Severity of an uncharacteristically large wildfire, the Rim Fire, in forests with relatively restored frequent fire regimes

Jamie M. Lydersen [a,*], Malcolm P. North [a,b], Brandon M. Collins [a,c]

[a] USDA Forest Service, Pacific Southwest Research Station, 1731 Research Park Dr., Davis, CA 95618, USA
[b] John Muir Institute, University of California, One Shields Ave., Davis 95616, USA
[c] Center for Fire Research and Outreach, University of California, Berkeley, Mulford Hall, Berkeley, CA 94720, USA

ABSTRACT

The 2013 Rim Fire, originating on Forest Service land, burned into old-growth forests within Yosemite National Park with relatively restored frequent-fire regimes ($\geqslant 2$ predominantly low and moderate severity burns within the last 35 years). Forest structure and fuels data were collected in the field 3–4 years before the fire, providing a rare chance to use pre-existing plot data to analyze fire effects. We used regression tree and random forests analysis to examine the influence of forest structure, fuel, fire history, topographic and weather conditions on observed fire severity in the Rim Fire, as estimated from an initial fire severity assessment based on the relative differenced normalized burn ratio (RdNBR). Plots that burned on days with strong plume activity experienced moderate- to high-severity fire effects regardless of forest conditions, fire history or topography. Fire severity was also highly negatively associated with elevation, with lower severity observed in plots over 1700 m. Burning index (a composite index of fire weather), time since the last fire, and shrub cover had strong positive associations with fire severity. Plots that had experienced fire within the last 14 years burned mainly at low severity in the Rim Fire, while plots that exceeded that time since last fire tended to burn at moderate or high severity. This effect of time since last fire was even more pronounced on days when the burning index was high. Our results suggest that wildfire burning under extreme weather conditions, as is often the case with fires that escape initial attack, can produce large areas of high-severity fire even in fuels-reduced forests with restored fire regimes.

Published by Elsevier B.V.

1. Introduction

Forests that evolved under the influence of frequent, low-severity fire have undergone dramatic change following a century of fire suppression, including a buildup of surface fuels, increased density of small, shade-tolerant trees and a loss of spatial heterogeneity (Parsons and Debenedetti, 1979; Scholl and Taylor, 2010; Lydersen et al., 2013). Following these changes, fires in low- and mid-elevation forests are burning with a greater proportion and larger patch sizes of high severity than historical levels (Mallek et al., 2013). These uncharacteristically large and severe wildfires have significant impacts on sensitive wildlife habitat (North et al., 2010), air quality (Fowler, 2003) and greenhouse gas concentrations (Muhle et al., 2007; Liu et al., 2014). In addition, the costs of fire suppression and post-fire rehabilitation associated with these fires continue to increase (NIFC, 2013).

The 2013 Rim Fire is the largest fire on record in the Sierra Nevada, and the third largest in California. It ultimately burned 104,131 ha, with the majority occurring in forest vegetation types. The Rim Fire occurred under extreme drought and weather conditions, with notably unstable weather occurring soon after ignition, leading to two days of extreme fire growth. Increasing occurrence of large wildfires has been linked to higher spring and summer temperatures and earlier snowmelt, as well as increasing drought severity across the west (Westerling et al., 2006; Dennison et al., 2014). Work in Yosemite National Park has also found that decreased spring snowpack is associated with an increased frequency of ignitions and that larger fires burn with a greater proportion of high severity (Lutz et al., 2009). Given that spring snowpack in the Sierra Nevada has been decreasing, a trend that is forecast to continue due to temperature rise (Kapnick and Hall, 2010), along with the growing frequency of extreme fire weather (Collins, 2014), fires of this size and severity may not be rare events in the future (Marlon et al., 2012; Stephens et al., 2014).

* Corresponding author. Tel.: +1 530 759 1767; fax: +1 530 747 0241.
  E-mail address: jmlydersen@fs.fed.us (J.M. Lydersen).

Restoration of forests with altered structure following fire suppression is of high interest to managers and stakeholders of Sierra Nevada forests (North, 2012). Following the recognition of fire as an important ecosystem process, since the late 1960s Yosemite National Park has made use of prescribed and wildland fires burning under moderate weather conditions to meet management objectives (Stephens and Ruth, 2005; van Wagtendonk, 2007). This has resulted in a number of forest stands in the park where repeat burning has occurred, at frequencies and intensities similar to the historical fire regime (Collins and Stephens, 2007; Lydersen and North, 2012). There is considerable interest in characterizing ecosystem structure and function within these stands, as frequent-fire reference conditions operating under recent climate are rare (Stephens and Fule, 2005).

Under a frequent, low-severity fire regime, forests are characterized spatially by diverse sizes of tree clumps interspersed with forest gaps and widely spaced single trees (Larson and Churchill, 2012). This heterogeneity was likely the product of an intact fire regime that allowed fires to burn under a range of weather and fuel conditions (Skinner and Taylor, 2006). In addition to creating and maintaining spatial heterogeneity, repeat fire in these forests maintains a lower fuel load and tree density (Webster and Halpern, 2010). Collectively, these forest conditions have been associated with increased resilience to environmental stressors (e.g., drought, insects, disease) and wildfire (Stephens et al., 2008). To the extent that forest conditions in contemporary stands with a restored fire regime resemble that of historical forests, it could be expected that restored contemporary forests would burn with a lower proportion of high-severity fire under most wildfire conditions, as compared to areas with ongoing fire suppression that have not burned in over a century. However, even in areas that have recently burned in multiple low- and moderate-severity fires there is often a persisting legacy of tree densification due to the fire exclusion period that pre-dated the re-introduction of fire in these stands (Collins and Stephens, 2007; Collins et al., 2011). The question remains as to whether these relatively restored forests are resilient to wildfire burning under extreme weather conditions.

In this study, we take advantage of a unique opportunity to use extensive on-the-ground measurements collected prior to the 2013 Rim Fire to explain factors associated with observed fire effects. The Rim Fire burned into stands in Yosemite National Park representing a diverse recent fire history, allowing for analysis of wildfire effects on forests with an active fire regime. The objective of our study was to identify factors that influenced Rim Fire burn severity in these forests. We assessed the influence of forest structure, fuel load, topography, fire history, and weather on satellite-derived fire severity, using field data from 53 plots collected 3–4 years prior to burning in the Rim Fire.

2. Methods

2.1. Field data

Field data were collected in 2009 and 2010 as part of a study on topographic variation in forest structure in Sierra Nevada mixed-conifer forests with an active, or restored, frequent, low-severity fire regime (Lydersen and North, 2012). Sample sites were mixed-conifer forest, with some lower elevation sites having a combination of ponderosa pine and mixed-conifer forest. Prior to the implementation of fire suppression policy in the early 1900s, these forest types had a frequent (<20 years), low severity fire regime that generally consisted of surface burns (Skinner and Chang, 1996). Sample sites were restricted to unlogged stands that experienced at least two fires within the previous 60 years, with the most recent fire occurring within the last 30 years. As this condition required somewhat less frequent fire than would have occurred historically, we

refer to the fire regime as "relatively" restored. Recent work has found that forests can approach historical conditions following two fires (Taylor, 2010; Webster and Halpern, 2010). Previous fires included prescription fires and wildfires (those managed for resource benefit as well as those targeted for suppression). While all fires included patches of high severity burning, field sampling was limited to areas that burned at low to moderate severity so that the recent fire activity would more closely mimic the low severity fire regime attributed to these forests (Skinner and Chang, 1996).

For each 20 m × 50 m (0.1 ha) plot local topographic characteristics as well as vegetation and fuels data were recorded. Topographic measures included slope position (lower, middle, upper or ridge), slope steepness, aspect, configuration (concave or convex) and distance to perennial stream. Topographic relative moisture index (TRMI) was calculated for each plot (Parker, 1982). Slope configuration was converted to a continuous variable, with values ranging from 0 (convex) to 10 (concave), matching the values used in calculating TRMI. Aspect was converted using a cosine function so that values ranged from 0 (200°, xeric) to 2 (20°, mesic). For live trees, diameter at breast height (dbh), height to live crown and bole char height were measured. Decay class, dbh and height were recorded for snags. Trees and snags between 5 and 50 cm dbh were measured in half of the plot while larger trees were measured over the entire plot. Shrub cover by species was recorded along a central 50 m transect. Number and height of seedlings and saplings (>10 cm in height and <5 cm dbh) were recorded in ten 1 m^2 quadrats. For each plot, fuels were measured on three 15 m transects using the planar intersect method (Brown, 1974). All logs within the plot >50 cm diameter and >1 m in length were measured.

The Rim Fire in 2013 reburned 53 of the original 150 plots included in Lydersen and North (2012) (Fig. 1). These 53 plots were distributed among 7 study areas (Table 1). Study areas were defined by overlapping fire perimeters, and averaged around 750 ha in size. Within study areas, plots were situated in order to capture unique combinations of slope position, aspect and slope shape, with random placement within a given topographic condition (Fig. 1, bottom left inset). Average distance between plots within sample sites was >1000 m apart, with a median of 1174 m and a range of 77–4333 m. In an effort to minimize pseudoreplication (Hurlbert, 1984), plots were separated by changes in slope, aspect and intervening fuel conditions to significantly reduce spatial autocorrelation in fire effects on forest structure (van Mantgem and Schwilk, 2009; Webster and Halpern, 2010).

2.2. Fire severity

Fire severity for the Rim Fire was calculated using the relative differenced Normalized Burn Ratio (RdNBR) (Miller and Thode, 2007) at a 30 m pixel scale, using imagery collected following fire containment in 2013. Plot area was buffered by 10 m in ArcMap 10.1 to create a bigger spatial analysis area for each plot to account for possible inaccuracies in GPS records and spectral imagery. To calculate an average RdNBR value for this buffered plot area, the 30 m RdNBR data was resampled to 5 m to better match pixel edge with plot area edge, and then zonal statistics were used to obtain the mean value of pixels intersecting the buffered plot area. At this scale there were 104–111 pixels per plot. In addition to this mean RdNBR score, a severity class (low, moderate or high) was assigned to each plot, based on the thresholds identified in Miller and Thode (2007). For simplification, plots that would be classified as unchanged were included in the low severity group.

2.3. Data analysis

The severity observed in the Rim Fire was assessed using a variety of covariates, including topographic, forest structure, fuels,
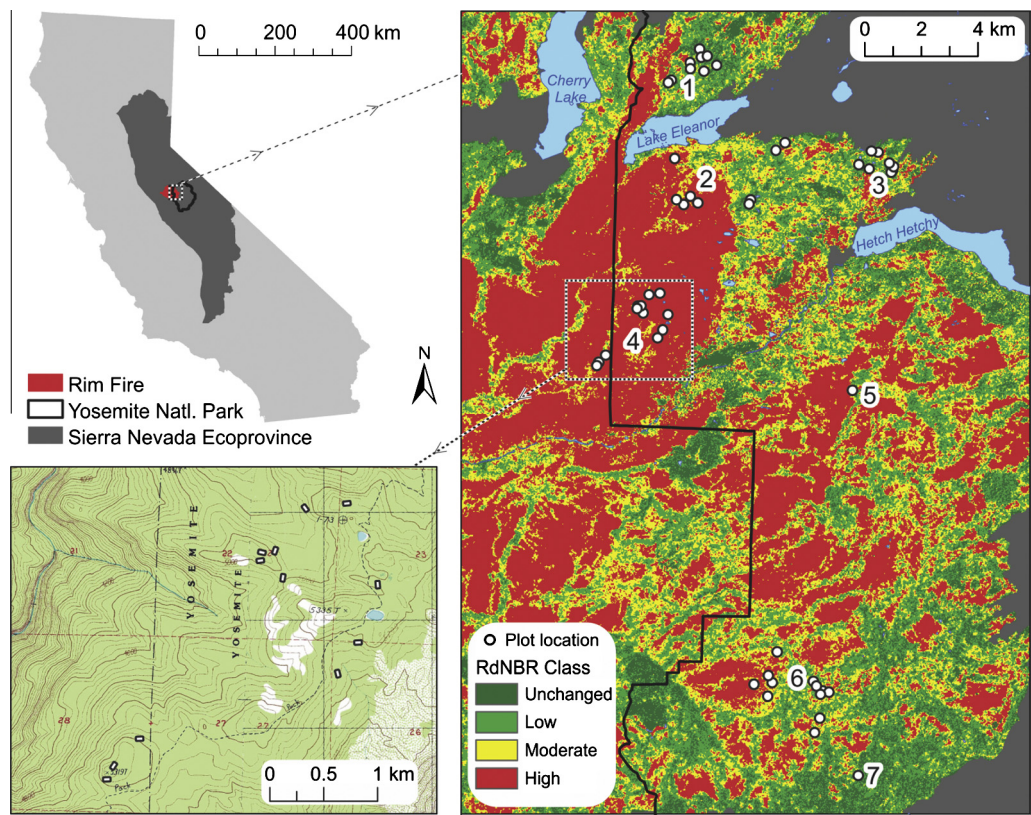
Fig. 1. Location of study areas from Lydersen and North (2012) that burned in the Rim Fire in California's Sierra Nevada Mountains. Inset on right shows the area where the Rim Fire crossed the boundary into Yosemite National Park, corresponding to the area within the black and white dashed box on the map of California. Numbers represent sites identified in Table 1. Fire severity shown is for the Rim Fire. Inset on the bottom left shows the plot locations at the North Mountain study area in relation to site topography, corresponding to the area within the black and white dashed box on the severity map inset. Dimensions of the plots after addition of the 10 m buffer are shown.

Table 1
Previous fire history and number of plots in study areas from Lydersen and North (2012) that burned in the Rim Fire in 2013. Study area numbers correspond to those in Fig. 1.

Study area (#)	# Of plots	Recent fire record[a]	Elevation range (m)	Size (ha)	RdNBR Ave. (St. Dev.)
N. Eleanor (1)	9	1986, 1999	1710–2000	600	68 (70)
S. Eleanor (2)	9	1978, 1996	1490–1780	1000	500 (397)
Laurel lake (3)	9	1978, 1991, 2005	1810–1940	350	124 (108)
North Mtn (4)	4	1950, 1987, 1996	1520–1550	2000	718 (148)
	3	1987, 1996	1530–1590		851 (163)
	2	1993, 1996	1560–1590		1232 (25)
	3	1994, 1996	1600–1620		520 (85)
Cottonwood Crk (5)	1	1996, 2009	1790	50	202
Aspen valley (6)	10	1983, 1998	1550–1800	1200	454 (173)
	1	1983, 1990, 1998	1630		483
	1	1983, 1990, 1999	1690		1017
Gin flat (7)	1	1989, 2000, 2002	2000	100	262

[a] Includes fires that occurred 1949–2011.

weather, and fire history variables (Table 2). Topographic and forest structure variables were derived from the field data collected in 2009 and 2010 (Section 2.1). Fire history variables were obtained from Yosemite's fire history geospatial data. Daily assessment of whether or not the fire was plume-dominated was evaluated by fire personnel on the ground (personal communication, Matthew Mehle – NOAA, Feb 26, 2014). During the interval the plots burned, only one day of plume-dominated fire occurred. As fire progression was only assessed daily, we could not include a finer scale assessment of plume behavior (e.g., hourly assessments of plume presence). Plumes often form when atmospheric conditions are unstable, and result in erratic fire behavior that is driven by its own local effect on surface wind and temperatures often exceeding the influence of more generalized climate factors measured at

nearby weather stations (Werth et al., 2011). The burning index (BI) and energy release component (ERC) were calculated for the day a plot burned in the Rim Fire using FireFamilyPlus version 4.1 and daily weather values for the Crane Flat weather station. Weather variables were assigned to plots by identifying the corresponding day plots burned in the daily fire progression maps (Collins et al., 2007).

To compare the relative influence of covariates, random forests analysis was performed using version 1.0-9 of the party package in R version 3.0.2. With this method a suite of regression trees is constructed, using a randomly selected subset of predictor variables and a random subsample of plots for each tree. Examining a large number of regression trees allows for identification and ranking of influential variables, and averages out the instability of individual

Table 2
Predictor variables used in random forests and regression tree analysis to explain fire severity observed in the Rim Fire. Range and mean (X) are shown for continuous variables and number of plots in each category is shown for discrete variables.

Variable	Description
Topography	
Elevation (m)	1487–1995, X = 1721
Slope position	Lower, Middle, Upper, Ridge (7, 24, 14, 8)
Aspect (cosine transformed)	0–2, X = 0.7
Slope steepness (%)	1–50, X = 25
Slope configuration[a]	0–10, X = 4.7
Distance to stream	⩽20 m, 21–100 m, >100 m (4, 7, 42)
TRMI	9–60, X = 28
Weather on day of burn	
Plume-dominated fire	yes, no (17, 36)
Energy Release Component	67–77, X = 74
Burning Index	63–85, X = 75
Fire History	
Years since last fire	4–17, X = 14
Years between previous fires	2–18, X = 12.5
Number of prior fires[b]	2–3, X = 2.3
Char height (m)	0.8–11, X = 3.3
Overstory characteristics	
Canopy cover (%)	3–81, X = 43
Proportion shade-intolerant	0–100, X = 56
Quadratic mean dbh	28–105, X = 66
Branch height (m)	1–19, X = 8
Live Basal Area ($m^2\ ha^{-1}$)	
Total	2–151, X = 56
Trees < 40 cm dbh	0–22, X = 6
Trees ⩾ 80 cm dbh	0–134, X = 32
White fir	0–69, X = 9
Incense-cedar	0–59, X = 16
Jeffrey pine	0–26, X = 1
Sugar pine	0–72, X = 8
Ponderosa pine	0–60, X = 22
Oak species	0–10, X = 1
Live tree density (ha^{-1})	
Total	10–770 X = 215
Trees < 20 cm dbh	0–220, X = 37
Trees 20–39 cm dbh	0–300, X = 71
Trees 40–59 cm dbh	0–210, X = 45
Trees 60–79 cm dbh	0–100, X = 27
Trees ⩾ 80 cm dbh	0–120, X = 36
Understory characteristics	
Shrub cover (%)	0–97, X = 24
Seedling/sapling density (ha^{-1})	0–5.4, X = 0.8
Seedling/sapling height (cm)	0–140, X = 26.2
Dead and down fuels	
Snag volume ($m^3\ ha^{-1}$)	0–1170, X = 98
Log volume ($m^3\ ha^{-1}$)	0–353, X = 39
Total woody ground fuels ($Mg\ ha^{-1}$)	0–162, X = 40
Fine woody fuels (1–100 h) ($Mg\ ha^{-1}$)	0.3–20, X = 7
Duff depth (cm)	0–6, X = 2.4
Fuel height (cm)	0.1–27, X = 5.9

[a] Calculated as a continuous variable, ranging 0 for convex to 10 for concave.
[b] Refers to all fires prior to the Rim Fire occurring 1949–2012.

regression trees that can exhibit large changes in structure due to random variation in the data (Strobl et al., 2009). We used the function cforest, which generates conditional inference trees that avoid the bias in variable selection that can be problematic with other regression tree methods (Strobl et al., 2007). The number of variables used in constructing each tree was six, following the standard practice of using the square root of the total number of predictor variables. Variable importance was assessed using the conditional method developed by Strobl et al., 2008. Traditional importance rankings tend to exaggerate the significance of variables that are highly correlated with influential predictors. The conditional method reduces this effect, providing a more accurate ranking of variable importance. The area under the curve approach was used, which performs better than the traditional approach when class variables are unbalanced (Janitza et al., 2013). To assess each variable's importance, its values are permuted then used along with the other (non-permuted) variables to predict the response for the out of bag observations (those not included in a tree's construction). A larger measure of variable importance arises when the misclassification rate of the out of bag observations increases following variable permutation, as averaged across all constructed trees containing a given variable. Covariates with an importance value greater than the absolute value of the lowest negative score were considered significant or of potential interest (Strobl et al., 2009). We used a large number of trees (5000) to stabilize variable importance ranking, and confirmed the ranking by repeating the process ten times using randomly selected start seeds. The analysis was performed twice, with and without plots
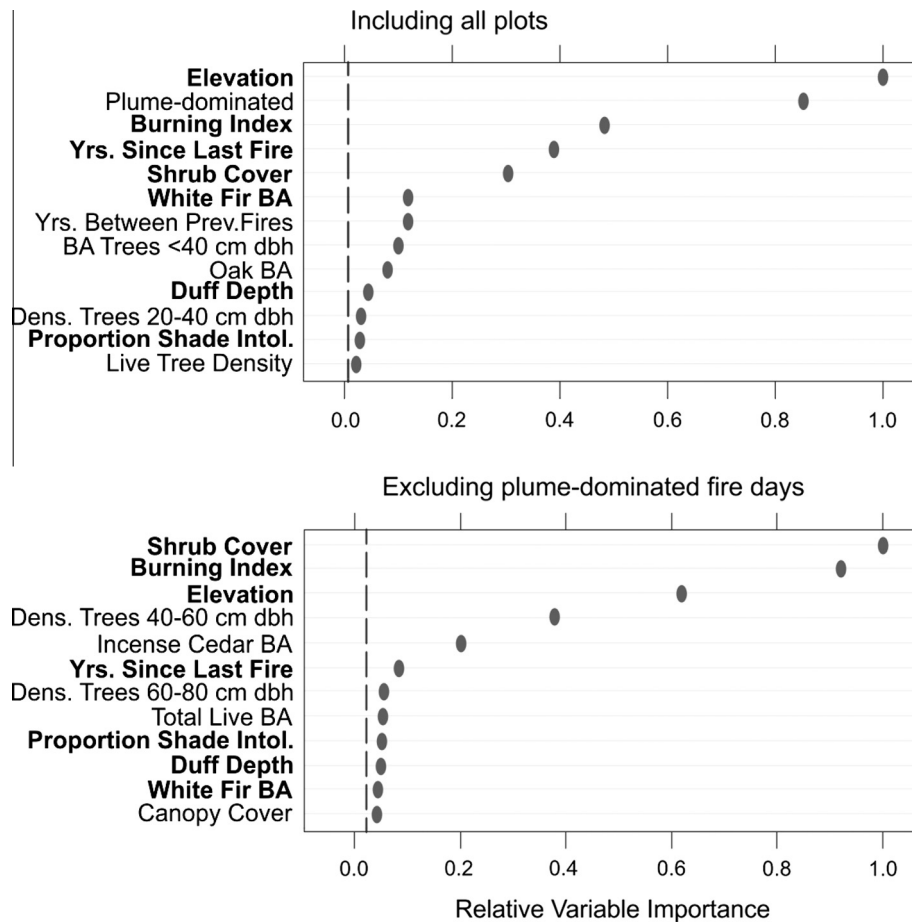
Fig. 2. Variable importance ranking of the influential variables on observed fire severity, as determined by random forests analysis. Variables with importance values higher than the absolute value of the lowest negative importance value (dashed vertical line) are considered influential. Upper chart shows results when all plots were included in the analysis, lower chart shows results after excluding plots burned on a day when the Rim Fire was plume-dominated. Variables in bold text appear in both charts.

burned under plume conditions. Importance values were relativized to the maximum value to facilitate comparisons between the two analyses.

To identify specific relationships and potential thresholds among covariates, average RdNBR values for plots were assessed using regression tree analysis. This analysis was performed using the ctree function in the party package in R, a method that avoids overfitting and biased selection among covariates (Hothorn et al., 2006). The analysis was performed both with and without the dominant variables identified by random forests analysis to enable visualization of relationships among the less influential predictor variables. A significance level of 0.05 was used in assessing all splits.

3. Results

Out of 53 plots, 12 (23%) were classified as high severity in the Rim Fire. 17 plots (32%) burned at moderate severity, and the remaining 24 plots were classified as unchanged or low severity. Some study areas burned predominantly at high and/or moderate severity, while others saw a range of severities (Fig. 1). The mean RdNBR value among plots was 418 (median 401), with a standard deviation of 353.

When assessing all plots, elevation, followed by plume effects, had the most influence on observed fire severities in our plots (Fig. 2). Burning index (BI), time since the last fire and shrub cover were also highly associated with differences in fire severity. The

time between the two previous fires as well as basal area (BA) of white fir, oak and small trees were moderately associated with observed fire severity, while duff load, density of trees 20–40 cm dbh, proportion of shade intolerant species and total stem density were marginally associated. With the exception of elevation, topographic variables did not appear to substantially influence fire severity. When plume-dominated fire plots were removed from the random forests analysis, many of the same variables remained highly ranked, indicating that their effect was not entirely due to correlation with plume-dominated burning (Fig. 2). The variables identified as important in both analyses were shrub cover, BI, elevation, years since last fire, proportion of shade-intolerant species, duff depth and white fir BA. When plume-dominated plots were not included, shrub cover and burning index were the most important variables, followed by elevation, density of trees 40–60 cm dbh, incense-cedar BA and years since last fire. Density of trees 60–80 cm dbh, total BA, proportion shade intolerant, duff depth, white fir BA and canopy cover were marginally important.

When all variables were included in the regression tree analysis, plots that burned on plume-dominated fire days were separated at the first split, with higher observed severity overall (Fig. 3A). The remaining plots were divided by shrub cover, with greater shrub abundance associated with greater severity. When plume presence was excluded as a variable, the resulting tree had only one split, separating plots higher than 1694 m in elevation (Fig. 3B). The higher elevation plots burned at predominantly low severity, while plots at lower elevation tended to burn at higher severity, but exhibited a greater range of observed
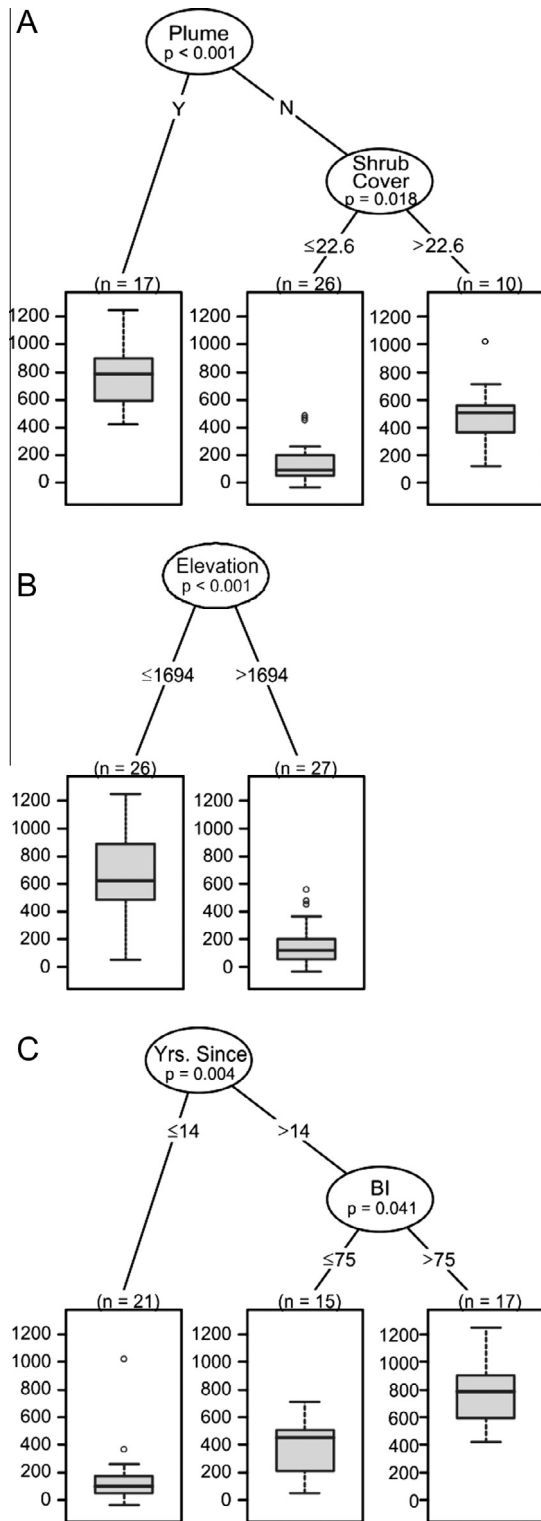
Fig. 3. Conditional inference trees for fire severity observed in the Rim Fire, (A) including all predictor variables; (B) excluding plume presence/absence; and (C) excluding both elevation and plume presence/absence as variables. Data from all plots are included in the diagrams. Plume is a categorical variable for whether or not a plot burned on a day when the fire behavior was plume-dominated, shrub cover is given as a percentage, elevation is shown in meters, time since previous fire (Yrs. Since) is shown in years and BI is the burning index for the day a plot burned in the Rim Fire.

Fig. 4. Fire severity classes observed in plots reburned by the Rim Fire, by time since previous fire. (A) Including all plots; and (B) excluding plots burned on a day when the Rim Fire was plume-dominated.

important. The split here combines plots in the middle of the represented elevation range that burned at moderate severity with the plots that burned under plume-dominated fire. When both plume presence and elevation were excluded from the suite of predictor variables, the resulting tree separated plots based on time since last fire, with the majority of those that had burned within 14 years of the Rim Fire burning at low severity. In contrast, those that had not seen fire in over 14 years burned predominantly at moderate and high severity (Fig. 4). Among plots that had not experienced fire in more than 14 years, the burning index on the day of burn was associated with Rim Fire severity, with plots that burned on a day with a BI > 75 showing mainly high severity, while those that burned on milder days having a more moderate severity (Fig. 3C). The 17 plots with BI > 75 burned under plume-dominated conditions.

In line with the random forests analysis, we also examined regression trees generated using just the 36 plots that burned on days when the fire was not plume-dominated. The resulting tree only had one split identified, which was the same shrub cover variable and break point indicated in the second split in Fig. 3A (results not shown). Removing shrub cover from the analysis on this subset of plots did not result in any additional significant splits at the 0.95 confidence level.

4. Discussion

Our study suggests that even fire-restored forests may not be resistant to high-intensity wildfire that escapes suppression during extreme weather conditions. Given that all of our plots previously burned at low or moderate severity in the recent (1949–2011) fire record, the high severity burning observed in the Rim Fire represents new high-severity patches in this landscape. Other work has suggested that previous disturbance patterns can influence the outcome of subsequent disturbance events (Larson et al., 2013). For example, fire severity in reburns can be strongly

severities. Elevation was correlated with plume-dominated fire, however even when plots burned under plume-dominated fire were excluded from random forests elevation was ranked as highly
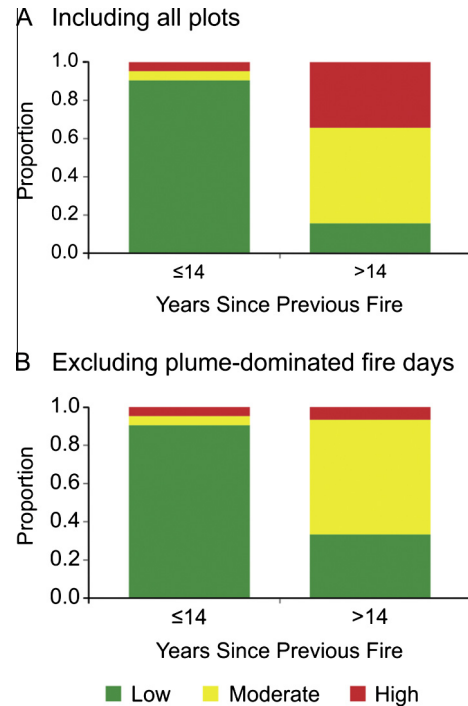
dependent on the severity of previous fires (Parks et al., 2013). While areas that burn at high severity in initial fires are more likely to reburn as high severity, there is a less consistent pattern for areas previously burned at low or moderate severity (Holden et al., 2010; Thompson and Spies, 2010; Van Wagtendonk et al., 2012; Parks et al., 2013). Our study supports this finding for low- to moderate-severity fire effect in previous fires. Char height from previous fire was not identified as an important variable in our analysis, indicating that fire intensity in previous fires did not influence observed Rim Fire severity among our plots. We instead found that time since last fire, shrub cover, elevation and the burning index were associated with Rim Fire severity, indicating that the interaction between fire history, understory and fire weather were influential on fire effects.

Our study has a few limitations worth discussing. First, the method of estimating fire severity for each plot was based on locations derived from a handheld GPS. As a result, plot locations are only known within approximately 10 m. To account for this we buffered the analysis area for each plot and averaged values from all pixels, resampled at a scale of 5 m, to estimate plot burn severity. However the 30 m resolution of the RdNBR data coupled with the small plot size may not give a perfect representation of fire severity. Second, the imagery used to derive fire severity was from the year of fire, resulting in what is called an "initial" assessment (Key and Benson, 2006). It is more conventional to use the "extended" assessment, which uses imagery from 1-yr post fire (Key and Benson, 2006; Miller and Thode, 2007). While the extended assessment may better capture short-term delayed mortality and be less influenced by the reflectance of ash, there would also be growth of herbaceous and understory plants, which could confound estimates of severity. The tradeoffs between initial and extended assessments are not well understood in these forests, and is a topic certainly worthy of future exploration. Third, although typically separated by more than 1 km within a given site, our plots could be spatially autocorrelated because they were grouped around sample sites with two or more past low-intensity burns. Many adjacent plots, however, did not burn on the same day, particularly among those that burned at low severity when rate of fire spread was low. This suboptimal plot dispersion is a tradeoff when using existing pre-fire data that could not account for future wildfire severity patterns.

The majority (10 out of the 12 plots classified as high severity) burned on a day when the fire was plume-dominated, which was associated with unprecedented fire growth for this region. The high BI value of 85 observed on this day somewhat captures these conditions. However, there are other more local factors related to the plume's influence on surface wind dynamics, including increased speed and turbulence (Rothermel, 1991; Werth et al., 2011) that are likely not captured by the BI value derived from a weather station 20 km away. What is interesting regarding the influence of the plume on fire behavior, and ultimately fire severity, is that despite having multiple previous burns, many plots burned at high severity. This suggests that extreme fire behavior can overwhelm well designed fuel treatments, which has been demonstrated in other extreme fire events (Finney et al., 2003). Perhaps extreme burning conditions can create enough inertia when encountering previously burned areas to maintain high fire intensity despite the ameliorated fuel conditions.

Time since fire and the burning index were also highly related to Rim Fire severity. These two variables have been identified as influential on burn severity (Van Wagtendonk et al., 2012) and in predicting whether or not an area would reburn (Collins et al., 2009). In our study, plots that had a previous fire within 14 years of the Rim Fire burned predominantly at low severity, regardless of weather conditions. Parks et al. (2013) also found that severity increased with time since previous fire, and that previous fires continued to lower severity of reburns for at least 22 years post-fire. This may occur since greater time since fire allows for the accumulation of surface (dead woody, and live shrub/herbaceous) and ladder fuels, which then contribute to greater flame lengths and ultimately higher severity effects. However an interesting result in this study is that plot-specific dead and downed fuel loads did not appear to relate to observed fire severity, with the exception of duff depth. Of the fuel variables we measured (Brown, 1974), only duff depth had a significant linear relationship with time since last fire (R^2 = 0.13, p = 0.0051). Woody fuel accumulation may be more tied to other factors such as overstory structure or site productivity, at least within the range of time since fire present in our plots. Among plots with greater than 14 years since previous fire, those that burned under more extreme fire weather conditions (BI > 75, and also corresponding to the day of plume-dominated burning) experienced mainly high severity effects, while moderate severity burning was observed under milder conditions. This suggests that even in areas lacking recent fire activity, fires allowed to burn under less-than-extreme conditions can still provide benefit to the ecosystem, assuming moderate-severity fire effects is a desired objective (Collins et al., 2011).

The inverse relationship of elevation and fire severity observed in our study was opposite of what has been reported for other western forests, but vegetation and burning conditions were also different. Parks et al. (2013) attributed an observed increase in severity with increasing elevation to greater productivity and water availability at higher altitudes, however they included a more diverse array of vegetation types than was present in our study. Some of the lower elevation plots in our study correspond to a drier vegetation type with greater shrub cover and sparser forest cover. The greater shrub cover coupled with sparser canopy may lead to an overestimation of fire severity, as there may be high consumption of the shrub layer but low overstory mortality, particularly among plots categorized as moderate severity (Miller et al., 2009). Without post-fire field data or some measure of overstory mortality and shrub regeneration it is hard to determine to what extent these high RdNBR values reflect ecological change such as shifts in species composition or vegetation type (Holden et al., 2010).

Several forest structure variables were somewhat important in predicting fire severity; however the nature of these relationships with fire severity was different than what is often suggested. For example, plots with greater white fir basal area, a species generally associated with greater sensitivity to fire, tended to burn with lower fire severity. This effect was marginal but still present when plots that burned on a plume-dominated day were removed from the analysis. Similarly, lower fire severity was also observed in plots with a greater proportion of shade-intolerant species (proportion of white fir and incense-cedar relative to pine and oak species), although the effect was marginal in both analyses. Density of small to intermediate size trees (20–40 cm dbh in the analysis with all plots and both 40–60 cm and 60–80 cm dbh in the analysis excluding plots burned on a plume-dominated day) were also related to Rim Fire severity, with plots with a greater small tree density tending to burn with lower severity. While these relationships were not the strongest to come out in our analysis, they are worth noting as they are contrary to the results of other studies. For example, Lentile et al. (2006) found higher severity in denser areas in ponderosa pine forests in the Black Hills, and Miller et al. (2012) found that areas dominated by small trees burned at higher severity. One difference could be that our sites had a restored frequent fire regime. Areas with higher basal area of shade-tolerant species and greater tree density may be more resistant to fire effects due to their association with cooler microsites such as north facing slopes and valley bottoms (Lydersen and

North, 2012), particularly if burning under more moderate fire weather conditions.

5. Conclusions and management recommendations

Our results suggest that even in forests with a restored fire regime, wildfires can produce large-scale, high-severity fire effects under the type of weather conditions that often prevail when wildfire escapes initial suppression efforts. During the period when the Rim Fire had heightened plume activity, out of 17 plots burned, 10 were classified as high severity and 7 were classified as moderate severity. No low severity was observed, regardless of fuel load, forest type, or topographic position. This appears to have been exacerbated by the longer time since previous fire (>14 years) present in these plots. Areas burning at high severity often grow back as montane chaparral rather than forest and are likely to reburn with high severity in future fires (Thompson and Spies, 2010; Van Wagtendonk et al., 2012; Parks et al., 2013). Conifer regeneration may be enhanced by management actions (Collins and Roller, 2013), but the trajectory of the high-severity patches found in the lower elevation sites of this study is uncertain given projections of increasing wildfire activity, particularly since lower elevations may have higher burn probability (Parks et al., 2011). Long-term monitoring of these patches could provide useful insight. Plots located at higher elevations (1700–2000 m) and those that had burned more recently burned predominantly at low severity despite recent drought conditions, suggesting that forests with restored frequent-fire regimes are resilient to wildfire under less-than-extreme fire weather conditions. To effectively influence fire behavior, agencies should coordinate fuel reduction and wildfire policies across large landscapes if both jurisdictions are within the same potential 'fireshed'.

Acknowledgements

References

Brown, J.K., 1974. Handbook for inventorying downed woody material. General Technical Report INT-16, USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, 24.

Collins, B.M., 2014. Fire weather and large fire potential in the northern Sierra Nevada. Agric. Forest Meteorology 189–190, 30–35.

Collins, B.M., Everett, R.G., Stephens, S.L., 2011. Impacts of fire exclusion and recent managed fire on forest structure in old growth Sierra Nevada mixed-conifer forests. Ecosphere 2, art51.

Collins, B.M., Kelly, M., van Wagtendonk, J.W., Stephens, S.L., 2007. Spatial patterns of large natural fires in Sierra Nevada wilderness areas. Landscape Ecol. 22, 545–557.

Collins, B.M., Miller, J.D., Thode, A.E., Kelly, M., van Wagtendonk, J.W., Stephens, S.L., 2009. Interactions among wildland fires in a long-established Sierra Nevada natural fire area. Ecosystems 12, 114–128.

Collins, B.M., Roller, G.B., 2013. Early forest dynamics in stand-replacing fire patches in the northern Sierra Nevada, California, USA. Landscape Ecology, 1–13.

Collins, B.M., Stephens, S.L., 2007. Managing natural wildfires in Sierra Nevada wilderness areas. Front. Ecol. Environ. 5, 523–527.

Dennison, P.E., Brewer, S.C., Arnold, J.D., Moritz, M.A., 2014. Large wildfire trends in the western United States, 1984–2011. Geophys. Res. Lett. 41, 2014GL059576.

Finney, M.A., Bartlette, R., Bradshaw, L., Close, K., Collins, B.M., Gleason, P., Hao, W.M., Langowski, P., McGinely, J., McHugh, C.W., Martinson, E.J., Omi, P.N., Shepperd, W.D., Zeller, K., 2003. Fire behavior, fuel treatments, and fire suppression on the Hayman Fire. In: Graham, R.T. (Ed.), Hayman Fire Case Study. General Technical Report RMRS-GTR-114, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT, 33–180.

Fowler, C.T., 2003. Human health impacts of forest fires in the southern United States: a literature review. J. Ecological Anthropology 7, 39–63.

Holden, Z., Morgan, P., Hudak, A., 2010. Burn severity of areas reburned by wildfires in the Gila National Forest, New Mexico, USA. Fire Ecology 6, 77–85.

Hothorn, T., Hornik, K., Zeileis, A., 2006. Unbiased recursive partitioning: a conditional inference framework. J. Comput. Graph. Stat. 15, 651–674.

Hurlbert, S.H., 1984. Pseudoreplication and the design of ecological field experiments. Ecol. Monogr. 54, 187–211.

Janitza, S., Strobl, C., Boulesteix, A.-L., 2013. An AUC-based permutation variable importance measure for random forests. BMC Bioinformatics 14, 119.

Kapnick, S., Hall, A., 2010. Observed climate-snowpack relationships in California and their Implications for the future. J. Clim. 23, 3446–3456.

Key, C.H., Benson, N.C., 2006. Landscape assessment (LA). In: Lutes, D.C., Keane, R.E., Caratti, J.F., Key, C.H., Benson, N.C., Sutherland, S., Gangi, L.J. (Eds.), FIREMON: Fire effects monitoring and inventory system. General Technical Report RMRS-GTR-164-CD, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, LA-1-55.

Larson, A.J., Belote, R.T., Cansler, C.A., Parks, S.A., Dietz, M.S., 2013. Latent resilience in ponderosa pine forest: effects of resumed frequent fire. Ecol. Appl. 23, 1243–1249.

Larson, A.J., Churchill, D., 2012. Tree spatial patterns in fire-frequent forests of western North America, including mechanisms of pattern formation and implications for designing fuel reduction and restoration treatments. For. Ecol. Manage. 267, 74–92.

Lentile, L.B., Smith, F.W., Shepperd, W.D., 2006. Influence of topography and forest structure on patterns of mixed severity fire in ponderosa pine forests of the South Dakota Black Hills, USA. Int. J. Wildland Fire 15, 557–566.

Liu, Y., Goodrick, S., Heilman, W., 2014. Wildland fire emissions, carbon, and climate: wildfire-climate interactions. For. Ecol. Manage. 317, 80–96.

Lutz, J.A., van Wagtendonk, J.W., Thode, A.E., Miller, J.D., Franklin, J.F., 2009. Climate, lightning ignitions, and fire severity in Yosemite National Park, California, USA. Int. J. Wildland Fire 18, 765–774.

Lydersen, J., North, M., 2012. Topographic variation in structure of mixed-conifer forests under an active-fire regime. Ecosystems 15, 1134–1146.

Lydersen, J.M., North, M.P., Knapp, E.E., Collins, B.M., 2013. Quantifying spatial patterns of tree groups and gaps in mixed-conifer forests: reference conditions and long-term changes following fire suppression and logging. For. Ecol. Manage. 304, 370–382.

Mallek, C., Safford, H., Viers, J., Miller, J., 2013. Modern departures in fire severity and area vary by forest type, Sierra Nevada and southern Cascades, California, USA. Ecosphere 4, art153.

Marlon, J.R., Bartlein, P.J., Gavin, D.G., Long, C.J., Anderson, R.S., Briles, C.E., Brown, K.J., Colombaroli, D., Hallett, D.J., Power, M.J., Scharf, E.A., Walsh, M.K., 2012. Long-term perspective on wildfires in the western USA. Proc. Natl. Acad. Sci. U. S. A. 109, E535–E543.

Miller, J.D., Knapp, E.E., Key, C.H., Skinner, C.N., Isbell, C.J., Creasy, R.M., Sherlock, J.W., 2009. Calibration and validation of the relative differenced Normalized Burn Ratio (RdNBR) to three measures of fire severity in the Sierra Nevada and Klamath Mountains, California, USA. Remote Sens. Environ. 113, 645–656.

Miller, J.D., Skinner, C.N., Safford, H.D., Knapp, E.E., Ramirez, C.M., 2012. Trends and causes of severity, size, and number of fires in northwestern California, USA. Ecol. Appl. 22, 184–203.

Miller, J.D., Thode, A.E., 2007. Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). Remote Sens. Environ. 109, 66–80.

Muhle, J., Lueker, T.J., Su, Y., Miller, B.R., Prather, K.A., Weiss, R.F., 2007. Trace gas and particulate emissions from the 2003 southern California wildfires. J. Geophys. Res.-Atmos. 112, D03307.

NIFC, 2013. National Interagency Fire Center, Suppression Costs 1985–2013. <www.nifc.gov/fireInfo/fireInfo_documents/SuppCosts.pdf>. Last (accessed 18.03.14).

North, M.P., 2012. Managing Sierra Nevada forests. General Technical Report PSW-GTR-237, USDA Forest Service, Pacific Southwest Research Station, Albany, CA, 184 p.

North, M.P., Stine, P., O'Hara, K.L., Stephens, S., 2010. Harnessing fire for wildlife. Wildlife Professional 4, 30–33.

Parker, A.J., 1982. The topographic relative moisture index: an approach to soil-moisture assessment in mountain terrain. Phys. Geogr. 3, 160–168.

Parks, S.A., Miller, C., Nelson, C.R., Holden, Z.A., 2013. Previous fires moderate burn severity of subsequent wildland fires in two large western US wilderness areas. Ecosystems 17, 29–42.

Parks, S.A., Parisien, M.-A., Miller, C., 2011. Multi-scale evaluation of the environmental controls on burn probability in a southern Sierra Nevada landscape. Int. J. Wildland Fire 20, 815–828.

Parsons, D.J., Debenedetti, S.H., 1979. Impact of fire suppression on a mixed-conifer forest. For. Ecol. Manage. 2, 21–33.

Rothermel, R.C., 1991. Predicting behavior and size of crown fires in the Northern Rocky Mountains. Research Paper INT-438, USDA Forest Service, Intermountain Research Station, Ogden, UT, 46 p.

Scholl, A.E., Taylor, A.H., 2010. Fire regimes, forest change, and self-organization in an old-growth mixed-conifer forest, Yosemite National Park, USA. Ecol. Appl. 20, 362–380.

Skinner, C.N., Chang, C., 1996. Fire Regimes, past and present. Sierra Nevada ecosystem project: final report to congress. Vol. II. Assessments and scientific basis for management options. Centers for Water and Wildland Resources, University of California, Davis, pp. 1041–1069.

Skinner, C.N., Taylor, A.H., 2006. Southern cascades bioregion. In: Sugihara, N.G., VanWagtendonk, J.W., Fites-Kaufman, J., Shaffer, K.E., Thode, A.E. (Eds.), Fire in California's Ecosystems. University of California Press, Berkeley, pp. 195–224.

Stephens, S.L., Burrows, N., Buyantuyev, A., Gray, R.W., Keane, R.E., Kubian, R., Liu, S.R., Seijo, F., Shu, L.F., Tolhurst, K.G., van Wagtendonk, J.W., 2014. Temperate and boreal forest mega-fires: characteristics and challenges. Front. Ecol. Environ. 12, 115–122.

Stephens, S.L., Fry, D.L., Franco-Vizcaino, E., 2008. Wildfire and spatial patterns in forests in northwestern Mexico: the United States wishes it had similar fire problems. Ecol. Soc. 13, 1–12.

Stephens, S.L., Fule, P.Z., 2005. Western pine forests with continuing frequent fire regimes: possible reference sites for management. J. For. 103, 357–362.

Stephens, S.L., Ruth, L.W., 2005. Federal forest-fire policy in the United States. Ecol. Appl. 15, 532–542.

Strobl, C., Boulesteix, A.-L., Kneib, T., Augustin, T., Zeileis, A., 2008. Conditional variable importance for random forests. BMC Bioinformatics 9, 307.

Strobl, C., Boulesteix, A.-L., Zeileis, A., Hothorn, T., 2007. Bias in random forest variable importance measures: illustrations, sources and a solution. BMC Bioinformatics 8, 25.

Strobl, C., Malley, J., Tutz, G., 2009. An introduction to recursive partitioning: rationale, application, and characteristics of classification and regression trees, bagging, and random forests. Psychol. Methods 14, 323–348.

Taylor, A.H., 2010. Fire disturbance and forest structure in an old-growth Pinus ponderosa forest, southern Cascades, USA. J. Veg. Sci. 21, 561–572.

Thompson, J.R., Spies, T.A., 2010. Factors associated with crown damage following recurring mixed-severity wildfires and post-fire management in southwestern Oregon. Landscape Ecol. 25, 775–789.

van Mantgem, P.J., Schwilk, D.W., 2009. Negligible influence of spatial autocorrelation in the assessment of fire effects in a mixed conifer forest. Fire Ecology 5, 116–125.

van Wagtendonk, J.W., 2007. The history and evolution of wildland fire use. Fire Ecology 3, 3–17.

Van Wagtendonk, J.W., Van Wagtendonk, K.A., Thode, A.E., 2012. Factors associated with the severity of intersecting fires in Yosemite National Park, California, USA. J. Assoc. Fire Ecology 8, 11–31.

Webster, K.M., Halpern, C.B., 2010. Long-term vegetation responses to reintroduction and repeated use of fire in mixed-conifer forests of the Sierra Nevada. Ecosphere 1, art9.

Werth, P.A., Potter, B.E., Clements, C.B., Finney, M.A., Goodrick, S.L., Alexander, M.E., Cruz, M.G., Forthofer, J.A., McAllister, S.S., 2011. Synthesis of knowledge of extreme fire behavior: for fire managers. General Technical Report PNW-GTR-854, US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Vol. I. Portland, OR, 144.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western US forest wildfire activity. Science 313, 940–943.