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Thinning with follow-up burning treatments have increased effectiveness at reducing severity in California's largest wildfire

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ABSTRACT

In historically frequent-fire forests of the western US there has been an increase in stand-replacing wildfire that is well outside of the historical range of variability (HRV), leading to forest loss at unprecedented scales. As a result, forest managers are increasingly applying forest management treatments designed to reduce the probability of stand-replacing wildfire, by reducing the tree densities and woody debris that have accumulated after more than a century of fire exclusion. Although these treatments have generally been shown to be effective, increasingly warm and dry conditions may challenge the efficacy of these treatments. We compared fire severity (% basal area mortality) in areas that had mechanical thinning with a follow up fire treatment (broadcast burning or pile burning), mechanical thinning without a follow up fire treatment, and untreated areas in California's largest wildfire to date, the 2021 Dixie Fire. We found that the probability of stand-replacing wildfire (defined here as 100 % basal area mortality) was highest on large fire growth days, and lowest in areas that were treated with mechanical thinning and fire; mechanical thinning treatments with no follow up fire treatment did not differ from untreated areas. Where stand-replacing wildfire did not occur, percent basal area mortality was reduced in both the mechanical plus fire treatment and the mechanical-only treatment, both of which were characterized by larger trees and lower densities. This suggests that the addition of the fire treatment is critical for reducing fire severity under more extreme burning conditions, but that the mechanical-only treatments can still be effective under milder burning conditions. We also found that the majority (93 %) of our treated plots were within the HRV for tree density prefire. Postfire, 79 % of the plots with a mechanical thinning plus fire treatment remained within HRV target conditions. In contrast, 48 % of the mechanical thinning only plots, and 58 % of untreated plots, had no live trees. This work contributes to a growing body of evidence that forest treatments to reduce both tree densities and surface fuels are critical for reducing fire severity and forest loss.

1. Introduction

The increase in both area burned and fire severity in the western US in recent years has been linked with increasing fuel aridity, driven primarily by warmer temperatures (Parks and Abatzoglou, 2020). In historically frequent-fire forests of the western US, fuel build up has also been identified as a driver of increased fire severity (Steel et al., 2015), where over a century of fire exclusion has enabled significant increases in tree densities and woody debris on the forest floor (Parsons and DeBenedetti, 1979). Forest managers are increasingly implementing forest treatments aimed at reducing fuel loads and restoring forest structures to reduce the risk of extensive high severity fires (California Wildfire and Forest Resilience Task Force, 2022), which have recently been occurring at scales that are outside of the historical range of variation for frequent-fire forest types (Steel et al., 2018; Williams et al., 2023). Increasingly severe wildfires in frequent-fire forest types can

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have substantial effects on biodiversity, recreational values, timber production, and soil and water quality (Dove et al., 2020; Maestrini et al., 2017; Miller and Safford, 2020).

The forest management treatments commonly used to reduce the risk of severe fire include mechanical thinning and prescribed fire, which are sometimes used in combination (Stephens et al., 2012a). Limited days with appropriate weather and fuel conditions for burning, staffing and other logistical constraints make prescribed fire incredibly challenging to implement (Kolden, 2019; Schultz et al., 2019; Striplin et al., 2020), leaving many forest managers to turn to mechanical thinning treatments (e.g. tree removal by heavy equipment or by hand crews using chain saws) as a more feasible fuel reduction treatment option. Treatments strictly aimed at fuel reduction are often characterized as "thinning from below" treatments, where smaller trees that can act as ladder fuels are targeted for removal. There is increasing recognition that additional removal of some larger trees is necessary to adequately reduce overall tree density and to meet broader structural restoration objectives for wildfire habitat and drought resilience (North et al., 2022; Stephens et al., 2021; Young et al., 2017). Forest restoration projects therefore often target a wider range of trees for removal, which can include larger, more merchantable trees that may help offset the cost of treatments. In addition to reducing the risk of high severity fire, forest treatments are also implemented to improve wildlife habitat, shift species composition and restore forest structure, with the goal of increasing resilience to drought and insect outbreaks (Fettig et al., 2022; Young et al., 2017).

A significant body of research has supported the efficacy of fuels treatments and forest restoration in moderating fire behavior, particularly when mechanical thinning is followed by prescribed fire (Fulé et al., 2012; Pollet and Omi, 2002; Prichard et al., 2020; Safford et al., 2012, 2009; Taylor et al., 2022; Tubbesing et al., 2019). While mechanical thinning can help reduce ladder fuels and increase tree crown separation, it does not remove surface fuels, which are a primary driver of wildfire spread and intensity (Scott and Burgan, 2005). Moreover, depending on the specific method of tree removal, mechanical thinning can increase surface fuels for some time after treatment due to slash creation (Stephens et al., 2012a), or through the creation of piles to be burned in the future. Following up mechanical treatments with broadcast burning or pile burning can help reduce surface fuels and any additional fuels that are created during the mechanical treatment.

Because these forest restoration treatments have been shown to be generally effective, some have claimed that fuel treatment effectiveness no longer merits investigation (Safford et al., 2012). However, wildfire impacts in treated areas remain of interest for two key reasons. First, there is concern that the warming climate may be reducing the efficacy of fuels treatments. Evidence already suggests that treatments are less effective at moderating fire behavior under extreme fire weather conditions (i.e. higher temperatures, lower relative humidities, etc. (Lydersen et al., 2014; Prichard et al., 2020)). In recent years the frequency of more extreme burning conditions is on the rise (Parks and Abatzoglou, 2020), to the extent that two recent wildfires in California's Sierra Nevada have crossed the Sierra Crest for the first time. Examining fuels treatments in recent large wildfires is still warranted, both to track and anticipate shifts in their efficacy, and to adapt future management actions to meet these changing conditions.

Second, most research attention around forest treatments and wildfire is focused on the ability of treatments to reduce fire severity (Fulé et al., 2012; Lydersen et al., 2014; Pollet and Omi, 2002; Prichard et al., 2020; Stephens et al., 2012b). Yet how a wildfire interacts with treatment to influence postfire stand trajectories is less well understood. With the recent increases in fire activity, there are rising calls to work *with* wildfire, leveraging beneficial effects where possible (Larson et al., 2022; Meyer et al., 2021; Prichard et al., 2021). Indeed, in some areas, wildfires can have similar restorative effects on forest vegetation as broadcast burning, thereby acting as either an initial fuels reduction treatment or a maintenance treatment (Chamberlain et al., 2023; Collins et al., 2016; Jeronimo et al., 2019; Low et al., 2023). Understanding how wildfires interact with fuel reduction treatments to impact postfire stand condition is critical for understanding the conditions under which wildfires can enhance or degrade forest conditions relative to restoration targets.

In this study, we examine the efficacy of forest restoration treatments in reducing the probability of stand-replacing wildfire (defined here as 100 % basal area mortality) and in moderating overall fire severity, in the 2021 Dixie Fire. We also examine how wildfire interacted with those treatments to influence postfire stand conditions. As California's largest wildfire to date (389,837 ha), the Dixie Fire serves as a suitable case study due to its size, heterogeneous burning conditions, and abundance and variety of pre-fire fuels reduction treatments, which collectively represent a spectrum of common conditions in western montane mixed conifer forest types. We sampled mechanical thinning treatments that targeted the removal of both smaller ladder fuels for fuel reduction goals and some larger trees for broader forest structure related goals. Some of these areas additionally had either a broadcast burn or pile burning following the thinning treatment. All treatment areas were paired with untreated areas. Specifically, we asked:

1) *What was the variation in prefire forest structure across treated and untreated areas?*
2) *What was the variation in basal area mortality and crown scorch across treated and untreated areas?*

3a) *How do prefire treatment, weather and topography influence the probability of stand-replacing wildfire?*
   3b) *Where stand replacement did not occur, what drove the variation in fire severity?*

4) *How closely did prefire stand structure match desired conditions, and how did those conditions interact with the wildfire to shape post-fire conditions?*

2. Methods

2.1. Study area

The Dixie Fire burned primarily on the Plumas and Lassen National Forests in northern California (Fig. 1). Our sampling sites ranged from 1537-m to 2248-m in elevation and were mostly in yellow pine and mixed conifer forest types, which included ponderosa pine (*Pinus*

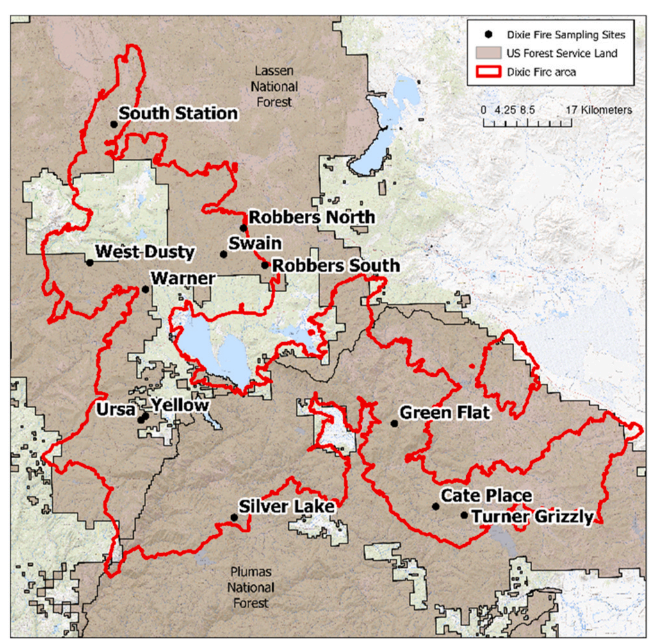

Fig. 1. Site sampling locations in the Dixie Fire.

ponderosa Lawson & C. Lawson), sugar pine (*Pinus lambertiana* Douglas), Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.), white fir (*Abies concolor* (Gordon & Glend.) Hildebr.), incense-cedar (*Calocedrus decurrens* (Torr.) Florin), and Pacific Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco *var. men-ziesii*), with a lesser component of black oak (*Quercus kelloggii* Newb.). Fires in these forest types were historically frequent, occurring at mean intervals of 11–16 years and resulting in predominantly low-moderate severity fire effects (Safford and Stevens, 2017). Roughly 17 % of surveyed plots were in red fir forests, which were dominated by red fir (*Abies magnifica* A. Murray bis), white fir and lesser components of the pine species, including two sites with lodgepole pine (*Pinus contorta* Louden *ssp. murrayana* (Grev. & Balf.) Critchf.). The fire return interval in red fir was 33–40 years (Van de Water and Safford, 2011). The climate is characterized as Mediterranean, with cool, wet winters and warm, dry summers.

The Dixie Fire ignited on July 13, 2021, and quickly spread to encompass 389,837 ha (963,309 acres) before it was contained on October 25, 2021 (CAL FIRE, 2021a). Heavy fuel loads and dense forest conditions, combined with hot weather, high wind speeds, exceptionally dry vegetation, and steep terrain, contributed to large fire growth, making the Dixie Fire the largest fire in California history to date. Approximately 45 % of the burned area (173,437 ha) experienced high severity fire effects (i.e., more than 90 % of the prefire basal area was killed), most of which occurred in large contiguous patches (RAVG, 2021).

2.2. Study design

To select sampling sites, we queried the US Forest Service (USFS) Forest Activity Tracking System (FACTS) database and selected treatment units where treatments occurred between 2001 and 2020. We selected mechanical treatments that were designed to restore forest structure and composition, and to facilitate reintroduction of low severity, frequent fire. For the Dixie Fire, these included the following activities, which we classified as mechanical treatments: commercial thin, group selection, compacting/crushing of fuels, piling of fuels (hand or machine), precommercial thin. These occurred singly or in combination, but most sites included removal of smaller trees that can act as ladder fuels (<25.4 cm (10”) diameter at breast height (DBH)) and larger trees (25.4 cm - 76.2 cm (30”) DBH) to meet density and structural targets. We lumped mechanical treatment types of varying intensities due to small sample size and lack of access to more detailed treatment information. These sites were classified as Mechanical only. We also selected mechanically treated sites that were followed up by a fire treatment (broadcast burning or pile burning) to reduce surface fuels which were classified as Mechanical + fire. We defined Untreated areas as having had no active management since 2000; most of our Untreated areas had no documented management history, with the exception of three sites that had some sanitation cuts between 1967 and 1998, which were generally single tree selection (Table 1). We selected treatment units that were at least 81 ha (200 acres) and that were situated where the boundary between untreated and treated areas did not cross features that could function as a fire break (e.g., a road, riparian area, trail). Access and safety were also considered, resulting in twelve treatment sites (Fig. 1, Table 1).

Within each study site, we installed forest inventory plots (i.e., modified USFS Common Stand Exam plots (USDA Forest Service, 2007)) inside and outside of the treatment areas. Plot locations were selected in relation to transects that began in the untreated area and moved into the treated areas, which were installed as part of a separate but related project on fuel treatment effectiveness, following methods from Safford et al. (2012) (note: data specific to the transects are not presented here but are included in Saberi et al. *in prep*; details on the transects are presented here to describe plot installation only). We installed 1–4 transects at each site, where each transect had at least one associated forest inventory plot inside the treatment area and one outside the treatment area. Of the 1–4 transects per site, we selected 1–2 transects where we installed four additional plots around the transect in the untreated area, and four additional plots in the treated area. This design resulted in variable numbers of plots per site (Table 1). In addition to relying on spatial data from the FACTS database to determine previous management, field crews inspected sampling areas to confirm the boundaries were accurate by looking for cut stumps and adjusting the transect and plot locations as needed. We initially installed 33 Mechanical + fire, 52 Mechanical-only and 86 Untreated plots for a total of 171 plots (Table 1). Because all treated plots were ≤38 % slope, we later excluded seven untreated plots that occurred on >38 % slopes, resulting in a total of 164 candidate plots. All sites were occupied by mature, Sierra Nevada mixed conifer or red fir forest types prefire.

Table 1
Treatment sites with treatment type, year of last treatment, the number of transects and forest inventory plots. In some cases, the treatments occurred up to two years apart at a given site so the last treatment is shown as a range (note: West Dusty had one plot that was re-treated 13 years after the initial 2001 treatment). For Mechanical + fire plots, the year of last treatment is the fire treatment. Note, transect data are not included in this study but the number of transects is shown here to detail the sampling design.

Site	Treatment class	Year of last treatment	Number of transects	Number of plots	
				Treated plots	*Untreated plots*
Cate Place	Mechanical-only	2004	2	6	6
Green Flat	Mechanical + fire	2003–2005	1	11	9
Robbers North	Mechanical + fire	2009	1	5	5
Robbers South	Mechanical + fire	2009	1	5	5
Silver Lake	Mechanical-only	2006	4	12	12
South station	Mechanical + fire	2010	1	5	5
Swain	Mechanical-only	2016–2018	1	7	10
	Mechanical + fire	2020	1	3	0
Turner Grizzly	Mechanical-only	2016	3	10	11
Ursa	Mechanical-only	2019	2	2	2
Warner	Mechanical + fire	2012	0	4	6
West Dusty	Mechanical-only	2001–2014	1	5	5
Yellow	Mechanical-only	2017–2019	2	10	10
Total:			*23*	*85*	*86*

2.3. Field measurements

At each 0.04 ha (~0.1 ac) circular plot, we measured all overstory trees (> 10 cm DBH), recording species, live/dead status (differentiating prefire snags, or trees that were dead before the fire, from fire-killed trees), DBH, tree height and percent crown damage (the proportion of the crown where needles were either consumed (torched) or killed but not consumed (scorched)). Trees were designated as prefire snags based on a qualitative assessment of the bark and branches; prefire snags typically are missing much greater proportions of bark and branches than trees live at the time of fire. It is possible some prefire snags were incorrectly classified as prefire live trees, and vice versa, but we believe that number to be small due to clear differences in prefire snag vs. prefire live tree characteristics.

2.4. Forest structure variables

We calculated total tree density and basal area per plot. We also classified each species by shade tolerance, (shade intolerant: ponderosa pine, Jeffrey pine, sugar pine; shade tolerant: white fir, red fir, incense cedar, Douglas-fir), and calculated tree density and basal area by shade tolerance. We calculated quadratic mean diameter (QMD), which is the diameter of the tree with average basal area. It is calculated as the square root of the arithmetic mean of squared diameters (Curtis and Marshall, 2000) and is commonly used as an indicator of forest structure or developmental stage. Stands with larger QMDs generally indicate a more advanced stage of development characterized by larger trees.

We also used relative Stand Density Index (relSDI) to assess stand condition (Reineke, 1933). This metric considers tree size and density and provides a relative measure of inter-tree competition or crowding. We used the summation method to calculate the relSDI (Long and Daniel, 1990), which is expressed as a percentage of the maximum Stand Density Index, where the maximum value is determined by forest type and local conditions. We followed methods described in North et al. (2022) to classify our plots into forest types based on basal area by species and then assigned maximum SDI values for each (ranging from 902 to 1112 trees ha^{-1}).

For all forest structure variables, we calculated prefire and postfire conditions. Prefire structure was reconstructed by summing both live and fire-killed trees but excluding prefire snags.

2.5. Consideration of desired conditions

Because HRV has been commonly used to define desired conditions, we classified prefire stand structure in relation to the Historical Range of Variation (HRV) to evaluate wildfire effects in forests that were within the HRV compared to those that were outside of the HRV prior to the fire. We also classified postfire stand structure in relation to HRV to evaluate how wildfire interacted with treatment to influence postfire conditions. We used HRV targets based on historical stand reconstructions from throughout the Sierra Nevada region, which suggest a basal area of 21 m^2ha^{-1} to 54 m^2 ha^{-1} and tree density of 60 ha^{-1} to 328 ha^{-1} (Safford and Stevens, 2017). Plots were classified as being in *above HRV within* HRV or *below* HRV for both basal area and tree density separately; for tree density, there were only two plots *below HRV* prefire, so they were lumped into *within HRV*. For postfire HRV classifications, we separated *within HRV* from *below HRV*, and additionally identified plots where there were *no live trees* postfire.

We also compared our relSDI with two established relSDI thresholds: the established threshold of "low competition" (34 % of maximum SDI), and the relSDI for historical reference conditions (defined as 23–28 %; (North et al., 2022)). We also explored how postfire conditions compared to management goals to shift stands toward more open conditions that are characterized by fewer, larger trees, and that are pine-dominated (North et al., 2009), by exploring shifts in QMD as well as shifts in basal area and tree density by shade tolerance.

2.6. Weather and topographic variables

For the Dixie fire, we created a fire progression map using MODIS fire detection data following established protocols (Parks, 2014). We then assigned a burn date to each plot, and for each date extracted the following weather variables from GridMET (Gridded Surface Meteorological Data (Abatzoglou, 2013)): minimum and maximum temperature, minimum and maximum relative humidity, vapor pressure deficit, 1000 hour fuel moisture, Energy Release Component (ERC) and Burning Index (BI). GridMET has a horizontal resolution of ~4-km and captures mesoscale features in weather across a landscape but does not capture finer-scale weather-terrain details that may be present in complex terrain. Both BI and ERC were derived from the US National Fire Danger Rating System (Cohen and Deeming, 1985) for a common fuel model (G – dense conifer stands with abundant dead surface fuels). These metrics integrate weather and fuel characteristics, where higher indices reflect the potential for increased fire behavior. BI reflects fire-line intensity and is more strongly influenced by wind speed, whereas ERC is more related to the seasonal drying of available fuel, including the larger diameter fuels that are found in forested ecosystems.

We also explored two proxies for extreme fire behavior. We tested the total hectares burned across the entire wildfire on the date the plot burned. But, since the fire was so large, there could be large growth in total area that was spread across multiple flaming fronts, so we also tested the perimeter to area ratio of area burned on the date the plot burned. To examine the effect of topography, we extracted percent slope and aspect from 10 m digital elevation models. Aspect was cosine transformed into "northness" for analyses.

2.7. Statistical analyses

We tested differences in forest structure variables by the three-class treatment variable (Q1), using generalized linear mixed models (GLMMs). For prefire tree density (trees ha^{-1}), we used a negative binomial distribution, and for the remaining prefire forest structure variables (basal area, QMD and relSDI) we used a Gaussian distribution. All models had a transect identifier nested within site as the random effect and were run using the glmmTMB package (Brooks et al., 2017) in R (R Core Team, 2023). We then used the emmeans package (Lenth, 2023) to calculate pairwise comparisons within the treatment variable using Tukey contrasts. Basal area was square root transformed to meet assumptions of normality.

To explore differences in fire severity by treatment (Q2), and to model the influence of topographic, weather, forest structure, treatment and time-since-treatment on fire severity (Q3), we used percent basal area mortality as our response variable. Because percent basal area mortality was heavily one-inflated due to 100 % mortality at many plots, we used a two-stage modelling approach. First, we used GLMMs with a binomial distribution to explore the drivers of stand-replacing wildfire (defined here as 100 % basal area mortality) versus non-stand replacing wildfire (<100 % mortality). High mortality that is less than 100 % can still result in stand replacement, depending on how a stand is defined (e.g., the USFS defines a forested area as having >10 % tree cover (USDA Forest Service, 2023)), but here we are using the term to refer to complete loss of overstory trees, to capture the drivers of the extreme end of the high severity fire effects (which generally includes 75–100 % basal area mortality (Miller et al., 2009)). We then explored GLMMs with a beta distribution on a subset of the data that was <1 (<100 % basal area mortality), adding 0.001 to zeros in the dataset to meet the assumptions of the beta distribution. All analyses were conducted at the plot level, with the transect identifier nested within site as the random effect.

One of the sites (South Station; 10 plots) burned with very high mortality on one day (September 10th) with extreme weather conditions for our dataset that are not generally linked with severe fire weather, including maximum relative humidities of 100 %, a BI of 0 and ERC of 51 (substantially lower than the other burn days). We hypothesize that this was the result of a frontal passage that occurred on that day and brought erratic winds with gusts up to 46 mph (CAL FIRE, 2021b), and that the plots burned prior to the onset of rain. Since this represented unique conditions at just one site, we excluded that site from further analysis. After removal of this site, there were 28 Mechanical + fire plots, 52 Mechanical-only plots and 74 Untreated plots for a total of154 plots in the binomial model predicting the probability of stand-replacing wildfire (Q3a).

For the beta models assessing the drivers of percent basal area mortality in the absence of stand replacing fire, there were 83 plots that did not experience stand-replacement. However, 17 of these plots lacked a paired match in both the untreated and treated areas within a site (for instance, all plots within the untreated area burned with 100 % basal area mortality). We found large relative differences in percent basal area mortality between treated and untreated areas across sites and were concerned that these 17 unpaired plots would skew the results. We therefore excluded those 17 plots from this analysis, leaving 66 for the beta model analyses (20 Mechanical + fire, 919 Mechanical only and 27 Untreated).

To build comprehensive models for Q3a and Q3b, we first examined univariate models for all variables of interest (treatment, weather, topography, forest structure variables) and considered any that were significant at $p < 0.1$ to be candidate variables for a comprehensive model (Hosmer and Lemeshow, 2000). For variables that were moderately to highly correlated *(Pearson correlation coefficient > 0.5)*, we selected the final candidate variable that had the lowest Akaike information criterion (AIC). AIC is the log-likelihood of the model (a measure of overall model fit) adjusted for the number of parameters in the model. We scaled and recentered all predictors in the comprehensive model. We then examined models with all candidate variables included, and removed those that were no longer significant when their inclusion did not improve model fit by at least two AIC units.

We tested how well prefire HRV classifications alone predicted mortality for Q4, using the same two-stage modelling approach as for Q2 and Q3 (binomial to predict stand-replacing wildfire and beta to predict the percent of basal area mortality on plots that did not experience stand replacement).

3. Results

3.1. Variation in forest structure across treatments

Prefire tree density was roughly three times lower in both Mechanical-only plots and Mechanical + fire plots than in the Untreated areas ($p < 0.001$ for both; Fig. 2), but there was no difference between the two treatment types ($p = 0.667$). Median basal area was roughly twice as high in the Untreated plots (median: 52 m^2ha^{-1}) as compared to the Mechanical+ fire plots (median: 24 m^2ha^{-1}, $p < 0.001$) and the Mechanical-only plots were intermediate between the two (median: 39 m^2ha^{-1}, $p = 0.003$); differences between the two treatments were only marginally significant ($p = 0.070$). Median relSDI in the Untreated plots was higher (78 %) than Mechanical + fire and Mechanical-only plots ($p < 0.001$ for both), but there was no difference between the Mechanical-only plots (46 %) and Mechanical + fire plots (31 %; $p = 0.131$). Finally, QMD was significantly higher in the Mechanical-only plots (median 50 cm) than the Untreated plots (median: 33 cm; $p < 0.001$) and the Mechanical + fire plots (median 42 cm; $p = 0.001$), and the difference between treatments was also significant ($p = 0.014$; Fig. 2).

3.2. Variation in first order fire effects across treatments

When considering pairwise comparisons, the probability of stand-replacement in Mechanical + fire plots (4 %) was significantly lower than in Untreated plots (61 %, $p = 0.004$) and Mechanical-only plots (42 %, $p = 0.049$; Fig. 3a). Of the 28 Mechanical + fire plots, only three experienced stand-replacing wildfire. There was no difference in the probability of stand-replacement between the Untreated and Mechanical-only plots ($p = 0.321$). For plots that did not experience stand-replacing wildfire, there was no difference in percent basal area mortality between the Mechanical-only and Mechanical + fire plots ($p = 0.224$), but both had significantly lower percent basal area mortality than the Untreated plots ($p < 0.001$ for Mechanical + fire; 0.003 for Mechanical only). Fig. 3a shows the raw percent basal area mortality by treatment for all plots.

We did not test for differences in first order fire effects on the canopy as they are directly correlated with stand-replacement and basal area mortality; however, we present the results here to show the range of effects across treatment types. Percent crown scorch was generally

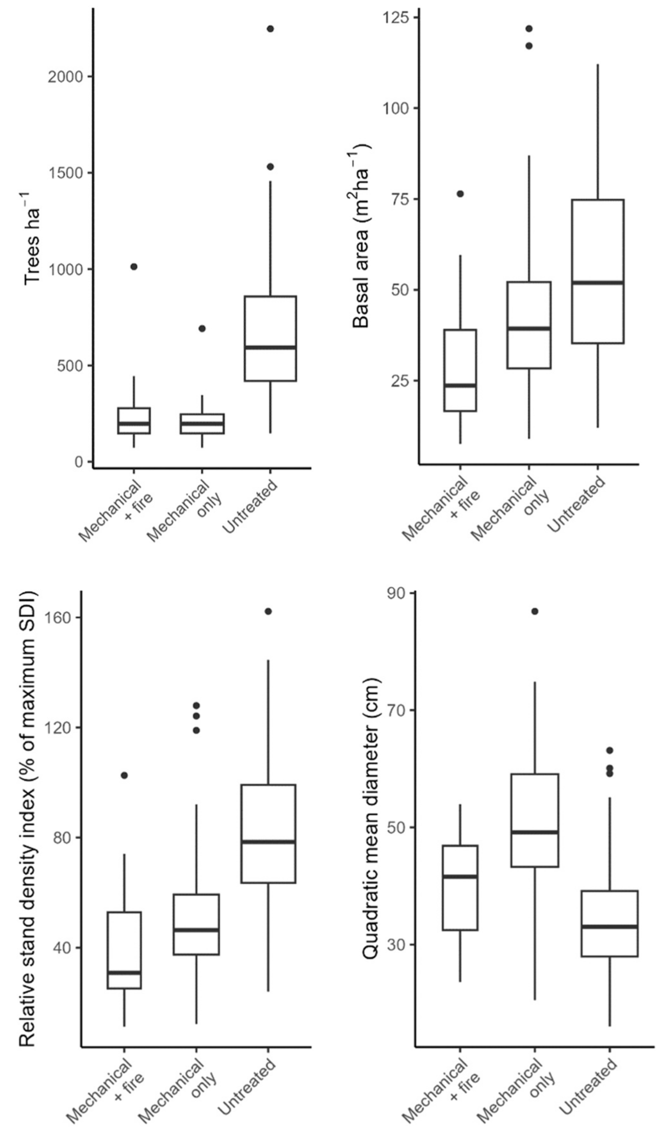

Fig. 2. From left to right, plot-level prefire tree density, basal area (top row), relative Stand Density Index (relSDI) and quadratic mean diameter (QMD) (bottom row) by treatment class. Boxplot width is scaled by sample size, where boxes denote first and third quartiles, lines the median, and whiskers the 1.5 inter-quartile range. Dots are outliers.

highly variable within treatment, but the median percent torch was much lower in Mechanical-only plots compared to Untreated plots, and even lower in the Mechanical + fire plots (Fig. 3b).

3.3. Modeling results

3.3.1. Drivers of stand-replacing wildfire

Based on the univariate binomial models testing the drivers of stand-replacing fire (100 % vs. <100 % basal area mortality), final candidate variables were tree density, QMD, percent slope, daily hectares burned, perimeter:area of daily hectares burned (PAratio), minimum relative humidity and maximum relative humidity, ERC and treatment (p-values, coefficients and AIC values for all univariate models can be found in Supplemental Table A1). Increasing tree density, percent slope, daily ha burned, PAratio and ERC were all associated with an increase in the probability of stand-replacing wildfire; in contrast, increases in QMD, minimum relative humidity and maximum relative humidity all decreased the probability of stand-replacing wildfire (p-values, coefficients and AIC values for all univariate models are provided in

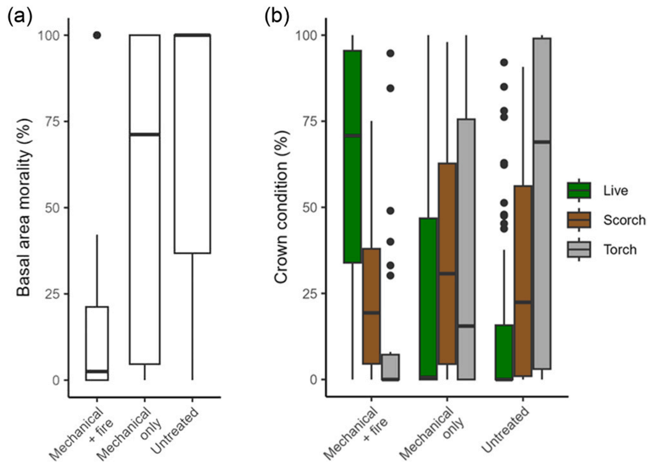

Fig. 3. Percent basal area mortality (a) and postfire crown condition (b) by treatment. Boxplot width is scaled by sample size, where boxes denote first and third quartiles, lines the median, and whiskers the 1.5 inter-quartile range. Dots are outliers.

Supplemental Table A1).

Total daily ha burned was somewhat correlated with PAratio (*Pearson correlation coefficient (r)* = 0.67) and PAratio performed better in terms of AIC (166.5 vs. 169.1), so we explored PAratio in the comprehensive model. Minimum and maximum humidity were also correlated ($r = 0.80$) and the univariate models did not differ in terms of AIC (169.6 vs. 171.6, respectively), so we explored minimum relative humidity as it is the more traditional metric used to predict fire severity.

The best comprehensive model included PAratio and treatment. The other candidate variables became insignificant, and their inclusion did not improve AIC. The probability of stand-replacing wildfire increased with decreasing PAratio (indicative of large growth days; $p < 0.001$). The probability of stand-replacing wildfire was significantly lower in the Mechanical + fire treatment ($p < 0.001$) as compared to the Untreated plots, but the Mechanical-only plots did not differ from the Untreated plots ($p = 0.261$; Fig. 4). Note that the Mechanical + fire treatments burned on days with generally lower relative humidities, so these could be confounded; however, BI's were higher for the Mechanical + fire plots, suggesting the weather data overall are somewhat difficult to interpret. Moreover, this model still outperformed models that included minimum relative humidity in addition to, or instead of, the treatment variable.

3.3.2. Variation in basal area mortality

For our models predicting percent basal area mortality on plots that did not burn with stand-replacement, the final candidate variables were: tree density, shade-tolerant tree density, basal area, QMD, relSDI, treatment and BI (p-values, coefficients and AIC values for all univariate models can be found in Supplemental Table A1). Tree density, shade-tolerant tree density, basal area and relSDI all had positive relationships with increasing percent basal area mortality, whereas QMD had a negative relationship. BI was counterintuitive, with increasing mortality related to decreasing BI, but it was not significant in the comprehensive model and did not improve fit in terms of AIC. Since tree density and shade tolerant tree density were highly correlated (*Pearson correlation coefficient:* 0.91), we explored total tree density in the comprehensive model because it had a lower AIC in the univariate models (174.0 vs. 171.4).

Combining the treatment variable with the forest structure variables did not improve the model over the univariate model with treatment alone (AIC: −219.3), where percent basal area mortality was reduced in areas that had either a Mechanical + fire treatment ($p < 0.001$) or a Mechanical-only treatment ($p < 0.001$; Fig. 5). We note that when QMD

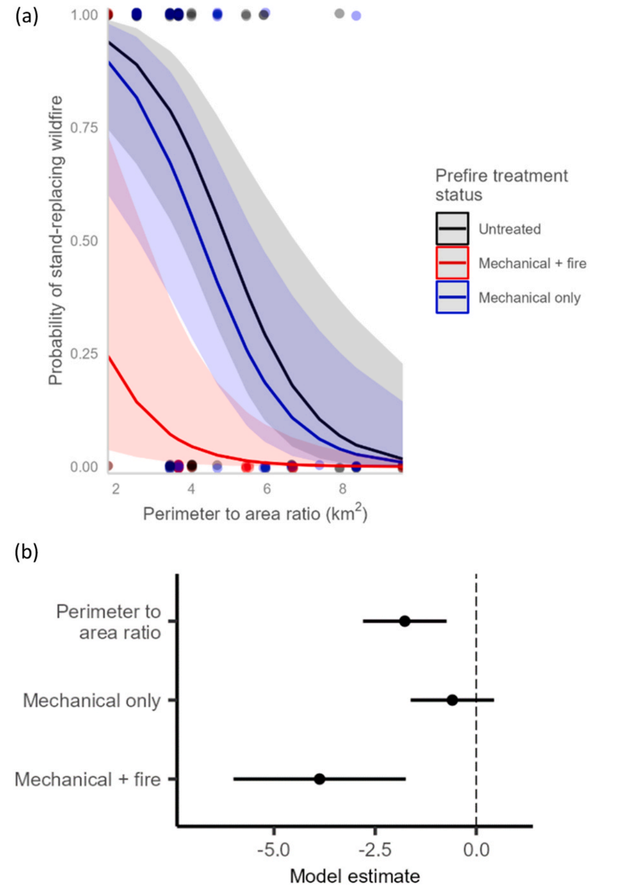

Fig. 4. (a) Probability of stand-replacing wildfire as predicted by perimeter to area ratio with a fitted line for the treatment variable from the final comprehensive binomial model. (b) Model coefficients with 95 % confidence intervals from the comprehensive binomial model.

is included in the model, the Mechanical-only treatment becomes only marginally significant ($p = 0.068$), suggesting that the differences in response by treatment are partly explained by differences in QMD. Both treatments had a higher QMD than the Untreated plots, with the Mechanical-only treatment having the highest median QMD.

To explore this further, we also created a model with the forest structure variables and a version of the treatment variable that only accounted for the fire treatment. In this alternative treatment variable, we lumped the Mechanical-only plots with Untreated plots that had no prefire fire treatment, so that the forest structure variables could explain the differences in forest structure that resulted from the thinning treatment, while still accounting for the reduction of surface fuels that occurs

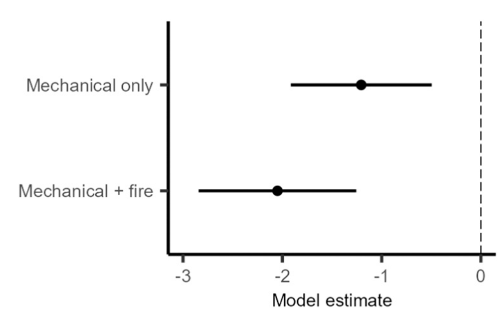

Fig. 5. Model coefficients with 95 % confidence intervals from the comprehensive model predicting the change in basal area mortality on plots that did not experience stand replacement, as a function of treatment type. Model estimates are relative to the Untreated treatment class.

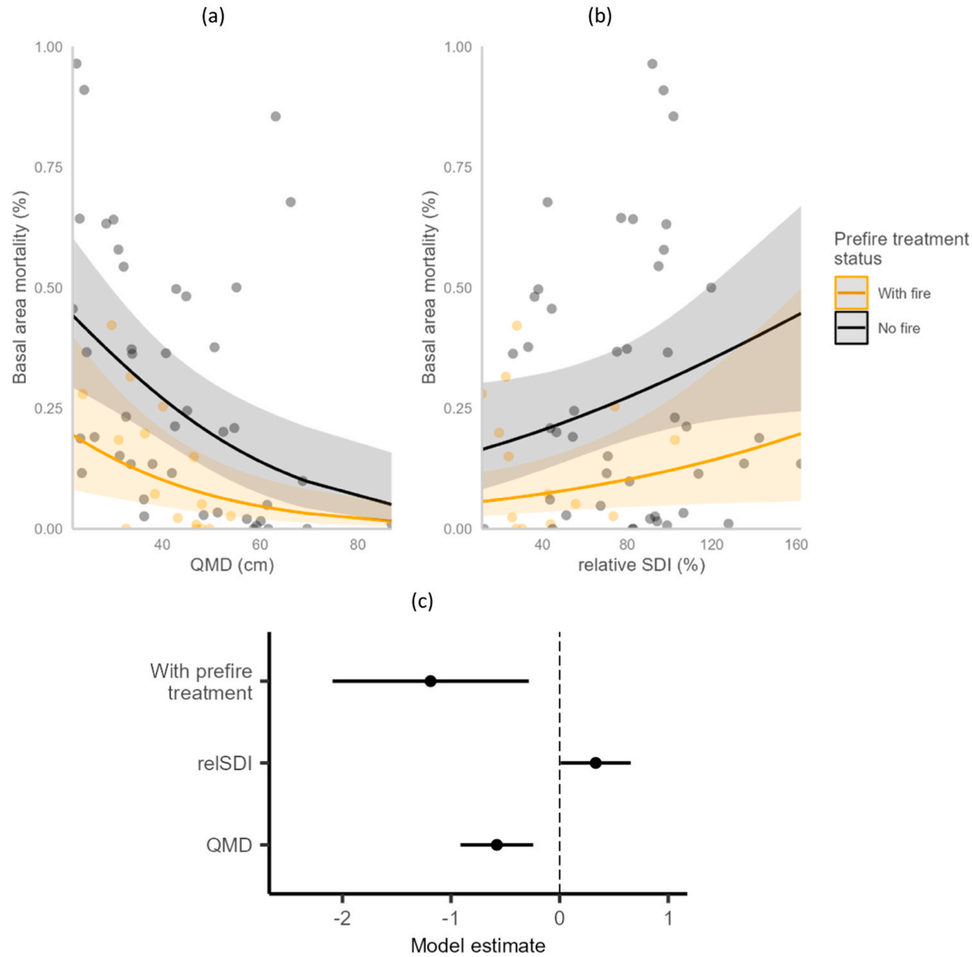

Fig. 6. Percent basal area morality for plots that did not experience stand replacement as predicted using an alternative treatment characterization (prefire fire treatment vs no prefire fire treatment). Percent basal area mortality was also predicted by (a) QMD and (b) relSDI; the fitted lines are for the alternative treatment variable. (c) Model coefficients with 95 % confidence intervals, where model estimates are relative to the No prefire fire treatment class.

with a fire treatment. The best comprehensive model using this alternative treatment variable (prefire fire treatment vs no prefire fire treatment) also included relSDI and QMD. This model performed better (AIC: −222.3) than the model with the three-class treatment variable alone (-219.3) or any of the forest structure variables on their own in univariate models (Supplemental Table A1). Percent basal area mortality was lower in areas that had the prefire fire treatment ($p = 0.010$), and increasing mortality was associated with increasing relSDI ($p = 0.044$) and decreasing QMD ($p < 0.001$; Fig. 6). This suggests that the significant reduction in percent basal area mortality in the Mechanical-only treatments in the model with the three-class treatment variable (Fig. 5) is due to a forest structure that is dominated by a lower density of larger trees, as compared with Untreated areas (Fig. 2). Where this structure was naturally occurring in some of the Untreated areas, fire severity was also reduced.

3.4. Pre- and post-fire forest structure comparisons

3.4.1. Comparison of pre- and postfire HRV for tree density and basal area

Broadly, the fire moved basal area and/or tree density of some plots from *above HRV* into target ranges for HRV, but it also moved many plots to well below those ranges, to the extent that many plots had no live trees postfire. Fig. 7 shows where the plots fit in relation to both basal area and tree density HRV ranges, which is outlined in the shaded box, both pre- and postfire.

When using the HRV classes as predictors in statistical models, plots with prefire tree density *within HRV* had significantly lower probability of burning with stand replacement (29 %, $p = 0.007$) than plots that were above the HRV range (61 %). For plots that did not burn with stand-replacement, plots that were *within HRV for* prefire tree density had significantly lower fire-caused percent basal area mortality (13 % $p < 0.001$) versus those that were *above HRV* (37 %). Prefire basal area HRV classes were good predictors of stand replacing wildfire. For plots that did not burn with stand replacement, percent basal area mortality was higher in areas that were *above HRV* and lower in areas that were *below HRV* for basal area as compared to *within HRV*, but those differences were not significant ($p = 0.083$; $p = 0.091$).In terms of AIC, models with the HRV classification based strictly on tree density (binomial: 166.6; beta: −212.0) outperformed the classification based on basal area (173.3; −200.0); adding basal area to the tree density model did not improve model performance (168.2; −208.6), so we base our remaining exploration of HRV on tree density only.

Prefire median tree densities for both Mechanical + fire and Mechanical-only treatment types were within the target HRV range, but the Untreated median density was well above the HRV range. Postfire, the median tree density for the Mechanical + fire treatment remained in the target HRV range, whereas the median for both the Mechanical-only and Untreated areas were near zero or zero (no live trees) (Fig. 8). The difference in prefire to postfire density was greatest for the Untreated plots.

3.4.2. Pre- and postfire transitions in HRV classes for tree density

Prior to the fire, 24 (86 %) of the Mechanical + fire plots were *within HRV* for tree density, and of those plots, 82 % stayed *within HRV,* and

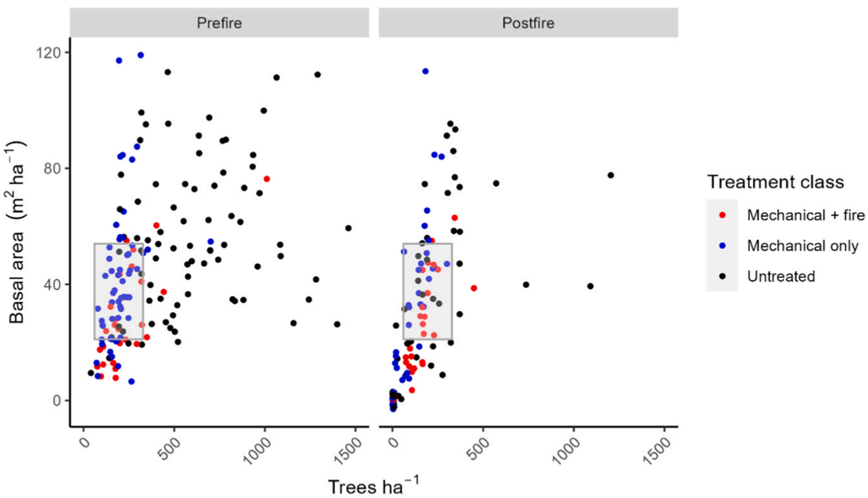

Fig. 7. Plots by basal area and tree density, pre- and postfire and by treatment class. Gray boxes outline plots that are within the HRV for both basal area and tree density. Note how many exceeded these targets prefire and how many shifted to below these targets postfire. Two Untreated plots >1500 trees per hectare were removed and points were jittered to increase plot readability.

14 % had no live trees remaining postfire (Fig. 9). For the Mechanical-only treatment, 96 % of the plots were *within HRV* prefire, but in contrast with the Mechanical + fire treatment, only 42 % of the plots remained *within HRV* and 48 % had no live trees remaining postfire, and the remaining 10 % of plots were *below HRV* following the fire. In the Untreated plots, only 15 plots (20 %) were *within HRV* prefire; of these, half had no live trees postfire. The majority of Untreated plots (85 %) were in the *above HRV* class for tree density prefire. Postfire, 58 % of the Untreated plots had no live trees postfire, whereas 16 % remained above HRV, and 5 % were *below HRV* (Fig. 9).

3.4.3. Comparison of pre and postfire QMD and relSDI with desired conditions

We present two additional metrics that are relevant to forest restoration: QMD and relSDI. We are unaware of quantitative restoration goals that rely specifically on QMD, but generally, increasing QMD would help meet overarching goals of growing lower density forests dominated by larger trees. The Mechanical + fire treatment plots had a slight increase in median QMD postfire, whereas Mechanical-only treatment plots had a substantial decrease in median QMD, and Untreated stands had a median postfire QMD of zero (Fig. 10a).

Prefire median relSDI was below the low competition threshold (34 % of maximum SDI) for Mechanical + fire, but slightly above the

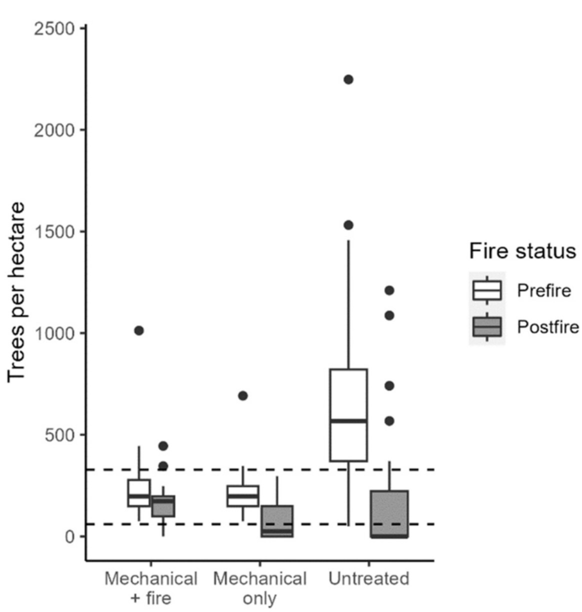

Fig. 8. Tree density by treatment type, and prefire and postfire. The dashed lines represent HRV target ranges. Boxplot width is scaled by sample size, where boxes denote first and third quartiles, lines the median, and whiskers the 1.5 inter-quartile range. Dots are outliers.

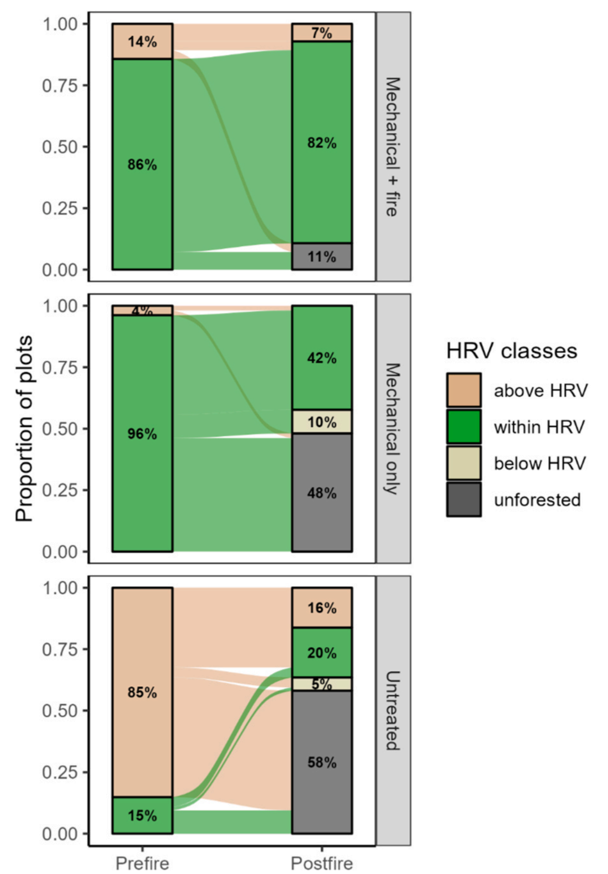

Fig. 9. The proportion of plots in the Dixie fire that were classified into HRV ranges for tree density both prefire and postfire, highlighting the transitions between the two states.

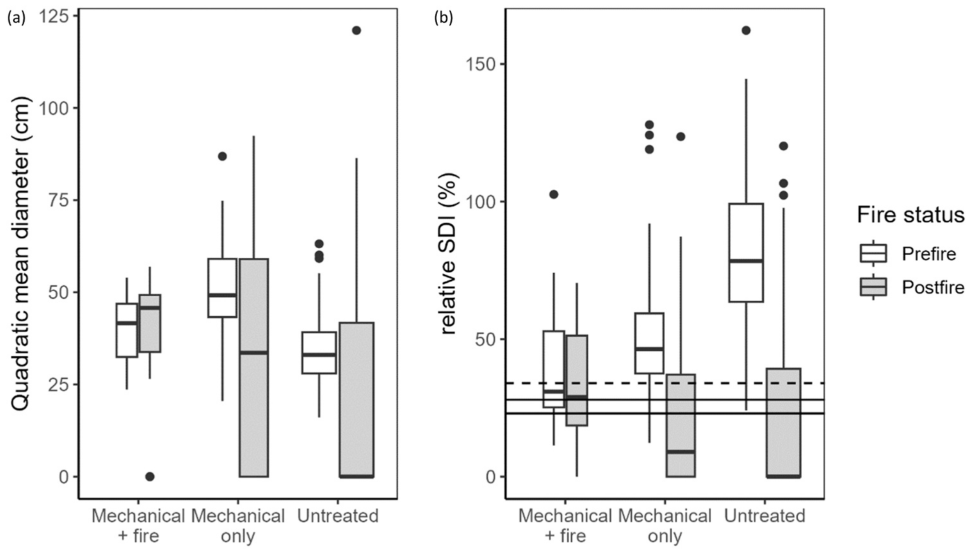

Fig. 10. (a) Quadratic mean diameter (cm) and (b) relative Stand Density Index (relSDI, %) by treatment class, pre- and postfire. For relSDI (b), the threshold for low competition (34 %) is shown with a dashed line. Solid lines represent the historical range of variation estimated for stands in the southern Sierra Nevada (23–28 %) by North et al. (2022). Boxplot width is scaled by sample size, where boxes denote first and third quartiles, lines the median, and whiskers the 1.5 inter-quartile range. Dots are outliers.

reference range (23–28 %) from North et al. (2022), whereas the Mechanical-only and Untreated plots exceeded both the low competition threshold and reference range. Wildfire reduced the relSDI for all treatment classes, but had the strongest effect in Untreated stands, were the postfire median was zero. In Mechanical-only plots, the postfire median was slightly higher (9 %), but still well below the reference range. The fire moved the median relSDI for Mechanical + fire to just above the reference range (29 %, Fig. 10b).

3.4.4. *Comparison of pre- and postfire conifer species composition with desired conditions*

Since a common restoration goal for mixed conifer forests in the Sierra Nevada is to shift stands toward pine dominance, we also looked at changes in the proportion of shade intolerant species (sugar pine, ponderosa pine, Jeffrey pine) pre- and postfire by treatment class. For Mechanical + fire treatments, the basal area of shade intolerant species was virtually unchanged, and shade intolerant tree density increased slightly. For Mechanical-only and Untreated plots, there was a larger, but still modest decrease in the proportion of shade intolerant basal area and tree density (Fig. 11).

4. Discussion

Our results suggest that, while mechanical thinning treatments can be effective at restoring forest structure to within the historical range of variation, the combination of mechanical and fire treatments is most effective at creating forest conditions resilient to wildfires burning under a range of conditions. The inclusion of a fire treatment (pile or broadcast burning) with the mechanical treatment resulted in a lower probability of stand replacing fire, reduced levels of canopy torching, lower percent basal area mortality, and fewer plots transitioning to an unforested state than areas that had only mechanical treatments or were untreated. Other important predictors of stand replacing fire were slope steepness and large fire growth (represented by the perimeter:area ratio). In areas

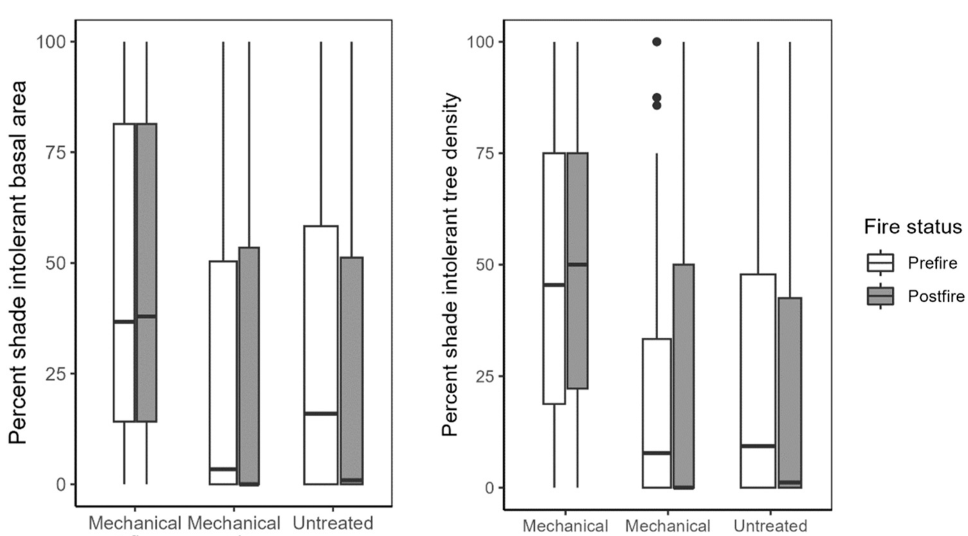

Fig. 11. Pre- and postfire proportions of shade intolerant tree species by basal area (left) and tree density (right). Boxplot width is scaled by sample size, where boxes denote first and third quartiles, lines the median, and whiskers the 1.5 inter-quartile range. Dots are outliers.

where stand-replacing wildfire did not occur, fire severity was reduced in both the Mechanical-only and Mechanical + fire treatments, which had higher QMDs and lower relSDIs than the Untreated areas.

4.1. Drivers of stand-replacing wildfire and gradients of fire severity

Our finding that the addition of the fire treatment after mechanical thinning reduced both the probability of stand replacement as well as percent basal area mortality is consistent with a growing body of evidence supporting the importance of following mechanical treatments with a fire treatment to reduce surface fuels and slash (Brodie et al., 2024; Davis et al., 2024; Fulé et al., 2012; Kalies and Yocom Kent, 2016; Prichard et al., 2020). Although we do not have data quantifying prefire surface fuels on our plots, many other studies have shown that fire treatments reduce total surface fuel loads, which are important drivers of fire spread and intensity (Pollet and Omi, 2002; Stephens et al., 2023, 2012a, 2009). We found very little difference in forest structure and composition between our mechanical thinning treatments (with and without fire), which suggests that the difference between the two treatments were likely differences in surface fuel conditions prior to the fire. The importance of the fire treatment was also identified in a spatial analysis of the Dixie Fire by Taylor et al. (2022), who detected a strong "ecological memory" of past fire severity, where lower fire severity in a prior fire was linked with lower severity in the Dixie Fire (Taylor et al., 2022). Lower severity wildfires that occurred prior to the Dixie Fire likely had the same effect as active management treatments that included broadcast burning or pile burning. These results highlight how prefire broadcast burning or pile burning treatments can initiate a positive feedback, where lower severity burning via active management can promote lower severity burning under wildfire conditions (Larson et al., 2013; Steel et al., 2021; Taylor et al., 2022).

Many fuel treatment effectiveness studies have found that, though somewhat less effective, mechanical-only treatments can result in reductions in fire severity, but our results were mixed between our two modelling approaches. For stand-replacing fire, the Mechanical-only treatment did not differ from the Untreated plots and the forest structure variables, which quantify the reduced tree densities and altered forest structure in Mechanical-only plots, were not important predictors. We hypothesize that this is because stand-replacing wildfire occurred during more extreme burning conditions. The PAratio, which can be understood as a proxy for large fire growth, was strongly associated with stand-replacing wildfire. The correlation between PAratio and relative humidity was weak (*Pearson's correlation coefficient:* 0.33), but lower PAratios did tend to coincide with lower minimum relative humidity. We therefore hypothesize that the ratio is likely representing several drivers of large fire growth; these could include minimum relative humidity, as well as landscape-level fuels patterns and topographic variation, including topography's impact on winds, that are not captured in our other explanatory variables. In that case, our finding that forest structure variables were not associated with stand replacing fire is consistent with other studies documenting that fuels treatments can be less effective under more extreme fire behavior conditions (Lydersen et al., 2014). Taylor et al. (2022) also found limited mechanical treatment effectiveness in the Dixie Fire, but they found that treatment efficacy was dependent on the treatment occurring within ten years prior to the fire, whereas we found no effect of time since treatment (note: our sampled treatments spanned 20 years prior to the fire).

In contrast, while the Mechanical + fire remained important in reducing percent basal area mortality for plots that did not experience stand replacement, the Mechanical-only treatments also reduced percent basal area mortality over Untreated areas. Additional exploration revealed that this reduction in mortality was linked with higher QMDs and lower relSDI values. These forest structure characteristics are generally indicative of lower density forests dominated by larger trees, which resulted in reduced mortality, including when they occurred in Untreated plots. However, these structures were more common where mechanical treatments were applied (i.e., both the Mechanical + fire and Mechanical-only treatments), with the Mechanical-only treatment having the highest prefire median QMD. The effectiveness of mechanical thinning alone under more moderate conditions highlights that, even though it is less effective than mechanical thinning followed by a fire treatment, it is still more effective than no treatment for promoting forest persistence on the landscape.

Finally, several other studies have documented weather variables as strong drivers of fire severity (Estes et al., 2017; Lydersen et al., 2014; Taylor et al., 2022, 2020), and although we did detect relationships with weather variables for both the probability of stand replacement and percent basal area mortality in our univariate models, none were important once they were combined with other predictor variables. Similar to the Taylor et al. (2022) work in the Dixie Fire, we detected a relationship between fire severity and both ERC and maximum humidity, but these variables were not strong predictors in our final models. We hypothesize that this difference in results could be due in part to differences in approach, where Taylor et al. (2022) covered the entire fire area (and therefore a wider range of weather and forest conditions), used remotely-sensed estimates of burn severity rather than plot-based estimates that provided information on forest structure. Lydersen et al. (2014) found BI to be an important predictor of fire severity, but they also used remotely-sensed burn severity. Brodie et al. (2024) did use plot data to test how first order fire effects varied depending on BI and treatment type, but they do not present results of the effect of BI alone, so we cannot directly compare our results (Brodie et al., 2024). We hypothesize that though weather variables, particularly relative humidity and related indices (ERC, BI), are known drivers of fire severity, the influence of stand structure and fine scale variation in topographic position may result in more variation in severity patterns at the plot-level (Jeronimo et al., 2020).

4.2. Prefire and postfire forest conditions in relation to target conditions

One fundamental goal of forest restoration treatments is to reduce the probability of stand-replacing wildfire (USDA Forest Service, 2012). To meet this goal, treatments are often designed to manipulate forest structure and composition with the intent of moving conditions closer to HRV structural targets and greater pine dominance (North et al., 2009). Compared to Untreated stands, the mechanical thinning treatments in our study area resulted in a prefire forest structure (i.e., tree density, basal area, QMD and relSDI) that closely matched desired conditions as defined by HRV and restoration objectives. Stands that were treated with mechanical thinning (both Mechanical only and Mechanical + fire) had significantly fewer trees, lower basal area, and larger trees than adjacent untreated stands, and were largely within HRV target ranges.

Despite these similarities in prefire forest structural attributes, the two treatments differed in their postfire trajectories. Most of the Mechanical + fire plots (82 %) stayed within HRV, which is consistent with recent work that documented how wildfires can extend the effective lifespan of a fuel treatment by acting as a maintenance treatment (Low et al., 2023). In contrast, 49 % of all Mechanical-only plots had no live trees postfire (moving them well below the HRV). This suggests that meeting HRV or restoration targets for tree density alone may not be enough to maintain forests within those target ranges after a wildfire.

Although Mechanical + fire plots had the greatest proportion of plots within the HRV postfire, all three treatment classes had at least some plots that were within HRV after the wildfire. This highlights the opportunity for managers to work with wildfire to achieve restoration targets. Stands that burned at low-moderate severity in a wildfire, and that have postfire forest structure that is consistent with restoration targets, present opportunities to maintain forests on the landscape. Although postfire conditions will vary on the ground depending on site productivity, disturbance history, and degree of fire severity (even within severity class), lower severity areas often have live mature trees, reduced live tree density, and some reduction in surface fuels (Collins et al., 2016; Jeronimo et al., 2019). Maintaining or enhancing these conditions via follow-up maintenance treatments or managed wildfire for ecological benefit can help retain mature forests on the landscape (Low et al., 2023; Prichard et al., 2021). There will likely be substantial variation in the timing of retreatment needs based on local conditions and treatment history. For example, sites that had at least one treatment prior to the fire, making the wildfire a second "treatment," can likely be put into a longer maintenance treatment schedule than sites that experienced wildfire as an initial entry treatment. For the few Untreated sites that were within HRV for tree density postfire, retreatment will likely be needed sooner, as numerous studies have shown that in long-unburned forests, multiple treatments are often required to meet targets for forest structure and fuels (Lydersen and North, 2012; Taylor, 2010; Webster and Halpern, 2010). This is likely because, in stands with a high density of trees, the first low severity fire typically creates a lot of dead material and may not substantially change forest structure (Collins et al., 2018, 2011).

It is also important to consider that while a single low-moderate severity fire treatment may reduce tree densities to within the HRV, it may not be enough to shift species composition into alignment with historical patterns, where the shade-intolerant pines are more dominant than the shade-tolerant species (North et al., 2009; Paudel et al., 2022). In our stands, the median proportions of shade intolerant species basal area and tree density saw little change to a slight increase in the Mechanical + fire plots, but declined in the Mechanical-only and Untreated plotsrepresenting a shift further away from target conditions.

The Mechanical + fire plots had essentially no change in the proportion of shade intolerant basal area and only a very slight increase in the proportion of shade intolerant tree density.

More recently, relSDI competition thresholds have been proposed as an alternative to HRV for defining target conditions (North et al., 2022). North et al. (2022) suggest that historical mixed conifer stands that experienced frequent-fire disturbance regimes had relSDI values that ranged from 23 % to 28 % of maximum SDI, indicating low to non-existent levels of competition. Prior to the Dixie Fire, only the Mechanical + fire plots had a median relSDI below the 34 % threshold for low competition, and that median just met the high end of the historical relSDI range after the fire. The Mechanical-only and Untreated plots both had prefire medians above the 34 % threshold, and although some of these plots shifted into target ranges postfire, the medians for both of these classes were well below the lower end of the target range, with many plots unforested postfire. Reference conditions defined by HRV, relSDI or species composition were more likely to be met both prefire and postfire in Mechanical + fire plots. This suggests that, in addition to reducing fire severity, thinning treatments followed by fire may also be more effective at setting wildfire up to have restorative effects on forest conditions than mechanical treatments alone.

4.3. Study limitations

Our study is based on a single large wildfire encompassing a variety of treatment, site, and wildfire conditions with results applicable to other western US forests historically adapted to frequent fire, but we acknowledge several limitations. We examined local scale effects of fuels treatments using plot data but did not measure landscape level or "downstream" effects of fuels treatments (i.e. effects of treated areas on fire behavior and severity in adjacent untreated areas). Due to sample size, we combined pile burning and broadcast burning treatments into a single treatment category and are unable to tease apart differing effects from these two management practices. We have inferred that the reason for reduced probability of stand replacement and percent basal area mortality in Mechanical + fire plots versus Mechanical-only and Untreated plots is due to a reduction in surface fuels with the fire treatment, which has been shown in many studies, but we do not have data quantifying pre-fire surface fuels, and thus are unable to directly test that hypothesis. We also did not quantify pre- and post-fire spatial variability in forest structure as a possible driver of wildfire severity patterns. Finally, our metrics of fire weather are imperfect since they do not capture real-time conditions at the microsite level, but rather are daily averages representing a broader spatial scale than our plots (i.e. 4 km grid size for gridMET and our 0.04 ha plots).

5. Conclusions

Our study corroborates many others in highlighting the importance of following up mechanical thinning with a fire treatment to increase treatment effectiveness at reducing wildfire severity (Davis et al., 2024; Fulé et al., 2012; Pollet and Omi, 2002; Prichard et al., 2020; Safford et al., 2012, 2009; Stephens et al., 2023; Taylor et al., 2022; Tubbesing et al., 2019). Although we do not have data quantifying prefire surface fuels, many other studies have shown that fire treatments reduce total surface fuel loads, which are important drivers of fire spread and intensity (Pollet and Omi, 2002; Stephens et al., 2023, 2012a, 2009). We found very little difference in forest structure and composition between our mechanical thinning treatments (with and without fire), which suggests that the patterns we observed were likely a result of differences in surface fuel conditions prior to the fire.

Our study is unique in its approach to examining pre- and postfire forest structure in relation to target conditions and prefire treatments. By explicitly looking at stand transitions and treatment history, forest managers can better anticipate postfire outcomes and can also identify opportunities to work *with* wildfire by capitalizing on wildfire's restorative effects. Although recent guidance from the US Forest Service outlines a clear approach to include the entire fire area in an evaluation of postfire management needs (Meyer et al., 2021), most postfire management plans by federal agencies are still limited to reforestation and restoration activities in high severity areas. Ensuring that forests that survived the wildfire and that are in line with restoration targets persist on the landscape by conducting long-term forest management that maintains them in a resilient condition could have significant habitat and carbon benefits (Moomaw et al., 2019).

CRediT authorship contribution statement

Alison K. Paulson: Writing – review & editing, Formal analysis, Conceptualization. **Kristen N. Wilson:** Writing – review & editing, Visualization, Funding acquisition, Conceptualization. **Kristen L. Shive:** Writing – original draft, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Michelle Coppoletta:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Conceptualization. **Rebecca Bewley Wayman:** Formal analysis, Project administration, Supervision, Roles/Writing – original draft, Writing – review & editing. **Saba J. Saberi:** Writing – review & editing. **Becky L. Estes:** Writing – review & editing, Conceptualization. **Hugh D. Safford:** Conceptualization. **John T. Abatzoglou:** Writing – review & editing, Data curation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Kristen Wilson reports financial support was provided by Community Initiatives. If there are other authors, they 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 will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2024.122171.

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