

Topography, Fuels, and Fire Exclusion Drive Fire Severity of the Rim Fire in an Old-Growth Mixed-Conifer Forest, Yosemite National Park, USA

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ABSTRACT

The number of large, high-severity fires has increased in the western United States over the past 30 years due to climate change and increasing tree density from fire suppression. Fuel quantity, topography, and weather during a burn control fire severity, and the relative contributions of these controls in mixed-severity fires in mountainous terrain are poorly understood. In 2013, the Rim Fire burned a previously studied 2125 ha area of mixed-conifer forest in Yosemite National Park. Data from 84 plots sampled in 2002 revealed increases in tree density, basal area, and fuel buildup since 1899 due to fire exclusion. A dendroecological fire history and reconstruction of forest structure in 1899 showed that this area historically experienced frequent, low-severity fire. In contrast with this region's historical fire regime, burn severity from Landsat imagery showed that this area

burned at mixed-severity in the Rim Fire, with 13% of plots classified as unchanged, 31% low severity, 32% moderate severity, and 24% high severity. A random forest model was used to identify the controls of fire severity in this portion of the Rim Fire, using daily area burned, daily fire weather, and fuels and vegetation data for the surface and canopy. Topography, tree species composition, and cover of forbs and shrubs best explained the fire severity. As an example of a re-entry burn, this study demonstrates how fire exclusion alters fire-vegetation interactions, leading to uncharacteristically severe burns and potentially new fire-vegetation dynamics.

Key words: burn severity; fire suppression; alternative stable states; Yosemite; Rim Fire; Landsat; normalized burn ratio (NBR); random forest model.

INTRODUCTION

Recurring fire is an important ecological process in many ecosystems that consumes biomass, alters

vegetation composition and structure, and creates or maintains landscape heterogeneity (Agee 1993; Perry and others 2011). Fire effects on ecosystems within and among fires are remarkably diverse (Turner and others 1994; Collins and others 2009) and variability in these effects contributes significantly to the rates and type of post-fire vegetation development (Turner and others 2004; Johnstone and Chapin 2006; Schoennagel and others 2009; Pierce and Taylor 2011). Both modeling and

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empirical studies suggest that the probability of fire spread is related to the rate of post-fire vegetation recovery and that fire-forest structure mosaics can be self-regulating (Peterson 2002; Taylor and Skinner 2003; Collins and others 2009; Scholl and Taylor 2010; Parks and others 2014). Self-regulation results from the consumption of fuel in a burn patch which, in turn, constrains the patterns and effects of subsequent fires until sufficient fuels accumulate for the patch to burn again. In ecosystems with an intact fire regime, feedbacks between fire and vegetation would strongly influence ecosystem structure and function (Bowman and others 2009) and may generate fire-forest structure mosaics that are resilient to disturbance (Bonnicksen and Stone 1982; Halofsky and others 2011).

Changes in fire regimes over the last century caused by fire exclusion have altered fire-vegetation mosaics in western USA dry forests. Fire exclusion effects have been most dramatic in pine-dominated forests that experienced frequent, every 5–15 years, low-to-moderate severity surface fires before fire exclusion (Brown and others 2004). In these forests, exclusion of fire has led to significant changes in ecosystem structure and composition that has virtually erased the system's ecological memory (Peterson 2002), or the historical heterogeneity generated by self-regulating fire effects. There has been a several-fold increase in forest density, basal area, carbon stocks, and forest fuels, and a shift in dominance toward less fire-tolerant species (Scholl and Taylor 2010; Collins and others 2011; Knapp and others 2013; Taylor and others 2014). The increase in vegetation, biomass, and fuels has increased the risk of surface fires transitioning into the crown to cause high-severity fire (Agee and Skinner 2005). These ecosystem changes are thought to be the major reason for an increase in area burned and area burned at high severity in California pine-dominated forests in recent decades (Miller and Safford 2012), although climate warming has also contributed (Westerling and others 2006; Miller and others 2009a).

Uncharacteristically severe fires may create novel vegetation patterns and initiate positive feedbacks between fire and vegetation, shifting fire-vegetation relationships over wide areas to a different state (Lindenmayer and others 2011). Accumulating evidence from a range of temperate forest ecosystems indicates that high-severity forest fires initiate shrub lands. These shrub lands exhibit self-reinforcing fire behavior, tending to burn severely again in subsequent fires (Thompson and others 2007; Odion and others 2010; Collins and others 2009; Lindenmayer and others 2011; van Wag-

tendonk and others 2012; Parks and others 2014). The threat of uncharacteristically severe fires in fuel-rich forests is a key management concern on Park and Wilderness lands where prescribed fire and wildfires are the tools used to reduce fire risk and reintroduce fire as a regulating disturbance process in forests highly modified by fire exclusion (NPS 2006). Re-entry burns after a long period of fire exclusion can restore conditions similar to those with a functioning fire regime (Fulé and others 2004; Taylor 2010), but if burns are too severe they may generate new vegetation patterns that can be perpetuated by subsequent fires. The resulting vegetation patterns may have little resemblance to those that developed with a functioning fire regime (Savage and Mast 2005; Collins and Roller 2013; Fulé and others 2014).

In August and September of 2013 the Rim Fire, the third largest fire in California history (1042 km²), burned through a 2125 ha landscape of pine-dominated mixed-conifer forest in Yosemite National Park (YNP) in which pre-fire exclusion (1899) and contemporary (2002) forest structure, and the pre-fire exclusion fire regime had been quantitatively described in detail (Scholl and Taylor 2010; Taylor and Scholl 2012). The landscape (Big Oak Flat, or BOF) had never been logged. Prior to fire exclusion, fires were frequent (Median point fire return interval 10 years), there was evidence of self-regulation in the spatial structure of successive fires, and forests were moderately dense and dominated by pines. In 2002, the forest had attributes (that is, high density and basal area, carbon stocks, forest fuels) characteristic of mixed-conifer forests that had not experienced fire for more than a century (Scholl and Taylor 2010; Collins and others 2011; Knapp and others 2013; Taylor and others 2014). These vegetation changes would be likely to increase the prevalence of high-severity fire effects compared to those in the pre-fire exclusion period (Agee and Skinner 2005; Scholl and Taylor 2010; Taylor and others 2014). Lydersen and others (2014) also examined drivers of fire severity in the Rim Fire but in “relatively” restored areas that had burned twice or more in the past 60 years. In contrast, BOF was largely unburned since 1899 and pre-fire suppression forest structure and fire regime were known, permitting an assessment of the impacts of fire suppression driven vegetation changes on fire severity for the Rim Fire in BOF. Most mixed-conifer forests in the Sierra Nevada have not burned since the onset of fire suppression (Skinner and Chang 1996).

In this paper, we use the area burned by the Rim Fire in BOF as a ‘natural experiment’ to determine if the severity of the Rim Fire was outside the range of historical variability as represented by patterns of fire severity in 1899. Given the difficulty, or impossibility, of conducting large-scale fire severity experiments in real landscapes, researchers must often rely on slightly imperfect ‘natural experiments’ to evaluate the effects of different vegetation characteristics on fire severity (Ritchie and others 2007). We specifically address two questions. (1) What were the most important factors determining the patterns of severity in the Rim Fire? Given the dramatic changes in vegetation and fuels caused by fire suppression and the importance of weather on fire behavior, we expected these variables to be most important in controlling fire severity. (2) Were fire severity patterns in the Rim

Fire outside the range of historical variability? The fire exclusion-forest thickening vegetation change model for these forests predicts that fire exclusion would lead to more area burned at high severity compared to severity in 1899.

METHODS

Study Area

The BOF study area in YNP is 2125 ha and ranges in elevation from 1300 and 2000 m (Figure 1). The region has a Mediterranean climate, characterized by cold wet winters and warm dry summers. In YNP (south entrance station, 1560 m), mean monthly temperatures (1941–2002) in January and July are 2 and 18°C, respectively. Most (86%) of the 109 cm of mean annual precipitation falls as

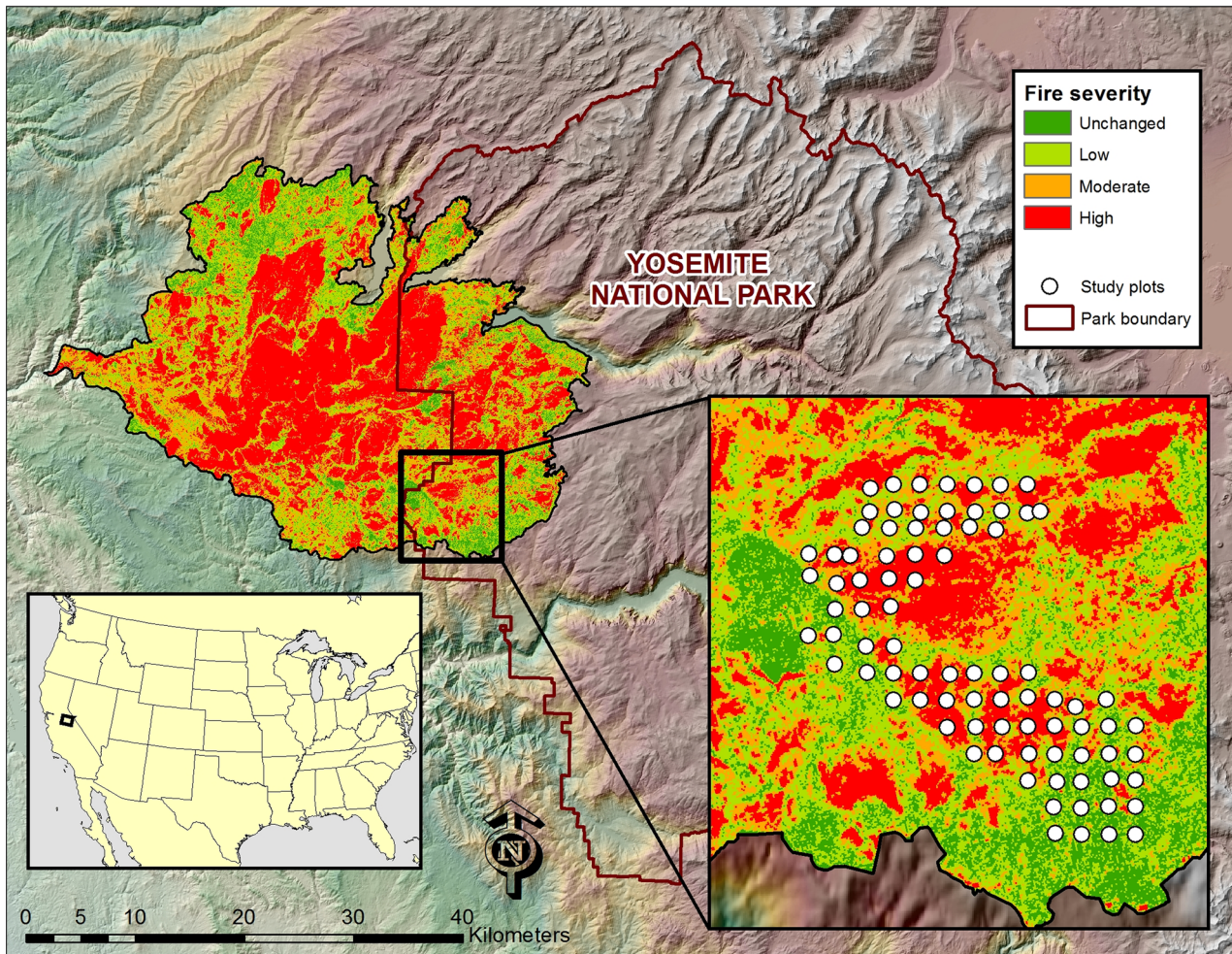


Figure 1. Burn severity (RdNBR) from the Rim Fire, classified using threshold values from Miller and Thode (2007). The *inset* at left shows the location of the study area within the continental US, and the *inset* at right shows the locations of the study plots.

snow between November and April. Soils are developed from Mesozoic-age granite and they are shallow (<1 m), excessively drained, and of medium acidity (Hill 1975; Huber 1987). Forests are of the mixed-conifer type and are a variable mixture of ponderosa pine (*Pinus ponderosa*) (nomenclature following Hickman 1993), white fir (*Abies concolor*), incense cedar (*Calocedrus decurrens*), sugar pine (*Pinus lambertiana*), Douglas-fir (*Pseudotsuga menziesii*), Jeffrey pine (*Pinus jeffreyi*), California black oak (*Quercus kelloggii*), and Pacific dogwood (*Cornus nuttallii*) (Scholl and Taylor 2010).

Pre-fire Vegetation and Fuels

In 2002, forest vegetation in BOF was sampled at 85 grid points spaced 500 m apart using nested circular plots: a 1000 m² plot for measuring the diameter (dbh) of large trees, a 250 m² plot for measuring the dbh of small trees (10–35 cm dbh for conifers and 5–15 cm dbh for hardwoods), and a 100 m² plot for counting seedlings (0.5–1.4 m tall) and saplings (>1.4 m tall). Percent covers of grasses, forbs, shrubs, mineral soil, and rock were also visually estimated in the 250 m² plot using the following cover classes: <1%, 1–5, 6–25, 26–50, 51–75, 76–100. We excluded one plot from the analysis because its GPS location was far from the other plots, making its location suspect. Data on fuels in 2002 were determined using the photo series for mixed-conifer forests type (Blonski and Schramel 1981) and then FMAPlus version 3 (Fire Program Solutions 2007) to identify the 1982 and 2005 Fire Behavior Prediction System (FBPS) fuel models for a plot. Coarse woody debris (CWD) and duff biomass were also estimated using values from the photo series (Blonski and Schramel 1981) and soil depth was measured once in each plot.

Forest composition in the plots varied with topographic setting, as shown in the nonmetric multidimensional scaling (NMDS) ordination of species' importance value (IV; the sum of relative density and basal area, 0–200) (Figure 2). Ponderosa pine and California black oak were more abundant on warmer and dryer ridgetops, while white fir, Pacific dogwood, and Douglas-fir were more abundant in more mesic valleys. Although white fir and ponderosa pine were concentrated on different topographic positions, their elevation ranges overlapped (Figure 2).

Scholl and Taylor (2010) used dendroecological methods to reconstruct the forest structure in 1899, the last year a widespread fire burned in the study area. The 1899 forest had an average density and basal area of 160 trees/ha and 30 m²/ha and forest

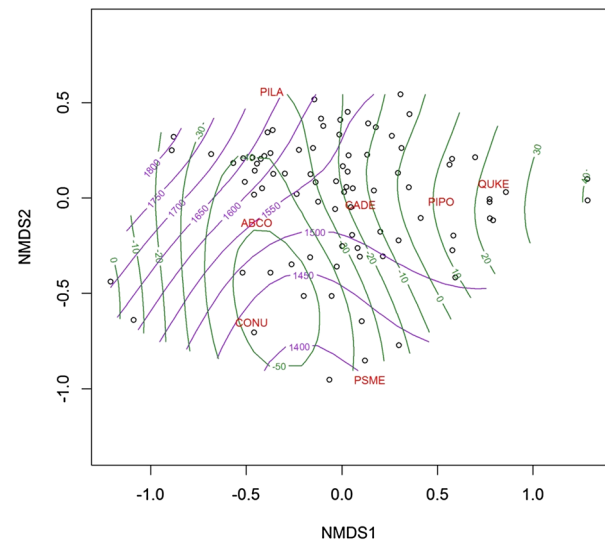


Figure 2. NMDS ordination plot using importance values (IVs) of each tree species. Circles represent individual vegetation plots. The smoothed surface of elevation (purple lines) and the TPI (green lines) are shown. PIPO = *Pinus ponderosa*, ABCO = *Abies concolor*, QUKE = *Quercus kelloggii*, PSME = *Pseudotsuga menziesii*, CONU = *Cornus nuttallii*, PILA = *Pinus lambertiana*, CADE = *Calocedrus decurrens* (Color figure online).

dominants were fire-tolerant pines. During the period of fire exclusion (1899–2002), the basal area and density of less fire-tolerant and shade-tolerant white fir increased tenfold (1.8 m² to 17.5 m²/ha, 25.3–248.9 trees/ha), the basal area and density of incense cedar doubled (9–18 m²/ha, 57.5–128.1 trees/ha), while there was only a moderate increase in the basal area and density of ponderosa pine (10.4 to 16.8 m²/ha, 37.4–44.2 trees/ha). Additional details on the forest reconstruction method, including a sensitivity analysis and validation with early forest survey data, are provided in Scholl and Taylor (2010).

Pre-fire Suppression Fire Regime

The fire regime in BOF was previously reconstructed from four sources: documentary records of fire, radial growth of tree rings, fire scars from wood samples collected in and near each plot, and the tree age structure of plots (Scholl and Taylor 2010). The mean and median point fire return interval from fire scars for BOF from 1575 to 2000 were 12.4 and 10 years, respectively. Large fires were related to drought and warm temperatures driven by variability in the Pacific North America Pattern (PNA) (Trouet and Taylor 2010; Taylor and Scholl 2012). Fire extent was also influenced by land use. The rate of burning doubled in the late 18th and early 19th

centuries during the Spanish Colonial Period, and declined in the gold rush and fire suppression period (Taylor and Scholl 2012). The average fire rotation, or number of years needed to burn an area the size of the study area, was 10 years before fire exclusion and 378 years after fire exclusion. A reconstruction of forest age structure in 1899 in each of the plots showed that they were multi-aged stands; on average, plots contained trees in 5.3 different age classes (Scholl and Taylor 2010). This multi-aged stand structure is evidence of a regime of mainly low-to-moderate severity fires before fire exclusion because higher severity fires would kill most trees and initiate even-aged stands.

Rim Fire Data

We quantified the severity of the Rim Fire using the Relative Differenced Normalized Burn Ratio (RdNBR). RdNBR is produced from Landsat TM imagery and corresponds well with field-based measurements of fire severity including the composite burn index and percent change in forest basal area and canopy cover (Miller and Thode 2007; Miller and others 2009b). RdNBR data are available through the Rapid Assessment of Vegetation Condition after Wildfire program (<http://www.fs.fed.us/postfirevegecondition/index.shtml>, 9 Nov. 2013). The Normalized Burn Ratio (NBR) is calculated from bands of Landsat TM imagery as follows:

$$\text{NBR} = \frac{\text{Band4} - \text{Band7}}{\text{Band7} + \text{Band7}}$$

Because NBR is not comparable across different areas, it is relativized to create an index that can be used for different fires and vegetation types (Miller and Thode 2007):

$$\text{RdNBR} = \frac{\text{PrefireNBR} - \text{PostfireNBR}}{\sqrt{|\text{PrefireNBR}/1000|}}$$

Due to the potential for GPS error, RdNBR values for the plots in BOF were assessed in ArcMap using bilinear interpolation, taking values from each adjacent $30 \times 30 \text{ m}^2$ cell into account. We used RdNBR from the year of the fire, 2013, using the “initial” assessment instead of the more usual one-year “extended” assessment (Key and Benson 2006). The extended assessment may capture delayed tree mortality and regrowth of vegetation not apparent in the initial assessment (Key and Benson 2006). Lydersen and others (2014) also used RdNBR for the Rim Fire from this initial assessment.

Management-ignited fires or burnouts were used to influence fire behavior in the Rim Fire. Burnouts were set in areas near the vegetation plots, al-

though they are unlikely to have influenced burn severity in the study area. Burnouts were confined to the Tuolumne Grove, south of the study area, on a day when weather created minimal risk of fire spread (Douglas F. Smith, National Park Service, pers. comm., Jan. 30 2014). Burnouts set west of the plots could have crossed a road that was being used as a fire line and moved into the study area, but the clear spread of the fire from northwest to southeast (Figure 3) suggests that fire effects are only the result of natural fire spread.

Topographic, Weather, and Fire History Variables

In addition to the vegetation and fuels variables, we also considered topography, weather, and fire history as potential predictors of the severity of the Rim Fire. We derived topographic variables for each vegetation plot from a 30 m digital elevation model (DEM) (<http://nationalmap.gov/elevation.html>, 31 Oct. 2013). The variables determined included elevation, slope, aspect, and the Topographic Position Index (TPI), an index where low values represent canyons and high values represent ridges (Jenness and others 2013). We also calculated the Topographic Relative Moisture Index (TRMI), a measure of potential soil moisture (on a 0–60 scale from xeric to mesic, Parker 1982) for each plot using field estimates of slope, aspect, slope configuration, and topographic position (Scholl and Taylor 2010).

Weather conditions on each day of the burn were identified using daily fire perimeter maps (<ftp://ftp.nifc.gov/>, 9 Oct. 2013) and 24-h fire weather data from the nearby (<3 km) Crane Flat RAWS station (2025 m). For each day of the burn, we calculated the mean, minimum and maximum temperature, and relative humidity, and the mean and maximum wind speed for that 24-h period. Fire Family Plus (v4.1) was used to calculate the burning index (BI), a measure of how difficult a fire is to contain. The burning index relates closely to flame length and fireline intensity (Bradshaw and others 1983). We also estimated the Haines index (Haines 1988) over BOF using daily maps of the index (<http://www.wfas.net/>, 25 Mar. 2014). The Haines index (HI) combines lower atmospheric components of stability and moisture into a measure of potential for erratic fire behavior, potential wildfire growth, and fire risk. Atmospheric instability is an important factor in fire growth via its enhancement of uplift, fire, and convective surface winds. Years in northern California with high area burned are associated with high values of HI (Trouet and others 2009).

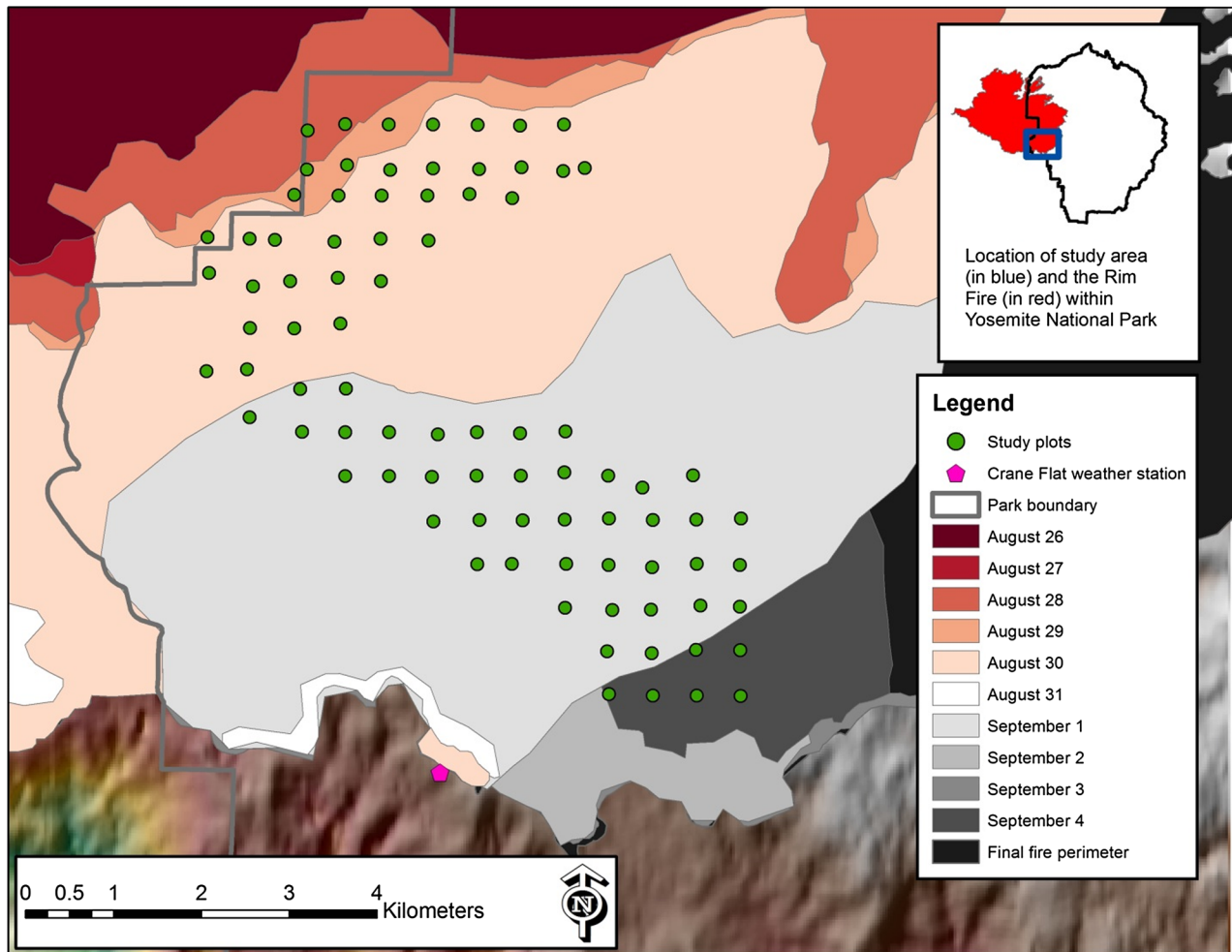


Figure 3. The spread of the Rim Fire through Big Oak Flat (BOF) in YNP in 2013.

Although the study area experienced no widespread fire between 1899 and 2013, 13 plots lie within the perimeters of controlled burns from 2002 or 2005 according to fire history polygons (1930–2011) for YNP (<https://irma.nps.gov/App/Reference/Profile/2170431>, 20 Jan. 2014). To account for possible impacts of these fires on fuels and subsequent fire severity, we calculated time (years) since last fire for these points as a potential predictor of fire severity based on the fire history polygons. Although little evidence of burning from these fires was seen during data collection in BOF from 2002 to 2005, adding this variable considers the possible confounding factor of recent fire history.

Modeling Fire Severity

We developed a predictive model of RdNBR, or fire severity, using vegetation, fuels, and topographic variables from the 84 plots from Scholl and Taylor (2010) along with fire weather variables. Redun-

dant variables were removed from the analysis to aid interpretation of the results and to focus on ecologically distinct drivers of fire severity rather than evaluating the relative importance of similar variables. From an initial pool of variables, we excluded the following: (1) the type of species for seedling and sapling in 2002 because species was thought to be less important than their overall density and (2) redundant variables such as TPI values for neighborhood sizes of 500, 1000, and 2000 m. In the case of redundant variables we retained the variable with the strongest correlation with RdNBR, which was the 2000 m neighborhood size in the case of TPI (Spearman $r_s = 0.46, 0.41,$ and 0.35 for a 2000, 1000, and 500 m neighborhood, respectively). Species-specific basal areas and densities were also removed in favor of the IV, which encapsulates both basal area and density. The remaining 45 variables (Table 1) were considered for building models to explain variation in RdNBR.

Table 1. Variables Considered as Potential Predictors of Fire Severity, Divided into Categories (Topography, Vegetation and Fuels, and Weather), and Presented in order of Variable Importance from the Full Random Forest Model (as Measured by Increase in Mean Standard Error when a Given Variable is Randomized within the Model)

	Inc. in MSE	Range and mean/median or number in each class
Topography		
TPI	26.1	-131 to 154 (-13)
Elevation (m)	12.9	1310-2003 (1566)
TRMI	12.9	12-54 (31)
Aspect	2.5	E (15), N (21), S (16), W (32)
Slope (%)	-0.4	2.9-52.8 (23.6)
Vegetation and fuels		
ABCO 1899 IV	17.7	0-100 (19)
Forbs	16.8	<1 to 75-100 (1-5)
PIPO 2002 IV	13.3	0-174 (36)
Shrubs	12.9	<1 to 75-100 (<1)
Soil depth (cm)	12.1	9-95 (65)
2002 density (stems/Ha)	8.3	130-1560 (806)
Years since last burn	7.5	8-83 (62)
ABCO 2002 IV	7.4	0-200 (72)
1899 density (stems/Ha)	5.7	20-410 (111)
CONU 2002 IV	5.3	0-61.3 (1)
2002 basal area (m ² /Ha)	5.1	29-198 (100)
QUKE 2002 IV	4.9	0-107 (14)
Total carbon 2002 (Mg C/Ha)	3.5	130-1068 (453)
Down carbon 2002 (Mg C/Ha)	3.5	14-151 (49.8)
Rock	3.0	<1 to 50-75 (<1)
CWD (Mg C/Ha)	2.5	0.6-10.1 (5.3)
QUKE 1899 IV	2.4	0-119 (16)
2005 FBPS fuel model	2.0	TL03 (17), TL04 (49), TL05 (1), TL07 (9), TL08 (5), TU03 (3)
PIPO 1899 IV	1.2	0-200 (64)
PILA 1899 IV	1.1	0-200 (29)
PSME 1899 IV	0.6	0-67.8 (4.4)
CADE 1899 IV	0.2	0-175 (66)
PILA 2002 IV	-0.3	0-98.4 (23)
Mineral soil	-0.5	<1 to 75-100 (<1)
Total saplings	-1.0	0-42 (9.3)
Total carbon 1899 (Mg C/Ha)	-1.1	15.5-564 (154)
PSME 2002 IV	-1.3	0-75.2 (5.1)
Litter	-2.8	<1 to 75-100 (75-100)
Total seedlings	-2.9	0-189 (13)
1982 FBPS fuel model	-3.0	FB02 (3), FB08 (26), FB09 (5), FB10 (2), FB11 (46), FB12 (2)
1899 basal area (m ² /Ha)	-3.1	0.2-90.3 (31.1)
2002 duff biomass (Mg C/Ha)	-3.5	11.5-145.9 (44.5)
Grass	-4.1	<1 to 50-75 (<1)
CADE 2002 IV	-4.7	0 to 140 (48.4)
Weather		
Burning index	1.0	44-52 (44.6)
Day of burn	0.9	1-8 (5)
Haines index	0.0	3-3 (3)
Avg. relative humidity (%)	-0.1	29-52 (42.5)

Table 1. continued

	Inc. in MSE	Range and mean/median or number in each class
Average air temperature (°C)	-0.2	18.5–21.7 (19.8)
Avg. wind speed (m/s)	-1.0	2–3.7 (2.2)

The top 8 variables are bolded. The following are reported according to the type of variable: range and mean for continuous variables, range and median for ordinal variables, and number of plots falling within each class for nominal variables.

All topography variables were derived from a digital elevation model (DEM) except for TRMI (the Topographic Relative Moisture Index), which was derived from field data. All vegetation/fuels variables were derived from plot-level field data except for years since last burn, which was derived from fire history polygons for Yosemite National Park (<https://irma.nps.gov/App/Reference/Profile/2170431>, 20 Jan. 2014). All weather variables were derived from data from the Crane Flat weather station except for the Haines Index, which was derived from daily maps of the index (<http://www.wfas.net/>, 25 Mar. 2014). “Total carbon” and “Total carbon 1899” refer to total aboveground carbon from trees only based on measurements in 2002 and the reconstruction of forest structure in 1899 (Scholl and Taylor 2010), while total down carbon refers to carbon contained in trees identified as dead and down in 2002. Additional information on how variables were derived is found in “Methods” section.

TPI = Topographic Position Index; IV = importance value; CWD = coarse woody debris; FBPS = Fire Behavior Prediction System; IRMA = Integrated Resource Management Applications; PIPO = *Pinus ponderosa*; ABCO = *Abies concolor*; QUKE = *Quercus kelloggii*; PSME = *Pseudotsuga menziesii*; CONU = *Cornus nuttallii*; PILA = *Pinus lambertiana*; CADE = *Calocedrus decurrens*.

We used random forest (RF) to identify the variables controlling fire severity. RF (Breiman 2001) is an extension of classification and regression trees (CART; De’ath and Fabricius 2000) that is increasingly used in ecological research (Prasad and others 2006; Iverson and others 2008; Holden and others 2009; Dillon and others 2011; Peterson and others 2013). RF works by building a large number of classification or regression trees and aggregating the results. For each regression tree, a bootstrap sample is drawn from the dataset, and the tree is built by selecting from a random sample of the predictors at each node (Liaw and Wiener 2002). RF models were developed using the randomForest package in R (Liaw and Wiener 2002). For each RF model, we built 4000 regression trees, using a large number of trees in order to generate stable results. One-third of the predictors were selected for building each tree, the default setting (Liaw and Wiener 2002). Because results from RF can vary slightly from run to run, we used average results from 10 runs for each model. Model fit was assessed using the pseudo- r^2 , calculated using the mean squared error and variance in the same way as the r^2 from a linear regression (Liaw and Wiener 2002). Graphical analysis was used to ensure that residuals were randomly distributed and homoscedastic across the range of fitted values. The importance of a predictor variable was assessed using the increase in mean standard error (MSE) when a given variable is randomized within the model. The relationship between variables and fire severity was also evaluated using partial dependence plots, which display the marginal effect of an individual predictor on the response variable (Liaw and Wiener 2002). We first developed a “full” RF model with all 45 variables and then a “top” RF model using the top eight variables in the “full” model according to the increase in MSE. Eight

variables were selected for this ‘top’ model because of a gap in variable importance beyond the top eight variables (Table 1) and because the top 8 variables yielded a higher pseudo- r^2 than using any other number of top variables.

We also ran RF models of fire severity using only vegetation and fuels variables, only topographic variables, and only weather variables (three separate pools of variables), following the above procedure. The purpose of these models was to evaluate the relative influence of each category of variables on fire severity. We first ran models using all variables in each category and then variables with the lowest importance were individually removed to assess how many of the ‘top’ variables in each category were needed to maximize the pseudo- r^2 . We only report models with the highest pseudo- r^2 in the results.

RESULTS

Fire severity across BOF was highly variable. According to the RdNBR classification of fire severity thresholds used by Miller and Thode (2007), 11 plots were “unchanged” (13%), 26 plots were low (31%), 27 plots were moderate (32%), and 20 plots were high-severity plots (24%). See Figure 4 for examples of how plots in these severity classes appeared in the summer of 2014, after the Rim Fire.

The RF model of RdNBR produced patterns of fire severity visually similar to the observed patterns (Figure 5). Three topographic variables and five vegetation and fuels variables were important in explaining fire severity (Table 1). TPI had the highest variable importance (Table 1), followed by the white fir IV in 1899 and then forb cover. The RF model with the top eight variables had the highest pseudo- r^2 (0.38, Table 2). Two of the



Figure 4. Characteristic vegetation plots in BOF for each of four fire severity classes, based on RdNBR threshold values from Miller and Thode (2007).

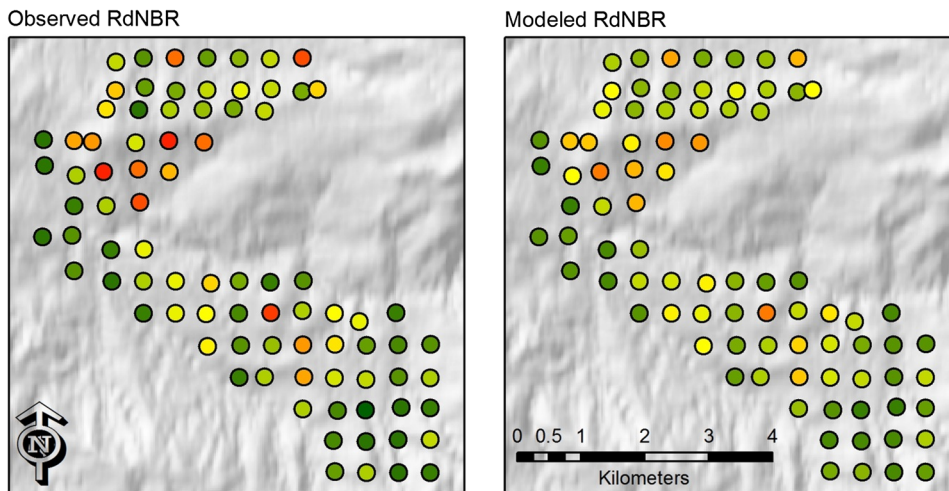


Figure 5. Observed RdNBR (left) and RdNBR modeled using RF (right) for the plots in BOF. RdNBR is displayed on a continuous color gradient, with green and red representing low and high RdNBR, respectively. This RF model used the 8 variables identified in Figure 5 (Color figure online).

topographic variables, TRMI and TPI, were correlated ($r_s = -0.39$) but both variables were retained because they are ecologically distinct; TRMI is a measure of potential soil moisture, while TPI measures the topographic setting relative to the surrounding neighborhood (2000 m in this case). Weather variables were not included in

RF model with the eight most important variables, nor was the fire history variable (years since last burn). RF models using topography alone (pseudo- $r^2 = 0.26$) and vegetation and fuels alone (pseudo $r^2 = 0.29$) partly explained fire severity, while weather variables alone (pseudo- $r^2 = 0.03$) did not.

Table 2. RF Models Constructed Using Four Pools of Variables: All Variables, Vegetation and Fuels Variables Only, Topographic Variables Only, and Weather Variables Only

Pool of variables	Pseudo R^2	Variables used
All	0.23	All variables in Table 1
Top 8	0.38	TPI, ABCO 1899 IV, forbs, PIPO 2002 IV, elevation, shrubs, soil depth, TRMI
Vegetation only	0.29	ABCO 1899 IV, forbs, PIPO 2002 IV, shrubs, soil depth
Topography only	0.26	TPI, elevation, aspect, TRMI, slope
Weather only	0.03	Day of burn, average wind speed, average temperature, average RH, HI, BI

Table 1 includes further details on each variable.

Partial dependence plots from RF reveal how fire severity responded to each individual variable (Figure 6). Topographically high areas burned more severely than low areas, plots at 1450–1700 m elevation burned more severely, and areas with lower soil moisture (TRMI) burned more severely than those with higher soil moisture. Plots with shallower soils also burned more severely than those with deeper soils. The IV of white fir in 1899 had a greater variable importance than it did in 2002 (Table 1). Areas high in white fir in 1899 tended to burn at low severity (Figure 6). Conversely, plots tended to burn at low severity if they had little ponderosa pine in 2002. Understory vegetation also influenced fire severity. Areas with high forb and shrub cover tended to burn more severely (Figure 6). Moreover, areas of high forb and shrub cover in 2002 also tended to coincide with locations of high ponderosa pine IV; plots with 76–100% cover of forbs and shrubs had average ponderosa pine IVs of 91 and 72, respectively, compared to with 30 and 35 in plots with less forb coverage.

DISCUSSION

Controls on Fire Severity

Prior to fire exclusion, mixed-conifer forests in BOF experienced a multi-century regime of frequent low-severity fire. Forests that developed under this regime were moderately dense, multi-aged, and had a fine-grained spatial structure (<0.2 ha) of overlapping groups of similar aged trees. Variation in fire frequency and fire severity were not significantly related to forest composition or topography and area re-burned by consecutive fires was 10-fold smaller than on sites not burned by the previous fire (Scholl and Taylor 2010). This suggests that the effects of burns constraining the patterns and effects of subsequent burns were important mechanisms of self-regulation that shaped the fire-forest structure mosaic in BOF. After a hiatus of fire for

more than a century, the Rim Fire burned through the entire study area, the only recorded burn to do so in the period of record (500 years) (Scholl and Taylor 2010). Such an unusually extensive fire and the initiation of new fire-vegetation patterns are consistent with the idea of fire suppression reducing a system's ecological memory by eliminating fire-generated heterogeneity within a burn patch mosaic (Peterson 2002).

As we expected, Rim Fire severity in these fuel-rich forests was influenced by vegetation and fuels variables but topographic variables were also important. The importance of topographic position, elevation, and relative soil moisture in explaining fire severity reflects the strong influence of topography on vegetation composition and fire behavior. In complex terrain, variation in topography affects weather, fuel moisture, and species composition, which all can influence flammability (Agee 1993; Holden and others 2009; Lydersen and North 2012). Fire spreads more readily upslope than downslope, and daytime upslope winds that develop from differential heating in mountainous terrain can drive upslope fire spread (Werth and others 2011). Moreover, middle and upper slope positions often experience higher fire line intensities because of higher effective wind speeds, lower canopy cover, and preheating of fuels as fires move upslope (Rothermel 1983). Lower TRMI should correspond with lower soil moisture and drier fuels, which would increase fire intensity. However, the long dry summers in the Sierra Nevada tend to create dry fuel conditions across all topographic setting in mixed-conifer forests by late July or August (Estes and others 2012; Banwell and others 2013). This suggests that the fire severity response to TRMI is likely related to some aspect of site condition rather than fuel moisture. Topography is also important in explaining fire severity in other regions. Across forests and woodlands in the western USA, topographic variables were rel-

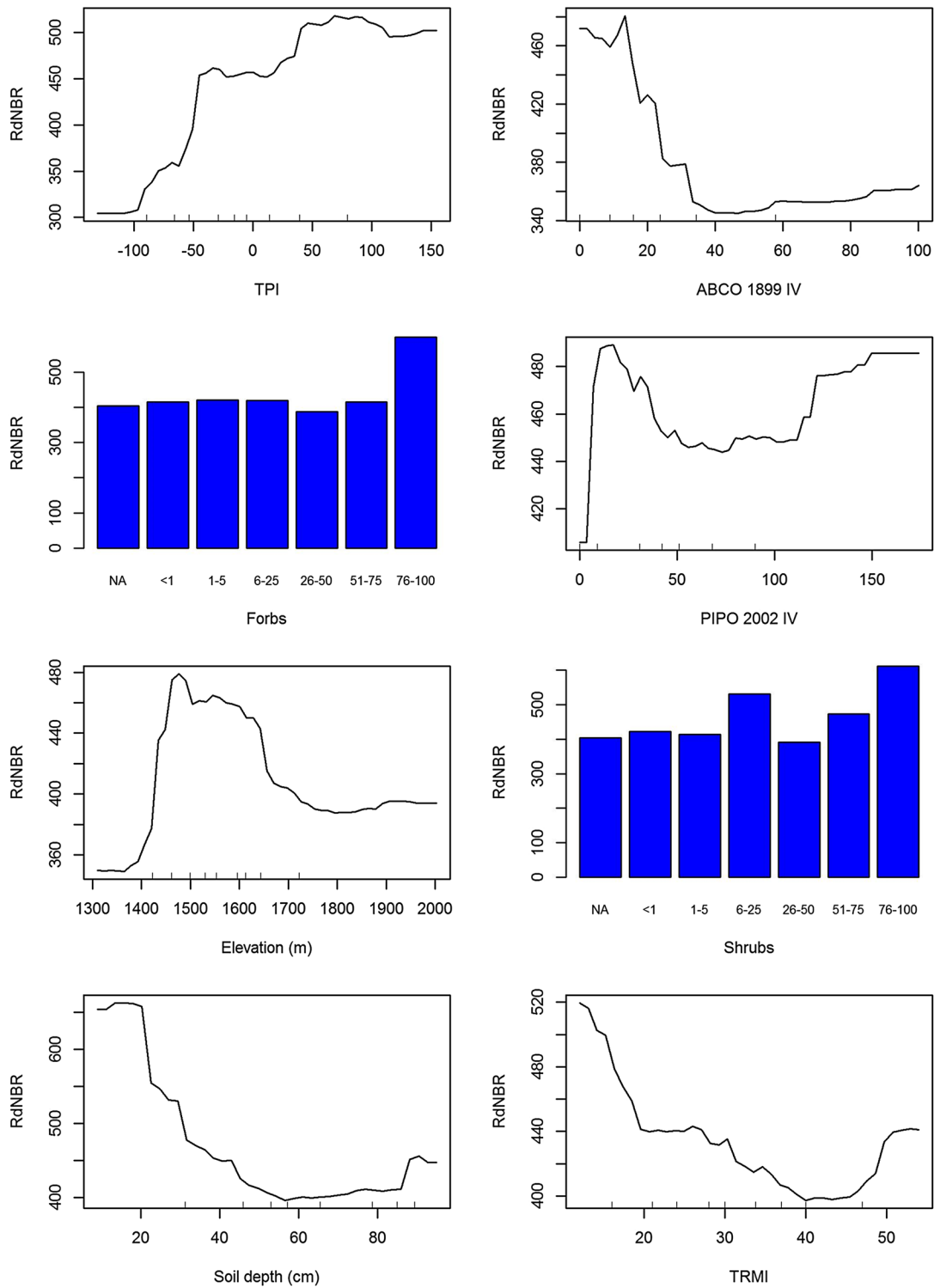


Figure 6. Partial dependence plots for the random forest model run using only the top 8 variables identified in the full model, showing the response of fire severity (RdNBR) to individual predictor variables. The variables shown are aspect, topographic position index (TPI), importance value of *Abies concolor* in 1899 (ABCO 1899 IV), cover classes of forbs (grouped by percent coverage), importance value of *Pinus ponderosa* (PIPO IV), elevation, cover classes of shrubs, soil depth, and the topographic relative moisture index (TRMI). Together, these predictor variables generated modeled RdNBR values between 67 and 1095 with a mean of 435.

atively more important predictors of fire severity than weather or climate (Dillon and others 2011).

Vegetation and fuel variables were important for explaining fire severity. Plots with ponderosa pine burned at higher severity than those with little or no ponderosa pine, likely because long-needled litter from ponderosa pine is more flammable than litter from short-needled fir (Agee 1993). Severe crown damage in other fires in California has also been associated with higher dominance of ponderosa pine (Weatherspoon and Skinner 1995). High forb and shrub covers were also associated with high-severity fire in BOF. We hypothesize that this relationship was due mainly to the high cover of bear clover (*Chamaebatia foliolosa*). Bear clover is a highly flammable forb, and leaf and needle litter that falls on it remains elevated, allowing more oxygen to circulate through the fuel bed creating intense fire (van Wagendonk 1974). Shrub abundance has also been linked to high fire severity in previously burned areas in other parts of the Rim Fire (Lydersen and others 2014) and in other fires in the western USA (Thompson and Spies 2009; Halofsky and others 2011). Pine dominance and high forb and shrub covers likely interacted to produce patches of high-severity fire effects. On the other hand, areas with abundant short-needled white fir in 1899 tended to burn at low severity. Fir-dominated mixed-conifer sites tend to be more mesic and cooler than pine-dominated sites (Beatty and Taylor 2001; Scholl and Taylor 2010), suggesting that the white fir abundance in 1899 in the RF model is an indicator of environmental factors like temperature and moisture.

Fire weather is known to strongly influence fire behavior and fire severity (Agee 1993) but fire weather variables were not important in explaining fire severity in BOF. This contrasts with previous research in YNP which identified relative humidity, wind speed, temperature, or BI as important variables explaining fire severity along with vegetation type (Collins and others 2007, 2009; Collins and Stephens 2010). One reason for this difference may be that weather conditions associated with different fire severities were not reached. Weather thresholds for relative humidity (23.7%), wind speed (7.1 m/s), and temperature (26.3°C) explaining fire severity in a 2001 fire in YNP (Collins and others 2007) were rarely or never exceeded during the burning period of the Rim Fire in BOF (Figure 7).

Studies on other areas burned by the Rim Fire have drawn different conclusions about the relative importance of fuels, topography, and weather in explaining fire severity patterns. Lydersen and others (2014) used data from plots that had burned

at low-to-moderate severity two or more times from either prescribed burns or wildfire in the past 60 years. These recently burned plots were considered to represent a partially restored fire regime. In contrast, BOF was largely unburned since 1899 and more strongly reflects the impacts of fire exclusion on fuels and forest structure. BOF represents the more typical forest condition. Most mixed-conifer forests in the Sierra Nevada have not experienced fires in more than a century (Skinner and Chang 1996). Fire history (years since last burn) was not an important driver of fire severity in BOF, likely reflecting this lack of fire. Similar to BOF, Lydersen and others (2014) found that elevation and shrub cover were important. Areas with higher shrub cover and at lower elevation burned at higher severity. Surprisingly, topographic variables were not identified as being important, while topographic position was the single most important variable in BOF. Moreover, two weather variables, BI and “plume-dominated” fire days, a qualitative estimate of fire weather, were top variables in Lydersen and others’ (2014) models of fire severity. HI, a quantitative index of atmospheric instability that measures potential for fire growth, was not important in explaining fire severity during the days of burning in BOF. However, HI index values were high during the period of initial rapid growth of the Rim Fire, suggesting a response to atmospheric instability (Figure 7). Spikes in HI have been shown to correspond with days of rapid fire growth (Werth and Ochoa 1993; Luo and others 2013). A comprehensive analysis of the entire Rim Fire, however, would be needed to test the hypothesis that fire severity patterns shifted from being under exogenous control (that is, extreme weather) to local or endogenous control (that is, topography, vegetation/fuels) over the course of the fire.

Vegetation and weather variables also explained fire severity patterns in the large (>200,000 ha) 2002 Biscuit Fire in northern California and southern Oregon (Thompson and Spies 2009). High fire severity was associated with high temperatures in the Biscuit Fire, but they were notably higher (mean = 27°C) than during the period of burning in BOF (18–23°C). In the Biscuit Fire, the single most important variable explaining fire severity was shrub cover. Areas where high-severity fire effects in a preceding fire had switched vegetation from forest to shrub lands burned at high severity again. Shrub cover was an important variable in BOF but not the top variable, likely because BOF was characterized by closed-canopy forests with lower shrub cover than in the Biscuit Fire area.

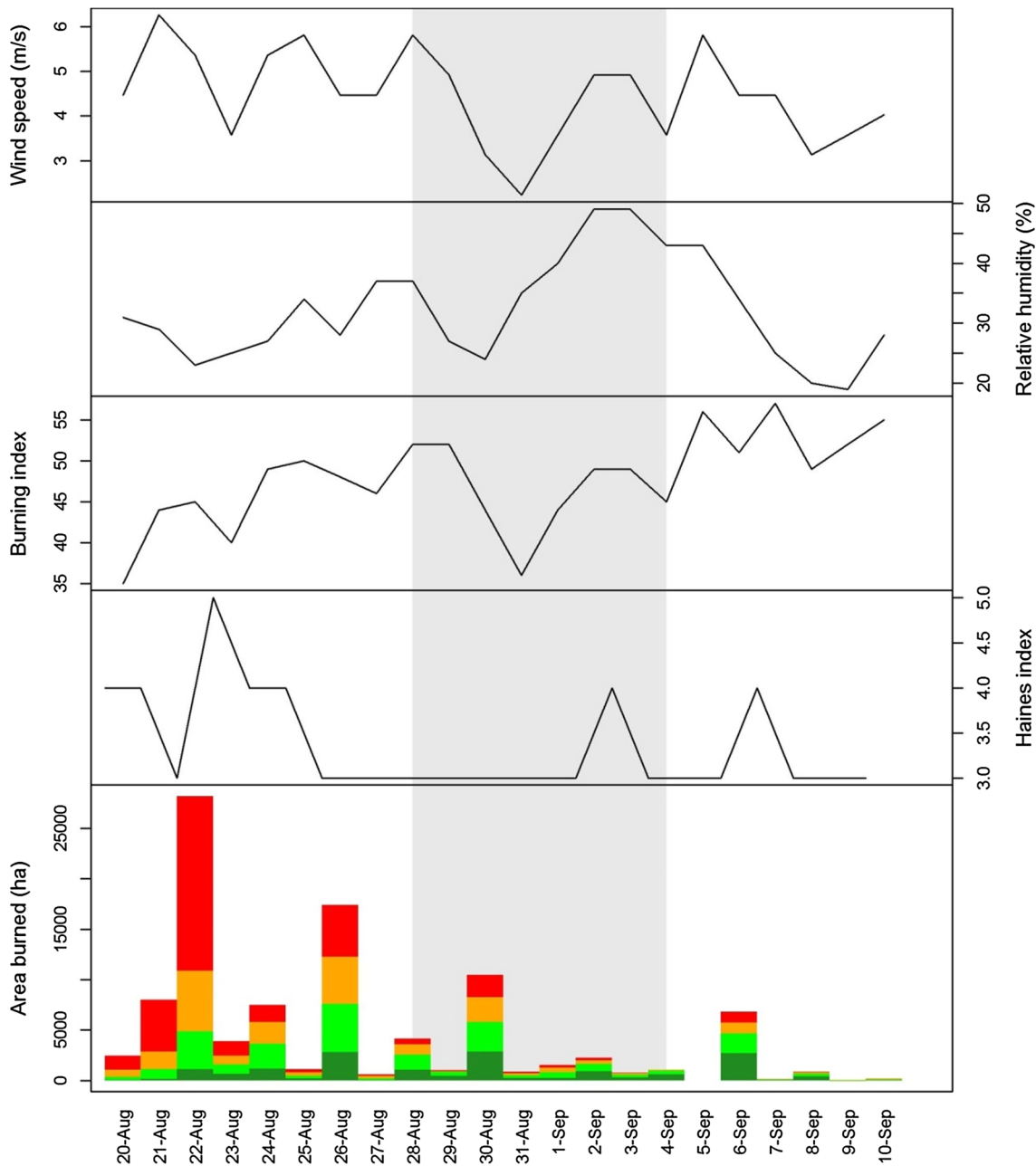


Figure 7. Daily area burned by the Rim Fire between August 20 and September 10, 2013 and weather conditions on those days. The days over which BOF burned are shaded. Each bar represents a 24-h period, roughly 12:00 AM–12:00 AM. The color of the bars represents severity: dark green is unchanged, light green is low, orange is moderate, and red is high. The Haines index, a measure of lower atmospheric stability, is offset in this figure by –12 h from the burning index, relative humidity, and wind speed because it is calculated once for each morning instead of being a 24-h mean (Color figure online).

Historical Context of the Rim Fire in BOF

As we expected, the severity patterns of the Rim Fire in BOF were very different from the severity of fires before fire exclusion. In the Rim Fire, 32% of plots burned at moderate severity and 24% burned at high severity. There was no evidence of high or

moderate severity fire in BOF before fire exclusion (Scholl and Taylor 2010). From this comparison, we conclude that the severity patterns in the Rim Fire were outside the range of historical variability of fire severity in BOF and this is likely true for other mixed-conifer forests that experienced high

proportions of moderate and high-severity fire in the Rim Fire. Overall, the proportionally high severity of the Rim Fire in BOF is consistent with predictions of the fire exclusion-forest thickening model for a shift to higher severity fire for dry western forests (Fulé and others 2014). Other dry western forests that historically burned frequently have experienced similar increases in vegetation density, biomass, and fuels, and shifts in species composition and are expected to experience more high-severity fire than they did historically (Agee 1993; Taylor and Skinner 2003; Coker and others 2005; Sakulich and Taylor 2007; Knapp and others 2013; Taylor and others 2014; O'Connor and others 2014).

The relatively high proportion of moderate and high-severity burn in BOF is even more notable given the relatively mild weather conditions during the burn. From the RF model, it may be inferred that the Rim Fire left BOF with patches of very low and very high tree density and basal area, and affected ponderosa pine stands on ridges more than historically fir-dominated stands on lower slopes and valley bottoms. In this way, the Rim Fire altered forest structure, while increasing structural heterogeneity, potentially contributing to novel patterns of species composition and vegetation structure compared to historical conditions. The evidence from BOF suggests that re-entry burns may not restore fuel-rich forests to their pre-fire suppression structure if the fires burn at uncommonly high severity due to extreme conditions (for example, drought, and fire weather) or high fuel loads. The unusually high proportion of moderate and high-severity fire for the Rim Fire in BOF compared to pre-fire exclusion severity contradicts claims that the Rim Fire and other recent large high-severity fires in mixed-conifer forests restore historic conditions (Baker 2014; Dellasala and others 2014; Odion and others 2014).

Future Fire and Landscape Dynamics in BOF

A key premise of landscape ecology is that the effects of disturbance on current landscape patterns are influenced by current vegetation characteristics, which are in turn, an artifact of the history of previous disturbance (Turner 1989; Peterson 2002; Collins and others 2009). These interactions historically led to self-regulating fire effects, but changes in these interactions due to altered vegetation structure and unusual burns may lead to new types of fire effects (Peterson 2002; Collins and others 2009; Parks and others 2014). Recent re-

search has demonstrated that overlapping wildfires in Sierra Nevada mixed-conifer and dry forests in other regions of the western USA exhibit self-regulating behavior after only two or three burns over several decades. Initial burns reduced the spread and severity of subsequent fires, rates of fuel accumulation or time since last fire was important in determining persistence of burn effects, and different vegetation types generated by initial burn severity tended to burn with the same severity again (Collins and others 2007, 2009; van Wagendonk and others 2012; Parks and others 2014). These general patterns are, of course, mediated by local factors such as fire weather or topography that would influence variability in fire effects (Collins and others 2007, 2009; Collins and Stephens 2010; Holden and others 2009; van Wagendonk and others 2012; Parks and others 2014; Kane and others 2015).

The propensity of different fire-generated vegetation types to reburn at the same severity can lead to new stable states if fire severity causes a switch in vegetation type (Gunderson 2000; Lindenmayer and others 2011). High fire severity in California mixed-conifer forests initiates a period of dominance by fire dependent shrubs (montane chaparral) that establish from a buried seed bank (Knapp and others 2012) and repeat burns perpetuate montane chaparral on sites otherwise capable of supporting trees (Nagel and Taylor 2005; Collins and others 2009; van Wagendonk and others 2012; Collins and Roller 2013). Severity-influenced vegetation type mosaics are thought to be stable over time (Thompson and others 2007; Odion and others 2010; Halofsky and others 2011; Collins and Roller 2013) but they would be influenced by vegetation type switching caused by succession or new fires. In the case of BOF and other forests highly altered by fire exclusion, a proportional shift to higher severity fire may transition significant portions of landscapes to areas that persistently burn at high severity. Such a shift is catalyzed by fuel buildup from fire exclusion and may be exacerbated by recent climate change (Miller and others 2009b).

Our work on Rim Fire effects in BOF demonstrates that fire severity patterns in a re-entry burn under moderate weather conditions were related to variation in topography and fuels and that the re-entry burn had an unusually high proportion of moderate and high-severity fire compared to severity before fire exclusion. From a management perspective our work indicates the following: (1) multiple low-moderate severity burns may be needed to reduce connectivity of surface fuels and

thin the canopy before wildfires could restore a self-regulating fire-vegetation mosaic resembling those of the pre-fire exclusion period; (2) topographic variation could be used as a guide to identify locations with a risk of high-severity fire and where fuels reduction would have a high impact (e.g., mid and upper slopes) on potential fire severity across landscapes (Taylor and Skinner 1998; Holden and others 2009; North and others 2009; Lydersen and North 2012); and (3) the severe effects of the Rim Fire were historically unusual and have the potential to transition areas to shrub lands that fire would maintain in a new state (Gunderson 2000; Lindenmayer and others 2011).

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