

How big is enough? Vegetation structure impacts effective fuel treatment width and forest resiliency

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Citation: Kennedy, M. C., M. C. Johnson, K. Fallon, and D. Mayer. 2019. How big is enough? Vegetation structure impacts effective fuel treatment width and forest resiliency. *Ecosphere* 10(2):e02573. 10.1002/ecs2.2573

Abstract. Fuel treatments are designed with multiple management goals, including improving suppression capacity and restoring the historical structure of dry forests. Fuelbreaks are a class of fuel treatment that remove fuels within a wide strip of land, with an overarching objective to reduce fire behavior and provide safe access for suppression. In an empirical analysis of shaded fuelbreaks that burned during the 2014 Bald Fire (15,950 ha on the Lassen National Forest, California, USA), we found that overall fire severity was reduced in the treated areas relative to untreated. A non-linear mixed effects model estimates that the reduction was detected more than 400 m into the treated area, greater than the standard width of the prescribed fuelbreak. Both pre- and post-fire species composition differed between treated and untreated forest, with few living stems remaining in the measured untreated areas. In the post-fire treated area, we documented a mixed conifer forest dominated by larger diameter *Pinus*, implying that the fuelbreak did result in a more resilient post-fire structure and composition. These results indicate that fuelbreak design may need to be wider than generally prescribed and that even during extreme fire conditions fuel treatments can result in resilient forest structures.

Key words: defensible fuel profile zone; fuel treatment effectiveness; fuelbreaks; spatial patterns.

Received 29 August 2018; revised 1 December 2018; accepted 10 December 2018. Corresponding Editor: Carrie Levine.

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INTRODUCTION

Fire activity has been increasing throughout the western United States (Calkin et al. 2005, Westerling 2016), attributed to a disruption of the historic regimes driven by human management practices (Hessburg et al. 2005) and by increasing temperatures and fuel aridity (Abatzoglou and Williams 2016). Relative to historical conditions, many dry forests have increased stand density and their composition has shifted to more shade-tolerant/fire-intolerant species that act as ladder fuels, creating forest structure associated with dangerous stand-replacing wildfire

(Hessburg et al. 2005). These fire hazards are predicted to be exacerbated by changing climate (Westerling and Bryant 2007, Littell et al. 2009, Abatzoglou and Williams 2016).

A fuel treatment is a management action designed to reduce fire hazard, restore historical fire regimes, and increase forest resiliency (Peterson et al. 2005). A fuelbreak is a class of fuel treatment that historically was designed as a strategically located strip in which fuels are removed (Green 1977). The fuelbreak concept has been updated to a shaded fuelbreak, where some forest canopy is maintained in the treated area (Agee et al. 2000). In the northern Sierra

Nevada in California, a network of defensible fuel profile zones (DFPZ) was established under the Herger-Feinstein Quincy Library Group (HFQLG) Forest Recovery Act of 1988 (Cheng et al. 2016). Defensible fuel profile zones are prescribed to be shaded fuelbreaks between 0.4 and 0.8 km in width treated with a combination of mechanical thinning from below and prescribed fire, located to leverage existing features such as roads or ridge tops. Defensible fuel profile zones are designed to provide safe access for firefighters to perform suppression activities, limit fire behavior to prescribed levels, and reduce the likelihood that canopy fires will spread (Moghaddas et al. 2010). Defensible fuel profile zones have generally been found to meet the goals of reducing severity and facilitating suppression actions (Moghaddas and Craggs 2007, Moghaddas et al. 2010, Murphy et al. 2010), although the performance of such prescriptions under extreme wildfires is unclear (Agee et al. 2000, Moghaddas and Craggs 2007).

In the design of fuel treatments, it is important to consider landscape context and existing vegetation structure (Stephens and Moghaddas 2005, Stephens et al. 2010). For example, the legacies of previous timber harvest and fire suppression in the landscapes in the DFPZ network were thought to have depleted those areas of large trees (Cheng et al. 2016). This would make it difficult to fulfill a fuel treatment objective to retain large-fire resilient trees (Agee and Skinner 2005). The guidelines for the implementation of DFPZs were seen as overly prescriptive and inhibited the ability to make site-specific decisions (Cheng et al. 2016). A given fuel treatment prescription may not be equally successful in different landscape contexts, and it is important to understand what characteristics explain variability in fuel treatment effectiveness.

There is a substantial body of evidence that fuel reduction treatments that include mechanical thinning followed by prescribed fire are most effective at reducing fire severity relative to untreated forest (Stephens et al. 2012, Kalies and Yocom Kent 2016). This binary comparison (severity reduced or not) masks possible variability in severity within the treated areas themselves. For example, when estimated spatially, the distance into a fuel treatment at which fire severity is reduced may be relatively close to the

treatment edge (40 m; Safford et al. 2009, 2012) or hundreds of meters into the fuel treatment (Symons et al. 2008, Kennedy and Johnson 2014). This variability in spatial patterns of wildfire severity may be explained by the context of the surrounding landscape or by the structural characteristics of the fuel treatment itself. In order to improve fuel treatment planning and effectiveness, it is important to understand what explains the variability in the spatial pattern of severity as the wildfire moves from untreated forest into the treated area (Kennedy and Johnson 2014). This requires opportunistic documentation of wild-fire-treatment interactions.

On 30 July 2014, an ignition from a lightning strike started a wildfire on Bald Mountain (Lassen National Forest; Fig. 1) that burned unsuppressed through a series of modified DFPZs, providing an opportunity to assess empirically the spatially explicit pattern of fire severity and its relationship with stand structure under extreme fire conditions. Our goals are to (1) compare stand structure and species composition between treated and untreated forest reconstructed before and after the fire; (2) identify stand structure variables that explain variability in severity between treated and untreated forest, and within the fuel treatments; and (3) estimate the distance into treatment area at which severity was reduced.

METHODS

Site description

The Bald Fire ignited on the east flank of Bald Mountain, 12.9 km southeast of Fall River Mills, California, burning from the North over 15,950 ha on the Lassen National Forest, Hat Creek Ranger District, between 30 July and 6 August 2014 (Fig. 1). The climate in Hat Creek Valley is typically Mediterranean with wet, cool winters and dry, warm summers. Temperatures ranging from -34° to 43°C and with an annual mean of 10° . Precipitation averages 101.6 cm/yr falling primarily as snow above 1200 m (USDA Forest Service 1993), with most precipitation occurring from November to April. The study area lies within a transition zone between the southern Cascade mountain range, the northern Sierra Nevada mountain range of northeastern California, and the Modoc Plateau (Ramirez

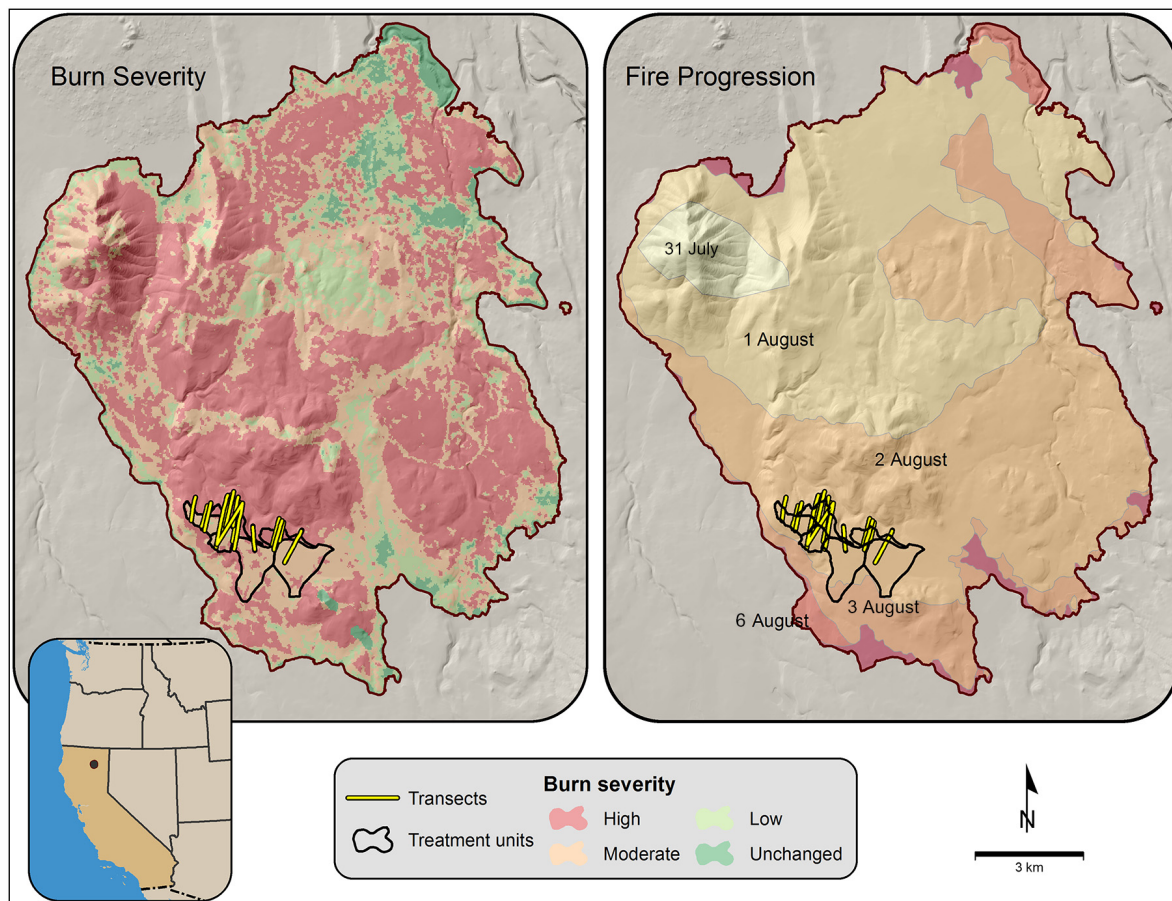


Fig. 1. Map of study area and location of transects, including immediate post-fire classifications of burn severity and fire progression dates. Topographic relief is also shown in both maps.

and Stawairski 2015). Elevation ranges from 1000 to 1700 m. Dominant geologic features are volcanic cones and their associated valley flows with soils derived from andesite, basalt, and rhyolite that vary from shallow to deep. Soil parent materials in the project activity areas are from various volcanic sources: basalt, andesite, rhyolite, cinder, and tephra. Soils from rhyolitic parent material are specifically listed in the Forest Plan (a document that directs the management of the National Forest; USDA Forest Service 1992) as erodible. The dominant soil surface texture is loam with varying rock contents, covering about 67% of the project area (USDA Forest Service 1984). Sandy loams dominate about 33% of the area. The climate is characterized by hot, dry summers and cold, moist winters

Predominant conifer tree species within the project area include ponderosa pine (*Pinus ponderosa*), Jeffery pine (*Pinus jeffreyi*), incense cedar (*Calocedrus decurrens*), Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), sugar pine (*Pinus lambertiana*), gray pine (*Pinus sabiniana*), and western juniper (*Juniperus occidentalis*). Hardwoods found include the following: aspen (*Populus tremuloides*), cottonwood (*Populus trichocarpa*), and oak (*Quercus chrysolepis* and *Q. kelloggii*). Common shrub species include sagebrush (*Artemisia tridentata*), bitterbrush (*Purshia tridentata*), goldenbush (*Ericameria bloomeri*), tobacco brush (*Ceanothus velutinus*), snowbrush (*Ceanothus velutinus*), manzanita (*Arctostaphylos patula* and *A. nevadensis*), and rabbitbrush (*Ericameria nauseosa*). Timber extraction has been widespread throughout the area. Many of the larger

trees have been removed, and thousands of acres of smaller trees have been thinned. Plantations of various sizes and age classes occurred in the project area.

Weather from the Ladder Butte Remote Automated Weather Station (RAWS) on 2 August 2014 indicated wind speed was 14.5 kph, temperature 31.1°C, and relative humidity 13%. FireFamily Plus (Bradshaw and McCormick 2000) fuel moisture conditions were reported as 1 h = 2%; 10 h = 3%; 100 h = 5%, and 1000 h = 7%.

Fuel treatments and field design

With assistance from the district fire management officer and fuels specialist, we identified treatment units that burned on 2 August 2014. These treatment areas were burned without any suppression tactics, so the wildfire burned freely through the treatment area with no backburning. Prior to the fuel treatment, many of the units in the area were commercially harvested. The primary vegetation type within the project is known as eastside pine forest, along with shrub, juniper, and riparian communities. Timber extraction has been widespread throughout the area. Many of the larger trees have been removed, and thousands of acres of smaller trees have been thinned. Plantations of various sizes and age classes occurred in the project area. Fuel treatment units were designated as DFPZs as part of a HFQLG prescription, but local managers increased the size of the DFPZ based on their own knowledge of the area. The treatment units were underburned in 1998–1999 and then thinned from below to basal area 27.5 m²/ha followed by surface fuel treatments (prescribed fire, pile burns) in 2001–2002.

In the summer of 2015, we used geographical information system maps, planning maps, aerial photographs, fire progression maps, and field reconnaissance to determine the location of 17 linear transects. These transects were placed 80 m apart. Subsequent to field measurements, we could not verify documentation of treatment polygons for two of the transects, so final analysis was conducted on 15 transects (Fig. 1). Note that estimates and inference changed only slightly with the exclusion of two transects. The number of plots along each transect in the untreated and treated areas is given in Appendix S1: Table S1.

The placement of transects was not completely random as they were installed to avoid major roads, drainages, riparian buffers, reserve areas, and other wildlife habitat areas. We first placed the transects on the fireside of each treatment, based on the fire progression map (Fig. 1). In the field, individual transects were oriented by the fire spread direction indicated from burn severity indicators such as crown (needle) freeze, crown scorch, and basic knowledge of fire behavior and topography. Starting at the treatment boundary, permanent plot centers were placed every 30 m along each line transect using a laser range finder, with 5–10 plots extending into the untreated area and into the treated area until the back edge of the treatment unit was reached. All trees >12.7 cm diameter at breast height (dbh) were measured on 0.04 ha plots at plot center, and all trees ≤12.7 cm dbh were measured on 0.008 ha plots at plot center. The placement of transects extending linearly from the untreated forest into the treatment ensured that the measured forest structure and severity represent the conditions as the fire entered the treated unit.

We recorded the slope, aspect, and elevation of each plot. For each tree, we identified the species and measured dbh, tree height, crown base height, and height-to-live crown. Each tree was classified by a burn severity index (BSI) with five levels: 1 = unburned, 2 = scorched foliage, 3 = lightly burned (some foliage and small twigs consumed), 4 = moderately burned (foliage and small stems consumed), and 5 = severely burned (only charred stems remain). For each plot, we summarize severity as the proportion of stems with burn severity index ≥3 (at least partially consumed; BSI3). Crown scorch (CS) was estimated visually as the percentage of crown volume that had been consumed and/or browned. Maximum height of char along the bole of each tree (bole char height) was estimated with a laser range finder, and bole char ratio (BCR) as bole char height divided by tree height.

Stand structure reconstruction

For each plot, we used the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS; Rebertus et al. 2010) to calculate canopy base height (CBH, m), canopy bulk density (CBD, kg/m³), quadratic mean diameter (QMD, cm), stand density (TPH, trees/ha), and canopy

cover (CC, %). To reconstruct pre-fire structure, we assume all stems not classified as snags were alive prior to the fire. To reconstruct post-fire structure, we assume trees classified with burn severity index ≤ 2 (some scorched foliage) survive and will not experience delayed mortality (we observed 99.6% of trees with BSI ≥ 3 have 100% crown scorch).

Statistical analysis

We use non-linear mixed effects (nlme; Pinheiro et al. 2018) to estimate the complementary cumulative Weibull curve for our proxies of tree-level severity (CS, BCR) with distance into treated area (following Kennedy and Johnson 2014; Appendix S1). Transect is included as a random effect, and distance along transect is the fixed effect (Appendix S1). The location parameter of the Weibull curve estimates the distance into the treated area at which the severity measure crosses a value of 0.368 (e.g., 36.8% for CS and 0.368 for BCR). The value 0.368 is a consequence of the mathematical structure of the Weibull curve, which Kennedy and Johnson (2014) argue can be exploited to indicate the distance at which there is confidence severity is reduced. For example, using this mathematical relationship, Kennedy and Johnson (2014) estimated that the expected crown scorch in one of the fuel treatments in the Wallow Fire (Arizona) fell below 36.8% at 147.5 m into the treated area, whereas in a different treated area, the expected crown scorch fell below this threshold 532.7 m into the treated area.

We compare stand structure variables between treated and untreated forest using a randomized t-test (5000 replicates) that assumes no spatial autocorrelation in the stand structure variables (Appendix S1). We estimate a logit model with mean plot severity as a response variable, individually for each plot-level stand structure variable as a covariate. To perform hypothesis tests on the coefficient associated with each stand structure variable, we use a restricted randomization test (Appendix S1) to account for spatial autocorrelation in the mean severity (Fortin and Payette 2002). For each randomization test, a *P*-value is estimated based on the rank of the observed statistic in the randomly generated null distribution. Any *P*-value ≤ 0.05 is considered a significant result, and *P*-value ≤ 0.10 results in

marginal significance. All analyses were conducted in R version 3.0.1 (R Core Team 2018; Data S1).

RESULTS

Stand structure reconstruction

Tree species composition in the reconstructed pre-fire untreated forest was a mixture of *Calocedrus decurrens* (hereafter *Calocedrus*) and *Pinus ponderosa* and *Pinus jeffreyi* (hereafter *Pinus*), with some *Abies concolor* (hereafter *Abies*; Fig. 2). The remaining species only comprised 2.6% of total stems and are listed as other.

On average, reconstructed pre-fire tree density is reduced by 63% in the treated forest relative to untreated. Relative to untreated, the fuel treatment before the fire has a significant increase in QMD (48%) and CBH (165%), and significant reductions in CC (28%), TPH (66%), and CBD (43%; Fig. 3, Table 1). Note that mean basal area is only reduced 10.8% in the treated area relative to untreated (mean BA 22.3 m²/ha in untreated, 19.9 m²/ha in treated). After the fire, there are almost no surviving trees in the untreated forest (Fig. 2). In the reconstructed post-fire treated forest, there is a higher density of surviving trees relative to the reconstructed post-fire untreated forest. The remaining trees in the post-fire treated forest are dominated by *Pinus* (Fig. 2).

Non-linear curve estimates

For trees ≥ 10 m in height, CS and BCR are estimated to have been reduced 636 and 478 m into the treated area, respectively (Table 2, Fig. 3). In the treated area, reductions of 75%, 50%, and 25% of maximum severity are accomplished into the treatment area at 447, 576, and 692 m for CS and 261, 405, and 547 m for BCR, respectively (Appendix S1: Table S2).

Randomization tests

When all plots are included, mean CS and BCR, and BSI3 significantly decreased with increasing QMD and CBH, and significantly increased with increasing CC, CBD, and TPH (Table 1; Appendix S1: Figs. S1–S3). Within the treated area, mean CS is predicted to decrease significantly with increasing QMD, and proportion of stems at least partially consumed (BSI3) is

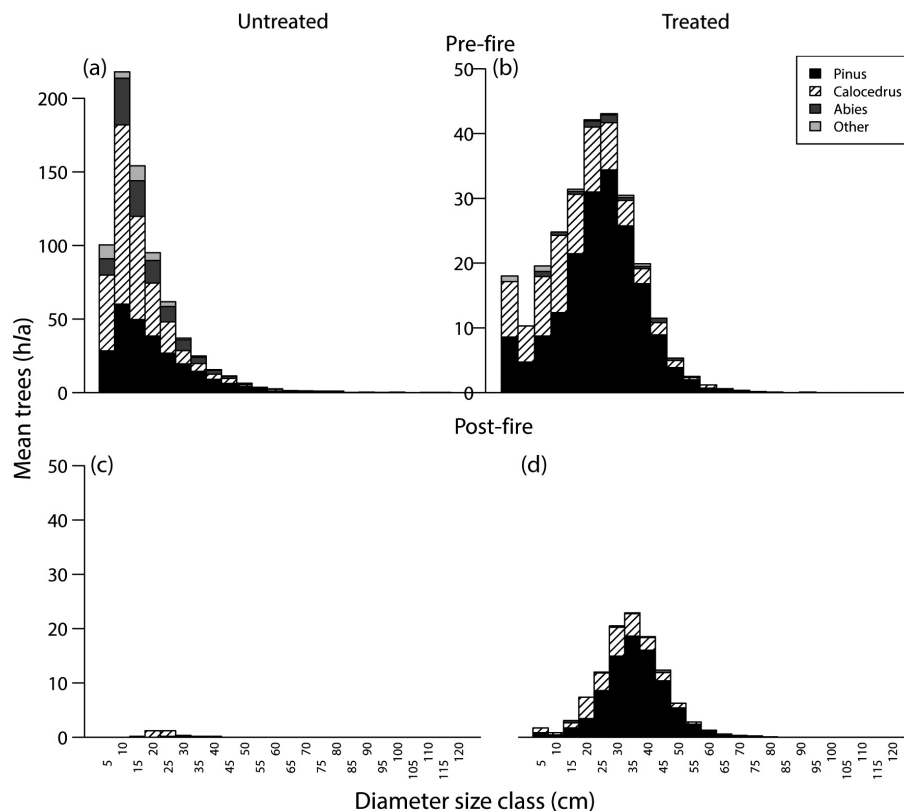


Fig. 2. Species composition and diameter distribution for trees in the (a) untreated reconstructed pre-fire, (b) treated reconstructed pre-fire, (c) untreated post-fire, and (d) treated post-fire forest. Note the change in y -axis scale for pre-fire untreated (a).

predicted to decrease significantly with increasing QMD and CBH (Table 1; Appendix S1: Fig. S4). Mean BCR decreases with marginal significance with increasing QMD and CBH. All other relationships are not significant within the treated area.

DISCUSSION

Assessment of fuel treatment or fuelbreak effectiveness is not a simple question of detecting a reduction in severity relative to untreated forest. As an entry point for suppression activities, it matters where the reduction is accomplished to enable safe access for firefighters (Safford et al. 2009). Here, we find that mean severity was reduced 470–640 m into the treated area, well beyond the narrower 400 m prescribed width of a DFPZ (Fig. 3a, b). A growing number of studies are establishing a range of variability in

distances for severity reduction, depending on landscape context, stand structure and fire intensity in the wildland surrounding the fuel treatment, and treatment prescription. Estimates range from very close to the treatment boundary (Safford et al. 2009, 2012) to hundreds of meters into the treated area (Symons et al. 2008, Kennedy and Johnson 2014).

Given this range of variability, even the seemingly larger width fuelbreaks under the HFQLG may be inadequate. It seems necessary to update designs of fuelbreaks to be effective for fires burning under extreme conditions and to understand the landscape and vegetation characteristics that explain this variability. These principles also apply to fuel treatments surrounding communities in the wildland–urban interface (Kennedy and Johnson 2014)—if the fuel treatment buffer around a community is too narrow, then it may not be possible to actively protect human

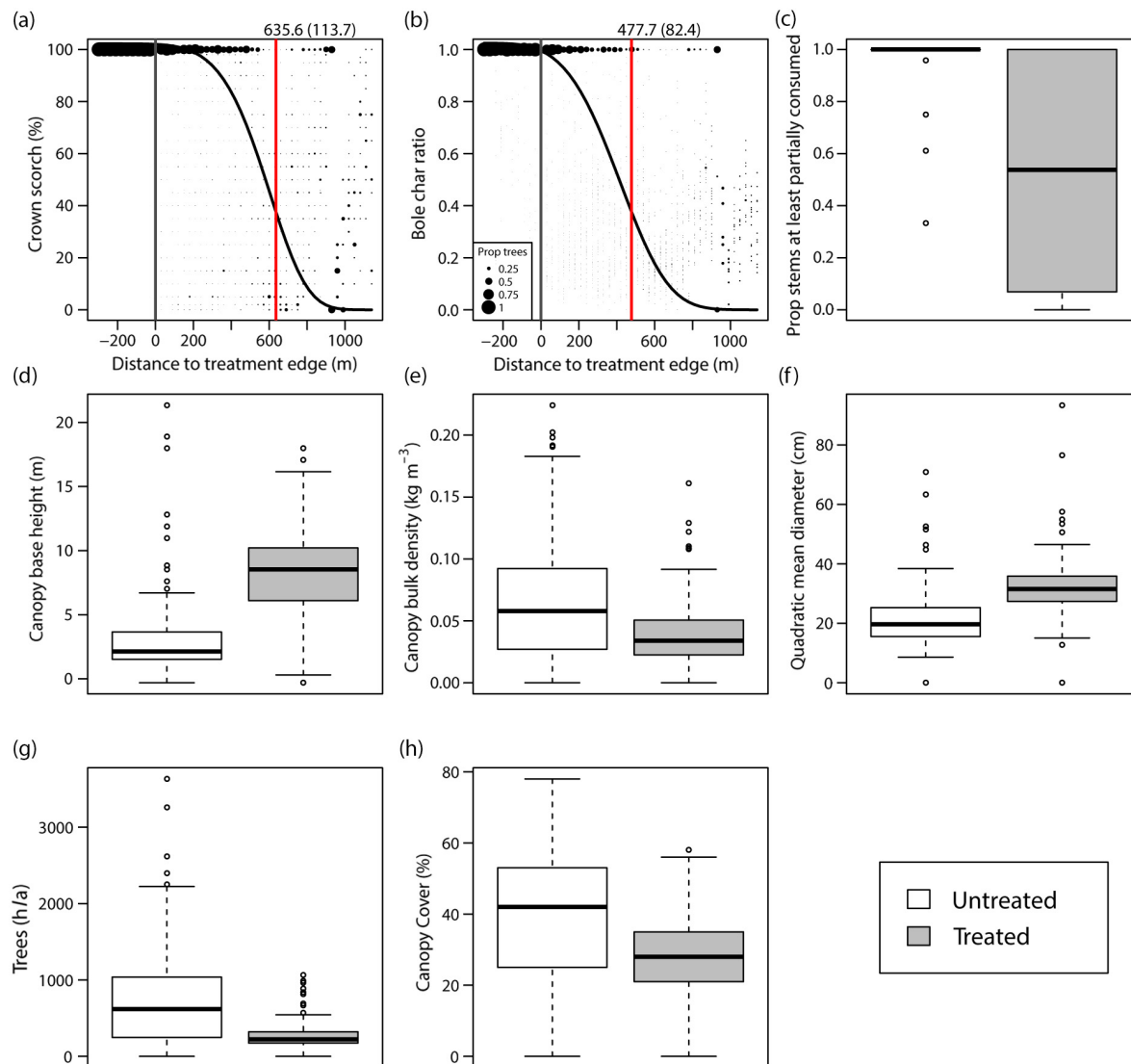


Fig. 3. Relationship between fire severity and distance into treatment edge for trees ≥ 10 m in height, for (a) crown scorch and (b) bole char ratio. The red vertical line is the estimated distance at which severity is reduced below $0.368 \times \text{maximum}$. The estimated distance (m) is given above the line with the standard error in parentheses. Point size is scaled by the proportion of trees at a given combination of severity and distance (prop trees). Gray vertical line is the treatment boundary, and solid black line is fitted curve. (c–h) Distribution of fire severity and stand structure metrics, comparing untreated (white, on left) to neighboring treated forest (gray, on right) pre-fire reconstructed values.

lives and property (Safford et al. 2009, 2012). There is also the potential during a fire burning under extreme conditions for embers to be distributed ahead of the fire front beyond a fuel treatment area. This could possibly cause high-severity fire effects outside of the treated area or impact wildland–urban interface communities

surrounded by a fuel treatment (Safford et al. 2009).

Another aspect of fuel treatment effectiveness is the resiliency of the forest both after a fuel treatment and after a wildfire (Stephens et al. 2010). An immediate consequence of a fuel treatment is the modification of forest structure,

Table 1. Summary statistics and randomization results for pre-fire reconstructed stand structure variables.

	Untreated: mean (SD)	Treated: mean (SD)	All plots: CS	All plots: BCR	All plots: BSI3	Treated only: CS	Treated only: BCR	Treated only: BSI3
CBH (m)	3.12 (3.35)	8.28 (3.28)	−0.148***	−0.173***	−0.196***		−0.067	−0.077*
CBD (kg/m ³)	0.067 (0.05)	0.038 (0.02)	14.91***	14.41***	16.57***			
QMD (cm)	21.3 (10.6)	31.6 (8.9)	−0.041***	−0.049***	−0.060***	−0.011*	−0.013	−0.021*
TPH (ha ^{−1})	752.4 (655.0)	258.6 (151.7)	0.0025***	0.0024***	0.0028***			
CC (%)	38.3 (19.2)	27.6 (10.6)	0.026***	0.029***	0.025***			

Notes: CS is crown scorch (%), BCR is bole char ratio, and BSI3 is the proportion of stems at least partially consumed (burn severity index [BSI] ≥ 3). Mean value and standard deviation of treated and untreated plots. Coefficient estimates for logit regression (interpreted as the change in logit of response variable for every unit increase in explanatory variable) including all plots and then including only plots in the treated area. Results of hypothesis test relating severity metric to each stand structure variable. No results with $P > 0.10$ are given in the table. t -Test comparison between treated and untreated is significant for all stand structure variables. CBH, canopy base height; CC, canopy cover; QMD, quadratic mean diameter; TPH, stand density.

*** $P < 0.001$; * $P < 0.05$.

Table 2. Estimates of distance into treatment area (m) for severity reduction at Weibull-predicted 0.368* maximum reduction in severity metric.

	All trees	Trees ≥ 5 m	Trees ≥ 10 m
CS	767.4 (120.5)	759.2 (125.9)	635.6 (113.7)
BCR	482.1 (77.3)	473.2 (76.7)	477.7 (82.4)

Notes: Estimates that include trees at different height thresholds are given for crown scorch (CS) and bole char ratio (BCR). Standard errors are given in parentheses.

regardless of whether a fire burns through the treatment. There is recent evidence that fuel treatments increase predicted forest resiliency, particularly under repeated burning (Stevens-Rumann et al. 2013). In the Bald Fire, high-severity fire persisted relatively far into the treated areas, yet a year after the fire there is low-density persistence of large-diameter *Pinus* in the treated area (Fig. 2d). This is a preliminary result limited to one year post-fire, where both delayed mortality (Prichard and Kennedy 2012) and additional regeneration are possible. However, it does indicate the potential that there will be a patch of restored forest in the fuel treatment. In contrast, the untreated area had essentially no surviving stems (Fig 2c), such that absent further management intervention the untreated area will likely not establish a forest more resilient to the next wildfire.

In the HFQLG Pilot Area, a history of timber extraction and fire suppression left a high density of smaller trees (Cheng et al. 2016). This is corroborated here by the relatively high density, but corresponding low values of CBD and canopy cover reconstructed in the untreated forest

neighboring the fuel treatments (Fig. 3). Within the fuel treatments, where the mean diameter is lower higher severity is expected (Appendix S1: Fig. S4). If larger trees are not present, then it is not possible to create large trees in the near term regardless of treatment prescription. This impacts post-treatment structure and its relationship with wildfire severity. Note that this discussion pertains to tree-level severity effects. It is possible that the higher severity patterns seen here were obtained as a consequence of the relatively small trees, whereas fire behavior and fire intensity may have still been sufficiently lowered to prevent other severe fire effects such as soil heating.

In general, when basic principles of fuel reduction (Agee and Skinner 2005) are followed reductions in fire severity are accomplished (Fig. 3). However, there is still substantial variability in severity within a treatment unit during a wildfire. Some of that variability may be attributed to the edge effects of the fire as it enters the treatment unit (Ritchie et al. 2007, Symons et al. 2008), but additional variability in severity can be explained by the structure within the treatment unit. Here, we find that some of the variability in severity within fuel treatments can be explained by a negative relationship between quadratic mean diameter and severity, and CBH and severity (Appendix S1: Fig. S4; Table 1). If within the fuel treatment trees are on average larger, then severity is expected to be lower. If within a treatment unit there are patches of smaller trees, then it can be expected that those will experience higher severity than other areas within the treatment unit (Methven 1973,

Symons et al. 2008). Although this may not be surprising given established relationships between tree size and severity, it nevertheless must be understood and highlighted when fuel treatments are prescribed. Note also that some small-scale high-severity patches may be desirable depending on ecological objectives (Safford et al. 2012).

Limitations

This study suffers from a common limitation of opportunistic field studies of fuel treatment effectiveness and in the study of natural disturbances in general. The measured plots can be thought of as pseudoreplicates (Van Mantgem et al. 2001), and in effect, our sample size in this study is 1. The estimated relationships between stand structure variables and severity, and between severity and distance into treated area, are descriptive of the observed in these plots, after this fire, which burned on this day. An interpretation of these results beyond the context described here would be inappropriate. However, in a context where controlled experiments are not possible, we can treat each case study of fuel treatment effectiveness as an independent replicate that increases the total sample size across all fires by 1. Each individual case study thereby makes a valuable contribution to our overall body of knowledge of how fuel treatments interact with wildfire, improving our ability to make generalizations.

These results are further limited by the relative spatial proximity of the measured fuel treatments. These all burned at the same time, on the same day, in the same area. Absent real-time observation of the wildfire as it burned into the treatment area, we cannot fully account for the possibility of stochastic events, such as a shift in wind speed or direction, that may have impacted the fire behavior and subsequent high-severity fire effects. Although we do find statistically significant results that are consistent with previous studies, the results should be interpreted in the context of the domain implied by these temporal and spatial limitations.

Recommendations

We can make several general recommendations in the context of the results of this study and previous research.

1. Consider spatially explicit study of fuel treatment effectiveness and design. This includes expanding assessments of fuel treatment effectiveness beyond a binary classification of whether severity is reduced in the treated area relative to untreated, to quantifying the spatial pattern of severity as the wildfire burns into the treated area. These should be interpreted in the context of the fire behavior just outside of the fuel treatment as an important predictor of severity within the fuel treatment.
2. Allow for flexibility in considering local knowledge and conditions when initiating fuel treatment programs and planning prescriptions. For example, DFPZ guidelines were considered overly prescriptive (Cheng et al. 2016) and did not necessarily consider the context of landscapes with a history of timber extraction and fire suppression. The implementation of DFPZs in the Bald Fire was modified slightly to include a larger treatment area than was prescribed, which gave room for high-severity fire effects to be reduced within the treatment area. These high-severity effects were observed further into the treatment area than the size of fuel treatments defined for DFPZs. A larger funded project such as that under the HFQLG should allow local managers to adapt the prescriptions based on their own individual local knowledge.
3. If designing treatments and breaks for extreme conditions, consider wider buffers in the context of the surrounding landscape. As we continue to quantify expected distances of higher severity fire effects, and the conditions under which these are observed, we can better plan for effective fuel treatment width.
4. Implement strategically placed fuel treatments in the wildland to mediate fire behavior before the fire reaches the fuelbreak. The behavior of a fire just outside of a fuel treatment modifies the severity inside the fuel treatment (Kennedy and Johnson 2014), and strategically placed fuel treatments may modify wildfire intensity across the entire fire (Finney 2001).

ACKNOWLEDGMENTS

Funding for this project was provided by the U.S. Forest Service Pacific Northwest Research Station. We thank Jeffrey Kane and Hugh Safford for thoughtful comments on earlier drafts of this manuscript and Erik Thompson, Garrett Ahern, Urianna Sanchez, Cindy Jeffress, Tim Fedor, Joseph Restaino, Trisha Bauer, Mary Price, David Collins, Diane Travis, Greg Mayer, and Crystal Danheiser for logistical support assistance in the field and data entry. We thank Kit Mullens for this research opportunity. Robert Norheim designed Fig. 1.

LITERATURE CITED

- Abatzoglou, J. T., and A. P. Williams. 2016. Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences* 113:11770–11775.
- Agee, J., B. Bahro, M. Finney, P. Omi, D. Sapsis, C. Skinner, J. van Wagten, and C. P. Weather-spoon. 2000. The use of shaded fuelbreaks in landscape fire management. *Forest Ecology and Management* 127:55–66.
- Agee, J. K., and C. N. Skinner. 2005. Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* 211:83–96.
- Bradshaw, L., and E. McCormick. 2000. FireFamily Plus User's Guide, Version 2.0. General Technical Report. RMRS-GTR-67WWW. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, Utah, USA.
- Calkin, D. E., K. M. Gebert, J. G. Jones, and R. P. Neilson. 2005. Forest service large fire area burned and suppression expenditure trends, 1970–2002. *Journal of Forestry* 103:179–183.
- Cheng, A. S., R. J. Gutierrez, S. Cashen, D. R. Becker, J. Gunn, A. Merrill, D. Ganz, M. Liquori, D. S. Saah, and W. Price. 2016. Is there a place for legislating place-based collaborative forestry proposals? Examining the Herger-Feinstein Quincy Library Group Forest Recovery Act Pilot Project. *Journal of Forestry* 114:494–504.
- Finney, M. A. 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. *Forest Science* 47:219–228.
- Fortin, M., and S. Payette. 2002. How to test the significance of the relation between spatially autocorrelated data at the landscape scale: a case study using fire and forest maps. *Ecoscience* 9:213–218.
- Green, L. 1977. Fuelbreaks and other fuel modification for wildland fire control. USDA Forest Service Pacific Southwest Research. Station Agricultural Handbook 499:1–84.
- Hessburg, P., J. Agee, and J. Franklin. 2005. Dry forests and wildland fires of the inland Northwest USA: contrasting the landscape ecology of the pre-settlement and modern eras. *Forest Ecology and Management* 211:117–139.
- Kalies, E. L., and L. L. Yocom Kent. 2016. Tamm Review: Are fuel treatments effective at achieving ecological and social objectives? A systematic review. *Forest Ecology and Management* 375:84–95.
- Kennedy, M., and M. Johnson. 2014. Fuel treatment prescriptions alter spatial patterns of fire severity around the wildland–urban interface during the Wallow Fire, Arizona, USA. *Forest Ecology and Management* 318:122–132.
- Littell, J. S., D. McKenzie, D. L. Peterson, and A. L. Westerling. 2009. Climate and wildfire area burned in western U.S. Ecoprovinces, 1916–2003. *Ecological Applications* 19:1003–1021.
- Methven, I.R. 1973. Fire, succession and community structure in a red and white pine stand. Information Report PS-X-43.
- Moghaddas, J. J., B. M. Collins, K. Menning, E. E. Y. Moghaddas, and S. L. Stephens. 2010. Fuel treatment effects on modeled landscape-level fire behavior in the northern Sierra Nevada. *Canadian Journal of Forest Research* 40:1751–1765.
- Moghaddas, J. J., and L. Craggs. 2007. A fuel treatment reduces potential fire severity and increases suppression efficiency in a Sierran mixed conifer forest. *International Journal of Wildland Fire* 16:673–678.
- Murphy, K., P. Duncan, and C. Dillingham. 2010. A Summary of Fuel Treatment Effectiveness in the Herger-Feinstein Quincy Library Group Pilot Project Area. USDA R5-TP-031 (December): 1–21. <http://www.fs.fed.us/r5/hfqlg>
- Peterson, D. L., M. C. Johnson, J. K. Agee, T. B. Jain, D. McKenzie, and E. D. Reinhardt. 2005. Forest Structure and Fire Hazard in Dry Forests of the Western United States. In *United States Department of Agriculture Forest Service, Pacific Northwest Research Station General Technical Report: PNW-GTR-628*.
- Pinheiro, J., D. Bates, S. DebRoy and D. Sarkar. 2018. nlme: linear and Nonlinear Mixed Effects Models. R package version 3.1-137.
- Prichard, S. J., and M. C. Kennedy. 2012. Fuel treatment effects on tree mortality following wildfire in dry mixed conifer forests, Washington State, USA. *International Journal of Wildland Fire* 21:1004–1013.
- R Core Team 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

- Ramirez, T.P. and S. Stawairski. 2015. Silviculture Report: bald Salvage and Restoration Project. Hat Creek Ranger District, Lassen National Forest. <https://www.fs.usda.gov/project/?project=45965> as of 2018_30_11
- Rebain, S., E. Reinhardt, N. Crookston, S. Beukema, W. Kurz and J. Greenough. 2010. The fire and fuels extension to the forest vegetation simulator: updated model documentation. Internal Report U.S. Department of Agriculture Forest Service Forest Management Service Center, Fort Collins, Colorado RMRS-GTR-1:396.
- Ritchie, M. W., C. N. Skinner, and T. A. Hamilton. 2007. Probability of tree survival after wildfire in an interior pine forest of northern California: effects of thinning and prescribed fire. *Forest Ecology and Management* 247:200–208.
- Safford, H. D., D. A. Schmidt, and C. H. Carlson. 2009. Effects of fuel treatments on fire severity in an area of wildland–urban interface, Angora Fire, Lake Tahoe Basin, California. *Forest Ecology and Management* 258:773–787.
- Safford, H. D., J. T. Stevens, K. Merriam, M. D. Meyer, and A. M. Latimer. 2012. Fuel treatment effectiveness in California yellow pine and mixed conifer forests. *Forest Ecology and Management* 274:17–28.
- Stephens, S. L., J. D. McIver, R. E. J. Boerner, C. J. Fetting, J. B. Fontaine, B. R. Hartsough, P. L. Kennedy, and D. W. Schwilk. 2012. The effects of forest fuel-reduction treatments in the United States. *BioScience* 62:549–560.
- Stephens, S. L., C. I. Millar, and B. M. Collins. 2010. Operational approaches to managing forests of the future in Mediterranean regions within a context of changing climates. *Environmental Research Letters* 5:024003.
- Stephens, S. L., and J. J. Moghaddas. 2005. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. *Forest Ecology and Management* 215:21–36.
- Stevens-Rumann, C., K. Shive, P. Fulé, and C. H. Sieg. 2013. Pre-wildfire fuel reduction treatments result in more resilient forest structure a decade after wildfire. *International Journal of Wildland Fire* 22:1108–1117.
- Symons, J. N., D. H. K. Fairbanks, and C. N. Skinner. 2008. Influences of stand structure and fuel treatments on wildfire severity at Blacks Mountain Experimental Forest, northeastern California. *California Geographer* 48:61–82.
- USDA Forest Service. 1984. Forest management plan and Soil Survey of Lassen National Forest Area CA. Pacific Southwest Region.
- USDA Forest Service. 1992. Land and Management Resource Plan. Pacific Southwest Region.
- USDA Forest Service. 1993. Lassen National Forest Land and Resource Management Plan Record of Decision (1993) and Final Environmental Impact Statement (1992). USDA Forest Service, Pacific Southwest Region, Vallejo, California, USA.
- Van Mantgem, P. J., M. Schwartz, and M. Keifer. 2001. Monitoring fire effects for managed burns and wildfires: coming to terms with pseudoreplication. *Natural Areas Journal* 21:266–273.
- Westerling, A. L. R. 2016. Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B Biological Science* 371:20160373.
- Westerling, A. L., and B. P. Bryant. 2007. Climate change and wildfire in California. *Climatic Change* 87:231–249.

SUPPORTING INFORMATION

Additional Supporting Information may be found online at: <http://onlinelibrary.wiley.com/doi/10.1002/ecs2.2573/full>