two thin-only units, two burn-only units, and one control unit (Rossman et al., 2018). The un-treated control unit remaining after the wildfire is at a relatively low elevation and represents relatively arid and low productivity conditions within the scale of the study.

2.3. Data collection

Each experimental unit contains up to 40 sample plots on which fuel profiles and stand structure were measured. Plots were arranged on a 40-meter grid system within units. These plots were measured in 2000–2001 (pre-treatment) and again in 2004–2006 (short-term post-treatment). We resampled 204 permanent plots in 2019 and 2020 (71 plots from three thin plus burn units, 58 plots from two burn-only units, 52 plots from two thin-only units, and 24 plots from one untreated control unit). The protocols detailed below match those followed in pre-treatment surveys (Agee and Lolley, 2006; Agee and Lehmkuhl, 2009), except where noted.

At each plot, we re-measured surface fuel in two planar intercept transects (Brown, 1971) at the same locations as were measured during pre-treatment. The surface fuel transects radiated from plot center with the first transect oriented towards a random azimuth and the second oriented randomly within the range of possible azimuths at least 90 degrees from the first azimuth. In each surface fuel transect, we counted 1-hour fuel for 2 m, 10-hour fuel for 3 m, 100-hour fuel for 5 m, and 1000-hour fuel for 20 m. Differences in inclusion of bark pieces in the fuel transects necessitated subsequent calibration and correction for the contribution of bark to 1-, 10-, and 100- hour fuels; see Appendix 2 for details. For 1000-hour fuel, the diameter, decay class, and species of each piece were also recorded. Litter depth, duff depth, and woody fuel height were measured at three points per transect.

The protocol for determining tree plot size was different for pre-treatment surveys than for our survey, though measurements on individual trees were the same (Agee and Lolley, 2006; Agee and Lehmkuhl, 2009). Pre-treatment surveys used variable rectangular plots with coarser size increments than in our survey. We measured overstory structure with a circular adjustable radius design. Specifically, we used one radius for 'smaller trees' (≥0.1 cm diameter at breast height [dbh] and <30 cm dbh), and another radius for 'larger trees' (≥30 cm dbh), to avoid the possibility of sapling clumps causing under-sampling of larger, more fire-resistant trees. We customized each plot radius to sample at least ten trees per plot, at least five of which had to be larger trees. The maximum allowable plot radius was 18 m. Radii were adjustable in meter increments. The smaller tree plot could have an equal or lesser area than the larger tree plot, but not greater. For each tree, we recorded species, dbh, total height, and height to base of live crown.

Fuel profiles and stand structure were measured during the pre-treatment and soon after treatments were implemented (Agee and Lolley, 2006), but we could not locate detailed short-term post-treatment data in either paper or digital format. Therefore, all analyses in this manuscript compare only pre-treatment and long-term data collection periods. Although more plots were measured in the pre-treatment and short-term post-treatment measurements, all analyses and summaries reported here are based on the 204 plots we resampled in the long-term. Data from the Mission Creek FFS site addressing stand structure (Harrod et al., 2009), tree regeneration (Rossman et al., 2020), and understory plants (Rossman et al., 2018) are from a separate network of 20 × 50 m plots within the experimental units.

Because we did not have access to short-term post-treatment field data on treatment outcomes for each plot, we estimated treatment intensity using the satellite-derived relativized differenced normalized burn ratio (RdNBR) as an indicator of vegetation change caused by treatment (Knipling, 1970; Knight et al., 2022). We calculated RdNBR without offsets from Landsat 7 imagery with 30-m resolution, using Google Earth Engine and Python code modified from (Parks et al., 2021) to gather composite imagery from the growing season. In calculating RdNBR, we used the 2001 growing season as the base year to reduce interannual bias among units and the growing season after treatment as the post-treatment reference. For example, RdNBR was calculated for units burned in 2006 by comparing the growing seasons of 2001 and 2007.

2.4. Modelling potential fire behavior

We modelled surface flame length, total flame length, torching probability, torching index, and crowning index using the Forest Vegetation Simulator Fire and Fuels Extension (FVS-FFE) (Reinhardt and Crookston, 2003) version 20220311, East Cascades variant (Rebain et al., 2010), and modelled tree mortality as a proportion of density and basal area using the First Order Fire Effects Model (FOFEM) (Reinhardt et al., 1997) version 6.7. We entered inputs and generated outputs at the plot level to visualize distributions and to use model outputs in the same analyses as field variables. To model diameter distributions following wildfire, we implemented the FOFEM equations from Lutes (2020) in statistical program R, which allowed us to efficiently obtain estimates of mortality probability for individual trees.

In FVS-FFE, we used field-measured fuel and stand structural inputs to represent surface fuel profiles and as the base inputs for indicators of ladder fuel and canopy fuel profiles (e.g., canopy base height, canopy bulk density, torching index, and crowning index). We allowed FVS-FFE to assign the fuel model automatically based on our field-measured fuel and stand structural data (Rebain et al., 2010), using a hierarchical decision process tuned for the East Cascades model variant. Automatic fuel model assignment eliminated the potential for bias in fuel model assignment between field crews from different years; see Fig. A2 for average fuel model weighting by period and treatment. In our model implementation, fuel model assignment did not affect fuel profiles, but affected estimated surface area to volume ratio of some fuel classes, dead fuel extinction moisture, and fuelbed depth (Rebain et al., 2010).

In FOFEM, we used field-measured species, dbh, height, and live crown ratio inputs along with predictions of surface flame length from FVS-FFE. FOFEM crown scorch equations use these inputs to estimate bark thickness and percentage of crown scorched as independent predictor variables of tree mortality. FOFEM does not account for delayed mortality, torching, or crown fire, and therefore is a conservative estimate of tree mortality, particularly when crown fire is likely (Lutes, 2020).

We modelled fire behavior using three weather scenarios, "mild", "moderate", and "severe." For tree mortality models we added a fourth "null" scenario. To determine parameters for each weather scenario, we used Fire Family Plus (Bradshaw and McCormick, 2000) version 5 to gather weather and fuel moisture data from the nearby Swauk and Dry Creek Remote Automated Weather Stations (Agee and Lolley, 2006).

Fuel moisture, temperature, and windspeed parameters were selected so that the mild and moderate scenarios corresponded to the 60th and 80th percentiles of daily average fire season conditions and the severe scenario corresponded to the 97th percentile of daily maximum fire season conditions. The severe scenario used daily maximum temperatures and windspeeds to reflect an extreme fire weather event. In tree mortality models, we applied the FVS-FFE default 1.22 m (four foot) flame length to plots in the 'null' condition, to isolate the effect of tree size from those of fuel profiles and wind friction. The reference climate window was 2002–2017; this interval likely reflects warmer and drier conditions than were considered in the original FFS study design. We defined the fire season as June 15 through September 15. For each fire weather and fuel moisture parameter, we calculated values for each weather station and then used the average values as model inputs. See Table A1 for fuel moisture and fire weather parameters.

2.5. Statistical analyses

We addressed Q1 (stand structure and fuel profiles) and Q2 (potential fire behavior and severity) with nonmetric-multidimensional scaling (NMDS) and generalized linear mixed models (GLMMs). NMDS was used to assess general changes at the plot and treatment scale among the 204 plots and two sample periods (i.e., 408 total plot measurements). We scored plots based on all response variables, including fuel, stand structure, and modelled fire behavior variables. Modelled fire behavior variables were obtained from the moderate weather scenario as this best reflects FFS design for 80th percentile fire weather (McIver and Weatherspoon, 2010). We relativized each variable by its maximum before calculating the Euclidean distance matrix. We chose the fewest number of axes that produced a stress below 0.20 (McCune and Grace, 2002). The final solution contained three axes and a stress of 0.11. We ran one ordination with all plot measurements but graphed each sample period separately. To represent the location of the predictors in ordination space, we calculated the weighted average value for each predictor in ordination space, using the 'wascores()' function in R package vegan (Oksanen et al., 2022). We also graphed the trajectory of each plot by translating its coordinates so that its pre-treatment value was at the centroid and its long-term location the same distance and direction from there as in the original ordination space.

We used GLMMs to test potentially significant drivers of variation for each response variable in the long-term period on a fine-scale (e.g., plot-level). Fixed effects included pre-treatment condition, topographic wetness index (TWI), heat load index (HLI), treatment type, and the nested effect of treatment intensity (RdNBR) within treatment type (see Table 1 for more information on collection and use of these variables). We included the experimental unit as a random intercept term to allow for plot-level analysis while accounting for potential within-unit correlation and within-unit variability that we were unable to account for with fixed effects (Zuur et al., 2009; Bolker et al., 2009). We used the same model structure and set of predictors for every response variable so that effect sizes could be directly compared between models (Zuur et al., 2009). Models included a gamma distribution of errors with a log link function, and continuous variables were scaled by their standard deviation (Zuur et al., 2009). We generated models with the 'glmer()' function in the R package lme4 (Bates et al., 2019). Models were screened for collinearity of fixed effects using a threshold of 0.7 (Fig. A3). We generated confidence intervals by bootstrapping with replacement, using 1000 iterations of each model including random effects. We used the function 'confint.merMod()' in R package lme4 (Bates et al., 2019) to generate confidence intervals of fixed effects parameter estimates, and the function 'bootMer()' in R package lme4 (Bates et al., 2019) to generate confidence intervals of predicted values for marginal effects plots.

To test whether modelled fire behavior met target metrics reflecting low severity wildfire effects (Q3), we used threshold analyses for surface flame length, basal area mortality, torching index, and crowning index.

Table 1
Predictor variables used in the generalized linear mixed models. All variables are fixed effects unless noted otherwise.

Predictor variable	Justification and model structure	Collection methods
Pre-treatment value	Pre-treatment conditions may constrain possible long-term treatment effects (Jain et al., 2012).	The pre-treatment value of the response variable being tested in each model. For example, the model predicting long-term basal area includes the pre-treatment basal area value.
Topographic wetness index (TWI)	Topography is related to site productivity in moisture-limited dry forests (Tai et al., 2020), and topographic wetness index primarily reflects catchment position (Qin et al., 2011).	Calculated using the 'rsaga.wetness.index()' function in the RSAGA package (Brenning et al., 2018), using the methods of (Qin et al. (2011), and using SAGA GIS (Böhner and McCloy, 2006) version 6.3.0. Based on a 10-m digital elevation model (University of Washington Earth and Space Science, 2010).
Heat load index (HLI)	Topography is an indirect indicator of site productivity in moisture-limited dry forests (Tai et al., 2020), heat load index primarily reflects slope aspect and angle (McCune and Keon, 2002).	Calculated using the 'hli' function in the SpatialEco package (Evans et al., 2021), using the methods of (McCune and Keon, 2002). Based on a 10-m digital elevation model (University of Washington Earth and Space Science, 2010).
Relativized differenced normalized burn ratio (RdNBR)	Used as an indicator of change in vegetation and fuel profiles (treatment intensity) since short-term post-treatment data is no longer available. Strong basis in physics (Knipling, 1970), strong relationship with basal area loss in wildfires (Harvey et al., 2019), and used to track silvicultural treatments (Knight et al., 2022). Nested within treatment type to account for the likelihood that a given RdNBR value may indicate different types and amounts of fuel removed when used to measure different treatment types.	RdNBR without offsets calculated from Landsat 7 imagery with 30 m resolution, using Google Earth Engine and Python code modified from (Parks et al., 2021) to gather composite imagery from the growing season. The 2001 growing season was used as the base year for each treatment unit to reduce potential interannual bias, and the growing season after treatment used as the post-treatment reference. For example, units burned in 2006 had RdNBR calculated by comparing the growing seasons of 2001 and 2007.
Treatment type	Intent of the original study design. Used as a stand-alone categorical fixed effect, and as a factor to nest treatment intensity as measured by RdNBR. Control was used as reference for model output.	Treatment type applied (control, burn-only, thin-only, or thin plus plus).
Replicate unit (random effect)	Used as a random intercept to account for pseudoreplication that may occur because of plots being clustered within experimental units (Zuur et al., 2009).	Experimental unit.

Target metrics were selected to reflect FFS goals and thus were based on the moderate weather scenario, corresponding to 80th percentile fire weather (McIver and Weatherspoon, 2010). The threshold for basal area mortality was 20 %, directly taken from FFS study goals (McIver and Weatherspoon, 2010). The surface flame length threshold was 1.2 m, which represents a relatively low severity fire that most trees above 12.7 cm can survive (Ryan and Noste, 1985), and that is usually manageable by hand crews of wildland firefighters (Alexander and Cruz, 2019). The threshold for torching and crowning indices (i.e., the windspeeds that would support passive and active crown fire, respectively) was 28 km per hour. This threshold was based on wind gusts likely to be encountered at nearby RAWS stations under 80th percentile fire weather conditions, determined with the same methods used to select weather and fuel moisture parameters for fire modelling. We reported results in terms of the percentage of plots that met the thresholds within each combination of treatment, period, and metric.

Finally, to assess the resultant stand structure from the effects of treatments (Q1) and modelled wildfire 15-years post-treatment (Q3), we present diameter distributions of live trees across each of the treatment and control conditions at each relevant point in time.

3. Results

3.1. Question 1: Long-term effects of fuel treatments on fuel profiles and stand structure

All fuel treatments had long-term effects on stand structure and canopy fuel profiles. Thin plus burn treatment had the strongest long-term effects relative to pre-treatment conditions, with a 40 % reduction of basal area, 64 % reduction of tree density, 55 % reduction in canopy bulk density, 98 % increase in canopy base height, and 53 % increase in quadratic mean tree diameter (Table 2). Trees in the smallest diameter classes are important components of ladder fuel, and were reduced most strongly following burn-only and thin plus burn treatments; conversely, trees of the smallest diameter classes increased in thin-only treatments (Fig. 1, far-left and middle-left columns). Quadratic mean diameter and woody surface fuel increased long-term in all treatments and the un-treated control (Table 2). Trends among plots within treatment types were highly variable in the direction and magnitude of change in ordination space, with thin plus burn as the primary exception where plots trended consistently toward lower basal area, density, and canopy fuel loads (Fig. 2b-e). Untreated controls and thin-only treatments had the most varied effects on stand conditions, shifting plots in many directions in ordination space (Fig. 2b & e).

Treatment intensity affected long-term stand structure and canopy fuel loads for all treatment types (Fig. 3, Fig. 4). Greater treatment intensity generally produced greater long-term reductions in stand density, basal area, and canopy bulk density, with large effect sizes but wide confidence intervals for treatment-level predictions. The thin plus burn treatment produced the greatest reductions in basal area, density, and canopy bulk density across most of the treatment intensity spectrum, although trends were within the confidence intervals of other treatments (Fig. 4h, i, k). For surface fuel loads, the magnitude and direction of the treatment intensity effect varied among treatments. Burn-only treatments showed the strongest positive correlation between treatment intensity and fuel loads for many surface fuel variables (Fig. 4a–g), but more intense burn treatments showed the greatest reduction of litter loads (Fig. 4f). Thin-only treatments showed the smallest variability and magnitude of treatment intensity (not including un-treated control) (Fig. 4).

Long-term values of nearly all response variables were positively correlated with their pre-treatment value (Fig. 3, Fig. 5). Pre-treatment value (a continuous variable) usually had smaller effect size than treatment type (a categorical variable), but narrower confidence intervals (Fig. 3). The greatest reductions in fuel loads, basal area, and density were for plots with the highest pre-treatment values for these variables; treatments generally shifted these relationships so that reductions were greater from the pre-treatment to the long-term (Fig. 5). Stand structure and fuel profiles were less affected by topographic variables than by treatment type, treatment intensity, and pre-treatment value (Fig. 3).

3.2. Question 2: modelled fire behavior and severity

Overall, modelled surface flame length increased and potential for crown fire (as measured by modelled torching and crowning indices) decreased in treated stands, though long-term and pre-treatment confidence intervals generally overlapped. Potential for crown fire decreased most strongly in thin plus burn (94 % increase in torching index, 91 % increase in crowning index) and burn-only (160 % increase in torching index, 6 % increase in crowning index) treatments (Table 2, Fig. 4m-p. In thin-only treatments, modelled surface flame lengths increased by 17 % and crowning index increased by 26 %, while torching index decreased by 12 %. Modelled fire-caused tree mortality increased modestly in thin-only treatments (Table 2, Fig. 6). In the null scenario, treatments showed either a decrease in or smaller increase in modelled tree mortality, compared with models in other weather scenarios (Fig. 6).

Pretreatment conditions and treatment intensity both affected long-term treatment outcomes. All predicted long-term fire intensity and severity metrics were positively correlated with their predicted pre-

Table 2
Response variables, by treatment type. The 'Pre-treatment values' section shows mean values ± 95 % confidence intervals, while the 'Long-term change' section shows percent change of the treatment-level averages from the pre-treatment to the long-term period.

		Pre-treatment values				Long-term change			
Variable	Units	Control	Burn	Thin	Thin + burn	Control	Burn	Thin	Thin + burn
1-hour fuel	Mg/ha	0.5 ± 0.2	0.6 ± 0.2	0.4 ± 0.1	0.8 ± 0.3	+ 17 %	+ 103 %	+ 153 %	+ 5 %
10-hour fuel	Mg/ha	2.0 ± 0.7	2.8 ± 0.7	1.8 ± 0.6	2.3 ± 0.5	+ 148 %	+ 134 %	+ 352 %	+ 105 %
100-hour fuel	Mg/ha	2.2 ± 1.2	5.0 ± 1.5	5.5 ± 1.5	3.8 ± 1.0	+ 53 %	+ 11 %	+ 86 %	+ 40 %
1000-hour fuel sound	Mg/ha	4 ± 3	12 ± 5	13 ± 5	12 ± 4	+ 134 %	+ 31 %	+ 37 %	+ 59 %
1000-hour fuel rotten	Mg/ha	3 ± 3	8 ± 4	15 ± 7	8 ± 3	-62 %	-32 %	-25 %	+ 10 %
Litter	Mg/ha	26 ± 4	27 ± 3	26 ± 3	24 ± 2	+ 13 %	-6 %	+ 1 %	-14 %
Duff	Mg/ha	14 ± 5	22 ± 4	16 ± 3	11 ± 2	-17 %	-29 %	+ 41 %	+ 3 %
Canopy base height	meters	3.5 ± 1.0	2.4 ± 0.5	4.1 ± 0.7	3.1 ± 0.6	-2 %	+ 98 %	+ 3 %	+ 98 %
Canopy bulk density	kg/m^3	0.05 ± 0.01	0.06 ± 0.01	0.05 ± 0.01	0.07 ± 0.01	+ 10 %	+ 10 %	-3 %	-55 %
Basal area	m^2/ha	24 ± 5	24 ± 4	26 ± 4	25 ± 4	+ 27 %	+ 14 %	+ 5 %	-40 %
Density	trees/ha	529 ± 151	810 ± 191	527 ± 139	653 ± 167	-38 %	-56 %	-1 %	-64 %
Quadratic mean diameter	cm	27 ± 3	23 ± 2	28 ± 2	27 ± 2	+ 46 %	+ 55 %	+ 52 %	+ 53 %
Surface flame	meters	1.7 ± 0.1	1.9 ± 0.2	1.8 ± 0.2	1.9 ± 0.2	+ 7 %	+ 5 %	+ 17 %	+ 12 %
Total flame	meters	2.5 ± 0.7	3.9 ± 0.9	3.2 ± 0.9	5.3 ± 1.5	+ 9 %	-14 %	+ 50 %	-40 %
Torching index	km/hr	22 ± 12	13 ± 5	27 ± 8	17 ± 5	-15 %	+ 160 %	-12 %	+ 94 %
Crowning index	km/hr	65 ± 10	59 ± 7	64 ± 9	59 ± 9	+1 %	+ 6 %	+ 26 %	+ 91 %
Basal area mortality	percent	38 ± 10	47 ± 8	38 ± 7	48 ± 7	+ 1 %	+ 3 %	+ 23 %	+ 0 %
Density mortality	percent	51 ± 10	62 ± 7	50 ± 8	60 ± 7	+ 10 %	-8 %	+ 15 %	-3 %

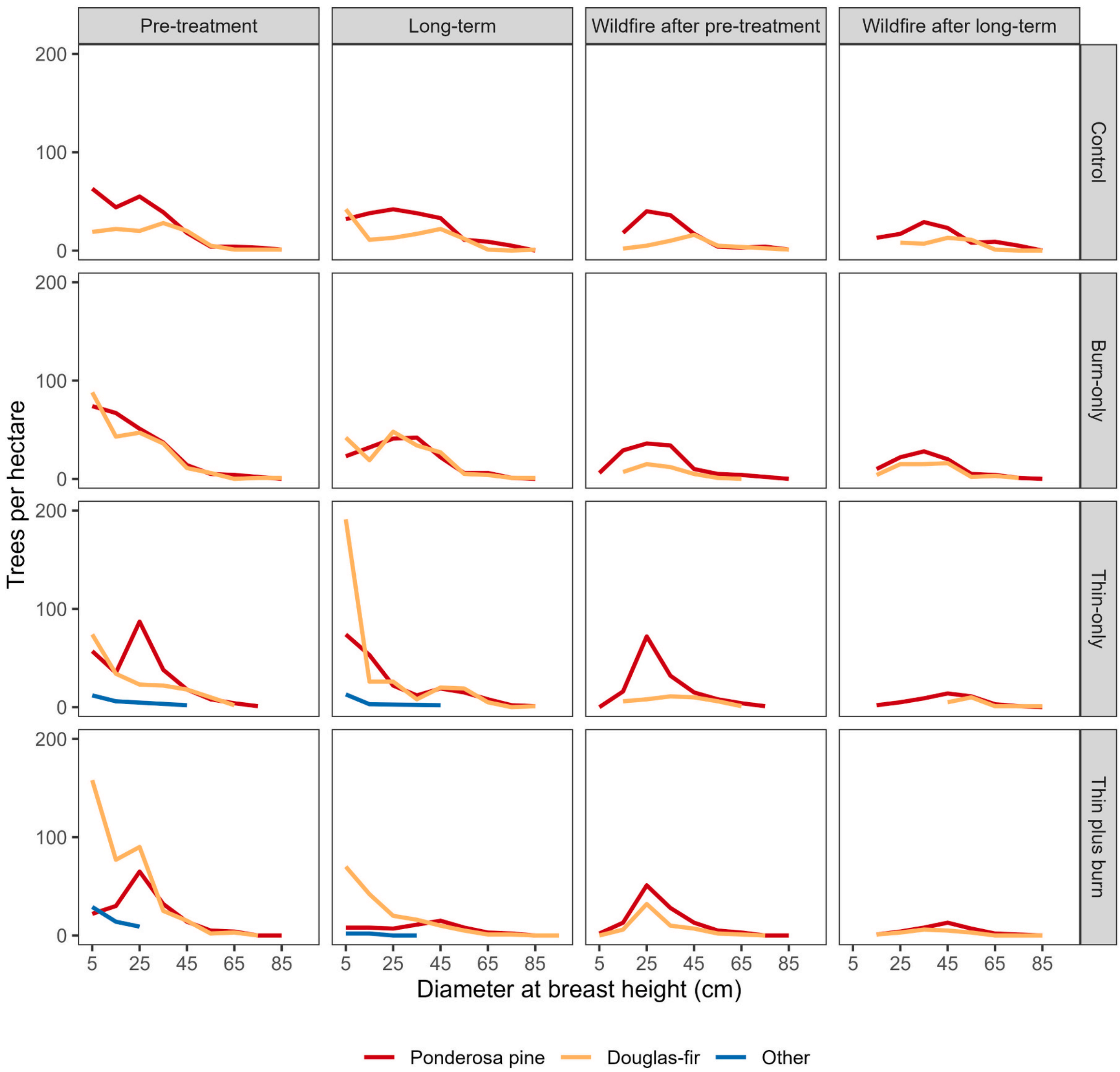

Fig. 1. Tree diameter distributions by period (column) and treatment type (row). Densities (trees per hectare) are aggregated in 10 cm diameter classes (0–10 cm, 10–20 cm, etc.), and drawn at the midpoints of the classes. 'Wildfire after pre-treatment' and 'Wildfire after long-term' conditions represent FOFEM-modelled tree survival following an FVS-FFE-modelled wildfire burning immediately after the pre-treatment sample period and the long-term sample period, respectively, in the 'moderate' fire weather condition.

treatment values (Fig. 5m-p, Fig. 7). Across treatment types, treatment intensity increased crowning index and canopy base height, whereas treatment intensity decreased litter, basal area, density, and canopy bulk density—albeit with wide confidence intervals of effects (Fig. 4f, h, i, k, l, and p). Surface flame lengths and total flame lengths were less affected by treatment intensity than other response variables (Fig. 4m-n).

3.3. *Question 3: Target thresholds of predicted fire behavior and severity*

Under 80th percentile weather conditions, modelled fire behavior met target thresholds for crowning index in most plots of all treatment types – including untreated controls, but thresholds were not met for surface flame length or basal area mortality (Table 3, Fig. 6). Thin plus burn treatment increased the number of plots meeting the torching index threshold (from 26 % pre-treatment to 53 % long-term) and the crowning index threshold (from 77 % pre-treatment to 94 % long-term) (Table 3). Burn-only treatments increased the number of plots meeting the torching index threshold (from 19 % pre-treatment to 41 % long-term) and modestly decreased the number of plots meeting the crowning index threshold (from 91 % pre-treatment to 79 % long-term) (Table 3). Thin-only treatments decreased the number of plots meeting the basal area mortality threshold (from 37 % pre-treatment to 21 % long-term) (Table 3). Pre-treatment values and weather had stronger effects than treatment for surface flame length and basal area mortality, while treatment, pre-treatment values, and weather affected torching index and crowning index (Fig. 6). Untreated units started with lower pre-treatment modelled basal area mortality values and higher torching indices than treated units (Fig. 6). Stand structure after wildfire was simulated under moderate weather conditions in long-term treated stands shifted live-tree diameter distributions to the right (i.e., toward larger-diameter trees) (Fig. 1, far right column) compared to stand structure after wildfire was simulated under moderate weather conditions in pre-treatment stands (Fig. 1, middle right column). These stand structure shifts were strongest for thin plus burn and thin-only treatments and weaker for burn-only and control stands.

4. Discussion

This study presents several insights about long-term treatment dynamics that are important for managing frequent-fire dry forests. Fifteen

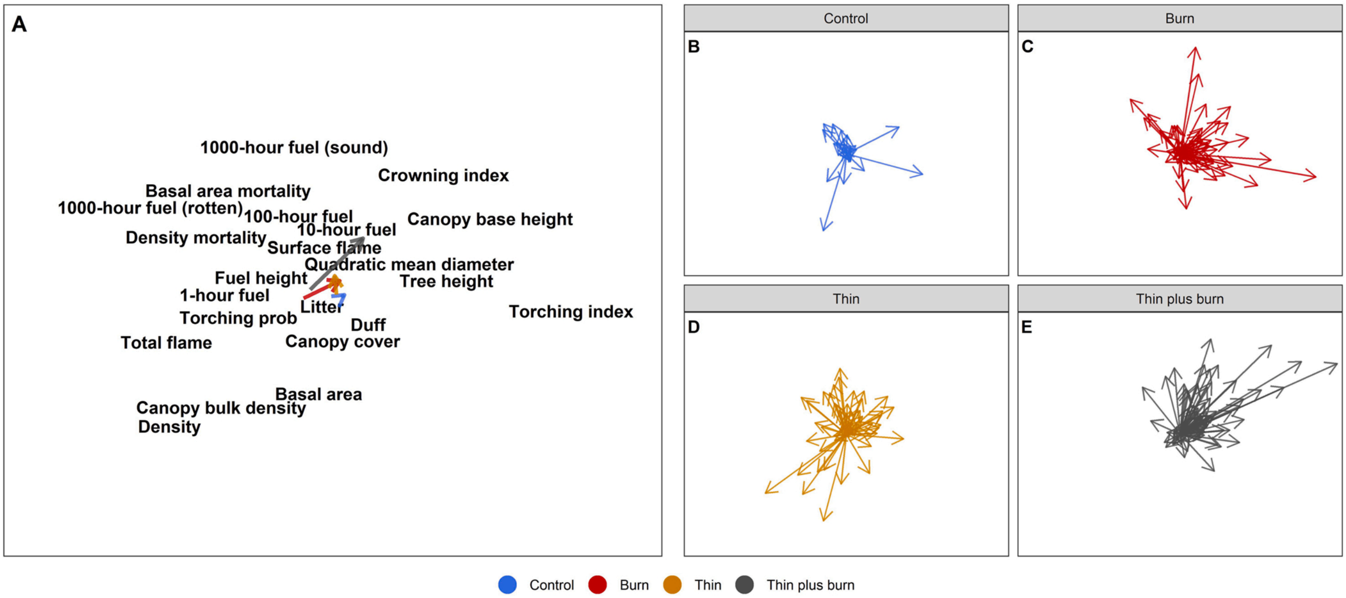

Fig. 2. Arrows representing change in location within NMDS ordination space from pre-treatment to long-term at the treatment level (A) and the plot level (B-E). Text locations in plot A represent weighted average scores of the response variables used in the ordination. In the plot-level ordinations (B–E), each plot was translated so that its pre-treatment location is shown at the centroid; this enables direct comparisons of the direction and magnitude of change. Separate pre-treatment and long-term ordinations with absolute scores of plots are shown in Fig. A4.

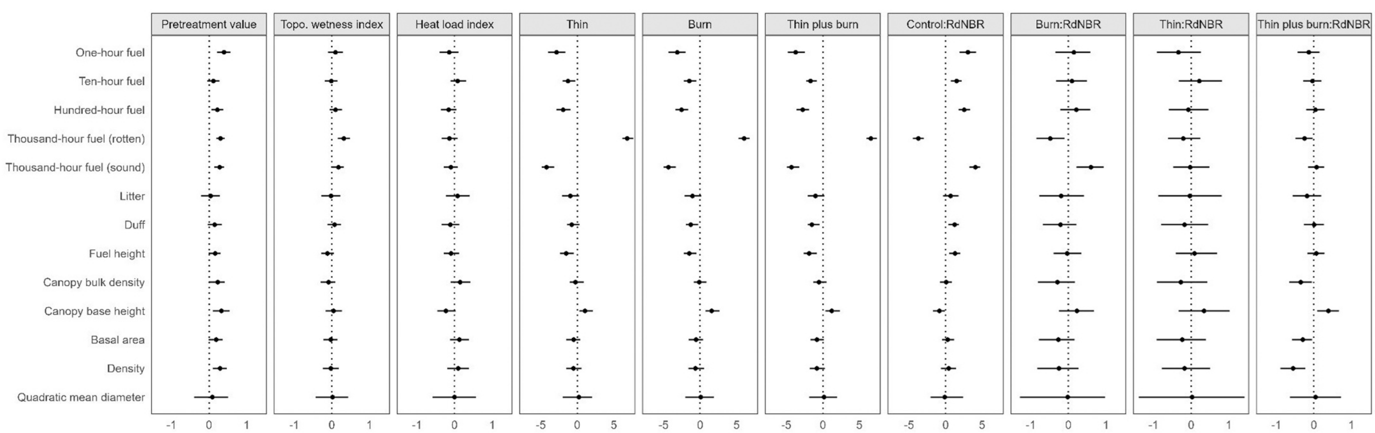

Fig. 3. GLMM coefficient estimates with 95 % confidence intervals, for field-measured response variables (y-axis) and faceted predictor variables. The x-axis represents coefficient estimates in terms of standard deviations. Confidence intervals fully right of 0 (dotted vertical line) denote significant positive correlations and intervals fully left of 0 denote significant negative correlations. Note different x-axis scales for continuous and categorical variables.

years after treatment, basal area, density, and potential for crown fire were reduced relative to pre-treatment conditions and un-treated controls. However, modelled surface flame length and wildfire-induced tree mortality were higher in the long-term than pre-treatment. Accounting for pre-treatment conditions and treatment intensity, two drivers that vary at a fine-scale, can help clarify long-term effects of treatments and illustrate where treatments of a given type may have the greatest longevity. Threshold analyses and evaluating stand-structure outcomes of simulated wildfire can provide context about management objectives that may not be apparent from statistical comparisons of treatment and control values.

4.1. On average, treatments reduce long-term crown fire potential but not surface fire potential or modelled fire severity

Overall, treatment type can drive important differences in long-term stand structure and fire potential, and thin plus burn (the most intense treatment type) exhibited the strongest effects. In thin-only treatments, the low torching index and canopy base height we found are likely due to ladder fuel recovering quickly as advanced regeneration of shade-tolerant trees grow in response to treatment (Fig. 1) (Hood et al., 2020). While this suggests greater potential for surface fire to transition to crown fire, the high crowning indices suggests that fuel in the upper canopy is well spaced and less likely to support active crown fire. Conversely, in burn-only treatments, relatively low crowning indices suggest that canopy fuel is less affected by prescribed burning (Agee and Lolley, 2006) and maintains greater potential for supporting active crown fire in the long-term than other treatments. However, long-term increases in torching indices and canopy base heights, and decreases in density, suggest that prescribed burning reduced understory vegetation and smaller tree saplings (Agee and Lehmkuhl, 2009), decreasing potential for surface fire to transition to crown fire. As expected, the thin plus burn treatment demonstrated benefits of both thin-only treatments (reducing canopy fuel) and burn-only treatments (reducing ladder fuel). As such, thin plus burn treatments exhibited the greatest long-term reductions of overall fuel profiles, as well as the most consistent response

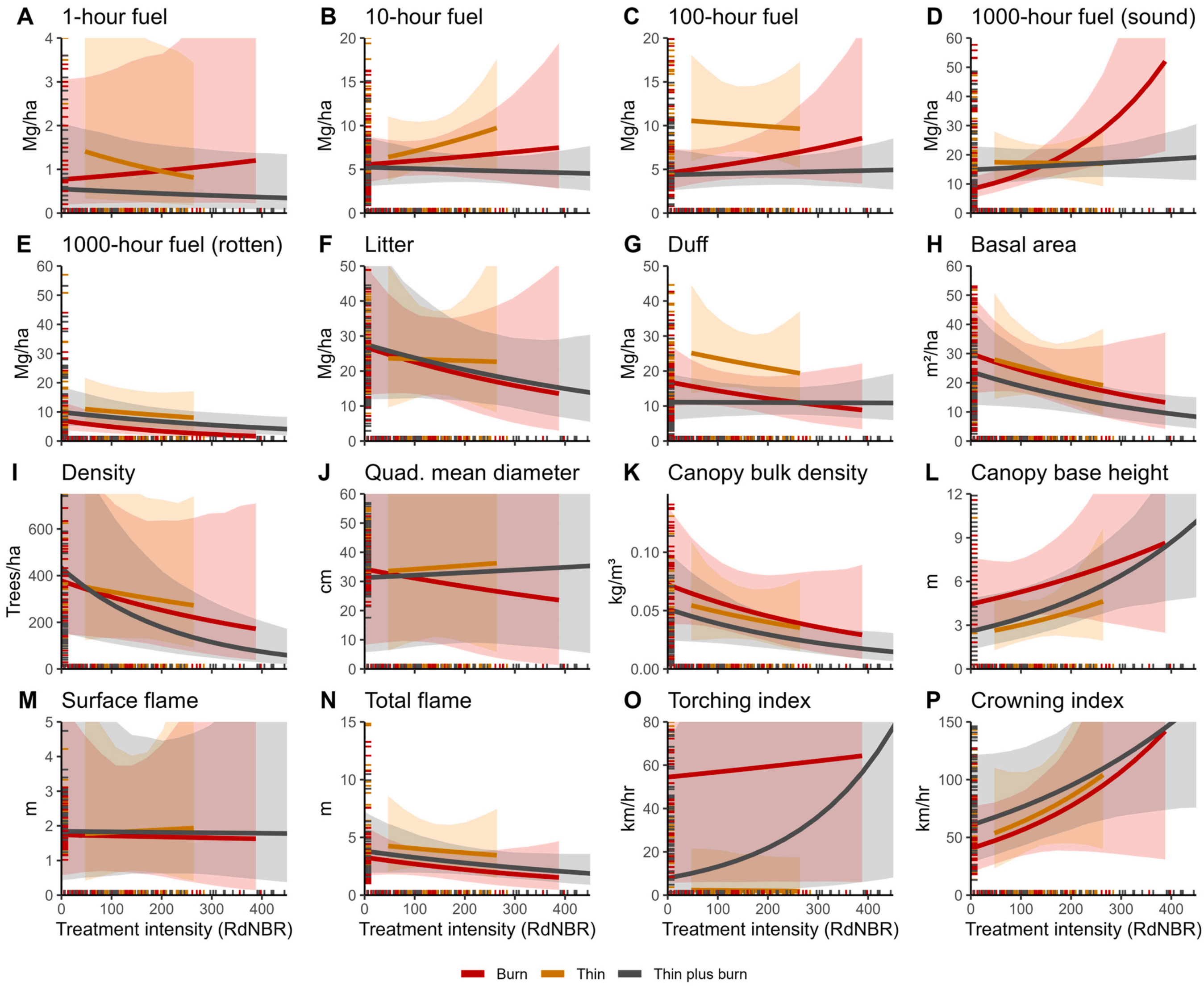

Fig. 4. Marginal effect plots of treatment intensity and treatment type on long-term response variables, with bootstrapped 95 % confidence intervals. All covariates not shown were held at average values. Rug plots show plot-level treatment intensity (RdNBR) values, colored by treatment category. Un-treated controls not shown due to low domain of RdNBR values on the x axes and large ranges on the y axes.

among plots within any treatment type.

In contrast to their effects on crown fire potential, none of the treatments resulted in long-term reductions in surface fire potential. Modest increases in modelled surface flame lengths across all treatments may relate to observed changes in surface fuel and to reduced wind friction within the thin plus burn treatment (Rebain et al., 2010), but the relative contributions of these observed changes to our FVS-FFE fire modelling results are unknown. Long-term increases in surface fuel may be partially due to factors external to treatments, as some increases in woody surface fuel and concurrent decreases in tree density (indicating tree mortality) were observed in all treatments including untreated control. Tree mortality contributes pulses of surface fuel as dead canopy fuel falls to the ground (Reed et al., 2023), and could be due to drought, succession, competition, and/or other local-scale disturbances across all stands (Kolb et al., 2016; Andrus et al., 2021). However, relatively large increases in surface fuel in thin-only units, and some sustained reductions in litter for burn-only and thin plus burn units, suggest that some short-term treatment effects on surface fuel (Schwilk et al., 2009) persisted for ~15 years (Busse and Gerrard, 2020).

Ponderosa pine and Douglas-fir trees that are > 50 cm in diameter are more likely to survive wildfires in dry forests (Harrod et al., 1999; Peterson and Ryan, 1986; Swezy and Agee, 2011), and low abundance of such trees in stands where treatments are applied (Fig. 1) constrains the potential for treatments to increase resilience to wildfire. However, both treated and untreated units are likely to become more resilient to wildfire over time as individual trees grow, barring a stand-replacing disturbance. For example, our study shows long-term increases in quadratic mean diameter, and slight long-term decreases in modelled basal area mortality under the null weather scenario. Multiple decades are likely required to grow substantial populations of large, highly fire-resistant trees. Wildfire resistance may develop more rapidly in treated units due to greater growth releases in remaining trees (Tepley et al., 2020). Continued reductions of surface fuels may be especially critical to buy time for large, fire-resistant trees to develop in stands are currently dominated by medium-diameter (e.g., 30–50 cm dbh) trees.

4.2. *Accounting for fine-scale drivers can improve detection of treatment effects*

The legacy of pre-treatment conditions is a common theme in restoration ecology (Thompson et al., 2018), and our work supports the assertion that pre-treatment conditions are important to consider in dry

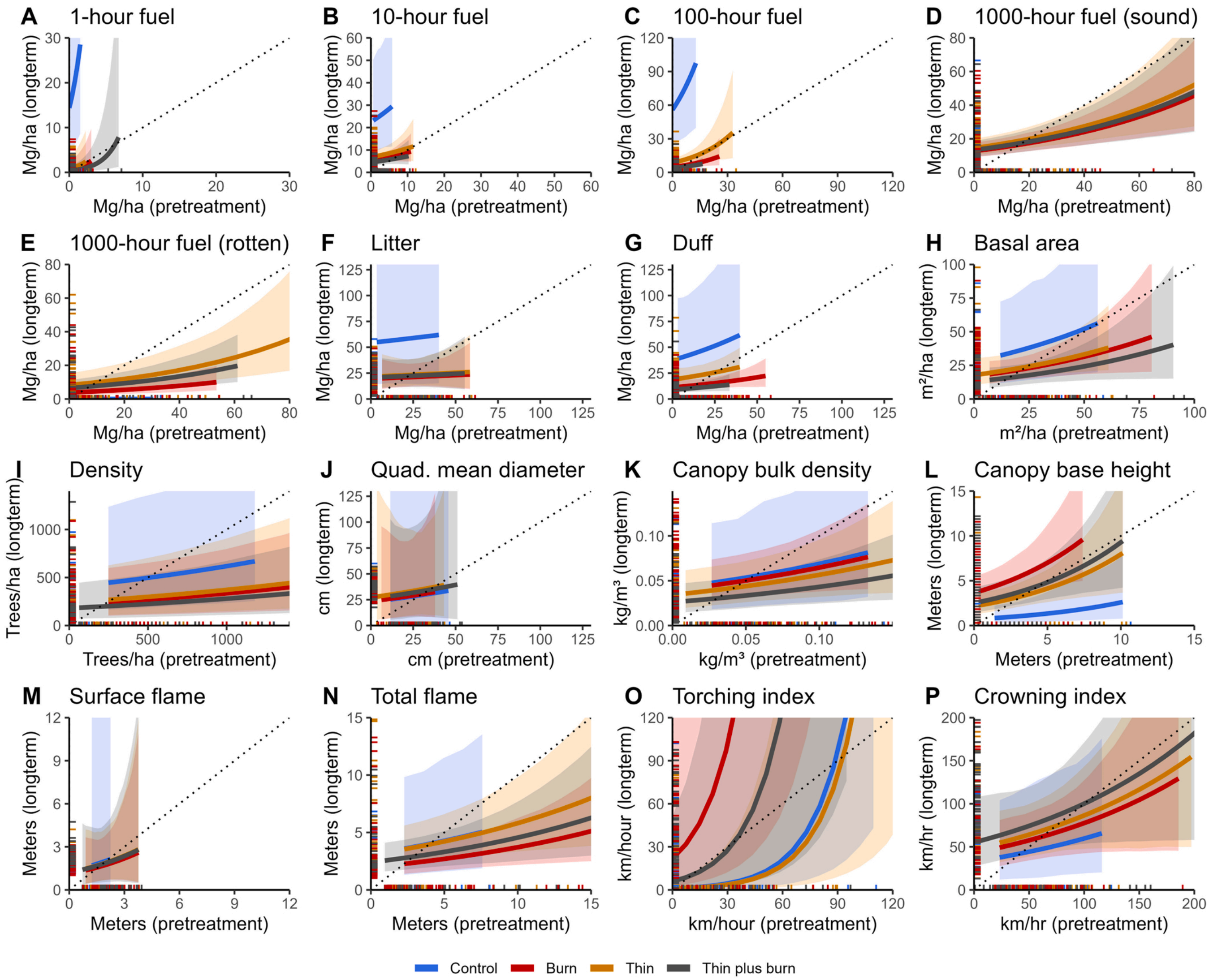

Fig. 5. Marginal effect plots of pre-treatment value and treatment type on long-term response variables, with bootstrapped 95 % confidence intervals. All covariates not shown were held at average values. Rug plots show plot level pre-treatment values (x-axis) and long-term values (y-axis) for the relevant variable, colored by treatment category. Dotted lines represents 1:1 relationship between pre-treatment and long-term values.

forest restoration (Jain et al., 2012; Zald et al., 2024). However, we generally detected larger effect sizes for treatment type than for pre-treatment conditions, suggesting that treatments can offset some of the constraints imposed by pre-treatment conditions. Future studies could sample and/or analyze within one treatment type, to remove the categorical variable of treatment type so that the ecological significance of pre-treatment values may be more directly compared with other continuous variables such as treatment intensity.

Although a treatment intensity-longevity tradeoff has been proposed (Jain et al., 2012), our findings do not support this tradeoff 15 years after treatment. Persistent effects of treatment intensity on stand structure, canopy fuel, and potential crown fire behavior likely relate to sparse long-term tree regeneration in our study area (Rossman et al., 2020). A treatment intensity-longevity tradeoff may be more likely in areas with rapid tree regeneration and/or crown responses to treatment, where treatments effects on stand structure and canopy fuel will diminish more rapidly (Ex et al., 2019; Jain et al., 2012; Zald et al., 2024). Future studies could benefit from consideration of the effect of treatment intensity across a wider productivity gradient, and use field data to more directly measure treatment intensity when data are available immediately following treatment.

For woody surface fuel, different effects of treatment intensity among treatment types likely reflects variable timing of tree mortality and subsequent fuel deposition. Short-term, activity fuel loads are greater in thin-only treatments than burn-only or thin plus burn treatments (Schwilk et al., 2009), which may reduce the ability of thin-only treatments to moderate wildfire severity immediately following treatment unless accompanied by surface fuel management (e.g., Stephens et al., 2009, Prichard and Kennedy, 2012). In burn-only and thin plus burn treatments, however, trees killed by burning will also eventually contribute pulses of surface fuel (Battaglia et al., 2008; van Mantgem et al., 2016). In burn-only treatments, the pattern of greater surface fuel in more intensely treated plots was stronger in larger fuel classes (Fig. 4a–d). Larger fuel classes are expected to have more lagged responses to treatment and disturbance as their lower surface area to volume ratios drive lower decay rates (Harmon et al., 2020). It is plausible that when we made our long-term re-measurements, burn-killed trees had dropped most of their fine woody fuel (1–100 h), and that these burn-induced inputs of fine woody fuel were at least partially decomposed. The burn-only treatments in our study were predominately low intensity (Agee and Lehmkuhl, 2009), so it is possible that high deposition of woody surface fuel was localized to small areas of higher severity burn. In thin-only treatments, the negative association of treatment intensity with most woody surface fuel

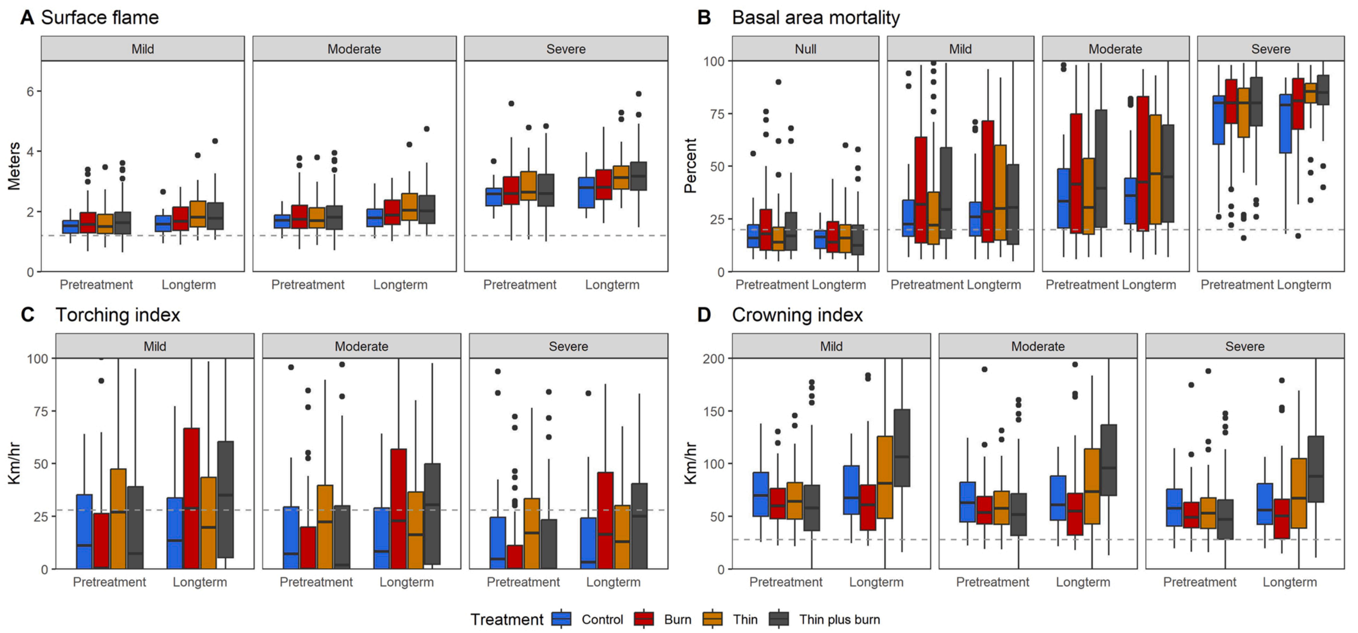

Fig. 6. Fire modelling results compared with thresholds (dotted lines) proposed in literature. In each boxplot, the center line represents the median response within a treatment type; a treatment is considered acceptable if the median response is below the dotted line for surface flame (A) and basal area mortality (B), or above the dotted line for torching index (C) and crowning index (D). Surface flame length threshold reflects likely low severity fire effects (Ryan and Noste, 1985; Alexander and Cruz, 2019), basal area mortality threshold is from Fire and Fire Surrogates study goals (McIver and Weatherspoon, 2010), torching and crowning index thresholds reflect 80th percentile wind gusts during the fire season near our study area.

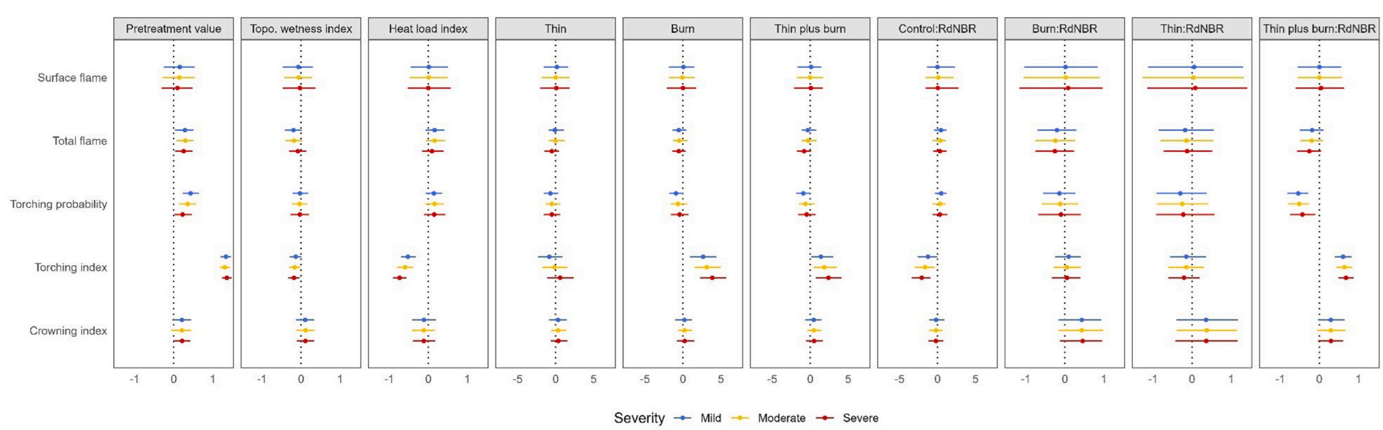

Fig. 7. GLMM coefficient estimates with 95 % confidence intervals, for modelled response variables (y-axis) and faceted predictor variables under multiple fire weather scenarios (colors). The x-axis represents coefficient estimates in terms of standard deviations. Confidence intervals fully right of 0 (dotted vertical line) denote significant positive correlations and intervals fully left of 0 denote significant negative correlations. Note different x-axis scales for continuous and categorical variables.

Table 3
Percentage of plots meeting proposed thresholds of fire behavior and effects, by specific metric and by number of metrics.

	Control		Burn-only		Thin-only		Thin + burn	
Metric	Pre-treatment	Long-term	Pre-treatment	Long-term	Pre-treatment	Long-term	Pre-treatment	Long-term
Surface flame	8 %	4 %	9 %	5 %	10 %	2 %	9 %	1 %
Basal area mortality	21 %	25 %	28 %	26 %	37 %	21 %	23 %	24 %
Torching index	25 %	25 %	19 %	41 %	40 %	40 %	26 %	53 %
Crowning index	96 %	88 %	91 %	79 %	94 %	87 %	77 %	94 %
0 of 4 metrics 'acceptable'	4 %	8 %	9 %	12 %	4 %	13 %	19 %	3 %
1 of 4 metrics 'acceptable'	58 %	58 %	59 %	47 %	46 %	42 %	49 %	43 %
2 of 4 metrics 'acceptable'	21 %	21 %	14 %	22 %	19 %	27 %	14 %	33 %
3 of 4 metrics 'acceptable'	17 %	8 %	16 %	16 %	27 %	15 %	17 %	21 %
4 of 4 metrics 'acceptable'	0 %	4 %	3 %	3 %	4 %	2 %	1 %	0 %

components could be caused by the decomposition of activity fuels, in combination with more intense thinning treatments having lower residual crown biomass and thus reduced ongoing contributions of woody surface fuel (Johnston et al., 2021).

The importance of fine-scale predictor variables is further supported by our GLMMs often predicting larger treatment-associated reductions in long-term wildfire potential than indicated by treatment-level summaries. The units sampled during our long-term re-measurement do not span the same productivity gradient for all treatments, so differences between GLMM predictions and summary level results may reflect GLMMs controlling for some of the variance in pre-treatment conditions and productivity. Specifically, the sampled control unit is at a lower elevation and therefore in a less productive area of the study area than the two control units that burned in the 2012 wildfire. Therefore, more productive areas were more likely to be represented in other treatments in the long-term sample period. This productivity difference between treated stands and un-treated control stands may reduce estimates of long-term effects in treated stands relative to untreated stands, especially if more productive stands respond more quickly to treatment (Jain et al., 2012).

4.3. Broadening assessments of long-term treatment efficacy and future research directions

Threshold analyses can add ecological and management context to studies of fuel treatment outcomes, but have limitations which necessitate they are used in conjunction with other approaches. Managers may plan for different weather scenarios across varying contexts, and different thresholds of acceptability for potential fire behavior and/or different metrics of fire behavior altogether may be warranted in different ecological and societal contexts (Stephens et al., 2020; North et al., 2021). The thresholds we used reflect FFS goals of restoring low severity fire regimes in treated stands (McIver and Weatherspoon, 2010), but managers could specify different threshold targets when goals are to mitigate potential for severe wildfire across broad landscapes with limited resources. For example, Ager et al. (2014) used a 2.4 m surface flame length threshold to characterize stands where severe wildfire effects are likely. In addition, stand structure after modelled wildfire in our long-term treatment units is large-tree dominated and may be compatible with principles of fire resistance (Agee and Skinner, 2005), although our treatments did not meet the target objectives of tree basal area survival set forth in the FFS guidelines. Despite the clear sensitivity of threshold analysis to the selection of thresholds and threshold metrics, threshold analysis may provide context about management goals that statistical comparisons of treatment and control values cannot provide alone.

Ongoing improvements in fire modelling methods can further inform threshold analyses of fuel treatment effectiveness. FVS-FFE and similar Rothermel-based fire behavior models can under-predict some aspects of fire behavior, due to poor representation of surface-to-crown fire transitions, spotting, and spatial heterogeneity (Parisien et al., 2019). In addition, FOFEM does not account for crown fire or delayed tree mortality (Lutes, 2020), and thus actual fire effects may be more severe than our modelled outputs. Therefore, models may not represent the relative effects of treatment accurately where those treatments substantially alter canopy fuel loads. FVS-FFE and FOFEM are useful because they are widely used and well-documented tools (Rebain et al., 2010; Lutes, 2020) with strengths and shortcomings that are well-known within the fire science and management communities. Ongoing improvement to widely-used fire modelling tools such as physics-based fire models (e.g., Hoffman et al., 2016; Parsons et al., 2017; Ritter et al., 2022; Ritter et al., 2023) may enable more precise expectations of fire behavior and effects, and thus more precise threshold analyses.

5. Conclusion

Understanding long-term fuel treatment effects is crucial for scheduling effective, efficient, and context-dependent treatment maintenance (Kolden, 2019; North et al., 2021), which can align treatment application with restoration goals (Laughlin et al., 2023). Our findings suggest that treatment-related reductions in basal area and potential for crown fire can persist for at least 15 years, especially where treatment intensity is greater. Maintenance treatments after this period can address potential for high surface flame lengths and resultant tree mortality in subsequent wildfire, though wildfire under moderate weather conditions may result in stand structure that meets restoration target objects. Including fine-scale drivers in analyses can yield insights about long-term treatment efficacy not apparent when aggregating plots within stands or within treatment types. Additionally, threshold analyses of long-term treatment effectiveness provided context about the ecological and management outcomes of treatments. Future studies more specifically designed to explore processes at fine spatial and temporal scales will likely improve insights on fuel treatment longevity and efficient treatment maintenance planning.

CRediT authorship contribution statement

Don C. Radcliffe: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Jonathan D. Bakker:** Conceptualization, Methodology, Writing – review & editing, Visualization, Funding acquisition, Project administration. **Derek J. Churchill:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Ernesto C. Alvarado:** Conceptualization, Writing – review & editing, Funding acquisition. **David W. Peterson:** Methodology, Investigation, Writing – review & editing. **Madison M. Laughlin:** Methodology, Investigation, Writing – review & editing. **Brian J. Harvey:** Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data analyzed in this study are available on Zenodo: https://doi.org/10.5281/zenodo.10215266

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Appendices A and B. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2023.121594.

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