FINAL REPORT

Fuel treatment effectiveness in the Caldor Fire (2021) perimeter, Lake Tahoe, California: a report to the Tahoe Science Advisory Council, the League to Save Lake Tahoe, and The Tahoe Fund

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Executive Summary

We investigated the effectiveness of forest fuel reduction treatments in mitigating fire severity and reducing tree mortality in wildland urban interface environments during the Caldor Fire (2021) in the Lake Tahoe Basin, California. We found that: (1) Across all treatment types, trees were 3x more likely to survive fire in treated areas, and three of five forest stand-level fire severity measures (crown scorch percent, crown torch percent, torch height) as well as the remotely sensed RdNBR fire severity measure were significantly lower in treated versus untreated areas; (2) The presence of unburned fuel piles in a number of areas led to higher than expected fire severity and tree mortality in those areas and resulted in higher scorch height and bole char height than in neighboring untreated forest; and (3) The most effective fuel treatment – which surprisingly did not include prescribed fire or pile burning – was multiple entry (pre-2005 and 2019) mechanical and hand thinning followed by mastication (with a 15-cm maximum fuel depth restriction). Hand thinning and fuel piling followed by pile burning was also an effective treatment. Important considerations related to these findings and others are discussed in the main text.

Introduction

In fire-prone conifer forests in the western United States, the mean annual area impacted by severe wildfire (where >75% of canopy biomass is killed) has increased notably over the last four decades (Parks and Abatzoglou 2020, Parks et al. 2023). The trend has been particularly well-documented in California, where 2018 burned 2x more area at high severity than the next most severe year (2014), and the years 2020 and 2021 burned more area at high severity than the preceding 28 years combined (Miller et al. 2009, Mallek et al. 2013, Steel et al. 2015, Williams et al. 2023). These trends are increasingly threatening forest sustainability and multiple important ecosystem services (e.g., Miller et al. 2018, Richter et al. 2019, Dove et al. 2020). At the same time, the rising severity of wildfires has been accompanied by an increase in destructiveness. In California alone, an annual average of 8500 structures (c. 60% homes) was destroyed by wildfire between 2015 and 2021, and insured losses have been in the $10s of billions (Safford et al. 2022).

In response, federal, state, and local land and fire management agencies have redoubled efforts to reduce fuels in the wildland urban interface (WUI), where 10s of millions of Americans now live. California is on the front line of the situation: with > ¼ of its population living in the WUI, it has experienced 9 of the 10 most destructive wildfires in US history (https://www.fire.ca.gov/our-impact/statistics). The Lake Tahoe Basin (LTB) on the California-Nevada border is one of the landscapes most threatened by wildfire in the western US. The presence of many fire stations and a high level of readiness in the LTB result in a low average response time to ignitions, and for much of the 20th century forest fires of more than a few hectares in size were unknown in the LTB. This began to change in 2002 with the Gondola and Showers Fires, and then accelerated with the Angora Fire of 2007 and other more recent fires of moderate size. In 2018, 2020 and 2021 the LTB was filled with smoke for much of the summer and early fall, and then in 2021 the Tamarack Fire threatened the basin from the south in July, followed by the huge Caldor Fire a month later, which was the second recorded wildfire to burn across the Sierra Nevada crest (following the Dixie Fire, which accomplished the same feat a day earlier).

The Caldor Fire occurred during a very dry summer under extreme weather conditions. The 2021 water year (October 1 to September 30) was one of the driest in California history, and July through September were the driest on record. Multiple large fires occurred during the summer (including the enormous Dixie Fire, which competed with the Caldor for resources), and fire staffing was a major issue throughout most of the fire's burn period. More than perhaps any other USFS unit in California, the Lake Tahoe Basin Management Unit (LTBMU) has been proactive in reducing fuels and forest density in and adjacent to the WUI. Most of the treatments assessed in this study were part of the South Shore Fuel Reduction and Healthy Forest Restoration Project, which began in 2012 and is just winding down. These WUI fuels treatments neighbored and interfingered with extensive urban fuel reduction work carried out by the LTBMU's Urban Lots program and the California Tahoe Conservancy, and defensible space efforts led by the Tahoe Fire and Fuels Team. Coordination among these efforts was rooted in the LTB Multijurisdictional Fuel Reduction and Wildfire Prevention Strategy (LTB 2014). In sum, these fuel reduction efforts were widely credited with the "miraculous" events of August 30 and 31, when not a single structure was lost when the Caldor Fire entered the LTB at Christmas Valley and Meyers. Fire fighters recounted how fire intensities dropped markedly when the fire encountered treated fuels and how fuels conditions on the ground allowed safe and rapid response to ember-generated ignitions.

Although prefire fuel reduction was a major part of the Christmas Valley "miracle", the actual effectiveness of the fuel treatment network in reducing fire severity and mitigating tree mortality has not been assessed. This question is especially important in the high-profile Lake Tahoe Basin, which is increasingly threatened by severe wildfire and where very high levels of funding are expended on fuel management, but where capacity issues can lead to long surface-fuel residence times after mechanical and hand thinning work is completed. To a great extent, reducing fire severity in a forested landscape equates to reducing the occurrence of crown fire, which further translates into lower fire intensity and flame lengths and reduced spotting distances, and increases the potential for successful direct attack. Importantly, in the yellow pine and mixed conifer forests that dominate the LTB, forest management that reduces stand densities and fuel loadings and proportionally increases the dominance of fire- and drought-tolerant species also equates to ecological restoration (Safford and Stevens 2017, Safford et al. 2021).

Here we report on a scientific investigation of the effectiveness of the fuel treatments in the Meyers and Christmas Valley area in mitigating fire severity and reducing tree mortality. Our work was guided by three major questions:

1. Given the record drought and the severe fire weather conditions at the time of the Caldor Fire, to what extent would prefire fuel reduction reduce tree mortality and fire severity in treated forest stands?

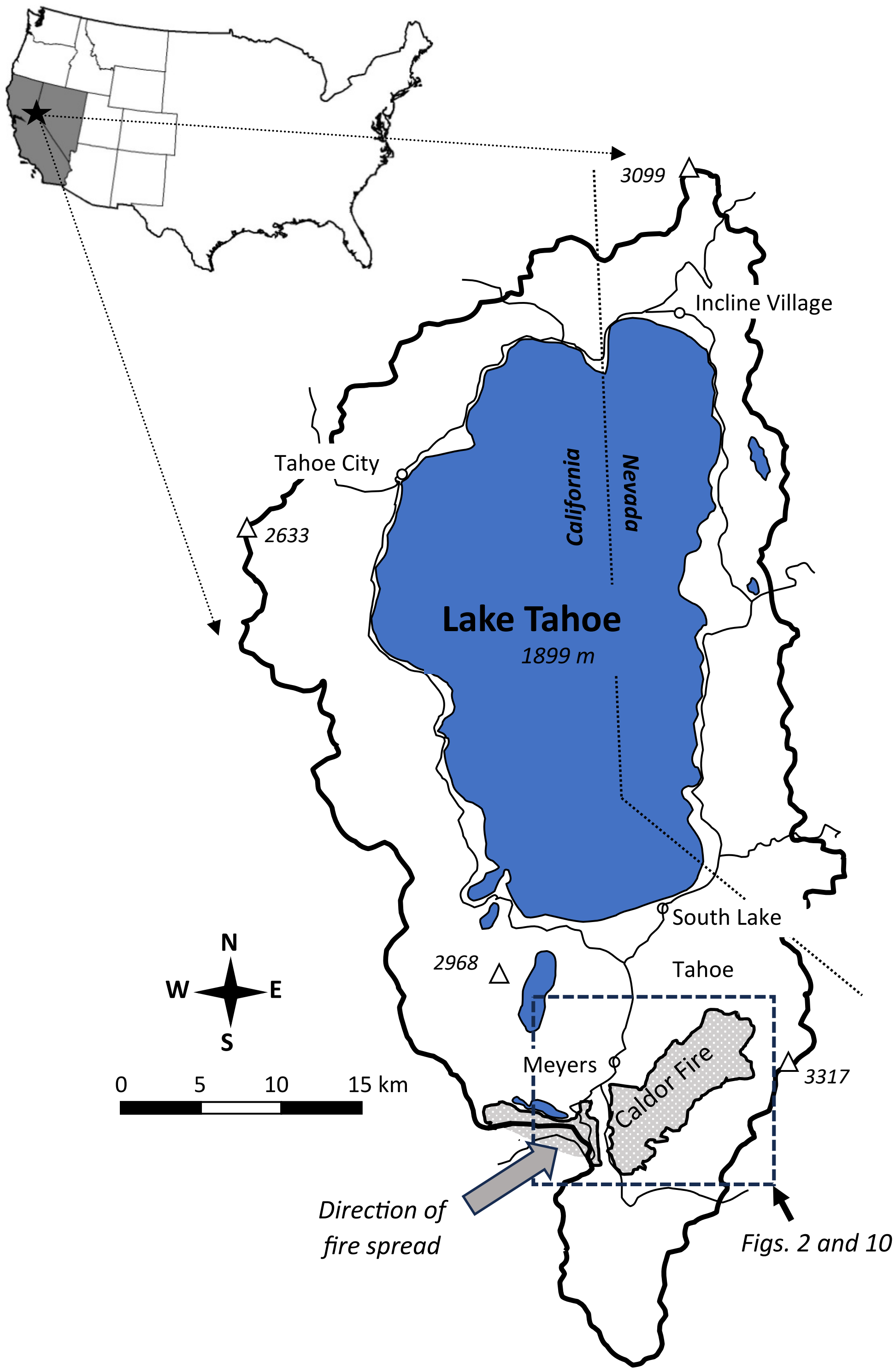


Figure 1. Location of the Caldor Fire in the Lake Tahoe Basin, California and Nevada, USA. Arrow indicates approximate vector of fire arrival from the Eldorado National Forest. Outer polygon demarcates the boundary of the USDA-Forest Service Lake Tahoe Basin Management Unit.

2. Which types of fuel treatment were most successful in mitigating fire severity and tree mortality?
3. What role would the widespread presence of unburned fuel piles in the study area play in explaining postfire conditions?

Materials and Methods

Study Site

The study site is found within the Lake Tahoe Basin (LTB), in the northern Sierra Nevada of California and Nevada, USA (Fig. 1). The LTB is located 240 km ENE of San Francisco and includes 83,000 ha of terrestrial habitats and urban areas and 49,600 ha in Lake Tahoe itself. The study site itself is found south and east of the town of Meyers and east of Christmas Valley (Figures 1 and 2). Elevations within the study site range from 1950 m to about 2300 m. Climate is Mediterranean-type, with warm, dry summers, and cold, wet winters. At the Lake Baron Remote Automated Weather station (1925 m elevation, 1.3 km NW of the study site, record from 2012-2023), the January mean minimum temperature is -8.3 °C, the July mean maximum is 28.8 °C; extreme recorded temperatures are -28.3 and 35.8 °C. Precipitation averages 867 mm per year, with 82% of precipitation falling as snow between November and April (WRCC 2023). The Lake Tahoe Basin Management Unit (LTBMU) of the USDA-Forest Service (USFS) manages all of the lands included in this study.

Forests in the study site are dominated by the conifers Jeffrey pine (*P. jeffreyi*) and white fir (*Abies concolor*), with variable densities of incense cedar (*Calocedrus decurrens*), sugar pine (*P. lambertiana*), lodgepole pine (*P. contorta*), and red fir (*A. magnifica*) (the latter two being more common at the highest elevations we sampled). Broadleaf tree species are found in some wetter areas and include aspen (*Populus tremuloides*) and Scouler's willow (*Salix scouleri*). Common shrubs include a number of *Ceanothus* and *Arctostaphylos* (manzanita) species*, Quercus vaccinifolia* (huckleberry oak), and *Chrysolepis sempervirens* (chinquapin). Bedrock geology is dominated by Cretaceous granodiorite, a few of the easternmost transects also cross areas of Quaternary glacial till and outwash (Saucedo 2004). Soils are dominated by the Cassenai (deep soils on granodiorite colluvium), Cagwin (moderately deep soils on granodiorite), and Meeks (morainal soils) Series, all of which are rocky and somewhat excessively well-drained (CSRL 2023)

The Caldor Fire

The Caldor Fire began on August 14, 2021, as a result of a human ignition near the town of Grizzly Flat, about 40 miles to the WSW of South Lake Tahoe. The fire was extinguished three months later on October 21, after burning 89,773 hectares. The fire entered the LTB on the evening of August 30, after evacuation of more than 25,000 people from the towns of Meyers, South Lake Tahoe, and outlying neighborhoods. The area of the Caldor Fire in the LTB is indicated in Figure 1.

Fuel treatments in the Caldor Fire area

Forest management activities in forest stand compartments sampled by this study were carried out before 2005, and then again between 2012 and 2019 (Table 1). In stands sampled by four of our transects (Transects 11, 16, and half of 11 and 13), mechanical commercial thinning (timber harvest activities with selective cutting, 76.2 cm dbh limit; "CT" in Table 1) and precommercial thinning (usually hand thinning; "PCT") operations were carried out in ~2002 (these treatments are not in the USFS FACTS database and we are searching for more information); in 2019 these stands subsequently experienced mechanized cut-to-length operations ("CTL"; maximum 76.2 cm dbh, but very few trees were anywhere near this size), followed by mastication ("Mast") of activity fuels left from the CTL operation, found mostly along the forwarding trails (see Walker et al. 2011 for a description of this

Table 1. Transect information, including transect number, forest stand compartment number, treatment name, harvest and fuel treatment dates and methods, years since treatment, and pre- and immediate post-treatment measurements of forest structure, tree size, and fuels. In the "Pile burn completed" column, gray cells indicate transect-halves that sampled forest where unburned fuel piles were still on site when the Caldor Fire burned the study site. See text for descriptions of treatment and data collection methods.

Transect	Treatment stand compartment	Notes	Treatment Name	Pre-2005 timber harvest*	Fuel treatment*	Date	Pile burn completed	Pile Burn Date	Additional/Notes	Fuel treatment prescription†	Year since first entry	Years since first fuel treatment	Years since last fuel treatment	Pretreat basal area (m^2/ha)	Pretreat dead volume (m^3/ha)	Pretreat mean dia (cm)	Pretreat density (trees/ha)	Pretreat SDI	Pretreat canopy cover (%)	Pretreat fuels (tons/ha)	Post-treat basal area (m^2/ha)	Post-treat density (trees/ha)	Post-treat fuels (tons/ha)
1	91		Monitor		HT/Pile	9/15/2016	No	n/a	10% of 91 pile-burned, but did not intersect transect	leave 247 TPH	5	5	5	46.6	55.9	27.9	706.4	354	57	44.5	35.6	247.0	not measured
2	91	Untreated portion of transect found on very steep and rocky, cliff-broken ground with low tree densities and physiographic protection of trees from fire	Monitor		HT/Pile	9/15/2016	No	n/a	Ibid.	leave 247 TPH	5	5	5	46.6	55.9	27.9	706.4	354	57	44.5	35.6	247.0	not measured
3	91 (Pts 1-5), 1091 (Pts 6-10)	Does not sample untreated forest, but rather two different treatments	Monitor (91)		HT/Pile	9/15/2016	No	n/a	Ibid.	leave 247 TPH	5	5	5	46.6	55.9	27.9	706.4	354	57	44.5	35.6	247.0	not measured
			Twin Peaks (1091)		HT/Pile	11/8/2012	Yes	10/11/2016		leave 173 TPH	9	9	5	46.6	55.9	27.9	706.4	354	57	44.5	30.5	158.1	24.7
4	90 (Pt 10 possibly in 1091)		Twin Peaks (90, see line above for 1091)		HT/Pile	11/8/2012	Yes	10/15/2016		leave 247 TPH	9	9	5	62.4	89.7	35.6	624.9	436	66	44.5	50.5	247.0	22.2
5	94	Improperly installed, runs across slope, begins in treated, crosses to untreated, then back into treated	Toads		HT/Pile	8/26/2013	Yes	1/16/2018		leave 173 TPH	8	8	3	31.7	97.6	35.6	358.2	227	43	39.5	22.9	170.4	17.3
6	94	Improperly installed, runs across slope,uneven numbers of treated and untreated sampling points	Toads		HT/Pile	8/26/2013	Yes	1/16/2018		leave 173 TPH	8	8	3	31.7	97.6	35.6	358.2	227	43	39.5	22.9	170.4	17.3
7	92		Up Truck 2015		HT/Pile	6/2/2016	No	n/a		leave 173 TPH	5	5	5	30.0	94.3	48.3	168.0	187	34	86.5	29.8	160.6	not measured
8	1036		Monitor II		HT/Pile	10/21/2016	No	n/a		leave 173 TPH	5	5	5	31.4	129.9	38.1	269.2	213	38	37.1	Unknown	172.9	not measured
9	37	FACTS does not show 2018 burn, but this site did not have hand piles at the time of the Caldor Fire and other nearby treatments were burned in 2018 (Safford, pers. obs)	Force Account 2013		HT/Pile	6/6/2013	Yes	1/2018?		leave 173 TPH	8	8	3	56.9	24.2	43.2	377.9	367	65	37.1	48.2	237.1	not measured
10	10 (Pts 1-5), 193 (Pts 6-10)	Does not sample untreated forest, but rather two different treatments; Pioneer treatment had additional underburn in 2007	Pioneer (10)		HT/Pile	6/20/2002	Yes	12/20/2002	Underburn 2007	No info	19	19	14	No info	No info	No info	No info	No info	No info	No info	No info	No info	not measured
			Osgood (193)	CT and PCT 2002	CTL/Mast	7/26/2019	No	n/a		Leave 41.3 BA	19	2	2	51.6	21.3	22.9	1207.8	427	58	37.1	48.9	249.5	not measured
11	193		Osgood	CT and PCT 2002	CTL/Mast	7/26/2019	No	n/a		Leave 41.3 BA	19	2	2	51.6	21.3	22.9	1207.8	427	58	37.1	48.9	249.5	not measured
12	90	Untreated portion of transect found on very steep and rocky, cliff-broken ground with low tree densities and physiographic protection of trees from fire	Twin Peaks		HT/Pile	11/8/2012	Yes	10/15/2016	Unburned piles at center of 90	leave 247 TPH	9	9	5	62.4	89.7	35.6	624.9	436	66	44.5	50.5	247.0	22.2
13	194 (Pts 1-5), 192 (Pts 6-10)	Does not sample untreated forest, but rather two different treatments	Lily Lake (194)		HT/Pile	12/29/2017	No	n/a		leave 247 TPH	4	4	4	41.1	9.8	17.8	1605.5	375	58	93.9	36.2	279.1	not measured
			Osgood (192)	CT and PCT 2002	CTL/Mast	11/8/2019	No	n/a		Leave 41.3 BA	19	2	2	50.7	44.3	22.9	1281.9	426	64	93.9	41.3	Unknown	not measured
14	88		Saxon HT 2017		HT/Pile	7/8/2019	No	n/a		leave 247 TPH	2	2	2	49.5	51.1	40.6	363.1	326	51	54.3	44.0	227.2	not measured
15	1192	Untreated portion of transect found on very steep and rocky, cliff-broken ground with low tree densities and physiographic protection of trees from fire	Lily Lake		HT/Pile	12/29/2017	No	n/a		Leave 420 TPH	4	4	4	50.7	44.3	22.9	1281.9	426	64	93.9	Unknown	419.9	not measured
16	192 (but Pt 6 and maybe 7 in 1192)		Lily Lake (1192)		HT/Pile	12/29/2017	No	n/a		Leave 420 TPH	4	4	4	50.7	44.3	22.9	1281.9	426	64	93.9	Unknown	419.9	not measured
			Osgood (192)	CT and PCT 2002	CTL/Mast	11/8/2019	No	n/a		Leave 41.3 BA	19	2	2	50.7	44.3	22.9	1281.9	426	64	93.9	41.3	Unknown	not measured
17	59		Twin Peaks		HT/Pile	11/8/2012	Yes	10/28/2016		Take all WF up to 15-cm dbh and thin all species up to 35.5-cm, leaving 247 TPH	9	9	5	58.0	112.5	22.9	1585.7	494	65	130.9	Unknown	Unknown	not measured
18	83		Fountain		HT/Pile	9/18/2016	Yes	1/18/2018		leave 173 TPH	5	5	3	39.4	38.1	25.4	810.2	318	50	49.4	33.3	195.1	22.2
19	94		Toads		HT/Pile	8/26/2013	Yes	1/16/2018		leave 173 TPH	8	8	3	31.7	97.6	33	358.2	355	43	39.5	22.9	170.4	17.3
20	94	Untreated portion of transect found on very steep and rocky, cliff-broken ground with low tree densities and physiographic protection of trees from fire	Toads		HT/Pile	8/26/2013	Yes	1/16/2018		leave 173 TPH	8	8	3	31.7	97.6	33	358.2	355	43	39.5	22.9	170.4	17.3

* CT = commercial thin; PCT = pre-commercial thin (usually hand thinning); HT/Pile = hand thin followed by piling of fuels.

† TPH = trees per hectare; BA = basal area in m^2/ha

fuel reduction technique); masticated materials were limited to an average of 15 cm depth and redistribution of surface fuels or piling and burning were carried out where necessary. All other transects sampled forest stands where the first treatment consisted of hand-thinning ("HT") of marked trees up to 35.6 cm dbh, followed by cutting and piling of thinned material and other activity fuels. Second entry fuel-pile burning occurred in 2016 and 2018 in stands sampled by nine of our transects but was not completed before the Caldor Fire in the remaining hand-thinned stands (Table 1). One transect (10) had half of its length hand-thinned, piled, and pile burned in 2002, with a subsequent underburn in 2007.

Field Methods

Pre-treatment measurements were made in 2006 and 2007 by the USFS as part of data collection for the Lake Tahoe South Shore Project on LTBMU lands. Variable radius ("plotless") data collection methods were used for trees ≥12.7 cm dbh, and ~40 m^2 fixed plots were used to measure trees <12.7 cm dbh. Plotless and plot-based methods were performed from the same centerpoint. Each data collection point represented an area of approximately 4 ha, and measurements were averaged from these points across each forest stand compartment, a maximum number of 10 plots was sampled in any given stand compartment. Basal area data were collected with a prism or basal area gauge, the approximate volume of standing dead wood was calculated allometrically in Forest Vegetation Simulator (FVS: Crookston and Dixon 2005) from the density and dbh of standing snags, tree density (/ha) was measured in the fixed plots, Stand Density Index and canopy cover were both calculated using FVS. Average tree size includes trees ≥12.7 cm dbh, and tree density includes trees of all diameters. Fuel loadings were estimated using the fuel photo series from Blonski and Schramel (1981), values provided in Table 1 are the sum of fuels of all sizes (1-1000+ hour classes).

Original post-treatment measurements (BA, density, and fuel loadings) were estimated from FVS simulations of the effects of the planned treatment prescription (Table 1). Post-treatment fuel loadings were only estimated for forest stands that were burned. Table 1 also includes notes regarding idiosyncrasies in some of the transects.

Field work related to the assessment of fuel treatment effects and effectiveness was carried out in the fall of 2021 and the summers of 2022 and 2023; this report is based on the results from 2021 (done pro bono) and 2022 (funded principally by TSAC/SNPLMA, The League to Save Lake Tahoe, and the Tahoe Fund). Figure 2 shows the center points of the transects and the fuel treatments they sampled. For those transects installed in 2021 (Transects 1-6), we repeated all tree and fire severity measures in 2022 and we report those data here. We performed the same protocol used in a number of previous studies of fuel treatment effects and effectiveness in California (e.g., Safford et al. 2009, 2012; Stevens et al. 2014, 2015). In summary, we installed 225-m long transects at 20 locations within the footprint of the Caldor Fire in the Lake Tahoe Basin (LTB). Locations were chosen to represent different forest stand compartments and, where possible, different types of treatment. For each stand compartment, transects were centered at random points sited along the boundaries between forest stands that had been treated for fuels and adjacent untreated forest (three exceptions were transects 3, 10, and 13, see below). Transects ran downhill, beginning in untreated forest (except for transects 5 and 6). Along the transects, five sampling points were located in burned untreated forest and five sampling points in burned treated forest, with 25 m separating sampling points (Figure 3). At each point, we carried out a series of tree-based measurements on four trees, choosing the nearest tree ≥ 10 cm dbh in each of the four compass quadrants. Measurements included tree species identification, determination of live or dead status, tree height and dbh, height to live crown (estimate of prefire status); bole-char, scorch, and torch height; and scorch and torch percent. At each

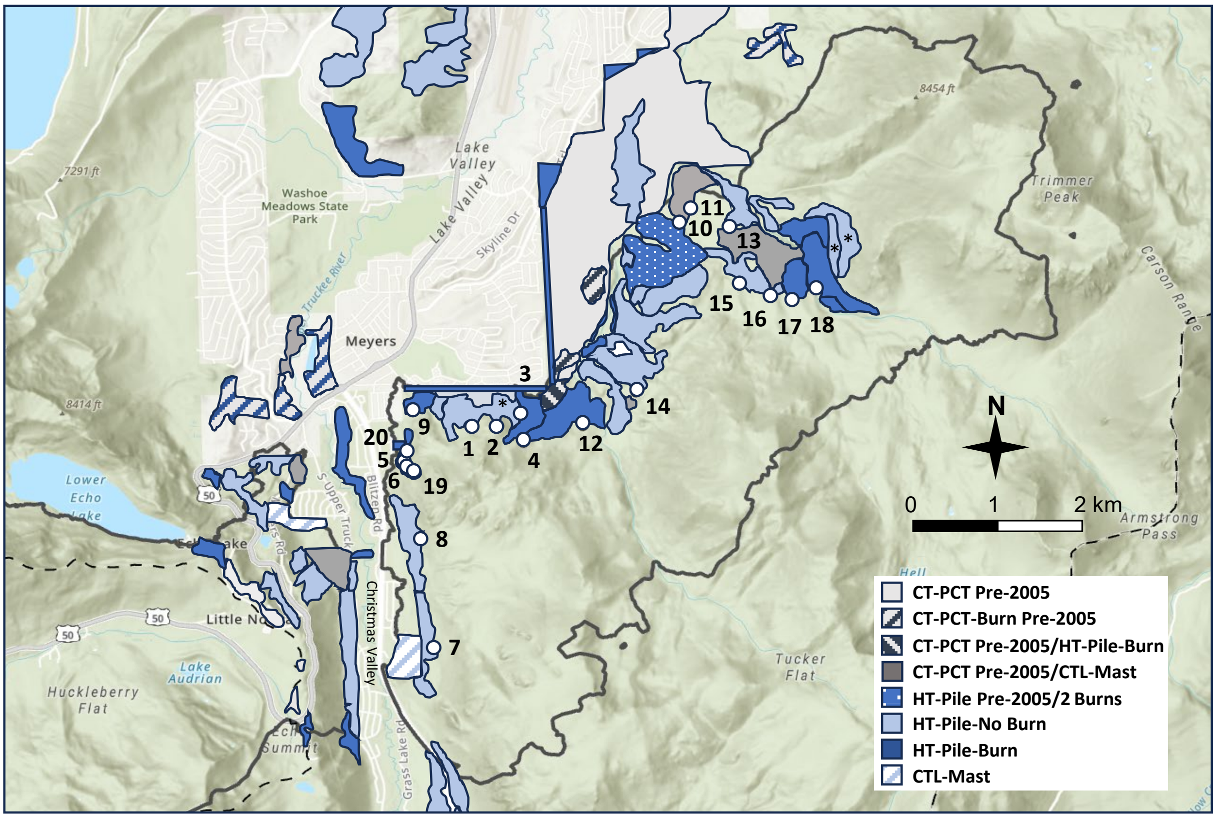


Figure 2. Fuel treatments in the Caldor Fire area and locations of our transects. CT = commercial thinning; PCT = precommercial thinning; HT = hand thinning; CTL = cut to length operations; Mast = mastication. * = these stand compartments were partially pile-burned before the Caldor Fire. 10% of compartment 91 was pile-burned at its NE edge (location of asterisk), but none of our transects (1,2,3) intersected this area.

point we also used a basal area gauge (default basal area factor = 20, but the factor was reduced if < 5 trees were counted) to estimate stand basal area for live and for dead trees; we approximated an 8-mradius plot (200 m^2) with a laser rangefinder and counted the density of live and dead trees $\geq$ 10 cm dbh within that radius; and we measured slope (clinometer) and aspect (compass). We also measured overstory and shrub cover along the entire transect using a line-intercept transect.

At each point we also sampled a 2-m radius circular plot for: ground cover (bare soil, ash, rock, basal vegetation, litter, coarse woody debris [$\geq$ 7.62 cm diameter]), vegetation cover (ocular estimate of herbaceous, shrub, and tree layers), seedlings (ID and number), and plant species (life form, species ID, and ocular cover). We do not report data from these plots in this report.

Note: We also sampled 50 common stand exams (400 m^2 forest inventory plots) in the Meyers/Christmas Valley area, in which comprehensive data were collected on forest structure, tree size and status, plant diversity, ground cover, and fuels. Over 100 similar plots were also sampled in the Eldorado National Forest in the Caldor Fire. Both of these projects were multifunded, with most funding coming from the USFS Region 5 Regional Office. We have not yet analyzed the data collected

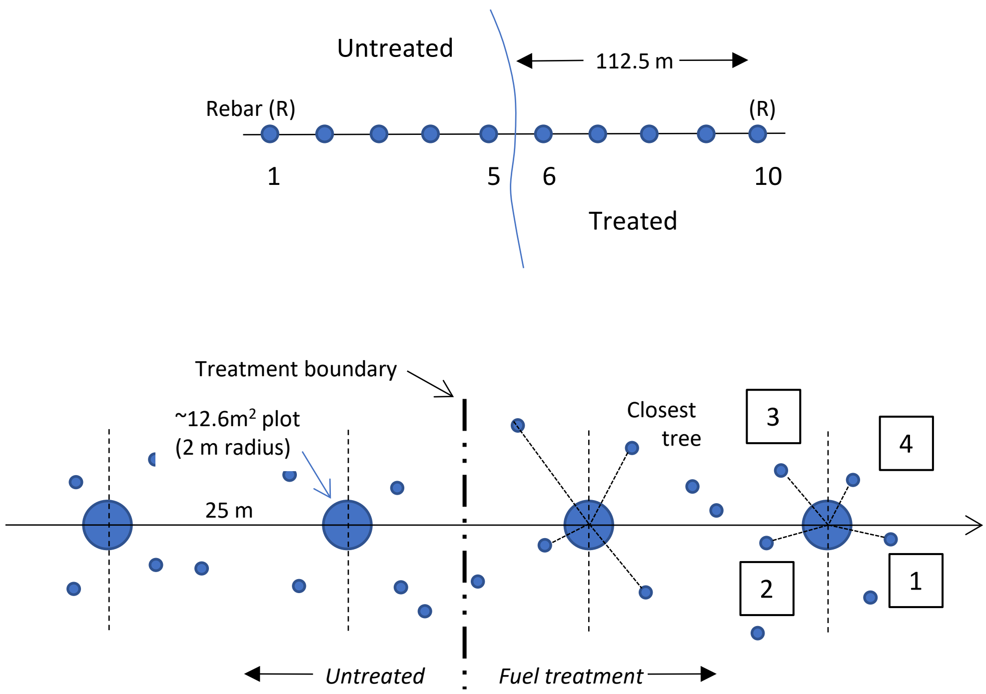


Figure 3. Schematic of fuel treatment effectiveness survey transects. Top: general layout of 225 m transect. Bottom: detail of sampling points and plots on either side of fuel treatment boundary. Transects were always sampled beginning in treated areas and finishing in untreated areas. Numbers in boxes represent order of data collection from nearest trees in each compass quadrant.

in these projects, but the fuels data will be important to our modeling of tree survival and fire severity. We'll probably get to this in the next 3-4 months.

Analytical methods

We carried out statistical analysis in SPSS version 29.02 (IBM 2023) and *R*.

<u>Tree and stand measures</u>

For the prefire condition, we summarized our 2021/2022 data in order to estimate mean prefire stem density, mean prefire relative density by species, and mean prefire basal area for treated and untreated areas (Figure 4). We compared prefire stem density and basal area between treated and untreated forest using the nonparametric Mann-Whitney U Test.

For the post-fire condition, we calculated the percent of trees surviving after fire in treated versus untreated stands and compared them using the Mann-Whitney U Test. We also generated a summary of the percent of trees surviving by species for both untreated and untreated stands. Finally, we calculated the means for five measures of fire severity (percent crown scorch, percent crown torch, scorch height, torch height, and bole char height) for all trees in treated and untreated stands and compared them with the Mann-Whitney Test (Figure 5).

<u>Fuel treatment linear graphs</u>

We generated diagrams comparing percent trees surviving, percent crown scorch, percent crown torch, scorch height, torch height, and bole char height for each transect. In most cases, the diagrams begin in untreated forest (sampling points 1-5, with Pt 1 being the furthest [112.5 m] from the treatment boundary) and finish in treated forest (sampling points 6-10, with Pt 10 being the furthest [112.5 m] from untreated forest) (see Figure 3). In the cases of transects 3, 10, and 13, the transects crossed the boundary between two different treatment types. The diagrams show the mean value calculated from the four trees sampled at each point, along with the standard error in the measure in question (except for the percent survival measure). We also generated summary diagrams for the mean responses across all transects. Before building these diagrams, we removed transects 5 and 6, which were improperly installed and are not comparable to the other transects, and transects 3, 10, and 13, because they did not sample the untreated/treated forest gradient (see Table 1). Additionally, we also built a set of diagrams without transects 2, 12, 15 and 20, as the untreated portions of these transects sampled very steep and rocky, cliff-broken terrain where prefire tree densities were low and protection from fire damage was afforded by the physiography. By removing the untreated half of these abnormal transects from some of our analyses, we are better able to match the background environment of the treated and untreated transect halves and can therefore better assess the effects of fuel management (versus physiography) on resulting patterns. We plan to build statistical models relating these trends with fire severity, stand structure and composition, fuels, and physiographic variables (as in Stevens et al. 2014), but those analyses will not be undertaken for some months.

Fire severity measures

We compared tree survival and fire severity measures in untreated stands versus three types of fuel treatments – HT/Pile-No Burn, HT/Pile + Burn, and "CPCM" (CTL and masticated stands that had also had two thinning entries before 2005) and used the nonparametric Wilcoxon Rank Sum Test to compared untreated forest with the three fuel treatment groups (HT/Pile-No Burn, HT/Pile + Burn, CPCM). We also compared among treatment types using a Nonparametric ANOVA (Kruskal) followed by Dunn comparisons.

We extracted continuous values of RdNBR (Relativized delta Normalized Burn Ratio; Miller and Thode 2007) from the MTBS fire severity map of the Caldor Fire for each point of every transect and compared untreated forest with the three fuel treatment groups (HT/Pile-No Burn, HT/Pile + Burn, CPCM). We compared untreated forest with each of the treatment groups using Wilcoxon Rank Sum Tests, and we compared among treatment types using a Nonparametric ANOVA (Kruskal) followed by Dunn comparisons.

As noted above, we have not yet carried out statistical modeling of survival or fire severity measures, as we are awaiting processing of fuels and other data collected during our parallel common stand exam projects. However we did carry out an exploratory correlation analysis between percent survival and elevation, slope, prefire basal area, and prefire density. We examined Q-Q plots for each variable and subsequently transformed percent survival and percent slope by Arcsin-square root, and density and basal area by Log_{10}.

Results

Prefire, mean stem density (trees/ha) was 250.88 +/- 31.5 (SE) in treated stands and 448.26 +/- 47.2 in untreated stands; this difference was significant at $P < 0.001$ (N = 200, Mann-Whitney std test statistic = 5.317); prefire densities were higher in untreated stands at all but two transects (19 and 20; Figure 4-top). Prefire relative densities were highly variable among species (Figure 4-middle), but white fir was the most common tree in both treatment types, and Jeffrey pine was the second most

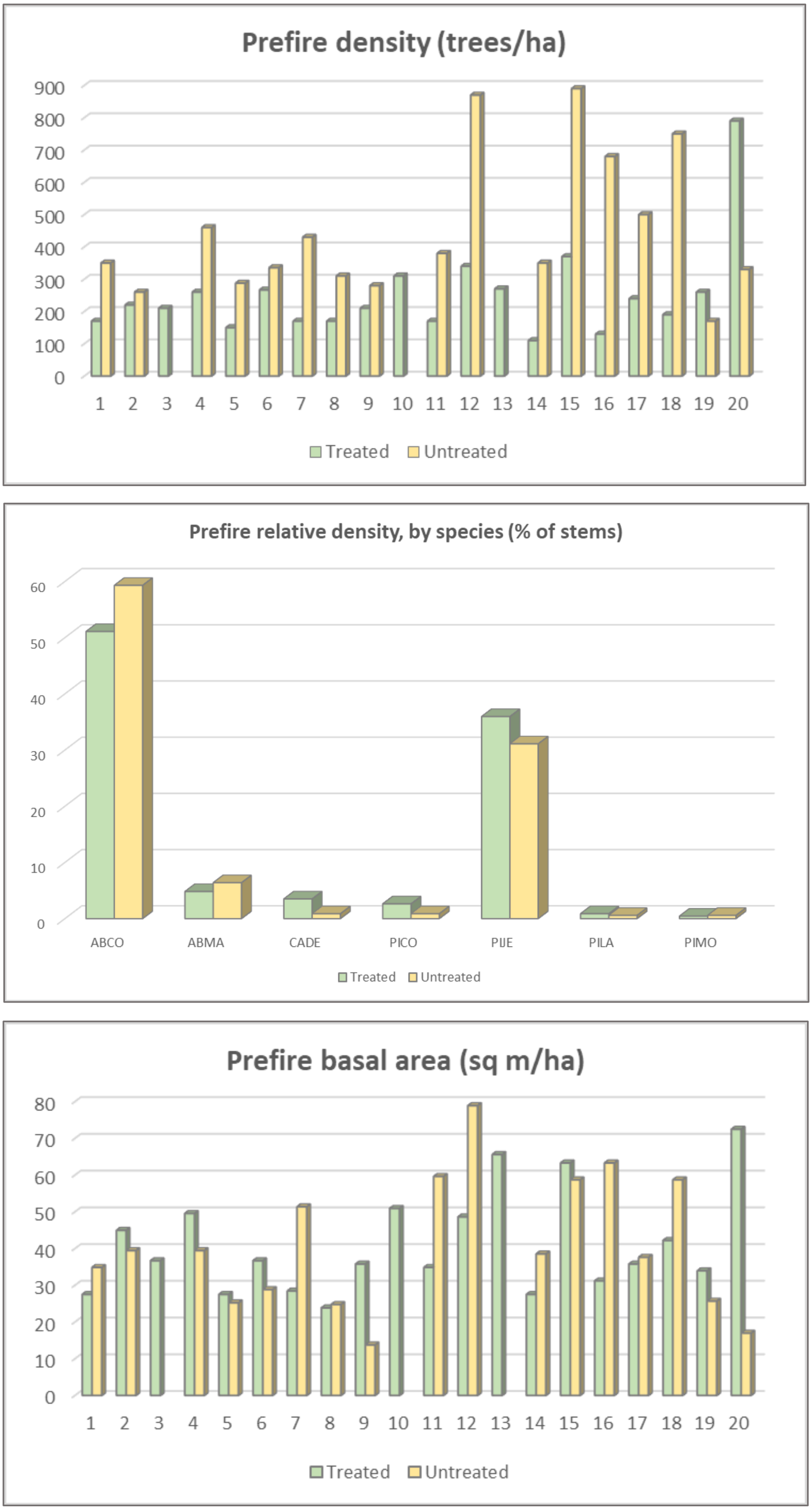


Figure 4. Density, relative density by species, and basal area for treated and untreated forest. ABCO – white fir, ABMA – reed fir, CADE – incense cedar, PICO – lodgepole pine, PIJE – Jeffrey pine, PILA – sugar pine, PIMO – western white pine.

common. Jeffrey pine, incense cedar, lodgepole pine and sugar pine were relatively more common in treated stands, while the two fir species were relatively less common in treated stands. Mean prefire basal areas (m^2/ha) were very variable among transects but were not different between treated (40.87 +/- 3 [SE]) and untreated stands (40.93 +/- 3.9) (Figure 4-bottom).

After fire, the mean percent of trees surviving across all transects at all points was 31.64 +/- 6.5 in treated stands and 11.7 +/- 3.8 in untreated stands (data from 200 m^2 density plots sampled at each transect point); this difference was significant at $P < 0.001$ (N = 200, MW std test statistic = 3.624) (Figure 5-top); transects 2, 12, and 15 showed reversed trends, with more survival in untreated than treated stands (this was driven by the very steep, open, and rocky terrain in the untreated areas of these transects). Sugar pine (50%), Jeffrey pine (48%), and incense cedar (39%) were the best survivors of fire in treated stands, but incense cedar and sugar pine had very small sample sizes compared to Jeffrey pine (18 and 4 total trees versus 164 in treated areas); white fir survived at 27%. Jeffrey pine was by far the best survivor in untreated stands at 26%, white fir survived at 12.3%; we sampled no survivors for any of the other conifer tree species in untreated stands (Figure 5-middle). When we removed from the analysis those transects and points that had unburned fuel piles on the ground at the time of the Caldor Fire (see Table 1) the overall percent survival was 42.2 +/- 4.8 in treated stands and 12.7 +/- 3.3 in untreated stands.

Figure 5-bottom compares five fire severity measures (percent crown scorch, percent crown torch, scorch height, torch height, and bole char height) in treated and untreated stands. Crown scorch and torch, and torch height were significantly higher in untreated stands, but scorch height and bole char height were actually higher in treated stands (sample sizes 782 to 793, in all cases MW std test statistic >3.9 and $P < 0.001$).

Figure 6 is a summary graphic and compares the linear run of tree survival (from the four trees sampled at each transect point) and all of the fire severity metrics, averaged among all transects; graphs depicting percent survival, percent crown scorch, and percent crown torch along the linear run of each transect are provided in the Appendix. The solid blue line (diamonds) in Figure 6 includes all of the transects that included an untreated half and a treated half (as explained in the Methods and Table 1, transects 3, 5, 6, 10, and 13 are excluded). The dashed orange line (squares; “Group 2”) additionally removes data from those transects that sampled very rocky, steep, and sparsely forested stands in their untreated halves (insert Photo) (these are transects 2, 12, 15, and 20; see the Methods and Table 1). The Group 2 data in the graphs show how inclusion of the untreated areas in these transects leads to an underestimate of fire severity, especially at sampling points 1, 2, and 3.

In both transect groups, the overall trend patterns were similar, but in untreated forest survivorship was lower and mean fire severity was higher when the physiographically anomalous transects 2, 12, 15, and 20 were excluded (Group 2 values vs. all transect values; Figure 4). Percent tree survival generally rose with distance from the treatment boundary, from about 15% at the boundary to about 35% 62.5 m into the treated area. Mean percent crown scorch dropped from about 97% at the treatment boundary to 82% 62.5 m from the boundary, while mean torch percent dropped from 45% to <20% within 87.5 m. Mean torch height was about 8 m at the treatment boundary and dropped to about 5 m at 87.5 m along the transect. Scorch height and bole char height did not follow the same pattern as the other mortality and severity measures, and actually rose slightly within the treated areas (Figure 6).

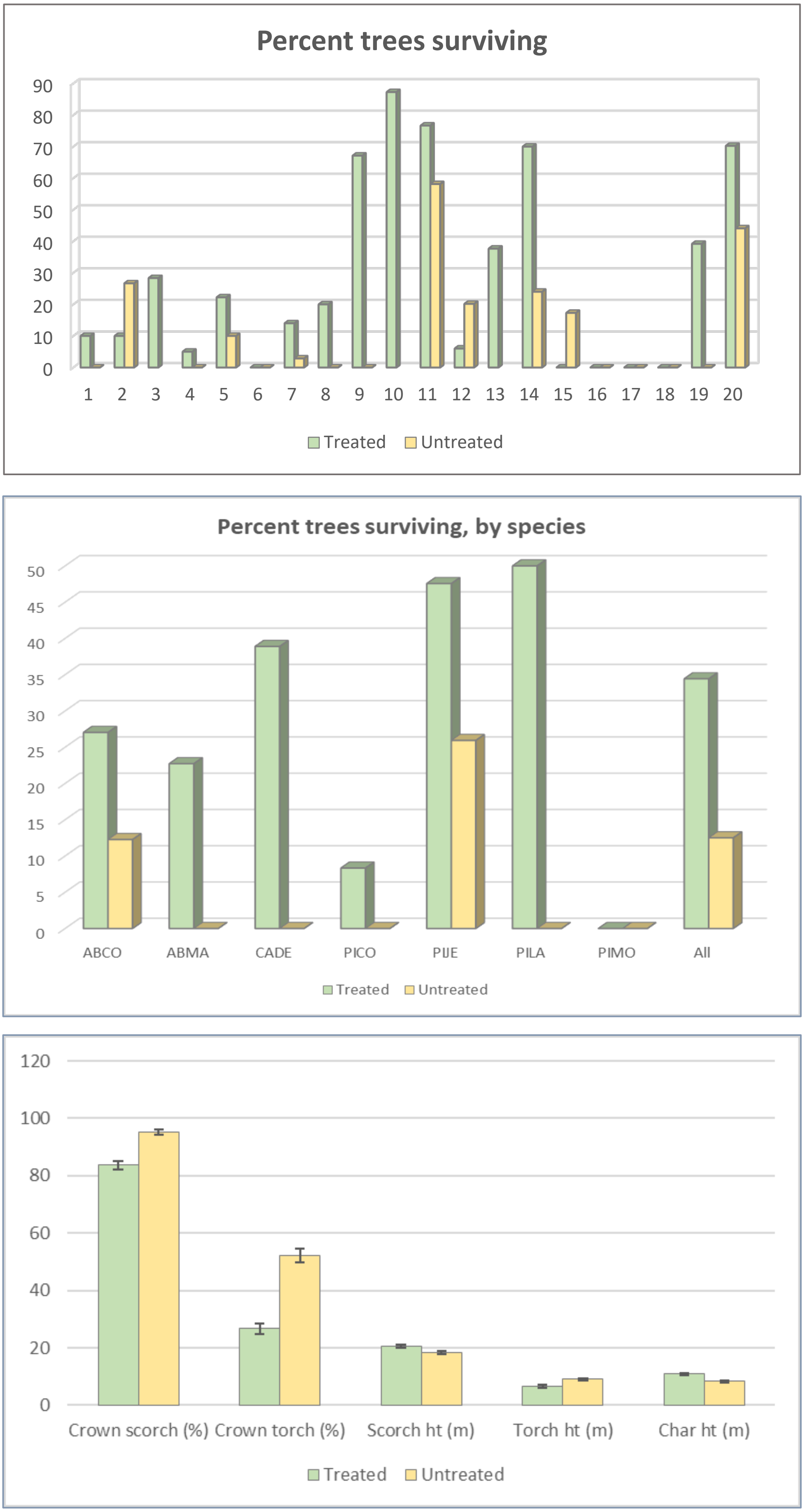


Figure 5. Top: Percent of sampled trees surviving fire in 2022 by transect, in treated and untreated forest stands. Middle: Percent of trees surviving fire, in treated and untreated forest stands, by species. Bottom: Means comparisons for five measures of fire severity in treated and untreated forest stands. Error bars represent standard error.

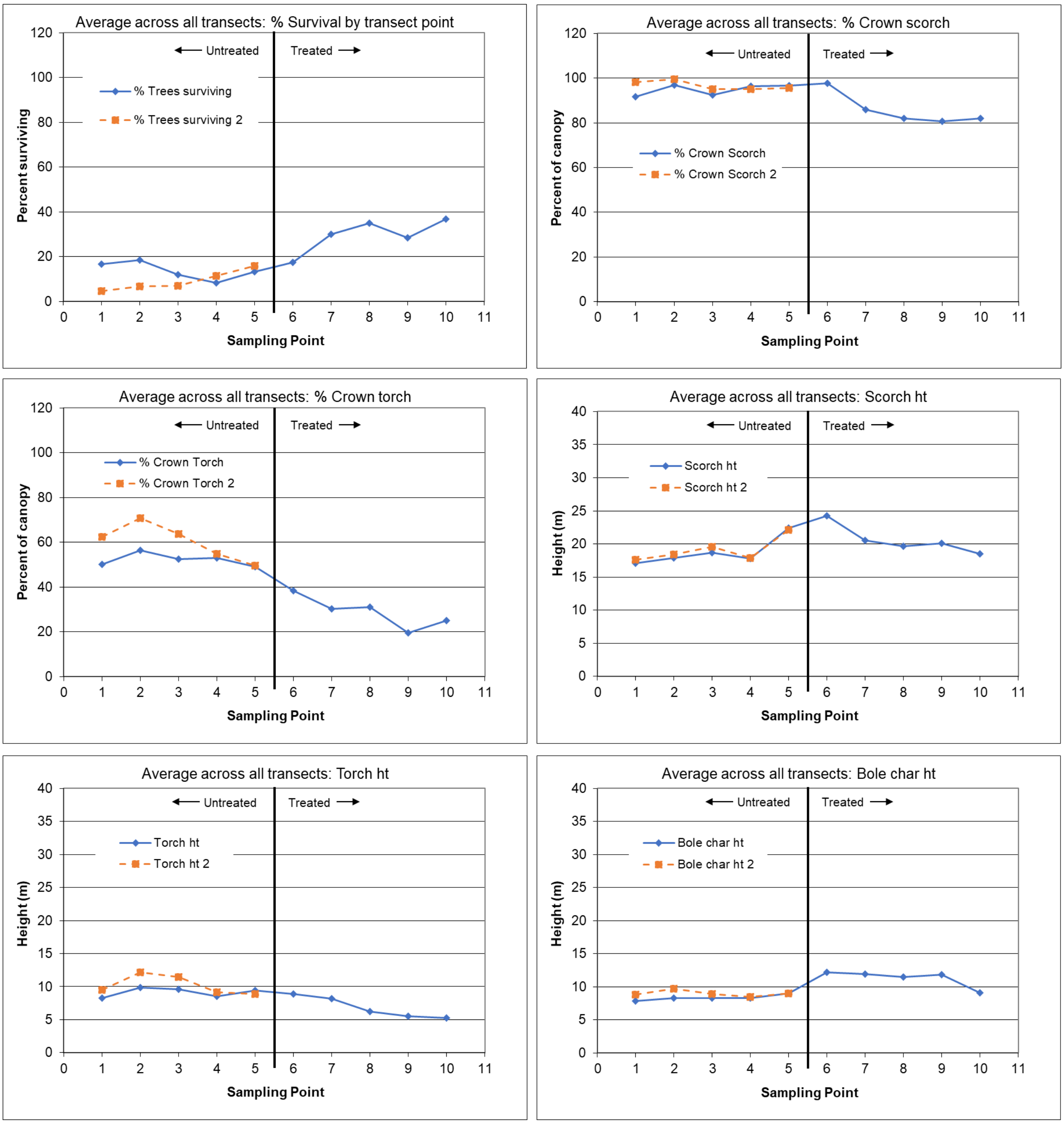
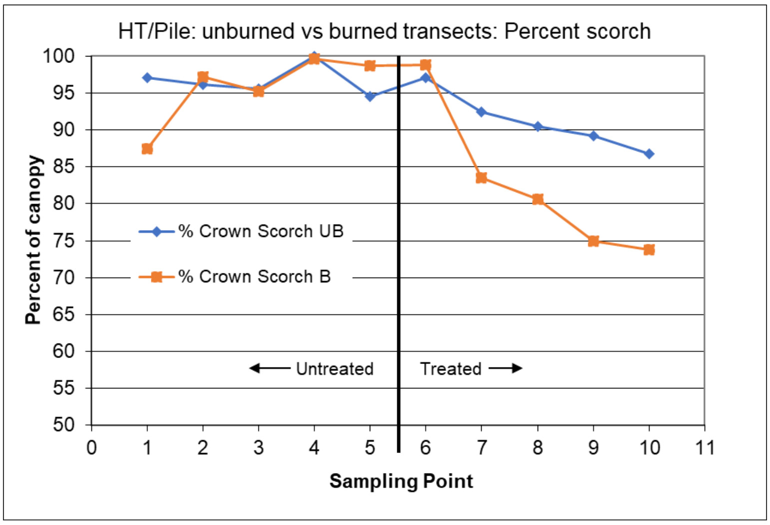


Figure 6. Linear trend of fire severity measures along sampling transects. Means of all transects shown by blue solid line/diamonds; means of all transects minus 4 transects that sampled anomalously steep, rocky, and sparsely vegetated lands in their untreated halves shown by dashed orange line/squares (Group 2).

Figure 7 shows percent scorch and tree survival along the linear run of transects that were subject to hand thinning and fuel piling and compares transects where piles were burned before the Caldor Fire with transects where unburned fuel piles were still on site. Percent scorch was notably lower in HT/Pile stands where pile burning was accomplished (HT/Pile + Burn group), and tree survival was higher.



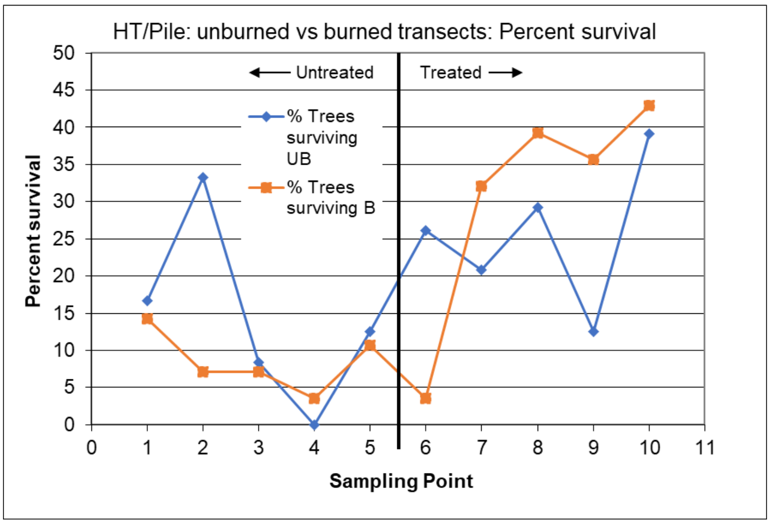


Figure 7. Linear trends of percent canopy scorch and percent survival along transects that sampled forest that had been treated by hand thinning and fuel piling, differentiated by whether piles had been burned ("B") or unburned ("UB") at the time of the Caldor Fire.

Comparisons of tree survival and fire severity measures in untreated stands versus three types of fuel treatments – HT/Pile-No Burn, HT/Pile + Burn, and "CPCM" (CTL and masticated stands that had also had two thinning entries before 2005) – are shown in Figure 8 and Table 2. Crown scorch, crown torch, and torch height all followed the same pattern, such that values in untreated forest were significantly higher than both HT/Pile + Burn and CPCM (with CPCM being lower in all cases than HT/Pile + Burn) but were not significantly different from HT/Pile-No Burn. Percent survival followed the inverse pattern, with untreated forest significantly lower than HT/Pile + Burn and CPCM, but again not significantly different from HT/Pile-No Burn (Figure 8, Table 2). For bole char height and scorch height, HT/Pile-No Burn was significantly *higher* than the untreated forest, while CPCM and HT/Pile + Burn were not significantly different from untreated forest.

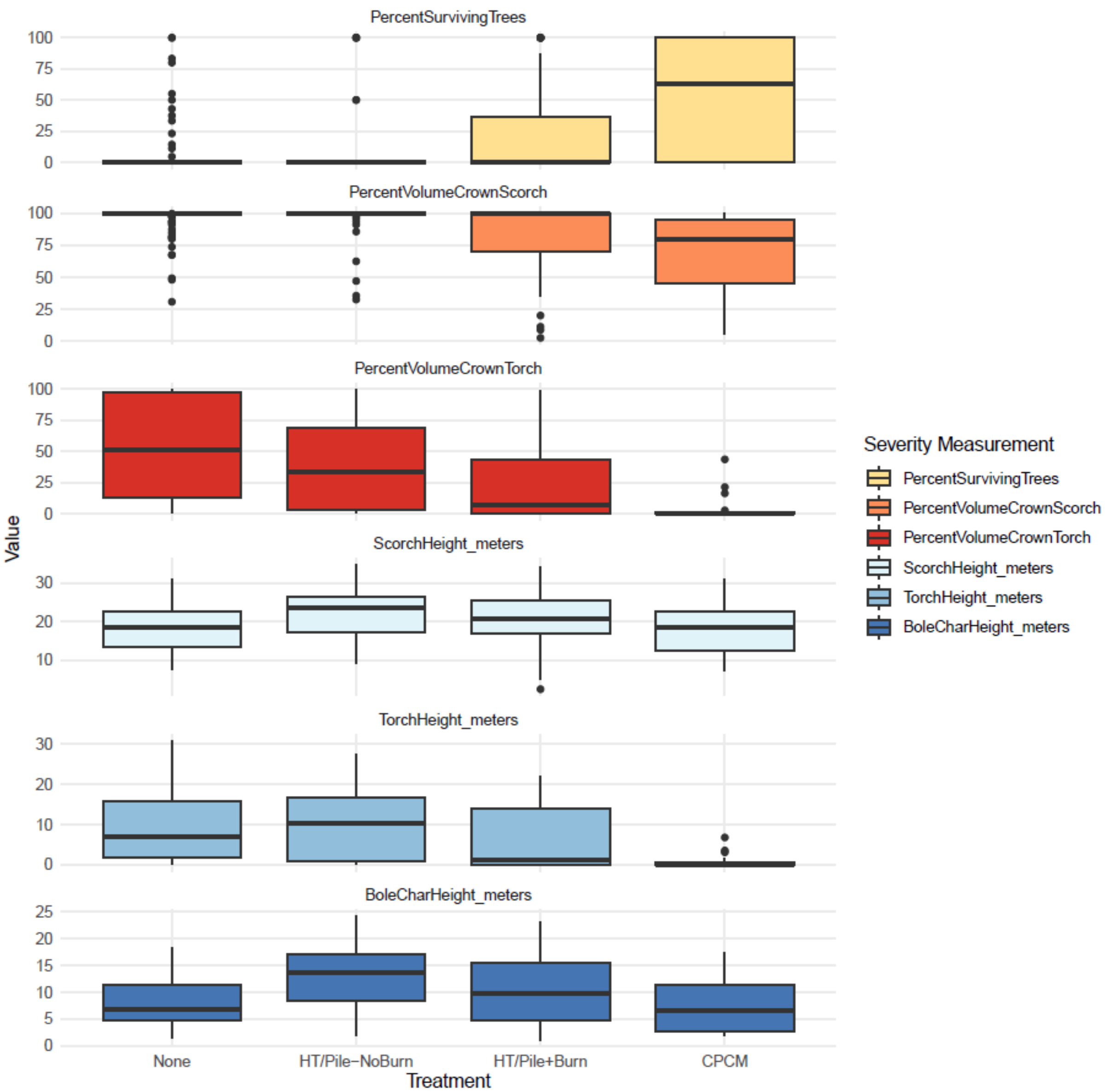


Figure 8. Box plots comparing tree survival and five fire severity metrics measured along the transects for untreated forests ("none") and three treatment types (see text for definitions). Horizontal lines depict the median, and the boxes delineate the 25^{th} and 75^{th} percentiles.

Figure 9 compares RdNBR medians and ranges for the same groups compared in Figure 8. The highest severity burning occurred in untreated areas, followed by HT/Pile-No Burn, then HT/Pile + Burn; the CPCM treatment group experienced the lowest severity burning. Severity in untreated forest was significantly higher than in all of the treatment types (Wilcoxon Rank-Sum Test, all *P* values $\leq$ 0.006), but among the treatment types the only significant pairwise comparison was HT/Pile-No Burn > CPCM (Dunn Test after Nonparametric ANOVA, *P* = 0.007). A map of the fuel treatments and transect centers overlaid on the RdNBR fire severity map is shown in Figure 10.

Figure 11 is a correlation table between percent survival and four potential predictor variables collected during the field sampling. Three variables showed statistically significant correlations with survival, all of them showed negative relationships with survival: elevation showed a moderately

Table 2. Results of Wilcoxon Rank-Sum Tests comparing untreated forest ("None") versus the three treatment groups. Blue cells indicate statistically significant differences.

MeanTorchHeight	W	P-value
None vs HT/Pile+Burn	2610.5	0.009517
None vs HT/Pile-NoBurn	1583.5	0.8701
None vs CPCM	1220.5	3.90E-06
MeanTorchPercentVolume		
None vs HT/Pile+Burn	3258.5	9.24E-06
None vs HT/Pile-NoBurn	2004	0.06176
None vs CPCM	1246	2.16E-06
MeanScorchHeight		
None vs HT/Pile+Burn	1837	0.06926
None vs HT/Pile-NoBurn	1066.5	0.002703
None vs CPCM	732.5	0.932
MeanScorchPercentVolume		
None vs HT/Pile+Burn	2921	0.0005816
None vs HT/Pile-NoBurn	1747.5	0.5357
None vs CPCM	1197	4.96E-07
MeanBoleCharHeight		
None vs HT/Pile+Burn	1905.5	0.1293
None vs HT/Pile-NoBurn	922.5	7.73E-05
None vs CPCM	838	0.3018
MeanProportionSurviving		
None vs HT/Pile+Burn	602	0.0010701
None vs HT/Pile-NoBurn	729	0.8622
None vs CPCM	101	8.65E-07

strong correlation, and density and slopes showed weak correlations. Basal area was not correlated with survival.

Discussion

We identified three important patterns in our analysis. First, fuel treatments in the Meyers and Christmas Valley area generally reduced crown scorch, crown torch, and torch height, and resulted in levels of tree survival that were much higher than in untreated forest. Second, the presence of unburned fuel piles in many of the hand thinned treatments resulted in notably higher fire severity and tree mortality in these areas. Third, areas that had been mechanically and hand-thinned in the early 2000s and were mechanically thinned again in the 2010s and then masticated (the "CPCM" group) tended to experience the lowest overall fire severity, both as measured on trees and by RdNBR. We discuss these findings and other results below.

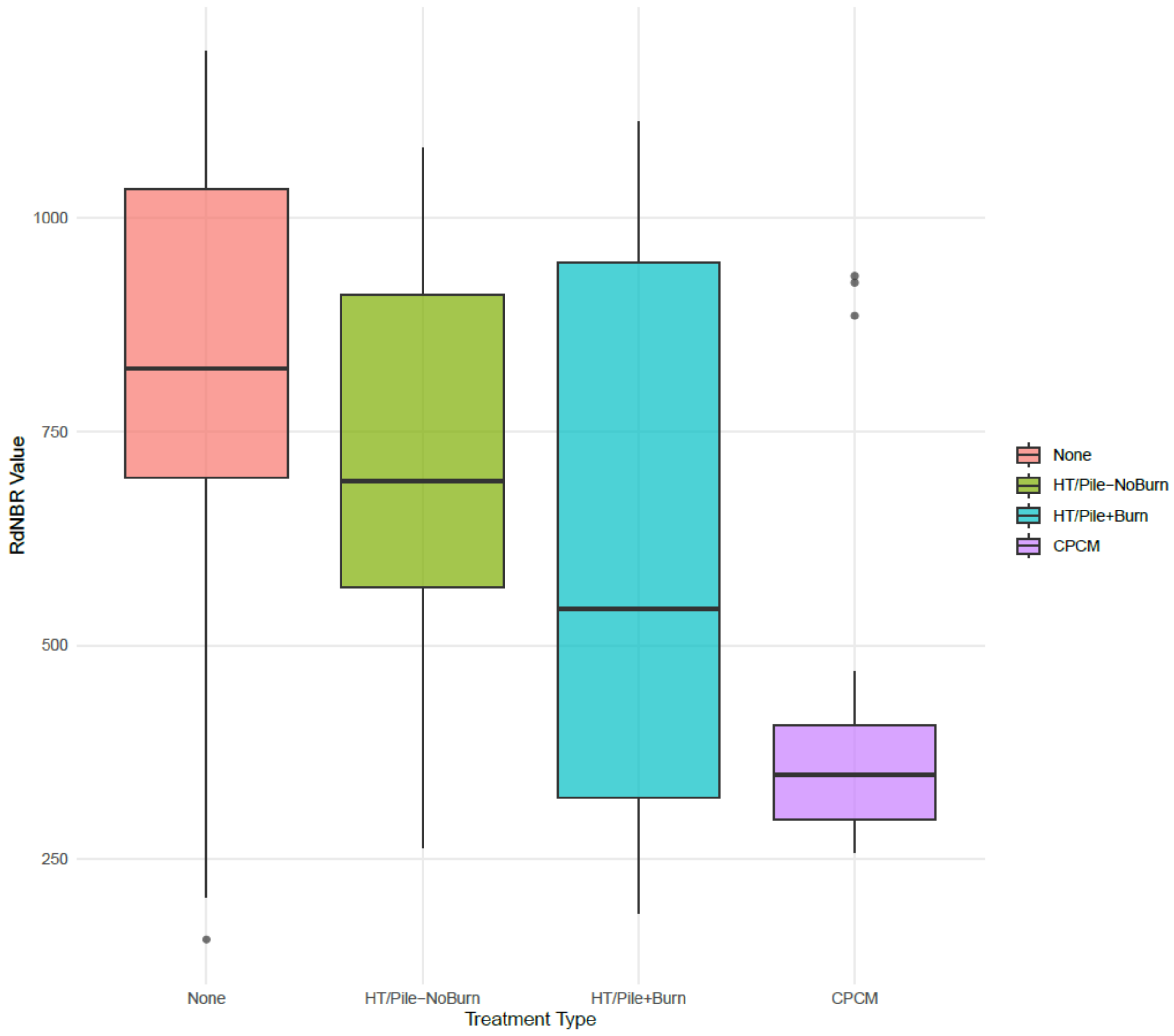


Figure 9. Box plots comparing the RdNBR remotely sensed fire severity among untreated forests ("none") and three treatment types (see text for definitions). See text for methodological detail. Horizontal lines depict the median, and the boxes delineate the 25th and 75th percentiles. Horizontal lines depict the median, and the boxes delineate the 25th and 75th percentiles.

Although weather conditions during the Caldor Fire were often extreme, and although the fire as a whole was very severe (45% high severity, according to vegetation burn severity measurements made by MTBS), fuel treatments still notably ameliorated fire behavior, such that the key measures of fire severity and drivers of tree mortality – crown scorch and torch percent (Sieg et al. 2006, Safford et al. 2009; Hood et al. 2010, 2018) – were notably reduced and tree survival was about 3x higher than in untreated forest. This confirms our hypothesis that fuel treatments would reduce fire severity and tree mortality as compared to untreated forest. At this point the literature is full of empirical demonstrations of the general efficacy of standard fuel reduction practices (Agee and Skinner 2005) that focus on surface fuels but also reduce ladder fuels and canopy continuity (Safford et al. 2009, 2012; Stephens et al. 2012, 2023; etc.), and knowing the high standards of the LTBMU we were not surprised at our finding. However, it is notable that fuel treatments in the Caldor Fire were generally

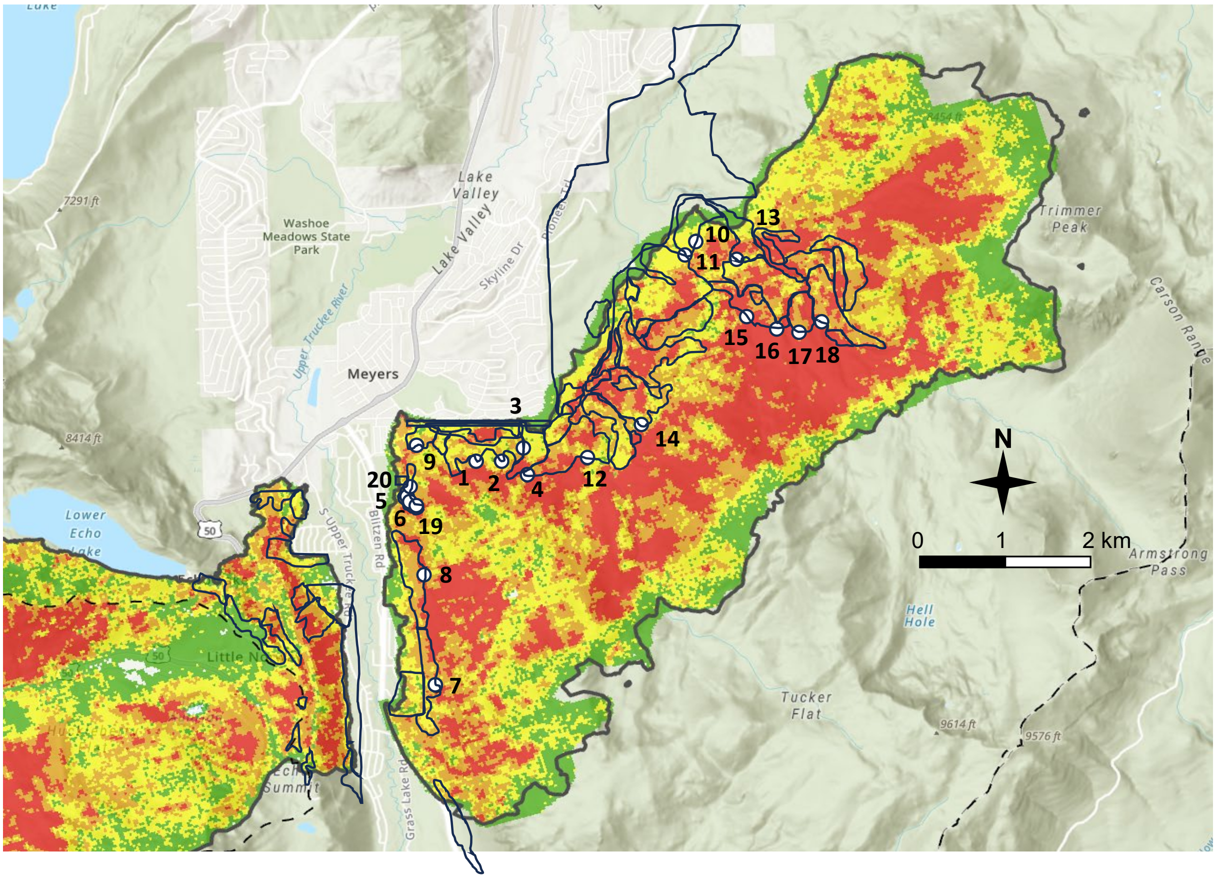


Figure 10. RdNBR fire severity map of the Caldor Fire from the MTBS program. Green = unburned and very low severity; yellow = low severity; orange = moderate severity; red = high severity

Table 3. Results of correlational analysis between percent survival, elevation, slope, prefire basal area, and prefire density. Percent data were transformed by Arcsin-Square Root, and basal area and density by Log_{10}.

Correlations

Variable	Variable2	Correlation	Count	Statistic Lower C.I.	Upper C.I.	Notes
ASINlive	Elevm	-.437	200	-.543	-.318	
	ASINslope	-.174	200	-.306	-.036	
	LogPrefireBA	.078	199	-.062	.215	
	Logprefiredensity	-.157	199	-.290	-.018	

less successful (in terms of ameliorating fire severity and reducing tree mortality) than treatments in the 2007 Angora Fire. We discuss this phenomenon in more depth in a later paragraph, but a major driver of this difference was certainly the prevalence of unburned fuel piles on much of the study site when the Caldor Fire arrived.

In 2007, the Angora Fire burned 250 homes only a few km to the north of the Caldor Fire perimeter. Nonetheless, prefire fuel treatments saved many other homes and resulted in much lower fire severity and tree mortality (Murphy et al. 2007, Safford et al. 2009). One of the findings in the Safford et al. study was that unburned fuel piles in a key area resulted in higher-than-expected fire severity and tree mortality and, together with an adjoining treatment where thinning had been minimal due to steep slopes, permitted passage of the fire through an area that had otherwise been well buffered by fuel reduction. Our results in the Caldor Fire are very reminiscent of our work in the Angora, but the extent of unburned fuel piles was much greater in 2021 than in 2007: there were 31 stand compartments that including fuel piling in the South Shore Project in the study area that were at least partially impacted by the Caldor Fire, and only 12 of the compartments had been burned by August 2021 (R. Mustatia and Casey Hoffman, USFS, pers. comm.). As in the Angora Fire, these unburned fuel piles resulted in high fire severity (such that some measures of severity were actually *higher* in treatments than outside them) and high tree mortality. Burn piles – typically about 3 m x 2 m (diameter x height) in size on the LTBMU (Busse et al. 2013) – tend to be primarily composed of medium-diameter logs that under the right conditions can burn/smolder for long durations. This escalates heat transfer to nearby trees and may increase the level of crown scorch, bole char, and canopy mortality (Daily and Reiner 2020, Berrill et al. 2024; Safford, pers. obs.).

The high number of unburned fuel piles in the Lake Tahoe Basin, which is a well-known and long-term issue – in an interview in early 2021, LTBMU staff suggested that as many as 250,000 unburned piles were present on USFS lands in the LTB (https://www.sierrasun.com/news/tahoe-fire-agencies-working-to-burn-hazardous-fuels-around-basin/) – is the product of a high rate of thinning and piling but a comparatively lower rate of pile burning (see also the “Forest management activities” paragraph on Page 10). Striplin et al. (2020) showed that during most years there are multiple single burn days appropriate for burning in the Lake Tahoe Basin, especially in the spring and autumn, but multi-day burn windows are relatively uncommon. On the LTBMU and other Region 5 units, burning dozens to hundreds of acres usually requires multiple, consecutive days of staff availability and appropriate weather and fuels conditions. Many of the multi-day burn windows identified by Striplin et al. occurred during the fire season, when fire staff is likely to be unavailable, and when – at least in recent years – Forest Service units are often forbidden to set prescribed fires by the Regional or Washington Offices. Like most Forest Service units, the LTBMU does not staff a dedicated burn crew, and the lack of burning capacity is at least partly due to the lack of fire personnel during the shoulder seasons, when many staff are laid off. An additional issue is that the fire season is expanding over time as the climate warms, which is progressively reducing the length of the traditional prescribed burning season.

It is worth noting that the LTBMU does not traditionally conduct broadcast burning (although a broadcast burn was carried out in 2023 for the first time in many years), which does a more complete job of reducing surface fuels than pile burning (e.g., Fornwalt et al. 2011, Prichard et al. 2020). On the LTBMU, a “creepy” pile burn (aka “pilecasting”) is sometimes implemented, where ignitions are made at strategically located piles and fire is allowed to creep between piles (see Dailey and Reiner 2020). In this way the effects of a prescribed fire can be approximated with less risk of escape. Many piles are burned in the winter however, when snow cover greatly reduces the potential for escape. Of course, burning under snow and/or under the high fuel moistures and relative humidities of the winter months also negates the general reduction of surface fuels that can be accomplished in pilecasting. In our study area, of the seven forest compartments that had their piles burned before the Caldor Fire, three were burned in December or January [Table 1]).

We were surprised to find that the most successful treatment type in reducing fire severity and promoting tree survival, the CPCM treatment group, did not include the use of controlled fire to reduce surface fuels. Most scientific studies of fuel treatment effectiveness highlight the benefits of multiple entries and combining methods, but common to almost all of these is the conclusion that prescribed burning is an essential component (Stephens et al. 2009, 2023). Previous literature also suggests that masticated fuels can be effective in lowering the probability of crown fire and abetting safer and more effective fire suppression, but tree mortality in masticated fuels can be high due to long duration burning/smoldering, especially where the masticated fuel layer is deep and/or there has been little time between treatment and wildfire for surface fuels to compact and decompose (e.g., Safford 2008, Prichard et al. 2021). The efficacy of the CPCM treatment group in this study in reducing crown scorch and torch (see, e.g., transect graphics in the Appendix) was therefore unsurprising, but the very low mortality in these treatments – given the weather and fuel moisture conditions – was a bit of a surprise. The fact that masticated fuels were only found along forwarding trails and that a project requirement was that masticated fuel depth be kept $\leq$ 15 cm were likely both factors.

Our earlier work in the Angora Fire (Safford et al. 2009) demonstrated that mechanical thinning was important to fuel treatment efficacy, especially in steep, wind-exposed terrain where fire moves rapidly and can more easily jump to the forest canopy. A recent paper by Stephens et al. (2023) studying 20 years of forest experimental work in the Sierra Nevada also found that mechanical treatment + prescribed fire was overall the most successful treatment combination for both reducing fire hazard and increasing forest resilience. Our results seem to support this finding, but it is important to note that in the case of the Caldor Fire three of the four transects subject to the CPCM treatment were protected behind a belt of HT/Pile treatments that bore the brunt of the flaming front as it moved east, and the fourth of the CPCM treatment areas suffered complete mortality (as did the neighboring HT/Pile treated areas), possibly or probably because it was on the front line in an area of very severe burning (see locations of transects on the fire severity map in Figure 11). Better understanding the value of mechanical thinning + mastication as a stand-alone fuel reduction option will a focus of deeper analysis as we move forward with this project.

We have not yet modeled tree survival or fire severity as we must first process and analyze our common stand exam data, which include fuel loading values. Our simple correlation analysis statistically assessed 1-to-1 relationships between tree survival and a handful of predictor variables. Elevation showed the strongest relationship with survival, which was expected, since untreated areas were always found uphill of treated areas in our study site. Therefore, elevation is not as much a predictor of survival as it is a correlate. Slope is also partly a correlate, and slopes often (but not always) increased as our transects entered untreated forest, but fires run faster uphill and steep slopes are often centers of high severity burning due to pre-heating of fuels and layering of the vegetation canopy. Prefire density was the other variable with a significant 1-to-1 correlation, and its negative relationship with survival was expected. We expect that density will prove to be a more important predictor of survival and fire severity once we account for the effects of important correlates like elevation and slope in our modeling.

As expected, Jeffrey pine survived fire at by far the highest rates of any of the species we sampled. Jeffrey pine tends to have thicker bark than the other species, with the difference especially pronounced in the fire-sensitive younger age-classes, and it self-prunes lower branches as it ages, reducing the occurrence of crown fire (Safford and Stevens 2017). Overall tree survival in the Caldor Fire was somewhat lower than in the 2007 Angora Fire. In the Angora Fire one year after fire, 42.5% of all burned trees were still alive in treated areas (as sampled along the fuel treatment transects) versus 26.5% in untreated areas; in the Caldor Fire the values were 34.4% and 12.5%. When we removed from the analysis transects and points that still contained unburned fuel piles at the time of fire, the differences were greater: Caldor – 42.2% and 12.7% (treated and untreated) vs. Angora – 59.1% and 33.2%. There are a few potential explanations for these differences. First of all, our data from the Angora Fire include all trees $\geq$ 12.7 cm dbh while Caldor includes all trees $\geq$ 10 cm dbh (after 2009 we made a change in the sampling protocols in the USFS Region 5 Ecology Program [the first author worked for the USFS until 2022]). This certainly accounts for a few percent of the difference. Higher mortality in the Caldor is probably also due to the record dry conditions of 2021 and ongoing water stress from a very dry decade, plus the fact that the Angora Fire burned earlier in the season (late June vs. late August for the Caldor). Finally, the area supporting high surface fuels was much more extensive in the Caldor Fire treatments (especially the large areas of unburned fuel piles) and this clearly increased fire severity and tree mortality.

Forest management activities generally met their targets in density or basal area (compare Table 1 to Figure 4), except in the cases of Transect 20, where densities were 4x greater than prescription, and Transect 13, where basal area was about 75% higher than prescription. However, pile burning was only accomplished on seven of the 13 stand compartments where fuels were piled (Table 1). The LTBMU has a well-deserved reputation for meeting or beating annual targets for fuel reduction, but without sufficient capacity to annually burn all of the fuel residues left over from previous years, and with LTBMU piles requiring two to three years to cure (B. Garrett, USFS, pers.comm.; see below), piles have begun to clog some portions of the forest landscape. This problem has been understood since at least 2007, when unburned piles in the Angora Fire became a source of major contention when a key fuel treatment did not perform as expected and the flaming front passed through an adjacent neighborhood. Hand thinning on the LTBMU includes trees up to 14 inches (35.6 cm) dbh, notably larger than the more typical "precommercial" hand-thinning dbh limit of 10 inches (25.4 cm) dbh. These larger logs require longer to dry sufficiently to meet the LTBMU's 80% consumption goal during pile burning (B. Garrett, USFS, pers.comm.). These are important considerations, but of the nine transect halves that sampled stand compartments where fuel piles were still on site, five had fuel piles that had been on site for 5 years, three for 4 years, and one for 2 years, i.e. eight of the nine sites represented backlogs. We hope that the clear contribution of unburned piles to higher fire severity and tree mortality in the Caldor Fire will further underline the importance of resolving the pile burning backlog issue in the near future.

Overall, the c. 3x higher survival of adult trees in the treated portions of our study site and other studies of fuel reduction effectiveness (e.g., Safford et al. 2009, 2012) suggest that the LTBMU and other landholding agencies in the LTB should consider whether expansion of forest thinning to forested areas outside of the WUI defense zone is warranted, for forest restoration purposes rather than only for protection of human infrastructure. Forests today in the LTB are much higher density than they were when Euroamerican settlement began, and the relative component of fire- and drought-intolerant species is much higher (Taylor 2004, Maxwell et al. 2014, Safford and Stevens 2017). With climate warming, more severe fire weather, increased drought- and insect mortality, and constantly increasing fuels, LTB forests are at high risk of loss. The 17-year-old scar of the Angora Fire, the denuded mountainsides near Reno, Markleeville, and Lake Topaz, and the more recent loss of forest in the Caldor Fire are warnings of where much of the forest land base in the central Sierra Nevada is headed under the current (lack of) management regime. In our view, forest sustainability under climate change will require reduction of stand densities to levels that greatly reduce water competition (North et al. 2022) and better mimic the open, resilient conditions that characterized yellow pine and mixed conifer forests before Euroamerican settlement (Safford and Stevens 2017). Some of this work can be accomplished using a judicious mix of hand and mechanical thinning, but we cannot avoid the simple truth that fire will ultimately treat most of the landscape in the LTB and the surrounding Sierra Nevada. The choice we have is whether we use fire proactively as a management tool under more controlled circumstances, or whether we allow severe and uncontrolled burning to define our future (Safford et al. 2022).

During fire suppression operations, burnouts were carried out in some parts of the study site to reduce fuels in advance of the oncoming fire. We know approximately where these operations took place (e.g. above the “Upper Apache” neighborhood SSE and SE of Meyers) but need to confirm exact locations and we also need to collect information on weather conditions (etc.) at the time of ignition.

In the near future (2024) we will also (1) build models for linear effects of treatment along our transects, including physiographic variables, weather, and treatment age; (2) validate tree mortality equations for LTB species; (3) assess fire and treatment impacts to plant diversity and soil cover; (4) evaluate distance and treatment area effects on fire severity; and (5) analyze our common stand exam plots. We are also involved in a collaborative project with the Humboldt-Toiyabe National Forest, The Nature Conservancy, and UC-Berkeley that is studying fuel treatment effectiveness in three 2021 fires (Caldor, Dixie, Tamarack), and we expect to submit a summary manuscript sometime this summer.

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Dr. Hugh Safford is the Chief Scientist of Vibrant Planet, an environmental public benefits corporation, and a research ecologist at the University of California-Davis. Safford was Regional Ecologist for the USDA-Forest Service's Region 5 (California, Hawaii, Pacific territories) between 2001 and 2021. Safford is director of the Sierra Nevada section of the California Fire Science Consortium, and he is PI of the California Prescribed Fire Monitoring Program (a partnership with CALFIRE) and the California State Parks Vegetation Treatment Monitoring Program. Safford has provided international technical assistance on fire, forest management, and climate change issues since the 1990s. Recent projects include data science support to wildfire risk mitigation in Chile, fire risk mapping in the country of Georgia, fire management planning in Mexico, climate change adaptation in Brazil and Peru, and forest restoration and management in North Africa and the Middle East. Safford was a Fulbright Fellow between 2017 and 2019, where he studied post-fire ecosystem restoration practices in France, Portugal, and Spain. Safford co-edited the 2021 *Postfire Restoration Framework for National Forests in California*, which provides guidance for management decision-making in burned ecosystems under changing environmental baselines. Visit the Safford Lab at UC-Davis at: https://safford.faculty.ucdavis.edu/research/. Safford splits his time between Davis and Meyers, California.

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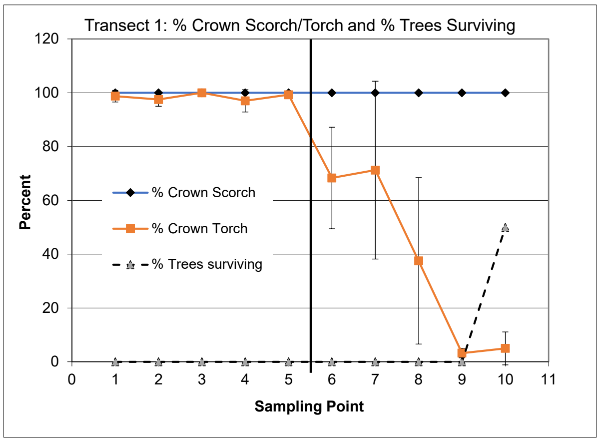
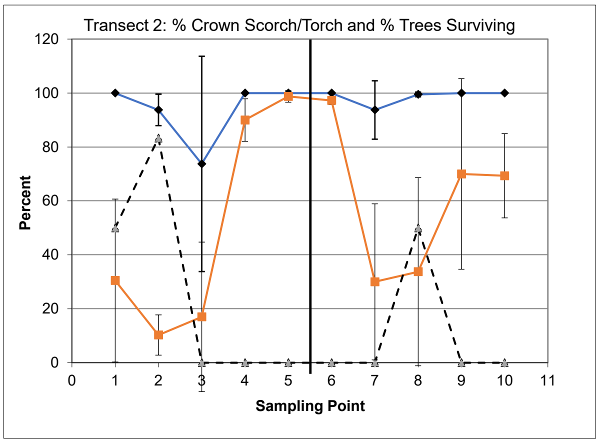
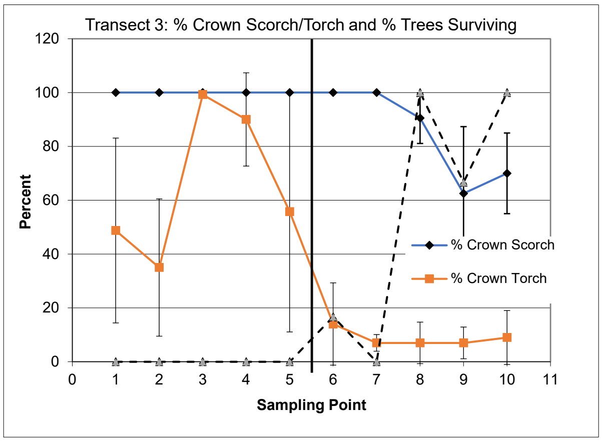
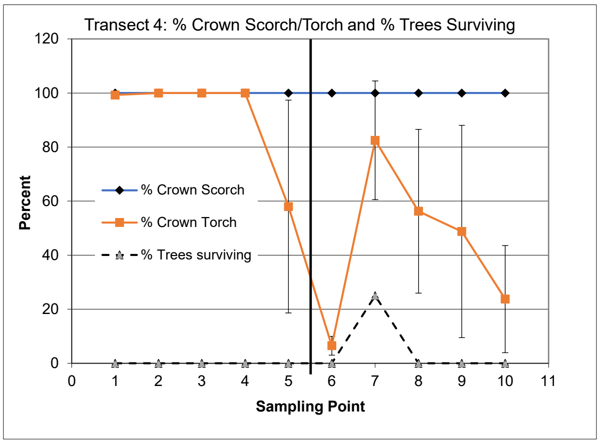
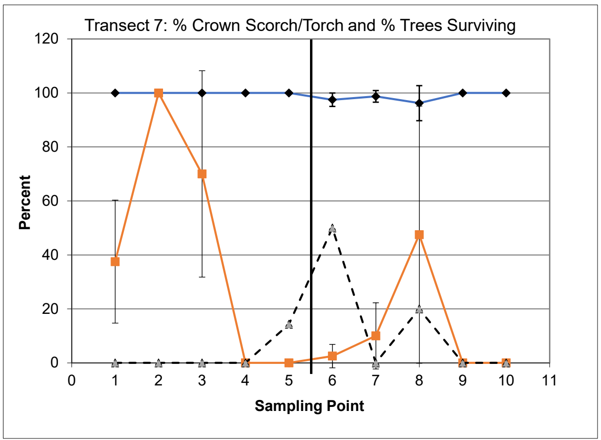
Supplemental material. Linear trends of crown scorch %, crown torch %, and % surviving trees along transects 1-20 (5 and 6 not shown, see text)

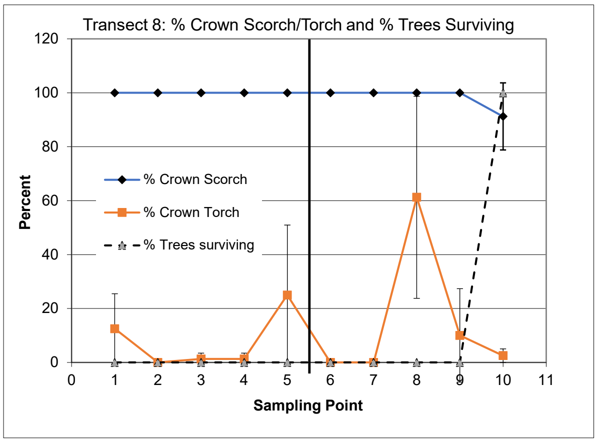


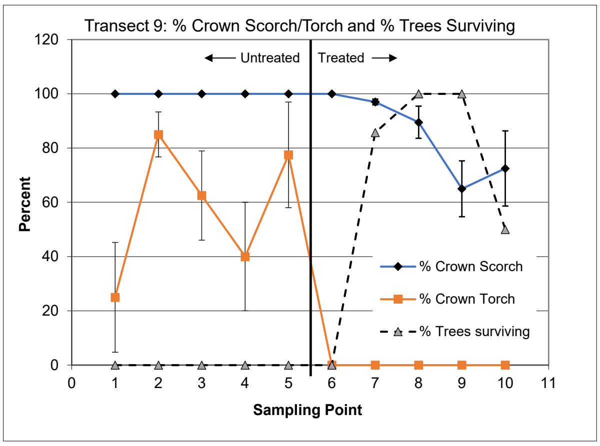


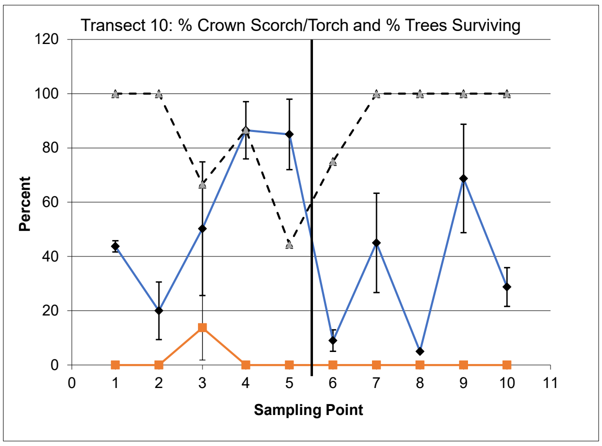









Transect 9: % Crown Scorch/Torch and % Trees Surviving
Untreated
Treated
Percent
Sampling Point
% Crown Scorch
% Crown Torch
% Trees surviving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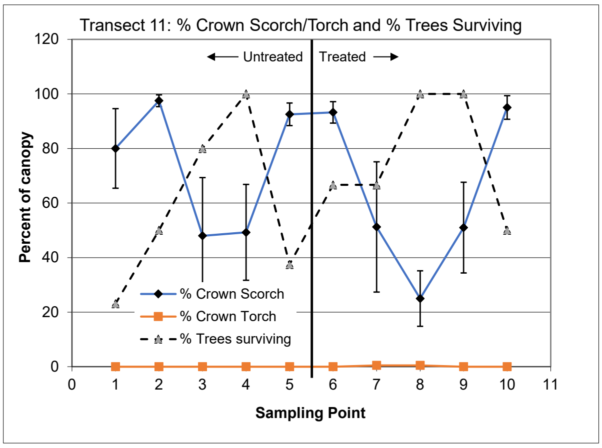
Percent
Sampling Point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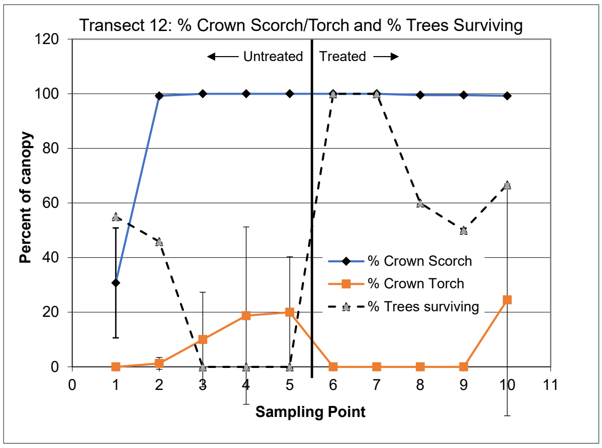
Untreated
Treated
Percent of canopy
Sampling Point
% Crown Scorch
% Crown Torch
% Trees surviving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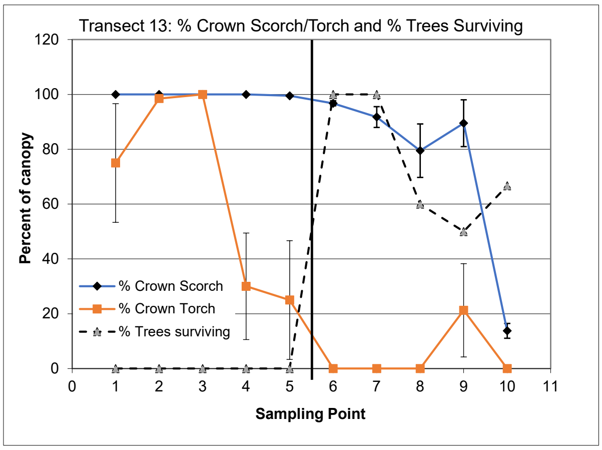
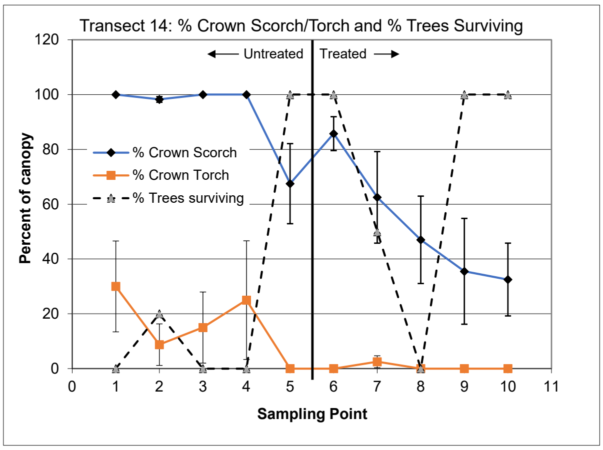
Untreated
Treated
Percent of canopy
Sampling Point
% Crown Scorch
% Crown Torch
% Trees surviving


Transect 13: % Crown Scorch/Torch and % Trees Surviving
Percent of canopy
Sampling Point
% Crown Scorch
% Crown Torch
% Trees surviving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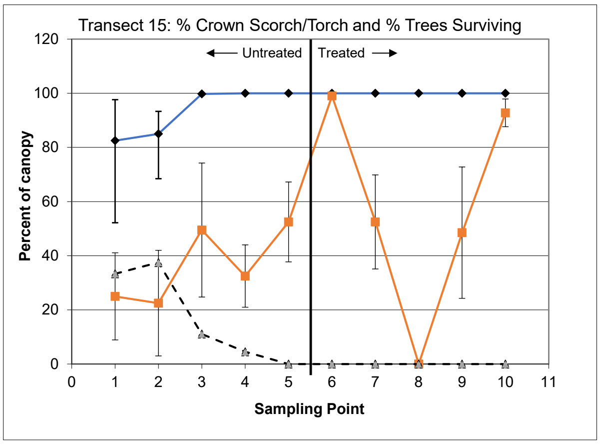
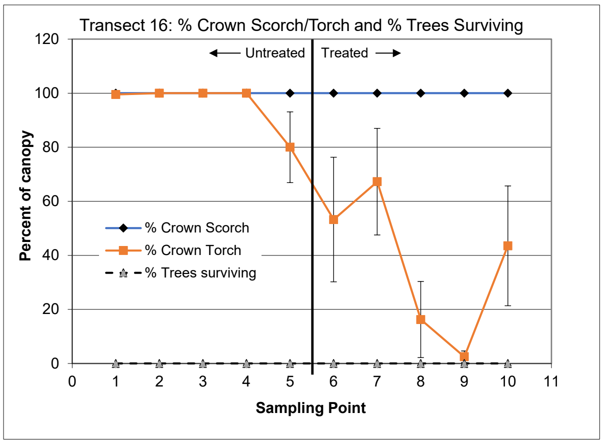
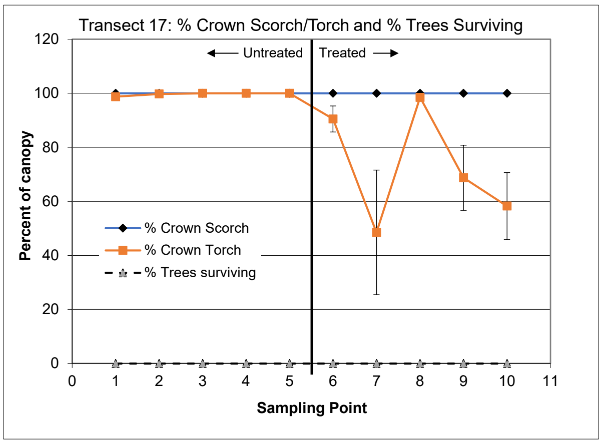
Untreated
Treated
Percent of canopy
Sampling Point
% Crown Scorch
% Crown Torch
% Trees surviving


Transect 15: % Crown Scorch/Torch and % Trees Surviving
Untreated
Treated
Percent of canopy
Sampling Point
0 20 40 60 80 100 120
0 1 2 3 4 5 6 7 8 9 10 11


Transect 16: % Crown Scorch/Torch and % Trees Surviving
Untreated
Treated
% Crown Scorch
% Crown Torch
% Trees surviving
Percent of canopy
Sampling Point
0 20 40 60 80 100 120
0 1 2 3 4 5 6 7 8 9 10 11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Untreated
Treated
% Crown Scorch
% Crown Torch
% Trees surviving
Percent of canopy
Sampling Point
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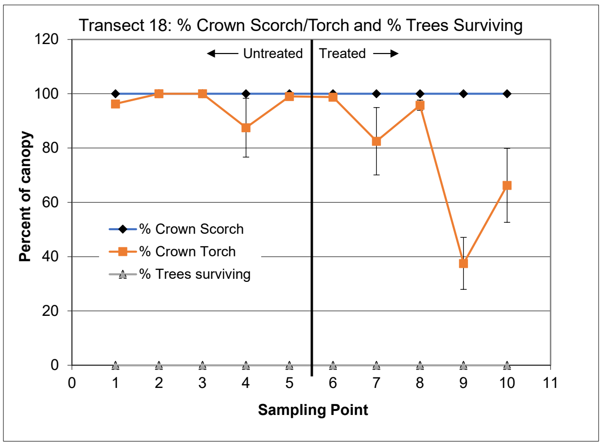
0 1 2 3 4 5 6 7 8 9 10 11


Transect 18: % Crown Scorch/Torch and % Trees Surviving
Untreated
Treated
% Crown Scorch
% Crown Torch
% Trees surviving
Percent of canopy
Sampling Point
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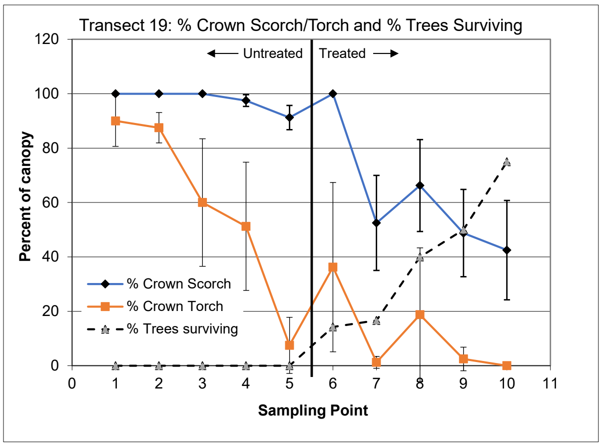
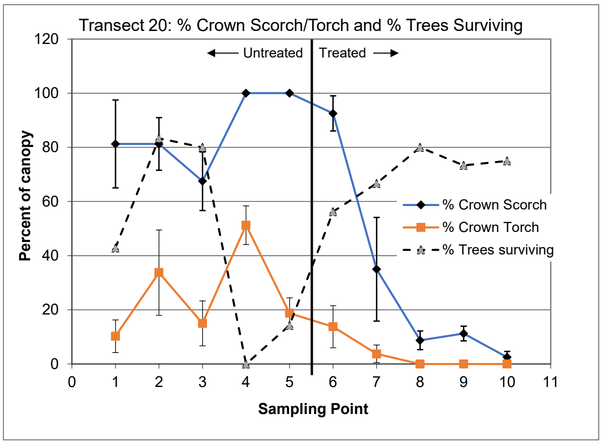
0 1 2 3 4 5 6 7 8 9 10 11


Transect 19: % Crown Scorch/Torch and % Trees Surviving
Untreated
Treated
% Crown Scorch
% Crown Torch
% Trees surviving
Percent of canopy
Sampling Point
0 20 40 60 80 100 120
0 1 2 3 4 5 6 7 8 9 10 11


Transect 20: % Crown Scorch/Torch and % Trees Surviving
Untreated
Treated
% Crown Scorch
% Crown Torch
% Trees surviving
Percent of canopy
Sampling Point
0 20 40 60 80 100 120
0 1 2 3 4 5 6 7 8 9 10 11