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Altered vegetation structure from mechanical thinning treatments changed wildfire behaviour in the wildland–urban interface on the 2011 Wallow Fire, Arizona, USA

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Abstract. Fuel reduction treatments are designed to meet multiple management objectives, resulting in unique vegetation structures that do not conform to standard classifications and vary considerably over space and time. We evaluated how different post-treatment vegetation structures relate to patterns in wildfire severity. To reconstruct both untreated and treated pre-fire forest structure, we used post-fire stand data measured at three different fuel treatment units burned by the 2011 Wallow Fire (Arizona). We describe (1) how forest structure differs among the treatment units, both in the untreated forest and within the treated area; and (2) how those differences in forest structure explain variability in burn severity. We show that the retention of smaller trees (ladder fuels) for wildlife cover relates significantly to higher severity within one treatment unit. Further variability in within-treatment severity is explained by the severity of the wildfire in the untreated forest as the fire approached the treated area. The untreated forest structure and species composition constrain post-treatment structure and composition, which was related to within-treatment structure and post-fire composition and structure. The study design presented in this paper suggests that evaluations of fuel treatment effectiveness can move beyond simple classifications of treatment type and fire behaviour.

Additional keywords: bole char, crown scorch, fire severity, fuel treatment effectiveness.

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Introduction

Following decades of fire exclusion in the western United States dry coniferous forests with low- to mixed-severity fire regimes (Covington *et al.* 1994; Graham *et al.* 2004; Hessburg *et al.* 2005), fuel reduction treatments are advocated to restore fire-adapted ecosystems and to increase forest resilience, defined as the capacity of an ecosystem to return, over time, to its pre-condition state following disturbance (Agee and Skinner 2005; Peterson *et al.* 2005; Reinhardt *et al.* 2008; Fulé *et al.* 2012; Waltz *et al.* 2014). Various empirical studies of fuel treatment efficacy use a simple factorial design that compares wildfire severity outside a fuel treatment with severity inside the treatment unit, with treatment classified by type (Pollet and Omi 2002; Raymond and Peterson 2005; Prichard and Kennedy 2014). In general, these studies have found that fuel treatments that combine mechanical thinning followed by surface fuel treatment such as prescribed fire tend to experience lower fire severity than neighbouring untreated forest (Kalies and Yocom Kent 2016). Although there is general understanding that these kinds of fuel treatments tend to reduce severity, as treatment prescriptions are modified to accommodate multiple management objectives (Lehmkuhl *et al.* 2007), it becomes less useful to classify fuel treatments into one of a small number of treatment types.

Empirical measurements of post-treatment vegetation structures and fuel loadings have also been reported (Pollet and Omi 2002; Roccaforte *et al.* 2015; Vaillant *et al.* 2015), and simulation models predict the impact of the fuel treatments on fire behaviour and severity (Stephens and Moghaddas 2005*a*; Stephens *et al.* 2009*a*; Johnson *et al.* 2011). However, observing and empirically quantifying the interaction between post-treatment structure and wildfire severity require a wildfire to encounter fuel treatments with measured pre-fire post-treatment structure data – a rare and unpredictable occurrence (Pollet and Omi 2002). More typically, a wildfire encounters fuel treatments documented by a description of the prescription, with little to no measurement of post-treatment forest structure. We require opportunistic, observational field studies to help us understand how the resulting vegetation structure of a fuel treatment performs in a real wildfire because there is no opportunity to experimentally evaluate fuel treatment effectiveness in the United States (Agee and Skinner 2005).

For example, a major goal of the White Mountain Stewardship Contract (WMSC) was to reduce fuel accumulation and decrease fire hazard (defined as the potential magnitude of fire behaviour and effects as a function of fuel condition; Peterson *et al.* 2005) in the Apache–Sitgreaves National Forest (ASNF), Arizona (Sitko and Hurteau 2010). WMSC fuel treatments had multiple management objectives, including ecological restoration and wildlife conservation, economic benefit and facilitating the protection of residences in the wildland–urban interface (WUI; Neary and Zieroth 2007), resulting in over 75 unique fuel treatment prescriptions (Sitko and Hurteau 2010). With such variability in fuel treatment prescription, it becomes difficult to simply compare the performance of one treatment with another, without understanding the post-treatment vegetation structure that results from a particular fuel treatment. That is, these unique treatments no longer fall under a simple comparison of a standard thin-only treatment with a standard thin-only with prescribed fire treatment.

The 2011 Wallow fire, Arizona State's largest recorded wildfire and the largest in the history of the south-western US, burned through several completed WMSC fuel treatment areas. These treatment areas were credited with reducing wildfire behaviour (crown fire) and allowing the protection of homes (Kennedy and Johnson 2014). Although most of the WMSC fuel treatments were shown to have 'worked' in this sense (Bostwick *et al.* 2011), Kennedy and Johnson (2014) demonstrated that in three of the WMSC fuel treatments, there was substantial variability in the spatial pattern of fire severity. However, Kennedy and Johnson (2014) did not determine quantitatively the forest structure characteristics of the fuel treatments and the surrounding landscape that explain this variability in severity, relying instead on qualitative descriptions of the fuel treatments. In the Wallow fire, Waltz *et al.* (2014) showed that fuel treatments did modify stand structure, and they found lower fire severity in the treated units relative to untreated forest. They also show substantial variability in severity both in treated and untreated areas in the Wallow fire, although like Kennedy and Johnson (2014), they do not evaluate relationships between stand structure and severity, nor do they consider how landscape conditions affect severity in treated areas.

As forest managers design fuel treatment prescriptions to meet multiple management objectives (Lehmkuhl *et al.* 2007; Sitko and Hurteau 2010), this is likely to result in a variety of post-treatment structures. To expand our understanding of how fuel treatments modify fire severity, we need to quantitatively relate post-treatment stand structure to the fire severity experienced inside a fuel treatment during a wildfire. The primary goal of the present study was to determine which characteristics of the forest both inside and immediately outside the fuel treatments best explained the observed variability in fire severity within fuel treatments. We used both empirical measures of stand structure and remotely sensed burn severity to evaluate two main hypotheses (Table 1): (1) forest structure differed among the transects measured by Kennedy and Johnson (2014), both inside the fuel treatment and in the surrounding forest, and both before and after the wildfire; (2) fire severity is affected by variability in forest structure and the context of the forest surrounding the treatment unit. Through detailed analyses of stand structure and by incorporating the context of the surrounding forest, the present study demonstrates how we can expand our understanding of fuel treatment effectiveness beyond simple classifications of treatment type and improve our understanding of treatment effectiveness in a larger management context (Schmidt *et al.* 2008). Our study results show treatments increase forest resilience (Reinhardt *et al.* 2008) and indicate that the size and prescription type are important components for successful treatment strategies in dry forests in western North America. Our overall study design provides support for the guiding principles for developing fire-safe forests (Agee and Skinner 2005).

Methods

Study area

The 2011 Wallow fire burned over 217 000 ha on the ASNF Alpine ranger district, in east-central Arizona (Fig. 1). Study areas were in mid-to-high-elevation mixed-conifer forests. Dominant vegetation includes Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.), south-western white pine (*Pinus strobiformis* Engelm.), blue spruce (*Picea pungens* Engelm.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), corkbark fir (*Abies lasiocarpa* (Hook.) Nutt. var. *arizonica* (Merriam) Lemmon), ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson var. *scopulorum* Engelm.), quaking aspen (*Populus tremuloides* Michx.) and Gambel oak (*Quercus gambelii* Nutt). Mean minimum temperature (January) is −7.2°C and mean maximum temperature (July) is 31.5°C. Mean annual precipitation is 510 mm, characterised by high-intensity, short rainstorms typical of the monsoon season in this region. Most precipitation occurs as snow between November and April (Western Regional Climate Center, http://www.wrcc.dri.edu, accessed 10 March 2013 (data from 2001 to 2011)). Soils are of volcanic origin (Laing *et al.* 1989), consisting of volcanic ash of rhyolitic or esitic (acid igneous extrusive) and basalt lava flows and volcanic cinders of basaltic composition.

Fuel treatment descriptions

Kennedy and Johnson (2014) consulted with the local forest silviculturist and fire management officer to identify three treatment units within the Wallow fire perimeter that burned unimpeded by fire suppression tactics (Fig. 1), and that experienced crown fire behaviour as the fire approached the treatment unit. The goal was to observe treatment effects on severity in a crown head-fire, and to avoid confounding with suppression activities including burnouts. The units were located adjacent to the WUI communities of Alpine (Alpine 2, 6; AP2, AP6 respectively) and Nutrioso (NU), Arizona.

Treatments were implemented in 2004, 2008 and 2010 for AP2, AP6 and NU respectively. In AP2 and AP6, trees up to 0.9 m tall and up to 40.6 cm diameter at breast height (DBH) were thinned from below to an average of 4.6 m horizontal distance between crown drip lines. Aspen, oak, riparian hardwoods and junipers were excluded from harvest. In NU, trees up to 0.9 m tall and up to 40.6 cm diameter were leave-tree-marked (meaning do not cut these trees) and trees >40.6 cm were cut tree marked (meaning only take these trees). In NU, stands were thinned from below, with a diameter limit of 40 cm to a crown spacing of 3–6 m. Exceptions were made to create structural diversity (e.g. small groups of trees with interlocking crowns were retained to reduce even spacing between trees) and improve wildlife habitat, and in response to public discontent towards homogeneous forest structure. Both NU and Alpine

Table 1. Wallow fire statistical hypotheses, tests and interpretations

CBH, canopy base height (m); CBD, canopy bulk density (kg m^{-3}); BA, basal area (m^2/ha^{-1}); QMD, quadratic mean diameter (cm); Density, trees per hectare; CS, crown scorch (proportion); BCR, bole char ratio; BSI, burn severity index; RdNBR, Relative Difference Normalized Burn Ratio AP2 = Alpine 2, AP6 = Alpine 6, NU = Nutrioso.

Hypothesis	Response variable	Null hypothesis	Procedure	Interpretation
(1) Stand structure	CBH, CBD, BA, QMD, Density	1a. Fuel treatment did not modify stand structure: $\mu_{treated} = \mu_{untreated}$	Unrestricted randomisation *t*-test	Significant *P* value implies change in stand structure variable between treated and untreated stands. Tested separately for each treatment unit
	CBH, CBD, BA, QMD, Density treated plots	1b. Stand structure within the treated area did not differ among the treatment units: $\mu_{treated/AP2} = \mu_{treated/AP6} = \mu_{treated/NU}$	Unrestricted randomisation *F*-test	Significant *P* value implies differences in stand structure among the treatment units within the treated area
	CBH, CBD, BA, QMD, Density untreated plots	1c. Stand structure outside the treated area did not differ among the treatment units: $\mu_{untreated/AP2} = \mu_{untreated/AP6} = \mu_{untreated/NU}$	Unrestricted randomisation *F*-test	Significant *P* value implies differences in stand structure among the treatment units outside the treated area
(2) Fire severity	CS, BCR, BSI3 treated and untreated plots	2a. Fire severity was not modified by changes in each stand structure variable: $\beta = 0$, where β is the slope coefficient for a logistic regression	Restricted randomisation logistic regression with a logit link	Significant *P* value implies that across treated and untreated plots, changes in that particular stand structure variable modified fire severity. Tested separately for each treatment unit
	CS, BCR, BSI3 treated plots only	2b. Fire severity was not modified by changes in each stand structure variable: $\beta = 0$, where β is the slope coefficient for a logistic regression with a logit link	Restricted randomisation logistic regression with a logit link	Significant *P* value implies that within the treated area, changes in that particular stand structure variable modified fire severity. Tested separately for each treatment unit
(3) Landscape context	RdNBR	Burn severity did not change as the fire approached the treatment boundary: $\beta = 0$, where β is the slope of the relationship between burn severity and distance to treatment edge on the windward side of the treatment	Linear regression	Significant *P* value with a positive coefficient implies that burn severity was decreasing as the fire approached the treatment boundary. Intercept term is interpreted as expected burn severity at the treatment boundary

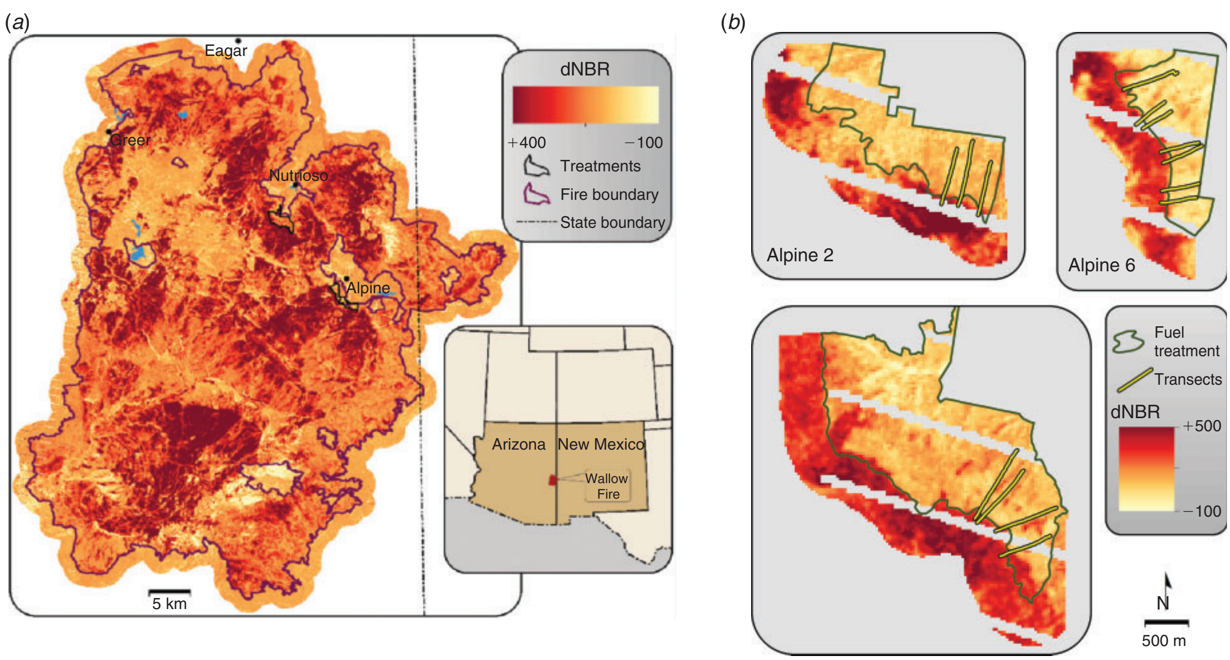

Fig. 1. (*a*) Wallow Fire fuel treatment units and remotely sensed burn severity. (*b*) Remotely sensed burn severity on the windward side of each treatment unit and in the treatment interior. The windward side is clipped 500 m from treatment edge. It is assumed that the fire approached the treatment unit on the windward side. Sample transects are shown in each treatment area. The Landsat 7 satellite imagery is affected by missing data lines caused by a system malfunction, but we found no bias in the distance to the treatment edge in the missing data, which represented ~20% of the pixels (dNBR, Differenced Normalized Burn Ratio).

Table 2. Mean burn severity measures and post-fire surface fuel loadings (s.d. in parentheses) for each treatment unit, treated and untreated
CS% is the visual assessment of the percentage of the trees crown scorched or consumed, BCR (bole char ratio) is the ratio of the maximum height of bole char to the tree height, and BSI3 is the proportion of stems with burn severity index ≥3 (at least partially consumed)

Unit	Treatment	CS%	BCR	BSI3	1-h (Mg ha^{-1})	10-h (Mg ha^{-1})	100-h (Mg ha^{-1})
AP2	Untreated	98% (11%)	0.85 (0.29)	0.86 (0.31)	0.033 (0.05)	0.23 (0.16)	0.03 (0.02)
	Treated	48% (47%)	0.14 (0.21)	0.14 (0.17)	0.037 (0.03)	1.00 (0.98)	0.07 (0.06)
AP6	Untreated	98% (15%)	0.90 (0.23)	0.77 (0.27)	0.028 (0.03)	0.18 (0.14)	0.03 (0.03)
	Treated	71% (43%)	0.29 (0.31)	0.19 (0.28)	0.034 (0.02)	0.59 (0.61)	0.055 (0.05)
NU	Untreated	97% (17%)	0.97 (0.17)	0.97 (0.05)	0.006 (0.008)	0.12 (0.12)	0.01 (0.02)
	Treated	85% (33%)	0.42 (0.30)	0.22 (0.31)	0.008 (0.009)	0.29 (0.29)	0.02 (0.03)

stands were whole-tree harvested, and the slash from the harvest was piled and burned.

During the Wallow fire, these treatment units burned on 3 June (AP2, AP6) and 5 June (NU), burning 24 000, 16 000 and 20 000 ha respectively. High temperatures ranged from 23 to 28°C, relative humidity from 4 to 14%, and wind gusts were up to 20 m s^{-1}. Spotting distances were reported up to 4.8 km. Red flag warnings were issued for the days the fire burned through the measured treatment units, and Haines indices (Haines 1988) were predicted between 5 and 6 (moderate to high potential for wildfire growth).

Sampling design

In summer 2012, Kennedy and Johnson (2014) installed 273 permanent plots on 14 linear transects (three in AP2, seven in AP6, and four in NU; Fig. 1) that spanned the treatment boundary, extending into both untreated and treated areas. The transects were not placed completely randomly, as they were installed to avoid major roads, riparian zones, reserve areas, wildlife habitat areas, untreated forest patches and drainages. For each treatment unit, the global position system (GPS) coordinates of the fuel treatment boundary between burned and untreated and burned and treated was recorded. The final length of each transect varied with the size of the treatment unit and no plot was placed on the treatment boundary. Kennedy and Johnson (2014) oriented the direction of the transects to be in line with the direction of fire spread, as inferred by fire progression maps and on-the-ground burn severity indicators such as such as crown (needle) freeze, crown scorch and basic knowledge of fire behaviour and topography. Note that these transects do not represent a random sample of each treatment unit. Rather, we use the treatment units to group the transects for the purpose of statistical analysis. Unit-level summaries of stand structure and the relationship between stand structure and severity describe the observed relationships for each set of transects.

For each transect, three 0.05-ha (500 m^2) plots were installed every 30 m up to three plots in the untreated area and one 0.10-ha (1000 m^2) plot every 30 m in the treated areas until we reached the boundary of the treatment unit (Fig. 1). Plot size difference was implemented to account for the higher stem density in untreated areas. Tree regeneration, including *Quercus* sprouts and conifer seedlings <1.37 m, was measured on a 0.01-ha (100 m^2) subplot and was tallied by species, condition (living or dead) and height class: 0–38, 38.1–76, 76.1–137 cm. At plot centre, we recorded aspect, elevation, slope gradient and slope position. Downed and dead woody fuel was measured on four 20-m transects using Brown's (1974) planar intercept method. The azimuth of first transect was selected randomly, and the other established at by adding 90° to the first. We recorded 1-h (<0.64 cm) fuels from 19 to 20 m; 10-h (0.64–2.5 cm) fuels from 18 to 20 m, 100-h (2.5–7.6 cm) fuels from 17 to 20 m, and 1000-h (>7.6 cm) fuels from 0 to 20 m (Table 2). Woody fuel loadings were calculated using standard equations (Brown 1974).

Stand structure reconstruction

In each plot, we measured all trees and snags >1.37 m tall for DBH, total tree height, crown base height and height to live crown. Snags were defined as dead trees before the wildfire, based on external characteristics such as degree of retention of fine twigs, bark retention, beetle activity, bole colour, bole breakage and professional experience (Keen 1955). Species were identified as one of the following: *Pinus ponderosa* P. & C. Lawson (*Pinus* hereafter), *Abies concolor* var. *concolor* (Gord. & Glenda.) Lindl. Ex Hildebr. (*Abies* hereafter), *Pseudotsuga menziesii* (Mirb.) Franco (*Pseudotsuga* hereafter), *Quercus gambelii* Nutt. (*Quercus* hereafter), or other (including <1% of total identified stems, and the stems that could not be identified owing to extreme burn severity). For pre-fire reconstruction, we estimated only canopy fuels data, because we had no estimate of pre-fire surface fuels. For each plot, we used the Central Rockies variant of the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS; Rebain 2010) to calculate canopy base height (CBH, m), canopy bulk density (CBD, kg m^{-3}), canopy cover (Cover, %), density (trees per ha) and quadratic mean diameter (QMD, cm). For estimates of post-fire composition and density, we assumed stems with a burn severity index ≤2 to have survived the fire (see fire severity measurements below).

Fire severity measurements

For each tree, we made visual estimates of the percentage volume of crown scorch (CScorch), which included consumed and scorched conditions, and used a laser range finder to measure minimum and maximum bole char height (m). Bole char height was transformed to bole char ratio (BCR) by dividing maximum bole char height by tree height. Each tree was also assigned a burn severity index: 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;

US Department of the Interior National Park Service 2003). For each plot, we calculated the proportion of trees classified with burn severity index ≥3 (at least partially consumed; Table 2). Trees classified with burn severity index ≤2 (Table 2) were assumed to survive the first year after the fire, and these were used to characterise stand composition after the wildfire.

Remotely sensed burn severity

Monitoring Trends in Burn Severity (MTBS; http://www.mtbs.gov/, accessed 28 January 2019) provides spatial layers at 30-m resolution of the Differenced Normalized Burn Ratio (dNBR) and the Relative Differenced Normalized Burn Ratio (RdNBR), which are calculated based on pre-burn and post-burn Landsat Thematic Mapper™ images (Eidenshink *et al.* 2007). The Landsat 7 satellite imagery is affected by missing data lines caused by a system malfunction (Fig. 1), but in comparing the distributions of the distance to treatment edge, we found no bias in the missing data, which represented ~20% of the pixels. MTBS also provides a spatial layer of severity classifications based on the dNBR values: increased greenness, unchanged, low severity, moderate severity and high severity. These classifications were used to compare the frequency of burned pixels in each level of severity. For our analysis, only those untreated pixels that were assumed to have burned on the windward side of treatment units were evaluated, and these were clipped using a 500-m buffer from the treatment edge (Fig. 1*b*). For each pixel in the untreated area windward of the fuel treatment, the minimum Euclidean distance from the pixel to the treatment boundary was determined. The remote sensing data allowed us to characterise burn severity across the entire area within and surrounding the treatment units, providing a check against any possible bias introduced by the placement of measurement transects.

Statistical analysis

As the measured transects and treatment units do not comprise a truly random sample, all statistical analysis performed serves as a description of the relationships and patterns within the measured transects, grouped by treatment unit. Furthermore, because the sampling design in this study does not meet the assumptions of standard statistical analyses, we use randomisation techniques to perform hypothesis tests (Fortin and Jacquez 2000). The details of each randomisation procedure are given in S1, available as Supplementary Material to this paper. The general principle is to randomly shuffle values of the explanatory variable and calculate the test statistic for each random set. If the null hypothesis is false, then the observed statistic would be in the tail of the distribution of randomly generated statistics. For each randomisation test, a P value is estimated based on the rank of the observed statistic in the null distribution. We assume any P value ≤0.05 to represent a significant result, and P values ≤0.10 to represent results of marginal significance. Two different randomisation procedures were implemented depending on whether the response variable was spatially autocorrelated. The randomisation tests account for within-transect variability in hypothesis testing. All statistical analyses and simulations were conducted in *R version 3.0.1* (R Core Team 2013) and 5000 randomisations were performed for each test.

Stand structure

To test the hypothesis that the fuel treatment modified stand structure variables separately for each treatment unit, we compared each stand structure variable individually between the treated and untreated area using a randomised t-test, for all plots and for the first three plots on either side of the treatment boundary (to balance the number of plots in the treated and untreated area, at the treatment boundary). To test the hypothesis that the treatment units differed in stand structure characteristics, we used a randomised F-test for each stand structure characteristic within the treated areas (randomised one-way ANOVA), and separately for plots in the neighbouring untreated area. Interpretation of these tests is limited to the set of measured transects, as these are not a perfectly random sample of each treatment unit.

Fire severity

Logistic regression was estimated with a logit link separately for each set of transects grouped by treatment unit, with each stand structure variable entered individually as a covariate. Response variables were plot-level mean crown scorch (CScorch) as a proportion (0, 1), plot-level mean BCR, also (0, 1), and the plot-level proportion of trees with burn severity index ≥3 (at least partially consumed; BSI3). The estimated coefficient is the change in log odds for each unit increase in the explanatory variable. We used restricted randomisation to perform inference (Fortin and Payette 2002; Supplementary Material) using all plots (to understand overall treatment effects) and separately for plots only in the treated area. The restricted randomisation procedure accounts for possible within-transect effects of autocorrelation. We isolated plots only in the treated area to identify stand structure characteristics that explain variability in severity within the treated areas. Note that this was not conducted within the untreated-only plots because there was little variability in severity in untreated areas to be explained.

For the remotely sensed burn severity within 500 m of the treatment boundary, boxplots were used to compare among the treatment units the distribution of both dNBR and RdNBR. We performed a simple linear regression of burn severity (dNBR or RdNBR) predicted by distance to treatment boundary outside the treated area for each unit. The intercept of this model is an unbiased estimate of the expected burn severity at the treatment boundary. A significantly positive slope indicates that severity was reduced as the fire approached the boundary before entering the fuel treatment. This provides a description of the burn severity independent of the location of measurement transects.

Results

Pre-fire vegetation structure

In the measured transects, the untreated areas differed in species composition (Fig. 2), with transects in AP2 dominated by *Abies*, AP6 a mixed distribution of *Abies*, *Quercus*, *Pseudotsuga* and *Pinus*, and NU dominated by *Quercus* with a sizeable proportion of stems that could not be identified because of severe wildfire effects. The diameter distribution of *Quercus* in NU is smaller than that of AP2 and AP6. Fuel treatments modified species composition relative to the neighbouring untreated area. Across

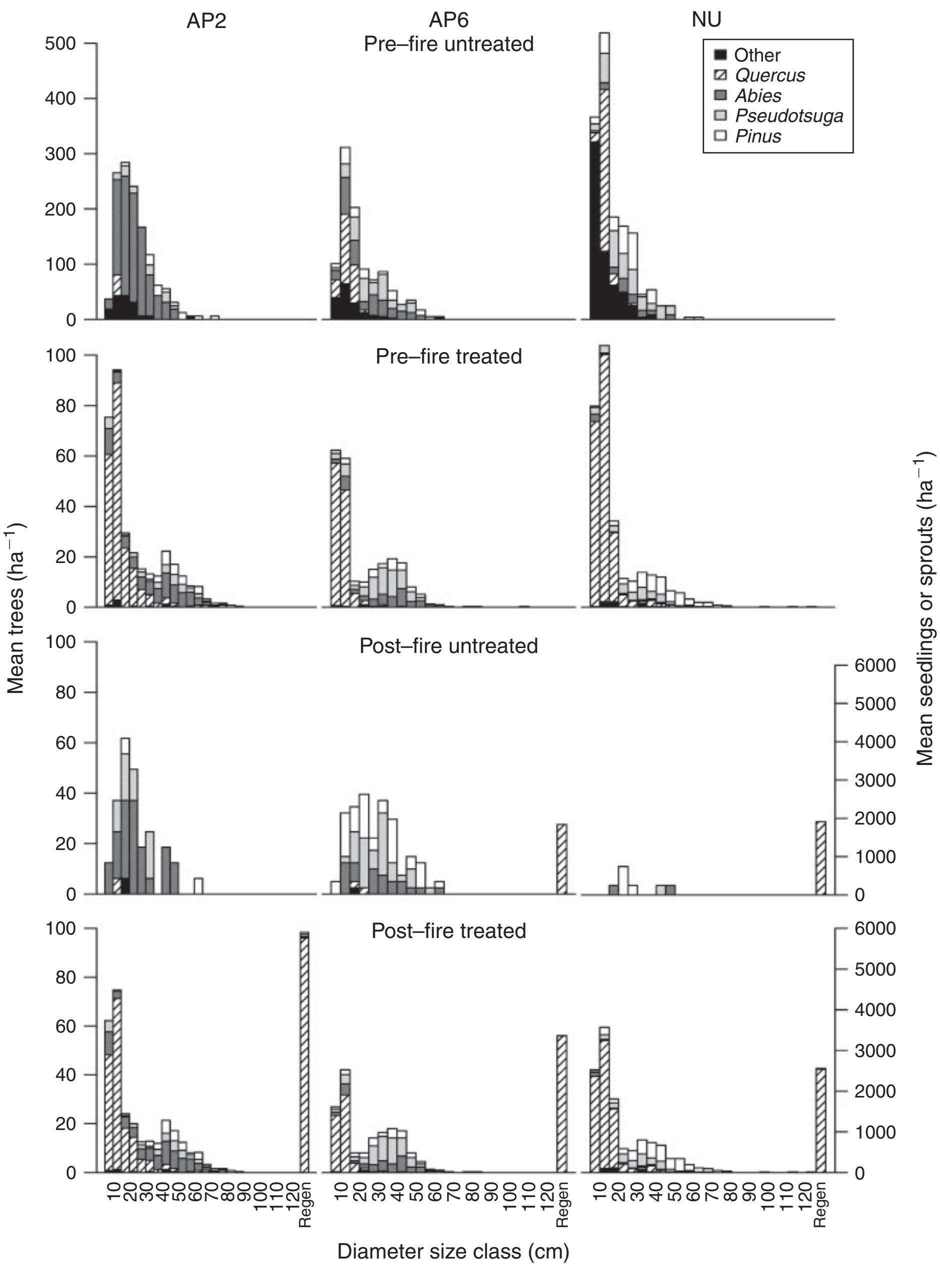

Fig. 2. Diameter distribution by species for untreated and treated forest, reconstructed pre-fire and post-fire (burn severity index, BSI $\leq$ 2). DBH (diameter at breast height) size classes of 5 cm, with the *x* axis labelled by the upper limit for every two size classes (e.g. 10 labels the upper limit for size classes (0,5) and (5,10)). Note the difference in *y* axis scales between post-fire untreated and the remaining graphs. Regeneration densities by species are given for post-fire distributions, on the right-hand side of the diameter axis.

all treatments, the proportion of *Quercus* stems increased relative to the untreated area (Fig. 2), resulting in a distinct peak of smaller, understorey *Quercus* in all three treatment units. In the treated areas, there was a second mode of larger trees in the diameter distribution (Fig. 2), with species compositions similar to those observed in the neighbouring untreated areas. In general, post-fire dead woody fuel loadings were very low (Table 2) although post-fire dead woody fuel loadings cannot be used to reconstruct pre-fire loadings.

In transects measured in all three treatment units, there were significant differences between measured plots in the treated area and measured plots in the neighbouring untreated area for all stand structure variables (Table 3). For all units, the mean value of the stand structural variables was greater in plots in the treated area relative to neighbouring plots in the untreated area, with the exception of CBH, which increased in the NU treatment relative to the neighbouring untreated area (Fig. 3). In NU, there was no significant difference in CBH within three plots of the

Table 3. Summary statistics, estimated coefficients and inference for all randomisation tests

See Table 1 for descriptions of each hypothesis. * $P \leq 0.10$; ** $P \leq 0.05$; *** $P \leq 0.01$. For hypothesis 1a, values are mean with standard deviation in parentheses, with significant differences between treated and untreated indicated. For hypotheses 1b and 1c, only significance of the randomised F-test is given, indicating significant differences among the treatment units. For hypotheses 2a–2b, only significant coefficients are reported with the level of significance indicated. Significant coefficients represent the change in $\log(p/(1-p))$ for a unit increase in the explanatory variable, where p is the indicated severity measure. Empty cells indicate no significant relationship. 'Trt only' indicates only plots in the treated forest were included. CBH, canopy base height (m); CBD, canopy bulk density (kg m^{-3}); QMD, quadratic mean diameter (cm); TPH, trees per hectare; CC, canopy closure (%); CS, crown scorch (proportion); BCR, bole char ratio; BSI3, proportion of stems at least partially consumed

Hypothesis	Units	CBH	CBD	QMD	TPH	CC
Stand structure	A2 All	1.46 (0.97)	0.26 (0.07)***	22.5 (2.3)***	1306.9 (560.3)***	59.1 (10.8)***
	A2 Trt only	1.56 (1.7)	0.07 (0.05)	15.8 (13.4)	337.9 (393.9)	23.8 (8.3)
1a	A6 All	0.91 (0.72)	0.15 (0.06)***	16.6 (6.8)**	1009.6 (442.5)***	49 (12.1)***
	A6 Trt only	1.29 (1.37)	0.04 (0.02)	12.2 (9.9)	230.8 (219.5)	16.6 (6.1)
	NU All	0.46 (0.27)***	0.18 (0.06)***	11.4 (3.9)	2560.9 (974.7)***	55.4 (7.5)***
	NU Trt only	1.83 (2.64)	0.04 (0.04)	10.4 (10.5)	313.2 (209.8)	17.6 (9.7)
1b	All units Trt only		***	**	**	***
1c	All units Untrt only	***	***	***	*	*
Severity	A2 All		8.4***	0.037**	0.002***	0.072***
CS	A6 All	−0.18*	22.7***		0.003***	0.06*
2a	NU All	−0.24***	10.7***	−0.064***	0.004***	
	A2 Trt only					
2b	A6 Trt only			−0.03**		
	NU Trt only	−0.22**		−0.06***	0.004**	
BCR	A2 All		11.2***		0.002***	0.09***
2a	A6 All	−0.15**	24.8***		0.002***	0.07***
	NU All	−0.18***	10.1***		0.002***	0.04***
	A2 Trt only					
2b	A6 Trt only			−0.01*		
	NU Trt only	−0.12**		−0.03*		
BSI3	A2 All		9.1***		0.001**	0.07***
2a	A6 All		20.5***		0.002***	0.06***
	NU All	−0.29***	12.6***	−0.03*	0.003***	0.05***
2b	A2 Trt only					
	A6 Trt only		24.1*			
	NU Trt only	−0.19*		−0.06***		

treatment boundary (Fig. S3; Table S2). In AP2, CBH increased 7%, CBD decreased 73%, QMD decreased 30%, TPH decreased 74% and canopy closure (CC) decreased 60% in the treated areas relative to the untreated. In AP6, CBH increased 42%, CBD decreased 74%, QMD decreased 25%, TPH decreased 77% and CC decreased 66% in the treated areas relative to the untreated. In NU, CBH increased 307%, CBD decreased 79%, QMD decreased 6%, TPH decreased 79% and CC decreased 67% in the treated areas relative to the untreated.

With the exception of CBH, there were significant differences in stand structure among transects grouped by treatment unit (Table 3). Cover, Density and CBD were highest in Alpine and lowest in NU (Fig. 3). We also found that CBD, Cover, CBH, QMD and Density of untreated areas differed significantly among the treatment units (Table 3). Cover, CBD, CBH and QMD were all highest in plots measured outside AP2 and similar among plots measured outside the AP6 and NU treatment units. Total Density was highest in the NU untreated area (Fig. 3).

Post-fire density, composition and regeneration

To estimate post-fire density and composition, trees with a burn severity index ≤2 were used. In the untreated area, post-fire density in measured transects was reduced relative to reconstructed pre-fire densities, with a similar diameter distribution and species composition (Fig. 2). Regeneration in the untreated area surrounding AP6 and NU was dominated by *Quercus* sprouts, with no notable regeneration observed in the forest surrounding AP2. Species composition and diameter distribution were similar in the treated area between reconstructed pre-fire and estimated post-fire measurements. We observed notable reductions in the density of stems in the smallest diameter size classes (Fig. 2) in the post-fire estimates relative to the pre-fire reconstruction. Regeneration within the treatment units was dominated by *Quercus*, with some mixed conifer (Fig. 2).

Fire severity related to pre-fire structure

In transects measured across all units and within untreated and treated areas, CScorch increased significantly with increasing CBD and Density (Table 3; Fig. 4). For AP2 and AP6, CScorch increased significantly with increasing Cover, and for NU, CScorch decreased significantly with increasing CBH. Results were mixed for CScorch and QMD, with a significantly positive coefficient found in transects measured in AP2, and a significantly negative relationship in transects measured in NU (Fig. 4). All other relationships with CScorch were

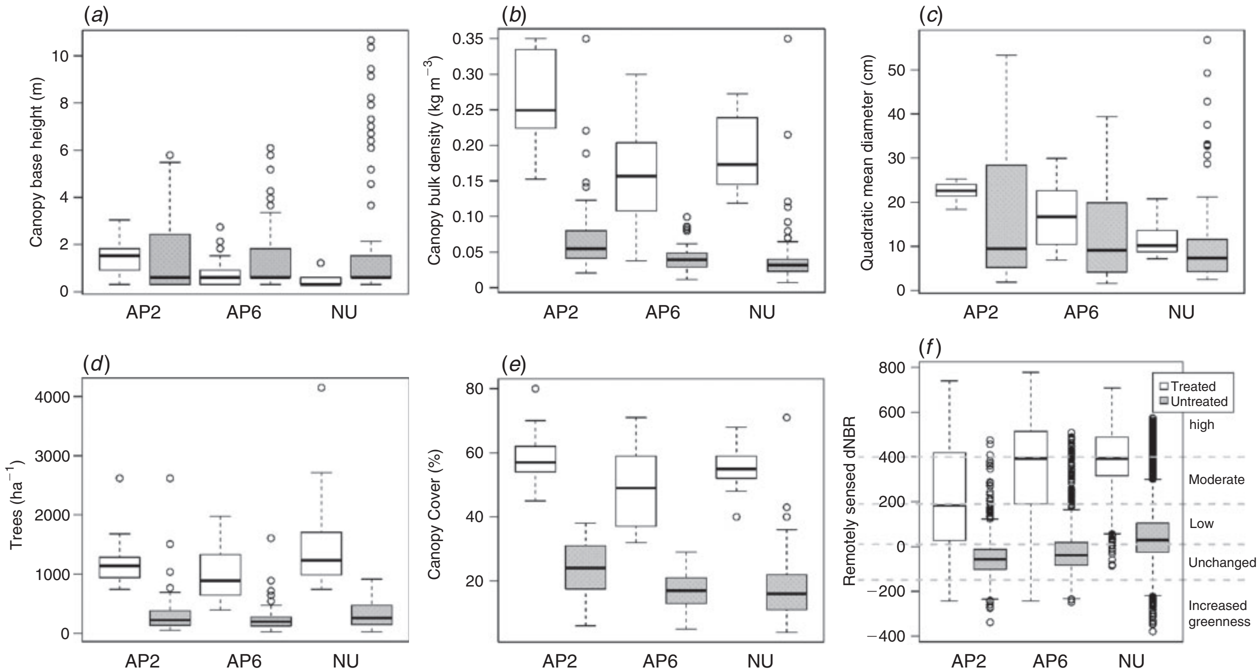

Fig. 3. (*a–e*) Distributions of reconstructed pre-fire vegetation characteristics comparing untreated (white) with treated (grey) among the three fuel treatment units. (*f*) Remotely sensed burn severity (dNBR, Differenced Normalized Burn Ratio) for untreated (within 500 m of the fire side of treatment edge) and treated pixels. Cut-offs for burn severity classifications are shown.

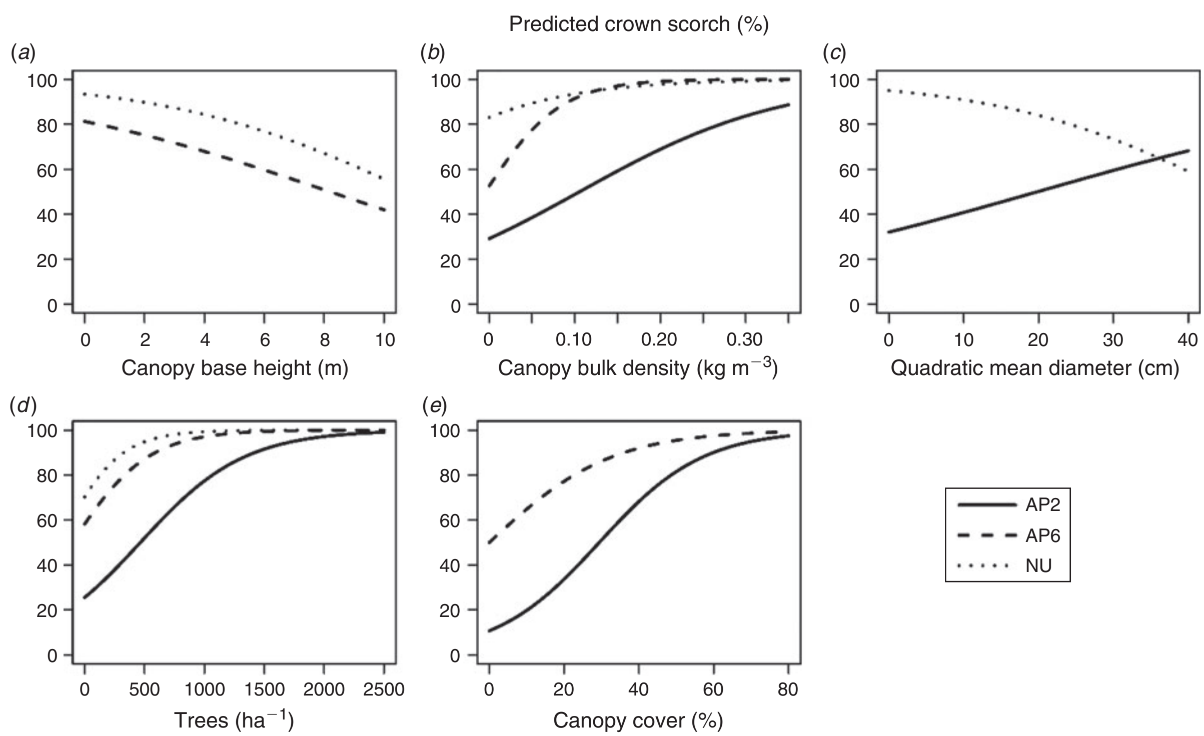

Fig. 4. Crown scorch (percentage), as predicted by each stand structural variable for each treatment unit (using all plots for prediction). Note that only coefficients deemed significant are pictured. Predicted curves for the other severity metrics are provided in Supplementary Material (Fig. S4).

Table 4. Linear regression slope and intercept of dNBR (Differenced Normalized Burn Ratio) related to distance from treatment edge on the fireside of the fuel treatment

The intercept is the expected value of dNBR at the treatment edge; the slope is the expected change in dNBR with increasing distance to treatment edge, with a positive slope implying dNBR is lower closer to the treatment edge and higher further from the treatment edge. Models are estimated with pixels within 500 m of treatment edge in untreated area on the fire side of the fuel treatment

Coefficient		Estimate	s.e.	*t*-statistic	p(*t*)
Intercept	AP2	66.8	9.33	7.16	<0.001
	AP6	350.4	11.6	30.2	<0.001
	NU	376.8	5.12	73.5	<0.001
Slope	AP2	0.58	0.03	19.0	<0.001
	AP6	−0.0087	0.04	−0.22	0.824
	NU	0.078	0.017	4.41	<0.001

non-significant. Similar results were obtained for maximum BCR and the proportion of trees with burn severity index ≥3, with a few exceptions (Table 3; Fig. S4).

Once the fire entered the treated area, fewer stand structure variables significantly predicted fire severity. For transects measured within the treated area of NU, all severity measures decreased significantly with increasing CBH and marginally with increasing QMD (Table 3, Fig. 4); CScorch increased significantly with increasing tree density. In transects measured within the AP6 treatment unit, CScorch and BCR both decreased with marginal significance with increasing QMD, and BSI3 decreased significantly with increasing CBD (Table 3).

Remotely sensed burn severity

We found no major differences in our conclusions when using dNBR or RdNBR, so we present results for dNBR here and give the results for RdNBR in the Supplementary Materials (Table S1; Fig. S2). Based on a comparison of fire severity within the untreated 500-m windward areas, the Wallow fire burned at comparable severity as it approached AP6 and NU and at lower severity as it approached AP2 (Table 4). A significantly positive relationship between dNBR and distance to treatment edge suggests that the fire had decreased in severity before reaching the treatment edge in AP2, and a smaller but significant slope for NU, with no detectable signal for AP6 (Table 4). For all treatment units, fire severity was lower within the treatment unit than it was within 500 m of the windward side of the treatment unit (Fig. 4), and remotely sensed burn severity was highest in the treated area of NU, second highest in AP6 and lowest in AP2.

Discussion

Fuel treatments are often designed to accommodate multiple management objectives (Reinhardt *et al.* 2008), so novel combinations of vegetation structure inevitably occur. Our study presents a new approach for retrospective evaluations of fuel treatment effectiveness. Consistent with other studies on fuel treatment effectiveness in the 2011 Wallow fire (Kennedy and Johnson 2014; Waltz *et al.* 2014), we found that fuel treatments reduced fire severity relative to untreated areas (Fig. 3*f*). Lower fire severity means increased tree survival and opportunities for fire suppression. Thinning prescriptions were designed to reduce hazardous fuels, potential crown fire behaviour and tree mortality, and to develop fuel conditions that would allow effective fire suppression (Sitko and Hurteau 2010). Kennedy and Johnson (2014) argued that the Wallow fire transitioned from an active crown fire in the untreated windward area to a surface fire in the fuel treatments, but that the distance into the fuel treatment at which that occurred differed among the fuel treatments. Here, we attribute those differences to variability in vegetation structure both inside and outside the fuel treatment.

Fuel treatment stand structure varies with prescription and existing stand structure

In the measured transects, we observed modified stand structure between the treated and untreated areas in ways consistent with the principles of a fire-safe forest (Agee and Skinner 2005; Table 3; Fig. 3). In the untreated units, the mean values of CBD were 0.26 (AP2), 0.15 (AP6) and 0.19 $kg\ m^{-3}$ (NU) (Table 4). In the treated area, mean CBD was reduced to 0.070 (AP2), 0.041 (AP2) and 0.040 $kg\ m^{-3}$ (NU; Table 4), well below the threshold considered to limit active crown fire behaviour (0.10 $kg\ m^{-3}$; Agee 1996). However, the resulting treated stand structures measured in our transects were not the same. This result is not surprising in the case of NU, which had a different stated treatment objective (to retain pockets of high density for wildlife habitat). In contrast, although AP2 and AP6 had the same stated treatment prescription, differences were detected between them in stand structure and species composition (Figs 2, 3), at least in the transects measured. This example shows that a given fuel treatment prescription is limited by the structure of the forest in which it is implemented (Table 3, Fig. 3). In California, Vaillant *et al.* (2015) found that differences in post-treatment structure between fire-only and mechanical treatments depended on the pre-settlement fire regime of the treated forest. Although Stephens and Moghaddas (2005*a*) found differences in post-treatment structure depending on the prescription, they did not find differences in species compositions when the pre-treatment forests showed no differences. Taken together, these examples have important management implications. When evaluating fuel treatment design, it is important to consider landscape context and existing vegetation structure (Stephens and Moghaddas 2005*a*; Stephens *et al.* 2009*a*).

In all three fuel treatments studied here, a common pattern regardless of prescription was the high density of small-diameter *Quercus* found in the treated areas (Fig. 2). *Quercus* sprouts vigorously following disturbance such as timber extraction and fire (Harper *et al.* 1985; Abella 2008; Abella and Fulé 2008), and even in treatments for which ladder fuels were completely removed, it is likely that the sprouting of *Quercus* contributed to increased density of ladder fuels over time in the treated area, therefore limiting fuel treatment longevity. Fuel treatment longevity is an important management consideration in planning and implementing fuel treatments. After initial fuel treatments, our data show follow-up fuel treatments such as prescribed fire will be necessary to maintain wildfire resilience. Historically, *Pinus* and *Quercus* forests are understood to have experienced frequent low-severity fire (Abella and Fulé 2008), and *Quercus* contributes to fire behaviour, with observations of crowning during low-intensity controlled burns (Harrington 1985). The benefits of *Quercus* for wildlife habitat and biofuels are also recognised (Harper *et al.* 1985); thus, when managing for multiple values, reducing the density of *Quercus* should be approached with caution.

Among the goals stated by the WMSC for fuel treatments are ecological restoration and facilitating the protection of residences in the WUI (Sitko and Hurteau 2010). The stand structure values we found in our three fuel treatments before the Wallow fire are consistent with the reference conditions found by Waltz *et al.* (2014) in the same forest, and our values for the neighbouring untreated area were consistent with their measurements of current forest conditions. However, the effectiveness of fuel treatments for ecological restoration should also take into consideration the structure of treated and untreated areas after wildfire (Stevens *et al.* 2014). For example, 5 years after the Wallow Fire, Springer *et al.* (2018) found higher cover of the establishment of native species in treated areas than in untreated areas. In our plots, we found that in the untreated areas of AP2 and AP6, the post-fire composition was similar to that pre-fire, with lower densities (Figs 2, 3). In the treated forest after the fire, we found evidence that *Quercus* can become a dominant component, at least in the understorey, with high densities of small-diameter *Quercus* and a strong pulse of *Quercus* regeneration via sprouting. However, the treated areas all retained some large mixed-conifer species, which may allow the forests in the treated area to persist as mixed conifer (Fig. 2). In different areas within the fire perimeter, 5 years after the Wallow Fire, Roccaforte *et al.* (2018) also found substantial regeneration of hardwood species and argued that the possibility of a pine-dominated forest converting to a woodland would be affected by the conditions before the fire and severity of the fire.

The treatment prescription in NU specified leaving clumps of smaller trees to provide habitat for focal species that depend strongly on forest structural characteristics. Among the transects that we measured, we found this thinning prescription to be manifest in a treated stand with a low CBH and QMD. These results suggest that such treatments may be able to produce resilient forest structures that maintain habitat even after wildfire, while still reducing severity sufficiently to satisfy overall goals for fire hazard reduction. Further study of such wildlife fuel treatments is warranted.

Variability in severity is explained by variability inside stand structure and neighbouring treatment units

In the measured transects, changes in stand structure between treated and untreated areas correlated significantly with reduced burn severity (Agee and Skinner 2005). Correlations between severity and structure metrics depended on within-stand characteristics and larger context (Stephens and Moghaddes 2005*a*). Where significant changes in structural metrics occurred, there was a corresponding detection of a relationship to severity (Fig. 3, Table 3). Within the treatment units, we found few significant relationships between structure and severity in our measured transects. In AP2, the mean severity was reduced very close (9–200 m) to the treatment boundary (Kennedy and Johnson 2014), so whatever variability in severity that remained inside the treatment area was likely small and not attributable to minor variability in stand structure. For AP6, in the measured transects, higher severity persisted further into the treatment unit (141–349 m), and within that unit, mean severity decreased significantly with increasing QMD. In NU, high-severity fire persisted much further into the measured transects in the treatment area (327–602 m); we found significant negative relationships between mean severity and CBH and QMD and a significantly positive relationship with Density. Given that reduced overall canopy fuels with CBD below the threshold are associated with higher probability in crown fire (0.10 kg m^{-3}; Agee 1996), variability in severity measured on the transects inside the NU treatment unit is explained by higher-density pockets of smaller trees (Methven 1973).

Considering the relationship between stand structure and severity within the treated area avoids confounding of relationships with overall treatment effects. This allows increased understanding of the impact of smaller-scale changes in stand structure on severity (Ziegler *et al.* 2017). An example of the confounding that occurs when considering all plots (treated and untreated) is the mixed results of QMD. In AP2, QMD decreased significantly between treated and untreated plots, explained by the large trees present in the untreated area and the high density of very small *Quercus* in the treatment unit (Fig. 2). Change in fuels led to a significantly positive relationship between QMD and severity in AP2 (Fig. 4), confounded by the treatment effects of the other canopy structure variables, such as the large reduction in CBD. However, when only treated plots were considered, the relationship between QMD and severity was negative in AP6 and NU. This result is consistent with findings from other studies where individual tree diameter was a strong predictor of survivorship after fire (Prichard and Kennedy 2012).

Although severity measures such as crown scorch and bole char are inconsistent proxies for fire behaviour and intensity (Cain 1984; Alexander and Cruz 2012), they tend to be strong predictors of individual tree mortality (Regelbrugge and Conard 1993; Ryan and Amman 1996; McHugh and Kolb 2003; Fowler and Sieg 2004; Sieg *et al.* 2006; Hood and Bentz 2007; Hood *et al.* 2007; Prichard and Kennedy 2012), and they are therefore good indicators of fire severity. Individual-tree mortality also decreases with increasing tree diameter (Prichard and Kennedy 2012), such that even if the overall CBH is raised and the CBD is reduced, the presence of smaller trees likely results in local increases in severity (Methven 1973) within the treatment area (Fig. 3, Table 3).

Our results suggest (i) that stand-level measures of vegetation structure may not be sufficient to assess treatment efficacy, and (ii) that individual stand characteristics and the spatial pattern of how those are implemented should also be considered in both empirical and simulation analyses (Ziegler *et al.* 2017). Stephens *et al.* (2009*b*) recommended various post-treatment targets depending on local knowledge and landscape context. Waltz *et al.* (2014) found that post-fire understorey communities are influenced by pre-fire composition. Stephens and Moghaddas (2005*a*) recommended considering individual stand characteristics to plan fuel treatments and to consider trade-offs in design. One trade-off that we documented here is that pockets of high severity can be expected in clumps of small trees that are retained for wildlife habitat, even when overall stand-level severity is reduced.

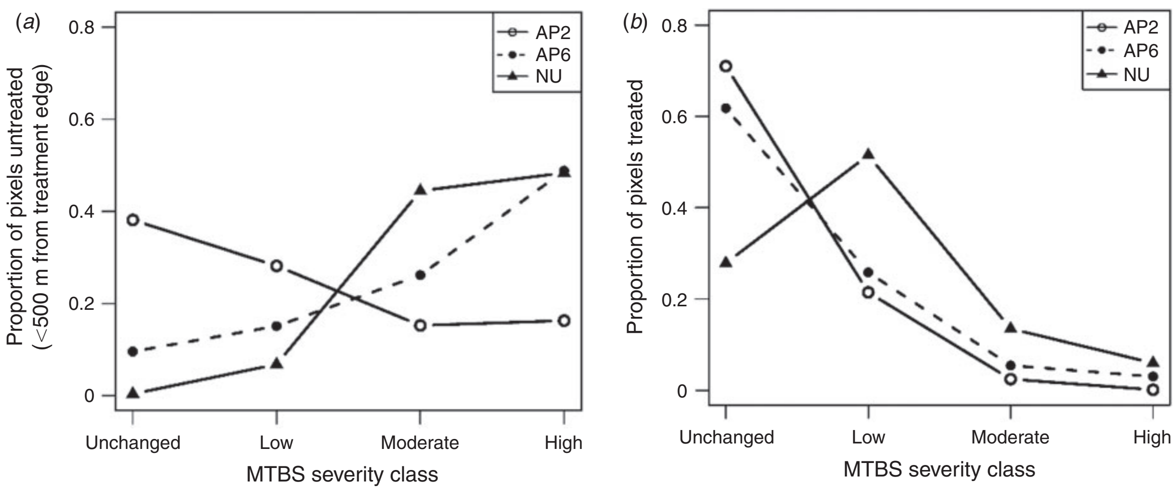

Fig. 5. Remotely sensed burn severity classifications for (*a*) untreated area within 500 m of the treatment edge, and (*b*) treated forest.

Landscape context and edge effects

We found evidence for the importance of edge effects in patterns of severity. With one notable exception (NU), for all stand structural metrics in all treatment units, the variables that change significantly between treated and untreated were detectable within 90 m (the first three plots) of the treatment edge. In NU, however, CBH did not change significantly within 90 m of the treatment edge (Table S2, Fig. S3). This response provides circumstantial evidence that the fuel treatment structure at the edge of the treatment boundary allowed the higher-severity fire to persist further into the fuel treatment, even though overall severity was reduced in NU. Through simulation, LaCroix *et al.* (2013) also found that fire spread was sensitive to changes to fuel dynamics at edges in a fragmented forest.

It is possible that edge effects just outside a fuel treatment can modify fire severity at the border of a fuel treatment (Ritchie *et al.* 2007), with radiant heat from the incoming fire causing high-severity fire effects inside the treated forest. In the transects measured in our study, we found significant differences in forest structure neighbouring the treatment units (Fig. 3, Table 3) that corresponded to differences in fire severity in the untreated area neighbouring each treatment unit (Fig. 3*f*). Kennedy and Johnson (2014) found that the fire severity in AP2 dropped very close to the treatment boundary, and here we found that AP2 had the lowest proportion of pixels classified as high severity in the neighbouring untreated area (Fig. 5), and the highest proportion of pixels classified unchanged in the neighbouring untreated area (Fig. 5). These classifications based on remotely sensed severity are fairly arbitrary (Kolden *et al.* 2015) and are not necessarily appropriate to compare severity between wildfires. However, they do give a relative measure of fire severity in a given wildfire. We also found evidence that the remotely sensed burn severity was decreasing as the fire approached the AP2 fuel treatment (Table 4).

Overall landscape context is important in fuel treatment design (Agee *et al.* 2000), where, for the same fuel treatment prescription, different fire severity can be observed depending on how the fire enters the fuel treatment. The stated fuel treatment prescription of AP6 was the same as AP2, yet AP6 experienced higher severity inside the treated area than AP2. This difference corresponds to higher severity fire in the untreated area neighbouring AP6 (Fig. 4), with no indication that remotely sensed burn severity decreased as the fire approached the AP6 fuel treatment (Table 4). For the NU fuel treatment, the forest both neighbouring and inside the fuel treatment experienced high severity relative to the other treatment units (Table 1), with stand structure metrics that corresponded to higher severity (Fig. 3; Table 3). These results provide preliminary evidence that the stand structural characteristics in untreated areas outside the treatment unit are likely to impact fire severity within the fuel treatment.

Limitations

We acknowledge several limitations to this study. We were limited by our access to only post-fire observations, which we used to infer pre-fire stand conditions. We were unable to account for important components of the fuelbed related to fire severity: pre-fire loading of dead woody fuel, shrub and non-woody vegetation. Our analysis offers an incomplete picture of the fuelbed effects on fire severity (Agee and Skinner 2005; Peterson *et al.* 2005).

We relied on FFE-FVS to estimate stand structure metrics, from a tree list generated from the stems we assumed to be living before the wildfire. Although any reconstruction of past structure not based on direct observation is subject to additional uncertainty, our stand structural metrics are consistent with those estimated in a similar dry conifer forests (Waltz *et al.* 2014), which lends confidence to our reconstruction.

Given these limitations, our conclusions are restricted to canopy structure and composition, as well as to surface fuel data collected after the wildfire (Table 1), with the understanding that unobserved differences in surface fuels may further explain the variability seen in fire severity. Nevertheless, we were able to detect significant relationships with canopy structure that explain the observed variability in the severity of the Wallow fire. We made no attempt to quantify pre-fire conditions of dead and down woody fuel surface components post hoc, because those components that contribute most to surface fire spread are consumed in most fires (Ottmar *et al.* 1993).

Any retrospective investigation of fuel treatment effectiveness would be prone to a biased sampling design, because *a priori* randomisation is not an option (Pollet and Omi 2002). In the present study, the chosen treatment units are not a representative random sample of all treatment units within the fire perimeter, and within each treatment unit, the transects cannot be considered representative random samples of each individual treatment unit. We use the treatment units to group the transects, and all summary statistics and estimated relationships between stand structure and severity are unbiased descriptions for those sets of transects. It would be inappropriate to assume that these summaries represent conditions across the entire treatment unit, or for other treatment units in the same wildfire.

Finally, fire behaviour dynamics as the fire transitioned into the treatment areas could not be explained. Our results show that burn severity (based on the burn severity index) decreased as the fire approached the fuel treatment boundary in AP2. We cannot explain this phenomenon and acknowledge fire–weather dynamics at the treatment edge may have influenced fire severity. As the Wallow fire descended into the Alpine and NU fuel treatment areas, a change in fuel moisture, wind speed, topography or vegetation composition could have influenced fire behaviour, causing this observed reduction in burn severity. The transition from steep slopes (untreated areas) to low slopes (treated areas) may have influenced fire spread and therefore changed fire behaviour as the fire entered the fuel treatment areas. Similar studies (Safford *et al.* 2009; Kennedy and Johnson 2014) documented similar responses. To potentially understand fire dynamics and fuel treatment edge effects, physics-based fire models such as the WUI Fire Dynamics Simulator (WFDS) could be used to recreate the fuelbed and fire weather conditions (Mell *et al.* 2010). Despite these limitations, our study results are consistent with other studies on fuel treatment effectiveness (Fulé *et al.* 2012).

Management implications

Our quantitative analysis of post-treatment stand structure and burn severity has implications for our understanding of treatment effectiveness and forest management in a larger context. This opportunistic event provides additional real-world evidence on the efficacy of treatment effects in changing wildfire behaviour. The results from our study and Kennedy and Johnson (2014) will help inform managers on fuel treatment size and thinning prescription development. The linear transects extending from the untreated area through the treated area inform effective fuel treatment size required to accomplish specific management objectives. The fuel treatment area in the NU shows the potential consequences of managing for multiple resources. These study results validate the guidelines for developing effective fuel treatments in the western United States (Agee and Skinner 2005) and they indicate a shift in focus to landscape-level strategies to improve overall fuels management. Empirical assessments of fuel treatment effectiveness help forest managers prepare future National Environmental Policy Act (NEPA) documentation for projects involving hazardous fuels treatments and can help managers communicate management objectives of fuel treatments to the public and policymakers. Our study results provide essential information on fuel treatment effectiveness under wildfire conditions between control and thinned treatment areas, providing an opportunity to communicate with stakeholders about treatment effects on fire severity (Fulé *et al.* 2012). There was not total public support for fuel treatments in WUI communities before the Wallow fire. These study results may improve social acceptability for fuel treatments, emphasising the importance of fuel treatments for protecting homes in the WUI (Shindler 2002).

Conclusions

The approach taken by this study advances our understanding of fuel treatment effectiveness beyond simple classifications of treatment type and binary comparisons of mean severity in treated vs untreated areas. As multiple objectives are increasingly incorporated into forest management decision-making (Lehmkuhl *et al.* 2007), further studies that report stand structure metrics in addition to relative severity and fuel treatment prescriptions will help inform fuel treatment design. As post-treatment structures are documented (Roccaforte *et al.* 2015; Vaillant *et al.* 2015), when these structures encounter wildfire they can be used to better quantify the relationship between fuel treatment design and fire severity.

The performance of a fuel treatment in modifying fire severity is likely a complex interaction of the post-treatment stand structure and the expected fire behaviour in the neighbouring untreated area. Fire severity exhibits significant residual autocorrelation even when the effects of fuel treatments are included in a statistical model (Wimberly *et al.* 2009; Prichard and Kennedy 2014; Kennedy and Prichard 2017). However, without a fuel treatment encountering a wildfire, assessments of fuel treatment design tend to rely on simulation models that compare estimated fire behaviour in a given stand before and after the simulated fuel treatment, usually under extreme environmental conditions (Stephens and Moghaddas 2005*a*; Stephens *et al.* 2009*a*; Johnson *et al.* 2011). Such analysis ignores the contagious effects of fire behaviour on fire effects as the fire spreads from the untreated area to the treated stand. Regardless of the predicted effectiveness of the fuel treatment when considered in isolation (Ritchie *et al.* 2007), it is possible that a treated stand may experience high severity in extreme fire weather conditions.

As the wildfire moves from the untreated area into the fuel treatment, the fuelbed structure near the edge of a fuel treatment may affect the spatial pattern of the fire's severity (LaCroix *et al.* 2013). Quantifying such edge effects, by relating spatially explicit analysis of fire severity to forest structure variables, will also aid in planning the spatial detail and the size of a fuel treatment prescription (Safford *et al.* 2009; Kennedy and Johnson 2014). Fuel treatment planning will benefit from spatially explicit modelling efforts (Ziegler *et al.* 2017) that incorporate these edge effects and spatial autocorrelation in fire severity.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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