SPATIAL INFORMATICS GROUP

REPORT TO
AMERICAN FOREST FOUNDATION

DEVELOPING AN APPROACH TO MODEL FIRE RESILIENCY THROUGH FUEL TREATMENTS AT THE LANDSCAPE SCALE

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Report prepared by

SPATIAL INFORMATICS GROUP

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Conditional burn probability: the probability of a cell in the study area burning given an ignition in the study area

Conditional flame length: the mean flame length (ft) of each 30m cell when that cell burns in the context of a Monte Carlo fire simulation

Mean10: a treatment scenario with a roughly log-normal distribution of treatment sizes and a mean treatment size of 10 ac

Mean40: a treatment scenario with a roughly normal distribution of treatment sizes and a mean treatment size of 40 ac

No priority: a treatment scenario where treatments are allocated according to the ratio of private and public lands in the treatment area

Private prioritized: a treatment scenario where treatments are placed on private parcels until 85% of the area of private parcels have been treated

Study area: the total Sonora fireshed area (425 square miles)

Treated areas: areas within the treatment area where fuels were transitioned to simulate fuels reduction treatments

Treatment area: the combined area of non-industrial private parcels >10 acres and federally owned parcels within the study area

Data and code available at https://github.com/kyle-woodward/aff-treatments

Introduction

Wildfires on forested lands of the western US are becoming larger, more frequent, and more severe.

Forest management practices seek to reduce fuel loads in fire-prone areas. These practices, including thinning, prescribed fire, and mastication, are used to reduce fuel loads, reduce horizontal and vertical fuel continuity, and create fuel breaks for more effective firefighting in the event of a wildfire.

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Fuel treatments can occur across a range of spatial scales. Private landowners can treat small parcels, while treatments on public lands may cover thousands of acres. A general goal of managers is to apply treatments where they will have the most optimal impact on fire behavior, typically referred to as prioritization. The optimization of the spatial arrangement of treatments has been a focus of study, where simulations of fire behavior have been used to assess the effect of landscape-scale treatment size and placement on fire behavior. While this research is informative, the placement of planned treatments is typically limited due to constraints such as access, topography, or property ownership boundaries. Thus, while prioritization is often a goal, increasing the pace and scale of treatment throughout fire-prone landscapes also includes treating opportunistically to reach the desired acreage of area treated as quickly as possible.

In this report, we describe an approach for evaluating the effectiveness of forest treatments for reducing simulated fire behavior for several scenarios in which treatment intensity, treatment size, and the spatial distribution of treatments were varied. Rather than simulating treatments to optimize treatment effectiveness, the objective was to determine the level of treatment required to reduce fire risk if treatment locations are not optimized in a prioritization process, given varying treatment sizes and varying distribution of treatments across private and public lands. This allows for an evaluation of the scale and concentration of activity required to moderate fire behavior across a fireshed. For this report, we use the Sonora fireshed in the central Sierra Nevada as a case study.

In this report, we describe an approach for evaluating the effectiveness of forest treatments for reducing simulated fire behavior for several scenarios in which treatment intensity, treatment size, and the spatial distribution of treatments were varied.

Methods

Case study area

The 425 square mile Sonora fireshed study area (Figure 1) is typical of low- to mid-elevation foothill areas of the Sierra Nevada. The elevation of the study area ranges from approximately 1000-6500 ft. Major drainages in the study area include the Middle Fork Stanislaus River, the South Fork Stanislaus River, and the North Fork Tuolumne River. At lower elevations, surface fuel types include dry-climate grass, grass shrub, and shrub fuel types. As elevation increases, surface fuel types include timber litter and timber-understory fuel types.

Within the study area, we selected the treatment area based on ownership type and vegetation type. We differentiated between non-industrial private lands (referred to below as ‘private’) and federally-managed public lands (referred to below as ‘public’). The mean private parcel size was 10 acres and the mean public parcel size was 145 acres. When defining the treatment area, we excluded areas with herbaceous vegetation cover based on National Land Cover Database (NLCD) classification, because these areas would not be treated for forest fuels reductions. We also excluded parcels less than 10 acres because they are unlikely to be treated for fuels reduction under this specific AFF program. The total area of private lands in the treatment area was 155 square miles (42% of total treatment area). The total area of public lands in the treatment area was 212 square miles (58% of total treatment area). When summarizing fire behavior metrics in this report, we report summaries for the entire study area (425 square miles) shown in Figure 1, including parcels less than 10 acres and herbaceous vegetation types.

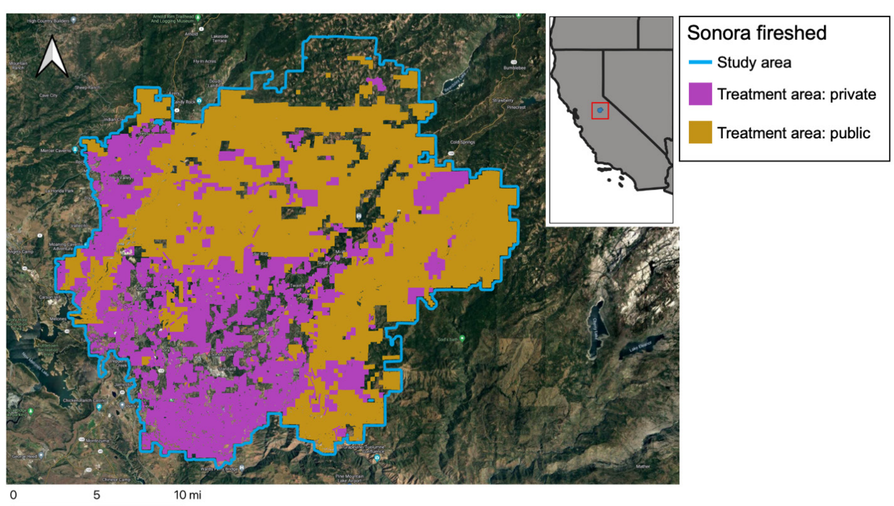

Figure 1. The Sonora fireshed study area. Fire behavior results were summarized for all cells within the study area. Treatments were placed only in the treatment areas, which exclude cells with herbaceous vegetation cover and parcels less than 10 ac.

Treatment scenarios

Overall, we tested the effect of three variables on fire behavior: treatment intensity (intensity here refers to the percent area treated, rather than the magnitude of change caused by the treatment), treatment size distribution, and ownership priority scenario. In total we tested 13 treatment intensity levels, two treatment size distributions, and two ownership priority scenarios, for a total of 52 scenarios.

To test the effect of treatment intensity, we simulated a recent (within 1-5 years), moderate-severity harvest where fuels were removed from the treated area. Treatment intensity ranged from 0%-60% of the treatment area in increments of 5%.

To test treatment size distribution, we compared a scenario with a roughly log-normal distribution and a mean treatment size of 10 acres (referred to below as Mean10) and a scenario with a roughly normal distribution and a mean treatment size of 40 acres (referred to below as Mean40). For simplicity, we designated four treatment size classes for each scenario: 10, 40, 100, and 400 ac. We then assigned the probability of simulating each size class for the two treatment size distributions (Table 1). Sampling from these predetermined probabilities, rather than true normal or log-normal distributions, allowed us to ensure that some larger treatment sizes would be included in each simulation. The Mean10 treatment scenario simulates a scenario where most treatments occur on individual small parcels, while the Mean40 treatment scenario simulates a scenario where treatments are coordinated across multiple parcels with the cooperation of the landowners. We refer to this set of scenarios as the treatment size scenarios below.

	Probability of 10-acre treatment	***Probability of 40-acre treatment***	***Probability of 100-acre treatment***	***Probability of 400-acre treatment***
Mean10	0.60	0.25	0.13	0.02
Mean40	0.25	0.60	0.13	0.02

Table 1. Probabilities of each of the four treatment size classes for the two treatment size distributions

Additionally, we evaluated two scenarios regarding property ownership. The first scenario prioritized treatment of private parcels, assuming that most of the fuels treatments would be undertaken on private lands (referred to below as the "private prioritized" scenario). In this scenario, we placed simulated fuels treatments only in private parcels until a saturation point of 85% of private lands treated was reached. This corresponded to 35% of the treatment area. After 85% of private lands (35% of the treatment area) was treated, the simulated treatments were placed on public lands. In the second scenario, treatments were allocated according to the ratio of private and public lands in the treatment area (referred to below as the "no priority" scenario). In this scenario, 42% of the treated area was on private lands and 58% of the treated area w To simulate fuels reduction as a result of forest treatment, we developed a workflow in Google Earth Engine to create treated areas and transition fuels in those treated for each of the 52 scenarios tested. We first determined the total acres to be treated on public and private lands for each scenario based on the area treated, the treatment size distribution, and the priority scenario. Using the probability of each size class (Table 1), we estimated the number of treatments per size class for each scenario. These treatments were randomly placed in the treatment area. Treatment edges were allowed to touch but did not overlap. For each area treated increment (0%-60%), treatments from the smaller increments remained the same but additional treatments were added. The final image for each scenario was a 30m pixel raster with treated areas masked (Figure 2). as on public lands. We refer to this set of scenarios as the treatment priority scenarios below.

Simulating treatment areas

To simulate fuels reduction as a result of forest treatment, we developed a workflow in Google Earth Engine to create treated areas and transition fuels in those treated for each of the 52 scenarios tested. We first determined the total acres to be treated on public and private lands for each scenario based on the area treated, the treatment size distribution, and the priority scenario. Using the probability of each size class (Table 1), we estimated the number of treatments per size class for each scenario. These treatments were randomly placed in the treatment area. Treatment edges were allowed to touch but did not overlap. For each area treated increment (0%-60%), treatments from the smaller increments remained the same but additional treatments were added. The final image for each scenario was a 30m pixel raster with treated areas masked (Figure 2).

To transition surface and canopy fuels in treated areas, we used the LANDFIRE surface and canopy fuels dataset (v2.0.0; accessed at www.landfire.gov) as the baseline fuels data. Four canopy fuel layers (canopy cover, canopy height, canopy base height, canopy bulk density) and one surface fuel layer (40 Scott and Burgan Fire Behavior Fuel Model, referred to below as FM40) are used as inputs into the fire models. To transition fuels after disturbance, LANDFIRE uses a three-digit code to indicate the disturbance type, severity, and time since disturbance. We assigned each simulated treatment a code indicating the treatment type was mechanical remove (a mechanical treatment where fuels are removed from the site, such as a group harvest or single-tree selection treatment), a moderate severity, and a time since disturbance of 1-5 years. We transitioned the five fuels layers according to the LANDFIRE Total Fuel Change Tool (LFTFCT) ruleset, as implemented in Google Earth Engine (details of the methodology can be found in Kearns et al. 2022). The four canopy fuels are updated using a linear regression equation with parameters specific to the disturbance code, biophysical Settings (BPS), fuel vegetation cover (FVC), fuel vegetation height (FVH), and fuel vegetation type (FVT). The FM40 surface fuels are transitioned using a lookup table applied to unique combinations of the disturbance code, BPS, FVC, FVH, and FVT. After running the process to transition the fuels for each scenario, we exported a raster stack of the five fuels layers for each of the 52 scenarios.

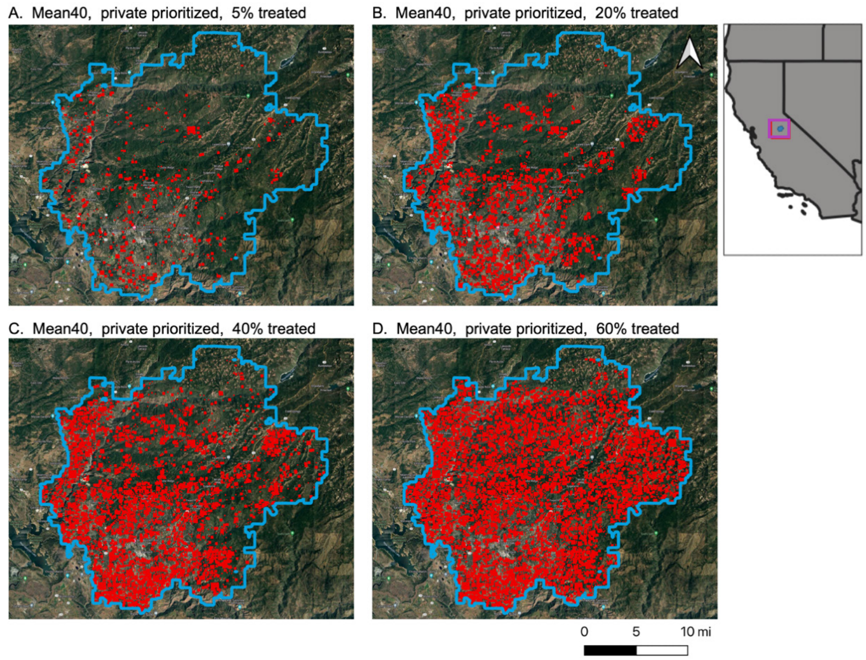

Figure 2. An example of treatment locations for selected scenarios in the study area. These panels show the locations of the simulated treatments for the Mean40, private prioritized scenario at treatment intensity levels of 5%, 20%, 40%, and 60%. The 40% treatment intensity level is the level at which treatments begin to be placed on public parcels.

To model fire behavior, we used GridFire, which is an open-source, raster-based fire behavior model which uses Rothermel surface fire spread equations to predict fire behavior. We used the raster stack of five modified fuels layers as the inputs for each GridFire run. We used a 16-hr burn period and ran 10,000 ignition simulations for each of the 52 scenarios. The ignition locations were random but were kept consistent between scenarios. Each simulation used fixed weather and fuel moisture conditions. The weather inputs represent the 98th percentile conditions based on 23 years of records (1999-2022) from the Mount Elizabeth remote automated weather station (RAWS). This RAWS is administered by the USDA Forest Service and sits at 4,933 ft near the center of the study area. We used Fire Family Plus software to summarize weather records over the period of record during the primary fire season (mid-April through mid-October). Based on these results we parameterized GridFire weather conditions with an ambient air temperature of 94°, a relative humidity value of 13%, a 20-ft wind speed of 18 mph from the southwest (270°), and a foliar moisture content value of 80%.

The outputs for each scenario include tabular data with a per-ignition summary of fire size (ac), crown fire size (ac), surface fire size (ac), mean flame length (ft), and mean fireline intensity (Btu ÷ ft ÷ sec). GridFire also produces per-ignition rasters of flame length and per-scenario summary rasters of conditional burn probability (CBP), maximum flame length, and summed flame length. We derived per-scenario rasters of mean flame length as well as conditional flame length (CFL) per 30-m cell, with flame length binned by 2-ft increments (0-2 ft, 2-4 ft, 4-6 ft, 6-8 ft, 8-12 ft, and >12 ft). Conditional burn probability here refers to the probability of a cell in the study area burning given an ignition in the study area (thus the divisor of the CBP is 10,000 because we simulated 10,000 ignitions per scenario.) Conditional flame length here refers to the mean flame length (ft) of each 30m cell when that cell burns (thus the divisor of CFL is the count of times the cell burned). The reason we separately derived CFL is that CFL provides the same intensity information as the mean flame length but it also incorporates a measure of probability.

Analysis

We were interested in comparing the effect of treatment intensity both within and between treatment priority by treatment size scenarios. Pre-processing of the tabular data included calculating percent crown fire (crown fire size ÷ total fire size). To assess the impact of treatment intensity within treatment priority by treatment size scenarios, we compared the treatment scenarios individually to baseline scenarios by plotting the joint probability distribution for each treatment scenario compared to baseline within the four treatment priority by treatment size scenarios. We did this for fire size, crown fire percent, mean flame length, and mean fireline intensity. These plots include the

PHOTO: CAL FIRE

1:1 comparison for all 10,000 ignitions and provide a qualitative comparison between the four treatment priority by treatment size scenarios for each treatment intensity level. A difference in slope between scenarios indicates that the effect of treatment compared to baseline differs.

To qualitatively evaluate whether there were thresholds at which treatments were most effective at mitigating fire behavior, we calculated the percentage of scenarios resulting in a reduction of at least 5%, 20%, and 50% for fire size, crown fire percent, mean flame length, and mean fireline intensity. We then compared these values across the four treatment priority by treatment size scenarios.

To evaluate treatment effects on CBP, we calculated the per-cell ratio of each treatment scenario's CBP to its corresponding untreated CBP. . We then binned these differences into one of four categories:

- CBP = 0: the percentage of cells in the treated scenario where CBP=0
- Treatment CBP < baseline: the percentage of cells where CBP is reduced in the treatment scenario compared to the baseline scenario
- Treatment CBP = baseline: the percentage of cells where CBP in the treatment scenario equals the baseline scenario CBP
- Treatment CBP > baseline: the percentage of cells where CBP is increased in the treatment scenario compared to the baseline scenario

We also looked at CBP in the study area versus CBP in just the untreated cells in the study area, to evaluate whether a treatment translated to a reduction in fire behavior adjacent to the treatments, or if treatment effects were confined only to treated cells.

To evaluate treatment effects on CFL, we compared CFL bins between treatment intensities for the four treatment priority by treatment size scenarios. We also mapped CFL for the baseline, 30% treated, and 60% treated intensity levels for each of the four treatment priority x treatment size scenarios to evaluate the spatial patterns of CFL reduction between treatment scenarios.

Results

Tabular data

We found that the patterns between treatment priority and treatment size scenarios were similar across the range of treatment intensity for the four variables we evaluated: fire size (ac), crown fire percent (%), flame length (ft) and fireline intensity (Btu/ft/sec; Figure 3). Increasing treatment intensity consistently reduced fire behavior metrics. In general, the 'private prioritized' scenarios had a smaller effect on reducing fire behavior than the 'no priority treatments.' There was an inflection point observed at 35% area treated, where the slope increased for all four variables, indicating an increase in effectiveness at reducing fire behavior once public land was also being treated. At the 60% treatment level, the treatment priority scenarios were similar due to much of the treatment area being treated, but the 'no priority' treatments still consistently had more of an effect of reducing fire behavior than the 'private prioritized' scenarios. The Mean10 and Mean40 scenarios differed slightly, where Mean40 scenarios had slightly reduced fire behavior relative to Mean10 for the four variables examined. Overall, treatment priority had a stronger effect on fire behavior than treatment size.

The joint distribution plots revealed similar patterns as above (Figures 4-7). Increasing treatment intensity consistently reduced fire behavior metrics. The slope of the regression lines representing the four treatment priority by treatment size scenarios and comparing treatment intensity scenarios to baseline differed most at the 25%-35% treatment levels. These are the levels at which treatment on private lands is nearly saturated, but no private land has been treated in the 'private prioritized' scenario.

The percent of ignitions that had a greater than 5%, 20%, or 50% reduction in fire behavior metrics showed generally consistent patterns between fire behavior variables. Overall, a similar pattern as above was observed, where the priority scenarios differed most in the effectiveness of reducing fire behavior at the mid levels of treatment intensity and where the 'no priority treatments' were more effective than the 'private prioritized' treatments. The treatment effectiveness between priority scenarios converged as treatment intensity increased. At a 20% treatment intensity, very few ignitions had a 20% reduction in fire size in any of the four treatment scenarios, and this increased to 36-39% of ignitions at 60% treatment intensity (Figure 8). At a 20% treatment intensity, 3-4% of ignitions had a 20% reduction in crown fire percent in any of the four treatment scenarios, and this increased to 57-58% of ignitions at 60% treatment intensity (Figure 9). At a 20% treatment intensity, very few ignitions had a 20% reduction in flame length in any of the four treatment scenarios, and this increased to 22-25% of ignitions at 60% treatment intensity (Figure 10). At a 20% treatment intensity, very few ignitions had a 20% reduction in fireline intensity in any of the four treatment scenarios, and this increased to 26-28% of ignitions at 60% treatment intensity (Figure 11).

Spatial data - CBP

There was a shift in CBP observed with increasing treatment, both for the study area as a whole and for the untreated cells within the study area. This indicates that the effects of the simulated treatments translated to untreated cells. Overall, treatment size had less effect on the proportion of cells in each CBP bin than the ownership scenarios did. It is important to note that in the figure representing the study area as a whole (left panel of Figure 12; Figure 13), each pane (treatment intensity) represents the same number of cells. In the right panel (untreated cells only), each pane represents a decreasing number of untreated cells as treatment intensity increases.

For the study area as a whole (Figure 12, left panel; Figure 13) there was a slight increase in the proportion of cells where CBP equals 0. In the study area as a whole, the proportion increased from 7.5% to 8%, while in the untreated cells only, the proportion increased from 7.5% to 10.5% for the 'no priority' scenario and to 9.75% for the 'private prioritized' scenario. The rate of increase in proportion of cells where CBP equals 0 in the untreated cells was only notably different between the 'no priority' and 'private prioritized' scenarios. It appears that most of the increase in the proportion of untreated cells where CBP equals 0 results from treating public lands (Figure 13).

For the study area as a whole (Figure 12, left panel; Figure 13) and for the untreated cells only (Figure 12, right panel; Figure 13), the 'private prioritized' scenario had a greater proportion of cells where treatment CBP equals baseline CBP compared to the 'no priority' scenario for treatment intensities from 5%-35%. This was offset by a greater proportion of cells where CBP was less than baseline in the 'no priority' scenario as compared to the 'private prioritized' scenario for treatment intensities from 5%-35%. After 35%, when public land is being treated in both scenarios, the two priority scenarios are quite similar (Figure 13).

There was also an increase in the proportion of cells where treatment CBP was greater than the baseline. This does happen on occasion when using the LFTFCT, typically due to the FM40 substitution in treated areas in some vegetation types. In this simulation, about 10% of cells in the study area saw an increase in CBP relative to baseline.

Spatial data - CFL

Notably, the CFL bin with the greatest proportion of cells was the >12 ft bin for all scenarios (Figure 14). In general, CFL was quite high throughout the study area. The average flame length in each ignition was 13.5 ft for the baseline scenario and 11.5 ft for the 60% treatment intensity scenario (Figure 3) and many cells had flame lengths of 25 ft or greater (Figures 14-17). With increasing treatment intensity, the proportion of cells in the highest CFL bins are reduced, while the proportion of cells in the lowest flame length bins remains consistent. As with CBP, the treatment priority scenarios had a larger effect on CFL than the treatment size scenarios. The 'private prioritized' treatments have a slightly greater proportion of cells in the >12 ft CFL bin compared to the 'no priority treatments.'

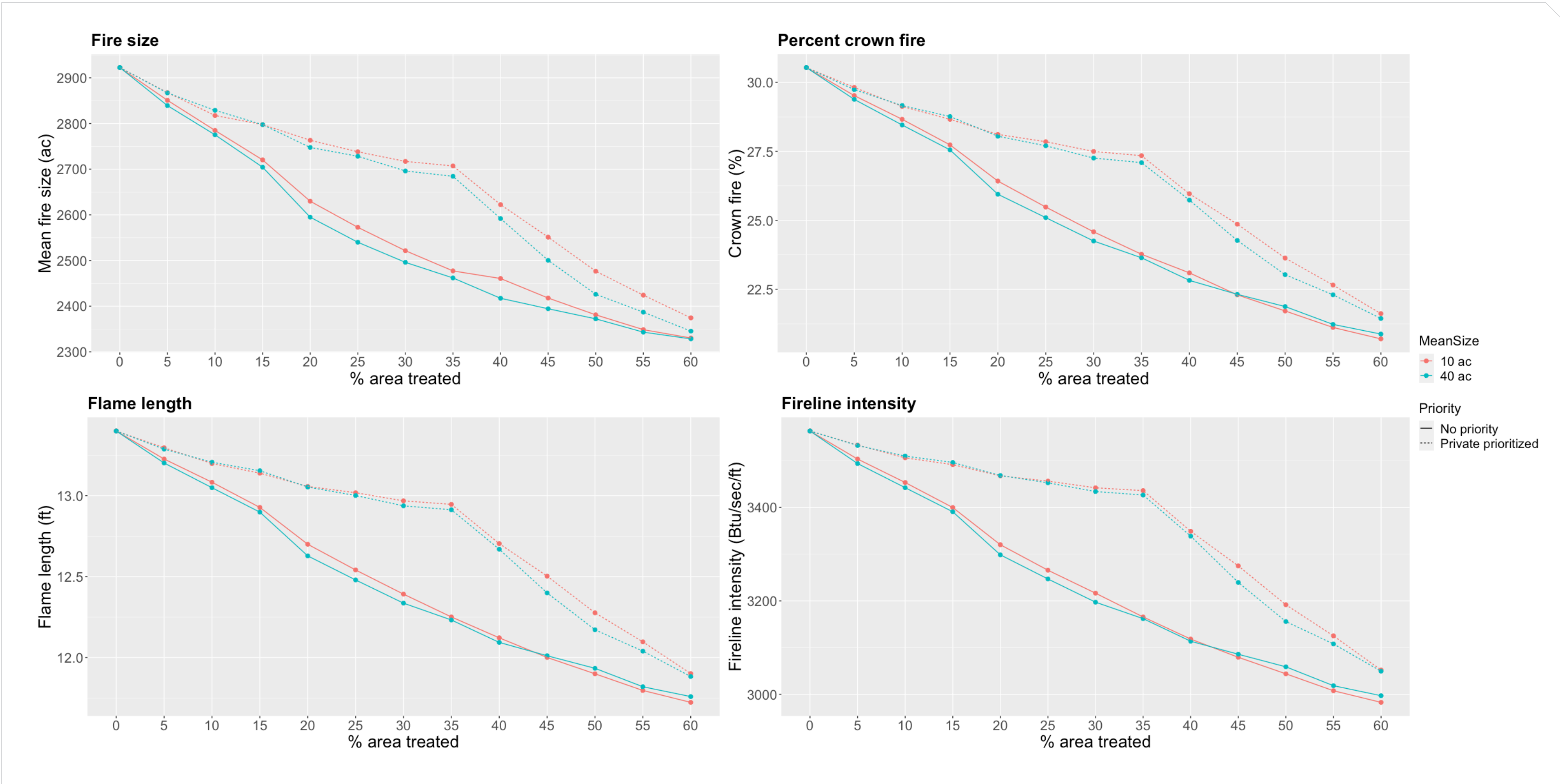

Figure 3. Fire behavior metrics by mean treatment size (10 acres and 40 acres) and treatment priority scenario (no priority in treatment placement, or treatments prioritized on privately-owned parcels

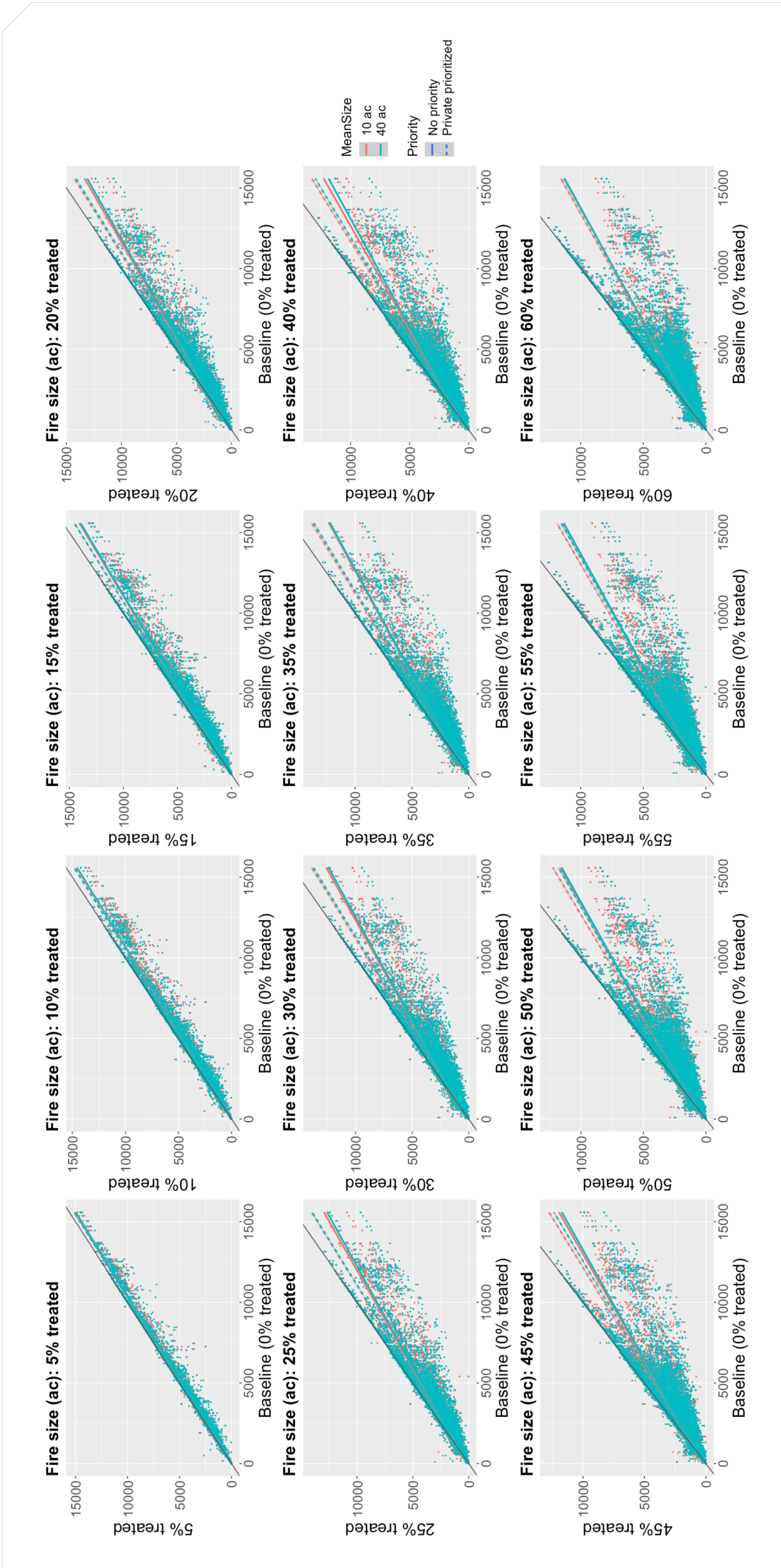

Figure 4. Joint distribution of baseline and treated fire size (ac) by mean treatment size (10 acres and 40 acres) and treatment priority scenario (no priority in treatment placement, or treatments prioritized on privately-owned parcels). The solid line is the 1:1 relationship. Increasing treatment results in overall lower fire size. In all cases the 'no priority' trend lines show a smaller slope than those of the 'private prioritized' trendlines.

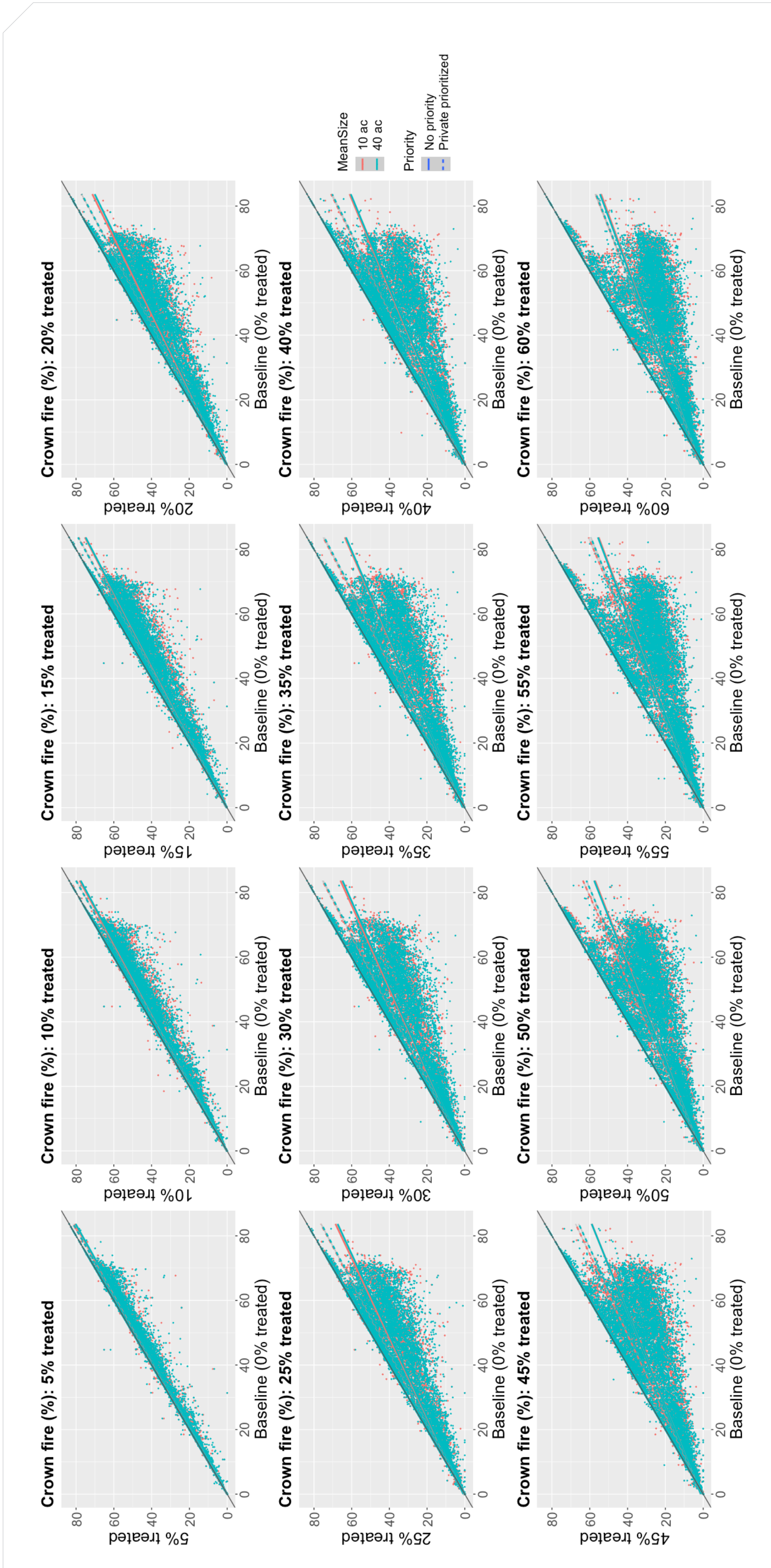

Figure 5. Joint distribution of baseline and treated crown fire percent by mean treatment size (10 acres and 40 acres) and treatment priority scenario (no priority in treatment placement, or treatments prioritized on privately-owned parcels). The solid line is the 1:1 relationship. Increasing treatment results in overall lower percent crown fire.

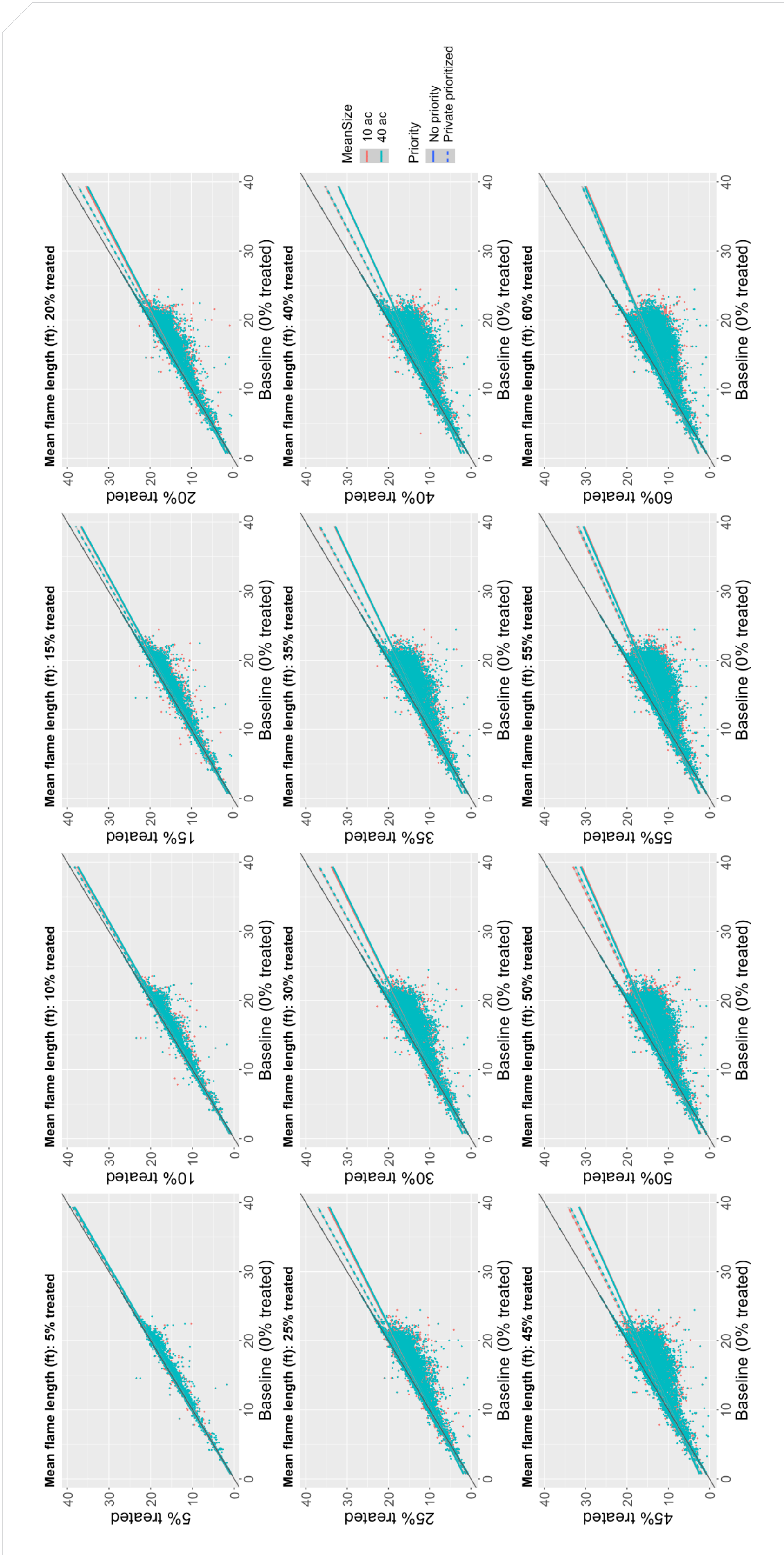

Figure 6. Joint distribution of baseline and treated mean flame length by mean treatment size (10 acres and 40 acres) and treatment priority scenario (no priority in treatment placement, or treatments prioritized on privately-owned parcels). The solid line is the 1:1 relationship. Increasing treatment results in overall lower mean flame length.

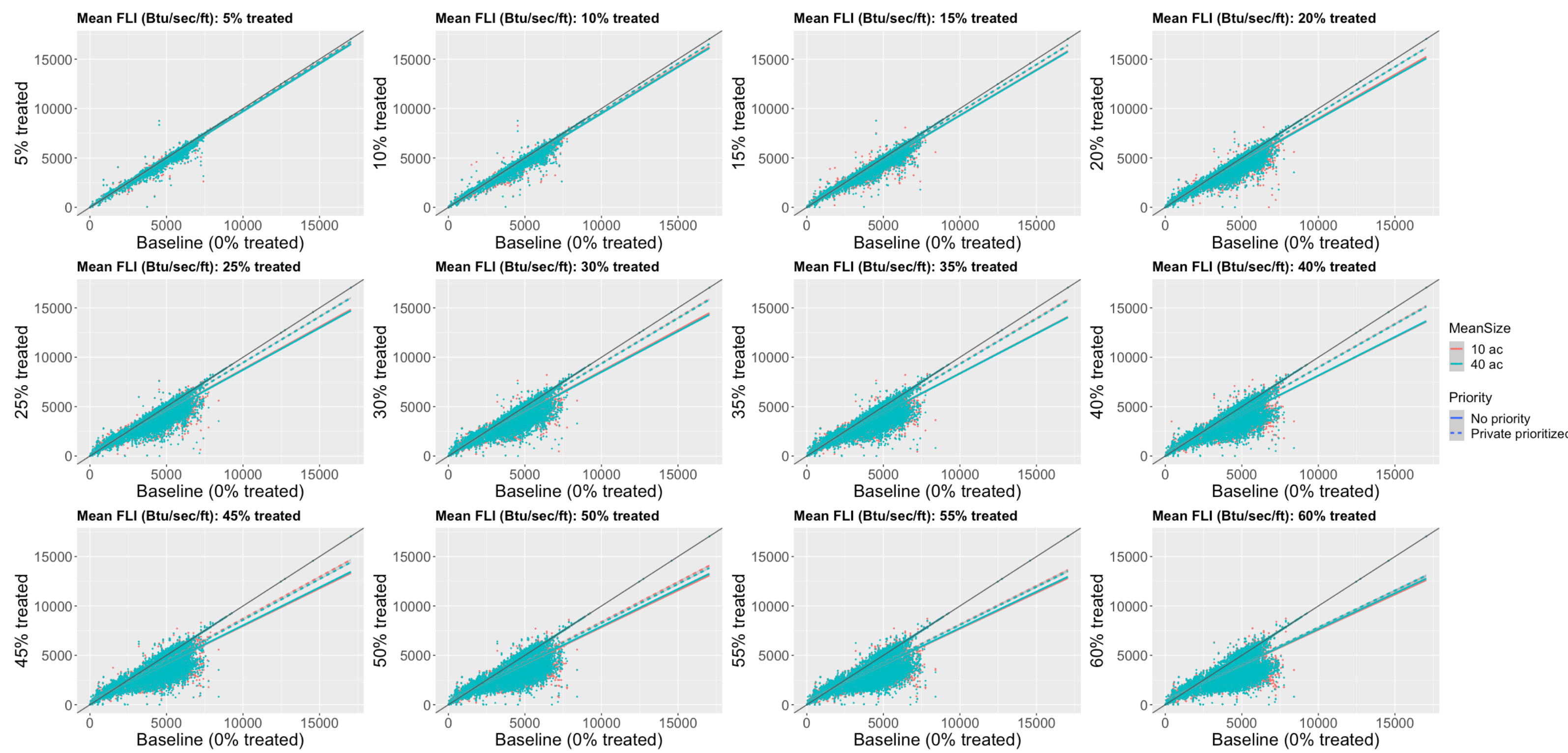

Figure 7.Joint distribution of baseline and treated mean fireline intensity by mean treatment size (10 acres and 40 acres) and treatment priority scenario (no priority in treatment placement, or treatments prioritized on privately-owned parcels). The solid line is the 1:1 relationship. Increasing treatment results in overall lower mean fireline intensity.

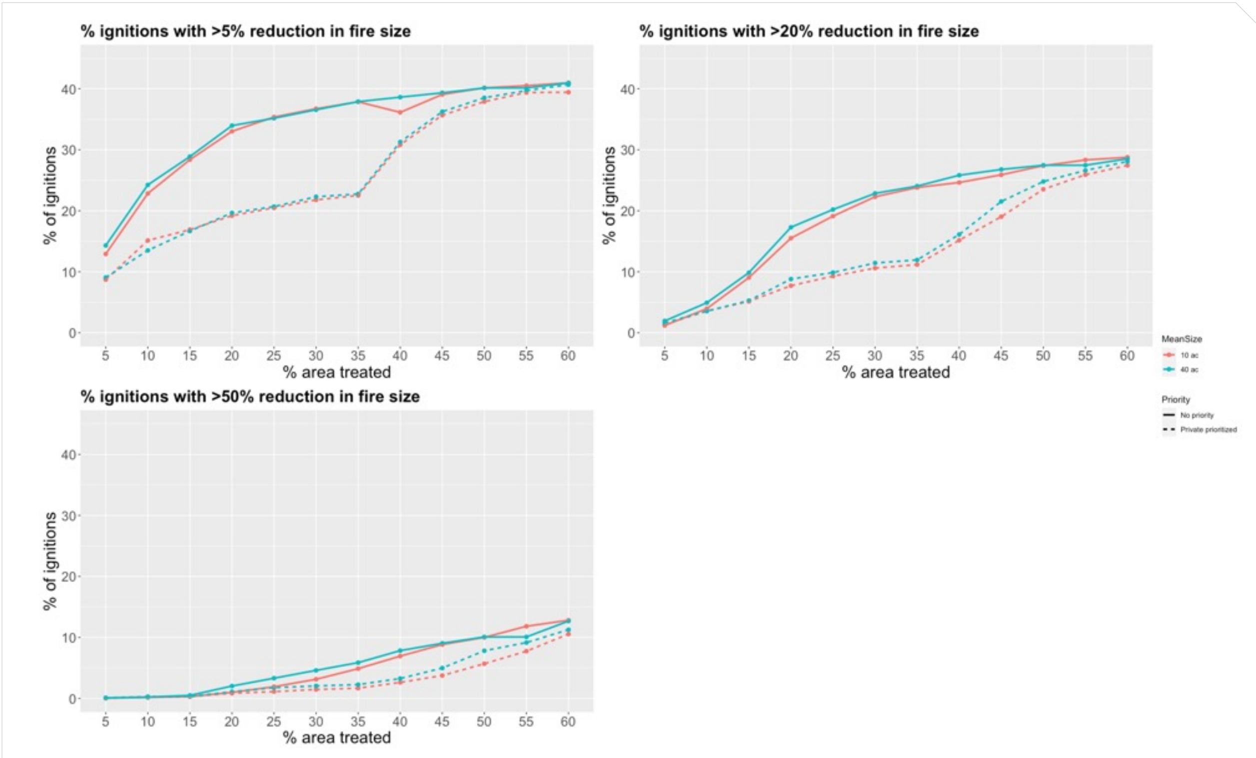

Figure 8. The percent of ignitions with a reduction in fire size (ac) of at least 5%, 20%, and 50% by mean treatment size (10 acres and 40 acres) and treatment priority scenario (no priority in treatment placement, or treatments prioritized on privately-owned parcels).

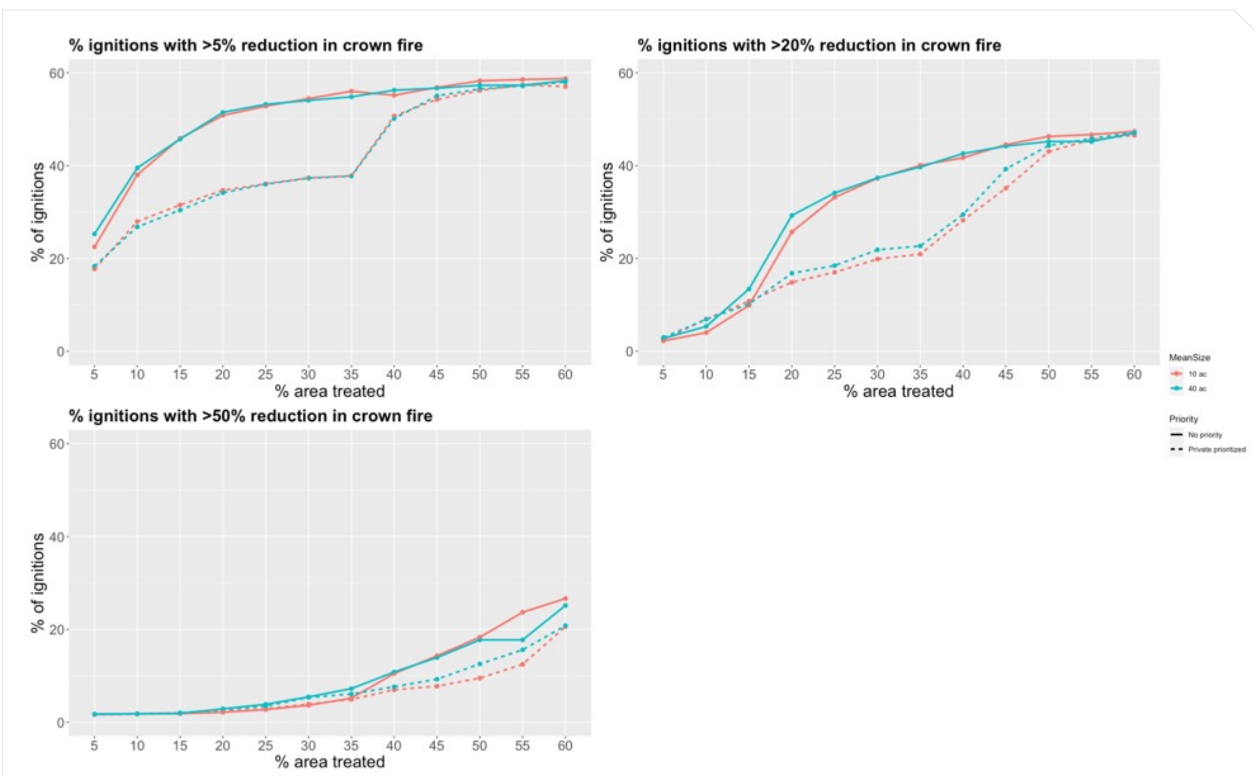

Figure 9. The percent of ignitions with a reduction in crown fire percent of at least 5%, 20%, and 50% by mean treatment size (10 acres and 40 acres) and treatment priority scenario (no priority in treatment placement, or treatments prioritized on private-ly-owned parcels).

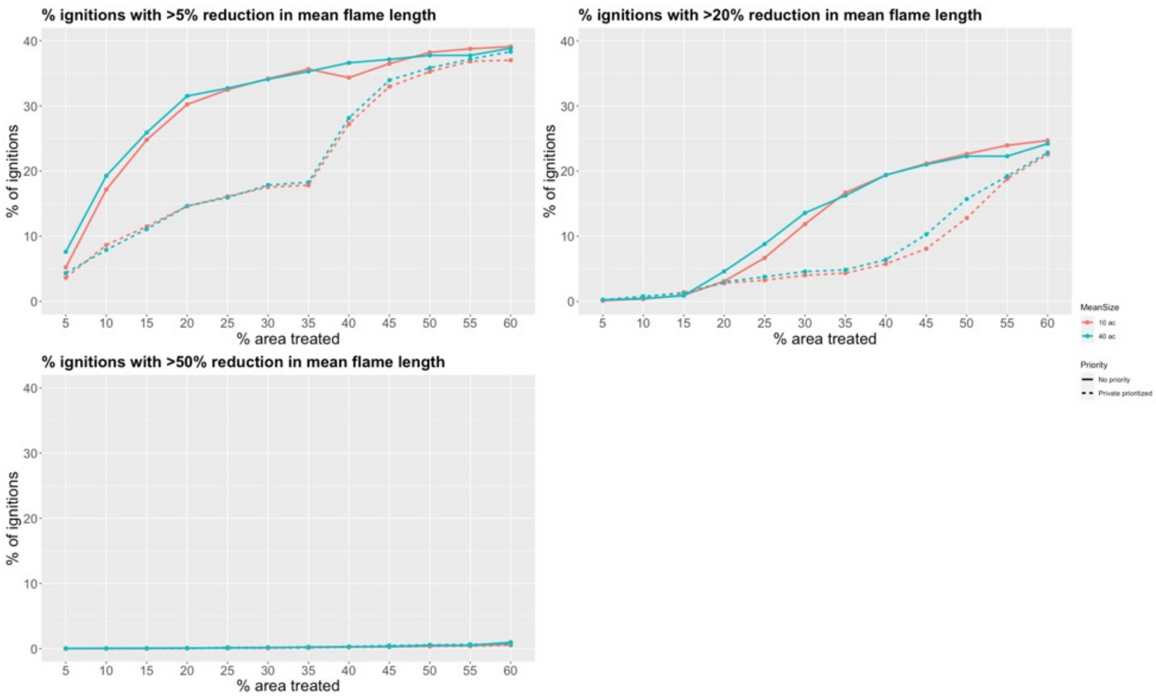

Figure 10. The percent of ignitions with a reduction in mean flame length (ft) of at least 5%, 20%, and 50% by mean treatment size (10 acres and 40 acres) and treatment priority scenario (no priority in treatment placement, or treatments prioritized on privately-owned parcels).

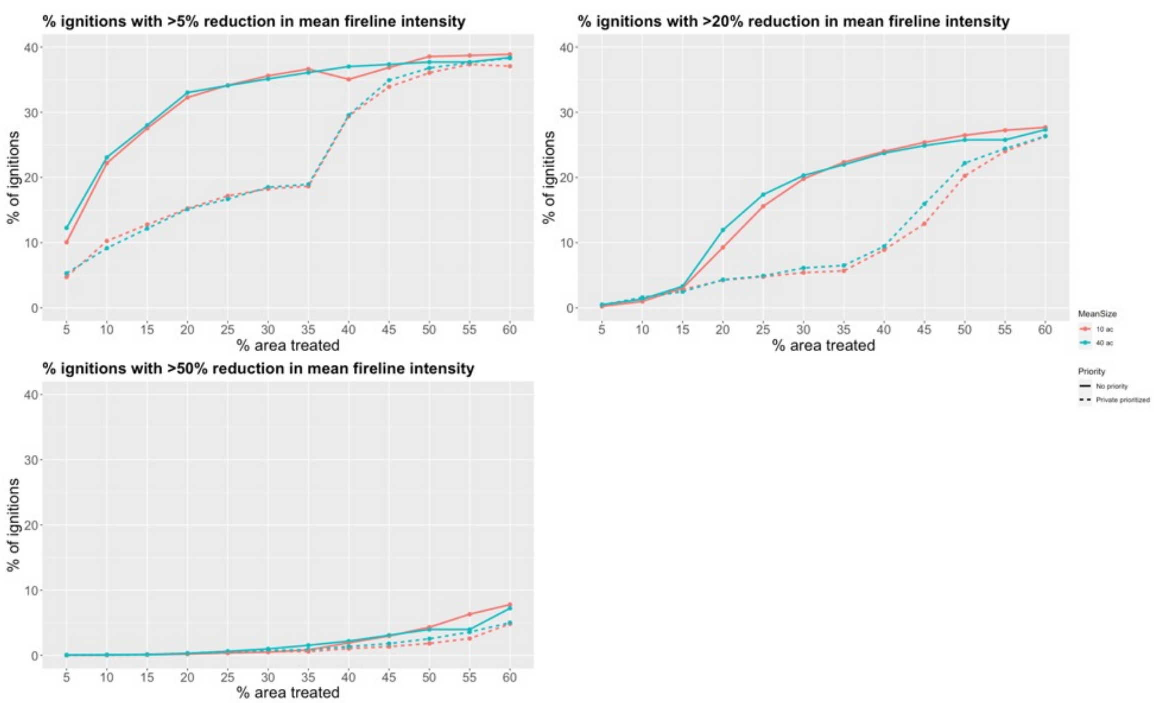

Figure 11. The percent of ignitions with a reduction in mean fireline intensity (Btu/ft/sec) of at least 5%, 20%, and 50% by mean treatment size (10 acres and 40 acres) and treatment priority scenario (no priority in treatment placement, or treatments prioritized on privately-owned parcels).

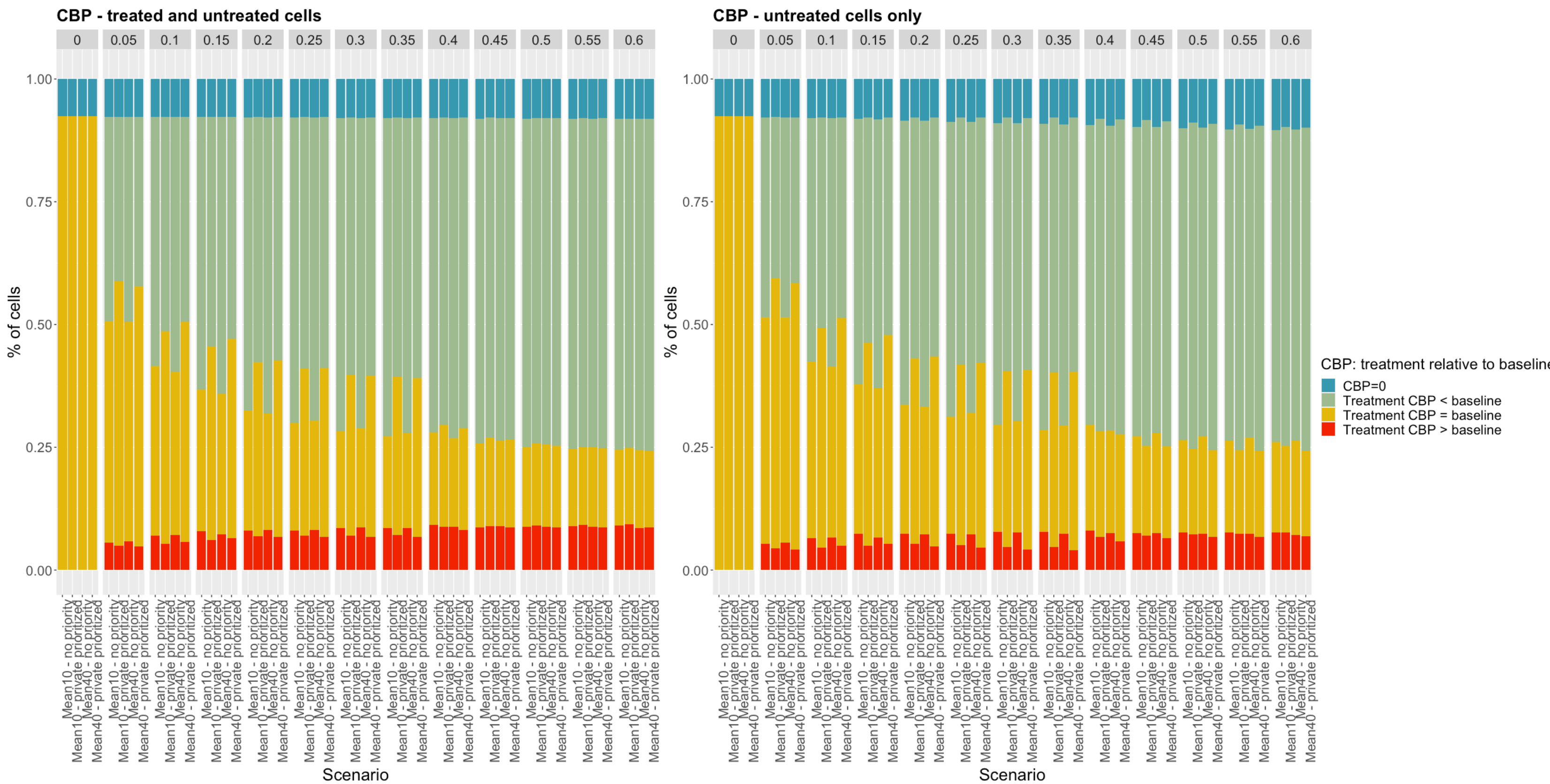

Figure 12. The difference between baseline and treatment conditional burn probability ratios by mean treatment size (10 acres and 40 acres), treatment priority scenario (no priority in treatment placement, or treatments prioritized on privately-owned parcels), and percent area treated. The pattern of CBP reduction (green bars) observed in the combined treated and untreated cells is almost exactly replicated in just the untreated cells, implying that fuels treatments can be just as beneficial to adjacent, untreated areas as they are within the treatments themselves, at least with respect to reducing conditional burn probability.

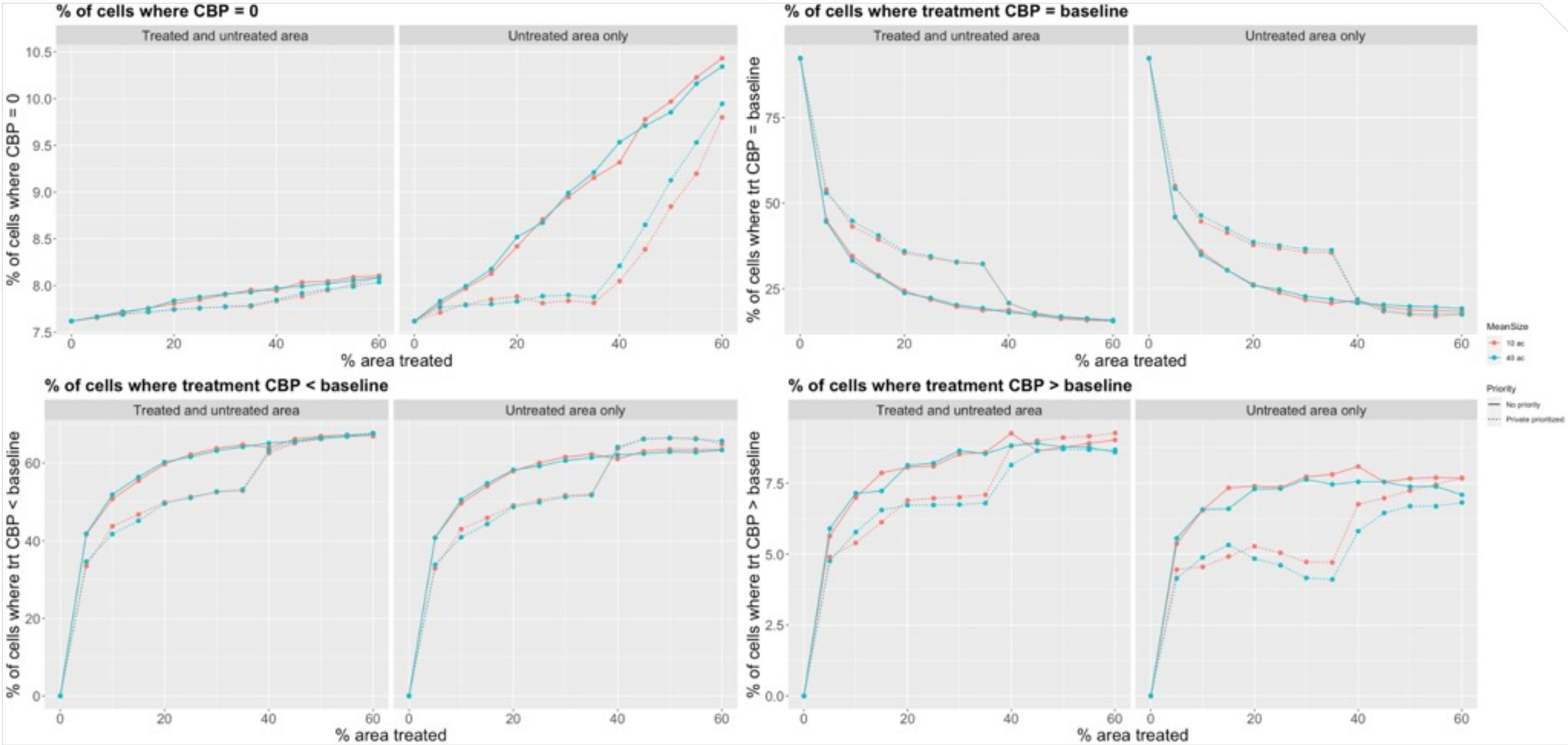

Figure 13. The difference between baseline and treatment conditional burn probability, by mean treatment size (10 acres and 40 acres), treatment priority scenario (no priority in treatment placement, or treatments prioritized on privately-owned parcels), and percent area treated. The percentage of cells with CBP ratio = 0 or treatment CBP > baseline is relatively constant with respect to percent area treated; the reduction in percentage of cells with treatment CBP = baseline, however, is substantial and is counter-balanced by the increase in the percentage of cells with treatment CBP < baseline.

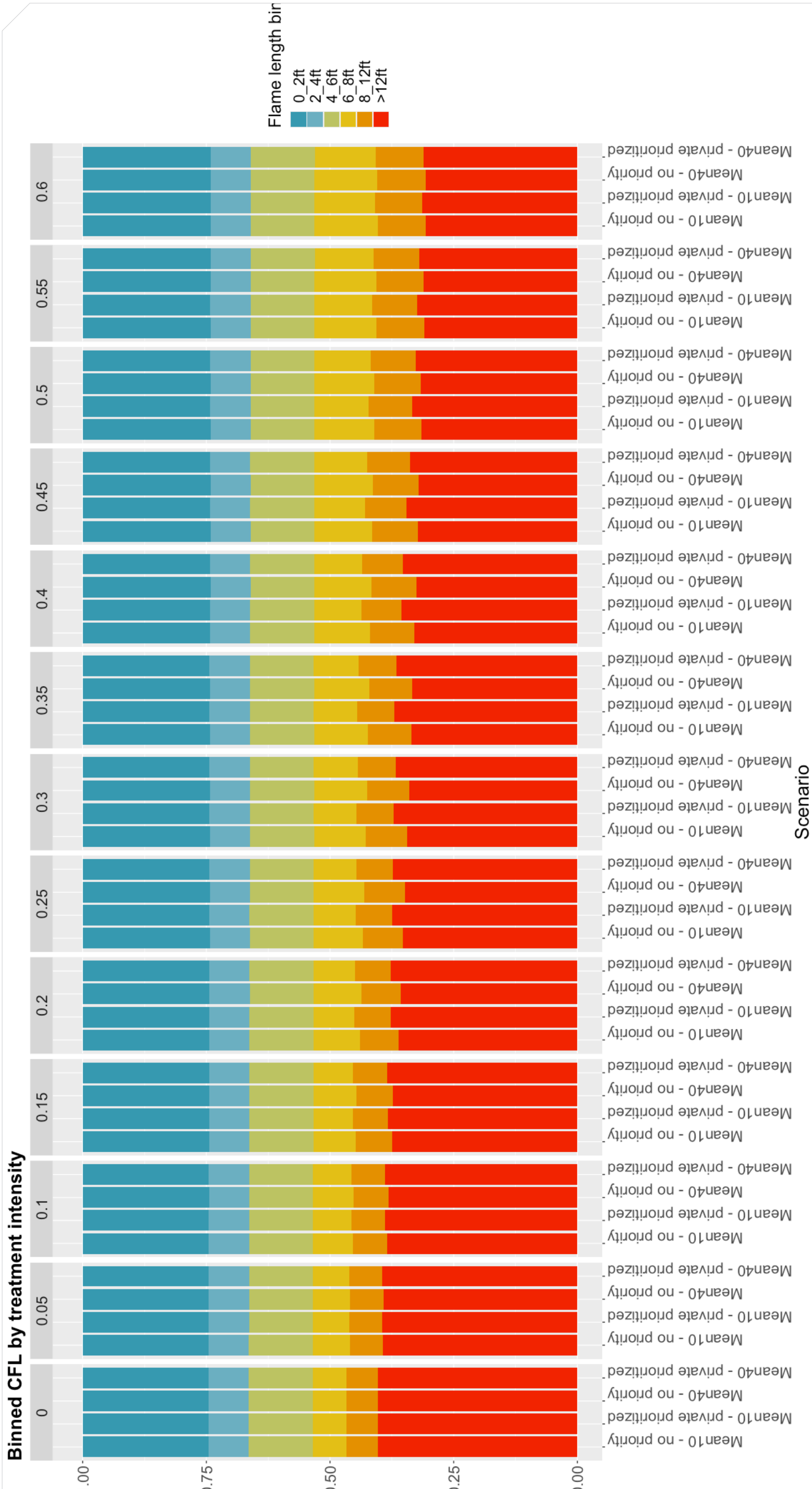

Figure 14. Conditional flame length (CFL; the expected flame length should a cell burn) binned by length class, by mean treatment size (10 acres and 40 acres), treatment priority scenario (no priority in treatment placement, or treatments prioritized on privately-owned parcels), and percent area treated.

Discussion

This study suggests that treatment is beneficial even if it is not planned with specific prioritization goals in mind. Overall, we found that increased treatment intensity consistently reduced fire behavior across the landscape, in both treated and untreated cells. While not surprising, this result confirms that if the goal is to reduce fire behavior, managers should treat as much area as possible. We did not find that there was an inflection point at which the benefits of increased treatment intensity saturated. It is possible that this may occur at treatment intensities greater than 60%, but it is unlikely that more than 60% of a landscape would be treated with a moderate fuels reduction treatment. Rather, the results of this study suggest that if the management goal is to reduce fire behavior, managers should strive to treat as much acreage as possible. Additionally, we found that the treatments replicated their impact in the untreated areas when looking specifically at CBP. Importantly, we performed these simulations under 98th percentile weather conditions, so these results reflect fire behavior that would be expected even under weather conditions more severe than those for which the treatments were designed. It is also worth noting that fuels treatments are typically designed to facilitate fire suppression and reduce a fire's damaging effects on both the built and natural environments. These goals can be achieved primarily by reducing flame lengths and secondarily by slowing, although not necessarily stopping, a fire's rate of spread. To some extent, then, a comparatively minimal effect on mean fire sizes between scenarios is not unexpected.

We found that the treatment priority scenarios had a greater effect of fire behavior reduction than the treatment size scenarios. That the Mean10 and Mean40 scenarios were quite similar implies that when treating areas randomly across this study area, treatment is relatively as effective at reducing fire behavior regardless of whether 10 acre parcels are treated or treatments are bundled across multiple parcels. While the effect was slight, the Mean40 scenarios were consistently more effective at reducing fire behavior compared to the Mean10 scenarios (Figure 1). Thus, if possible, treatments should be bundled, but if there is an increased cost associated with working to ensure landowner buy-in across multiple small parcels, the effort may be better spent increasing treatment acreage. In the future, we plan to test Mean100 and Mean500 scenarios to gain a better understanding of whether treatment size has a greater effect if treatments are larger. Typically, on public lands, treatments would not be as small as 10 or 40 acres, but this treatment size would be typical of treatments on smaller, privately-held parcels.

There are some caveats regarding the treatment priority scenarios worth mentioning. First, it is difficult to account for the interacting effects of land ownership and vegetation type. The private parcels are primarily in the southern and western portion of the study area, which due to the orientation of the Sierra Nevada range are lower in elevation and consist of more grass-shrub and shrub fuel types than the public lands, which are located at higher elevations with predominantly timber litter and timber-understory fuel types. Additionally, the spatial arrangement may contribute to the different effect of the 'no priority' and the 'private prioritized' scenarios on reducing fire behavior. In the 'no priority' scenario, treatments are located throughout the treatment area, while in the 'private prioritized' scenarios, they are clustered in the private parcels (Figure 2). Additionally, this workflow simulated only one spatial arrangement of treatment plots for each of the four treatment size by treatment ownership scenarios. As a result, we are not able to draw conclusions about the effect of randomization of treatment placement, but we do note that fire behavior metrics were reduced when treatment location was not selected to optimize treatment effectiveness. We plan to test additional randomized location scenarios in future work in addition to testing larger mean treatment sizes.

The comparison in CBP between the four scenarios is interesting because it implies that the effect of treating across the landscape translates to untreated cells as well, as we saw similar patterns between the study area as a whole and the untreated cells (Figure 12). The difference in the proportion of cells where treatment CBP was reduced as compared to baseline CBP between the 'no priority' and the 'private prioritized' scenarios is also notable. For the 5%-35% treatment intensity scenarios, the 'private prioritized' had a greater proportion of cells where treatment CBP equals baseline CBP and a smaller proportion of cells where treatment CBP < baseline CBP as compared to the 'no priority' scenarios. This is likely due to the spatial clustering of the treatments, so that the simulated ignitions burned similarly in the public lands where no treatments were simulated in the 'private prioritized' scenario. This implies that clustering treatments may have a more limited effect on reducing fire behavior as compared to distributing them more evenly across the landscape.

We found that CFL was generally quite high across the landscape, with the greatest proportion of cells in the >12 ft CFL bin for each scenario tested. The simulated treatments reduced the proportion of cells in the highest CFL bins, but the lower flame lengths remained the same. This indicates that the treatments are capable of reducing flame lengths that are most likely to impact structures and infrastructure, however, the proportion of high flame lengths even in the highest treatment intensities implies that forest thinning alone is likely not enough to systematically depress flame length in this study area should a fire occur during 98th percentile weather conditions. The spatial patterns of CFL are relatively similar between the four treatment scenarios, but looking at the spatial patterns may help managers make decisions regarding the protection of high value resources and assets (Figures 15-18).

A cost-benefit analysis would be a logical next step toward determining a realistic treatment acreage goal that incorporates real-world constraints on treatment location as well as costs, to determine the treatment intensity at which benefits can be maximized and costs minimized. The Sonora fireshed is typical of foothill areas throughout the Sierra Nevada, in that privately-owned parcels comprise the lower elevation zones and the higher elevation areas are composed primarily of public land. This study implies that incentivizing public-private partnerships to treat across this elevation gradient is likely to result in increased benefit of fuels reduction treatments throughout the Sierra Nevada region.

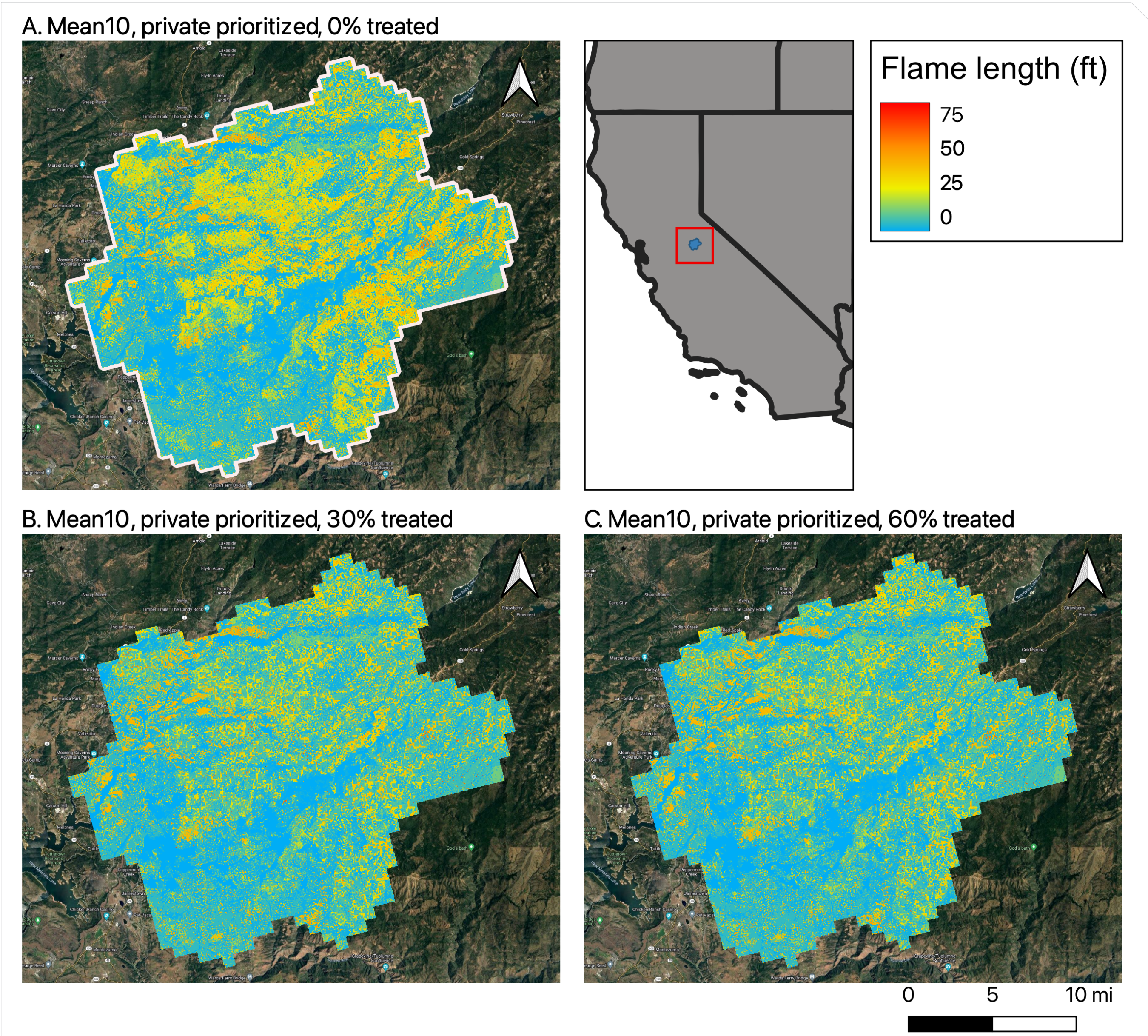

Figure 15. Conditional flame length across the study area for the Mean10, private prioritized, 0%, 30% and 50% treated scenarios.

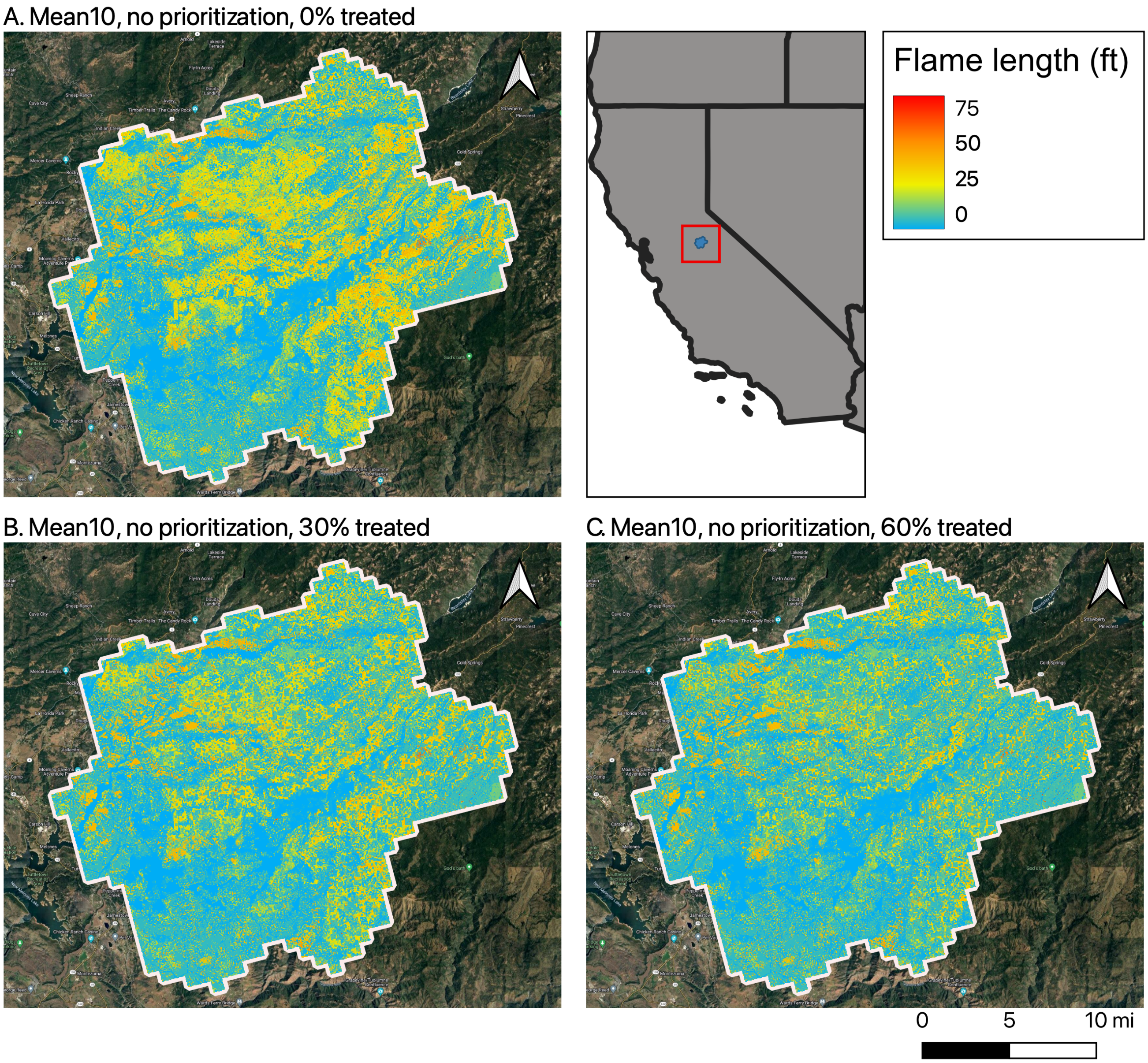

Figure 16. Conditional flame length across the study area for the Mean10, no prioritization, 0%, 30% and 50% treated scenarios.

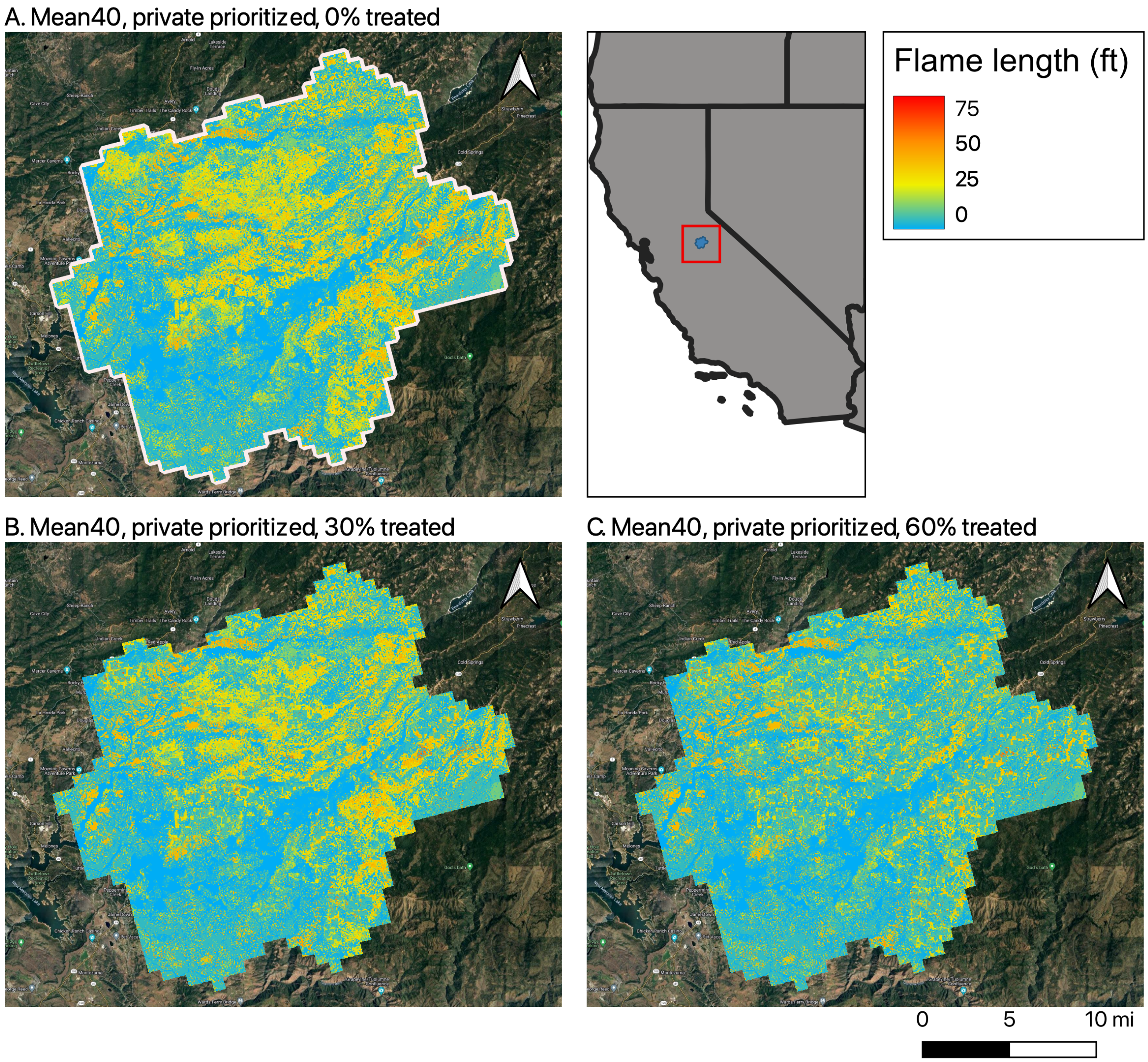

Figure 17. Conditional flame length across the study area for the Mean40, private prioritized, 0%, 30% and 50% treated scenarios.

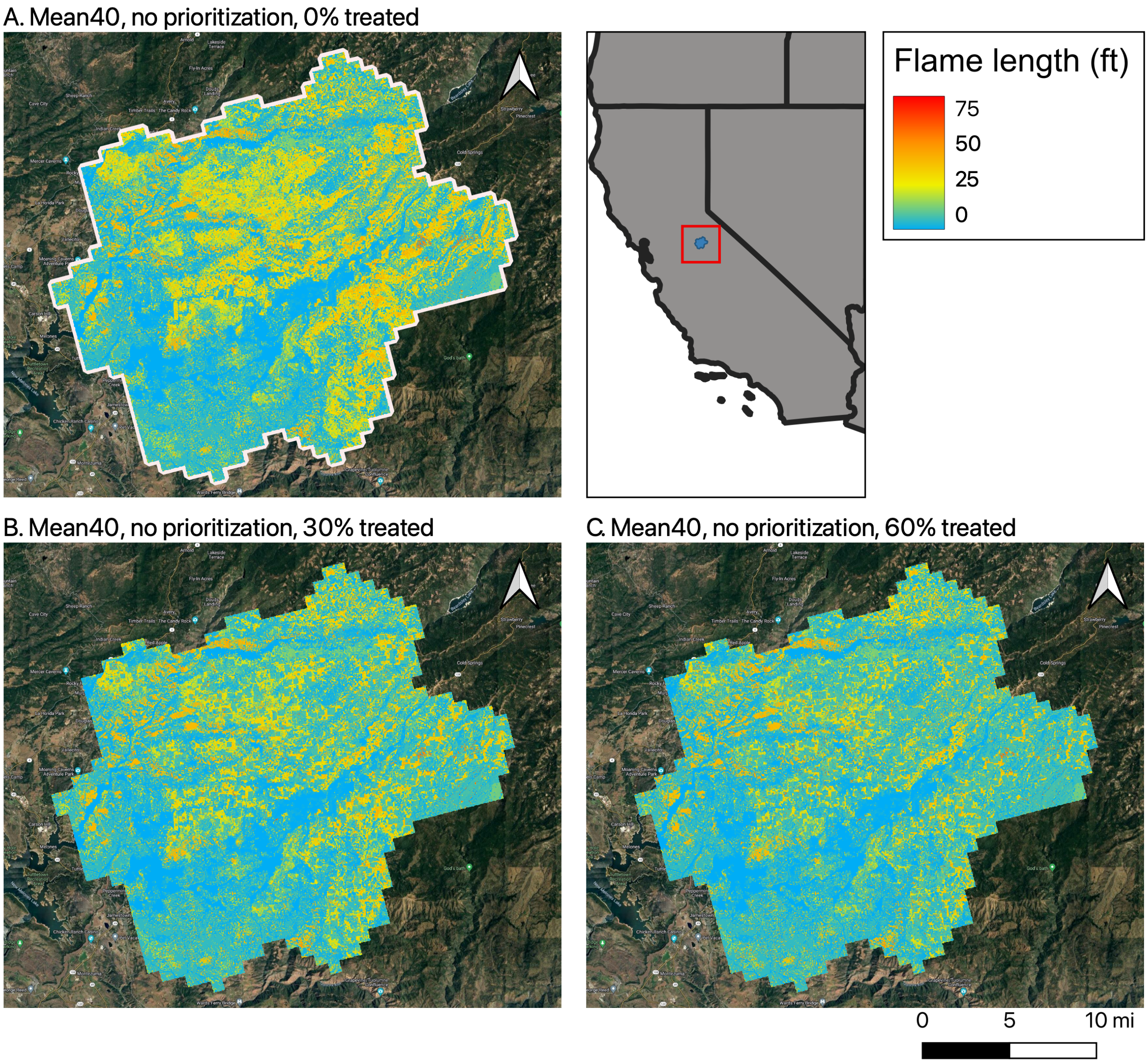

Figure 18. Conditional flame length across the study area for the Mean40, no prioritization, 0%, 30% and 50% treated scenarios.

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