Brodie *et al. Fire Ecology* (2024) 20:17
https://doi.org/10.1186/s42408-023-00241-z

Fire Ecology

ORIGINAL RESEARCH

Open Access

Forest thinning and prescribed burning treatments reduce wildfire severity and buffer the impacts of severe fire weather

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Abstract

Background The capacity of forest fuel treatments to moderate the behavior and severity of subsequent wildfires depends on weather and fuel conditions at the time of burning. However, in-depth evaluations of how treatments perform are limited because encounters between wildfires and areas with extensive pre-fire data are rare. Here, we took advantage of a 1200-ha randomized and replicated experiment that burned almost entirely in a subsequent wildfire under a wide range of weather conditions. We compared the impacts of four fuel treatments on fire severity, including two thin-only, a thin-burn, a burn-only, and an untreated control. We evaluated four fire severity metrics—tree mortality, average bole char height, percent crown volume consumed (PCVC), and percent crown volume affected (PCVA)—and leveraged data from pre-fire surface and canopy fuels to better understand the mechanisms driving differences in wildfire severity among treatments and how they changed with fire weather.

Results We found strong mitigating effects of treatments on fire behavior and tree mortality, despite 20 years having elapsed since mechanical thinning and 10 years since the second entry of prescribed fire. The thin-burn treatment resulted in the lowest fire severity across all four metrics and the untreated control the highest. All four fire severity metrics were positively associated with pre-fire canopy and surface fuel loads, with the exception that PCVC (a fire severity metric related to crown fire behavior) was not associated with surface fuel load. The fire weather conditions under which fuel treatment was most effective varied among fire severity metrics. Fuel treatment benefit was maximized at intermediate burning index values for tree mortality, intermediate to high burning index values for PCVA, and high burning index for bole char height and PCVC.

Conclusions We conclude that reducing canopy bulk density via mechanical thinning treatments can help to limit crown fire behavior for 20 years or more. However, reducing surface fuels is necessary to limit scorching and the total crown impacts associated with tree mortality. Further, while fuel treatment effectiveness may decline under the most severe fire weather conditions for fire severity metrics associated with tree mortality, it is maximized under severe fire weather conditions for fire severity metrics associated with crown fire behavior (bole charring and torching). Our results provide strong evidence for the use of fuel treatments to mitigate fire behavior and resulting fire severity even under extreme fire weather conditions.

Keywords Fuel treatment effectiveness, Wildfire-treatment outcomes, Thinning, Prescribed fire, Wildfire, Extreme fire weather

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Resumen

Antecedentes La capacidad de los tratamientos de combustibles forestales para moderar el comportamiento del fuego y la severidad de incendios subsecuentes, dependen de las condiciones meteorológicas y de los combustibles al momento del incendio. Sin embargo, las evaluaciones en profundidad sobre cómo estos tratamientos inciden en el comportamiento del fuego son limitadas, dada la dificultad y rareza de hallar conjuntamente incendios actuales y en esas mismas áreas contar con datos de incendios previos. En este trabajo, aprovechamos la oportunidad para estudiar un experimento de diseño al azar y con réplicas en una superficie de 1200 ha, que se quemó casi completamente en un incendio muy posterior al establecimiento del experimento y bajo un amplio rango de condiciones meteorológicas. Comparamos los impactos de cinco tratamientos sobre la severidad del fuego, incluyendo dos tipos de raleo, raleo y quema prescripta, quema prescripta sola, y control. Evaluamos cuatro parámetros de severidad del fuego -mortalidad de árboles, promedio de altura de carbonizado o chamuscado, porcentaje del volumen de copa consumido (PCVC) y porcentaje del volumen de copa afectado (PCVA)-, y aprovechamos datos tomados previo al incendio sobre superficies y combustibles del dosel, para entender mejor los mecanismos conducentes a mostrar diferencias en severidad del fuego entre tratamientos y cómo estos cambian con las condiciones meteorológicas del incendio.

Resultados Encontramos fuertes efectos de mitigación de los tratamientos en el comportamiento del fuego y en la mortalidad de árboles, a pesar de los 20 años transcurridos desde el raleo mecánico y 10 años desde la segunda intervención con quemas prescriptas. El tratamiento de raleo y quemas prescriptas resultó en la menor severidad del fuego entre todos los tratamientos, y el control resultó ser el de mayor severidad. La severidad registrada en los cuatro tratamientos estuvo positivamente asociada con la carga de combustibles superficiales y del dosel, exceptuando que la PCVC (el efecto de la severidad relacionada con el comportamiento del fuego en la corona) no se asoció con la carga de combustibles superficiales. Las condiciones meteorológicas bajo las cuales los tratamientos fueron más efectivos varió entre las medidas de severidad. El beneficio de los tratamientos fue maximizado a índices de quema intermedios para la variable mortalidad de árboles, intermedio para índices altos de quema para PCVA, y altos valores del índice de quema para la altura de chamuscado y PCVC.

Conclusiones Concluimos que la reducción de la densidad del dosel a través del tratamiento mecánico de raleo puede limitar el comportamiento del fuego en las copas por hasta 20 años o más luego de realizado este tratamiento. Sin embargo, es necesaria también la reducción de los combustibles superficiales para limitar los impactos del coronamiento y quema de la copa que se asocian con la mortalidad de los árboles. Además, mientras que la efectividad de los tratamientos puede declinar en condiciones meteorológicas extremas para medidas como la severidad asociada a la muerte de árboles, esta efectividad puede ser sin embargo maximizada en condiciones meteorológicas extremas, cuando la severidad se asocia con el comportamiento del fuego en la corona (chamuscado o coronamiento del fuego en las copas). Nuestros resultados proveen de una fuerte evidencia para recomendar el uso de tratamientos de combustibles para mitigar el comportamiento del fuego y la severidad resultante, aún en condiciones meteorológicas extremas.

Introduction

The primary goal of forest thinning and prescribed burning for fuel reduction, hereafter fuel treatment, is to mitigate the effects of wildfire on ecological and human communities by moderating fire behavior and reducing fire severity outcomes (Agee & Skinner 2005; Finney 2001). Reducing wildfire severity is a key management objective in dry mixed conifer forests in the western USA, where over a century of fire exclusion has increased fuel loadings (Hankin et al. 2023; Knapp 2015; Knapp et al. 2013; Stephens et al. 2015) and aridity associated with climate change is contributing to more intense fire behavior (Abatzoglou & Williams 2016). Together, such changes have resulted in larger and higher severity fires than those that were experienced historically (Hagmann et al. 2021; Parks & Abatzoglou 2020). A broad literature demonstrates that wildfire severity is reduced in areas that have received fuel treatments for wildfire hazard or forest restoration, especially when treatments combine the use of mechanical thinning and prescribed fire (for reviews, see Fulé et al. 2012; Kalies & Yocom Kent 2016). However, the extent to which treatments affect fire severity depends on fuel loads, weather, and topography at the time of burning, leading to different wildfire-treatment outcomes under different conditions (Prichard et al. 2020; Viedma et al. 2020). As large, wind-driven fire events become more common (Abatzoglou et al. 2023; Stephens et al. 2014) and as governments and communities work to increase the pace and scale of fuel treatments for forest health and community wildfire protection (Forest Management Taskforce 2021;

Riechman et al. 2014), understanding how fuels and weather interact to impact wildfire-treatment outcomes is increasingly important.

Though hot, dry, and windy conditions tend to increase fire behavior and fire severity outcomes, fuel treatments can still be effective at weather extremes (Finney 1998; Prichard et al. 2020; Prichard & Kennedy 2014). Indeed, if fuel treatment effectiveness is defined as a relative measure of the difference in fire severity outcomes between treated and untreated areas, effectiveness can increase as weather conditions become more extreme despite higher absolute fire severity (Povak et al. 2020; Prichard et al. 2020; Safford et al. 2012). Such evidence contrasts with the idea that bottom-up controls (e.g., fuel loading) are weakest under large, wind-driven fire events, with high severity expected regardless of treatment or fuel type (Lydersen et al. 2014; Graham et al. 2003). Disparities are not well studied, and study outcomes are difficult to compare given differences in the quality of fuel treatments, the many plot-based and remotely sensed measures of fire severity, and the variety of definitions (both relative and absolute) for fuel treatment effectiveness. Reduced treatment effectiveness, with similar outcomes between treated and untreated areas, may also occur when weather conditions are mildest and fire severity is low (Finney 1998; North et al. 2012). Given current evidence, we expect a unimodal relationship between fuel treatment effectiveness and weather, with little benefit conferred under the mildest conditions, maximum benefit under moderate conditions, and less benefit again under the most extreme weather and climate scenarios. However, more work is needed to explore the interaction between fuels and weather and to identify thresholds for desired wildfire-treatment outcomes (O'Connor et al. 2017).

Within and among treatments, wildfire-treatment outcomes are further influenced by the absolute amount and arrangement of fuels at the time of burning. Reducing fuels in the canopy via mechanical thinning of midstory or overstory trees lowers the probability of active crown fire (Finney 1998; Van Wagner 1977). However, thinning also opens the mid- and overstory, potentially enhancing fuel drying on the forest floor and leading to increased mid-flame windspeeds, especially under wind-driven conditions (Parsons et al. 2018). Thus, simulation studies have reported increased fire severity when the forest midstory is removed entirely compared to when it is only partially removed (Banerjee et al. 2020). Reducing fuels on the forest floor (known as surface fuels) via prescribed fire or pile burning lessens fire rate of spread (Rothermel 1972) and fireline intensity (Byram 1959). In empirical studies, treatments that target surface fuels along with canopy fuels are more likely to reduce tree mortality, crown scorching, and crown fire behavior (Prichard et al. 2020; Safford et al. 2009). However, studying the interaction of fuel treatments and wildfire is opportunistic in nature and few research studies with permanent plot networks have burned soon after sampling (e.g., Ritchie et al. 2007). Thus, empirical studies of wildfire-treatment outcomes generally lack pre-fire forest structure and fuel data, resulting in datasets ill-suited to comparing the influence of different fuel strata on fire severity.

Further, most existing empirical studies of wildfire-treatment outcomes are largely observational, with simple control-impact designs. Such observational designs are unavoidable when tackling large-scale ecological questions, but can lead to more biased results than designs that include pre-treatment data or randomly assign treatment and control (Christie et al. 2019; Larsen et al. 2019). Most fuel treatments are implemented nonrandomly on the landscape based on a series of environmental and economic considerations (i.e., community risk, funding allocation, distance from roads, and slope steepness). Thus, measured or unmeasured differences between treated and untreated areas may confound comparisons after a wildfire, a statistical phenomenon known as selection bias that can have important effects and even change the sign of results (Simler-Williamson & Germino 2022). While weight of evidence backs the effectiveness of fuel treatments in limiting wildfire severity, the field still lacks the gold standard: results from a long-term replicated and controlled experiment that has burned in a wildfire.

Here, for the first time that we are aware of, we test the effectiveness of fuel treatments at reducing subsequent wildfire severity using a large-scale completely randomized and replicated experimental design. We take advantage of the 2021 Antelope fire, which burned over 99% of a > 1300 ha, ~ 20-year-old silvicultural experiment testing a range of thinning and burning treatments for restoring dry mixed conifer forest. During the 6 days of burning within the experimental area, fire behavior ranged from mild to extreme, with red flag wind conditions observed on the second day. We use this unprecedented dataset to ask if fire severity outcomes were improved within treated areas and whether the treatment effect depended on fire weather conditions. We further leverage pre-fire fuel data to compare the influence of within-treatment canopy and surface fuels on fire severity outcomes.

Methods

Location

Treatment units were located within the Goosenest Adaptive Management Area (GAMA) on the Klamath National Forest in northeastern California (Fig. 1). This

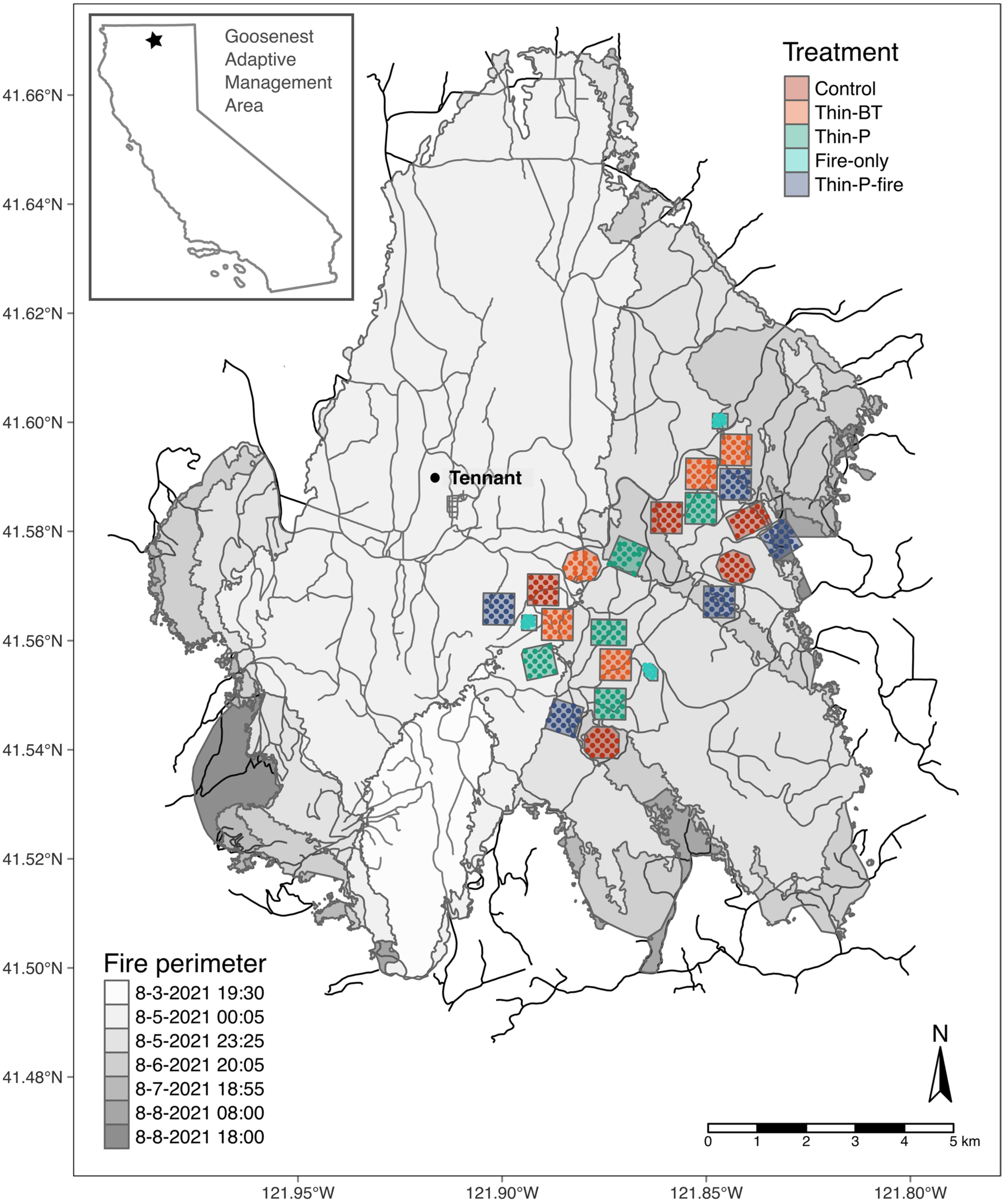

Fig. 1 Map of study units near the town of Tennant, California, on the Klamath National Forest. Colored dots represent the locations of study plots within units and gray shading reflects the perimeter of the Antelope fire at the flight times listed

area is moderately productive (site index ~ 90 at base age 50 (Barrett et al. 1978)), and characteristic of the interior pine forests of the Cascade Range. The local climate is characterized by cool winters, warm summers, and extended summer drought. Mean annual temperature is 9.2 °C and mean annual precipitation is 42.1 cm, with 66% arriving between November and March (Western Regional Climate Center 2022). Treatment units are located between 1460 and 1770 m elevation on gentle slopes (1 to 20%, median 5%) with northeasterly aspect and no surface water or riparian areas. Soils are volcanic and, in many places, topped by a 2.5–5-cm pumice layer.

Historically, the study area was dominated by ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws.), increasing in white fir (*Abies concolor* [Gordon & Glend.] Lindl. ex Hildebr.) abundance at higher elevations (Ritchie 2005). Red fir (*Abies magnifica* A. Murr.) was present at the highest elevations in the study area, but infrequent. Lower elevations contained occasional sugar pine (*Pinus lambertiana* Dougl.), incense cedar (*Calocedrus decurrens* Torr.), western juniper (*Juniperus occidentalis* Hook.), and Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco) (Ritchie 2005).

Fire exclusion and logging associated with Euro-American colonization changed forest composition and structure at the study site. Before colonization, a combination of lightning ignitions and indigenous burning resulted in a fire regime of frequent and predominantly low severity fires across much of California mixed conifer forest (Agee 1994; Crawford et al. 2015; Fry & Stephens 2006). As settler populations increased during the mid-1800s, forced removal of indigenous people, criminalization of cultural burning, and active fire suppression reduced fire frequency on the landscape (Taylor et al. 2016; Vinyeta 2021). A fire history study at the site indicated a median historical fire return interval of 11 years (Carl Skinner, unpublished report), within the 7–20-year range documented from similar forests in the region (Agee 1994). In the 1920s, commercial logging operations at GAMA prioritized large ponderosa pine for extraction (Ritchie 2005). At this site, as in others throughout California and the western USA, fire exclusion and the removal of overstory pines favored the more shade tolerant and fire-sensitive species, thus shifting the stands away from pine (Brodie et al. 2023) and resulting in a predominantly two species mix of white fir and ponderosa pine (Ritchie 2020). Fire exclusion also contributed to increased surface fuel loading and stand density (Agee & Skinner 2005; Knapp et al. 2013). Such forests are less resilient to wildfire and drought and have fewer of the large trees favored by special status wildlife species (North et al. 2017), resulting in widespread need for forest restoration.

Silvicultural treatment and design

Two studies evaluating forest restoration techniques are located at GAMA: the Little Horse Peak Interdisciplinary Study (LHPIS) and the national Fire and Fire Surrogates study (FFS) (McIver et al. 2009; Ritchie 2005). LHPIS was designed to evaluate management strategies to accelerate development of late-successional features (large trees, pine dominance, and an active fire regime) in second growth stands (Ritchie 2005). Treatments included (1) thinning only with emphasis on pine retention (hereafter “Thin-P”), (2) thinning with emphasis on pine retention and prescribed fire (hereafter “Thin-P-fire”), (3) thinning with emphasis on retention of big trees of any species (hereafter “Thin-BT”), and (4) a control treatment with no management activity (hereafter “Control”) (Table 1). Each treatment was replicated five times for a total of twenty ~ 40-ha treatment units that were assigned to units in a completely randomized design. Units were carefully selected based on uniformity of vegetation,

Table 1 Description of silvicultural treatments including number of replicates and total study plots per treatment

Study	Treatment	Description	Replicates	Total plots
LHPIS	Control	No management since logging in 1920s	5	90
LHPIS	Thin-BT	Thin from below leaving all trees DBH > 76 cm and with a target spacing of ~ 6–8 m between all dominant and co-dominant trees. All trees < 10 cm DBH were felled following harvest. This was a typical “fuel reduction” treatment for the Forest Service in California at the time	5	91
LHPIS	Thin-P	Radial thin from below leaving all pines with DBH > 30 cm and firs > 76 cm, with a target spacing around dominant and co-dominant trees of ((their diameter (cm) + 12.7) × 0.12) meters. All trees < 10 cm DBH were felled following harvest. To augment pine regeneration, 15% of the treatment area was converted to 0.2–1.4 ha openings planted with ponderosa pine seedlings. The long-term goal in this treatment was to create stands in which pine constituted at least 80% of basal area	5	89
LHPIS	Thin-P-fire	As in Thin-P above, but with broadcast burning in fall 2001 and fall 2010	5	91
FFS	Fire-only	Broadcast burning fall 2002 and fall 2011	3	30

slope, and evidence of historical pine dominance and had buffers of 100 m or more on all sides that were treated in the same way (Ritchie 2005). Thinning treatments were implemented between 1998 and 2000. Thinning was done using whole tree harvest methods, with trees skidded to landings and then trucked to staging areas for processing. This minimized the addition of slash and other surface fuels in the units. Broadcast burning was conducted in Thin-P-fire units in the fall of 2001 and again in the fall of 2010 under mild weather conditions with moderate fine fuel moisture (10-h fuel moisture averaged 11% in 2001 and 12% in 2010).

The FFS study was overlaid on the LHPIS study in 2002, and a portion of three replications of the Thin-P, Thin-P-fire, and Control treatments were used for collecting data according to FFS protocols (McIver et al. 2009; Weatherspoon & McIver 2000). Because LHPIS did not have a prescribed fire-only treatment, this was added in 2002 as part of the FFS study (hereafter "Fire-only"). The Fire-only treatment was implemented in three, 10-ha units with approximately 100 m treatment buffers that were burned in the fall of 2002 and again in the fall of 2011 under mild weather conditions with moderate fine fuel moisture (10-h fuel moisture averaged 11% in 2001 and 12% in 2010).

Prior to the Antelope fire, strong treatment differences remained in structure and composition in both the overstory and the understory (Fig. 2) (Ritchie 2005). Treatments that included thinning contained 98–120 trees per hectare, five to seven times less than those of

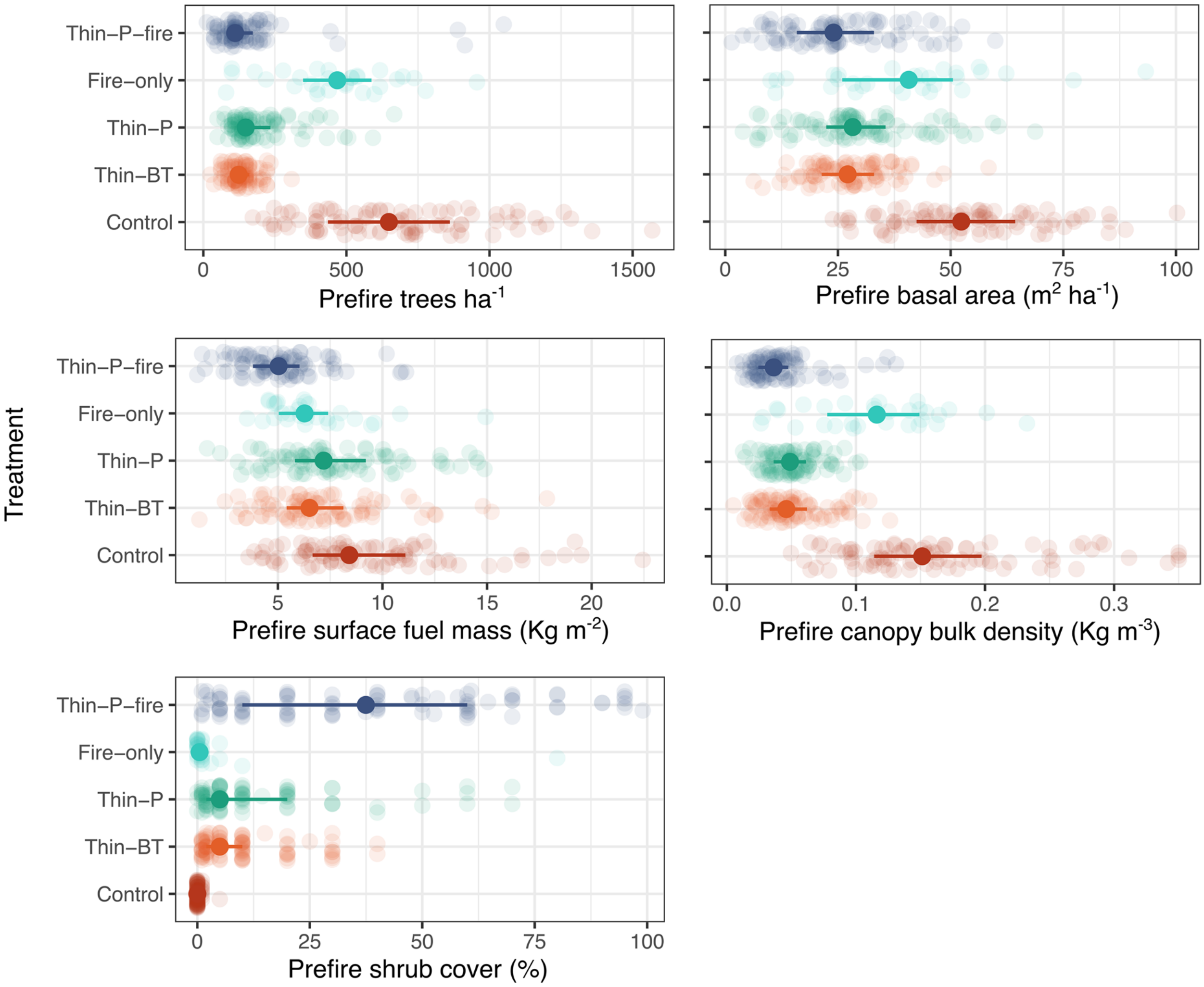

Fig. 2 Pre-fire tree density, basal area, surface fuel mass, canopy bulk density, and shrub cover summarized by treatment type. Large dots represent median, horizontal bars represent interquartile range, and small dots represent plot-level measures. Numerical values are in Additional file 1: Tables S1 and S2

unthinned Control stands. Both Thin-P and Thin-P-fire retained some higher density areas (e.g., planted openings or locations with higher pre-thinning pine density [Table 1]) leading to greater within-stand variation. Prefire variability was less in Thin-BT units, where target spacing between dominant and co-dominant trees was relatively uniform (Table 1). Median large (> 50 cm) tree height was 29 m and did not differ among treatments, but Control and Fire-only treatments contained substantially more pole-sized (9.1–29.2 cm) trees (see Additional file 1: Table S1). Pole-sized trees were not only shorter (median height 10 m), but had median crown base of 3 m compared to 11 m for large trees. Ten years after the last prescribed fire, surface fuel mass remained lowest in the Thin-P-fire treatment (5.0 kg m^{-2}), and highest in the Control treatment (8.4 kg m^{-2}). At the time of the Antelope Fire, the understory was relatively sparse, except in the Thin-P-fire treatment. Common shrub species included snowbrush (*Ceanothus velutinus*), Mahala mat (*Ceanothus prostratus*), greenleaf manzanita (*Arctostaphylos patula*), current (*Ribes* spp.), and big sage brush (*Artemesia tridentata*). The thin-only and Thin-P-fire treatments contained 5 times and 37 times more shrub cover, respectively, than the Control, likely in response to canopy opening (Knapp et al. 2013; Richter et al. 2019) and canopy opening combined with fire-stimulated seed germination (Knapp et al. 2012).

In 2021, the Antelope fire burned through all 23 units of the study. The fire began as a lightning ignition on the Klamath National Forest on August 1st, 2021. On August 4th—the same day the fire reached and began burning through the study units—a red flag warning was put in place and fire activity increased with spot fires observed 0.8 km from the main fire. On August 5th, a state of emergency was declared in Siskiyou County, California, due to the Antelope fire. Extreme fire behavior (spotting up to 1.6 km in front of the fire and flame lengths up to 30 m) continued through August 6th. The Antelope fire burned through the last of the study units on August 9th for a total of 6 days burning in the study area and including extreme, mild, and moderate fire behavior (Figs. 1 and 3). Only two out of 391 measurement plots in the study were outside the final fire perimeter.

Field sampling

Plot size and data collection protocol differed somewhat between LHPIS and FFS, though both surveyed trees (≥ 9.1 cm diameter at 1.37 m tall [DBH]), shrub cover, and surface fuels. For LHPIS, monuments for permanent plots were installed on a 100-m grid in each unit. Vegetation monitoring plots were then installed at every other grid point, or 17–19 per unit, for a total of ~ 90 plots per treatment and 361 plots total (Table 1). In 16-m radius (0.08 ha) circular plots centered at monuments, sawtimber-sized trees (DBH ≥ 29.2 cm) were tagged and DBH, height, and height to base of live crown were measured. In nested 8-m radius (0.02 ha) plots, DBH of pole-sized trees (9.1 to 29.2 cm DBH) were measured. Height and height to base of live crown were only measured on the first two pole-size trees encountered. Shrub cover was measured using a line intercept method (Canfield 1941). Woody surface fuel mass was measured using the planar intercept method, recording 1-, 10-, and 100-h fuels along a 100-m transect as in Brown (1974). Litter and duff depth were measured at six duff pins (large nails pounded into the ground leaving the head flush with the top of the litter) located at 7, 21, 36, 64, 79, and 93 m along the transect. The final measurement before the 2021 Antelope fire occurred in 2019 (Fig. 2).

After the fire, in fall 2021 and spring 2022, trees in LHPIS plots were resampled and data were taken for tree- and plot-level fire severity metrics. At the tree level, each sawtimber- and pole-sized tree was assessed for fire-induced mortality. Trees that had any green needles left on them were considered "live." Percent crown volume consumed (PCVC) and percent crown volume affected (PCVA; combined scorching and consumption in tree canopy) were assessed using ocular estimates, and minimum and maximum bole char height were measured with a laser rangefinder or measuring tape. When the tree was charred to the top, the tree height was recorded for bole char height. At the plot level, ocular estimates were made for likely total pre-fire shrub cover using horizontal photographs taken 23 m south of plot center. In three plots where photographs were not available/missing, values were imputed using parameters from a simple linear regression between ocular estimates of shrub cover and length of shrub cover on the 100 m transect in 2019. Shrub cover transect values were not used throughout because methods differed from FFS protocols, whereas photos were shot the same way across studies and captured a broader view.

For the FFS study (Fire-only treatment), 10 plots were established per unit at selected points on a 50-m grid for a total of 30 plots. These fire-only plots were 20 × 50 m (0.1 ha) rectangles divided evenly into ten, 10 × 10 m (100 m^2) subplots, each including two, 1 m^2 quadrats. In the five even-numbered subplots, trees > 10 cm DBH were measured and tagged and shrub cover was visually estimated. Surface fuel mass was calculated as above using two 20 m transects offset 2 m from the grid point and with small woody fuels (1-, 10-, and 100-h) measured distal to plot center. The last pre-fire measurements of FFS plots were made in 2013. Post-fire measurements were taken for trees and shrubs in fall 2021 and spring 2022 as noted above for LHPIS.

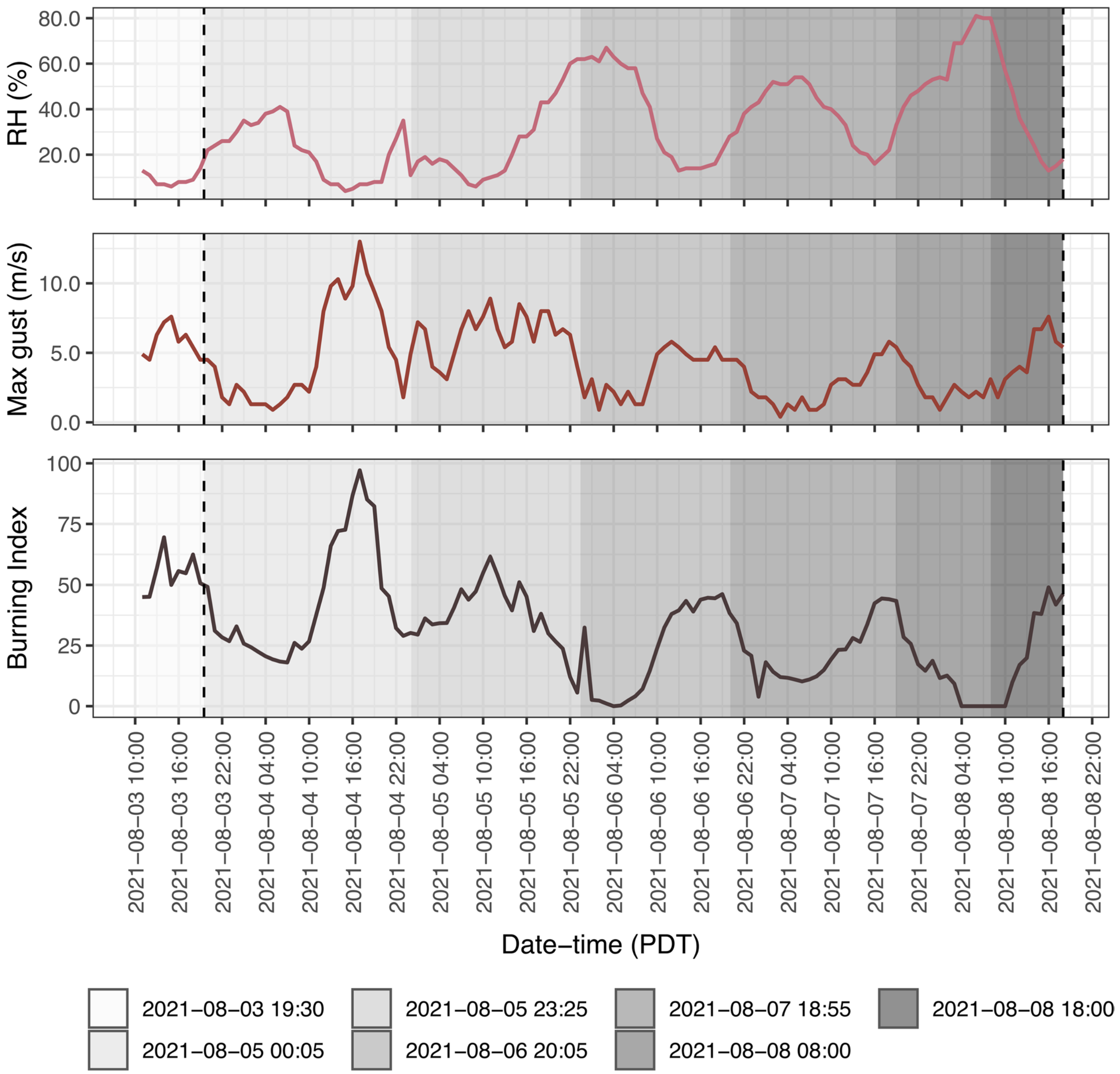

Fig. 3 Fire weather for the days that the Antelope fire burned through the study area. Burning index is shown along with the weather variables that most closely correlate with it: maximum wind gust (Max gust) and relative humidity (RH). Gray shading represents the fire progression periods ending at the flight time indicated

Data acquisition and variables

Time of burning was estimated using fire perimeter data from the National Interagency Fire Center's file transfer site (FTP, https://ftp.wildfire.gov/), which divided the study area into five roughly 24-h fire progression periods (see Fig. 1). Fire perimeters on FTP are generated from tactical infrared flights flown about once a day (usually at night) for use in fire suppression efforts by the incident management team. We error-checked the dates and times on fire perimeters by contacting the infrared interpreter on the incident command team and ensuring that time stamps on perimeters aligned with observations on the ground.

To capture variation in wind, relative humidity, temperature, and fuel moisture during the five progression periods, we calculated burning index using FireFamilyPlus version five and local weather data from the nearby Van Bremmer Remote Automatic Weather Station (RAWS) (Bradshaw & McCormick 2009; Deeming et al. 1977; Western Regional Climate Center 2022) (Fig. 3). Burning index is a unitless measure of potential fire intensity combining elements of fire spread and energy release and can also be conceptualized as ten times the predicted flame length (Cohen & Deeming 1985). The Van Bremmer RAWS is 6 km from the closest study plot and 13 km from the furthest study plot, and we believe its data are representative of the weather at the study site. We chose to use the maximum burning index for each time interval to represent the most extreme weather experienced within that period.

To capture within-treatment variation in surface and canopy fuels, we calculated canopy bulk density (kg/m^3) and surface fuel mass (kg/m^2) at each plot. We used the Forest Vegetation Simulator web version (release date: September 30th, 2022) to calculate canopy bulk density. We calculated small and coarse woody debris mass from fuel transects as in Brown (1974) using species-specific coefficients weighted by unit-level species composition (Van Wagtendonk et al. 1996). We calculated fuel bed mass using the linear relationship between litter and duff depth and dry weight from 50 litter and duff samples collected at GAMA (data not shown) (Van Wagtendonk et al. 1998; Weatherspoon & McIver 2000). Site-specific coefficients were lower than those published previously for Yosemite National Park (Van Wagtendonk et al. 1998) likely due to the comparatively lower productivity at GAMA and the presence of pumice particles that become incorporated within the humus layer over time due to their tendency to float during precipitation events. Lastly, because pre-fire data were collected in 2019 and 2013 for LHPIS and only in 2013 for FFS, we corrected for accumulation of fuels in Fire-only plots by adding the average plot-level change in fuels between 2013 and 2019 from Thin-P-fire plots: a difference of 2.4 kg/m^2 for surface fuels and 0.0 kg/m^3 for canopy bulk density.

Statistical modeling

To study how weather impacted the effects of treatment on fire severity, we modeled each of the four tree-level fire severity metrics (mortality, bole char height, PCVC, and PCVA) using the interaction of treatment and burning index. To better understand within-treatment variation and the relative influence of surface and canopy fuels on different fire severity response variables, we replicated each model replacing the burning index—treatment interaction with the interaction of burning index and both surface fuel mass and canopy bulk density. Each model also contained categorical predictors to account for variation in tree size (DBH) and species, which have demonstrated effects on tree-level fire severity metrics (Safford et al. 2012), as well as pre-fire shrub cover, which can contribute to fire activity (Lydersen et al. 2014).

Fire is a contagious process that may create its own weather, reinforcing activity especially in high severity areas and leading to spatial autocorrelation in the fire severity response (Bradstock et al. 2010; Peterson et al. 2017). While it is important and increasingly common to account for spatial autocorrelation when modeling fire severity (Prichard et al. 2020), the spatial term may bias estimates of the coefficients of interest if they are spatially indexed (i.e., weather and treatment/fuels) via a phenomenon known as spatial confounding (Hanks et al. 2015; Hodges & Reich 2010). For example, large high severity patches created during a single wind event may be attributed to the spatial closeness of measurements within the patch, thereby reducing the estimated effect of a wind or weather variable. Though spatial confounding has been recognized and studied for years, no clear solution has been reached. To strike a balance between accounting for the spatial nature of the response and recovering the most accurate estimates of the predictors, we modeled plot geographic coordinates with multivariate spatial smooths using a relatively low number of basis dimensions (15) (Wood 2017). We selected the number of basis dimensions such that meaningful spatial autocorrelation ($|\text{Moran's } I| < 0.25$) was eliminated from model residuals and large high severity patches coinciding with high wind events were identifiable on the smooth surface (Additional file 1: Figure S1). However, we did not allow smooths to fit small high severity patches more likely caused by tree density and surface fuel differences among treatment units. Because treatments were assigned randomly to plots with similar attributes, and because treatments are well-known to change fire behavior within 50 m of a treatment boundary (Ritchie et al. 2007; Safford et al. 2009), we believe that such unit-level differences largely represent a treatment effect.

We used three different model types for the four fire severity responses in our study. For mortality, treated as a zero or one outcome, we used a Bernoulli likelihood with a logit link function. We modeled both PCVC and PCVA as proportions using fractional logistic regression, in which fractional inputs are used in a logistic regression model with Binomial likelihood and logit link. While both PCVA and PCVC are continuous quantities, the binomial response is appropriate here because > 78% of the trees in the study were either fully unaffected or fully affected and the binomial likelihood can accommodate intermediate values. We also conducted analyses of proportions with zero–one-inflated beta models, a relatively common model type for proportional fire severity data (Saberi et al. 2022). However, when we compared models using estimated log pointwise predictive density (ELPD)—an approximation of leave-one-out cross validation—we found that these complex mixture models were not preferred with $\Delta ELPD$ of -985 (standard error 43) for the PCVA treatment model and -817 (standard error 62) for the PCVC treatment model (Vehtari et al. 2017). We modeled average bole char height with a square root transformation on the response and a Gaussian likelihood.

All models were constructed in R version 4.2.2 (R Core Team 2022) using the Bayesian modeling package *brms* (Bürkner 2017). Models were run using four chains with 2000 iterations each and moderately regularizing priors (i.e., Gaussian(0,1) on centered and scaled predictors). We assured adequate sampling by visually assessing trank plots and maintaining Rhat values of 1.01 or below (Bürkner 2018; McElreath 2020). Model fit to sample was evaluated using a series of posterior predictive checks to ensure agreement between a variety of attributes of the focal response variable and model-simulated responses. Contrasts for categorical variables were estimated using the *emmeans* package (Lenth 2023). Marginal effects for continuous variables were calculated using the *tidybayes* package (Kay 2020) at the means of continuous predictors and averaged over the two most numerous species in the study—ponderosa pine and white fir—which make up > 95% of the dataset. To reduce spatial influence for overall predictions, all marginal effects were predicted at the location where the smoothed surface was closest to zero. Because the majority of study units occupy the northeast and southwest quadrants of the surface, if the point closest to zero was in a data poor quadrant we selected the location next closest to zero and so on until the prediction point fell within one of the data-rich quadrants.

Results

While all treatments experienced lower fire severity than controls, reduction in severity was most pronounced for Thin-P-fire (Fig. 4A; Additional file 1: Tables S3-S6). Model-estimated probability of mortality was lower for Thin-P-fire than for Control by 0.60 (95% highest density continuous interval [HDCI] = [0.51, 0.69]) (Fig. 4A). Similarly, the estimated fire severity reduction between Thin-P-fire and Control was 7.38 m (6.42, 8.24) for average bole char height, 86% (76, 95) for crown volume consumed, and 68% (51,81) for crown volume affected (Fig. 4A). The Thin-P-fire treatment mean had low estimated model uncertainty for PCVC because only one tree fully consumed/torched. Across all fire severity response variables, estimates for Thin-BT, Thin-P, and Fire-only treatments were lower than Control and higher than Thin-P-fire.

Within treatments, fire severity response variables generally increased both with increasing pre-fire canopy bulk density and surface fuel loads (Fig. 4B,C; Additional file 1: Tables S7-S10). The exception was PCVC, which was not statistically associated with pre-fire surface fuel loading (Fig. 4C). Predicted marginal fire severity was also consistently lower for the Thin-P-fire treatment than for the lowest measured values of canopy bulk density or surface fuel mass (Fig. 4), indicating that, for individual trees, being in a unit that received Thin-P-fire treatment was more protective than being in a plot with lower relative pre-fire fuel loading irrespective of the treatment the plot received.

Though fire severity generally increased with burning index, the shape of this relationship depended on treatment and the fire severity response variable, and the Thin-P-fire treatment maintained the lowest and most stable fire severity response across burning index (Fig. 5A; Table Additional file 1: Tables S3-S6). Similar to model predictions for treatment main effects, the Control treatment formed the upper bound of fire severity marginal response for interactions (Fig. 5A). The exception to the trend of increasing severity with burning index occurred in the Thin-P treatment, for which average bole char height, PCVC, and PCVA declined with burning index (respective marginal slopes = -0.30 [$-0.43, -0.18$]; -0.13 [$-0.19, -0.08$]; -0.10 [$-0.18, -0.04$]). For the Fire-only treatment, PCVC also declined with burning index (marginal slope = -0.19 [$-0.32, -0.06$]) (Fig. 5A). Any observed decline of fire severity with burning index is unrealistic and we therefore expect that trends in these four cases were due to local factors that were not accounted for in the data such as variations in weather conditions at time scales shorter than the once-daily infrared imaging.

Plots with lower canopy bulk density had lower fire severity values that were more stable across burning index for all fire severity response variables (Fig. 5B). In other words, the difference in severity between low (15th percentile) and high (85th percentile) canopy bulk density plots increased as fire weather became more extreme (higher burning index). For surface fuel mass, fire severity generally increased across burning index with the same slope regardless of pre-fire values (Fig. 5C). The one exception to this was PCVA, for which the difference between 15 and 85th percentile surface fuel loads was unimodal across burning index.

To visualize the shape of the relationship between fuel treatment effectiveness and fire weather, we plotted the differences in model predictions between the most effective treatment (Thin-P-fire) and the Control (Fig. 6). We found unimodal or plateaued relationships between fire weather and fuel treatment effectiveness for tree mortality and PCVA, meaning that fuel treatment effectiveness was greatest at moderate to high-moderate burning index (Fig. 6). For bole char height

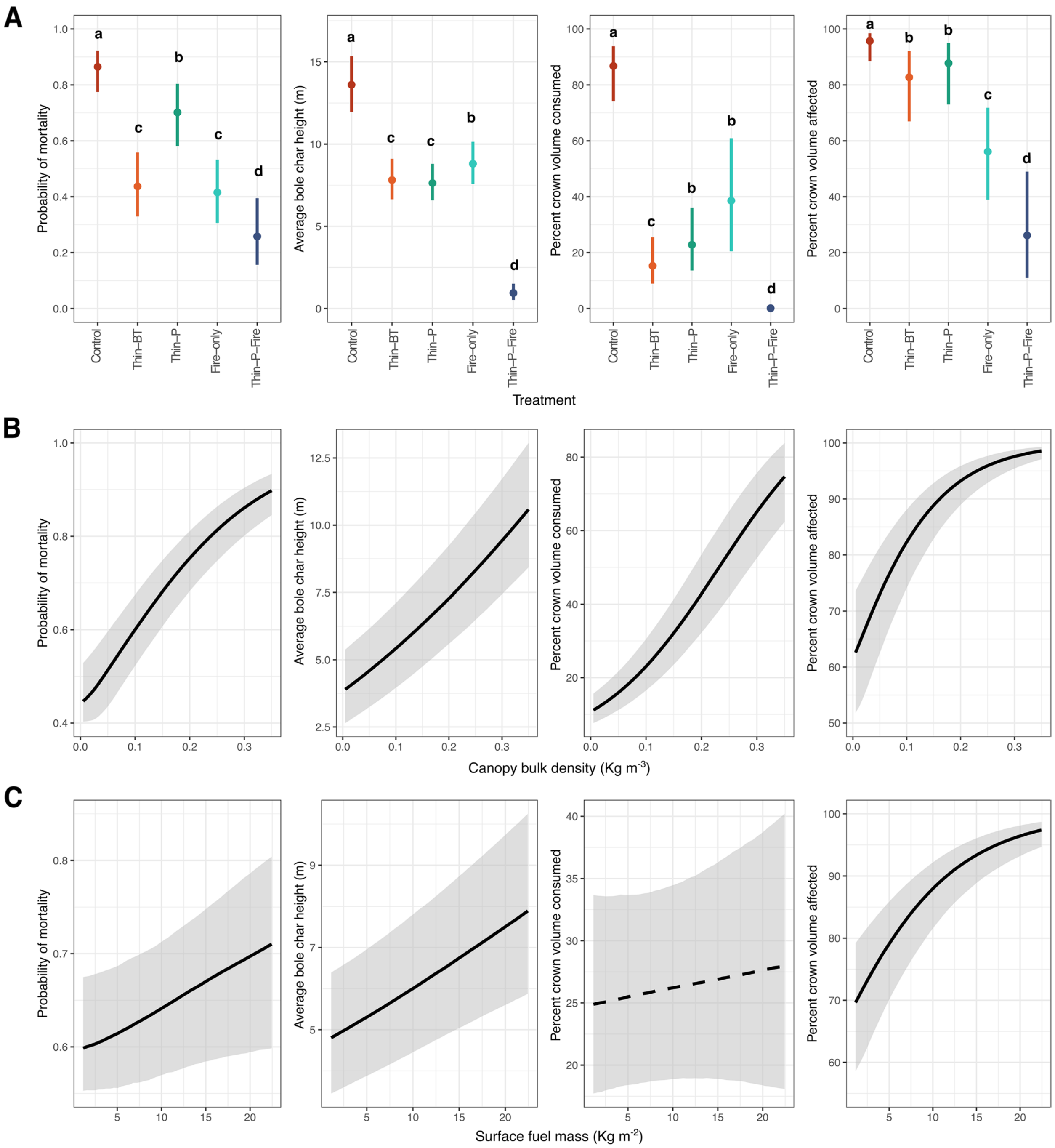

Fig. 4 Model-estimated marginal effects for **A** treatment, **B** canopy bulk density, and **C** surface fuel mass for four fire severity metrics: mortality, average bole char height, percent crown volume consumed, and percent crown volume affected. Dots and horizontal lines indicate predicted means. Vertical lines and shading represent 95% credible intervals for the mean. In **A**, letters indicate that 95% credible intervals for differences between treatment groups do not cross zero. In **B** and **C**, solid lines indicate that the 95% credible interval for the coefficient does not cross zero

and PCVC, we found plateaued to increasing relationships between fuel treatment effectiveness and fire weather, meaning that fuel treatment effectiveness continued to improve as burning index increased (Fig. 6).

We also found strong associations between fire severity metrics and non-focal predictors. Across all models, trees in plots with higher pre-fire shrub cover experienced reduced fire severity (Additional file 1: Tables S3-S10).

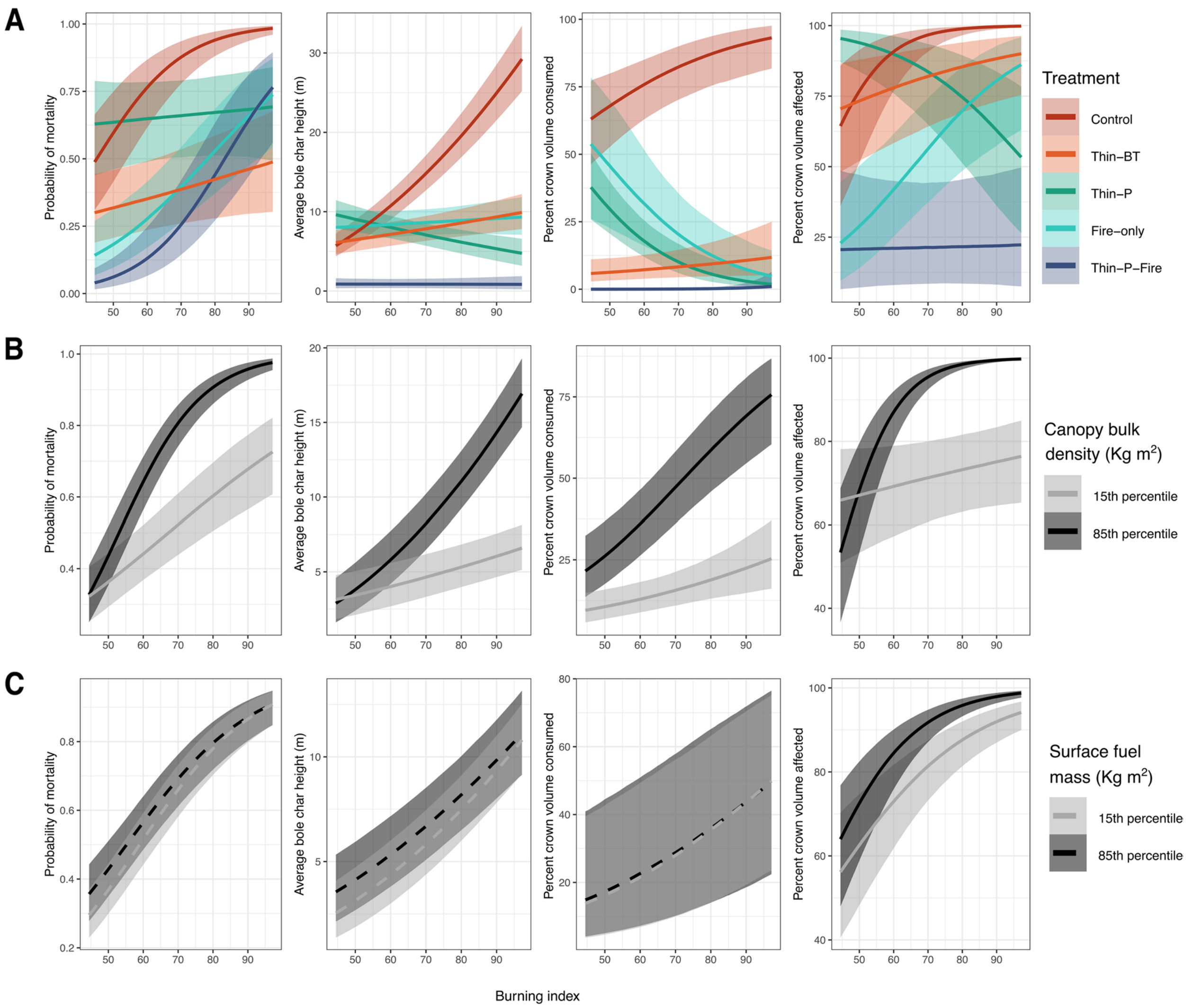

Fig. 5 Model-estimated marginal effects for the interaction between burning index and **A** treatment, **B** canopy bulk density, and **C** surface fuel mass shown for four fire severity metrics: mortality, average bole char height, percent crown volume consumed, and percent crown volume affected. Lines and shading indicate predicted means and 95% credible intervals. Solid lines indicate that 95% credible intervals for interaction coefficient do not cross zero

Larger trees were less likely to die and had reduced percentages of crown volume consumed and affected (Additional file 1: Tables S3, S5, S6, and S8-S10). However, because larger trees were also taller, they had greater absolute bole char heights (Additional file 1: Tables S4 and S7). Similarly, white fir (a species with a lower relative DBH in this dataset) had lower estimated bole char height than ponderosa pine in both models, and than sugar pine and incense cedar in the treatment and pre-fire fuel models respectively (Additional file 1: Tables S4 and S6). However, in both treatment and pre-fire fuel models, white fir had greater estimated mortality and PCVA than ponderosa pine and incense cedar, and sugar pine had greater mortality than ponderosa pine (Additional file 1: Tables S3, S6, S7, and S10). There was no evidence for a difference in PCVC among species (Additional file 1: Tables S3-S10).

Discussion

Although there have been many previous retrospective studies of burn severity, this is the first large-scale study of randomized and replicated thinning and prescribed fire treatments that we are aware of to burn almost entirely in a wildfire. We found that fuel treatments reduced tree mortality, bole char height, crown consumption, and crown scorching despite considerable time since treatment—20 years since mechanical thinning and 10 years since the last prescribed fire. In

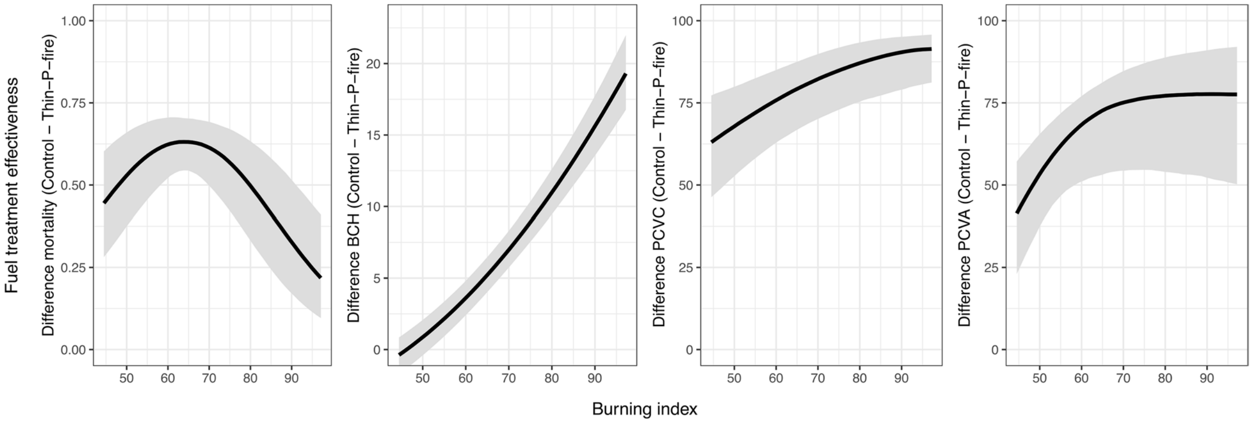

Fig. 6 Fuel treatment effectiveness across burning index. Fuel treatment effectiveness is shown here as the differences from Fig. 5 between Control and Thin-P-Fire for four fire severity response variables: tree mortality probability, average bole char height (BCH), percent crown volume consumed (PCVC), and percent crown volume affected (PCVA)

alignment with other studies (Fulé et al. 2012; Kalies & Yocom Kent 2016), we found that the combination of crown fuel reduction (thinning) and surface fuel reduction (prescribed burning) was by far the most effective treatment (Fig. 7). Further, absolute pre-fire canopy fuels were positively associated with all four fire severity response variables and pre-fire surface fuels were positively associated all fire severity response variables except crown consumption. Plots with lower pre-fire canopy fuels and those in units that received both mechanical thinning and prescribed fire also conferred greater stability and lower fire severity under extreme weather. Our findings are relevant in part because they provide strong empirical evidence that mechanical thinning of midstory and co-dominant trees mitigates fire behavior and resulting fire severity.

Despite numerous studies documenting the ameliorative effects of fuel treatments on subsequent wildfire severity, opponents of forest fuel management frequently cite papers highlighting the influence of thinning on within-stand microclimate (e.g., Banerjee et al. 2020; Countryman 1956) as evidence of the potential for fuel treatments to increase fire hazard. While reducing stand density can lead to greater surface fuel drying (Kane 2021; Whitehead et al. 2006) and higher surface wind speeds (Bigelow & North 2012; Russell et al. 2018), our data provide clear evidence that the suppressing effect of crown fuel reduction far outweighed any enhancing effect of increased drying or higher windspeeds on fire behavior. While outcomes are specific to forest type, treatment type, and treatment execution (i.e., whether there is abundant slash production), this finding is in line with other reports (Weatherspoon et al. 1996, Agee and Skinner 2005) as well as the numerous documentations of reduced wildfire severity from adjacent treated and untreated areas (e.g., Kalies and Yocum Kent 2016). Further, studies from forests where climate consists of long precipitation-free periods have generally not shown any

Fig. 7 Photo showing fire severity outcomes for one untreated Control unit (to the left of the road) and one adjacent Thin-P-fire unit (to the right of the road). Besides reduction in severity due to lower surface and canopy fuel loads, slower fire spread rate likely also resulted in a change in fire spread direction, from a head fire in the control to a flanking fire in the treated area. Additional photos of representative treatment outcomes are in Additional file 1: Figure S2

significant difference in woody fuel moisture between thinned and unthinned stands during wildfire season, when fuel moistures are at their seasonal lows (Bigelow & North 2012; Estes et al. 2012; Faiella & Bailey 2007). Overall, our results support findings that forests with much lower tree densities and surface fuel loadings than those in contemporary stands will be more resilient under a warming and drying climate (North et al. 2022; Stephens et al. 2020).

One proposed benchmark for operational resilience in modern forests is the historical range of variation for forest structure and fuels (North et al. 2022), which was likely achieved by many of the treatments in this study. Pre-Antelope Fire densities in thinned stands (98–120 trees ha^{-1}) were within the estimated historical range of variation for dry mixed conifer forest for trees > 10 cm (65–315 trees ha^{-1}) (Knapp et al. 2013; Safford & Stevens 2017; Scholl & Taylor 2006; Taylor 2004). Canopy bulk density in all thinning treatments was about half of the threshold of 0.1 kg m^{-3} thought to predispose stands to a risk of active crown fire behavior (Agee 1996; Graham et al. 1999). Prescribed fire effectively consumes long dead and down material (Knapp et al. 2005), so after two rounds of burning at intervals similar to the 11-year historical fire return, and 10–11 years having transpired since the last burn, surface fuel loading in the Thin-P-Fire treatment at the time of the Antelope Fire was likely close to or within the historical range of variation. Surface fuels in the Fire-only treatment likely exceeded historical values on account of the ingrowth trees killed by the first prescribed burn transitioning to fuel. Thin-only treatments, on the other hand, had been without fire for over a century and surface fuel loading values likely substantially exceeded historical values.

Fuel treatment effectiveness is generally assumed to decline with time after treatment and 20 years is considered close to the end of the practical life of a mechanical thin or prescribed burn (Hood et al. 2020; Prichard et al. 2017; Stephens et al. 2012). Studies of the self-limiting effects of wildfires also find 10 to 20 years to be an approximate cutoff beyond which previous fire perimeters fail to limit future wildfire spread (Collins et al. 2009; Parks et al. 2013, 2015). Even so, we showed that 20-year-old thin-only treatments substantially reduced bole char height and crown consumption compared to controls, providing evidence that even older thinning treatments can help to reduce crown fire behavior or prevent excessive fire severity (Drury 2019). Treatment longevity is related to site productivity, and in many forests—including those found at this study site—it likely takes longer than 20 years for the seedlings and saplings remaining or establishing after treatment to become canopy fuels (Ritchie 2020). Thus, crown fire potential is reduced until the new cohort reaches the canopy, contributing to increasing canopy bulk density and decreasing canopy base height (Agee & Skinner 2005; Van Wagner 1977). Fire intensity, on the other hand, is thought to be largely governed by surface fuel loads (Keane 2015). Greater mass of litter, duff, and dead and downed fuels are correlated with higher overall flame lengths and energy output (Agee & Skinner 2005; Rothermel 1972), which increase the probability of non-consumptive crown damage, or scorching (Varner et al. 2021). Correspondingly, we found that thinning alone mainly changed the proportion of the crown effect involving consumption or torching, but did not change total crown volume affected (combined volume scorched and consumed) compared to controls. Only treatments that included prescribed fire reduced total crown loss. Our results confirm longstanding theoretical relationships (Rothermel 1972; Van Wagner 1977) and provide empirical evidence that in wildfires, canopy fuels are more strongly associated with canopy consumption/torching and surface fuel loads are more strongly associated with crown scorch.

Surface fuel reduction is essential to limiting the combined crown volume scorched and consumed (Prichard et al. 2020; Raymond & Peterson 2005; Safford et al. 2009), which is the best predictor of tree mortality in gymnosperms (Barker et al. 2022; Cansler et al. 2020). While all treatments reduced tree mortality over the controls, we found the lowest mortality rates in combined thinning and prescribed fire treatment, followed by the fire-only treatment. The larger percentage of crown volume consumed and greater bole char heights for the Fire-only treatment suggests that it experienced more intense fire behavior, on average, than the other treatments. Two cycles of prescribed burning alone did not substantially thin the stand or reduce canopy bulk density (Fig. 2), which may help explain this result. Inadequate density and canopy fuel reduction is typical for prescribed burns conducted under milder burning conditions and in long-fire suppressed stands where many trees have reached fire-resistant sizes (Roccaforte et al. 2015; Schmidt et al. 2006). Furthermore, any trees killed by fire then fall to the ground and become fuel (Agee and Skinner 2005), which may have offset some of the immediate fuel reduction benefits of prescribed burning. Unless more stand thinning occurs with subsequent burns and the fire-killed trees are consumed, resilience to these more challenging wildfire conditions may be difficult to achieve.

Our tree mortality findings could change over time if tree death is delayed. Trees in our study were deemed "live" if they had any green needles and a substantial proportion, especially in treatments that did not include prescribed fire, were heavily scorched in the Antelope Fire with only a small amount of crown remaining green. We assessed whether delayed mortality is likely to change the significance of differences in tree mortality among treatments by re-defining live trees as those with 25% or more green crown and re-running models. Though not all trees with over 75% crown volume affected will die (Thies et al. 2008), we found that relaxing the definition of a dead tree eliminated the difference in mortality between the control and the pine emphasis thin treatment, but not the difference in mortality between the control and the thin that emphasized large trees. This result highlights the importance of retaining the largest most fire-resistant trees in forest restoration and wildfire hazard treatments if the goal is forest persistence.

In addition to having the lowest post-fire severity across metrics, the treatment that included both thinning and burning and plots with low pre-fire canopy bulk density were the most stable, sustaining fuel treatment effectiveness across the fire weather extremes sampled here. Our finding is in alignment with other published literature reporting sustained fuel treatment effectiveness under severe fire weather (Prichard & Kennedy 2014). Further, where the interaction between weather and fuel treatment has been tested, there is evidence that fuel treatment effectiveness may even increase with more extreme fire weather (Povak et al. 2020; Prichard et al. 2020; Safford et al. 2012). Safford et al. (2012) reported that the difference in mortality between treated and untreated stands increased with decreasing 10-h fuel moisture across 12 fires in dry mixed conifer forest in California. Using regression-tree analysis on remotely sensed fire severity data for single large fires, Prichard et al. (2020) and Povak et al. (2020) discovered stronger differences between treated and untreated areas under more extreme (even plume-dominated) weather, though only where variable importance was high. In contrast, other studies find little to no difference in fire severity between treated and untreated stands under the most severe fire weather conditions (Lydersen et al. 2014; Graham et al. 2003). Thus, existing literature contains examples of both decline and improvement of fuel treatment effectiveness under extreme fire weather.

Our results provide a possible explanation for such differences in the relationship between weather and fuel treatment effectiveness by demonstrating that this relationship depends on the tree-level fire severity metric used. For tree mortality and percent crown volume affected, we found that top-down effects began to overwhelm the difference between the most effective treatment and the control under extreme fire weather conditions. However, for both bole char height and percent crown consumption, treatment effects grew larger as fire weather became more extreme. That fire severity metrics associated with tree mortality were more sensitive to fire weather than those associated with fire behavior has broad implications for how we define both fire severity and fuel treatment effectiveness (Morgan et al. 2014). Furthermore, such subtleties may not be captured well by commonly used fire severity metrics derived from 30 m resolution Landsat imagery, which are not directly associated with tree-level measures of fire severity (Lydersen et al. 2016; Miller et al. 2009). Despite more severe absolute outcomes under extreme weather, our study builds on existing evidence and helps alleviate concerns that forest health and wildfire mitigation treatments may not be worthwhile under expected future weather conditions (Abatzoglou et al. 2021; Boxall 2019). On the other end of the fire weather spectrum, our results illustrate that under milder burning conditions, positive wildfire outcomes can be achieved in both treated and untreated stands (Boisramé et al. 2017; Huffman et al. 2020). Overall, we emphasize the importance of the fire severity response metric used to explore treatment-weather interactions.

Our ability to use treatment-weather interactions to identify weather thresholds for desired treatment effects was limited by coarse-scale data for time of burning. Fire progression maps on larger fires are typically based on daily infrared flights, often flown at night. While the majority of area within a fire progression period is likely to burn at the time of day when the most severe weather occurs, ~ 24-h fire progression maps still force a single value for weather variables during a burn period that experienced a range of conditions. Furthermore, there is typically more variation in temperature, relative humidity, and wind between night and day than between maximum values from 1 day to the next. Our selection of maximum burning index to characterize the entire period means that some plots are associated with more severe weather values than they experienced at the time of burning. The majority of the study plots also fell within four burn windows, increasing the possibility of spurious associations. For example, if a substantial number of the study plots assigned to the burn period with the highest burning index actually burned under milder conditions at night or in the early morning, it might produce an association between high burning index and low fire severity. Such issues are likely driving unrealistic results in which several fire severity variables for some treatments declined with burning index, which does not align with our understanding of the drivers of fire behavior (Finney 1998). Sub-daily progression maps that provide information about what time of day plots burned would allow for a deeper understanding of treatment-weather interactions.

Shrubs are known for burning with high intensity and contributing greater severity effects under extreme fire weather conditions (Coppoletta et al. 2016; Lydersen et al. 2014). However, we found that high pre-fire shrub cover was strongly associated with lower fire severity outcomes across all models. The three most common shrub species in the study area—snowbrush (*Ceanothus velutinous*), greenleaf manzanita (*Arctostaphylos patula*), and Mahala mat (*Ceanothus prostratus*)—are shade intolerant and have a fire-stimulated seedbank (Conard et al. 1985; Keeley 1987). Pre-fire shrub abundance was by far the highest in the Thin-P-Fire treatment (Fig. 2), where both a suitable light environment and seed scarification by fire occurred. Thin-only treatments, Fire-only, and Control treatments contained far less pre-fire shrub cover due to the lack of either higher light conditions, stimulation of shrub seedbank by fire, or both (Fig. 2). The ameliorative impact of shrub cover on fire severity in this study may be due to higher live fuel moisture levels and generally low rates of litter fall under shrubs, which might have impeded fire's spread. Prostrate ceanothus, in particular, typically does not burn (Ryan et al. 2013), and other common species such as snowbrush and greenleaf manzanita often have a dampening effect on fire behavior under milder fire weather conditions (Jaffe et al. 2021; North et al. 2019), mainly contributing to higher fire intensity and severity when live fuel moistures are low (Agee et al. 2002) and/or winds are strong. Alternatively, it may be that plots with higher shrub cover were more likely to be in the Thin-P-fire treatment, which also had the lowest overall pre-fire surface and canopy fuels.

The same attributes of shrubs that possibly contributed to reduced fire severity under wildfire conditions in this study may make prescribed burning more challenging in the future. Live shrubs and surface fuels associated with shrubs do not burn readily in the higher moisture conditions typical of prescribed burns conducted before and after the main wildfire season (Baeza et al. 2002; Jaffe et al. 2021; Kupfer et al. 2020). Thus, increasing shrub cover with treatment represents a paradox for managers. Opening stands initially facilitates the safe reintroduction of fire, but also may promote vegetation that limits the effectiveness of future prescribed fire. Future prescribed burns in such stands may need to be conducted under drier fuel moisture conditions for fire to spread, reduce fuels, and keep shrub cover in check. The difference in shrub response between the thinned and unthinned treatments also suggests that more gradual or progressive opening of the canopy may allay the shrub response by stimulating germination under shadier conditions that are less amenable to shrub growth (Kern et al. 2013; Matthews 1991). Burning prior to thinning has also been proposed and tested (Weatherspoon 1988), but the added challenges of reintroducing fire to unthinned and unnaturally dense stands as well as the high number of seeds in the seedbank (Knapp et al. 2012) may make this approach impractical.

Conclusions and implications for management

Weight of evidence has long supported the effectiveness of well-implemented fuel treatments at reducing fire severity compared to untreated areas and our results provide the first such evidence that we are aware of from a large-scale experiment with randomized and replicated treatment units. We show that, even 20 years after thinning, lower canopy bulk density limits crown fire behavior in thin-only treatments. Once fire moves into the crown and trees torch, ember production contributes to extreme fire behavior including high spread rates. Thus, there may be some longer-term benefit of thinning alone on moderating fire behavior, even if it does not reduce the proportion of trees dying. However, if the goal is forest persistence in addition to alteration of fire behavior, treatments that include burning are the most effective for limiting crown scorch and tree mortality. Post-fire mortality rates may also be lower in treatments that specifically target the retention of large trees.

Despite coarse data regarding time of burning, we show that differences in bole char height and percentage of crown volume consumed between untreated and treated stands increased with more extreme fire weather. For other variables, maximum benefit of treatment was found under moderate burning conditions (tree mortality proportion), or the relationship plateaued with greatest benefit under moderate to extreme burning conditions (percentage of crown volume affected). Under milder burning conditions (without high winds and/or at higher relative humidity), fire effects were largely beneficial in all treatments, including the untreated controls. If positive outcomes are possible for first-entry fire in mid-summer, this suggests that we are potentially missing significant opportunities for burning under less than extreme conditions at night or during the shoulder seasons. Taking advantage of such times might be necessary to meet aggressive new state and federal goals such as treating 1 million acres a year in California (Forest Management Taskforce 2021; Swain et al. 2023). Overall, our combined results represent overwhelming empirical support for the use of fuel treatments, such as those studied here, to reduce the severity of subsequent wildfire and maintain lower fire severity. Further, our finding that the benefits of fuel treatments are not eliminated by severe fire weather validates the continued use of thinning and burning treatments for forest restoration and enhancing resilience to wildfire even with changing climate and fire regimes.

Abbreviations

GAMA	Goosenest Adaptive Management Area
FFS	Fire and Fire Surrogate Study
LHPIS	Little Horse Peak Interdisciplinary Study
DBH	Diameter at breast height (1.37 m)
PCVA	Percent crown volume affected
PCVC	Percent crown volume consumed

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-023-00241-z.

Additional file 1: Figure S1. Smooth surfaces representing underlying spatial autocorrelation in fire severity for models in Tables S1-S8. Numbered treatment units displayed for reference. **Figure S2.** Representative photos of treatments after the 2021 Antelope fire for Control (a), Thin-BT (b), Thin-P (c), Fire-only (d), and Thin-P-fire (e). Fire severity outcomes were extremely variable within treatments and photos were selected such that ocular estimates of percent crown volume affected matched the mean observed value for each treatment type as closely as possible: 0.81 for Control, 0.66 for Thin-BT, 0.88 for Thin-P, 0.74 for Fire-only, and 0.30 for Thin-P-fire. Note that most of crown volume affected was consumed for controls and scorched for treated areas. **Table S1.** Prefire tree density and basal area median and interquartile range shown by treatment and tree size. **Table S2.** Prefire surface fuel mass, canopy bulk density, and shrub cover median and interquartile range shown by treatment. **Table S3.** Summary for mortality model with treatment effects. **Table S4.** Summary for bole char height model with treatment effects. **Table S5.** Summary for model of percent crown volume consumed with treatment effects. **Table S6.** Summary for model of percent crown volume affected with treatment effects. **Table S7.** Summary for mortality model with prefire fuels. **Table S8.** Summary for bole char height model with prefire fuels. **Table S9.** Summary for model of percent crown volume consumed with prefire fuels. **Table S10.** Summary for model of percent crown volume affected with prefire fuels.

Acknowledgements

We thank the Klamath National Forest for their efforts installing the study units and maintaining them for more than 20 years, and numerous individuals who helped us take advantage of this unique opportunity by assisting with the post-wildfire data collection, including Celeste Abbott, Ben Armstrong, Joseph Birch, Rosemary Bloodnick, Bob Carlson, Joey Chong, Bonni Corcoran, Kaelyn Finley, Drew Gilberti, Ethan Hammett, Elizabeth Hinojosa, Chris Looney, Keli McElroy, Claire Monahan, Virginia Price, Kaitlyn Toledo, and Katherine Wood.

Authors' contributions

EEK and MWR participated in design of existing experiments at GAMA. EGB, EEK, and SAD conceived of study goals and questions. EGB, EEK, MWR, and WB consulted on and performed analysis. EGB wrote the majority of the manuscript and all authors contributed substantially to revisions.

Funding

Funding for post-wildfire measurements was supported by the California Department of Forestry and Fire Protection (Grant number 8GG19804) as part of the California Climate Investments Program and by the USDA Forest Service Pacific Southwest Research Station. Post-treatment but pre-wildfire data collection was funded, in part, by the National Fire Plan and the USDA/DOI Joint Fire Science Program (National Fire and Fire Surrogate Study).

Availability of data and materials

The data used to draw conclusions in this paper are currently in use by the authors and will be published in their entirety simultaneous with the final in-progress publication. Until that time, the data may be accessed upon request from the corresponding author.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Received: 22 August 2023 Accepted: 14 December 2023

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