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Fuel treatments change forest structure and spatial patterns of fire severity, Arizona, U.S.A.

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Abstract: Fuel reduction treatments are often designed to achieve multiple resource management objectives in addition to reducing potential fire hazard. In the White Mountains of Arizona State (U.S.A.), the 2014 San Juan Fire burned through several thinning prescriptions designed to achieve wildlife habitat objectives. Many studies have documented reduced fire severity for a standard set of fuel treatments, but the range of variability in fuel treatment effectiveness for alternative treatment designs is poorly understood. We used nonlinear mixed-effects modeling to estimate the distance into the treated area at which fire severity decreases and randomization tests to compare forest structure. High-severity fire effects were estimated to be reduced between 114 m and 345 m into the treated area. The range of variability in observed-distance high-severity fire effects persist into the treated area and, in conjunction with estimated relationships between posttreatment forest structure and severity, can inform the design of alternative fuel treatment prescriptions with various target prescriptions. We found that as cover was maintained in a treatment unit for wildlife habitat, the size of the fuel treatment necessary to observe a reduction in severity needs to be larger. Our study will inform decision makers on the size of treatments required to accomplish management objectives.

Key words: fuel treatment effectiveness, crown scorch, crown fire, forest thinning, fire hazard, bole char.

Résumé : Les traitements visant à réduire les combustibles sont souvent conçus pour atteindre plusieurs objectifs d'aménagement des ressources en plus de réduire les risques potentiels d'incendie. Dans les montagnes blanches de l'Arizona (É.-U.), le feu de San Juan de 2014 a dévasté plusieurs prescriptions d'éclaircie conçues pour atteindre des objectifs d'habitat faunique. Plusieurs études ont documenté la réduction de la sévérité du feu associée à un ensemble standard de traitements des combustibles. Par contre l'ampleur de la variabilité de l'efficacité d'autres types de traitements des combustibles est mal comprise. Nous avons utilisé la modélisation non linéaire à effets mixtes pour estimer à quelle distance dans les zones traitées la sévérité du feu diminue, ainsi que des tests de randomisation pour comparer la structure de la forêt. L'estimation de la distance à laquelle les effets d'un feu de sévérité élevée seraient réduits dans la zone traitée se situe entre 114 et 345 m. L'ampleur de la variabilité de la distance observée à laquelle les effets d'un feu de sévérité élevée persistent dans la zone traitée et, conjointement aux relations estimées entre la sévérité et la structure de la forêt après le traitement, peut influencer la conception de prescriptions alternatives de traitement des combustibles avec des cibles variées. Nous avons trouvé que la dimension du traitement des combustibles nécessaire pour observer une réduction de la sévérité doit être plus grande lorsqu'on maintient le couvert dans une unité traitée pour l'habitat faunique. Notre étude renseignera les décideurs concernant la dimension des traitements requise pour réaliser les objectifs d'aménagement. [Traduit par la Rédaction]

Mots-clés : efficacité des traitements des combustibles, roussissement des cimes, feu de cime, éclaircie de la forêt, risque d'incendie, brûlure du tronc.

Introduction

Relative to reconstructions of historical conditions (Covington et al. 1994; Agee 1996; Hessburg et al. 2005), contemporary dry coniferous forests prevalent across western North America have higher stem densities, higher canopy bulk densities, higher fine and coarse woody fuel loadings, and lower canopy base heights (Covington et al. 1994; Agee 1996; Hessburg et al. 2005; Agee and Skinner 2005). Collectively, these stand characteristics make these forests more susceptible to disturbances such as insect epidemics (Graham et al. 2004), increase the probability of crown fire initiation (Van Wagner 1977; Agee 1996), and increase potential burn severity (Prichard et al. 2010). In contrast, fire exclusion has benefited some threatened and endangered wildlife species by increasing their range, connectivity, and amount of habitat (Tempel et al. 2014). Some wildlife species (e.g., Northern Spotted Owl (*Strix occidentalis* (Xántus de Vésey, 1860)) and Pacific Fisher (*Martes pennant* (Erxleben, 1777)) benefit from conditions associated with higher fire hazard — multi-storied, high-density, closed-canopy forests — for survival and reproduction (Solis and Gutiérrez 1990).

A fuel treatment is the primary management action taken to ameliorate structural changes in dry forests altered by fire exclusion (Graham et al. 2004). In general, a fuel treatment is a modification of forest structure in which both canopy and surface fuels are reduced (Agee and Skinner 2005; Peterson et al. 2005). Here, we consider fuel treatment to mean a management action that causes changes to the fuel structure of a forest stand with the

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purpose of achieving one or more resource management objectives. A standard prescription for a fuel treatment for fire hazard reduction would be to reduce canopy bulk density and raise canopy base height (Agee and Skinner 2005). Often, the primary objectives of such a fuel reduction treatment are to reduce extreme fire behavior (crown fire), provide areas to actively suppress wildfires that are threatening valuable assets, and increase forest resiliency to future wildfires (Reinhardt et al. 2008; Stevens et al. 2014; Waltz et al. 2014). Fuel reduction treatments are not designed and implemented to stop wildfires or reduce wildfire extent (Omi and Martinson 2002; Finney and Cohen 2003).

Resource managers are increasingly concerned with the effects of fuel treatments in general on multiple resource management objectives (Lehmkuhl et al. 2007), including wildlife habitat, recreation, water quality, and timber production (Reinhardt et al. 2008). Management for multiple resources presents a significant challenge for managers of fire-prone forests (Collins et al. 2010). For example, restoration to historical forest structure of a dry forest has the secondary effect of decreasing the habitat connectivity of some wildlife species that rely on conditions (high density, closed-canopy forests) that increase the chance of active crown fire (Van Wagner 1977; Agee 1996; Tempel et al. 2014). To meet the challenge of implementing fuel treatments to reduce burn severity and increase forest resilience (capacity of an ecosystem to return to the precondition state following a perturbation) and simultaneously maintain wildlife habitat, managers are designing new fuel treatment prescriptions that do not strictly follow the guidelines advocated to maintain a fire-resilient forest (Agee and Skinner 2005).

Although many studies have documented a reduction in severity when a wildfire burns through a standard set of fuel reduction treatments (Pollet and Omi 2002; Raymond and Peterson 2005; Stephens and Moghaddas 2005; Ritchie et al. 2007; Prichard et al. 2010; Safford et al. 2009), these conclusions are insufficient to understand the consequences of alternative fuel treatment prescriptions that do not have fire hazard reduction as their primary objective (Kennedy and Johnson 2014). By necessity, such studies are opportunistic, requiring the coincidence of an alternative fuel treatment prescription with a wildfire (Pollet and Omi 2002). As wildfires burn areas with fuel treatments that do not strictly follow standard guidelines (Peterson et al. 2005), possibly resulting in novel post-treatment structures, there is an opportunity to build on the body of existing knowledge to increase our understanding of interactions between wildfire and fuel treatment.

The White Mountain Stewardship Project (WMSP) implemented several thousand hectares of fuel treatments within the Mineral Ecosystem Management Area on the Apache-Sitgreaves National Forest, Springerville Ranger District (Arizona, U.S.A.). The core objectives of the fuel treatments were to reduce fire severity and improve habitat for the Northern Goshawk (*Accipiter gentilis* (Linnaeus, 1758); U.S. Department of Agriculture (USDA) Forest Service 2002). In the summer of 2014, the San Juan Fire burned through several treatment areas within hours after ignition. This interaction provided an opportunity to quantify the patterns of fire severity from a wildfire that burned freely (unimpeded by suppression tactics) into several Northern Goshawk habitat fuel-treatment areas.

The primary goal of this study was to assess, in fuel treatments designed primarily to restore wildlife habitat, the implications of the post-treatment stand structure on fire severity experienced during a wildfire burning with extreme fire behavior. This will help us to understand how fuel treatments not designed with the primary goal of reducing fire behavior perform during an extreme wildfire event and to guide how we might be able to design fuel treatments to meet multiple management objectives. There are three primary hypotheses that we evaluate:

1. fuels treatments designed to achieve different wildlife habitat objectives will differ in post-treatment stand structure;
2. fuels treatments designed to achieve different wildlife habitat objectives will differ in high-severity fire effects and behavior experienced during a wildfire; and
3. fuels treatments designed to achieve different wildlife habitat objectives will experience lower severity fire effects and behavior than neighboring untreated forest.

In addition to testing these hypotheses, we also described the post-treatment species composition and estimated the distance into each treatment unit at which the high-severity fire effects were reduced. There is substantial variability in previous estimates of the spatial distance of high-severity fire effects experienced in fuel treatments (Ritchie et al. 2007; Safford et al. 2009, 2012; Kennedy and Johnson 2014), and this study will add to those previous estimates.

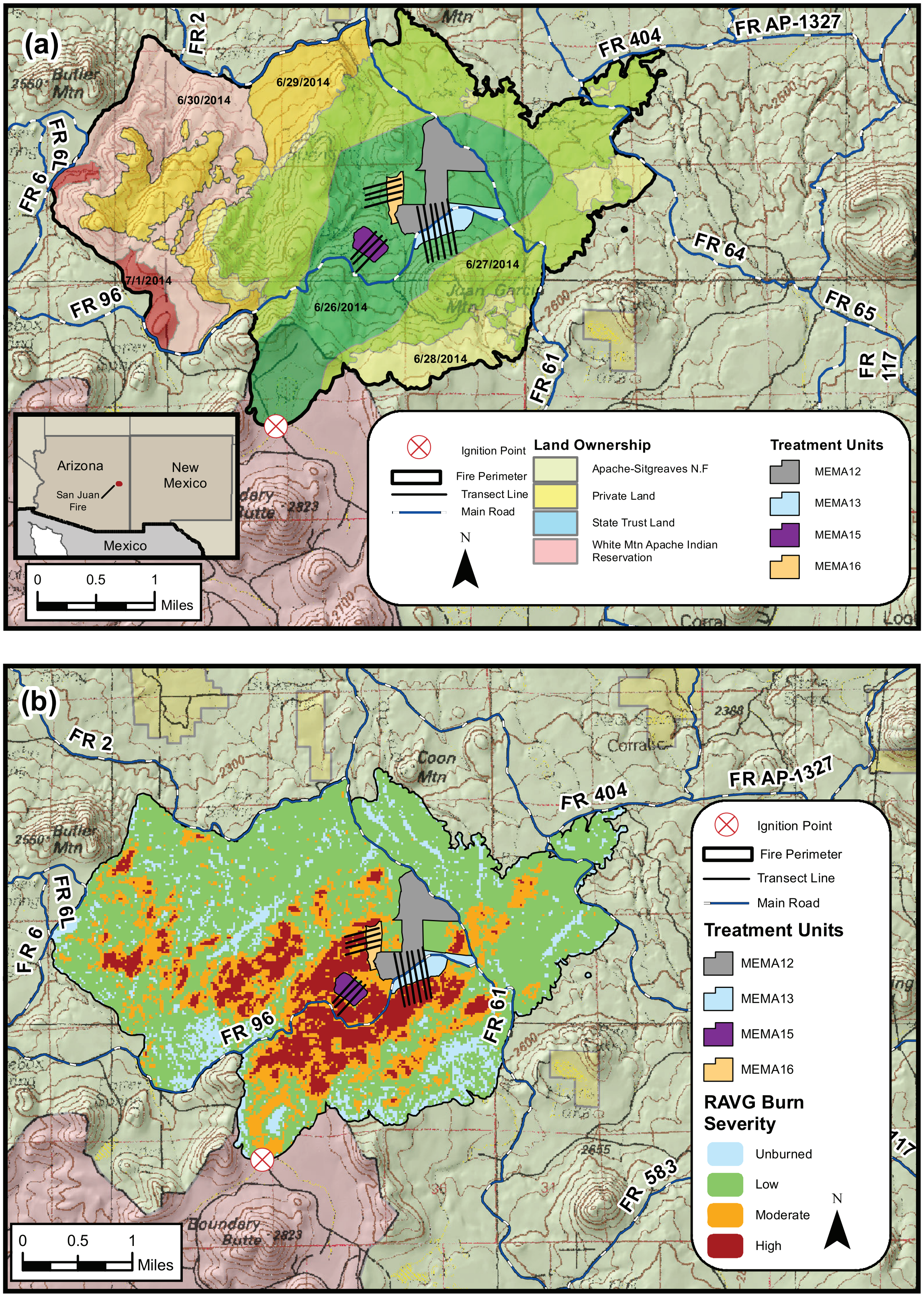
Methods

Study area

In 2004, the White Mountain Stewardship project (WMSP) on the Apache-Sitgreaves National Forest (ASNF) was initiated to reduce fire hazard, improve wildlife habitat, restore forest health, and stimulate employment opportunities in the wood products industry on 60 000 ha around communities-at-risk within the White Mountains of eastern Arizona (Sitko and Hurteau 2010). Our study sites were located in the 2014 San Juan Fire (latitude 34°10′N, longitude 109°38′W) in east central Arizona on the ASNF, Springerville Ranger District. The fire burned 2820 ha from 26 June through 2 July 2014, within the 16 190 ha Mineral Ecosystem Management Area (hereafter MEMA), 27 km west of Springerville, Arizona (Fig. 1). The fire ignited in grass around 1200 pm on the White Mountain Apache Reservation and burned northeastward into an extensive network of completed mechanically thinned and prescribed burned treatment areas (Fig. 1). The energy release component (ERC), a composite fuel moisture index that reflects the contribution of all live and dead fuels to potential fire intensity, indicated 97th percentile weather conditions. On 25 June 2014, the Lakeside remote automated weather station (RAWS), 24 km east of the San Juan Fire (closest RAWS to the fire), recorded a maximum temperature of 29 °C, minimum relative humidity of 6%, and windspeed and direction SSW at 17 km·h^{-1} with 37 km·h^{-1} gusts. Live fuel moistures were 87% for ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson var. *scopulorum* Engelm); dead woody fuel moistures were estimated as follows: 1 h = 2%; 10 h = 3%; 100 h = 5%; and 1000 h = 6%.

The San Juan Fire burned through dry mixed-conifer and ponderosa pine forest types. High-elevation forests are characterized as mixed-conifer forests dominated by a mix of Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and quaking aspen (*Populus tremuloides* Michx.). Low-elevation forests consist of ponderosa pine, Gambel oak (*Quercus gambelii* Nutt.), Utah juniper (*Juniperus osteosperma* (Torr.) Little), two-needle pinyon (*Pinus edulis* Engelm.), southwestern white pine (*Pinus strobiformis* Engelm.), Douglas-fir, white fir, and quaking aspen. The understory herbaceous plant community is characterized by a mix of mostly native perennial graminoids and forbs. Common perennial grasses include squirrel tail (*Elymus elymoides* (Raf.) Swezey), Arizona fescue (*Festuca arizonica* Vasey), mountain muhly (*Muhlenbergia montana* (Nutt.) Hitchc.), muttongrass (*Poa fendleriana* (Steud.) Vasey), Junegrass (*Koeleria macrantha* (Ledeb.) Schult.), and sedge (*Carex* L.). Common forbs include ragworts (*Packera* Á. Löve & D. Löve), fleabanes (*Erigeron* L.), Wheeler's thistle (*Cirsium wheeleri* (A. Gray) Petr.), pineywoods geranium (*Geranium caespitosum* James), alpine false spring parsley (*Pseudocymopterus montanus* (A. Gray) J.M. Coult. & Rose), groundcover milkvetch (*Astragalus humistratus* A. Gray), yellow hawkweed (*Hieracium fendleri* Sch. Bip.), and yarrow (*Achillea millefolium* L.). Soils are classified as a complex of Mollic Eutroboralfs, Lithic

Fig. 1. (*a*) Map of 2014 San Juan Fire study area in east central, Arizona, U.S.A., showing daily fire progression intervals, fuel treatment units, and placement of linear treatment transects. These fuel treatment areas burned within a few hours after ignition. 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. (*b*) Map of San Juan Fire Rapid Assessment of Vegetation Condition (RAVG) after the San Juan Fire.



Argiborolls, and Eutric Glossoboralfs, of fine to cobbly clay loam texture, derived from volcanic parent material (Laing et al. 1987). Elevations range from 2130 to 2560 m. Most precipitation falls in the winter and during the summer monsoon. Between 1984 and 2013, annual precipitation at Greer, Arizona (elevation 2500 m, 25 km southeast of the study site), averaged 494 mm with an average minimum temperature of 9.1 °C in January and an average maximum temperature of 24.3 C in July (Greer NCDC COOP Station ID 023683; Greer RAWS ID 020404, Western Regional Climate).

Fuel treatment prescriptions

The MEMA National Environmental Policy Act (NEPA) environmental assessment outlined several treatment alternatives to achieve management objectives (USDA Forest Service 2002). Core objectives of thinning treatments were to reduce crown fire hazard and develop habitat for the Northern Goshawk (USDA Forest Service 2002). The Northern Goshawk is a forest habitat generalist that uses a variety of forest types, structural conditions, and successional stages within a home range that consists of three components: nesting area, foraging area, and postfledging family area (Reynolds et al. 1992). Under the preferred alternative, 30% of the MEMA planning area was thinned under a presettlement thinning prescription, which is defined by the USDA Forest Service (2002) as "a conceptual treatment patterned after restoration studies designed to mimic the open, park-like stands in much of the Ponderosa pine type of a century ago." The remaining 70% was thinned to a Northern Goshawk habitat prescription. In this study, we quantified treatment effects of the prescriptions designed to improve Northern Goshawk foraging habitat (hereafter MEMARx1) and postfledging family area – old-growth habitat (hereafter MEMARx2; see Table 1 for thinning specifications; USDA Forest Service 2002). In 2007, the four treatment units were thinned and the slash (activity fuels) was grapple-piled and burned (USDA Forest Service 2002).

Sampling design

With assistance from the district fire management officer, we used forest planning maps, fire progression maps, and field reconnaissance to identify fuel treatment areas within the San Juan Fire perimeter that were burned by an active crown fire. These fuel treatment areas burned unimpeded by fire suppression operations.

The treatment areas burned within a few hours after ignition and were the first areas burned by an active crown fire (Fig. 1). In July 2015, we installed 274 nested, fixed-area plots (120 plots in untreated areas and 154 plots in treated areas) across 13 linear transects extending across the treated and adjacent untreated areas (Fig. 1). 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. 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. Within each treatment unit, we identified fire spread and direction from burn severity indicators such as crown (needle) freeze, crown scorch, and basic knowledge of fire behavior and topography. Crown freeze occurs when the fire is burning intensely, often moving in a specific direction with enough speed to freeze the needle in the direction that the fire is burning (National Wildfire Coordinating Group 2016). For example, when tree crowns are consumed by fire, crown color and crown freeze provide an indication of the direction and intensity of wildfire spread.

We quantified fire-severity effects and forest structure metrics of three treatment areas (i.e., MEMA13, MEMA15, and MEMA16) and adjacent untreated areas (Fig. 1). Because both MEMA13 and MEMA12 had the same thinning prescription, transects 5 through 10 extended into MEMA12 (Fig. 1). Transect length and number of plots varied according to the size (width) of the treatment units (Table 2). Plots were not installed on the treatment boundary. From the treatment boundary, we installed a plot every 30 m. Transects were situated parallel and 80 m apart. In the adjacent untreated areas, we installed 10 plots (300 m) in the windward side of the treatment boundary. In the treated area, we installed a plot every 30 m until we reached the end of the treatment boundary (Table 2). Sampling plots were limited in the untreated area adjacent to MEMA15 because trees were salvage-logged along the roadside. Note that all treatment units were oriented downhill relative to the direction of fire spread.

At plot center, we recorded average slope (%), average aspect (degree), and elevation (m). Trees > 12.7 cm diameter at breast height (DBH) were measured on a 0.05 ha (500 m^2) fixed-area plot and trees < 12.7 cm DBH were measured on a nested 0.02 ha (200 m^2) fixed-area plot. For each tree, we recorded species, DBH, total tree height (m), crown base height (CBH, m), and height-to-live crown (m). Crown base height represents the vertical distance from ground level to the lowest whorl with branches in at least two of four quadrants around the stem, and height-to-live crown is the vertical distance from the ground to the height of green needles (Scott and Reinhardt 2001). If green needles were present, the tree was recorded as live, otherwise the tree was recorded as dead. We determined if a tree was snag before the wildfire based on external characteristics such as the degree of retention of fine twigs, bark retention, beetle activity, bole color, bole breakage, and professional experience (Keen 1955). We used plot data and the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS; Rebain 2010) model to reconstruct prefire canopy structural variables associated with crown fire initiation (see below). Our analysis of differences in structural conditions between treated and untreated areas was based on these reconstructions.

For each tree, we recorded an ocular estimate of the percentage of crown volume scorched (Peterson 1985). Bole char height (height of surface flame effects on tree bole; BCH) was measured both as the minimum and maximum height along the bole of each tree, as well as the ratio of the minimum and maximum BCH to the tree height (bole char ratio; BCR). Each tree was assigned categorical measures of tree burn severity: 1, unburned; 2, scorched foliage; 3, lightly burned (some foliage and small twigs consumed); 4, moderately burned (foliage and small branches consumed); and 5, severely burned (only charred stems remain; U.S. Department of the Interior National Park Service 2003). Because severity values may differ by tree height regardless of fire intensity, we repeated analyses for three tree height thresholds (0, 5, and 10 m) whereby all conifer trees with a height ≥ the threshold are included in the analysis. We transformed BCH to BCR by dividing bole char height by tree height.

Stand structure reconstruction

The FFE-FVS is a growth-and-yield model that simulates fuel dynamics and potential fire behavior over time (Rebain 2010). For each plot, we used the Central Rockies variant of the FFE-FVS (FFE-FVS v. 2.06) to reconstruct common nonspatial stand structural metrics that influence crown fire initiation: stand density (TPH, number of trees·ha^{-1}), basal area (BA, $m^2 \cdot ha^{-1}$), canopy base height (CBH, m), and canopy bulk density (CBD, $kg \cdot m^{-3}$). We also calculated stand density index (SDI), canopy cover (CC, %), tree diameter distributions, species composition, top height (m), and quadratic mean diameter (QMD, cm). Most forest managers used FFE-FVS and these metrics to design thinning prescriptions. Specifications for calculating these variables are described in Rebain (2010).

Treatment unit topographic and vegetation characteristics

Each treatment unit was summarized by the elevation profile represented by the mean slope, species composition, and size distributions, including summary statistics for tree height

Table 1. Description of thinning prescription for Goshawk* habitat.

Prescription type	Prescription objectives	Prescription description
Goshawk foraging area MEMARx1	(1) Improve quality habitat for Goshawk prey (2) Improve conditions that enhance foraging opportunities for the Goshawk	(1) Retain all trees ≥ 41 cm DBH (2) In the VSS3 groups (12.7–30.5 cm), thin to 11.5 $m^2 \cdot ha^{-1}$ for conifers > 12.5 cm DBH; thin from below, select the largest healthy trees with a Douglas-fir mistletoe rating < 3 as leave trees and proceed down in size until the BA is met; leave unhealthy conifers only to accomplish the BA requirement and then leave the best of these
Units MEMA13 and MEMA15	(3) Lower the bark beetle outbreak potential by improving the health and vigor of the residual trees	(3) In the VSS4 (30.5–45.6 cm), VSS5 (45.6–60.9 cm), and VSS6 (>60.9 cm) groups, thin to 18.3–20.6 $m^2 \cdot ha^{-1}$, 22.9 $m^2 \cdot ha^{-1}$, and 22.5 $m^2 \cdot ha^{-1}$, respectively, of conifers > 12.4 cm DBH to achieve a canopy cover of 40%; leave only 12.4–40.4 cm trees needed to meet canopy cover requirement; if trees are overtopped, thus not contributing toward canopy cover, do not leave them regardless if the BA falls below the BA requirement for the VSS group; if trees are not overtopped, but the canopy cover requirement is already met by the larger trees (BA = 80, 100, and 110, respectively), then do not leave them either; consider all conifers > 12.4 cm DBH in the BA requirement; in all trees 0.91–12.4 cm DBH, leave mistletoe-free healthy trees at a spacing of 9.1 × 9.1 m taking all sizes of conifers into consideration in the spacing
Goshawk postfledging family area – old growth MEMARx2	(1) Improve hiding cover (from predators, siblings, and weather) for Goshawk fledglings (2) Improve for prey and foraging opportunities for adults and fledgling Goshawks during the fledgling-dependency period	(1) Retain all trees > 30.5 cm DBH (2) In the VSS3 groups, 11.5 $m^2 \cdot ha^{-1}$ of conifers > 12.4 cm DBH; thin from below choosing the largest healthy trees with a Douglas-fir mistletoe rating < 3 as leave trees and proceed down in size until the BA is met; leave unhealthy conifers only to accomplish the BA requirement and then leave the best of these; consider all conifers > 12.4 cm DBH in the BA requirement
Unit MEMA16	(3) Decrease the time for the units to become suitable old growth	(3) In the VSS4 groups, thin to 18.3–20.6 $m^2 \cdot ha^{-1}$ of conifers > 12.4 cm DBH; leave only 12.7–30.4 cm trees contributing toward the canopy cover requirement; leave only conifers that are not desirable for healthy trees when they are absolutely needed to help meet the canopy cover requirement, and then leave the best of these; consider all conifers > 12.5 cm DBH in the BA requirement; it is anticipated that with the 30.4 cm DBH limit, at least one-third of the area will have a residual BA > 22.9 $m^2 \cdot ha^{-1}$
	(4) Lower the bark beetle outbreak potential by improving the health and vigor of the residual trees	(4) In the VSS5 and VSS6 groups, thin to 25.3 and 27.5 $m^2 \cdot ha^{-1}$, respectively, of conifers > 12.4 cm DBH; leave only 12.4–30.4 cm trees contributing toward the canopy cover requirement; leave unhealthy conifers only to accomplish the BA requirement, and then leave the best of these (5) In all trees 0.91–12.4 cm DBH, leave mistletoe-free healthy trees at a spacing of 9.1 m × 9.1 m taking all sizes of conifers into consideration in the spacing

Note: Goshawk habitat is classified by six vegetation structural stages (VSS): VSS1, grass, forbs, and shrubs (0–2.5 cm DBH); VSS2, seedling and sapling (2.5–12.7 cm DBH); VSS3, young forest (12.7–30.5 cm DBH); VSS4, mid-age forest (30.5–45.7 cm DBH); VSS5, mature forest (45.7–61 cm DBH); and VSS6, old forest (>61 cm DBH). DBH, diameter at breast height; BA, basal area.

*Northern Goshawk (*Accipiter gentilis*).

Table 2. Summary of sampling effort and characteristics for each measured treatment unit.

						Elevation (m)*		Slope (%)*	
MEMA unit	No. of transects	No. of plots untreated	No. of plots treated	Total no. of plots	Mineral project Rx description	Treated	Untreated	Treated	Untreated
13	6	10	14–16	151	MEMARx1	2493–2579	2520–2620	3.8–9.0	7.5–19.5
15	3	5–8	11–12	55	MEMARx1	2469–2545	2491–2549	7.7–16.8	9.5–13.0
16	4	10	7	68	MEMARx2	2520–2562	2492–2581	5.3–6.2	8.7–10.5

Note: If transects differed in the number of plots in treated or untreated, ranges of the minimum and maximum number of plots across all transects for each treatment are shown. Ranges of minimum and maximum transect mean elevation and slope are also given for each treatment unit.

*At a distance 200 m along the transect.

(vertical distance from the ground level to the top of the tree, m), DBH (cm), and CBH (m) in treated and untreated plots. We used R version 2.15.2 (R Core Team 2012) for all data analysis.

Data analysis

Randomization tests

First, we used boxplots to visually compare the distributions of each severity metric between the treated and untreated areas in each treatment unit and to aid in interpretation of the ANOVA results. We then used randomization tests to compare the vegetation variables among the treatment units and between treated and untreated forest to assess our first hypothesis. The primary goal of sampling for this study was to characterize the spatial pattern of severity as the fire burned into the treated area. Given that the individual sampling plots did not represent an independent random sample and the units themselves were not experimentally assigned, standard frequency approaches to statistical inference were not appropriate. The data likely violate both the independence and normality assumptions of frequentist ANOVA. We therefore used randomization techniques to generate null distributions of test statistics for the ANOVA *F* test for three primary null hypotheses for each vegetation variable. We tested whether the treatment units differed in their mean value for each vegetation variable (unit main effect), whether the treated and untreated forests differed for each vegetation variable (treatment main effect), and whether there was an interaction between the unit effect and the treatment effect (unit × treatment interaction). This structure is the two-way factorial ANOVA including interactions.

The general principle of the randomization test is to randomly shuffle values of the explanatory variable and calculate the test statistic for each random set. If the null hypothesis is true, then the observed statistic (e.g., F_{obs}) would be indistinguishable from a randomly generated value. If the null hypothesis is false, then the observed statistic would be in the tail of the distribution of the randomly generated values. For each randomization test, a *p* value was estimated based on the rank of the observed statistic among the null distribution (including the observed). For example, for a right-tailed *F* test where the observed statistic is F_{obs} and n_{sim} randomizations are performed, the *p* value was estimated as

$$(1)\qquad \hat{p} = \frac{\sum_j I(F_{\mathrm{obs}} > F_j)}{n_{\mathrm{sim}} + 1}$$

where $j = 1, \ldots, n_{\mathrm{sim}}$ and $I(F_{\mathrm{obs}} < F_j)$ is an indicator function that takes a value of 1 if the statement is true or 0 otherwise. If the observed statistic was in the tail of the null distribution (more extreme than 5% of the null distribution for $\alpha = 0.05$), then there was evidence that the observed statistic was not observed by chance. We assumed any p value ≤ 0.05 to represent a significant (interesting) result. In general, randomization tests require that the observations are exchangeable under the null hypothesis, which is satisfied in these data when there is no spatial autocorrelation. In the presence of spatial autocorrelation, this is violated. A spatially restricted randomization procedure (Fortin and Payette 2002) in the presence of spatial autocorrelation mitigates this problem. All statistical analyses and simulations were conducted in R version 3.0.1 (R Core Team 2012), and 5000 randomizations were performed for each test.

Comparing severity among treatment units

For our study, we defined severity generally as the effect of a fire on ecosystem properties usually defined by the degree of soil heating or mortality of vegetation. We used crown volume scorch and consumption and the height of bole char relative to tree height as indicators of severity. To compare severity among the treatment units, we used generalized estimating equations using the geeglm function in the package geepack (Højsgaard et al. 2006) in the R statistical program. These combine a generalized linear model with an estimate of existing correlation structures for non-independent data (here we use the exchangeable correlation structure). In this case, we estimated crown scorch as a proportion (0, 1) and bole char ratio (0, 1) using logistic regression with a logit link, with observations grouped by individual plots (to account for within-plot correlation structure). We included treatment unit and treated or untreated as factor explanatory variables both as main effects and with an interaction. We included distance along transect as a quantitative explanatory variable to account for the spatial pattern of high-severity fire effects. For this analysis, we tested severity differences first among the treatment units, separately for the untreated forest neighboring the treatment units, and then for the forest within each treatment unit. We then tested, individually for each treatment unit, whether the severity in the neighboring untreated forest differed from the treated forest. Significance was assessed using Wald statistics.

Spatial analysis of severity metrics

We followed the method of Kennedy and Johnson (2014) to fit 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 three-parameter version of the complement of the Weibull cumulative distribution function (Haefner 1996) and has the following form:

$$(2)\qquad Y = k_0 e^{-\left(\frac{d}{k_1}\right)^{k_2}}$$

where Y is the severity metric ($Y \geq 0$), d is the distance along the transect ($d \geq 0$), 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 $0.368 \times k_0$ and the shape parameter (k_2) estimates how steeply the curve approaches that value.

The value of k_1 at $0.368 \times k_0$ is a mathematical feature of the Weibull curve that we exploited to make a statistical estimate of the linear distance from the treatment boundary at which severity is reduced below a threshold value. Although $0.368 \times k_0$ has no

Table 3. Sample mean value (standard deviation in parentheses) for each stand structure variable by treatment unit and untreated or treated forest.

	MEMA13		MEMA15		MEMA16	
Structure variable	Untreated	Treated	Untreated	Treated	Untreated	Treated
Basal area ($m^2 \cdot ha^{-1}$)	34.96 (14.56)	16.80 (6.56)	37.98 (8.87)	20.46 (8.75)	32.10 (9.47)	17.13 (6.66)
Canopy bulk density ($kg \cdot m^{-3}$)	0.15 (0.06)	0.05 (0.04)	0.18 (0.07)	0.06 (0.05)	0.10 (0.04)	0.03 (0.02)
Canopy base height (m)	2.41 (1.85)	6.40 (4.13)	2.90 (1.86)	7.55 (3.78)	4.93 (2.81)	9.13 (3.80)
Stand density index	279.74 (105.89)	116.21 (44.32)	310.87 (74.87)	139.99 (61.94)	262.97 (85.26)	117.31 (43.27)
Canopy cover	42.98 (12.67)	23.63 (8.24)	55.85 (10.18)	27.17 (11.96)	44.55 (11.79)	23.14 (8.14)
No. of trees (ha^{-1})	749.55 (317.42)	164.83 (70.09)	875.99 (327.57)	190.62 (111.73)	773.44 (436.77)	158.85 (58.41)
Quadratic mean diameter (cm)	24.90 (5.40)	35.95 (6.34)	24.14 (3.60)	38.45 (5.32)	24.97 (5.68)	35.80 (8.26)
Top height (m)	19.95 (3.70)	16.44 (3.06)	19.41 (2.34)	18.24 (2.73)	19.41 (1.74)	17.51 (4.00)
CS distance ($\hat{k}_1$)	177.6 (18.6)		345.3 (75.1)		217.8 (5.5)	
BCR distance ($\hat{k}_1$)	114.5 (16.3)		123.4 (27.2)		161.5 (15.9)	

Note: The last two rows give the estimated distance into the treated area ($\hat{k}_1$) at which the associated severity measure (crown scorch (CS) and bole char ratio (BCR)) is reduced below a threshold (0.368 × maximum value; eq. 2).

specific ecological meaning with respect to fire severity, we judged 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 pine) after the Rodeo-Chediski Fire had a mean crown scorch of 92% and live trees had 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 that 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 was fitted to the data, we derived the distance at which other thresholds of the severity metric were 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 used the nlme function in R (Pinheiro et al. 2013) to fit the Weibull curve to the severity data in each unit separately using nonlinear mixed-effects modeling (Lindstrom and Bates 1990), where the data were grouped by transect in each unit to account for possible within-transect variability.

Results

Randomization test (two-way randomized ANOVA)

All response variables differed significantly between the treated and untreated plots ($p < 0.001$; Table 3). Individual ANOVA tables are provided in the supplementary material.[1] For the response variables TPH, QMD, CBH, CC, and CBD, at least one unit differed significantly from the others ($p < 0.004$). The main unit effect of top height was not significant ($p = 0.096$). There was a significant interaction between treatment and unit for the response variables top height, CC, and CBD ($p < 0.05$), implying that significant differences among the units depend on whether the plots were in the treated or untreated areas. The response variables BA ($p = 0.12$) and SDI ($p = 0.054$) did not differ significantly among the treatment units, with no significant interaction between unit and treatment status ($p = 0.53$ and 0.59, respectively).

MEMA16 had the lowest CBD among the three treatment units in both the treated and untreated forests, whereas units MEMA13 and MEMA15 had similar values (Fig. 2). CBD decreased 67%, 64%, and 64% from treated to untreated in MEMA13, MEMA15, and MEMA16, respectively. In contrast, unit MEMA16 had the highest CBH in both the treated and untreated areas relative to units MEMA13 and MEMA15. CBH increased 166%, 160%, and 85% from treated to untreated in MEMA13, MEMA15, and MEMA16, respectively. Treatment unit MEMA15 had the highest canopy cover in the untreated area, but otherwise, all three units had similar canopy cover (Fig. 2). Canopy cover decreased 45%, 51%, and 48% from treated to untreated in MEMA13, MEMA15, and MEMA16, respectively. MEMA15 had higher values of TPH than the other treatment units. TPH decreased 78%, 78%, and 79% from treated to untreated in MEMA13, MEMA15, and MEMA16, respectively. Treatment unit MEMA15 also had higher values for QMD. QMD increased 44%, 59%, and 43% from treated to untreated in MEMA13, MEMA15, and MEMA16, respectively. For TOPHT (the average height of the 40 largest diameter trees), unit MEMA13 had the highest values in the untreated area and the lowest values in the treated area, accounting for the significant interaction between unit and treatment for this response variable. TOPHT decreased 17%, 6%, and 10% from treated to untreated in MEMA13, MEMA15, and MEMA16, respectively.

Species distribution and composition

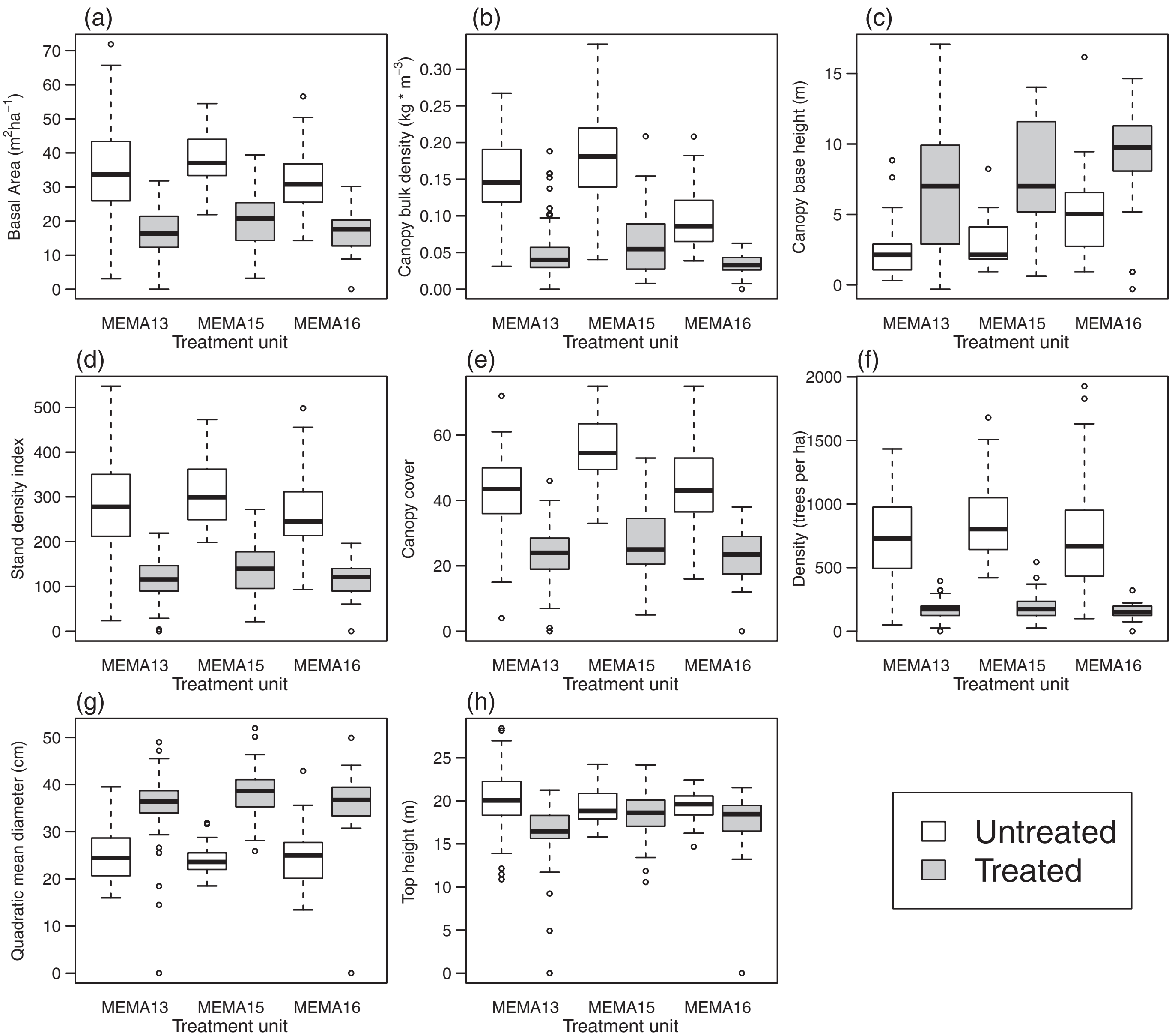
Species stem proportions differed among the untreated and treated areas (Fig. 3). The proportion of *Abies concolor* (hereafter *Abies*) in the untreated forest was highest near MEMA13 (0.65) and MEMA15 (0.53), whereas MEMA16 (0.09) had the lowest. The highest proportion of *Pinus ponderosa* was found in MEMA16 (0.83), followed by MEMA15 (0.18), and MEMA13 (0.09). *Abies* stem proportions were reduced in all treatment units: MEMA13 (0.21), MEMA15 (0.10), and MEMA16 (0.0). MEMA16 (0.97) had the highest stem proportion of *Pinus* followed by MEMA13 (0.61) and MEMA15 (0.58). The stem proportion of *Pseudotsuga* was highest in MEMA15 (0.20) followed by MEMA13 (0.18) and MEMA (0.03). Other tree species presence in both untreated and treated areas included *Pinus strobiformus*, *Populus tremuloides*, *Picea engelmannii*, and *Betula* spp. (Fig. 3).

Burn severity index

Nearly all trees in the untreated area of MEMA13 and MEMA15 were at least partially consumed, with the proportion of trees with burn severity index of 4 or 5 near 1 (Fig. 4*a*). This was substantially higher than the proportion in the untreated area of MEMA16. The proportion at least partially consumed decreased sharply near the treatment boundary for MEMA13 and MEMA15 and remained low further into the treated area (Fig. 4). In MEMA16, the proportion at least partially consumed decreased immediately after the first three plots in the treated area (Fig. 4*a*). In the untreated area, the high proportion of trees that were

[1]Supplementary material is available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjfr-2018-0200.

Fig. 2. Forest Vegetation Simulator (FVS) calculated vegetation structure variables in treated and untreated areas, across treatment units: (*a*) basal area; (*b*) canopy bulk density (maximum 4.5 m deep running mean of canopy bulk density for layers 0.3 m thick within a stand); (*c*) canopy base height (lowest height above the ground with at least 0.011 kg·m^{-3} of available canopy; Dixon 2002); (*d*) stand density index (a relative density measure based on the relationship between mean tree size and number of trees per unit area in a stand (Reineke 1933)); (*e*) canopy cover (the percentage of the ground area that is directly covered with tree crowns); (*f*) density; (*g*) quadratic mean diameter (the diameter corresponding to the tree of arithmetic mean basal area); and (*h*) top height (the average height of 40 largest diameter trees). For all graphs, the box is defined by the 25th and 75th percentiles (Q_1 and Q_3, respectively), the horizontal line is the median, the whiskers extend to the largest point ≤ Q_3 + 1.5 times the interquartile range (IQR) (Q_3–Q_1) and the smallest point ≥ Q_1 – 1.5 times the IQR. The circles represent any observations located beyond the whiskers.



partially consumed corresponded to CS values of 100% and BCR values of 1 across all trees, with a few individual trees with lower values (Fig. 4*b*).

Crown scorch and bole char

Percentage crown scorch (CS) was significantly greater in untreated areas relative to treated areas (Fig. 4; Table 4). It also differed significantly among the units in the treated areas, with MEMA16 having an overall greater percentage crown scorch (Fig. 4; Table 4) in the treated area. Bole char related measurements were significantly greater for the untreated areas compared with the treated areas (Fig. 4; Table 4). There was no significant difference in bole char ratio in the treated areas of MEMA13 and MEMA15, and bole char ratio in the treated area of MEMA16 differed from MEMA13 with only marginal significance (p = 0.08; Table 4).

Spatial pattern analysis

For all treated areas, fire-severity metrics declined with increasing distance from treatment edge, although there were 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 (Fig. 5). Percentage crown volume scorch, tree burn severity, bole char, and bole char ratio declined with

Fig. 3. DBH distribution and species composition of the untreated and treated units in MEMA for plots within 200 m of the treatment boundary. DBH, diameter at breast height; TPH, trees per hectare. Species: UNKN, unknown species; PSME, *Pseudotsuga menziesii*; PIPO, *Pinus ponderosa* var. *scopulorum*; ABCO, *Abies concolor*; QUGA, *Quercus gambelii*; PIEN, *Picea engelmannii*.

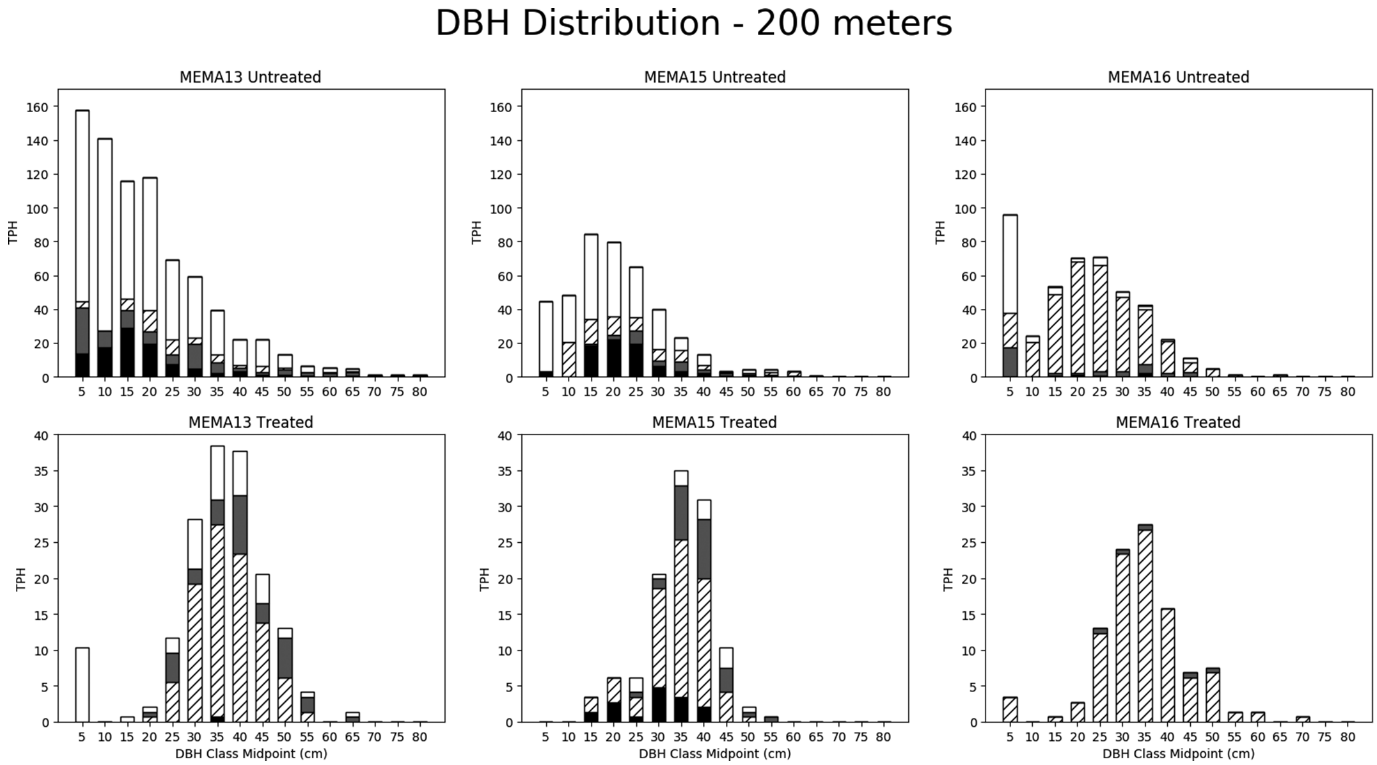
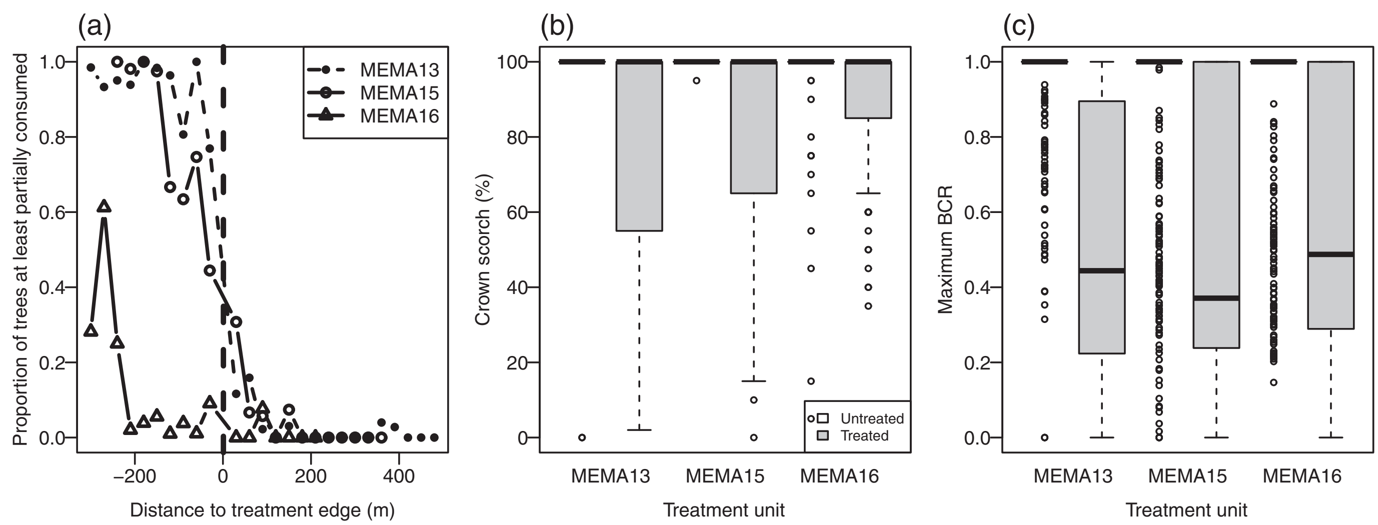


Fig. 4. (*a*) Proportion of trees at least partially consumed (severity index > 3) with distance to treatment edge. The proportion of trees with burn severity index > 3 drops sharply in the treated area near the treatment boundary for all three treatment units and remains low further into the treated area. (*b*) Percentage crown scorch and (*c*) maximum bole char ratio (BCR) were higher in untreated areas relative to treated area (plots only within 200 m of treatment boundary). The box is defined by the 25th and 75th percentiles (Q_1 and Q_3, respectively), the horizontal line is the median, the whiskers extend to the largest point ≤ Q_3 + 1.5 times the interquartile range (IQR) (Q_3–Q_1) and the smallest point ≥ Q_1 –1.5 times the IQR. The circles represent any observations located beyond the whiskers.



increasing distance from treatment edge for all treatment units (Fig. 5). Burn severity metrics declined with increasing distance from treatment edge in all treatment areas.

The point estimates of 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 3). Confidence intervals, however, overlapped due to the substantial variability associated with each individual estimate.

The furthest distance from the treatment edge was observed for unit MEMA15, with a reduction in crown scorch not detected until 345.3 m into the treatment unit. Units MEMA13 and MEMA16 were most similar, with treatment unit MEMA13 showing the smallest distance at which crown scorch was observed to be reduced. For BCR of all trees >10 m tall, unit MEMA16 was estimated to have the longest distance at which severity was reduced (161.5 m), with MEMA15 and MEMA13 with estimates of 123.4 and 114.5 m, respec-

Table 4. Estimate of a generalized estimating equation to predict fire severity by treatment unit, treatment, and distance along transect.

	Estimate	Standard error	*p* value
Crown scorch			
(Intercept)	4.93	0.60	<0.001
MEMA15	0.60	0.24	0.013
MEMA16	0.97	0.27	<0.001
Untreated	3.18	1.06	0.003
Distance along transect	−0.01	0.00	<0.001
MEMA15 × untreated	2.35	1.38	0.090
MEMA16 × untreated	−2.30	1.22	0.059
Bole char ratio			
(Intercept)	2.01	0.47	<0.001
MEMA15	0.14	0.21	0.517
MEMA16	0.47	0.27	0.081
Untreated	2.25	0.39	<0.001
Distance along transect	−0.01	0.00	<0.001
MEMA15 × untreated	−1.22	0.51	0.016
MEMA16 × untreated	−1.83	0.49	<0.001

Note: Each coefficient represents a change in log odds of the severity metric ($\log(p/(1-p))$) relative to a baseline of treated forest in MEMA13, at distance 0 along the transect. A negative coefficient corresponds to a reduction in severity, a positive coefficient corresponds to an increase in severity relative to the baseline. Observations are grouped by individual measurement plot to account for within-plot correlation structure.

tively. For treatment units MEMA15 and MEMA16, transect lengths were short relative to the estimated distances at which crown scorch severity was reduced. Although the empirical model seems to follow the pattern in the data well up to that point and there is evidence for reduced severity, anything beyond the distance of the last plot is an extrapolation and should be interpreted with care. For BCR, the estimated distances are well within the domain of the data.

Discussion

Treatment effects on forest structure

Canopy structural metrics linked to crown fire initiation (Van Wagner 1977) differed significantly between untreated areas relative to the treated areas. A major consequence of fire exclusion in dry forests is the establishment and survival of shade-tolerant trees (Peterson et al. 2005), which effectively increase the probability for crown fire initiation (Agee and Skinner 2005). In our study area, median stem density was nearly 2.5 times higher in the untreated areas relative to the treated areas (Fig. 3). The tree diameter distributions of the untreated forests resemble the reverse J-shaped curve, which indicates a dominance of small-diameter, shade-tolerant trees (Fig. 3). Compared with untreated areas, treated areas had higher CBH and lower CBD, metrics that limit crown fire initiation and propagation (Van Wagner 1977; Rothermel 1991; Agee 1996; Scott and Reinhardt 2001). Other stand structural metrics including BA, SDI, CC, TPH, TOPHT, and QMD (Fig. 2) differed between treated and untreated areas. This pattern is consistent with other studies that quantified forest structure metrics between treated and untreated forest (Pollet and Omi 2002; Waltz et al. 2014). For example, Roccaforte et al. (2015) reconstructed basal area of 9.2 $m^2 \cdot ha^{-1}$ (range: 6.1–12.3 $m^2 \cdot ha^{-1}$) and tree density of 86.2 trees·ha^{-1} (range: 48.3–123.3 trees·ha^{-1}) in our study area for the year 1880. Likewise, Waltz et al. (2014) showed that prefire tree density in the nearby Wallow Fire was lower by an average of 80% in treated units compared with untreated units.

The MEMA16 untreated area had the lowest median stand density, lowest median CBD, and highest median CBH relative to the untreated areas adjacent to MEMA13 and MEMA15. This indicates that the untreated plots neighboring MEMA16 had a vegetation structure similar to that of the treatment areas. The estimated median prefire CBD in MEMA16 (0.08 $kg \cdot m^{-3}$) was less than the theoretical threshold for active crown fire (0.10 $kg \cdot m^{-3}$; Agee 1996; Cram et al. 2006). In contrast, the estimated median prefire CBD in the MEMA13 and MEMA15 untreated areas was greater than 0.10 $kg \cdot m^{-3}$, and these areas likely supported active crown fire. It may be that although the stand characteristics in and around the MEMA16 treatment unit did not support active crown fire, they may have supported a passive crown fire or a surface fire of intensity sufficient to expose the needles of the crown to a lethal temperature, thereby scorching rather than consuming them.

Thinning treatment effects on fire severity

Percentage crown volume scorch and burn severity indices were significantly higher in untreated areas relative to treated areas (Figs. 4 and 5; Table 4). Our results corroborate existing empirical findings on fuel treatment effectiveness (Pollet and Omi 2002; Raymond and Peterson 2005; Stephens et al. 2009; Ritchie et al. 2007; Prichard et al. 2010; Safford et al. 2009). This is not surprising given that the untreated areas had significantly higher stand structural metrics that can support active crown fire (Fig. 3; Agee and Skinner 2005).

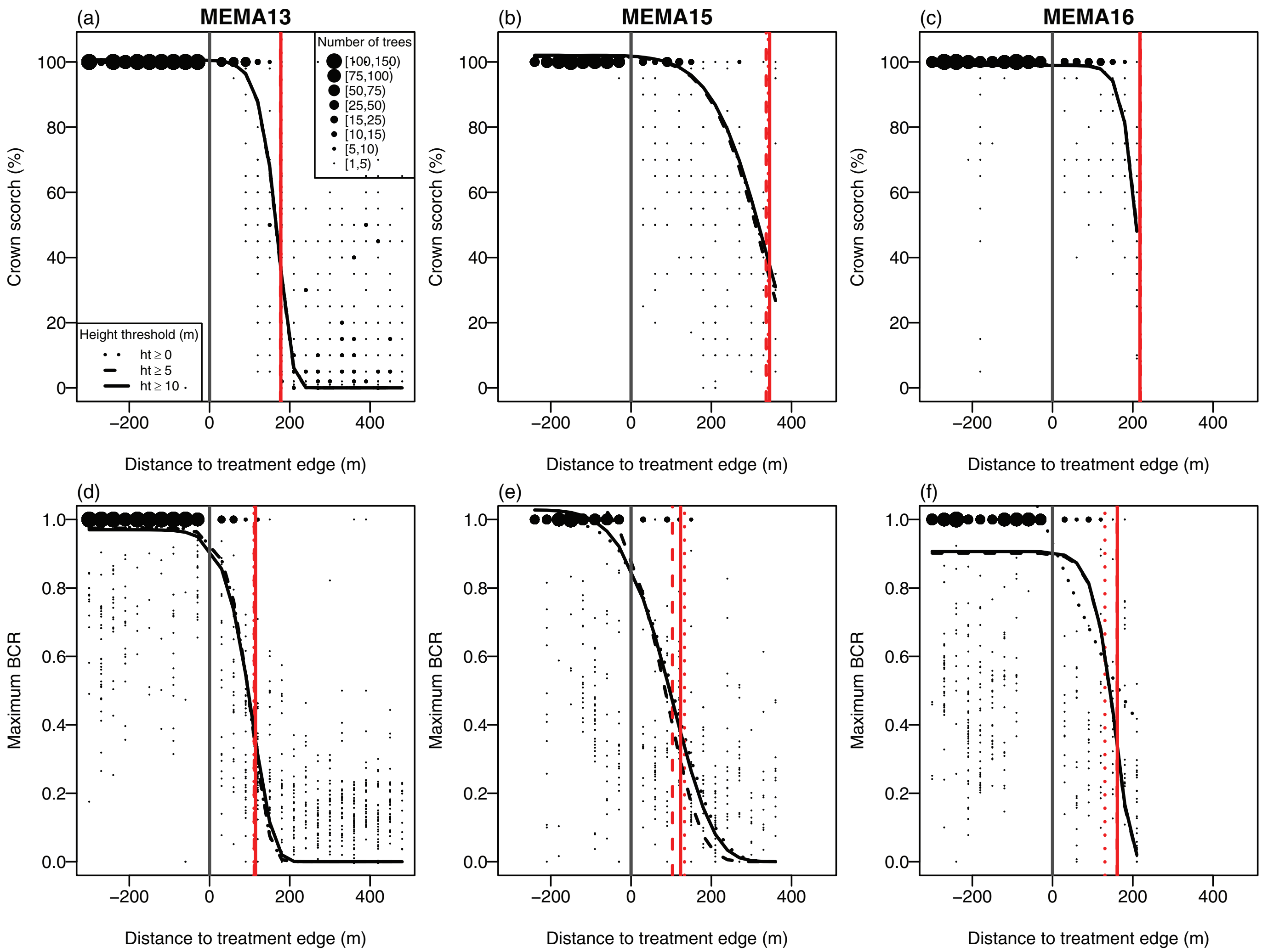
A divergence exists in the performance of fuel treatments depending on the severity metric considered relative to the structural characteristics of the treatment unit, and this divergence provides insight to the kind of fire behavior that might have occurred. In the untreated areas, all three treatment units had similar distributions of percentage crown volume scorch, with nearly all trees having 100% crown scorch after the wildfire (Fig. 4). Many studies have recorded similar responses in untreated stands (Pollet and Omi 2002; Safford et al. 2009; Prichard et al. 2010; Kennedy and Johnson 2014; Waltz et al. 2014; Roccaforte et al. 2015). In the untreated area neighboring the MEMA16 unit, most of the trees were fully scorched; however, unlike MEMA13 and MEMA15, a relatively low percentage of trees were consumed (lower burn severity index; Fig. 4). In the treated areas within 200 m of the treatment boundary, the MEMA16 treated unit had similar levels of BCR and percentage of trees at least partially consumed as the other two units, yet it exhibited higher levels of crown scorch than the other two units (Fig. 4; Table 4).

Crown scorch in MEMA16 indicates that there may have been other stand attributes driving fire effects. Crown volume scorch was highest in the treated units relative to the other treatment units (Table 4). MEMA16 is located adjacent to riparian drainages, so complex topography could explain the measured fire effects. Radiant and convective heat, from two nearby untreated riparian drainages, may have increased crown scorch and burn severity or it is possible that these units had higher loadings of understory vegetation (shrubs and herbaceous). To make credible inferences regarding patterns in fire severity within and near fuel treatments, inventories and monitoring of post-treatment (prefire) stand structure and surface fuels are needed. Absent such data, we are left with informed speculation as to the cause of the pattern in fire severity. We assume that the pile-and-burn and prescribed fire treatments reduced slash following the thinning treatments.

Spatial effects of fuel treatments

The MEMA fuel treatment areas appear to have affected the progression and spread of the San Juan Fire. Building on the work of Kennedy and Johnson (2014), we show here that a simple comparison of fire severity between treated and untreated forest is inadequate to inform fuel treatment planning and development of treatment prescriptions (Johnson and Kennedy 2019). It is also important to estimate quantitatively the expected spatial progression of high-severity fire effects as the fire burned into and through the treatment area. Is the treatment expected to reduce behavior over a relatively short distance, or are high-severity fire effects expected to persist for longer distances into the treated area? In our study, the three treatment areas had similar but not

Fig. 5. Scatterplots of tree-scale fire severity with distance into the treatment area for (*a*–*c*) crown scorch and (*d*–*f*) maximum bole char ratio (BCR) for each treatment unit. The vertical grey line indicates the treatment boundary. Black lines give the shape of the fitted curve for each height threshold. Vertical red lines give the estimated distance from the treatment edge at which fire severity is reduced (k_1), differentiated by whether all trees are included in the analysis (dotted lines), only trees ≥5 m in height (dashed lines), or only trees ≥10 m in height (solid lines). The size of the point scales with the number of trees at a given distance with the corresponding value for the severity measure (e.g., crown scorch is 100% for nearly all trees in the untreated area in MEMA13, illustrated by the large point size in the scatterplot). [Colour online.]



identical distances into the treatment area where crown scorch decreased (Fig. 4). All of the distances estimated for BCR are shorter than those estimated for CS (consistent with Kennedy and Johnson 2014). The distances measured here for crown scorch reduction can be considered the distance at which the intensity of the surface fire was reduced sufficiently to avoid exposure of needles to lethal temperatures.

For MEMA15 and MEMA16, we estimate the distance at which crown scorch is reduced to be near the edge of the domain of measured distances (Fig. 4). These distances for crown scorch should be interpreted with care as we do not have observations of crown scorch beyond the estimated distances; however, the spatial estimates for maximum bole char ratio are well within the range of the observed data.

These estimates should not be used as strict guidelines to determine the dimensions of fuel treatment areas in general, because the effectiveness of treatments is landscape specific and effects vary according to vegetation type and structure, natural fire regime, weather conditions, and local topography (Stratton 2004; Agee 1996). The curves that we estimate here show the wildfire transitioning from an active crown fire to a passive crown fire or a surface fire as the wildfire burned in the treatment areas with low tree density, high canopy base heights, and lower canopy bulk densities. Note that the wildfire burned downhill into these treated areas, possibly contributing to the observed reduction in severity. The spatial estimates indicate where high-severity fire effects are first reduced, providing a guidance for the size of a fuel treatment with a given treatment structure and landscape context. If the fuel treatments are to be used as points of attack for suppression efforts, then the size of the treatment should be larger than those estimated. If the high-severity fire effects are reduced at these distances, an additional buffer is required to provide room for safe access for firefighter suppression actions (Stratton 2004).

Our Weibull curve estimates (statistical estimate of the distance into the treated area at which the fire-severity metric is reduced) are further into the treated area than those estimated by Safford et al. (2009) and by Ritchie et al. (2007). Those authors attributed high-severity fire effects near the treatment boundary to edge effects. Moghaddas and Craggs (2007) recorded a 65% decrease in crown scorch within 60 m from the edge of the treatment. In contrast, e.g., in the Wallow Fire, the treatment prescriptions around the town of Alpine were designed primarily to reduce fire behavior, and Kennedy and Johnson (2014) found that the severity was reduced very close to the treatment boundary. Also in the Wallow Fire, treatment prescriptions that accommodated clumps of small trees for wildlife habitat had the high-severity effects measured much further into the treated area. Here, with wildlife-oriented treatments, the distances are further than the wildfire-focused treatment but less then another wildlife-focused treatment. There are important caveats to be mentioned for our estimates, particularly for the crown scorch estimates in MEMA15 and MEMA16. The lengths of the transects into the treated area were limited by the size of the treatment area, and the estimated distances for crown scorch reduction are near or beyond the distance to the treated area for the last measured plot (Fig. 4).

As wildfires encounter fuel treatments that are designed to meet multiple resource objectives, there is an opportunity to expand our understanding of how these unique prescriptions perform during wildfire. Management for multiple resource objectives often implies a trade-off in which the outcome for one objective (e.g., hazard reduction) is sacrificed for the sake of improving outcomes for another objective (e.g., wildlife habitat conservation). It need not be an either–or proposition if the spatial dimensions of the fuel treatment are also taken into account (Kennedy and Johnson 2014). In particular, we show that the size of a fuel treatment required to observe a spatial reduction in fire severity is variable. Some of that variability is explained by the landscape context outside the fuel treatment (Johnson and Kennedy 2019), including the expected severity of the fire as it enters the fuel treatment. Some of the variability is also explained by the vertical and horizontal structure of the fuel treatment itself. We might consider a spectrum of fuel treatment sizes, from the most extreme fuel break (width determined by edge effects, sensu Safford et al. 2009) to an untreated forest. Along this spectrum, we can assess if the fuel treatment structure has changed fuel characteristics sufficiently to achieve some known thresholds, even if the prescription does not follow the standard treatment known to perform best during wildfire. For example, if canopy bulk density is reduced below 0.10 $kg \cdot m^{-3}$, a threshold understood to reduce the chance of active crown fire (Agee 1996). Managers might consider a trade-off between the width of a fuel treatment and the residual density of trees that are retained for other resource objectives (Kennedy and Johnson 2014).

Conclusions

We quantitatively assessed the effects of fuel treatments on wildfire severity on the 2014 San Juan Fire. The San Juan Fire overlap with completed fuel treatments has presented an opportunity to quantify the actual performance of fuel treatments designed primarily with multiple-resource management objectives, including reducing crown fire hazard and creating wildlife habitat for the Northern Goshawk (USDA Forest Service 2002). Overall, fuel treatment areas encountered by the 2014 San Juan Fire had lower fire severity and successfully mitigated the adverse effects of the wildfire. Studies that include actual wildfires and fuel treatment interactions provide the best empirical evidence of fuel treatment response (Pollet and Omi 2002; Fulé et al. 2012). Our results show estimated distances into the treatment area where fire behavior was reduced. Fuel reduction treatment size and subsequent effects on fire burn patterns have implications for fuel treatment design in the wildland–urban interface, firefighter safety, and suppression tactics. For example, previously we measured fuel treatments that were uphill of residential communities (Kennedy and Johnson 2014), where the fire was spreading downhill before encountering the fuel treatment. It is understood in general that fire behavior is potentially more extreme when spreading in the uphill direction. We anticipate that distances at which fire severity persists into a treated area will likely be larger for such uphill spread than those estimated here and in the Wallow Fire (Kennedy and Johnson 2014).

Fuel management on all federal lands must complete the requirements mandated by the NEPA, which requires comprehensive evaluation of the effects of proposed treatments including a no action alternative (NEPA 1969). Empirical assessments of fuel treatment effectiveness help forest managers complete future NEPA documentation. Managers have actual data to point to in response to NEPA comments. Our results quantify "real world" treatment effects between control and thinned treatment areas, providing an opportunity to communicate with stakeholders about treatment effects on fire severity. This may improve social acceptability of fuel treatments, emphasizing the importance of fuel treatments for changing wildfire behavior and for protecting homes in the wildland–urban interface (Shindler et al. 2002). Our Weibull curve estimates (Fig. 5) can be used to inform the size of fuel treatments needed to accomplished specific management objectives.

Wildfires are complex interactions between a large number of physical and chemical processes that occur over a wide range of scales (Linn et al. 2007). The transition from steep slopes (untreated) to the low slopes (treated areas) may have influenced fire spread and altered fire behavior as the fire entered the fuel treatment areas. Safford et al. (2012) and Kennedy and Johnson (2014) recorded similar responses on the 2007 Angora Fire on the Lake Tahoe National forest and 2014 Wallow Fire, respectively. As the San Juan Fire descended into the fuel treatment areas, a change in fuel moisture, windspeed, topography, or vegetation composition could have influenced behavior. To potentially understand fire dynamics and fuel treatment interactions on the San Juan Fire, physics-based fire modeling such as the wildland–urban interface Fire Dynamics Simulator (WFDS; Mell et al. 2010) could be used to simulate the fuelbed and fire weather conditions. Despite study limitations (see below), this study shows the effects of fuel treatment and change in wildfire behavior of actual treatment effects in dry forests in the western United States.

Limitations

Some limitations exist in our study. First, prefire data on tree canopy characteristics, dead woody fuel, and shrub and herbaceous coverage — major contributors to surface fire behavior and crown fire initiation — were not available. Ideally, these data would have been collected before and after fuel treatments (thinning and prescribed fire) and then after the wildfire (Pollet and Omi 2002). Postfire measurement of these variables would be an underestimation of the loading prior to the wildfire because the wildfire may have reduced the loadings (Ottmar et al. 1993). Due to this lack of prefire surface and shrub fuel data, we were only able to relate the differences in fire severity to differences in canopy structure. Additionally, we used a simulation model to estimate forest structural metrics (CBH, CBD) associated with crown fire initiation, which are inconsistently calculated and should be used with caution (Cruz and Alexander 2010; Fulé et al. 2012). Finally, our data show that fire severity (burn severity index) decreased as the fire approached the fuel treatment boundary — we could not explain this pattern.

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