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Evidence of fuels management and fire weather influencing fire severity in an extreme fire event

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Abstract. Following changes in vegetation structure and pattern, along with a changing climate, large wildfire incidence has increased in forests throughout the western United States. Given this increase, there is great interest in whether fuels treatments and previous wildfire can alter fire severity patterns in large wildfires. We assessed the relative influence of previous fuels treatments (including wildfire), fire weather, vegetation, and water balance on fire-severity in the Rim Fire of 2013. We did this at three different spatial scales to investigate whether the influences on fire severity changed across scales. Both fuels treatments and previous low to moderate-severity wildfire reduced the prevalence of high-severity fire. In general, areas without recent fuels treatments and areas that previously burned at high severity tended to have a greater proportion of high-severity fire in the Rim Fire. Areas treated with prescribed fire, especially when combined with thinning, had the lowest proportions of high severity. The proportion of the landscape burned at high severity was most strongly influenced by fire weather and proportional area previously treated for fuels or burned by low to moderate severity wildfire. The proportion treated needed to effectively reduce the amount of high severity fire varied by spatial scale of analysis, with smaller spatial scales requiring a greater proportion treated to see an effect on fire severity. When moderate and high-severity fire encountered a previously treated area, fire severity was significantly reduced in the treated area relative to the adjacent untreated area. Our results show that fuels treatments and low to moderate-severity wildfire can reduce fire severity in a subsequent wildfire, even when burning under fire growth conditions. These results serve as further evidence that both fuels treatments and lower severity wildfire can increase forest resilience.

Key words: fire progression; fire severity; fuels reduction; fuels treatment; landscape analysis; mixed conifer forest; Rim Fire; Stanislaus National Forest; thinning; wildfire; Yosemite National Park.

Introduction

Changes in forest stand structure and landscape vegetation patterns have increased vulnerability of dry temperate forests to ecological stressors and disturbance in the western United States. At the stand scale, higher contemporary tree densities, proportions of shade-tolerant tree species, and biomass of surface and ladder fuels have increased the potential for crown fire (Brown et al. 2008, Taylor et al. 2014) and individual tree mortality rates (Fettig et al. 2007, Collins et al. 2014). At the landscape scale (e.g., watershed, management district), loss of heterogeneity in vegetation types/structures and greater connectivity among vegetation patches (Hessburg et al. 1999, 2005) have contributed to uncharacteristically high tree mortality and fire extents and severities (Harris and Taylor 2015, Young et al. 2017). These changes in forest structure, fire behavior, and tree mortality have been attributed to two major factors: a history of fire exclusion and a warming climate associated with increasingly hot and dry conditions during the summer fire season (Agee and Skinner 2005, Westerling et al. 2006). Fire suppression has increased fire intervals, leading to the accumulation of forest understory fuels and thereby increasing the probability of high-severity fire (Parsons and Debenedetti 1979). A warming climate stresses trees, making them more susceptible to mortality (especially when coupled with insect pests and disease; van Mantgem and Stephenson 2007, Das et al. 2013). Beyond the ecological impacts, recent climate change has been associated with increased frequency of extreme fire weather (Collins 2014) and consequently, extreme fire events (Stavros et al. 2014). Collectively, these changes have increased the potential for erratic and extreme fire behavior that can lead to loss of property and lives (Calkin et al. 2015).

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Attempts to mitigate undesirable effects of past fire exclusion have focused on the implementation of fuel reduction treatments. These treatments have been designed to reduce understory tree density and surface and ladder fuels within stands and disrupt fuel continuity across landscapes (Agee and Skinner 2005). Fuel treatment activities include prescribed fire, mechanical tree removal (thinning), mastication of small trees and shrubs, and hand thinning or pruning followed by piling and burning. These fuel treatment activities may be spatially coordinated at the landscape scale with the intent of both moderating fire behavior across the entire landscape and improving the efficacy of fire suppression efforts (Collins et al. 2010). In addition to prescribed fire, managed wildfire, where managers allow naturally ignited fires to burn for ecological benefit, is being increasingly used as a landscape-scale fuel reduction and forest restoration "treatment" (Collins et al. 2009, Parks et al. 2014, Meyer 2015). In the United States, managed wildfire has been more common on National Park Service (NPS) land than on U.S. Forest Service (FS) land (van Wagtendonk 2007). This practice, combined with the very different influences of past timber harvesting, has led to distinct wildfire patterns on the two agencies' lands where fires on FS land tend to have a greater proportion of high-severity fire that occurs in larger patches as compared to fires on NPS land (Miller et al. 2012).

Although forest management conventionally occurs at the stand scale, ecosystem processes tend to operate at larger spatial scales, and there is growing interest in managing at these larger scales (e.g., for fire, wildlife; Hessburg et al. 2015). Throughout this paper, we use the term "landscape-scale" to refer to a scale smaller than ecoregion (e.g., the Sierra Nevada mountain range) that consists of multiple patches of vegetation of different types (e.g., shrub- or tree-dominated) or successional stages (sensu Hessburg et al. 2015). In contrast, "stand-scale" refers to a smaller scale consisting of a group or patch of trees that are relatively uniform in their composition, structure, and age-class distribution (Helms 1998). Despite the interest in landscape-scale management, it is inherently complex and there are often competing land management objectives and operational constraints that collectively limit type, timing, and placement of treatments at large spatial scales (Collins et al. 2010, North et al. 2015). Properly implemented stand-scale treatments clearly reduce wildfire severity relative to adjacent untreated areas (Ritchie et al. 2007, Safford et al. 2009, 2012, Arkle et al. 2012, Yocom Kent et al. 2015), and analyses carried out at larger spatial scales (landscape, regional) corroborate these results (Wimberly et al. 2009, Prichard and Kennedy 2013). Limited empirical information and fire simulation studies also suggest treatments can reduce fire behavior and effects on the lee side of treatments (Finney et al. 2005, 2007, Ager et al. 2010, 2014, Collins et al. 2013).

In addition to fuels treatments and managed wildfire, wildfires that escape initial suppression efforts also influence the behavior and severity of subsequent fires by changing the quantity, type, and arrangement of fuels across the landscape. The primary difference between these wildfires and other treatment types (including managed wildfire) is how fuels develop afterwards, particularly in wildfire areas burned at high severity. Most studies have found that areas burned at high severity tend to reburn at high severity, particularly when shrubs have replaced trees as the dominant vegetation after the first fire (Holden et al. 2010, Thompson and Spies 2010, van Wagtendonk et al. 2012, Parks et al. 2014, Kane et al. 2015*a*, Coppoletta et al. 2016). Low- to moderate-severity fire is also thought to be a self-perpetuating process as it maintains a forested state and restores structure and function in dry-mixed conifer forests, leading to increased stand and landscape resilience (North et al. 2012).

Despite the wealth of information demonstrating reduced wildfire severity in areas with completed fuel/restoration treatments, there is still uncertainty in the ability of these treatments to affect wildfire severity outside their footprint (i.e., landscape-scale effect). This is particularly true under more extreme burning conditions (e.g., plume-dominated fire), which are not represented by current fire spread models (Werth et al. 2016). The 2013 Rim Fire in the Sierra Nevada provides an opportunity to study fuels treatment effects across a large (100,000 ha) landscape that had both a rich history of fuels management and occurred during extreme burning conditions under which direct suppression efforts become less effective and fuels treatments may be particularly critical in mitigating fire severity and spread. The Rim Fire is also the largest fire to date in the Sierra Nevada and spanned the boundary of two land agencies (FS and NPS) with very different management histories, allowing for the comparison of very different treatment classes within the same wildfire. These conditions are not met by other fires in the Sierra Nevada bioregion. Approximately two-thirds of the total fire area of 104,131 ha was in mixed-conifer forest, with 22,994 ha in Yosemite National Park, 39,972 ha in the Stanislaus National Forest, and an additional 7,015 ha on private lands. A considerable portion (approximately 20%) of the mixed-conifer-dominated area on public land had been previously treated for fuels reduction/restoration (7,634 ha within Yosemite and 6,969 ha within the Stanislaus), including managed wildfire (Johnson et al. 2013). In addition, around 40% of the landscape burned in a previous wildfire (Table 1, Fig. 1).

High-severity fire is of particular interest in this system, due to its significant ecological effects and management focus. Previous work in the Rim Fire demonstrated that high-severity fire was strongly associated with crown fire and exhibited extremely high tree mortality (Lydersen et al. 2016). Because the historical fire regime consisted of frequent, predominantly low-severity surface fire (Scholl and Taylor 2010), areas of high severity within mixed-conifer forest at our study site, particularly when occurring as larger patches, are outside the

TABLE 1. Pre-Rim Fire fuel treatment and wildfire classes.

Treatment class, analysis area, and subclass	Within class (%)
Previous unchanged, 3.57% area	
1 fire	94.66
>1 fire (WF, MF)	2.36
Mechanical after fire	2.99
Previous low, 13.69% area	
1 fire	92.66
>1 fire (WF, MF)	6.25
Mechanical after fire	1.09
Previous moderate, 12.53% area	
1 fire	91.82
>1 fire (WF, MF)	7.55
Mechanical after fire	0.64
Previous high, 5.98% area	
1 fire	94.96
>1 fire (WF, MF)	5.02
Mechanical after fire	0.02
Surface, 0.36% area	
Pile burn	53.37
Other surface	46.63
Thin, 5.67% area	
Thin and pile burn	42.46
Thin and other surface	17.45
Thin only	40.09
Rx or small WF, 4.56% area	
1 fire (Rx, MF)	92.49
1 fire (WF)	1.65
>1 fire (WF, MF, Rx)	4.68
Rx and pile burn	1.18
Thin and Rx, 0.17% area	
Thin and Rx	53.15
Thin and small WF	5.36
Thin, Rx and pile burn	33.61
Thin, small WF, and pile burn	7.89
Untreated, 53.48% area	

Note: WF stands for wildfires targeted for suppression, MF stands for managed wildfire, and Rx stands for prescribed fire.

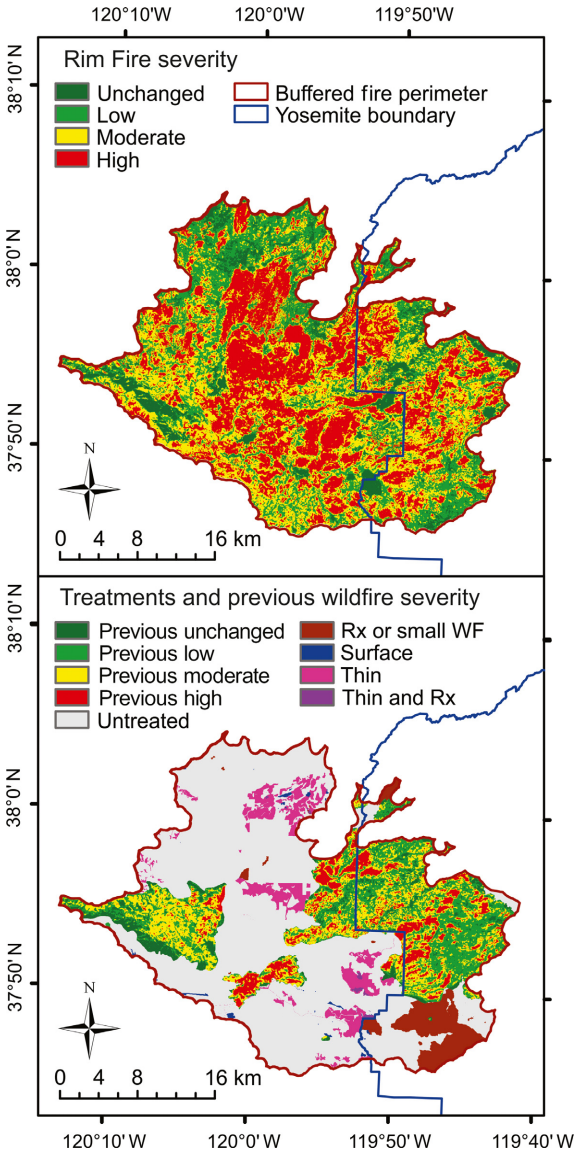

FIG. 1. Maps showing classified fire severity in the 2013 Rim Fire (California, USA), and location of previous fires and fuel treatments within the Rim Fire footprint. Rx is short for prescription fire; WF stands for wildfire. [Color figure can be viewed at wileyonlinelibrary.com]

historical range of fire effects (Mallek et al. 2013). In addition, many post-fire management activities (such as erosion control, salvage logging, and reforestation) are focused within high-severity burn areas. Another advantage of focusing on high severity is that remote-sensing-based classification tends to be very accurate in these areas (Miller et al. 2009, Lydersen et al. 2016).

Our primary goal was to understand how prior fuels treatment and wildfire affected the proportion of high-severity fire when considered at progressively larger spatial scales. The objectives of this study were to evaluate the (1) stand-scale effects of past fuels treatments and wildfires on fire severity within the Rim Fire; (2) landscape-scale effects of past fuels treatments and wildfires, fire weather, water balance, and vegetation on fire severity within the Rim Fire; and (3) changes in fire severity as a fire moves from an untreated, fire-excluded forest into a treated or previously burned area within the Rim Fire.

METHODS

Study site

Our study site is in the central Sierra Nevada, California, USA and covers portions of Stanislaus National Forest and Yosemite National Park that burned in the 2013 Rim Fire. The Rim Fire burned a total of 104,131 ha between 17 August and 23 October 2013, and was the third largest recorded fire in the state and the largest recorded in the Sierra Nevada. Elevation within the fire's footprint ranges from 265 to 2,400 m. The climate is Mediterranean with cool, moist winters,

and warm, generally dry summers. Mean monthly temperatures range from 4°C in January to 20°C in July (1992–2014, Crane Flat Remote Automated Weather Station [RAWS]). Precipitation varies with elevation and is predominantly snow at higher elevations, with an annual average at approximately 2,000 m elevation of around 100 cm. Prior to the Rim Fire, vegetation was predominantly conifer forest (68%), hardwood forest (16%), and shrubland (7%; LandFire 2012 Existing Vegetation Type). The predominant conifer species across most of the site are incense-cedar (*Calocedrus decurrens*), ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), and sugar pine (*Pinus lambertiana*), and the most common hardwood species are black oak (*Quercus kelloggii*) and canyon live oak (*Quercus chrysolepis*). Mixed conifer forest in the study area experienced frequent, low-severity burning historically (Scholl and Taylor 2010), but burned with uncharacteristically high proportions of high severity (>30%, Fig. 1) in the Rim Fire (Harris and Taylor 2015). The Rim Fire also burned with a greater proportion of high severity than other fires in the area since 1984 (Kane et al. 2015*a*), a pattern typical of larger wildfires across western U.S. forests (Lutz et al. 2009, Cansler and McKenzie 2013, Harvey et al. 2016) and consistent with observations of increasing fire severity in the Sierra Nevada (Miller and Safford 2012). The outer 500 m of the Rim Fire was excluded from all analyses to minimize the influence of fire suppression actions and possible inaccuracies in the fire's perimeter, leaving 90,506 ha of study area. Portions of the perimeter within Yosemite and the Stanislaus were suppressed by management ignited fire along roads and trails to pre-burn vegetation to rob the Rim Fire of fuels. Other portions of the perimeter burned fuels between rock outcrops later into the fall of 2013 and mapping in these areas was an estimation of final fire perimeter.

Fuel treatments and wildfire history

Fuels treatments and wildfires that occurred prior to the Rim Fire were compiled into one treatment layer for analysis (Fig. 2). Fuels treatment boundaries were obtained from FS and NPS geospatial records. Treatments were restricted to those that occurred since 1995 to ensure records of forest activities were reasonably accurate. Prior to 1995, there was inconsistent reporting of geospatial information for completed treatments. In addition, studies in Yosemite have shown that the ability of previous fires to influence the spread and severity of subsequent fires is diminished after 9–14 yr (Collins et al. 2009, van Wagtendonk et al. 2012, Lydersen et al. 2014). Fuels treatments in the Stanislaus included pre-commercial and commercial thinning of non-merchantable and merchantable trees, respectively, surface fuel treatments, and prescribed burning. The FS geospatial record consisted of separate polygons delineating specific

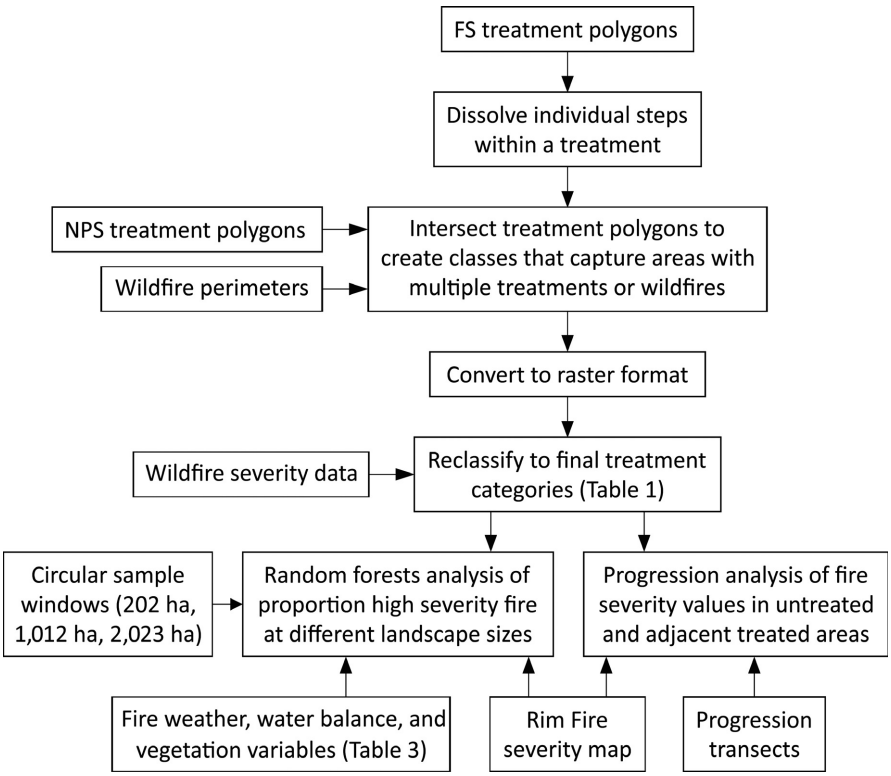

FIG. 2. Process diagram showing overview of analysis methods.

management actions that were part of an overall treatment, with overlapping polygons corresponding to the date an action was completed. Actions with missing dates were verified as having occurred prior to the Rim Fire with forest management personnel from the Stanislaus (M. Gmelin, *personal communication*). After conversion to single part polygons, all treatment polygons were examined and assigned a treatment type and an end date corresponding to completion of the most recent action (prior to the Rim Fire). For example, a common treatment combination was thinning (either commercial or pre-commercial) followed by yarding (removal of fuels by carrying or dragging) and then piling and burning. In those instances, all polygons were dissolved and given a treatment type of "thin and pile burn" and an end date corresponding to the latest date of the three polygons (typically the date of pile burning). The treatment layer was then dissolved by treatment name so that any polygons that were adjacent or overlapping, but belonged to the same treatment based on type and ending date, were merged into one polygon. Fuels treatments in Yosemite included prescribed burns, fires managed for resource benefit, and pile burning. Pile burning typically occurred near campgrounds or other developed areas. Overlapping fire polygons were not dissolved because all polygons represented distinct events rather than individual steps within a treatment. Wildfire boundaries were obtained from a statewide fire database maintained by the California Department of Forestry and Fire Protection, which includes fires 4 ha (10 acres) and larger (data *available online*).[9]

Wildfire perimeters and NPS and FS fuel/restoration treatments were merged into one file. At this step, new treatment classes, which included previous wildfire, were created to capture areas that had multiple treatments or fires since 1995 (e.g., thinned and burned in previous wildfire). This was relatively rare, making up about 3% of the Rim Fire footprint. This file was then converted to a raster, with values corresponding to treatment class.

We then modified the treatment layer to account for the severity of previous fires where available. Fire-severity data were available for large wildfires >38 ha (14 total) but not for small wildfires (13 total) or prescription fires (26 total). Fire-severity data were obtained from a database maintained by the FS Pacific Southwest Region (see Miller and Quayle [2015] for details) for 10 fires designated as suppression wildfires (WF), two fires designated as managed wildfire (MF), and two fires with different sections designated as either WF or MF. Fire severity was estimated from the extended relative differenced normalized burn ratio (RdNBR) assessment, which is calculated from imagery collected in the summer following the fire (described in more detail in the *Rim Fire severity* section). For one WF, the Bald fire in 2011, we used the initial assessment because the extended assessment was not available. These fires ranged in size from 38–23,934 ha. We did not have severity data for 13 small wildfires (5–38 ha), 26 prescription fires (4–1,359 ha), and one fire that was partially a prescription fire and partially designated as MF (1,033 ha total). After clipping by fire boundaries, the RdNBR layers for individual fires were mosaicked together so that overlapping regions were given the maximum value, and then classified into four severity classes (Table 2; Miller and Thode 2007). We chose to use the maximum value for pixels that had experienced more than one wildfire prior to the Rim Fire because higher severity fire is associated with greater changes to the vegetation by definition, and therefore has more of a lasting impact on fuel development than a lower severity fire. Kane et al. (2015*a*) also used the maximum severity value for areas with multiple preceding fires. This likely had minimal impact on the study results since areas burned in two wildfires between 1995 and 2013 occurred on only 2.2% of the study area. Thus, our fire-severity classes for previous fires represent the maximum observed severity for areas that burned multiple times during the 18 yr prior to the Rim Fire. This fire-severity raster and the original treatment raster layer were then combined using the raster calculator and a reclassification step to create a treatment raster where previous fire severity could be considered in separate treatment classes for most of the previously burned area.

To aid in analysis, treatment classes were simplified based on the following rules (Table 1). Commercial and pre-commercial thinning were not classified separately because they are likely reflective of site conditions such as tree size or plantation age prior to thinning rather than different treatment intensities applied to similar forest. Areas that included both surface fuel manipulation and thinning were classified as the "Thin" group, whereas those that only received a mechanical surface treatment were classified as "Surface." Surface treatments included pile burning, yarding, rearrangement of fuels, and chipping. Pile burning was included as a surface mechanical treatment, rather than a prescription fire. Areas that were burned in prescription fires or burned in a wildfire for which we did not have severity data were included in one class (Rx or small WF). For areas that were both thinned and burned, when the fire was a wildfire, thinning typically happened after burning (e.g., pre-commercial thinning of a plantation). These areas were designated according to their fire-severity class. In contrast, areas that were thinned and burned with prescribed fire were thinned prior to burning, and were maintained in a separate class (Thin and Rx). Overall 47% of the analysis area had received some form of previous fuel treatment or wildfire (Fig. 1, Table 1).

Rim Fire severity

A raster of classified Rim Fire severity was generated using RdNBR values and land ownership. For wildfires

[9] http://frap.cdf.ca.gov/data/frapgisdata-sw-fireperimeters_download.php

Table 2. Descriptions of fire severity classes commonly used for forests in California and their associated composite burn index (CBI) and relative differenced normalized burn ratio (RdNBR) thresholds (Miller and Thode 2007, Miller et al. 2009, Miller and Quayle 2015, Lydersen et al. 2016).

Severity category	CBI	Initial RdNBR	Extended RdNBR	Ecological effect
Unchanged	0–0.1	<79	<69	no change to overstory trees; affects vegetation in understory only, includes unburned islands within the fire perimeter
Low	0.1–1.24	79–360	69–315	little change in basal area; kills primarily smaller diameter trees and fire sensitive species
Moderate	1.25–2.24	361–732	316–640	greater range in fire effects (26–75% change in basal area); often represents a transition from surface to crown fire
High	2.25–3.0	≥733	≥641	most (typically >95%) of basal area is killed; associated with crown fire

that occur in forested lands of California, there are typically two versions of the RdNBR fire-severity map available, the initial and extended assessments (Miller and Quayle 2015, Lydersen et al. 2016). In the initial assessment, RdNBR is calculated by comparing imagery acquired immediately (30–45 d) after fire containment to imagery acquired prior to the fire. Because fire containment dates are typically in the fall in California, the pre- and post-fire imagery used in initial assessments is also acquired in the fall, when solar angles are not at their peak. In contrast, the extended assessment uses imagery acquired during the middle of summer when solar elevation angles are maximized. Tree shadows and topographic shadowing are therefore greater in the imagery used in the initial assessment as compared to the extended assessment. This shadowing, along with the high reflectance of ash present after fires, can reduce the accuracy of estimated severity values for the initial assessment in some areas (e.g., steep slopes and areas with dense tree cover). While the extended version avoids the issues of tree shadowing and ash-reflectance, its accuracy can be affected by post-fire management such as salvage logging and post-fire regrowth of vegetation. Salvage harvest and replanting typically occur within the first year following fire on private lands, but such actions require environmental review prior to implementation on public lands and therefore have not commenced by the time of post-fire image acquisition for the extended assessment. To avoid the impact of timber salvage operations and replanting on private lands, which accounted for 8.7% of the analysis area, we used the initial severity assessment on private lands and the extended assessment on public lands. Land ownership data was obtained from the California Department of Forestry and Fire Protection (*available online*).[10] Standardized fire-severity classes have been calibrated for both the initial and extended RdNBR assessments (Table 2), based on the relationship between RdNBR and the composite burn index (Key and Benson 2006), and validated with field data from fires throughout forested areas in California (Miller and Thode 2007, Miller et al. 2009, Miller and Quayle 2015). On all public lands, we used the extended RdNBR assessment and severity class thresholds from Miller and Thode (2007). On private lands, we used the initial RdNBR values and severity class thresholds calibrated to account for the reflectance of ash (Miller and Quayle 2015). Because the thresholds for these two assessments differ, we used classified fire severity as the response variable in our landscape analysis rather than raw RdNBR values. While the extended RdNBR assessment is more commonly used than the initial, the high-severity category tends to be stable across both assessments (Lydersen et al. 2016). Therefore the use of the initial assessment over part of the fire should have little impact on the study results.

Effect of previous fires and fuel treatments on landscape scale proportion of high-severity fire

Random forests analysis was used to assess the relative importance of previous fire and fuels treatments, fire weather, water balance, and vegetation on the proportion of high-severity fire at three spatial scales, which we refer to subsequently as "landscape analysis," using the "party" package in R version 3.3.1 (R Core Team 2016; Table 3). Fire weather variables included the burning index (BI) and the energy release component (ERC), which were calculated for each day of burning in the analysis area using FireFamilyPlus version 4.1 (Bradshaw and McCormick 2000) and daily weather values for the Crane Flat remote automated weather station (data *available online*).[11] These indices integrate weather with fuel and are related to expected fire behavior. BI reflects expected short-term fire-line intensity and ERC is related to seasonal drying of available fuel. Computations of BI and ERC were performed using a standard forest surface fuel model, NFDRS fuel model "G." Relative to other fuel models that can be used to calculate ERC, ERC (G) performs well at predicting large fire activity across the western United States (Andrews et al. 2003, Finney et al. 2011). The days of burning included in the buffered study area were 17 August through 16 September 2013. BI ranged from 53 to 89 with a mean of 71.0 and ERC ranged from 67 to 77, with a mean of 72.7. Using a fire progression map, these daily values were converted to 30-m rasters of BI and ERC. Water balance variables included actual

[10] http://frap.fire.ca.gov/data/frapgisdata-sw-ownership13_2_download

[11] http://www.raws.dri.edu/cgi-bin/rawMAIN.pl?caCCRA

TABLE 3. Variables included in random forests analysis of proportion high-severity fire for sample landscapes within the Rim Fire perimeter.

Variable	Source
Proportion treated	Forest Service, National Park Service, and statewide fire and management geospatial records
Burning index (BI)	calculated using daily data from the Crane Flat remote automated weather station
Energy release component (ERC)	calculated using daily data from the Crane Flat remote automated weather station
Actual evapotranspiration (AET)	the basin characterization model downscaled climate and hydrology data sets
Climatic water deficit	the basin characterization model downscaled climate and hydrology data sets
Proportion conifer forest	LandFire existing vegetation layer
Proportion hardwood forest	LandFire existing vegetation layer
Proportion shrubland	LandFire existing vegetation layer
Proportion riparian	LandFire existing vegetation layer
Proportion grassland	LandFire existing vegetation layer

evapotranspiration (AET) and annual climatic water deficit. These variables were obtained as 270-m raster files from the 2014 historical (1981–2010) version of the California Basin Characterization Model (Flint et al. 2013). The California Basin Characterization Model is available covering 30-yr intervals (1921–1950, 1951–1980, and 1981–2010 for the historical version and 2010–2039, 2040–2069, and 2070–2099 for the projected version), and was most recently updated in 2014. These data were then resampled from 270 to 30 m using bilinear interpolation to match the scale of the other covariates. Vegetation variables were calculated from the LandFire 2012 existing vegetation type layer (Rollins 2009).

The landscape analysis consisted of circular analysis windows of 202, 1,012, and 2,023 ha (500, 2,500, and 5,000 acres) generated at random locations across the analysis area, with a different random sample created for each size. Although this range of analysis window sizes may not fit with conventional definitions of a landscape, we consider these to capture landscape-scale effects because for most windows the proportion of treated area did not comprise a majority of the total window area. These analysis windows were the sample units in our analysis, with proportion high-severity fire within an analysis window as the response variable. Predictor variables included treatment history, fire weather, water balance, and vegetation variables (Table 3). The minimum distance between sample-window centers was restricted at each scale so that adjacent samples did not overlap more than 50% of their area. To determine an appropriate number of sample windows, we ran multiple iterations of the random forests model and examined how root mean square error changed with sample size (Appendix S1: Fig. S1). For all window area sizes, a final sample size of 100 was used to match the approximate sample size where root mean square error asymptotes. For the 2,023-ha windows, this was reduced to 84 samples due to the minimum distance between samples requirement. Total proportion of the window area previously treated, which includes areas previously burned at low to moderate severity, was calculated from a 30-m raster of treatment class. Previous high-severity wildfire was excluded from this (i.e., not considered a "treatment") based on its likelihood to reburn at high severity (Coppoletta et al. 2016). In addition to the proportion high severity and proportion previously burned or treated, for each random window sample, we extracted the average value of all pixels within a window for BI, ERC, AET, and climatic water deficit and the proportion of the window area in several vegetation classes: conifer, hardwood, shrubland, grassland, and riparian. Generation of samples and extraction of variables was done using the spatstat, maptools, and raster packages in R version 3.3.1. Random forest models were run using the party package, with 1,000 trees and the default setting of five variables per tree. The caret package was used to extract model error and R^2 values, and the edarf package was used to generate partial dependence plots for the three most influential variables.

Effect of previous fires and fuel treatments on fire-severity progression

To assess the effect of previous fires and fuel treatments on fire progression, we compared fire severity immediately outside fire/treatment boundaries to fire severity within previously burned or treated areas at varying distances from the treatment/fire boundary. Transects running out from the fire origin point along radial lines separated by 1° were generated in ArcMap (ESRI, Redlands, California, USA; Fig. 3). Each transect consisted of a series of points spaced 50 m apart along each radial direction (1°–360°, Fig. 3a). To account for the closer spacing of transects near the fire's origin point, points were deleted so that all adjacent transects had a minimum lateral distance of 500 m between transects (range of 500 m to 1,000 m; Fig. 3b). Each instance of a radial line crossing into a treated or previously burned area was considered a transect and included all points within 250 m of the treatment/fire boundary, so that transects were up to 500 m long. We also created a set of "control" transects that did not cross into a treatment or previous fire, using a random starting point for all portions of the radial lines with at least 500 m length outside of previously burned or treated areas. There were 233 treatment transects and 169 controls. All transects were classified using the majority

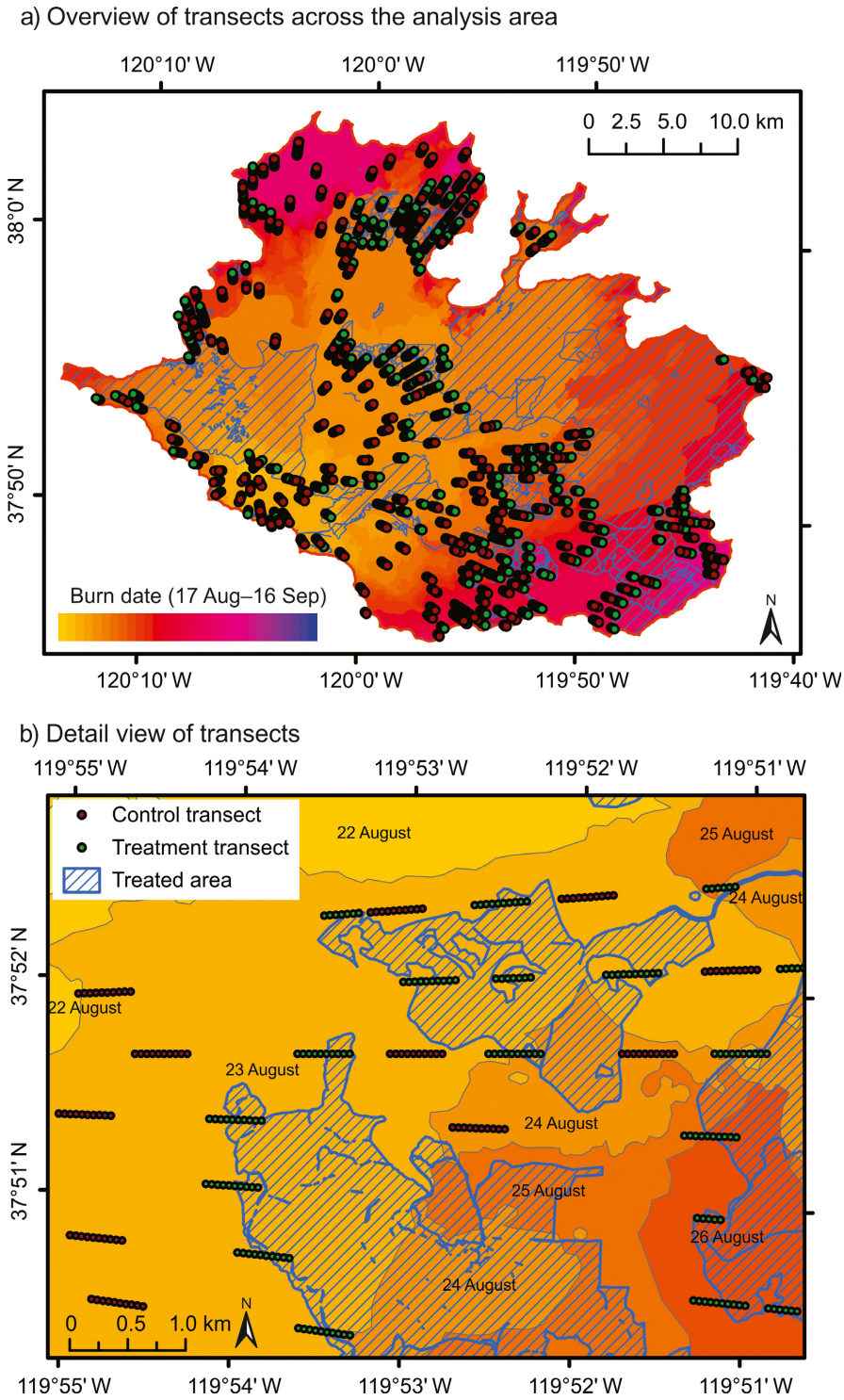

FIG. 3. Map showing treatment and control transects for measuring fire severity along the general direction of fire progression for (a) the entire study area and (b) a detail view. The background shading corresponds to the daily fire progression. [Color figure can be viewed at wileyonlinelibrary.com]

severity class of the Rim Fire for the points outside the previous fire or treatment ("incoming" fire severity), or the first five points for control transects (Fig. 4). The continuous RdNBR value from the extended assessment was extracted for each point, after excluding points that were located on private lands that may have had salvage

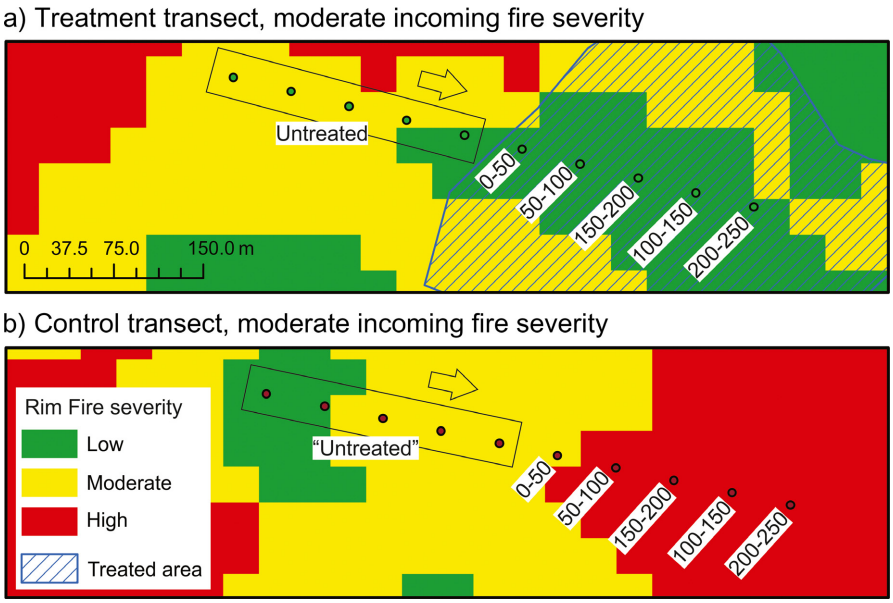

FIG. 4. Close-up view of two fire progression transects. The primary direction of fire spread was estimated using radial transects originating at the ignition point and extending to the final perimeter boundary (left to right in these examples, as shown by the arrow). Transects were classified based on "incoming" Rim Fire severity, using the majority severity class of (a) the points outside the treated area, or (b) the first five points for control transects, outlined in a black rectangle and labeled "Untreated." The numbered labels refer to the distance from (a) the treatment edge or (b) the center of the transect. The relative differenced normalized burn ratio (RdNBR) value for each labeled point was compared to the average RdNBR value of the five "Untreated" points. [Color figure can be viewed at wileyonlinelibrary.com]

harvest prior to acquisition of the imagery used in the extended RdNBR assessment. A mixed-model ANOVA (Proc Mixed) in SAS version 9.4 (SAS Institute, Cary, North Carolina, USA) was then used to compare RdNBR values within treated and previously burned areas, at varying distances from the treatment/fire boundary, to the average RdNBR outside a burned or treated area. For control transects, points at varying distances along the second half of the transect were compared to the average RdNBR of the first five points. Transect ID was included as a random factor, along with a power spatial covariance term based on UTM coordinates of all points included in the analysis.

RESULTS

Census of fire severity by treatment type

Averaging across the entire study area, the Rim Fire burned with 8.8% unchanged severity, 25.9% low severity, 32.6% moderate severity, and 32.7% high severity (Fig. 1). However, the proportions among these classes varied by past fire severity and treatment history (Fig. 5). There was a positive association between previous wildfire severity and Rim Fire severity. Previous high-severity fire had the greatest proportion of high-severity burning in the Rim Fire among all treatment/fire classes (49%), with an even greater amount of high severity than that observed in untreated pixels (38%). Areas that previously burned at low and moderate severity were more likely to burn with moderate severity in the Rim Fire (39% and 46%, respectively), although previous low severity also tended to reburn at low severity (32%). Areas that previously burned with unchanged severity had a large proportion of unchanged severity in the Rim Fire (40%).

The lowest fire severity was observed in areas that were previously treated with a combination of thinning and prescribed burning, with the vast majority classified

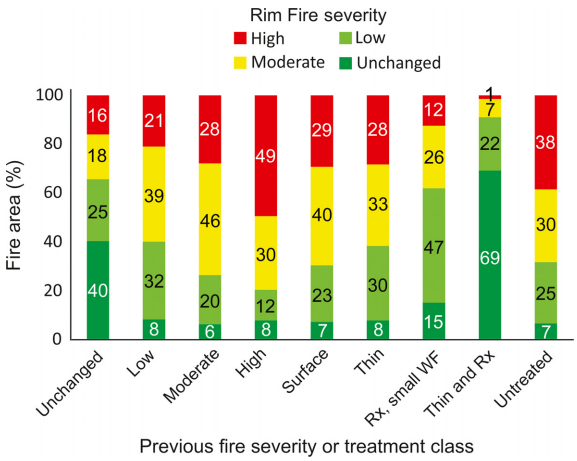

FIG. 5. Rim Fire severity by previous wildfire severity and fuel treatment class. Numbers over each portion of the bars show the percentage, rounded to the nearest whole number, within each fire-severity class. [Color figure can be viewed at wileyonlinelibrary.com]

as unchanged (69%) or low (22%) and only 1.5% classified as high severity in the Rim Fire (Fig. 5). Prescribed fire without thinning also tended to burn with low-severity fire in the Rim Fire (62% unchanged and low) and had only 12% high severity. Areas that were thinned or treated for surface fuels without fire were more intermediate in their burn patterns in the Rim Fire, each with around 30% high severity, although thinning had slightly more unchanged and low severity (38%) as compared to surface treatment alone (30%).

Landscape analysis

The amount of variation explained by the random forest models varied somewhat with analysis scale, with R^2 values of 0.46, 0.31, and 0.34 for landscape samples of 202, 1,012, and 2,023 ha, respectively. However, the relative influence and direction of relationship for factors influencing proportion high-severity fire in the Rim Fire were similar at all three spatial scales (Figs. 6 and 7). At all spatial scales, the two fire weather variables along with proportion of area treated had the greatest influence on proportion high severity across the landscape (Fig. 6). At the smallest spatial scale (202 ha), the burning index had the greatest influence, followed by proportion treated, and ERC only had a minimal affect. At the intermediate spatial scale (1,012 ha), BI was also the most influential variable, followed by ERC then percent of the landscape treated. At the largest scale (2,023 ha), percent treated was the most influential, but ERC and BI also had high relative importance in relation to percent high severity. At the larger two scales, AET also had a slight influence (Fig. 6).

The threshold responses (i.e., a small change in the independent variable leading to a relatively rapid change in the dependent variable) for BI and ERC were similar at all three scales (Fig. 7). For BI, there was a sharp increase in proportion of high-severity fire for BI values over 78, and a moderate increase at the two larger scales for values over 70. ERC showed an increased proportion of high-severity fire when ERC was >72. The relationship between the proportion of the landscape treated and the proportion that burned at high severity in the Rim Fire was consistently negative at all three scales with the proportion of high severity decreasing with proportion treated (Fig. 7), but the threshold at which an effect was seen varied by analysis scale. At smaller scales, a greater proportion treated was needed to influence fire severity, with thresholds of 50–75% treated for 202 ha, 25–60% for 1,012 ha, and 10–40% for 2,023 ha.

Progression analysis

Fire severity along progression transects was significantly different outside treatments and previous fire boundaries than inside the treated/burned area (Fig. 8). When the Rim Fire was burning at high or moderate severity, there was a significant reduction in fire severity within adjacent previously burned or treated areas. High-severity fire transitioned to moderate, and moderate severity transitioned to low-moderate. This was in marked contrast to patterns observed in control transects, which showed no significant change in fire severity between the first five points and the subsequent 200 m (all untreated). A different pattern was observed for transects located in areas where the Rim Fire was burning at low severity before encountering a treatment; after crossing a treatment boundary there was a small (<100 RdNBR units) but statistically significant increase in fire severity within treatments/previous fires. However, mean RdNBR values remained well below the moderate-severity threshold (RdNBR value of 316; Miller and Thode 2007).

Discussion

The overall extent of the 2013 Rim Fire and the patterns of fire effects were unprecedented in the recorded Sierra Nevada fire history. Given the extreme burning conditions that occurred over much of the fire area, the likelihood that many of the previous treatments would be "overwhelmed" by the fire was relatively high (Finney et al. 2003). However, we found that Rim Fire severity was generally lower in areas with previous fuels treatments or where past fire severities were of low or moderate severity as compared to untreated and unburned areas. The occurrence of some high-severity fire within all treatment types (1–29%) emphasizes that under high to extreme burning conditions fuel/restoration treatments reduce, but likely cannot completely eliminate, high-severity fire effects. Observed high-severity patches within treatments may be related to (1) treatment boundaries if fire severity remained high for a distance prior to decreasing (Safford et al. 2012, Kennedy and Johnson 2014), (2) small spatial scale of treatments relative to incoming fire behavior, (i.e., overwhelming a treatment), (3) older treatments (e.g., >9–14 yr since treatment) that may be less effective due to subsequent buildup of fuels (Collins et al. 2013, Tinkham et al. 2016), or (4) local feedbacks between fire weather, topography, and fuels. A previous study found that both an extended time since previous fire and the occurrence of extreme fire behavior were associated with moderate to high-severity fire in the Rim Fire (Lydersen et al. 2014). Note, however, that Lydersen et al. (2014) did not include a comparison to untreated areas, which, based on the results of this study, have a much greater proportion of high-severity fire overall (38%), even compared to older treatments.

Prescribed burning combined with thinning resulted in the lowest fire severity of all treatment types at the stand-scale, though this treatment represented only a small portion of the total area. This is in line with recent reviews of fuel treatment effectiveness that found that treatments including both thinning and burning led to lower fire severity, tree mortality, and crown scorch

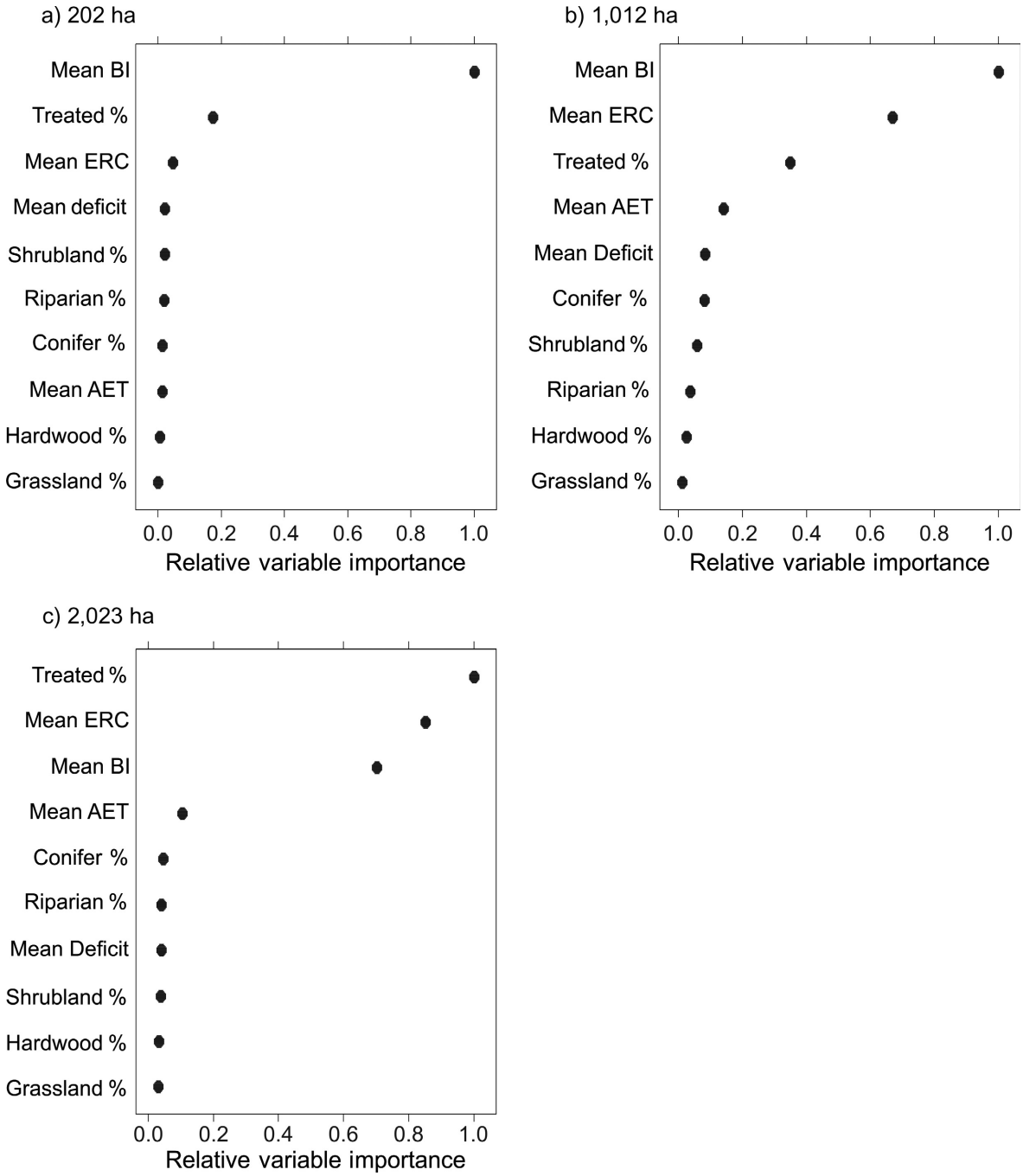

FIG. 6. Relative variable importance from random forests analysis of percent high severity at three landscape scales: (a) 202 ha, (b) 1,012 ha, and (c) 2,023 ha. Abbreviations are burning index (BI), energy release component (ERC); and actual evapotranspiration (AET).

compared to treatments with thinning or burning alone (Martinson and Omi 2013, Kalies and Yocom Kent 2016). The association between areas that burned with unchanged fire severity in both the Rim Fire and a previous wildfire suggests that fire severity in these areas may be linked to biophysical factors (Kane et al. 2015*a*, *b*). Some of the differences between treatment types could reflect a difference in the forest conditions that tend to receive a specific type of treatment. For example thinning may occur more frequently in plantations, whereas prescribed burning may be more likely in areas with remnant large trees that are targeted for restoration and

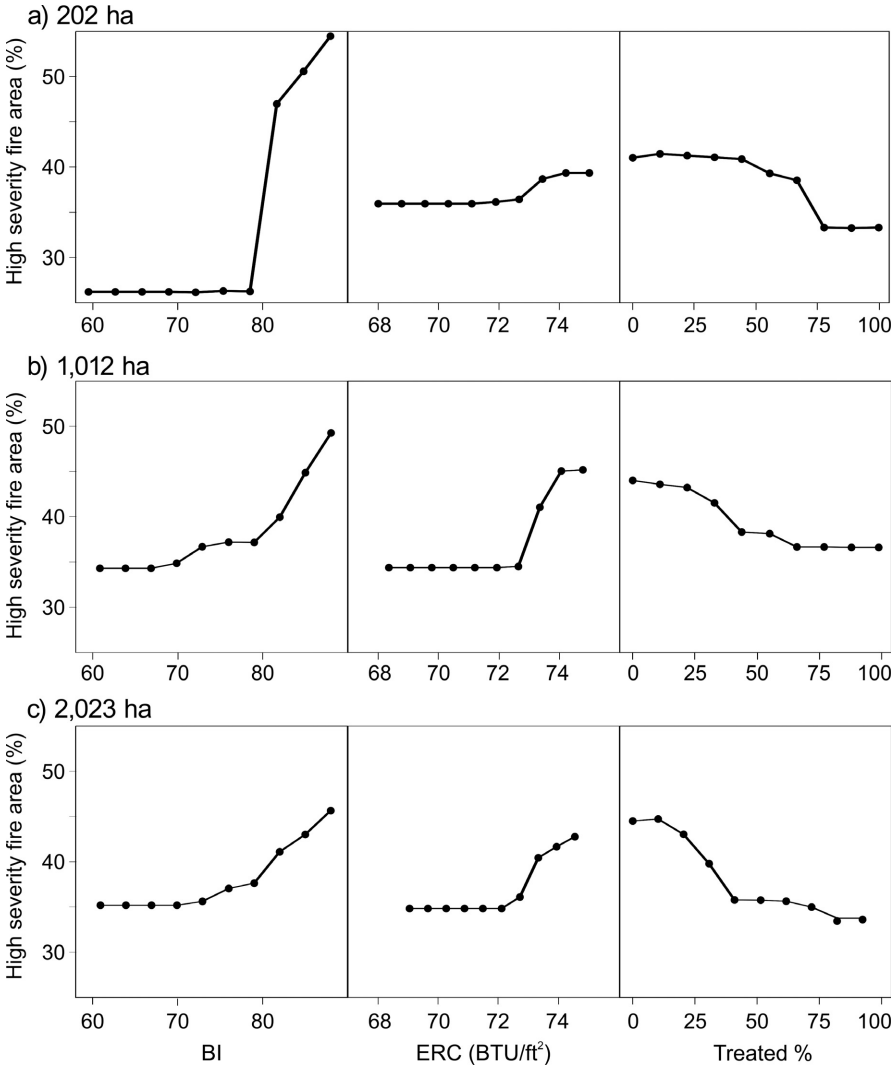

FIG. 7. Partial dependence plots for the burning index (BI), energy release component (ERC), and percentage of landscape treated at three landscape scales: (a) 202 ha, (b) 1,012 ha, and (c) 2,023 ha.

protection. These preexisting differences, in addition to differences from treatment efficacy, would be expected to influence wildfire severity. In addition topographic factors such as slope steepness, which affects fire behavior (Rothermel 1972), could differ between the various treatment types and untreated areas due to operational constraints.

The strongest drivers of high-severity fire at the landscape scale were proportion of area treated and fire weather (as indicated by two indices, BI and ERC; Fig. 6), and these were leading variables in random forest models across all three spatial scales tested (Fig. 7). At the largest spatial scale, 2,023 ha, proportion treated was the most important variable, whereas at the smallest scale, BI was overwhelmingly important, suggesting different mechanisms operating at the different scales (Fig. 6). These differences are also evident in the different shapes of the partial dependence plots (Fig. 7). We hypothesize the ability of extreme fire weather to override fuel conditions is most noticeable at finer spatial scale, whereas the effects of fuel treatments on fire inertia become more apparent as spatial scale increases. These differences emphasize the importance of analyzing landscape patterns at multiple spatial scales.

The proportion of landscape treated that resulted in a reduction of high-severity fire varied by spatial scale, with a greater proportion treated required to see an effect at smaller scales (Fig. 7). This may reflect that treatments need to be of a certain size to influence fire severity across a landscape (Finney et al. 2003). For example, at the smallest spatial scale of 202 ha, approximately 70% of the area needed to be treated to have an effect on subsequent high-severity fire levels, corresponding to around 141 ha. Individual fuel treatments are generally smaller than this (Barnett et al. 2016), although the cumulative total and configuration of

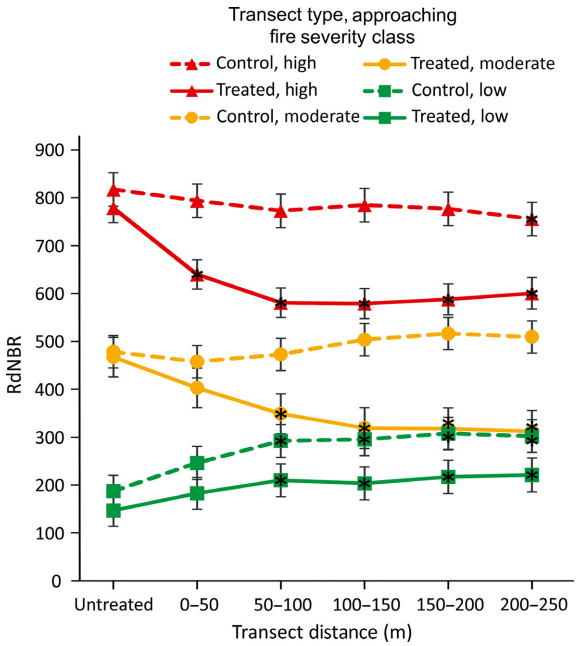

FIG. 8. Fire severity along 500-m transects roughly oriented in the direction of fire spread, classified by incoming fire severity. Treated transects include five points (250 m) outside a treatment or previous fire boundary and five points within. The control transects have no points within treatment or previous fire, and the Untreated point was calculated as the average of the first five points (250 m) of each transect. Asterisks denote significant difference ($P < 0.05$) from the Untreated point within each severity class. [Color figure can be viewed at wileyonlinelibrary.com]

treatments is important in altering landscape burn patterns (Finney et al. 2007). Stevens et al. (2016) found that modeled fuel treatments decreased the proportion of the landscape vulnerable to high-severity fire for a 7,820 ha area in the Tahoe Basin. However, the authors concluded that increases in the treated area beyond 13% of the landscape had a negligible influence on vulnerability to future fires. Our largest landscape scale of 2,023 ha had a similar threshold where exceeding 10% of the area treated was associated with a dramatic decrease in percent high severity, and we found that additional area treated, up to approximately 40%, further decreased proportion burned at high severity in our sample landscapes (Fig. 7).

Not surprisingly, our analyses demonstrated the strong influence of fire weather on landscape-scale fire severity. The Rim Fire occurred during a period of drought in California, with warm temperatures and extremely low relative humidity, which would be expected to increase fire activity. In addition, a large proportion (47%) of the area burned in the Rim Fire occurred during two large fire spread events (21 through 22 August and 25 through 26 August). Conditions during these events were related to the presence of unstable air in the upper atmosphere that increased surface wind speeds and, for the first spread event, also coincided with low overnight relative humidity (Peterson et al. 2015). In addition to high BI values on those days, the Rim Fire was burning under "plume-dominated" conditions, where the high fire radiative power and convective updraft increased air flow into the fire and accelerated surface winds, driving even higher fire intensity (Peterson et al. 2015, Werth et al. 2016). Previous work on the Rim Fire found a strong positive association between fire severity and both plume-dominated fire and BI among plots with a history of previous low to moderate fire severity (Lydersen et al. 2014). In contrast, Harris and Taylor (2015) did not find a fire weather signal in an untreated section of the Rim Fire that burned under moderate weather conditions. This is consistent with our results showing that proportion high severity was uniformly lower when BI was <70 (Fig. 7), and suggests that treatments may have more subtle effects when wildfire is allowed to burn under moderate conditions, since high fire severity is unlikely to occur regardless of past treatment history (Finney et al. 2007, Martinson and Omi 2013). In another study of Rim Fire severity, Kane et al. (2015*a*) found that including fire weather only minimally improved model results of Rim Fire severity for a study area that burned after the two large fire spread events. Perhaps the greater influence of weather in our study reflects the importance of fire behavior feedbacks on fire intensity that occur during more extreme fire. It should be noted that fuel conditions can have a strong influence on these perceived weather-driven feedbacks, e.g., plume formation (Werth et al. 2016).

It is somewhat surprising that vegetation had much less of an effect, compared with other variables, on landscape scale fire severity. Other studies have found vegetation characteristics such as cover type and canopy closure to be highly influential in some forests (Prichard and Kennedy 2013, Birch et al. 2015, Stevens-Rumann et al. 2016). The lack of effect in this study may be an artifact of our analysis, which only looked at proportion of each landscape sample in general cover type classes. Looking at a portion of the Stanislaus that burned in the Rim Fire, Lydersen et al. (2016) found high-severity patches had significantly greater densities of small trees, but no significant difference in basal area than areas that burned at lower severity, and in an untreated portion of Yosemite, Harris and Taylor (2015) found that tree species composition varied with fire severity. However in another study in Yosemite, Kane et al. (2015*a*) found no effect of forest structure on fire severity. Therefore differences in vegetation structure may have had an effect of fire severity across some but not all parts the fire, which would not be apparent under our coarse classification.

In addition to modifying fire severity, previous fires and fuel treatments have been shown to limit the spread of subsequent wildfires (Collins et al. 2007, Teske et al. 2012, van Wagtendonk et al. 2012, Parks et al. 2015*a*, *b*) and aid in suppression efforts (Thompson et al. 2016). While this likely occurred in the Rim Fire, by design, our analysis only captured the effect of fires that did not stop

the spread of the Rim Fire, and therefore does not include the full range of effects that previous fires and fuel treatments can have on wildfire. However, our results do show that fuels treatments and previous fires had an immediate (within the first 50 m) effect on fire severity when assessed along the general direction of the fire's progression (Fig. 8). When incoming high-severity fire encountered a previous fire or fuel treatment, the fire severity decreased to moderate severity, likely leaving a greater number of surviving overstory trees (Lydersen et al. 2016). Because fire is a contagious process, adjacent/subsequent points would be expected to have similar fire severity, with values at greater distances beginning to converge towards the average fire severity of the overall fire. This likely led to the slight increase in severity observed for transects where the incoming fire severity was low prior to encountering a treatment, and may also reflect that fuel moisture is often lower in treated areas due to the greater canopy openness, leading to more active fire behavior (van Wagtendonk 1996). However, the increase in severity tended to be less than that observed in control untreated transects indicating that treated areas maintained low-severity burning better than untreated areas.

Management Implications

Both fuels treatments and previous low- to moderate-severity wildfire increased landscape resilience by reducing the prevalence of high-severity fire, even under the extreme burning conditions of the Rim Fire. Treatments that included prescribed fire had the lowest fire severity in the Rim Fire, suggesting that prescribed burning is a highly effective tool for mitigating the potential for future high-severity fire. Our analysis did not test for the effect of treatment age. Older fuel treatments and wildfires would be expected to have less of an effect on subsequent fire severity due to fuel accumulation over the years following the treatment or fire (van Wagtendonk et al. 2012). However, studies such as ours that include only relatively recent treatments may not detect an effect of time since fire. Prichard and Kennedy (2013) found only a weak effect of treatment age on fire severity in the Northern Cascades in Washington over a 30-yr record of treatment history, Safford et al. (2012) found no effect of treatment age for treatments that occurred within 9 yr of subsequent fires in the Sierra Nevada, and van Mantgem et al. (2016) found that prescribed fires can reduce fire hazard compared to pre-treatment levels for decades on NPS land in the Sierra Nevada. Our study included treatments that occurred within 18 yr of the Rim Fire. Prior work among previously burned areas in the Rim Fire found that fire severity tended to be higher if more than 14 yr had passed since the previous fire. This implies that the oldest treatments in our study might have had less of an effect on Rim Fire severity than the more recent treatments. However, the exact extent to which these older treatments were able to reduce fire severity relative to untreated areas, and their effectiveness compared to more recent treatments, is unknown. Fuel treatment longevity is a much needed area for future research.

Although the Rim Fire had a greater proportion of stand replacing fire occurring in larger patches compared to historical patterns of fire severity in this area (Scholl and Taylor 2010, Collins et al. 2015, Stephens et al. 2015), around one-half of the fire area burned at low to moderate severity. Our results suggest that this is in part due to the substantial amount of previous fires and fuel treatments burned over by the Rim Fire. Lower severity fire patches provide ecosystem-level benefits by moving overstory structure towards historic density and composition, reducing unnaturally high fuel loads, and creating greater diversity in vegetation patches and wildlife habitat (Collins et al. 2011, 2016, Das et al. 2013, Kane et al. 2014, White et al. 2015, Lydersen et al. 2016).

It remains unclear to what extent "off-site" or "leeside" effects of treatments on adjacent untreated areas (sensu Finney et al. 2005, 2007) occurred in this extreme fire event. Although our findings from the larger spatial scales analyzed indicated greater reductions of percent high severity with increasing proportion treated, this could simply reflect lower severity fire effects within the larger footprint of treatments rather than a true "landscape" effect. Inherent limitations in the spatial and temporal resolution of our data sets precluded an explicit analysis of this potential effect. Regardless, it is clear from our results that if reducing the overall extent and patch sizes of stand-replacing fire is a land management objective, then increasing areal coverage of treatments appears to be an important component.

In contrast to the areas that burned with low to moderate severity, the Rim Fire also created large patches of high-severity fire effects. Our results suggest that fire weather, in particular the positive feedback between extreme fire behavior and burn conditions, contributed to the formation of these large stand-replacing patches. The occurrence of high to extreme fire weather has increased over the last 20+ yr in the Sierra Nevada (Collins 2014), and this trend is expected to continue (Westerling et al. 2011). This suggests that the potential for similar extreme fire events is likely to continue, if not increase in the future. At the landscape scale the intermixing of vegetation types can increase resilience to fire, but large patches of deforested land are undesirable due to negative consequences for some wildlife species of concern and the reduction of carbon dioxide uptake to offset greenhouse gas emissions (Hurteau and Brooks 2011, Stephens et al. 2016*b*). Natural conifer forest regeneration is often low or absent in large, high-severity patches (van Wagtendonk et al. 2012, Collins and Roller 2013). In addition, around one-half of the landscape that previously burned at high severity subsequently reburned at high severity in the Rim Fire. For conifer-dominated areas once characterized by a low- to moderate-severity fire regime, this shift towards greater high-severity effects may result in lower conifer

establishment rates and favor conversion of the landscape to shrub- or grass-dominated vegetation (van Wagtendonk et al. 2012, Stephens et al. 2013, Coop et al. 2016, Coppoletta et al. 2016). On FS lands, concern over the future trajectory of these patches often shifts limited forest management resources toward active reforestation, which in turn further limits their ability to restore fire-excluded forests (Stephens et al. 2016*a*).

Results from our study show a direct and lasting benefit from fires that burn at low to moderate severity, and that fires are more likely to burn at lower severity under more moderate weather conditions. These results suggest that managing more wildfires under moderate conditions could benefit the landscape by increasing the amount that is resistant to high-severity fire effects in subsequent fires. By using managed wildfire and fuels treatments, managers can promote forest resilience to future wildfires that may burn under more extreme conditions. In practice, wildfire may provide opportunities to accomplish fuel reduction objectives across a greater area than planned fuel treatments (Omi 2015). Large treatments may be more effective at reducing future fire-severity levels (Prichard and Kennedy 2013), and managed wildfires offer an opportunity to achieve fuels reduction objectives, particularly where mechanical constraints, limited access, and prohibitive costs preclude the use of mechanical treatments (North et al. 2015). Fire is an essential component of western dry forests and an effective restoration tool, particularly when burning within an established network of existing fuels treatments (North et al. 2012).

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Supporting Information

Additional supporting information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/eap.1586/full

Data Availability

Data available from the USDA Forest Service Data Archive: https://doi.org/10.2737/rds-2017-0020