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Surface fuel treatments in young, regenerating stands affect wildfire severity in a mixed conifer forest, eastside Cascade Range, Washington, USA

Christina Lyons-Tinsley [a,*], David L. Peterson [b]

[a] Fire and Mountain Ecology Laboratory, School of Forest Resources, University of Washington, Box 352100, Seattle, WA 98195-2100, USA
[b] USDA Forest Service, Pacific Northwest Research Station, 400 N. 34th St., Suite 201, Seattle, WA 98103, USA

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ABSTRACT

Previous studies have debated the flammability of young regenerating stands, especially those in a matrix of mature forest, and no consensus has emerged as to whether young stands are inherently prone to high-severity wildfire. This topic has recently been addressed using spatial imagery, and weak inferences were made given the scale mismatch between the coarse resolution of spatial imagery and the fine resolution of mechanisms driving fire severity. We collected empirical stand and fire-severity data from 44 regenerating stands that are interspersed in mature, mid-elevation forests in the Okanogan-Wenatchee National Forest (OWNF) on the eastside of the Cascade Range in Washington, USA. These stands are mixed-species plantations that were established to promote regeneration of seral to late-seral tree species (Douglas-fir, subalpine fir, Engelmann spruce, western larch) in small patches within a larger lodgepole pine forest. In 2006, the 70,925 ha Tripod Fire burned through all the plantations and the surrounding lodgepole pine matrix. To understand what drives fire effects in plantations, especially those that exist in spatially heterogeneous forests, we compared fire severity in plantations with and without fuels-reducing site preparation (i.e., fuel treatments), using three metrics to quantify severity: mortality (%), exposed mineral soil (%), and char height (m). We built generalized linear models for each severity metric and tested for a difference in all severity metrics between treated and untreated units using Permutational Multivariate Analysis of Variance. Units without fuel treatments have more severe fire effects: mortality is 77% in untreated units and 37% in treated units ($p = 0.0005$). Other variables contribute to differences in fire severity, including species composition, canopy closure, and canopy base height. Canopy base height and canopy closure both exhibit a reverse relationship with mortality from what was expected: the higher the canopy closure and the lower the canopy base height, the lower the mortality. In other words, stands that have trees closer together with crowns near the ground are more likely to have lower mortality. Overall, the results suggest that young stands in some dry mixed conifer forests can be resilient to wildfire if surface fuel loading is low upon stand establishment.

1. Introduction

Interior dry forests in western North America are potentially vulnerable to changes in disturbance regimes due to past land management and a warming climate. Increases in fire frequency and area may occur (McKenzie et al., 2004) as a result of current fuel loadings and changes in spring temperature (Westerling et al., 2006). More regionally specific, forest assessments in the eastern Cascade Range indicate that wildfire hazard on national forests in the United States has increased (USDA FS, 2004). Other forest disturbances, including insect and pathogen outbreaks, are expected to increase in the eastern Cascade region as well, which would further increase fire hazard (Hessburg and Flanagan, 1992). Increased forest disturbance, combined with predicted changes in the distribution and abundance of species, have led to more consideration of how larger landscape (e.g., watersheds, national forests) processes interact with disturbance (Bachelet and Neilson, 2000; Dale et al., 2000). Collaborative assessments of the eastern Cascades suggest active forest management, including thinning and prescribed fire, as an effective way to modify the hazard caused by wildfire, insects, and disease (Everett et al., 1994; USDA FS, 1996). Furthermore, managing forest landscapes at large spatial scales is necessary to adapt to a warmer future climate and potentially new forest structures and conditions (Millar et al., 2007; Joyce et al., 2009). Landscapes with multiple species assemblages, age classes, and structures are expected to be more resilient to increased disturbance than large homogeneous areas (Blate et al., 2009; Joyce et al., 2009).

* Corresponding author. Tel.: +1 206 543 9138 (Off.), mobile: +1 530 903 2552; fax: +1 206 685 0790.

E-mail addresses: ltinsley@u.washington.edu (C. Lyons-Tinsley), peterson@fs.fed.us (D.L. Peterson).

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Reducing the amount and continuity of surface fuels, both live and dead can decrease fire hazard and the probability of crown fire initiation (e.g., Agee and Skinner, 2005). Initiation of a crown fire is a function of surface fire intensity and canopy base height (Van Wagner, 1977), and fuel treatments decrease crown continuity and fuel loading (Rothermel, 1983; Peterson, 1985). Fuel treatments designed to mitigate fire spread and severity can include a combination of tree harvest and prescribed fire or other means of surface fuel removal. Specifically, effective fuel treatments can (1) reduce the surface spread of fire by removing fine fuels (Agee and Lehmkuhl, 2009), (2) reduce ladder fuels and inhibit vertical spread of fire by thinning from below or whole tree harvesting (Agee and Skinner, 2005; Raymond and Peterson, 2005; Stephens and Moghaddas, 2005), and (3) reduce canopy bulk density and raise canopy height (Peterson et al., 2005; Johnson et al., 2006). In young stands, site preparation conducted upon stand establishment can have long-lasting effects on fuel characteristics and fire severity. Lezberg et al. (2008) found that 21 year old pine plantations that had been scarified burned at lower severity than unscarified stands. In this study, site preparation was more important than harvest regime in determining fire severity. Site preparation broadcast burns are similar to fuel treatments, in that they remove fine surface fuels. These principles of fuel mitigation have been established mostly in forests with low-severity fire regimes, and their application in mixed-severity (Thompson et al., 2007) and high-severity fire regimes is less clear.

Compared to low-severity fire regimes, mixed-severity fire regimes by definition have a wider range of variability in fire severity and frequency, which can complicate management prescriptions (Agee, 1993). Variability in these landscapes is caused by spatial and temporal variations in species composition and forest age, which affect fuel loading, fire behavior, and response to disturbance (Hessburg et al., 2007). The 2002 Biscuit Fire (200,000 ha) in the Klamath-Siskiyou region of Oregon has been studied extensively as a key example of mixed-severity fire regimes. Raymond and Peterson (2005) examined fire effects in mature mixed-evergreen hardwood stands in the Biscuit Fire and found that (1) forest thinning followed by surface fuel removal with prescribed fire was effective in reducing fire severity, and (2) thinning without fuel reduction increased fire severity. One study suggested that the lack of vertical diversification in young stands makes them inherently vulnerable to fire, and that forest management may cause these young stands to burn at higher severity (Thompson et al., 2007). Variability in species composition, fuels, and fire effects in the Biscuit Fire has raised questions regarding mechanistic controls on patterns of fire behavior in mixed-severity fire regimes.

To understand fire patterns in complex landscapes, more empirical data are needed to address fire severity in young stands, especially because of their prevalence in forests of western North America. Spatial imagery has been used to investigate fire in young stands, but the resolution of the data has made it difficult to describe stand structure or surface fuels because of the difference in spatial scale between coarse-resolution imagery and fine-resolution surface fuels (Thompson et al., 2007). In young stands, surface fuels are a combination of downed woody fuels and live fuels (shrub or canopy), and existing live fuel layers can provide connectivity between surface fuels and the canopy. Without pre-fire fuel data, it is difficult to address the role of down woody fuels and shrubs on fire behavior, but the live fuel component can be addressed through *post hoc* reconstructions of live tree structure. Live fuel reconstructions are most easily done in ecosystems that do not have a significant shrub layer (e.g., high elevation forests). Absence of fuels information limits inferences from data collected following wildfires, but information on presence or absence of surface fuel treatments offers some insight regarding fuels.

Fig. 1. Green areas are patches of regenerating forest in a high- severity area of the Tripod Fire.

In this study, we quantified fire effects in mixed species plantations of the eastern Cascade Range of Washington, USA. These plantations burned in the Tripod Complex Fire (hereafter Tripod Fire) in 2006. Fire behavior was not uniform across the landscape, leaving green "islands" where vegetation was almost entirely unburned (Fig. 1). In high-severity areas, green patches often coincided with harvested areas including diverse fuel treatments and regeneration cuts (i.e., small clearcuts with young regenerating forests) that were conducted before the Tripod Fire; some of the plantations contained fuel treatments with prescribed fire that were also done before the wildfire. The contrast between the green islands and the surrounding burned areas exhibited a difference in fire effects that may have been influenced by management practices (Fig. 1).

We were interested in examining the mechanisms that controlled fire severity in the plantations. To test these observations we posed two questions to explain fire effects in young stands: (1) do fuel treatments reduce the severity of fire effects in regenerating stands? and (2) do species composition and stand structure influence fire severity? These questions were investigated in plantations across a large extent of the Tripod Fire, thus capturing variability in site characteristics, fire weather, and fire behavior during the fire.

2. Methods

2.1. Site description

The study was conducted in post-harvest mixed conifer stands in the Okanogan-Wenatchee National Forest (OWNF) on the eastern slope of the Cascade Range, Washington (Fig. 2). This region is characterized by cold winters and warm, dry summers with summer droughts. The nearest Remote Automated Weather Station, First Butte (48 °N, 120 °W, elevation 1674 m), has recorded a mean annual temperature of 15.1 °C, with a January minimum temperature of −11.6 °C and a July maximum temperature of 30.1 °C (Western Regional Climate Center, http://www.wrcc.dri.edu, data recorded between 1931 and 2005). Mean annual precipitation is 3600 mm, with 70% of precipitation falling between October and March, predominantly as snow.

In these watersheds, active land management has affected the spatial and temporal distribution of species assemblages and disturbance regimes on the landscape. Current management

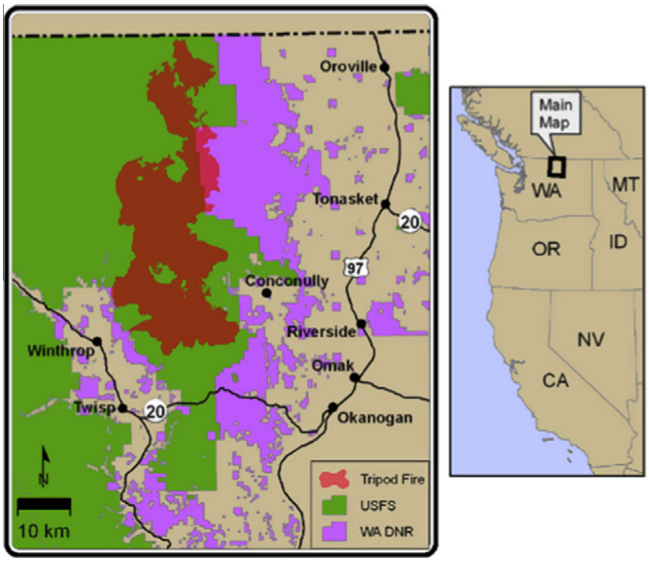

Fig. 2. Map of study area.

objectives of the OWNF are to (1) reduce stand density, (2) alter species composition to pre-settlement conditions (e.g., convert lodgepole pine [*Pinus contorta* subsp. *latifolia*] stands to mixed conifer stands), (3) reduce fuel loads to pre-settlement conditions, (4) replant forest openings created from harvest operations, and (5) maintain forest structure and fuel levels consistent with historical fire regimes (USDA FS, 2000). Consistent with management objectives, clearcut stands throughout the OWNF have been replanted to obtain stand densities much lower than present and alter species composition to pre-settlement conditions.

Lodgepole pine is the most common species at this elevation, but Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) are often found in the upper edge of the elevation range (Franklin and Dyrness, 1988). The distribution of lodgepole pine usually depends on disturbance regime, as indicated by the heavy presence of lodgepole pine in post-fire and harvested areas. Engelmann spruce and subalpine fir often occupy a smaller percentage of the growing space than lodgepole pine because of the competitive success of lodgepole pine following disturbance (Agee, 1993; Little et al., 1994). Tree regeneration after disturbance results in patches of vegetation with varying species distributions and abundance.

The vegetation mosaic combined with local topography and climate has created a mixed severity fire regime in this area. Mixed severity fire regimes occur in areas of the interior Pacific Northwest where wildfires occur with moderate frequency (fire return interval [FRI] of 25–100 years) and result in 20–70% basal area mortality (Hessburg et al., 2005). The fire regime varies by elevation, associated with differences in dominant tree species. Low-elevation ponderosa pine (*Pinus ponderosa* var. *ponderosa*) forests are classified as dry interior forests and have point-level FRIs of 11–37 years (Hessl and Peterson, 2004, Hessburg et al., 2005), whereas the mid to high elevation lodgepole pine forest is characterized by mixed severity fires (Agee, 1993, Hessburg and Agee, 2003).

The study units are post-harvest, regenerating stands located in mid- to high-elevation (1420–2020 m) cold, dry mixed-conifer forests dispersed throughout the lodgepole pine-dominated forest and extending into the subalpine fir-dominated forest of the Tripod Fire (Fig. 3). Species include lodgepole pine, Engelmann spruce, subalpine fir and western larch (*Larix occidentalis*). Most stands were in mid- to high-elevation sites above 1200 m to convert lodgepole pine stands to mixed conifer stands. Relatively moist soil

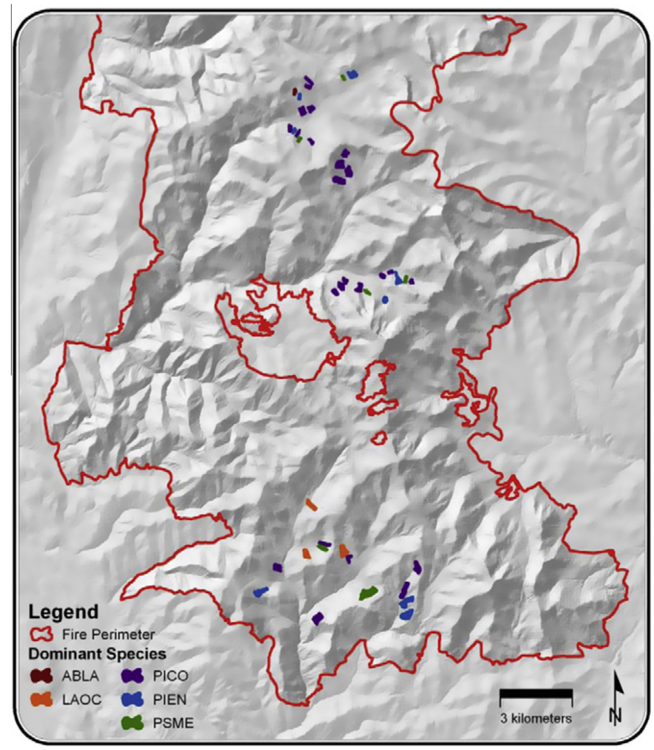

Fig. 3. Map of sample unit distribution and dominate species of each sample unit across the Tripod Fire.

conditions at the higher elevation sites has encouraged in-growth of riparian vegetation, including mountain alder (*Alnus viridis* subsp. *sinuata*), quaking aspen (*Populus tremuloides*), black cottonwood (*Populus balsamifera* subsp. *trichocarpa*), and willow (*Salix* spp.). No schlerophyllous shrubs are found in the regenerating units due to the cold climate. All of the regeneration units in the study were 10–30 years old at the time of the Tripod Fire. Some units were broadcast burned after the initial harvest and before the trees were planted, therefore stand age and time since treatment are the same. Hereafter, units that received a broadcast burn are referred to as "treated" and units that did not receive a broadcast burn as "untreated". Broadcast burns were conducted when funding allowed, resulting in a mix of treated and untreated stands across the landscape. It is important to note that these stands were initially established as mixed species plantations, but subsequent in-growth has resulted in more complex age and species structures than are commonly seen in plantations.

2.2. Tripod Fire conditions

All regeneration units burned under the following scenario. On 3 and 24 July 2006, lightning storms ignited two fires on the OWNF, which ultimately joined and became the Tripod Complex Fire. The fire burned 70,925 ha, of which 95% was in the OWNF. Fire suppression activities were extensive, including over 370 km of constructed fire line. The fire was contained on 31 October 2006 and was completely out by 1 December 2006. Over 60% of the Tripod Fire area was classified as moderate to high severity (Tripod Salvage Environmental Impact Statement 2008, Methow Valley Ranger District). The study units burned on seven nonconsecutive days. Averaged among the seven days, maximum temperature was 32.8 °C, mean temperature was 23.5 °C, relative humidity was 29.2%, 10 h fuel temperature was 26.6 °C, and wind speed was 3.8 km h^{-1} out of the north/northeast. During the seven days, the weather was relatively consistent, starting on the first day with less severe fire weather and reaching maximum fire danger a few weeks later and staying consistent for the remaining time (Appendix A).

2.3. Field sampling

Selection criteria required that each sample unit (1) have management history data that included pre-harvest species composition, fuel treatment plans and completion date, and planting density and species composition, (2) be located in an area with high-severity fire on at least three sides, especially the downhill side, and (3) have no evidence of fire suppression, including the use of activity burning (back burns). We sampled at least 5% of the total area of each unit, because in pilot sampling this proportion yielded a sufficiently low coefficient of variation (determined by the number of plots at which the coefficient of variation approached an asymptote) for tree diameters and height, tree density, and canopy closure.

Systematic random sampling was used to establish plots within both treated and untreated units. We started with a random point for the first plot and used either a 40 or 60 m grid depending on unit size for all subsequent plots (i.e., in larger units we used the 60 m grid to cover the whole unit). Each circular plot was 0.03 ha. The total sample size was 339 plots from 44 units.

2.3.1. Forest structure and fire damage

All forest structure variables were measured as reconstructions of pre-fire conditions. Because of the low intensity of fire in most units, tree characteristics were easily reconstructed; even dead trees still had brown foliage. All trees $\geqslant 2.5$ cm basal diameter were sampled in every plot. For each tree, we recorded basal diameter, height, height to crown base, species, live/dead status, and char height. Other traditional damage measures (e.g., foliage consumption, percentage of crown scorched) were not informative in these units, because trees were almost always either 0 or 100% scorched. Canopy closure was estimated on two 20 m planar transects, where we recorded percentage of total line covered in canopy. In each plot, we performed an ocular estimate of the percentage of exposed mineral soil.

2.3.2. Surface fuels

All surface fuel measurements were taken after treatment and exposure to wildfire. No data on pre-treatment or pre-wildfire fuels were available. Fine fuel and coarse woody debris measurements were taken using the planar transect method (Brown, 1974), with at least 365 m of line in each unit regardless of unit size. Fine fuels are defined by time-lag class, where 1 h fuels are 0.0–0.6 cm, 10 h fuels are 0.6–2.5 cm, and 100 h fuels are 2.5–7.6 cm in diameter. Coarse woody debris is defined as 1000 + h fuels, which is all downed wood >7.6 cm in diameter. One hour and 10 h fuels were measured along 3 m transects, 100 h fuels were measured along 6 m transects, and 1000 h fuels were measured along 20 m transects.

2.4. Data analysis

2.4.1. Data preparation

Three variables were used as metrics of fire severity: percentage of tree mortality (hereafter mortality), basal char height (m; hereafter char), and percentage of exposed mineral soil. To predict fire severity, we built two separate models at the unit scale, one that predicted mortality and one that predicted char. We did not build an individual model for percentage of exposed mineral soil because of the qualitative nature of this ocular estimate. To determine the appropriate model for mortality and char, we examined diagnostics of the model residuals for normality using Q–Q plots and Cook's distance for influential outliers. Mortality and char data had different distributions, so we used a different type of regression for each model. Mortality had a binomial distribution, so we used a generalized linear model (GLM) with a logit link. Char had a lognormal distribution, so linear regression with a log-transformed response was appropriate.

The predictor variables had the potential to influence fire severity at multiple spatial extents. Plot-scale observations indicated that fire effects depended on where plots were located in the unit, and edge plots appeared to exhibit higher fire severity. Because of this visible difference, we also built models at the plot scale in which we included plot distance to unit edge as a predictor variable to determine if spatial location within a unit influenced fire severity.

We used Wilcoxon signed rank tests to test individual parameter differences in treated and untreated units.

2.4.2. Mortality model

We used a GLM of the binomial family to estimate the probability of mortality in a given unit as a function of (1) abiotic variables (i.e., elevation, slope, aspect), (2) biotic variables representing stand and tree structure, stand age, and species composition, and (3) day of burning (Appendix B). The analysis was conducted using R 2.8.1 (open source software, http://www.r-project.org). We used a GLM to perform an analysis of covariance using a backward stepwise elimination approach, where the response variable was a proportion of live to dead trees in a unit, and the predictor variables included the treatment effect as a factor and all others as continuous variables.

We used several criteria to build the most parsimonious model. For each independent variable, we performed a likelihood ratio test with a chi-square test statistic ($\alpha = 0.05$). Every independent variable yielded a significant value using the chi-square distribution, so we shifted our emphasis to percentage of deviance explained (PDE) by each variable in a given model. Each variable needed to explain at least 5% of the total model deviance by itself. To avoid collinearity, we applied the variance inflation factor (VIF) to account for the large variances that often result from correlated predictors. If a variable had a VIF >3, we used backwards elimination to eliminate the variable that explained the least deviance and then tested the VIF again.

We used several selection criteria to compare full models and models with and without interactions. To test goodness of fit, we tested the residual deviance against a chi-square distribution with the remaining degrees of freedom from the full model in a classic analysis of variance (ANOVA) approach (Zar, 1999). After closer investigation, it became clear that the chi-square distribution did not suffice because of the over-dispersion of the data, so we used an F-distribution instead. A non-significant *p*-value suggests that the model explains enough of the total deviance (i.e., little deviance is unexplained). We also used the Akaike Information Criterion (AIC) to re-examine goodness of fit. AIC is a measure of the tradeoff between bias and variance in the model; the model yielding the lowest AIC is the best fit model. Finally, we calculated the PDE for each model (1 − (residual deviance/null deviance)), which is roughly equivalent to an R^2 in a regression model. The model with a non-significant *p*-value, the lowest AIC, and the highest R^2 was chosen as the most parsimonious model to predict mortality.

2.4.3. Char model

We used a linear regression model to predict char height as a function of the same set of predictor variables as for the mortality model in a given unit. Again, we used backward stepwise regression with treatment effect as the factor and the remaining variables as covariates. Each variable was tested against an *F*-distribution for significance ($\alpha = 0.05$). Model goodness of fit was tested against an F-distribution ($\alpha = 0.05$). We retained the more complex model if the additional variable significantly improved the model fit. The full model and the model with interactions were tested in the same manner as the mortality model.

2.4.4. Treatment effect

Because treatment effect was always the strongest predictor of fire severity, we further examined the relationship between fire severity and treatment unit using a Permutational Multivariate Analysis of Variance (PERMANOVA) and then visualized these data with Non-Metric Multidimensional Scaling (NMDS; Anderson, 2001; McCune and Grace, 2002). We used R 2.8.1 for all analyzes. Specifically, we used two functions in the vegan package (open source software, www.vegan.r-forge.r-project.org): adonis for PERMANOVA and metaMDS for NMDS and adjusted parameters accordingly. Using a PERMANOVA, we were able to combine mortality, char, and exposed mineral soil in a multivariate analysis with treatment as the predictor variable. PERMANOVA has no assumptions regarding data distribution, so raw data were used. We created a response matrix with all three severity variables and relativized the data by maximum. From the severity matrix we calculated a distance matrix using the Euclidean distance measure, which is the standard measure for continuously distributed data with few zeros (McCune and Grace, 2002).

2.4.5. Plot-scale edge effects

To analyze within-unit variation at the plot scale, we looked at how distance to unit edge influences fire severity. To determine plot distance to edge, we used ArcGIS 9.1. First, we created a new polygon around the existing treatment unit polygons and joined the two layers together. Second, we deleted the layer containing the treatment unit polygons in order to be able to calculate the distance from a plot to the nearest polygon edge (the edge of the polygon drawn around the treatment units). Lastly, we created a Euclidean distance grid at 5 m resolution that triangulated distance from a given plot to the nearest polygon edge. The plot distance to edge was then added as a covariate in two regression models to predict mortality and char, using plot-scale data.

2.4.6. Surface fuels

Summary statistics were calculated for post-fire fine and coarse woody fuel loadings. Fine fuel loadings were summarized by the standard time-lag classes defined above. Coarse woody loading was separated into four size classes: 7–23, 23–41, 41–64, and 64–252 cm. These size classes were again separated into the subcategories “sound” and “rotten”.

3. Results

3.1. Stand structure and fire severity

Severity and stand structure variables were compared for treated and untreated units (Table 1). Mortality is twice as high in the untreated units than in the treated units ($p = 0.0005$). Exposed mineral soil and char height are also significantly greater ($p = 0.02$ and 0.02, respectively), with char height three times as high in the untreated stands.

Tree heights and diameters are similar between treatment types. Basal area, however, is significantly higher in untreated units ($p = 0.03$). Although non-significant, canopy closure is lower in untreated units even though basal area and tree density are higher.

The only species with a significant difference in density is lodgepole pine ($p = 0.012$); there are twice as many lodgepole pine in untreated than in treated units (Table 4). Other notable, but non-significant, differences in species composition between treatment types are western larch, Douglas-fir, and Engelmann spruce, which are all more abundant in treated units. In fact, in untreated units where lodgepole pine dominates species composition, other species abundances are half as large (Table 2). Douglas-fir occurs in fewer than 5% of the units, and is therefore excluded from subsequent analyzes.

Table 1
Means (standard deviations) of severity and stand structure variables in treated and untreated stands.

Severity variables	Treated ($n = 25$)	Untreated ($n = 19$)
Mortality (%)	37 (27)	77 (26)[a]
Exposed mineral soil (%)	61 (22)	78 (17)[a]
Char height (m)	0.3 (0.3)	1.0 (0.8)[a]
Stand structure variables		
Tree height (m)	3.06 (0.09)	3.38 (1.40)
Tree diameter (cm)	6.0 (1.9)	5.6 (1.4)
Basal area (cm^2 ha^{-1})	30 (25)	49 (31)[a]
Canopy base height (m)	0.20 (0.19)	0.39 (0.40)
Tree density (stems ha^{-1})	57 (28)	81 (33)
Canopy closure (%)	19.5 (16.7)	12.2 (9.3)

[a] Means were significantly different using a Wilcoxon Signed-Rank Test.

Table 2
Stem count frequency in treated and untreated units.

Stem count Proportion (%)	Treated	Untreated
Douglas-fir	13	3
Engelmann spruce	27	16
Lodgepole pine	34	70[a]
Mountain alder	3	2
Subalpine fir	7	6
Western larch	9	2

[a] Means were significantly different using a Wilcoxon Signed-Rank Test.

3.2. Mortality model

Treatment group explains the largest proportion of the total deviance, often explaining >25%. Each of the other predictor variables explains 5–10% of the remaining deviance. Engelmann spruce presence is the only species variable that predicts mortality. Lodgepole pine presence was included in the model at initial model building, but the sign of its coefficient changed from positive to negative as more predictors were added, suggesting collinearity. Lodgepole pine abundance is different between the treatment groups (Table 3), so the contribution of treatment group may be enough to capture the influence of lodgepole pine in predicting mortality. Canopy base height and canopy closure are the only stand structure variables that remained in the mortality model (Table 3). Basal area is the only other variable that started as a significant predictor and dropped out of the model during stepwise building procedures. Canopy base height and canopy closure both exhibit a reverse relationship with mortality from what was expected: the higher the canopy closure and the lower the canopy base height, the lower the mortality. In other words, stands that have trees closer together with crowns near the ground are more likely to have lower mortality.

Canopy base height and canopy closure both have significant interactions with treatment effect and thus have different slopes. In treated units, canopy base height has a clearer linear relationship to mortality than untreated units (Fig. 4). Canopy closure also differs between groups, with a slope closer to zero in untreated units, and a more linear relationship with mortality in treated units (Fig. 5). The distribution of points also differs by treatment type. Untreated units have overall higher mortality, as seen in the

Table 3
Logistic models and diagnostics for mortality and char in treated and untreated stands.

	β_0	Engelmann spruce	Canopy base height	Canopy closure	Percent deviance explained	p-value
Mortality model						
Treated	−0.224	−0.022	2.581	−0.023	0.580	≈0
Untreated	3.016	−0.022	−1.271	−0.090		
Char model						
	β_0	Treatment	Engelmann spruce	Basal area	R^2	p-value
	−2.126	1.081	−0.028	0.021	0.43	4.51E-05

Table 4
Means (standard deviations) of surface fuel loading (Mg ha^{-1}).

		Treated	Untreated
Fine fuels			
	1 h	0.0 (0.0)	0.0 (0.0)
	10 h	0.1 (0.0)	0.1 (0.0)
	100 h	0.1 (0.1)	0.1 (0.0)
Coarse fuels			
	$SCWD_{7–23\ cm}$	3.0 (1.4)	2.3 (1.3)
	$RCWD_{7–23\ cm}$	0.6 (0.3)	0.6 (0.5)
	$SCWD_{23–41\ cm}$	1.1 (0.7)	2.9 (2.0)
	$RCWD_{23–41\ cm}$	0.4 (0.3)	0.6 (0.6)
	$SCWD_{41–64\ cm}$	0.5 (0.8)	0.0 (0.2)
	$RCWD_{41–64\ cm}$	0.1 (0.2)	0.0 (0.1)
	$SCWD_{64–252\ cm}$	0.2 (0.6)	0.0 (0.0)
	$RCWD_{64–252\ cm}$	0.0 (0.0)	0.0 (0.0)
	$TCWD_{7–252\ cm}$	5.7 (2.4)	4.0 (2.1)

Note: SCWD, sound coarse woody debris; RCWD, rotten coarse woody debris; TWCD, total coarse woody debris.

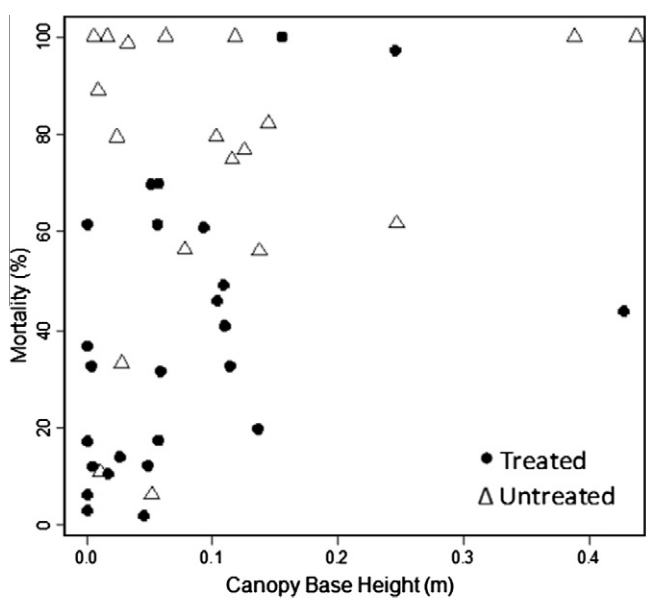

Fig. 4. The relationship between mortality and canopy base height differs between treated and untreated groups. Treated groups are less variable in terms of canopy base height and are clumped in the low mortality area of the plot. Untreated groups are more variable and have consistently higher mortality.

clumping pattern of untreated units in relation to canopy base height and canopy closure (Figs. 4 and 5).

3.3. Char model

The results of the char model also show the relationship between live fuel connectivity and fire severity. First, char significantly predicted mortality during exploratory analyzes, so variables that predict char may influence mortality. Treatment type is a predictor of char, but there are no interactions between treatment and other predictors, which suggests that the variables that predict char do not result from the influence of treatment type (Table 3). Engelmann spruce presence is also a predictor of char height and again has an inverse relationship with char. Basal area is an important predictor of char, reinforcing the relationship between live fuel connectivity and fire severity. Basal area does not predict mortality but does predict char, which could mean that stand density is important for mortality, especially in the context of live fuel connectivity.

3.4. Treatment effect

The multivariate PERMANOVA, which combined all three severity variables (mortality, char height, percentage of exposed mineral soil), also showed a significant difference between the treatments ($p = 0.0001$). This analysis shows that treatment type controls the severity differences among units. To further understand the differences in severity variables between treatments, we examined pairwise scatterplots of all three severity variables (Fig. 6). It appears that all three variables are correlated, but that the treatment differentiation is most pronounced in mortality, as seen by the horizontal distribution of points across the mortality x-axis in plots A and C, and the lack of horizontal differentiation of points in plot B.

3.5. Plot-scale edge effects

Despite observations of spatial variation in fire severity throughout units, no clear relationships emerged between distance to unit edge and either mortality or char. There may not be enough edge plots to overcome the large variability in the data. Even within plots that are 20 m from the edge, there is no significant difference in mortality from interior units.

3.6. Surface fuel loading

The mean post-wildfire fine fuel loading is the same in treated and untreated units, suggesting that the wildfire was present and consumed fine fuels in all units (Table 4). Many treated and untreated units have no fine fuels. Most of the coarse woody debris loading is concentrated in the smaller diameter classes and does not differ substantially between groups. However, both treatment types contain more sound than rotten logs, perhaps because most of the rotten logs may have been consumed in the wildfire. Overall, more coarse woody debris remained in the treated units, suggesting that coarse woody debris was not responsible for fire spread.

4. Discussion

Two major distinctions in fire effects were observed on the Tripod Fire landscape: (1) young stands burned differently than

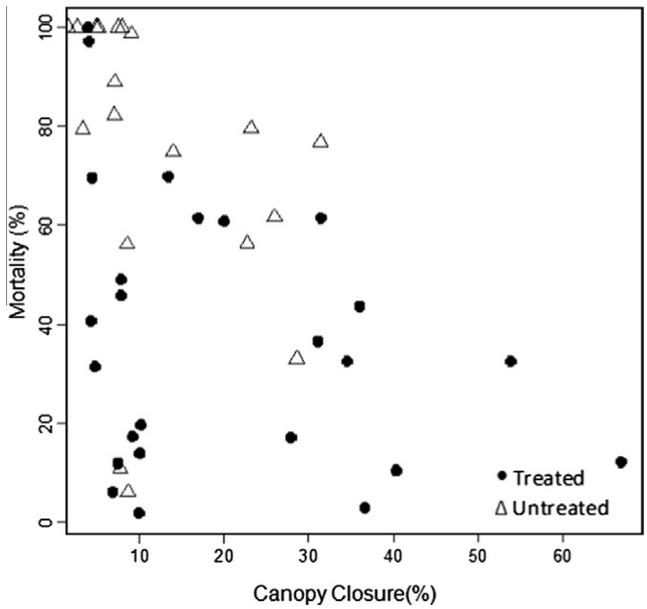

Fig. 5. The slopes for the two treatment types are similar (coefficients for canopy closure: Treated = −0.023 and Untreated = −0.09). However, the two groups show different clumping patterns and distribution of points.

mature stands, and (2) young stands did not all burn the same (Fig. 1). We examined the latter to try and address questions regarding flammability and potential fire effects in young stands. We found that three primary variables – presence of a surface fuel treatment, stand structure, and species composition – were correlated with fire severity. All three of these characteristics interacted to influence the fuels that were available for consumption.

Our results suggest that treatment of surface fuels following harvest significantly influences the probability of high-severity surface and crown fire in these mixed conifer forests. Further, fine surface fuels appear to be an important control of surface fire intensity and crown fire initiation in young stands, just as they are in mature stands.

Stand structure also influenced fire severity in the Tripod Fire, but because fuel treatments were done before planting and ingrowth of the young trees, we cannot attribute differences in stand structure to the fuel treatments themselves. Canopy base height and canopy closure are the only significant stand structure variables that predict fire severity. Canopy base height is usually negatively correlated with crown damage and mortality in mature stands (Peterson et al., 2005), but in the present study, the overall correlation is positive. That is, mortality decreases as canopy base height decreases, or in other words, trees with crowns closer to the ground are less likely to burn. A similar relationship emerges between canopy closure and mortality, such that mortality decreases as canopy closure increases. Canopy closure may have shaded surface fuels and contributed to higher fuel moistures than in more open stands. Similarly, closed canopies that are more proximal to the ground could decrease wind speed and therefore fire spread. This suggests that the live fuel component of young stands can decrease fire severity in some cases, confirming that fuel condition can be just as important as fuel abundance (Littell et al., 2009).

The relationship between mortality and canopy base height and canopy closure appear to differ in treated and untreated stands, including a possible interaction between stand structure and treatment. For example, canopy closure is higher in untreated units, and mortality is lower in these units, which leads to the question: Is

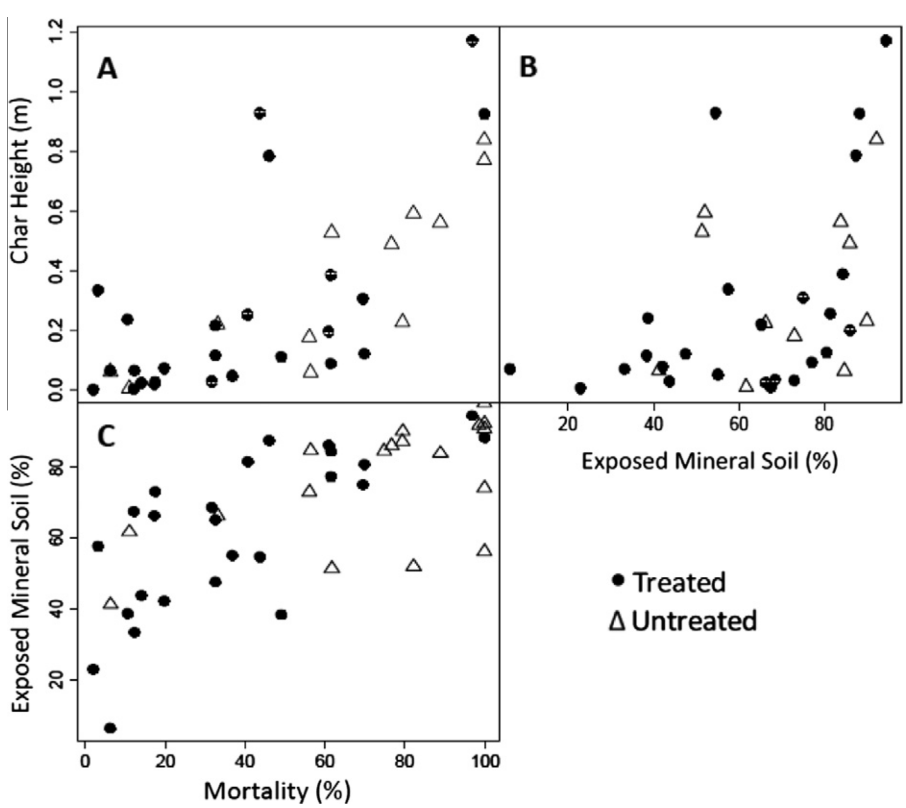

Fig. 6. The correlation between all three severity variables is shown in the three scatterplots. It appears that mortality is responsible for most of the difference between treated and untreated units, as evidenced by the horizontal distribution of points across the mortality x-axis in plots A and C, and the lack of horizontal differentiation of points in plot B. Because mortality is correlated with char height and exposed mineral soil, and most of the difference between treatments is explained by mortality, mortality alone may be a sufficient variable to explain the effects of fuel treatments on fire severity in young stands.

canopy closure predicting mortality only because the units with higher canopy closure also received a broadcast burn? If this were the case, we would have expected to see an interaction (in the statistical model) between treatment and canopy closure, but there was no interaction. We did see a clumping of untreated unit plots in the high mortality, low canopy base height area of the plot, which could be explained two ways. First, lower canopy closure led to higher mortality because of less fuel shading and increased wind speed, or second, *post hoc* canopy reconstructions resulted in lower canopy in more severely burned areas.

An interaction *is* present between canopy base height and treatment type, as seen by the difference in slope between the two groups (Fig. 4). Treated units have a positive slope, suggesting that mortality increases as canopy base height increases. Untreated units have a negative slope, suggesting that mortality increases as canopy base height decreases. In untreated units, with more surface fuels, an increase in canopy base height would have elevated the live fuels from the surface fuels, therefore decreasing vertical fuel continuity. This is consistent with results from previous studies, suggesting that lower canopy base height will lead to crown fire initiation (e.g., Scott and Reinhardt, 2001; Stephens and Finney, 2002). The difference in slopes between the treated and untreated stands suggests that different mechanisms control mortality in these two groups. In untreated stands, vertical connectivity may be most important, but in treated stands, lower canopy base height may have shaded the small amount of surface fuels enough that they retained higher moisture and were less flammable.

Differences in species composition between treated and untreated groups could have influenced flammability and tree density. Species composition differs between treatments, with significantly more lodgepole pine in the untreated group and more Engelmann spruce in the treated group. Four possible explanations exist for this difference in composition. First, broadcast burning could have killed residual lodgepole pine seedlings and seeds that remained on the site after harvesting. Second, the surrounding seed trees could have differed between units, influencing seed source. Third, planting stock and tree fitness may have influenced overall survival of trees of species other than lodgepole pine. Fourth, clearcutting without underburning can desynchronize the soil conditions and the microclimate, resulting in prolific colonizers that dominate the forest floor (Kimmins, 2004). Colonizers, such as lodgepole pine, dominate the forest floor because some species, in this case subalpine fir and Engelmann spruce, do not establish well on a late seral forest floor with high organic matter content.

Our results show that, in forest landscapes prone to high-severity wildfire, young stands can experience a lower-severity wildfire if treated for surface fuels. Fire severity in these young stands depended mainly on surface fuels, and treating surface fuels reduced vulnerability of young stands to the potential effects of wildfire. The finer-scale, empirical approach and differs from other studies, and our results suggest that it is not the management strategy itself (timber harvest, in this case) that changes fire severity, but the surface fuel reduction effort. In the system that we studied, surface fuel treatment may also trump other factors due to the lack of schlerophyllus shrubs and other highly-flammable, quick-growing understory species.

5. Conclusions

Young stands are a significant component of most contemporary forest landscapes, so understanding fire dynamics and fire severity in young stands is critical for managing multi-aged forests. Managing for ecosystems that are resilient to increased disturbance, especially in a warming climate, will be enhanced by managing for specific patterns and patch size distributions of forest structure, fuels, and fire (Hessburg et al., 2005). Historically, landscapes of the interior Pacific Northwest were characterized by a complex patchwork of fire regimes and patch sizes (Hessburg et al., 2005). More heterogeneous landscapes are inherently resilient because of higher species diversity and functional diversity (Gunderson and Pritchard, 2002; Joyce et al., 2008).

Heterogeneous landscapes can be engineered in systems where even-aged management and fire exclusion have combined to create landscapes susceptible to stand-replacing fire behavior. Fuel treatments can modify patch dynamics by creating discontinuity in surface and canopy fuels (Agee and Skinner, 2005), but other treatments can also create heterogeneity. For example, clearcuts are sometimes used to mimic openings created by stand-scale disturbance events, such as root pathogens, insect outbreaks, or even high-severity patches of wildfire in a mixed-severity fire regime (Kimmins, 2004). These openings can create resilience to large-scale disturbances, because different age classes respond to disturbances differently and provide structural complexity (Turner et al., 2001; Lovett et al., 2005).

True emulation of forest disturbances requires variation in disturbance frequency and severity, which is not the case with clearcuts that are implemented at one harvest rotation (Lertzman and Fall, 1998; Swetnam et al., 1999; Kimmins, 2004). The "hard" edges associated with clearcuts can also affect wildlife habitat, species richness, and plant mortality (Murcia, 1995). However, small harvested patches may facilitate development of a diverse age structure on a landscape that has been intensively managed (e.g., timber harvesting and fire exclusion). In this context, managers can emulate natural disturbances, not to duplicate natural events, but to create conditions in a managed landscape in which some ecological processes can perform in the same manner as in naturally disturbed landscapes (Thompson and Harestad, 2004).

After the 2006 Tripod Fire, young stands served three ecological purposes. First, they provided a seed source in a landscape in which the majority of trees were killed. Second, they provided desirable habitat for the largest Canada lynx (*Lynx canadensis*) population in the continental United States. Third, they provided stable root structures in a landscape with severe erosion potential. However, for a particular landscape, the optimal size, optimal number, and benefits of these young stands will depend on the management objectives.

Results from this study are applicable to management efforts on the Okanogan-Wenatchee National Forest and other interior dry forests of the Pacific Northwest where management objectives include restoring historic fire regimes and species compositions. Our study suggests that, for fire resilience and restoration to be successful, timber harvest must be done in tandem with surface fuel treatment. Young stands are common in interior dry forests, where disturbance and harvest operations have created openings where young trees are currently growing. If managed for resilience, young stands can be an important component of restoration in fire-prone landscapes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2011.04.016.

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