Forest Ecology and Management 318 (2014) 122–132

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Fuel treatment prescriptions alter spatial patterns of fire severity around the wildland–urban interface during the Wallow Fire, Arizona, USA

Maureen C. Kennedy[a,*], Morris C. Johnson[b]

[a] University of Washington, Box 352100, Seattle, WA 98195-2511, USA
[b] USDA Forest Service, Pacific Northwest Research Station, 400 N 34th Street Suite 201, Seattle, WA 98103, USA

ARTICLE INFO

Article history:
Received 23 October 2013
Received in revised form 6 January 2014
Accepted 10 January 2014
Available online 8 February 2014

Keywords:
Fuel treatment
Environmental management
Wallow Fire
Wildland–urban interface
Spatial analysis

ABSTRACT

Fuel reduction treatments are implemented in the forest surrounding the wildland–urban interface (WUI) to provide defensible space and safe opportunity for the protection of homes during a wildfire. The 2011 Wallow Fire in Arizona USA burned through recently implemented fuel treatments in the wildland surrounding residential communities in the WUI, and those fuel treatments have been credited with providing firefighter opportunities to protect residences during the Wallow Fire and thereby preventing the loss of homes that otherwise would have been burned. To characterize the spatial pattern of fire severity (represented by crown scorch and bole char) as the fire entered the treated areas from the wildland we fit non-linear models to the relationship between each severity metric and distance from the treatment edge in the direction of fire spread. The non-linear curve we chose provides an estimate of the distance into the treated area at which the severity metric is substantially reduced. Fire severity as measured by crown scorch and bole char was reduced a greater distance into the fuel treatment that allowed for clumps of trees and buffers for wildlife habitat than for the fuel treatment that resulted in evenly distributed trees with complete removal of ladder fuels. Crown scorch persisted further into the treated areas than did bole char, which implies that a high intensity surface fire was maintained in the treated areas. All of the fuel treatments we studied in the Wallow Fire demonstrated reduced fire severity before encountering residences in the WUI, demonstrating that there are multiple paths to fuel treatment design around the WUI.

1. Introduction

Many dry forests in the western United States are at risk for uncharacteristically extreme fire behavior because of historically high fuel accumulations (Covington and Moore, 1994; Graham et al., 2004; Hessburg et al., 2005; Agee and Skinner, 2005; Peterson et al., 2005). Fuel reduction treatments are implemented to reduce fire behavior in those forests (Graham et al., 2004; Johnson et al., 2011; Fulé et al., 2012) and to restore historical fire regimes and stand structures (Larson and Churchill, 2012). A priority for fuel reduction is the wildland–urban interface (WUI), where private residences coincide with undeveloped land that may have dense vegetation (Radeloff et al., 2005; Stewart et al., 2007). Residences in the WUI are at risk if a wildfire occurs in the surrounding forest, and this risk is heightened if the wildfire is of high severity. In the wildland forest surrounding the WUI fuel reduction treatments have the primary goal of reducing fire behavior as the fire approaches residences (Agee et al., 2000; Mell et al., 2010). Note that the fuel treatment is not intended to stop the fire itself, rather the reduction in fire behavior provides safer access for firefighter actions around homes. Wildfire risk to residences in the WUI depends both on residential fuels, which include structures and vegetation within the residential area, and on wildland fuels (Mell et al., 2010), which are the focus of this study and the target for wildland fuel treatments surrounding the WUI.

In 2002 the Rodeo-Chediski fire in Arizona (USA) burned 190,000 ha and destroyed 465 homes, serving as an example of the risk of wildfire to the WUI. Following the Rodeo-Chediski wildfire the nearby Apache-Sitgreaves National Forest (ASNF) was awarded the United States' first 10-year stewardship contract to reduce fuel accumulation and fire hazard on 60,000 ha around private lands in the White Mountains of Arizona (White Mountain Stewardship Contract, WMSC; Sitko and Hurteau, 2010). The WMSC names many goals to be met by management to obtain an "ecologically and economically sustainable system of resource extraction and benefits" (Sitko and Hurteau, 2010) including

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* Corresponding author. Tel.: +1 (206) 732 7810; fax: +1 (208) 732 7801.
E-mail addresses: mkenn@uw.edu (M.C. Kennedy), mcjohnson@fs.fed.us (M.C. Johnson).

http://dx.doi.org/10.1016/j.foreco.2014.01.014
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providing economic benefit through the extraction of wood products, achieving ecological restoration and wildlife conservation, and facilitating the protection of residences in the WUI during wildfire (Neary and Zieroth, 2007). Fuel treatment prescriptions both in the forest interior and surrounding the WUI were designed to balance these criteria in various ways (Sitko and Hurteau, 2010).

The Rodeo-Chediski wildfire was considered the largest and most destructive in Arizona history until 2011, when the Wallow Fire ignited under severe weather in the Bear Wallow Wilderness and developed into Arizona's largest recorded wildfire to date (215,000 ha), threatening several communities (Fig. 1). Many WMSC wildland fuel treatments had been completed or were in progress surrounding WUI communities when the Wallow Fire ignited, and qualitative observations documented that the WMSC fuel treatments provided firefighters with safer opportunities to perform spot protection of homes during the extreme conditions witnessed during the Wallow Fire (Jim Pitts USDA Forest Service, personal communication, April 11, 2013), and it has been reported that without the fuel treatments the fire behavior would likely have been too extreme for firefighter access (Bostwick et al., 2011). According to the report one home was lost in the Alpine community, and that was due to a smoldering ember that ignited after the fire had passed through the community. Otherwise the combination of fuel treatment, homeowner practices, and firefighter efforts prevented further residential losses in the community of Alpine (Bostwick et al., 2011).

There is empirical evidence that fuel treatments in the wildland forest that combine overstory tree removal and treatment of surface fuels (e.g., prescribed burns) reduce fire severity relative to untreated areas in a wildfire (Pollet and Omi, 2002; Raymond and Peterson, 2005; Ritchie et al., 2007; Safford et al., 2009, 2012; Prichard et al., 2010; Lyons-Tinsley and Peterson, 2012), although not in all landscapes and fire contexts (Martinson et al., 2003; Graham et al., 2012). Safford et al. (2012) suggest that in the context of this growing evidence further study of fuel treatment effectiveness is not necessary, yet there is considerable variability in the literature with respect to the fuel treatment prescriptions that are assessed and in the reduction in fire severity. In some cases thinning alone reduced fire severity (Martinson and Omi, 2003) and in others thinning alone had no effect or even worsened fire severity (Graham et al., 2012). The landscape context and expected fire behavior are likely important to fuel treatment efficacy, and further study is warranted to describe more of these contexts. Furthermore, while it is useful to understand that a fuel treatment lowers fire severity relative to untreated areas, this binary knowledge (fuel treatment worked or fuel treatment did not work) has limited use for managers who are designing and implementing fuel treatments, particularly in the wildland surrounding the WUI. Fuel treatments may need to meet management objectives beyond lowering fire severity, such as ecosystem restoration and habitat conservation. Additional study is required to understand the consequences of alternative fuel treatment designs in the way in which fire severity is modified relative to untreated forest. In this paper we provide progress in answering three questions related to the performance of fuel treatments surrounding the WUI during a wildfire:

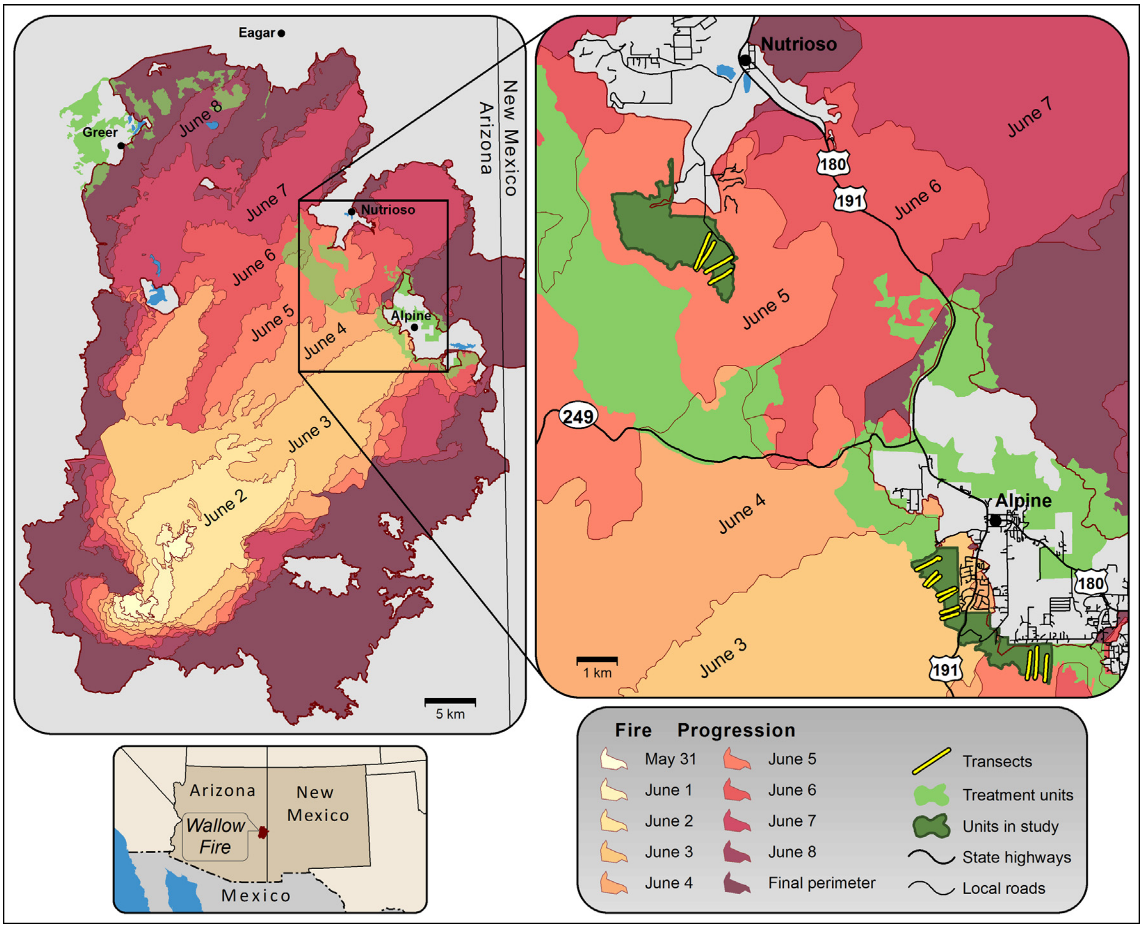

Fig. 1. Map of Wallow Fire progression and communities, including an inset showing the locations of sampled treatment units and transects measured in the treatment units relative to the communities. The darker green areas are the sampled treatment units, lighter green areas show all fuel treatments in the fire perimeter. Other colors differentiate the day of fire progression. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1. How do alternative treatment designs compare in their ability to reduce fire severity relative to untreated forest?
2. Is the size required of a fuel treatment to effectively reduce fire behavior to allow for firefighter access for defense of WUI residences consistent across various fuel treatment designs?
3. What knowledge about fire severity beyond a statistically significant reduction is necessary to guide treatment design in the wildland surrounding the WUI?

There has been progress in designing alternative fuel treatments to restore historical stand structures and take into account additional ecological values (Lehmkuhl et al., 2007; Kennedy et al., 2008; Churchill et al., 2013), but these have not been observed in a wildfire and certainly not in the wildland surrounding the WUI (Question 1). For Question 2, Safford et al. (2009, 2012) provide a qualitative estimate that fire behavior reduced from crown fire to surface fire within 50–70 m of entering a fuel treatment across several wildfires throughout California (similar to that observed qualitatively by Ritchie et al., 2007). Safford et al. (2009, 2012) suggest based on a 3 km hr^{-1} rate of spread in severe conditions and a 10 min response time that a fire could move 400–500 meters into a treated area before firefighters arrive (Safford et al., 2009, 2012). From that calculation they suggest 400–500 m as a sufficient minimum width for a WUI defense zone (Question 2). This is a fairly qualitative estimate not based on statistical properties of the fires they studied, and it requires further examples and stronger statistical evidence to be useful for the design of fuel treatments in the wildland surrounding the WUI. More examples of fires in different contexts should also be investigated to characterize the variability of these results in different wildfires and ecosystems. Finally, it is difficult to determine if a mean reduction in fire severity within a fuel treatment is sufficient to provide safer opportunities for firefighter action for WUI residences neighboring the fuel treatment. If alternative fuel treatments all show a statistically significant reduction in fire severity relative to untreated, yet exhibit variability in how that reduction is achieved and in the pattern of fire severity within the treated area, then it is important to quantify both the reduction in fire severity and its spatial pattern in order to design effective WUI fuel treatments (Question 3), and in this paper we quantify this signal. The unique coincidence of the WMSC fuel treatments and the Wallow Fire provides an opportunity to study these three questions in a wildfire event.

For this study we measured fire severity in the form of bole char and crown scorch near and within three different fuel treatment units neighboring two communities threatened by the Wallow Fire (Alpine and Nutrioso). We use the term fire severity as recommended by Keeley (2009): “Aboveground and belowground organic matter consumption from fire.” Keely lists both crown scorch and bole char as appropriate metrics to represent fire severity. We fit nonlinear models to the two metrics as functions of distance to treatment edge. Visually there appears to be a strong spatial signal in fire severity in the Wallow Fire as the fire burned from the wildland into the fuel treatments surrounding residential communities (Fig. 2), and the nonlinear models provide statistical estimates of the distance into the treated area at which fire severity is reduced, contributing to Question 2. Our comparison of two different fuel treatment designs also provides progress in answering Questions 1 and 3.

2. Methods

2.1. Study site

The project study sites are located on the Alpine and Springerville Ranger Districts of the Apache-Sitgreaves National Forest (Fig. 1), and the sites included any of the following trees: ponderosa pine, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), white fir (*Abies concolor var. concolor (Gord. & Glenda.) Lindl. Ex Hildebr*), southwestern white pine (*Pinus strobiformus*), Blue spruce (*Picea pungens* Engelm), Engelmann spruce (*Picea engelmannii* Parry ex Engelmann), corkbark fir (*Abies lasiocarpa* (Hook.) Nutt. var. arizonica), Gambel oak (*Quercus gambelii* Nutt.), New Mexico locust (*Robinia neomexicana* A. Gray), alligator juniper (*Juniperus deppeana*), alderleaf mountain mahogany (*Cercocarpus montanus* Raf.), willow (*Salix* L.) and Aspen (*Populus tremuloides*). Elevation ranges from 2400 to 2800 m.

We worked with the local forest silviculturist and fire management officer to identify fuel treatment areas within the Wallow Fire perimeter that burned unimpeded by fire suppression tactics. We selected three areas located adjacent to the Alpine (Alpine 2 and Alpine 6; AP2 and AP6, respectively) and Nutrioso (Nutrioso 1A; NU) WUI communities. The selected treatment areas burned within the first seven days of the Wallow Fire (Fig. 1; June 2, June 4 and June 5 2011 for AP6, AP2 and NU, respectively). On these days, the wildfire made 24,000, 16,000, 20,000 ha runs, respectively. Approximate burn dates and area burned were estimated from the fire progression map (Fig. 1), firefighter observations, and from on-the-ground observations. From the incident meteorologist weather forecast for May 31–June 5, high temperatures ranged from 23 to 28 °C, with relative humidity ranging from 4% to 14%, wind gusts up to 20 m s^{-1} and Haines indices ranging between 5 and 6 (moderate to high potential for wildfire growth, with 6 the maximum possible value; Haines, 1988). On the three dates the fire burned through the fuel treatments in this study the Haines index was forecast as 6. Spotting distances were reported as far as 2.4–4.8 km.

2.2. Fuel treatment prescriptions

Fuel treatment prescriptions were described to us by Jim Pitts (USDA Forest Service personal communication, April 11, 2013), a silviculturist for the Apache-Sitgreaves National Forest when the fuel treatments were implemented. The treatments were also described broadly in Sitko and Hurteau (2010). The fuel treatments surrounding the Alpine community (AP2 and AP6) were implemented within 800 m of private residences in 2004 and 2008, respectively. The treatment was a thin from below using whole-tree harvesting to a spacing of 3–6 m between trees with a 25 cm diameter cap. All ladder fuels and snags were removed, including trees >25 cm in diameter with crowns deep enough to be considered ladder fuels. The resulting stand structures exhibited an open canopy with wide and even spacing. These fuel treatments were designed to emphasize reducing fire severity surrounding the WUI, with less of an emphasis on wildlife. The fuel treatment neighboring the community of Nutrioso was implemented in 2010 and designed to leave more wildlife habitat and cover in response to public concerns (Steelman and DuMond, 2009). The treatment size was larger and there was no strict target spacing between trees. Substantial reduction in fuels was accomplished (Sitko and Hurteau, 2010), but the resulting stand structure was much different than in the treatment prescriptions implemented around Alpine. The Nutrioso treatment allowed for pockets of higher density of trees and ladder fuels if the resulting structure provided cover for wildlife for species including North American red squirrel (*Tamiasciurus hudsonicus*) and Abert’s squirrel (*Sciurus aberti*). For all three treated units the slash from the whole tree harvest was piled and then burned at the landing site. Prescribed fire was planned but not yet implemented at all three treatment units.

2.3. Sampling design

In June, August, and September 2012, three linear transects were installed in AP2, seven in AP6, and four in NU. The numbers

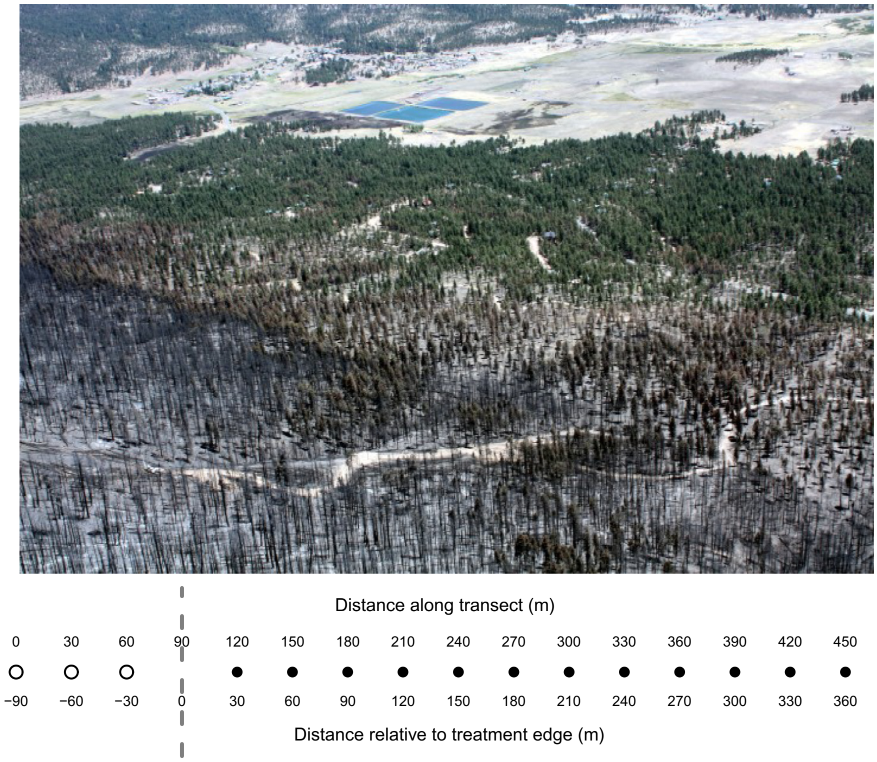

Fig. 2. (a) Photo of treatment unit AP2 after the Wallow Fire (photo credit Tim Sexton). The fire burned down the hill (black area) as it encountered the treatment unit (brown area) and approached residences (green area). The treatment edge is obvious as is the change in fire behavior. (b) Illustration of sampling design, showing a linear transect with systematically spaced circular plots oriented in the direction of fire spread, with three plots within the untreated and variable numbers in the treated portion. Grey dashed line represents the treatment edge. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of transects were determined by the size of the fuel treatment unit and the constraints of the field study. Although this resulted in an unbalanced design, we do not anticipate any issues with the analysis because statistical inference was not performed to compare the different treatments directly. Each transect was oriented in the direction of fire spread and originated in the untreated forest adjacent to the treatment boundary and spanned the width of each treatment. Each transect represents a continuum of severity as the fire spread from the untreated to the treated area, rather than separate sampling in each area. The full extent of each treated area was burned on the same day, although the three treatment units each burned on different days. We used geographical information system maps, planning maps, aerial photos and field reconnaissance to locate the placement of the linear transects (Fig. 1). Transects were installed to avoid major roads, riparian zones, reserve areas, wildlife habitat areas, untreated forest patches and drainages. For each treatment unit, the GPS coordinates of the fuel treatment boundary between burned/untreated and burned/treated was located and recorded. Starting at the treatment edge, permanent plots were placed every 30 m along each line transect using a laser range finder, with three plots extending into the untreated area (8 m radius) and plots placed along the transect in the treated area (11 m) until the back edge of the treatment unit was reached. The length of each transect varied with the size of the treatment unit and no plot was placed on the treatment boundary. A road that runs through the middle of treatment unit AP6 could not be avoided, and any plots that overlapped the road along each transect were not measured. The smaller plots in the untreated area were necessary due to the generally much higher tree densities in all size classes in the untreated plots. Plot centers were marked with a permanent center stake and numbered metal tag.

At each plot, general stand information was collected including site description, aspect, slope gradient, and slope position. All trees and snags >1.4 m in height were measured for tree structural characteristics and fire severity (Table 1). All trees within a plot are assigned the location of the plot center, so that distances between plot centers gives the distances for subsequent spatial analyses. The first plot in each transect is 90 m from the treatment edge in the untreated area.

2.4. Treatment unit topographic and vegetation characteristics

Each treatment unit is summarized by the elevation profile represented by the mean slope, species composition and size distributions including summary statistics for tree height (vertical distance from the ground level to the top of the tree, m), diameter at breast height (dbh, cm) and tree canopy base height (cbh, vertical distance from ground level to the lowest whorl with live branches in at least two of four quadrants around the stem, m) in treated and untreated plots. We use R version 2.15.2 (R Core Team, 2012) for all data analysis.

2.5. Fire severity summaries

All trees were classified using a severity index 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 location along the transect we calculated the proportion of trees at least partially consumed, with a tree severity index $\geqslant 3$. Both crown scorch and bole char of individual trees were measured for conifer trees, excluding all *Q. gambelii* trees (Table 1). Crown scorch was quantified as a percentage (CS, percentage of tree canopy that had been consumed and/or browned, estimated visually) and bole char (surface flame effects on the main tree trunk) was measured both as the minimum and

Table 1
Vegetation characteristics in the three plots in the untreated area and the first three plots in the treated area averaged across the transects in each unit. Proportion of stems for each species. Other = unidentifiable, mostly because the crown was torched so that that the tree was unrecognizable. Mean (sample sd) for tree size (dbh, height, cbh) and for percent slope.

Species	AP2		AP6		NU	
	Untreated	Treated	Untreated	Treated	Untreated	Treated
Abies	0.73	0.55	0.24	0.26	0.062	0.064
Pinus	0.059	0.054	0.12	0.11	0.14	0.14
Pseudotsuga	0.059	0.04	0.25	0.19	0.19	0.16
Quercus	0.025	0.34	0.24	0.42	0.24	0.63
OTHER	0.13	0.02	0.15	0.02	0.37	0.006
dbh (cm)	18.2 (11.9)	19.6 (15.9)	15.9 (12.0)	18.1 (15.9)	11.9 (10.0)	12.4 (12.0)
Height (m)	10.5 (5.1)	9.2 (6.1)	8.8 (6.1)	8.6 (7.0)	6.5 (5.1)	6.0 (5.3)
cbh (m)	7.0 (3.4)	3.8 (2.9)	4.7 (2.9)	3.8 (2.7)	4.2 (3.3)	3.1 (2.2)
Number of transects	3		7		4	
Mean transect length (m)	694.0		469.9		784.5	
Mean transect slope (%)	18.6 (7.74)		21.9 (6.73)		17.6 (6.58)	

maximum height of bole char along the bole of each tree (BCH, m), as well as the ratio of the minimum and maximum BCH to the tree height (bole char ratio; BCR). The distributions of each severity metric are compared between the treated and untreated areas using boxplots for each treatment unit. Since severity values may differ by tree height regardless of fire intensity, we repeat analyses for three tree height thresholds (0, 5, 10 m) whereby all conifer trees with a height $\geqslant$ the threshold are included in the analysis.

2.6. Severity metrics spatial analysis

During preliminary analyses the relationship between each severity metric and distance along the transect appeared nonlinear. We chose a three-parameter curve with a flexible shape and a distance parameter that gives a statistical estimate of the distance into the treated area at which the fire severity metric is reduced. This curve is a 3-parameter version of the complement of the Weibull cumulative distribution function (Haefner, 1996) and it has the form (Eq. (1)):

$$Y = k_0 e^{-\left(\frac{d}{k_1}\right)^{k_2}}, \tag{1}$$

where Y is the severity metric ($Y \geqslant 0$), d is the distance along the transect ($d \geqslant 0$), k_0 is the estimated value of Y at $d = 0$ (the first plot in the untreated area), k_1 is the location parameter and k_2 is the shape parameter. The location parameter (k_1) provides an estimate of the distance along the transect at which the curve crosses a Y-value of $0.368^{*}k_0$ and the shape parameter (k_2) estimates how steeply the curve approaches that value. The value of k_1 at $0.368^{*}k_0$ is a mathematical feature of the Weibull curve that we exploit to make a statistical estimate of the distance at reduction in severity. Although $0.368^{*}k_0$ has no specific ecological meaning with respect to fire severity, we judge it to be a value at which we can be confident that fire severity is reduced. For example, in a study of tree mortality Hood et al. (2007) found that dead yellow pine trees (including ponderosa and yellow pine) after the Rodeo-Chediski fire had a mean crown scorch of 92% and live trees a mean crown scorch of 45%. The mean crown scorch of 45% for live trees is near our 36.8% threshold value for crown scorch (assuming $k_0 = 100\%$). Across other fires for yellow pine and Douglas fir they found mean crown scorch of dead trees ranged from 36% to 98%, with the lower value commensurate with our 36.8%. These results imply that although 36.8% arises from the mathematical structure of the Weibull curve, it is also an ecologically robust value at which the fire severity metric is expected to represent trees that survive the fire. Once the Weibull curve is fitted to the data one can derive the distance at which other thresholds of the severity metric are expected to be obtained. The coefficient k_1 allows for a standard comparison of distance from the treatment edge among treated units at a given level of the severity metric. We use the nlme function in R (Pinheiro et al., 2013) to fit the Weibull curve to the severity data in each unit separately using non-linear mixed effects modeling (Lindstrom and Bates, 1990), where the data are grouped by transect in each unit to account for possible within-transect variability.

We assign the treatment boundary a distance of zero and assign negative values for distance from the treatment boundary into the treated area and positive values into the treated area (Fig. 2b), and produce scatter plots of each severity metric on the y-axis against distance from treatment edge on the x-axis. These plots provide a qualitative check on the appropriateness of the non-linear fit to the data and they help to visualize the variability of the data not explained by the non-linear regression. We also calculate residuals (observed-fitted) for each model fit and plot those against distance from treatment edge to characterize expected deviations from the fitted curves along the transect (see Supplementary material). To interpret k_1 from the fitted Weibull curve relative to the treatment edge we subtract 90 m from the estimated value because the treatment edge occurs at 90 m along each transect.

3. Results

3.1. Treatment unit topographic and vegetation characteristics

All transects exhibit negative slope in the direction of fire spread (Table 1). Species composition appears to differ among the units (Table 1), which can be ordered simultaneously with decreasing proportion of *Abies concolor* (hereafter *Abies*) and increasing proportion of *Quercus gambelii* (hereafter *Quercus*) in both the untreated and treated plots. AP2 has both the highest proportion of *Abies* and the lowest proportion of *Quercus*, AP6 has intermediate proportions of both species and NU has the lowest proportion of *Abies* and the highest proportion of *Quercus*. The proportion of trees unable to be identified is higher in the untreated area relative to the treated, and is highest in the untreated plots in unit NU. The proportion of stems that are *Pinus ponderosa* (hereafter *Pinus*) also declines from AP2 to AP6 to NU (Table 1). Finally, the proportion that are *Pseudotsuga menziesii* (hereafter *Pseudotsuga*) is highest in AP6, then NU, then AP2. Summary statistics for dbh, tree height and tree cbh show high variability in all three measures with AP2 showing higher average tree height, dbh and cbh than AP6, whose trees are larger than NU.

3.2. Fire severity summaries

All metrics are distributed lower in the treated area relative to the untreated in all units (Fig. 3). Nearly all trees in all units in the untreated area were at least partially consumed, with the proportion of trees with burn severity index $\geqslant 3$ near 1 (Fig. 3a). The proportion of trees with burn severity index $\geqslant 3$ drops sharply in the treated area near the treatment boundary for all three treatment units, and remains low further into the treated area (Fig. 3a). In the untreated area the high proportion of trees that are partially consumed corresponds to crown scorch (CS) values of 100% and bole char ratio (BCR) values of 1 across all trees (Fig. 3b and d), with a few individual trees with lower values. Across the metrics in the treated area the distribution in AP2 is lower than the distribution for AP6, which is distributed lower relative to NU. Maximum and minimum bole char height (BCH) in the untreated area probably underestimates severity relative to the treated area because almost all trees in the untreated area have maximum and minimum bole char ratios = 1, so the BCH reflects tree height and makes for a poor severity comparison as the distributions of tree heights vary among the treatment units.

3.3. Spatial analysis

All three severity metrics decline with increasing distance to treatment edge for all treatment units (Fig. 4), although there are individual trees with maximum values for both crown scorch (100%) and minimum and maximum bole char ratio (1.0) along the entire length of the transect. The estimated values for k_1 (distance into treated area at which severity is reduced) relative to the treatment edge vary among the units and between severity metrics (Table 2; Supplementary Tables S1–S5). For each severity metric and every tree height threshold the estimated values of k_1 can be placed in increasing order by AP2 < AP6 < NU (Fig. 4; Table 2), except for minimum bole char height where AP6 and NU cannot be distinguished. With a few exceptions the estimated value of k_1 did not vary substantially among tree height thresholds. The two glaring exceptions are maximum and minimum bole char height for all trees in NU compared to larger trees (Table 2). For NU the estimated values of k_1 for minimum and maximum bole char height of all trees have relatively large standard errors associated with them (Supplementary Tables S2 and S4), implying a poor fit of the curve to those metrics for all trees. Estimates for trees $\geqslant 5$

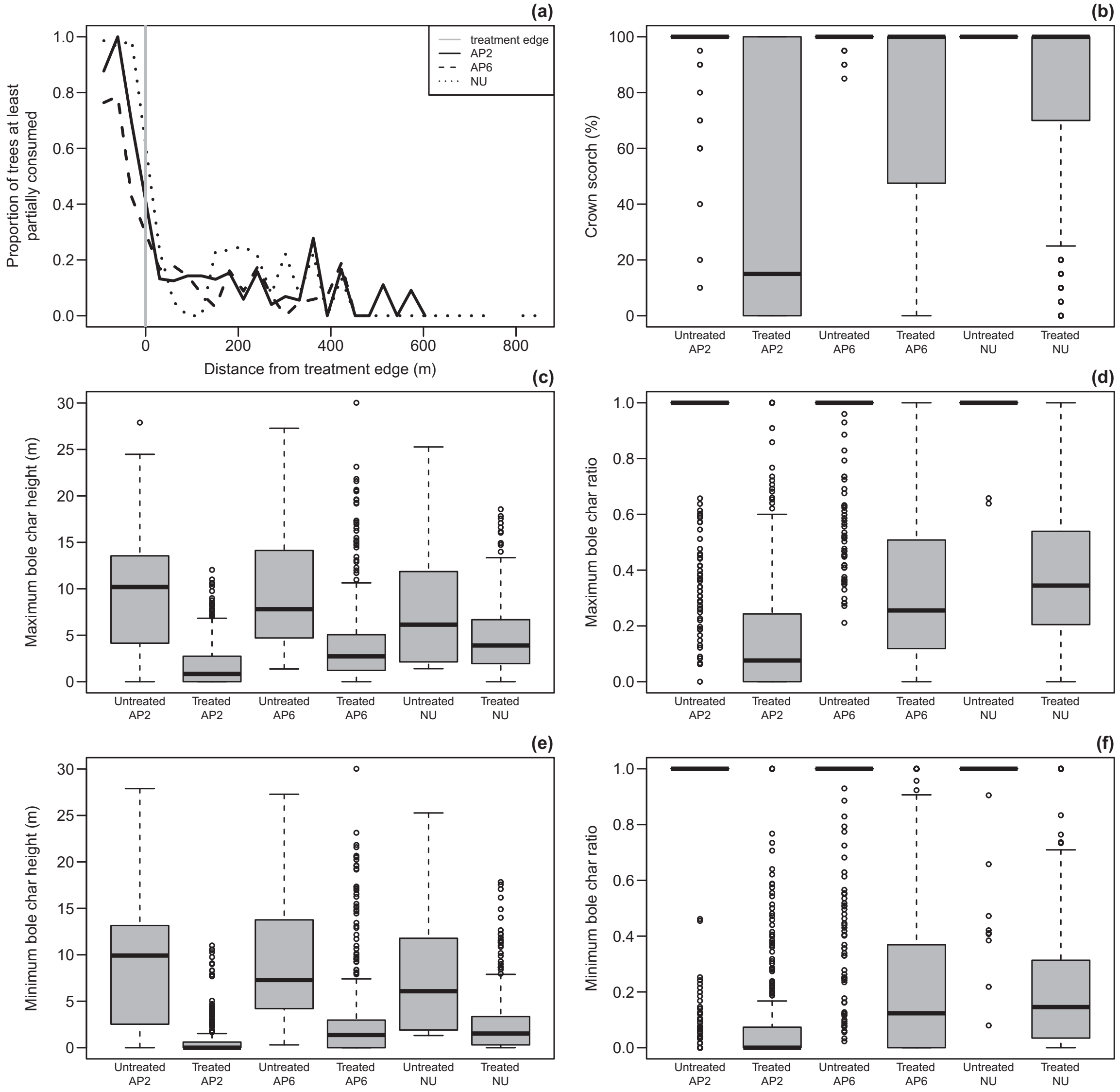

Fig. 3. (a) Proportion of trees at least partially consumed (severity index $\geqslant 3$) with distance to treatment edge. (b–f) Distribution of each severity metric comparing each unit and treated/untreated. The box is defined by the 25th and 75th percentiles, the horizontal line is the median, the whiskers extend to the largest point $\leqslant 1.5$ times the interquartile range, and the points any outlying data >1.5 times the interquartile range.

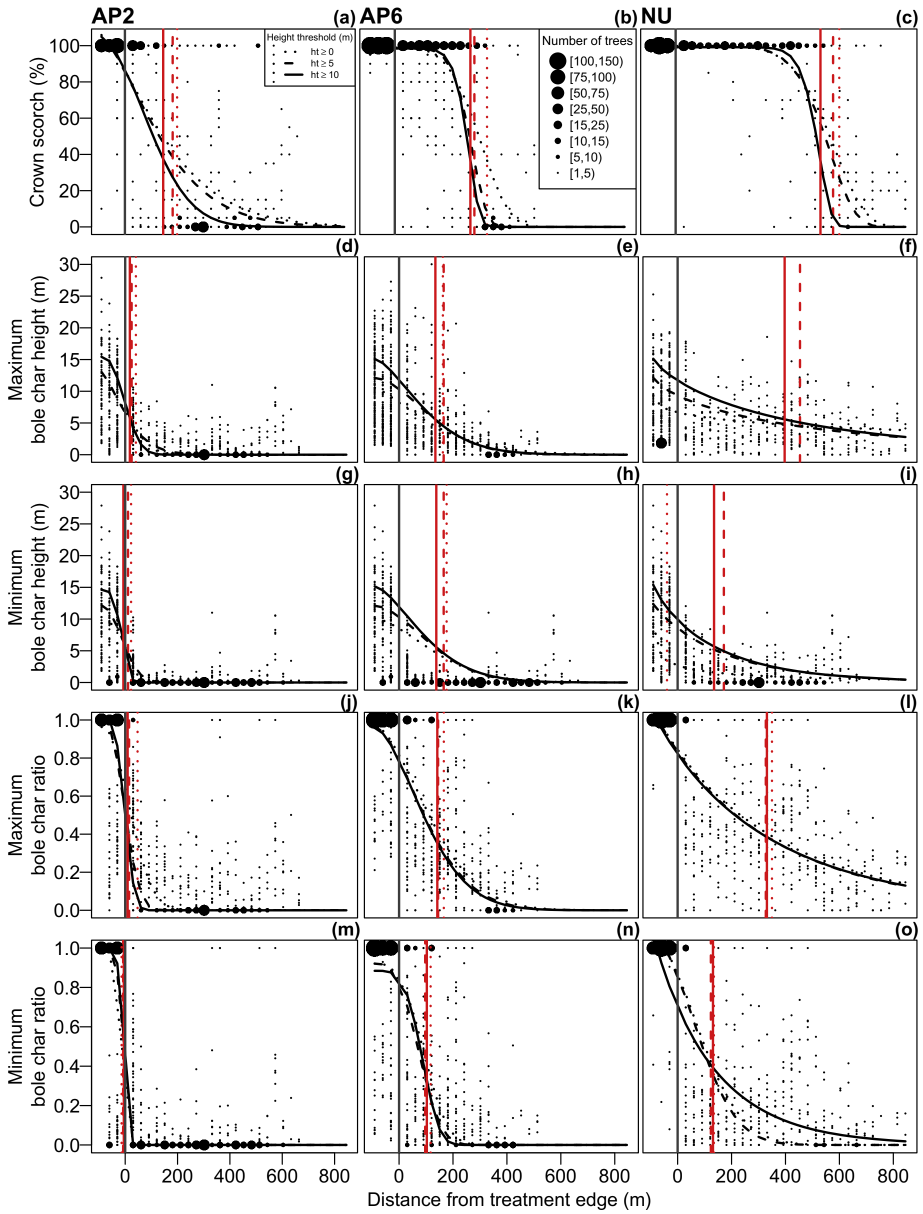

Fig. 4. Scatter plots of tree-scale fire severity on the y-axis with distance to treatment edge on the x-axis for all conifer trees. Distance is zero at the treatment edge, −30, −60 and −90 m for plots in the untreated area adjacent to the treatment edge and 30, 90 m, etc. for plots in the treated area. Multiple trees can have the same severity metric at a given distance (e.g., >100 trees with 100% crown scorch −90 m from the treatment edge), which is indicated by the size of the associated point. Black lines give the shape of the fitted curve for each height threshold. Vertical lines give the estimated distance from treatment edge at which fire severity is reduced (k_1). For example, crown scorch is 100% for nearly all trees in the untreated area in AP2, illustrated by the large point size in the scatter plot, and as we move from panel (a) to panel (c) we see the vertical line moving further from the treatment edge, illustrating high crown scorch persists further into the treated area for NU than for AP2. (a–c) Crown scorch percentage with distance to treatment edge in AP2, AP6 and NU, respectively. (d–f) Maximum bole char height with distance to treatment edge in AP2, AP6 and NU, respectively. (g–i) Minimum bole char height with distance to treatment edge in AP2, AP6 and NU, respectively. (j–l) Maximum bole char ratio with distance to treatment edge in AP2, AP6 and NU, respectively. (m–o) Minimum bole char ratio with distance to treatment edge in AP2, AP6 and NU, respectively.

and $\geqslant 10$ m (minimum and maximum BCH for NU) have standard errors commensurate with other metrics and more consistent estimates (Table 2; Supplementary Tables S2 and S4). The estimated values of k_1 imply that the distance from treatment edge at which the fire transitions from high severity to low severity increases from unit AP2 to unit AP6 to unit NU, that this distance is greater for CS than for either BCH or BCR, and it is greater for maximum values of bole char than it is for minimum values (Table 2). For AP2 the estimated values of k_1 for all four of the bole char metrics are near or less than the distance to the first treated plot, with negative values for minimum BCR, implying that the fire reduced in severity very near to the treatment threshold in AP2. Supplementary Tables S1–S5 give estimates and standard errors for all three coefficients in each unit and for each severity metric.

The scatter plots show the three-parameter curve to follow the general pattern of fire severity with distance from the treatment edge (Fig. 4), although the structure of the curve moving from a value of k_0 to zero results in a spatial pattern in the residuals (Supplementary Figs. S1–S5). The curve tends to have residual values $\leqslant 0$ in the untreated area and residual values $\geqslant 0$ further into the treated area. This pattern in the residuals would be problematic if the goal of the fit was to predict tree-level fire severity, but we judged the

Table 2
Estimated values of k_1 (m) for the Weibull curve presented relative to the treatment edge. Positive values are distance to treatment edge in the treated area, negative values are distance to treatment edge in the untreated area.

Response variable	Tree height (m)	AP2	AP6	NU
Crown scorch (%)	⩾0	201.2	339.3	601.9
	⩾5	184.0	292.8	579.1
	⩾10	147.5	278.1	532.7
Maximum bole char height (m)	⩾0	40.9	231.4	1173.7
	⩾5	24.5	155.5	453.9
	⩾10	17.8	138.1	397.0
Maximum bole char ratio	⩾0	45.0	166.0	349.9
	⩾5	14.8	144.9	327.1
	⩾10	9.3	141.9	331.2
Minimum bole char height (m)	⩾0	22.4	162.5	−39.3
	⩾5	10.8	165.5	171.5
	⩾10	−7.0	138.1	135.1
Minimum bole char ratio	⩾0	−13.8	117.1	134.5
	⩾5	−7.8	96.9	123.3
	⩾10	−5.2	103.0	131.1

fits to be adequate as the goal was to characterize the overall spatial pattern of fire severity in the treated area and no inference was performed on the coefficients themselves.

4. Discussion

4.1. Question 1: Alternative fuel treatment designs

The WMSC has embarked on what amounts to a large-scale experiment in fuel treatment design, implementing by their own count >70 different fuel treatments over the contract area (Sitko and Hurteau, 2010). These fuel treatments are all motivated by the goal to reduce the risk of high severity fire, but were also designed to take into account additional ecological, social, and economic goals. Two alternative fuel treatment strategies were unexpectedly tested by the Wallow Fire, and both achieved the overarching goal of reducing fire severity as the fire approached WUI residences, thereby affording firefighter opportunity to enter and protect residences. This shows that managers may incorporate multiple goals in designing fuel treatments surrounding WUI communities, depending on the landscape context. Fuel treatments such as that implemented in Nutrioso, where there were additional considerations for wildlife habitat and aesthetics, are still potentially successful in reducing fire behavior sufficiently to provide opportunity to protect residences in the WUI during a wildfire.

The severity data in the Wallow Fire show that although all three treatment units exhibited reduced fire severity before the fire reached the end of the treatment unit, the estimated distance at which this occurred varied among the three treatment units (Fig. 3; Table 2). For each of the fire severity metrics the estimated distance is less for AP2 than for AP6, which is less than NU. These treatment units were burned in the same fire on different days, and all under extreme weather conditions, and differed by their treatment prescription. That the distance estimated varied among these fuel treatments implies that there is likely an interaction in treatment design between post-treatment vegetation structure and recommended size of a treated area in the wildland surrounding WUI communities. It should be noted that some of the effects observed here could be due to the fuel treatments burning on different days, possibly at different times of day, and in different locations on the landscape. However, the weather conditions were extreme on all of those days and the fire made its largest runs over that time period, so we can assume that the general conditions were similar.

Unfortunately pre-fire data on post-treatment vegetation structure were not available for this analysis. Treatment descriptions and personal communications were relied on to reconstruct to the best of our ability the pre-fire post-treatment vegetation structure. Johnson and Kennedy (in review) use post-fire vegetation characteristics to infer pre-fire structure, but these measurements cannot reconstruct the surface fuels that are so important for predicting fire behavior. Pre-fire empirical data, particularly quantifying the surface fuels, would have been valuable in comparing the fire severity patterns we observed among the three treatment units. When fuel reduction treatments are implemented there is a need to gather consistent quantitative data on post-treatment vegetation and surface fuel structures. This will enable robust comparison of fuel treatment prescriptions, and if the fuel treatments encounter a wildfire then the post-treatment structure can be more directly linked to the performance of the fuel treatment in modifying fire behavior. As it is we cannot comment specifically on recommended post-treatment structures to achieve similar fuel treatment efficacies to those observed here.

4.2. Question 2. How large do fuel treatments in the wildland surrounding the WUI need to be?

In the Wallow Fire, the distance into the treated edge at which fire severity was reduced varied among the treatment units and by the measure of fire severity, which indicates that there is no single recommendation that can be made for fuel treatment width even within an individual fire and landscape, much less across different landscapes. For example, in the AP2 treatment severity was estimated to be reduced at −7 m, 18 m or 147 m from the treatment edge for minimum bole char height, maximum bole char height and crown scorch, respectively. In contrast, those distances estimated for the NU treatment were 135 m, 397 m, or 533 m from the treatment edge for minimum bole char height, maximum bole char height and crown scorch, respectively. Distances estimated for AP6 fall between those for AP2 and NU. These data indicate that there were clear differences in fire behavior among the units, and that the various severity metrics capture different characteristics of fire behavior.

Previous studies in California wildfires qualitatively identified distances of 25–70 m from treatment edge for reduction in severity metrics (Ritchie et al., 2007; Safford et al., 2012), which is consistent only with the estimates for distance to treatment edge found for bole char in the AP2 treatment. For all metrics in AP6 and NU and for crown scorch in all three units the distances estimated here are much longer than those proposed previously (Table 2). Ritchie et al. (2007) suggest that in their study the extreme intensity of the fire as it entered the treated area caused crown scorch to remain high further into the treated area than bole char, yet in their fire this effect dissipated tens of meters into the treatment units. In order to better understand the necessary treatment width to lower fire severity in the wildland surrounding the WUI additional study is necessary to compare how various fuel treatment prescriptions modify fire behavior in fires burning under different conditions including whether the fire spread is heading, flanking or backing, the underlying topography and the fuel treatment prescription. In the Wallow Fire, crown scorch persisted hundreds of meters into the treatment units and further than bole char, which is explained both by the high intensity of the fire and by the treatment prescriptions themselves.

The distances estimated in the Weibull curve (Table 2; Fig. 3) do not translate directly to treatment width because an additional buffer is required to give opportunity for firefighter access for the protection of WUI residences after severity is reduced. Using estimates of fire spread rates and response times Safford et al. (2012) recommend a treatment area that is ∼450 m beyond the distance observed to reduce fire behavior in the treated area. This provides a zone of reduced fire behavior in which a defense can be enacted. Furthermore, the recommended treatment width would depend on the post-treatment vegetation structure and the landscape context of the fuel treatment relative to the WUI.

The Wallow Fire was observed to be spreading over the ridge and then downhill towards the community of Alpine as a crown fire before it encountered the fuel treatments (Bostwick et al., 2011). In laboratory conditions fire spread is understood to slow in the downhill direction (Van Wagner, 1988) and the WUI communities studied here were located on the downhill side of fire spread. Given that the change in elevation and the distance along the transect are almost perfectly confounding there is no way to statistically separate them in our data. The steep threshold in the drop in fire severity that we observed near the treatment edge (Fig. 3) is much steeper than expected theoretically (Van Wagner, 1988), and there is no evidence of severity decreasing in the substantial portion of the untreated area above the treated area for which the fire was spreading downhill (Figs. 2a and 4). The steep threshold at the treatment boundary and no apparent downhill effect on severity in the untreated area both support our claim that the fuel treatments modified fire severity independently of the downhill spread. The distances into the treated area estimated here are the compounding effect of both the fuel treatment itself and spread downhill. If the communities had been located on a flat stretch of land or uphill of the fire direction then the distances estimated here for fuel treatment width would possibly need to be longer for a similar effect.

4.3. Question 3: Is a statistically significant reduction in severity sufficient to assess fuel treatment performance and design?

These data demonstrate a strong spatial signal in fire behavior as a fire spreads from an untreated area to a treated one (Fig. 3) and the importance of landscape context in assessing the performance of a fuel treatment. When evaluating fuel treatment efficacy for a fuel treatment designed to modify fire behavior before the fire reaches an area neighboring the treatment (such as a WUI residence), it is insufficient to simply perform a stand-scale assessment of fire behavior in the treated area relative to an adjacent untreated area. All three treatment units studied in the Wallow Fire exhibited reduced mean fire severity relative to the adjacent untreated forest, yet they varied markedly in the spatial distance into the treated area at which the severity was reduced. This distinction between stand-scale reduction in fire severity and a spatial analysis of fire severity in the direction of fire spread is crucial in designing fuel treatments in the wildland surrounding the WUI.

The spatial signal seen in the Wallow Fire data is likely due to the high intensity of the fire as it entered the treated unit (Ritchie et al., 2007). If the intensity of the fire is expected to be extraordinarily high in the untreated portion near the treated area then a wider buffer may be needed (Agee et al., 2000). Steps may also be taken to reduce fire behavior outside of the core treatment to further reduce fire behavior as the fire approaches the treatment edge (Finney, 2001), in effect providing speedbumps to constrain fire spread and intensity (Agee et al., 2000) and mimicking more complex landscape structures thereby providing barriers to fire spread (McKenzie and Kennedy, 2012).

4.4. Use of these results

The purpose of fitting the Weibull curves to these data was to provide a quantitative estimate of the distance from the treatment edge at which fire severity was reduced in the Wallow Fire and to describe the relationship between each severity metric and distance to treatment edge. These curve fits are not appropriate for the purpose of tree-scale predictions. If, for example, the goal is to predict crown scorch of trees a given distance from the treatment edge a more appropriate tree-scale statistical model should be chosen. Furthermore, these distances are not recommendations for fuel treatment width across all landscapes, fire conditions, and WUI contexts. The distance into a treated area at which severity is reduced varies with the local conditions, details of the treatment prescription, and larger landscape context.

The results for these fuel treatments are unique in that the treatments were seen to effectively reduce fire severity absent a surface fuel treatment (prescribed fire, mechanical or manual removal) to reduce the surface fuels (these had been planned as part of the treatment prescription, but not yet implemented). Many studies have found that thinning with prescribed fire has a greater reduction in fire severity than thinning alone (e.g., Raymond and Peterson, 2005; Ritchie et al., 2007; Lyons-Tinsley and Peterson, 2012), although there are individual examples where thinning alone did reduce fire severity and modify fire behavior (Martinson and Omi, 2003, 2013). Martinson and Omi (2013) suggest that the effectiveness of a thin-only fuel treatment may depend on whether the fire enters the treatment as an active crown fire, which is unlikely to be sustained in an open canopy. This behavior may have occurred during the Wallow Fire, which implies that the fuel treatments may have been less effective under different fire conditions. The data presented here cannot inform this speculation and as Martinson and Omi (2003) suggest, further study is necessary to understand the relationship between weather conditions and fuel treatment efficacy for various treatment prescriptions. In some cases thinning without surface fuel treatment when the residual slash is left on site may actually exacerbate rather than ameliorate fire behavior (Raymond and Peterson, 2005; Graham et al., 2012). These results emphasize the importance of context when assessing fuel treatment efficacy and design.

The scope of the research presented in this paper has been to quantify the pattern of fire severity with respect to ecological metrics of severity (crown scorch and bole char) in the wildland surrounding the WUI. From the perspective of a home within the WUI there are additional metrics of severity that cannot be informed by this paper. Maranghides and Mell (2013) have proposed a WUI fire and ember exposure scale that accounts for four primary sources for WUI residence exposure: wildland fuels, ornamental vegetation and burning of structures and vehicles. WUI residences not protected by firefighter actions can still be lost when a wildland fuel treatment reduces fire behavior to surface fire approaching residences if other sources of exposure are present around and within the residences, or if residences are ignited by embers flying from beyond the treatment buffer.

4.5. Fire behavior and fire severity

In the Wallow Fire, estimates of distance from treatment edge at which reduced fire severity was observed differed by the measurement used. Crown scorch was consistently reduced further into the treated area than the maximum bole char (height or ratio), which was consistently reduced further into the treated area than the minimum bole char (height or ratio). Furthermore, the proportion of trees at least partially consumed (severity index $\geqslant 3$) was near 1 in the untreated area of AP2 and NU, and near 0.8 in the untreated area of AP6 (Fig. 3a), and the proportion dropped immediately below 0.3 at the treatment edge. If we assume bole char is correlated with flame height (although char tends to underpredict flame height and flame length; Cain, 1984; Alexander and Cruz, 2012), then the reduction near the treatment edge in both bole char and proportion of trees consumed implies the fire was reduced to surface fire behavior with lower flame heights before evidence of reduced crown scorch was observed (Table 2). We infer that any further crown scorching is not caused by the fire moving into the crown, rather by the intensity of the surface fire near the trees that were scorched. Scorching rather than consumption occurs when foliage experiences temperatures above some lethal maximum (Van Wagner, 1973) from a fire burning on the ground (Alexander and Cruz, 2012) or in neighboring crowns (on the edge of the treated area). The intensity of the fire required to raise the temperature to lethal levels for foliage depends on the ambient temperature and wind conditions (Van Wagner, 1973); if the ambient temperature is already extremely hot, then a lower intensity fire is required to cause foliage scorch relative to more mild conditions. Ritchie et al. (2007) also observed bole char to be reduced closer to the treatment edge than crown scorch in a fire in Northern California, and they suggested that the persistence of crown scorch was caused by the radiative and convective heat from the fire burning in the adjacent untreated stand. It is likely that the extreme intensity of the Wallow Fire as it entered the treated areas caused high ambient temperatures, and the fire maintained its intensity even as it transitioned to surface fire behavior causing lethal scorch temperatures (usually considered >60 °C; Methven, 1971; Van Wagner, 1973) deeper into the treated area. Methvan (1973) observed pockets of high intensity fire that caused local crown scorch due to a clumped distribution of saplings that carried the fire upward during an otherwise low intensity prescribed burn. Presumed clumps of understory tree cover in the NU prescription (for the purposes of maintaining wildlife cover) likely maintained this high intensity surface fire above lethal scorch temperatures deeper into the treated area.

5. Conclusions

The variable performance of fuel treatments in reducing fire severity surrounding the WUI during the Wallow Fire shows that understanding the relationship between fuel treatment design and efficacy is more complex than answering the simple question of whether mean fire severity is reduced in the treated area relative to the neighboring untreated area. All three treatments reduced fire severity relative to adjacent untreated forest, yet the distance into the treated area at which reduced severity is detected varied among the treatment prescriptions. Although the fuel treatments differed in their performances, they all satisfied the overarching goal of providing firefighters opportunity to defend homes from the wildfire. Absent that reduction in fire severity those areas likely would have been inaccessible (Bostwick et al., 2011). These results reiterate the concept that there is no single action that can be taken to protect a residence from a wildfire. Even when the fire behavior is successfully reduced as the wildfire passes through a fuel treatment, a low severity surface fire can ignite susceptible homes. Protection of WUI homes requires fuel treatments to reduce fire severity as the fire enters a community, homeowner actions to reduce the flammability of the home and its immediate surroundings, and accessibility for firefighters to provide further protection.

Our results also imply that there are a variety of fuel treatment prescriptions for the wildland that may reduce fire severity adequately to provide safe access for WUI residence defense. Managers can take into account multiple objectives (such as retaining some wildlife cover) and the landscape context in designing fuel treatments. There is ongoing interest in expanding the portfolio of fuel treatment designs to those that better mimic historical stand structures (Larson and Churchill, 2012; Churchill et al., 2013) and those that incorporate multiple ecological values (Lehmkuhl et al., 2007; Kennedy et al., 2008; Scheller et al., 2011), yet the consequences of such fuel treatments for reducing fire severity in the wildland surrounding the WUI during a wildfire are unknown. The fuel treatment prescription outside of the Nutrioso community did allow for clumps of trees and ladder fuels to be left after the fuel treatment if they served the purpose of wildlife habitat, and this treatment did reduce fire severity before the fire reached the community. Further study of the performance of variable fuel treatment prescriptions in wildfire events is required to verify the results found here.

Acknowledgements

Miguel Cruz, Dave Peterson, E. David Ford and Donald McKenzie provided thoughtful comments that improved early drafts of this manuscript. Two anonymous reviewers helped in clarifying the scope and strengthening the inference of the study. Joe Restaino, Jon Dvorak, Bob Vihnanek, Brooke Cassell, and Conamara Burke conducted field work for this project. Jim Pitts, Robert Whitten, Rusty Bigelow organized site visits on the Wallow Fire and Rob Lever, Stephanie Coleman, Raymond Rugg, and Jim Schroeder provided information on the Wallow Fire. Stacey Weaver, Nancy Loving, and Patti O'Connor provided GIS data and support, and Rob Norheim supplied the maps in the manuscript. Brent Wachter provided fire weather data and fire photos. Richard Davalos, Pamela Bostwick, and Sue Sitko gave assisted with the data, and Maria Petrova provided database management. This project was funded by the U.S. Forest Service Pacific Northwest Research Station and Western Wildlands Environmental Threat Assessment Center.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2014.01.014.

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