FINAL REPORT

Effects of fuels management on fire intensity, rate of spread, severity, and resultant forest structure within the 2013 Rim Fire landscape

JFSP PROJECT ID: 14-1-01-23

October 2018

Brandon M. Collins
University of California, Berkeley

Jamie M. Lydersen
University of California, Berkeley

Van R. Kane
University of Washington

Nicholas A. Povak
USDA Forest Service, Pacific Northwest Research Station

Matthew L. Brooks
U.S. Geological Survey, Western Ecological Research Center

Douglas F. Smith
U.S. Geological Survey, Western Ecological Research Center

FIRESCIENCE.GOV
Research Supporting Sound Decisions

Table of Contents

List of Figures

List of Abbreviations/Acronyms

BI – Burning Index

ERC – Energy Release Component

NF – National Forest

PCNM – Principal Coordinates of Neighborhood Matrices

RdNBR – Relative differenced Normalized Burn Ratio

Keywords

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

Acknowledgements

We are grateful to Jim Baldwin for advice on the statistical analyses. Thanks to Becky Estes, Marty Gmelin, and Kent van Wagtendonk for assistance with compiling fuel treatment histories for the Stanislaus National Forest and Yosemite National Park. We thank E. Gasarch, C. Caruso, G. Roller, J. Dvorak, B. Tracy, E. Fales, C. Richter, B. Weise, K. King, A. Dencic, A. Potter, T. Womble, E. Fales, C. Tubbesing, T. Kline, H. Darling, K. Arnold, and S. Berkowitz for their efforts in collecting field data.

Abstract

Large wildfires with uncharacteristically high severity are occurring more frequently in western U.S. forests. The increasing size and severity of wildfires has been attributed to both an increase in weather conducive to fire spread and changes to forest structure and fuel loads due to management practices that included fire suppression over the previous century. Fuel reduction treatments aim to produce a more fire-resistant forest structure by reducing densities of small, shade-tolerant trees and surface fuel loads. Despite the wealth of information demonstrating reduced wildfire severity in areas with completed fuel reduction and 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 that often occur during days when large wildfires undergo rapid growth.

We conducted a series of studies to understand the influence of fuels treatments and previous wildfires, along with fire weather, vegetation, and topography, on fire spread and severity in the 2013 Rim Fire. We first performed a validation of classified fire severity using field plots collected pre- and post-Rim Fire in which we found that fire severity classes represented distinct states of vegetation change, with high severity being indicative of stand replacing fire. Assessing burn patterns across the Rim Fire, severity tended to be lowest in areas that had previously been treated with prescribed fire, and highest in areas that had previously burned in a high severity wildfire. Previous low to moderate severity wildfire was associated with lower fire severity in the Rim Fire, and was included as a fuel treatment in analyses of the landscape-level effects of fuel reduction. For sample landscapes within the Rim Fire footprint, there was a negative relationship between the incidence of high severity fire and the proportion previously treated or burned at low to moderate severity. High and moderate severity fire was reduced as the Rim Fire moved from untreated into treated or previously burned areas.

Daily fire weather had a strong impact on fire severity in the Rim Fire, with large areas burned at high severity occurring when the burning index and energy release component were relatively high. This “overriding” influence of weather may have been influenced by fuel conditions across the larger landscape. Fire severity across the fire footprint showed a high degree of spatial autocorrelation, suggesting a “momentum” effect in which fire severity was not immediately responsive to changes in fuels or topography. Pre-fire vegetation generally did not improve our ability to predict Rim Fire severity, but higher fire severity was associated with areas with a high density of small trees, a greater abundance of fir, and a greater amount of standing dead biomass.

Together, our findings imply that fuel reduction did reduce the incidence of high severity fire in the Rim Fire, but some fuel treatments had little effect compared to the overriding conditions of fire weather and the contagious nature of fire spread. Areas burned at high severity are vulnerable to long-term forest loss through type conversion, while areas burned at moderate severity can lead to mixed effects in a subsequent fire, depending on the resulting vegetation and fuel dynamics. In contrast, areas burned at low severity in either wildfire or prescribed fire were likely to reburn at low severity, increasing the resilience of the landscape to wildfire.

Objectives

The Rim Fire of 2013 burned 250,000 ac in the central Sierra Nevada, California, affecting a predominantly forested landscape with a rich history of previous wildfire and fuels treatments. This study focused the impact of fuels treatments on the Rim Fire. We proposed to meet the following objectives.

Objective 1 – Determine the effects of previous fuels treatments on fire intensity, inferred from field-based estimates of fire behavior.

This objective was partially met. We assessed measures of fire intensity for a set of field plots collected within a portion of the fire, but did not examine treatment effects on fire intensity.

Objective 2 – Determine the effects of previous fuels treatments on fire areal rate of spread, inferred from infrared remote sensing data.

This objective was removed following a reduction in funding. Removal of this objective was approved by JFSP.

Objective 3 – Determine the effects of previous fuels treatments on fire severity, inferred from Landsat remote sensing data.

This objective was fully met.

Objective 4 – Determine the effects of previous fuels treatments on forest structure, inferred from LiDAR remote sensing data.

This objective was partially met. The post-fire LiDAR data was acquired too early to accurately capture tree mortality due to the fire. We instead used a pre-fire LiDAR dataset to examine the influence of forest structure on Rim Fire severity for a portion of the fire.

Objective 5 – Determine the individual and interactive effects of various covariates (especially antecedent climate, wildfire, and land use) on fire severity.

This objective was met. We removed aspects of this objective associated with fire intensity, rate of spread, and forest structure due to a reduction in funding. The revision to the objective was approved by JFSP.

Objective 6 – Incorporate Rim fire predictor variables and fire severity into a geospatial model that can be used to evaluate the potential effects of future fuels treatment types, configurations, and placements on future fire severity and forest structure. This will allow fire planners to prioritize areas for treatments and fire suppression staff to forecast fire severity during current and upcoming burn periods.

This objective was partially met. We found that including many fires in single model failed to capture much of the influence of unique factors that affect fire behavior at a local scale by reducing the data to averages. This implies that broad characterizations of the main drivers of fire patterns across an ecoregion may be misleading given the high spatial variability associated within and among fires. We instead focused on identifying the shared and unique contributions *of climate, antecedent and fire weather, topography, fire history, and spatial autocorrelation for the Rim Fire.*

Objective 7 – Interpret and summarize all of the results for these analyses into journal articles, publication briefs for resource managers, and webinars.

This objective was met. We removed the workshop component of this objective due to a reduction in funding. The revision to the objective was approved by JFSP.

We hypothesized that:

1. Fire severity would be lowest and forest structure least altered in areas where treatments targeted surface and ladder fuels relative to untreated areas.
2. Areas that burned at low to moderate severity in previous wildfires would act as fuel treatments and lead to lower Rim Fire severity, while areas that previously burned at high severity would be more likely to reburn at high severity.
3. There would be a lower incidence of high severity fire with an increasing proportion of surrounding "landscape" treated.
4. Spatial scale of analysis (i.e., focal window size – see below) would influence treatment effectiveness.
5. Fire weather, fire suppression operations, topography, antecedent climate, previous wildfires, land management history, and existing vegetation type (prior to fire) influenced fuel treatment effects, particularly for mechanical, older, and smaller/lower proportional area treatment units.

Background

Following changes in forest stand structure and landscape vegetation patterns, along with a warming climate, the incidence of large wildfires has increased in Western U.S. forests. Fuel reduction treatments designed to mitigate forest changes attributed to past fire exclusion and logging are designed to reduce understory tree density and surface and ladder fuels within stands and disrupt fuel continuity across landscapes (Agee and Skinner 2005). Despite the wealth of information demonstrating reduced wildfire severity in areas with completed fuel reduction and 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 Rim Fire of 2013 provided an opportunity to study fuels treatment effects across a large (250,000 ac) landscape that had both a rich history of fuels management and burned during extreme 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 (Forest Service and National Park Service) with very different management histories, allowing for the comparison of very different treatment classes within the same wildfire. Approximately 20% of the mixed-conifer dominated area on public land had been previously treated for fuels reduction/restoration (18864 ac within Yosemite and 17220 ac within the Stanislaus), including managed wildfire (Johnson *et al.* 2013). In addition around 40% of the landscape burned in a previous wildfire (Figure 1).

Materials and Methods

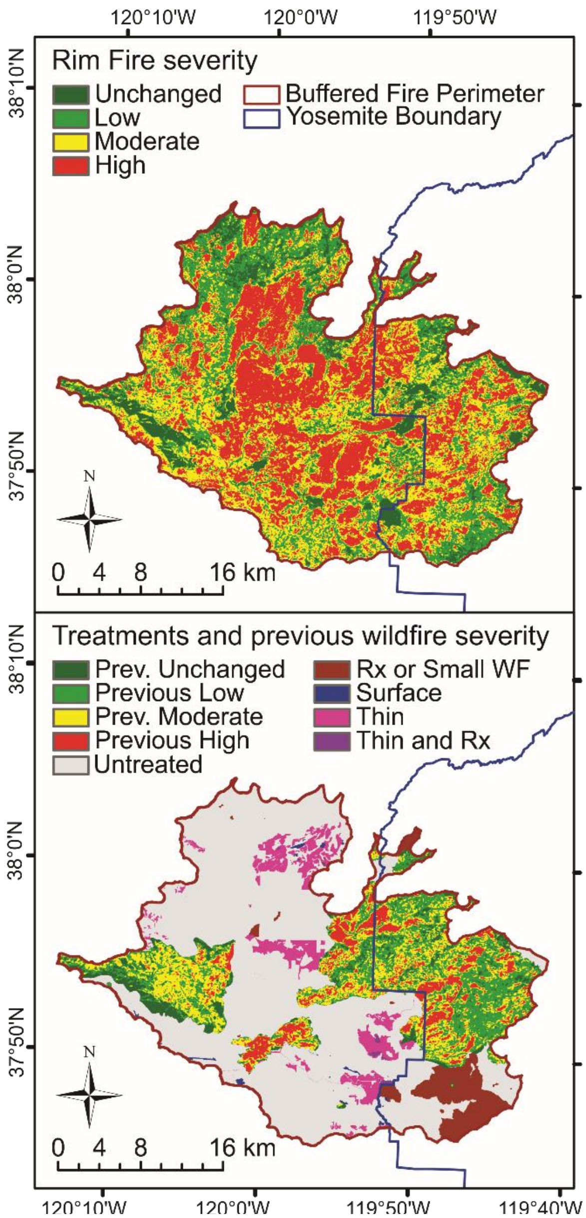

Figure 1. Maps showing classified fire severity in the 2013 Rim Fire (California, USA), and location of previous fires and fuel treatments within the Rim Fire footprint. Rx is short for prescription fire; WF stands for wildfire. From Lydersen et al. (2017).

Study area

The Rim Fire burned a total of 257,313 ac of Stanislaus National Forest and Yosemite National Park in the central Sierra Nevada, California between 17 August and 23 October 2013. Elevation within the fire's footprint ranges from 870 ft to 7900 ft. The climate is Mediterranean with cool, moist winters, and warm, generally dry summers. Precipitation varies with elevation and falls mainly as snow at higher elevations. Prior to the Rim Fire, vegetation was predominantly conifer forest (68%), hardwood forest (16%), and shrubland (7%) (LandFire 2012 Existing Vegetation Type). Mixed conifer forest in the study area experienced frequent, low-severity fire historically (Scholl and Taylor 2010), but burned with uncharacteristically high proportions of high severity (>30%) 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 pattern typical of larger wildfires across western US 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).

Validation of fire severity using field data (Lydersen et al. 2016)

To assess the accuracy of RdNBR as a measure of fire severity, we compared changes in live tree basal area and density in 175 field plots that were surveyed in 2013, prior to burning in the Rim Fire, and again in 2014. We first compared proportional change in tree density and basal area among four severity classes for the initial RdNBR assessment, which is estimated from remote imagery collected immediately after fire containment, and the extended assessment, which is estimated using imagery collected one year post-fire. We also assessed pre- and post-fire forest structure and measures of fire intensity within the four fire severity classes for this same plot data using mixed model ANOVAs.

Landscape effect of fuel treatments on fire severity (Lydersen et al. 2017)

We compared the efficacy of different treatment types and previous wildfires using a census of all pixels within the interior of the Rim Fire. We generated sample landscapes at three different scales (500 acres, 2500 acres and 5000 acres) across the fire footprint and used random forests analysis to assess the effect of proportional area treated, weather, site productivity and vegetation on proportion high severity fire. For this analysis, areas burned in previous wildfires at unchanged, low or moderate severity were included as a fuel treatment.

Effect of fuel treatments on fire progression (Lydersen et al. 2017)

To assess whether previous fire or fuel treatments had an effect on fire severity as the Rim Fire moved from untreated into previously burned or treated areas we created GIS transects along lines radiating out from the fire's origin point. As in the previous analysis, areas that burned at unchanged, low or moderate severity in a previous wildfire were included with intentional fuels treatments. We assessed fire severity along radial transects that crossed into previously burned or treated areas by comparing the severity outside the treatment to points placed at 50 m (164 ft) intervals within the treated area. We also assessed fire severity along "control" transects that did not cross into a treated or previously burned area. Transects were stratified by fire severity class and analyzed using a mixed model ANOVA with transect as a random factor and a power spatial covariance structure to account for spatial autocorrelation between nearby points. Dunnett's test was used to adjust significance values for multiple comparisons.

Multi-scaled drivers of Rim Fire severity patterns across land ownerships (Povak et al. in prep)

We compared fire severity patterns between Stanislaus NF and Yosemite NP and between reburned areas and first-entry fire using geospatial Random Forest models to relate fire severity to several climate, antecedent weather, fire weather, topographic, fire history and management history predictor variables. We used a method called Principal Coordinates of Neighborhood Matrices (PCNM; Borcard and Legendre 2002) to capture the influence of spatial autocorrelation across multiple scales. The resultant PCNM vectors were used as predictor variables in the Random Forest. We used the variable importance measures from the final model to assess the level of influence each of the final predictors had on fire severity patterns by land ownership and fire history using the `party` (Strobl *et al.* 2008) and `mlr` (Bischl *et al.* 2016) packages in R. Variance decomposition methods were used to quantify the shared and unique contributions of different variable groups, including (1) climate, antecedent and fire weather, (2) topography, (3) fire history and fuels, and (4) spatial autocorrelation. This allowed for an explicit inspection of the level of influence each variable group had on predicting Rim Fire severity patterns across ownerships and across reburns and first fires. We also mapped local variable importance for each sample point across the Rim Fire to assess spatial variation in the main drivers of fire severity across ownerships and across plume-driven progression days and non-plume days.

Influence of pre-fire forest structure on Rim Fire severity (Kane *et al.* 2015; Collins *et al.* 2018)

We completed two studies using vegetation data to assess Rim Fire severity. We first used Random Forest models to assess whether pre-fire LiDAR measurements could improve our ability to explain observed variation in Rim Fire severity. Pre-fire LiDAR data was available for a portion of the fire within Yosemite that burned in the Rim Fire under more moderate weather conditions. We also assessed the effects of local variations in climate, topography, and prior fire history, and how these controls differed for the Rim Fire compared to earlier fires in the area.

The second study focused on Rim Fire severity in areas that previously burned at moderate severity. Using field data collected 9–17 years following moderate-severity fire on Stanislaus NF, we developed 15 forest structure and composition variables and examined the influence of

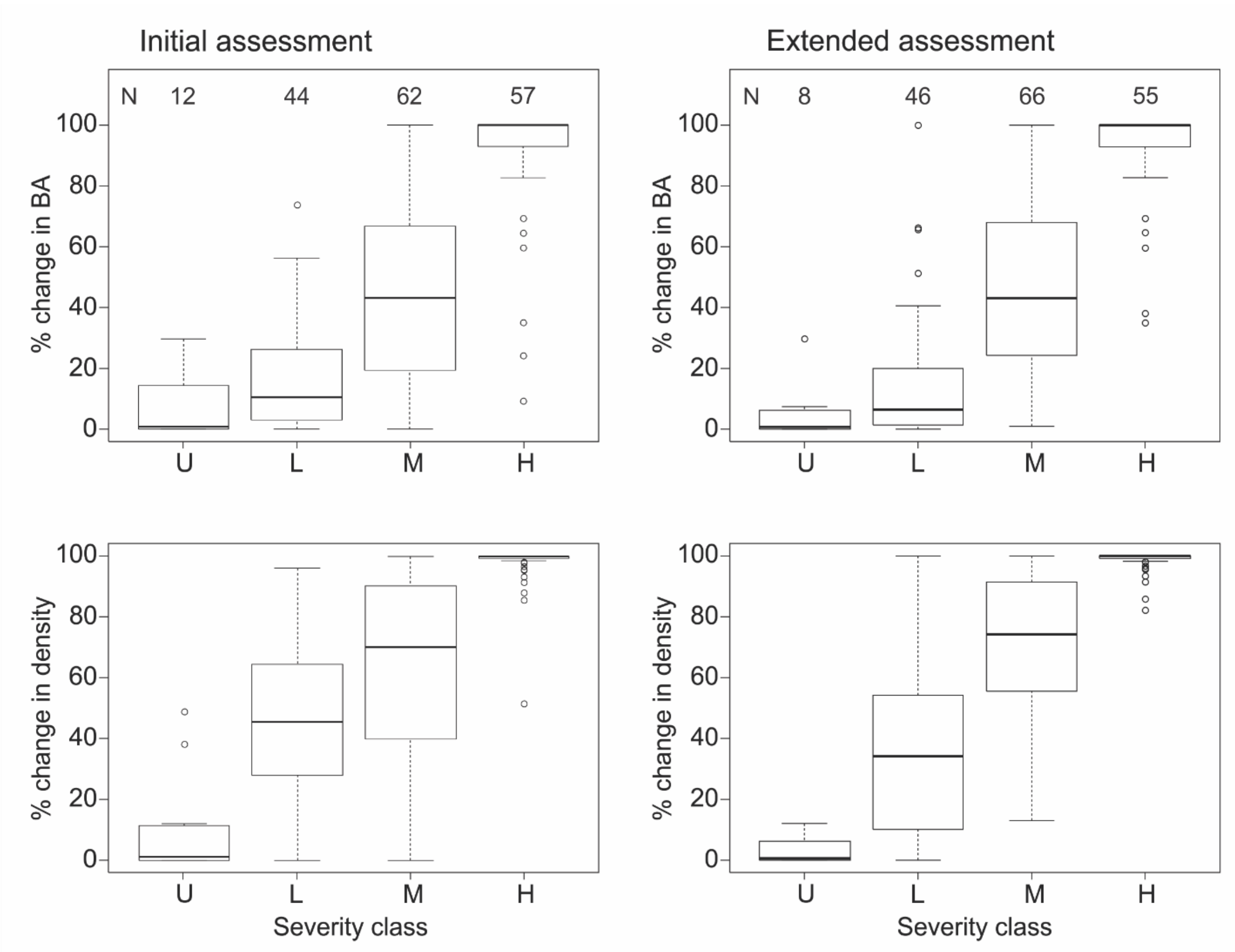

Figure 2. Change in live basal area and stem density pre and post Rim Fire in 182 plots in Stanislaus National Forest for initial and extended RdNBR assessments. Severity categories (U-unchanged, L-low, M-moderate, H-high) are based on the RdNBR thresholds in Miller and Thode (2007). Box and whisker plots depict median (horizontal band), interquartile range (white bar), range of data within 1.5 interquartile range of the lower and upper quartiles (vertical dashed lines), and outliers (points). From Lydersen et al. (2016).

forest structure, tree species composition, and shrub cover on Rim Fire severity using random forests and regression tree analysis.

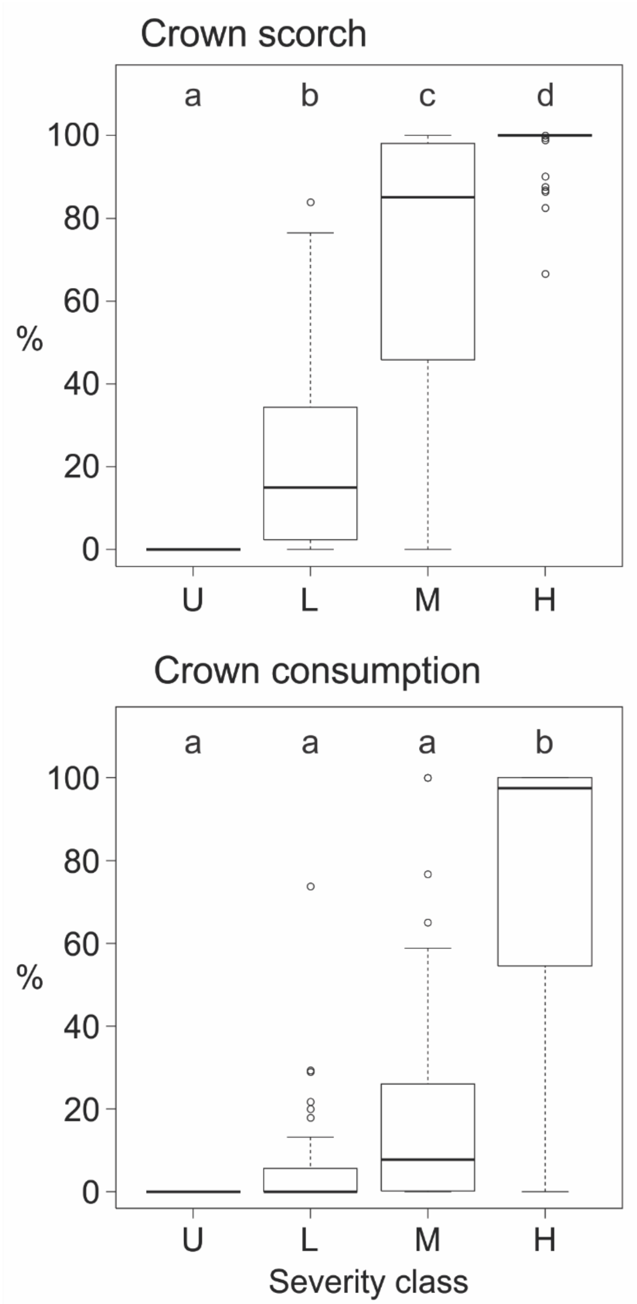

Figure 3. Distribution of average percent crown scorch and consumption for dominant and co-dominant trees by severity category in 182 plots in Stanislaus National Forest. U is unchanged, L is low severity, M is moderate severity, and H is high severity. Letters across the top of each chart refer to Games-Howell statistical comparisons, with different letters corresponding to significant differences between severity categories. From Lydersen et al. (2016).

Results and Discussion

Validation of fire severity using field data

We found that the extended RdNBR assessment better distinguished between severity classes than the initial assessment, based on the degree of overlap in forest change between adjacent classes (Figure 2).

Based on this result we used the extended assessment in subsequent analyses (Lydersen *et al.* 2016). The high-severity category clearly captured fire effects that would be considered stand replacing. This group was associated with >95 % change in basal area and >99 % change in stem density and was further distinguished by the majority of trees experiencing crown fire (Figure 3). This study also found that high severity fire was associated with areas that had greater pre-fire densities of small trees, but was not related to pre-fire basal area.

Landscape effect of fuel treatments on fire severity and fire progression

A census of fire severity across the fire interior found that treated areas tended to have lower overall proportions of high fire severity than untreated (Figure 4). Treatments that included prescribed burning had the lowest proportion of high severity fire in the Rim Fire (Lydersen *et al.* 2017). The areas with the greatest proportion of high severity fire were those that burned at high severity in a previous wildfire and those that were previously unburned or untreated. Mechanical treatments had an intermediate amount of high severity fire. All types of treatments and previous wildfire severities

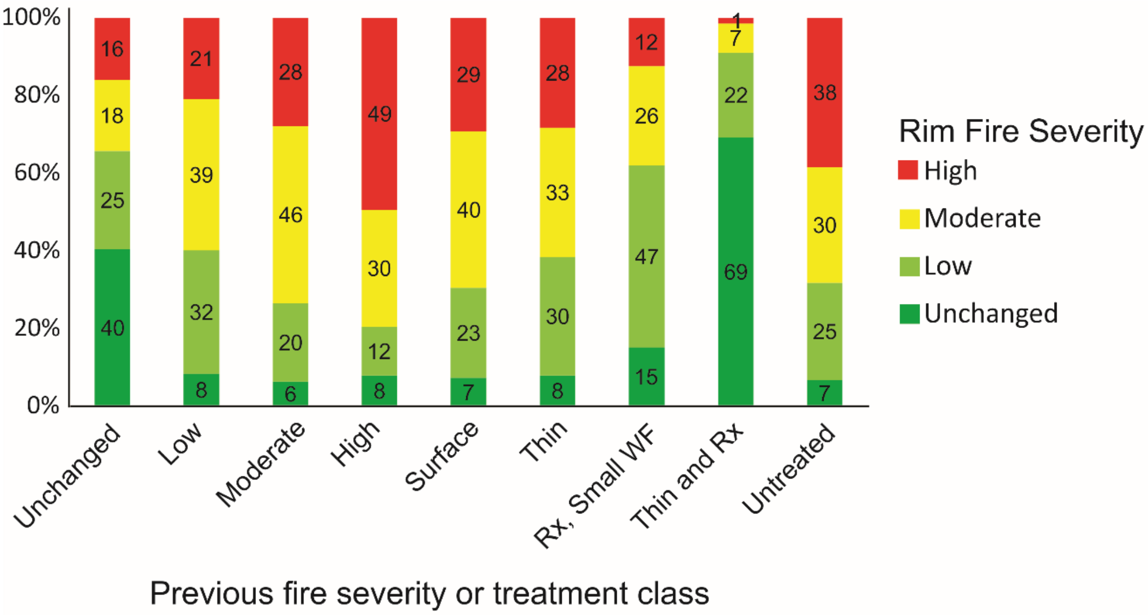

Figure 4. Rim Fire severity by previous wildfire severity and fuel treatment class. Numbers over each portion of the bars show the percentage, rounded to the nearest whole number, within each fire severity class. From Lydersen et al. (2017).

included some high severity fire, as well as some areas that were unchanged or burned at low severity. The occurrence of some high severity fire within all treatment types (1% to 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., greater than 9 to 14 years since treatment) that may be less effective due to subsequent buildup of fuels (Collins *et al.* 2013; Lydersen *et al.* 2014; Tinkham *et al.* 2016), or 4) local feedbacks between fire weather, topography, and fuels (Lydersen *et al.* 2014).

The proportion of high severity fire on sample landscapes within the Rim Fire was most influenced by previous fires, fuel treatments, and the two weather variables analyzed: burning index (BI) and energy release component (ERC). The identification of these variables as highly influential was consistent at all three landscape scales analyzed, but the actual order of importance varied (Figure 5). For the two smaller landscape scales, burning index had the greatest influence, while proportion treated was more important for the 5000 ac sample area. 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. 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 500 ac, approximately 70% of the area needed to be treated to have an effect on subsequent high severity fire levels, corresponding to around 300 ac. Individual fuel treatments are generally smaller than this

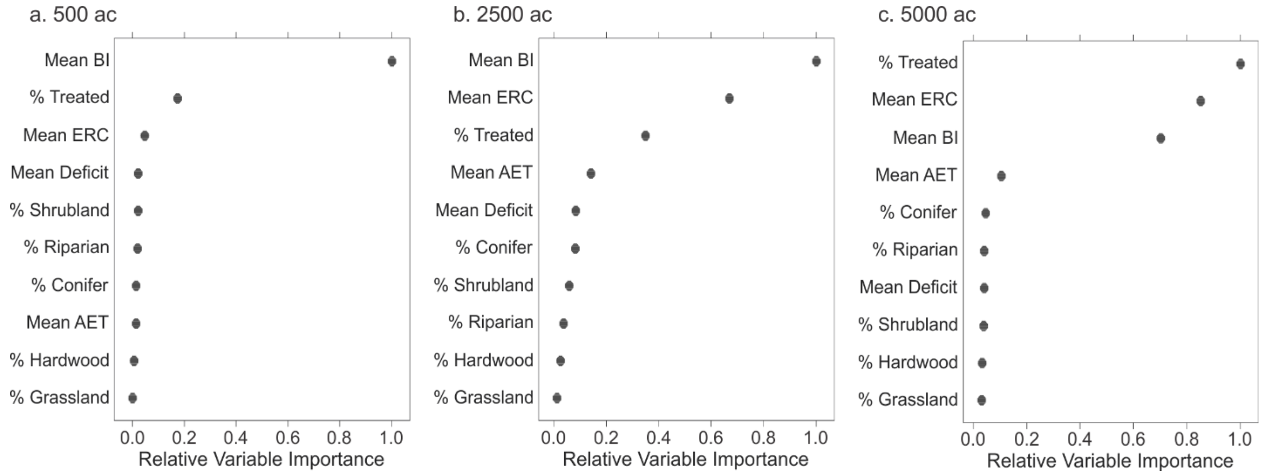

Figure 5. Relative variable importance from random forests analysis of percent high severity at three landscape scales: (a) 500 ac, (b) 2500 ac, and (c) 5000 ac. Abbreviations are burning index (BI), energy release component (ERC); and actual evapotranspiration (AET). From Lydersen et al. (2017).

(Barnett *et al.* 2016), emphasizing the need for coordinated fuels treatment planning or larger areas with reduced fuel loads, such as that arising from low to moderate severity wildfire. At our largest landscape scale of 5000 ac, exceeding 10% of the area treated was associated with a steep decrease in percent high severity, and we found that additional area treated, up to approximately 40%, further decreased the proportion burned at high severity in our sample landscapes.

We also found that fuel treatments and previous wildfires were able to reduce fire severity along an approximated path of fire progression when the incoming fire severity was moderate or high (Figure 6). When high severity fire encountered a burned or treated area, fire severity was reduced to moderate. When moderate severity fire encountered a burned or treated area, severity was reduced to the low to moderate severity range. When the Rim Fire was burning at low severity, fire severity remained low but showed increased values at distances >350 m (1148 ft) from the treatment boundary. However values still typically fell within the range of low severity burning.

The strong association between fire severity and weather has been clearly documented for the Rim Fire. Our analysis of sample landscapes found that days with BI >80 or ERC >73 were associated with a greater proportion of high severity fire at all scales. 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).

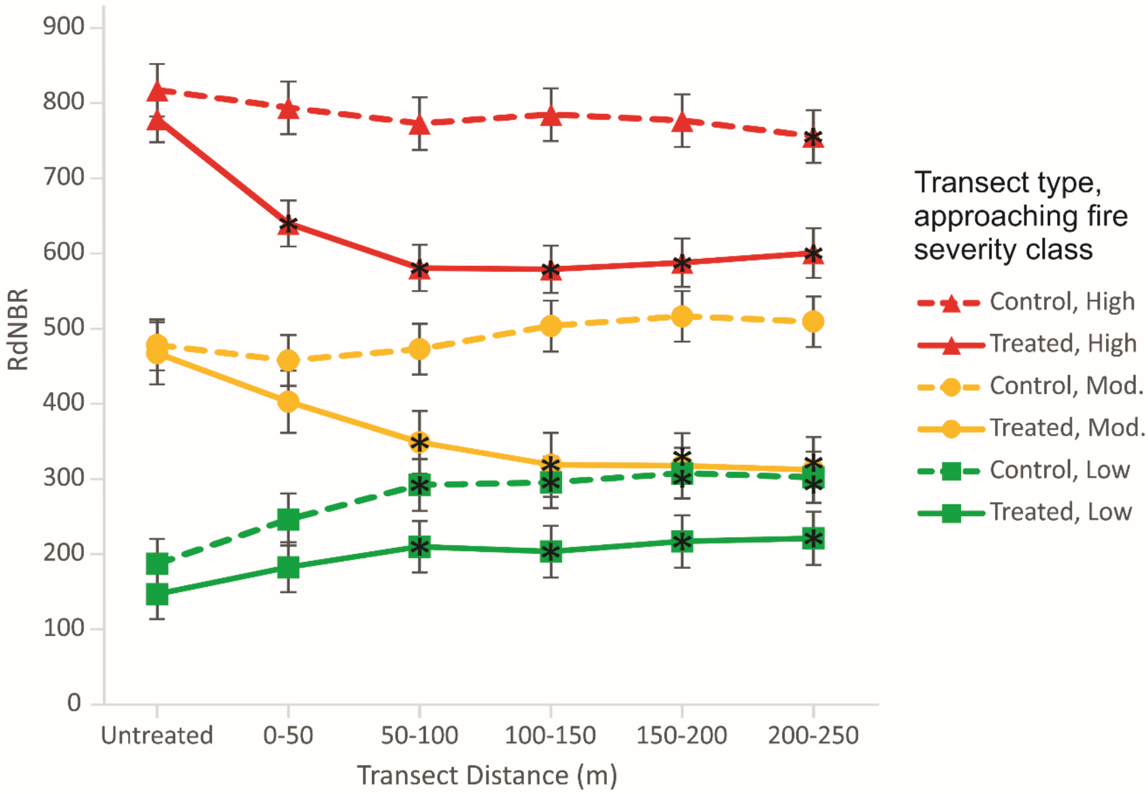

Figure 6. Fire severity along 500-m (1640 ft) transects roughly oriented in the direction of fire spread, classified by incoming fire severity. Treated transects include five points (250 m; 820 ft)) outside a treatment or previous fire boundary and five points within. The control transects have no points within treatment or previous fire, and the Untreated point was calculated as the average of the first five points (250 m; 820 ft) of each transect. Asterisks denote significant difference (P < 0.05) from the Untreated point within each severity class. From Lydersen et al. (2017).

Multi-scaled drivers of Rim Fire severity patterns across land ownerships

We found that the variables with the greatest influence on fire severity differed somewhat between land ownerships and previous fire history (Figure 7; Povak *et al.* in prep). For reburned areas, past fire severity and fire weather were important predictors in both ownerships. In Yosemite, previous fire severity was the main driver of reburn severity, with a positive linear relationship between previous and subsequent fire severity. Rim Fire severity in Yosemite increased dramatically on days where the daily burning index was greater than 63. Reburn fire severity also increased with increasing time-since-last fire, which ranged from 2 – 28 years. On the Stanislaus NF, previous fire severity and the burning index also had significant positive relationships with Rim Fire severity, but spatial autocorrelation and daily fire weather had a much greater influence on fire severity compared to Yosemite. In both ownerships increasing live fuels, as indicated by NDVI (Yosemite) or NDMI (Stanislaus), also had a positive relationship with reburn severity. In Stanislaus, the prevalence of NDMI, a measure of moisture stress, was likely related to lower fire severity near the Tuolumne River, which had low moisture stress and higher percentages of hardwoods associated with the riparian zone.

Fire severity for areas where the Rim Fire was the only fire in the recent fire record (i.e., first entry burn following fire exclusion) had lower predictability on average compared to reburned areas. In both Yosemite and Stanislaus NF the ERC had a significant positive relationship with

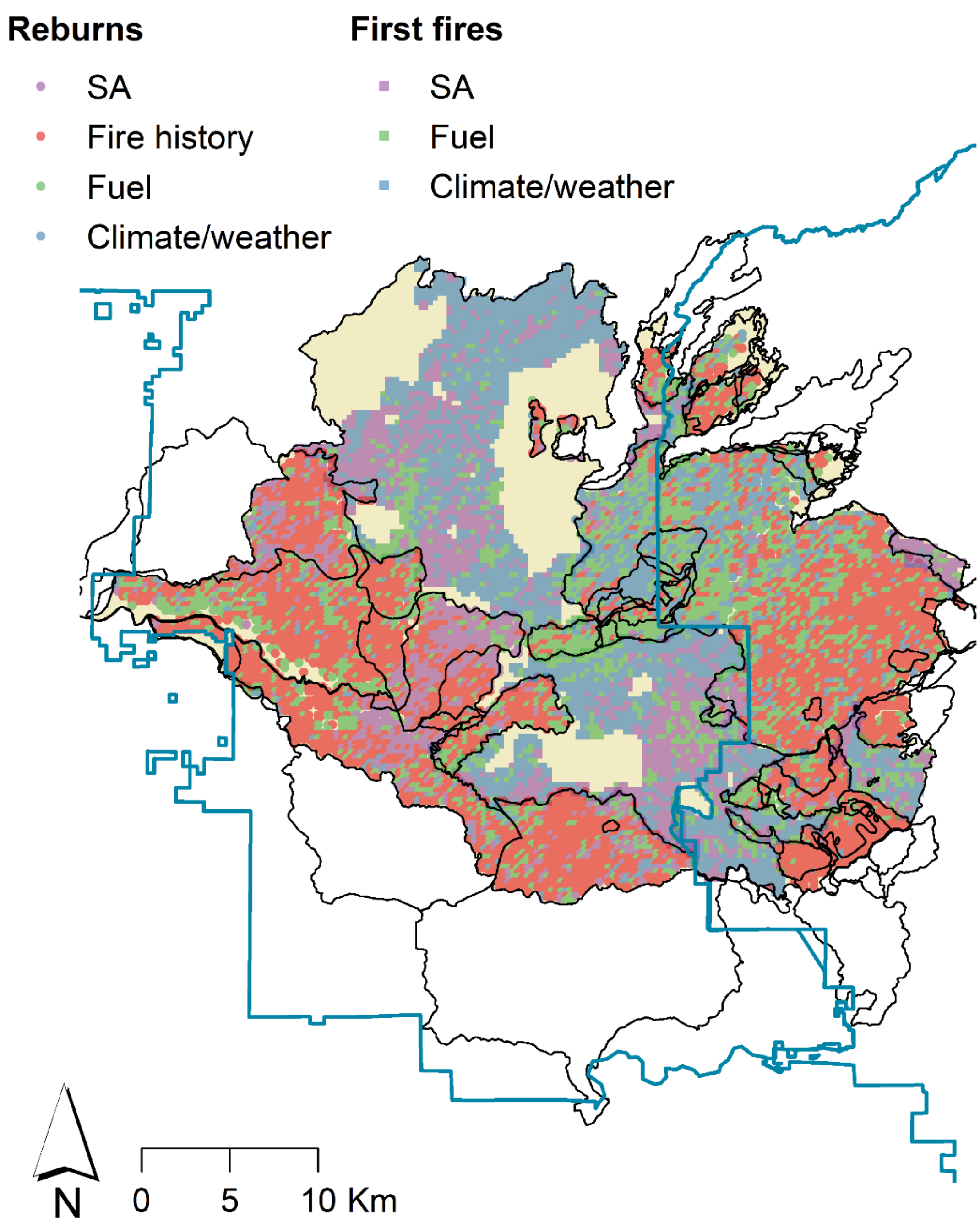

Figure 7. Map of local variable importance across the Rim Fire. Different colors denote the variable group with the highest local variable importance score for each sample point. Sample points are shown as circles for reburns, and as squares where the Rim Fire was the first fire in the modern record. Previous fire boundaries (1984-2013) are denoted by black lines, and Stanislaus NF and Yosemite land ownership boundaries are denoted by blue lines. SA is an abbreviation for spatial autocorrelation.

Rim Fire severity, but other important predictors varied between ownerships. In Yosemite, high fire severities occurred on ridgetops, within 5 km (3.1 mi) of roads, when daily ERCs were >70 and in areas where snowpack was low and maximum annual temperature was moderate (with peak severity observed at 62°F). On the Stanislaus NF, daily fire weather, spatial autocorrelation and mean annual precipitation were the main drivers of first-fire severity patterns in STF. Both BI and ERC were positively related to fire severity, which for BI was generally linear, but for

ERC there was saw a stark increase ERC values >70. Highest fire severities occurred for regions of moderate annual precipitation, with a peak in fire severity observed around 43 in. annual precipitation.

Spatial autocorrelation variables were identified as highly predictive of fire severity patterns. Only a fraction of the variance in fire severity was purely attributable to climate/weather, topography, fuels, and fire history variables alone. This suggests that the spatial patterns of fire severity were largely dependent on the strong spatial structure of the predictor variables and the contagious process of fire spread. It also was a potential indicator of non-stationarity in predictor variables, where the relative influence of a variable may change across the Rim Fire extent. In Stanislaus National Forest, fire weather was more extreme on average and previous management practices (e.g., thinning) did not appear to influence Rim Fire severity patterns. Some individual treatments appeared to have an effect, but across the NF the extent of thinning was low and the models did not identify management variables as important for predicting Rim Fire severity. However past fires did have a big influence on the Rim Fire. Even under plume dominated conditions, past fire severity was the main driver of Rim Fire severity, particularly in Yosemite. This finding, combined with the low predictability of first entry fire severity, suggests strong landscape memory where subsequent fire severity is determined by past fire patterns.

Influence of pre-fire forest structure on Rim Fire severity

Within Yosemite, pre-fire LiDAR measurements of forest structure did not improve our ability to explain Rim fire burn severity patterns (Kane *et al.* 2015). This may be because the LiDAR data does not adequately capture surface fuels that influence fire severity, or that we do not know what the right LiDAR-derived structural metrics/spatial scale are. Biophysical predictors that show stronger relationships with fire severity are typically available at an 18 ac scale. This coarser scale may be a better match to patterns of burn severity. Wildfire itself is a contagious process that both responds to its surrounding environment and self-propagates across a landscape, which leads to a high level of spatial autocorrelation in severity patterns (i.e., adjacent cells are more likely to have the same burn severity compared to distant cells). This high degree of spatial autocorrelation translates to a coarser scaled pattern of fire severity.

At the spatial scale of individual field plots (0.1 ac) areas previously burned at moderate severity exhibited a considerable range in fire severity when reburned in Rim Fire (Collins *et al.* 2018). Live *Abies* sp. (white and red fir) basal area and standing dead biomass had a significant positive association with Rim Fire severity. Areas with moderate fir basal area (>8 $ft^2 ac^{-1}$) or high dead standing tree biomass (>41 tons ac-1) were likely to reburn at high severity, while most other areas reburned at low to moderate severity. Both of these variables are associated with higher surface fuel loads (Lydersen *et al.* 2015), suggesting that the level surface fuels following moderate severity fire may be important for predicting subsequent fire severity.

Science delivery activities

Our project generated five articles in peer-reviewed journals (four published and one in preparation), six conference presentations, four field demonstrations, one webinar, and one research brief. A list is provided in Appendix B.

Conclusions (Key Findings) and Implications for Management/Policy and Future Research

- The extended RdNBR assessment clearly reflects change in forest structure, with little overlap in proportional loss of density and basal area between severity classes. The high severity class is particularly consistent in distinguishing areas burned with complete to near-complete overstory tree mortality. This differs from the common assumption that the high severity category is associated with >75% overstory mortality.
- Treatments that included prescribed burning were the most effective at reducing Rim Fire Severity. This type of treatment was more common in Yosemite than Stanislaus NF.
- Fuels treatments and low to moderate severity wildfire reduced the incidence of high severity fire on sample landscapes and along transects oriented in the direction of fire progression. But, the proportion of area treated was a critical to the actual magnitude of the reductions. At smaller spatial scales (500 ac) much greater treatment proportions were needed to reduce the amount of high severity effects relative to larger spatial scales. This suggests that at the stand-scale if survival of *a particular* stand is of great importance then a large majority (>70%) of it needs to be treated, but at the landscape-scale 20-40% of the area treated is need to reduce *overall* incidence of high severity effects.
- Weather conditions during the time of burning had a strong impact on fire severity in the Rim Fire, with large areas burned at high severity occurring when the burning index and energy release component were relatively high. It should be noted that this "overriding" influence of weather is in the context of a large landscape that is heavily fuel-loaded relative to historical forest conditions. It is unclear if this effect would continue to hold up in forested landscapes with more characteristic fuel levels.
- Fire severity across the fire footprint showed a high degree of spatial autocorrelation. While this is not surprising given the nature of fire spread and behavior, it may be suggestive of a sort of "momentum" effect in which fire severity is not immediately responsive to changes in fuels or topography.
- Previous fire severity had the strongest influence on Rim Fire severity. The areas with the greatest proportion of high severity fire were those that had previously burned at high severity. High severity begetting high severity in reburns has been corroborated by a few recent studies and indicates that high severity fire is *not* a fuel treatment, and if nothing is done to reduce fuels (dead woody and live shrubs) areas burned at high severity are vulnerable to long-term forest loss through type conversion.
- Pre-fire vegetation generally did not improve our ability to predict Rim Fire severity, but higher fire severity was associated with areas with a high density of small trees, a greater abundance of fir, and a greater amount of standing dead biomass.
- Previous moderate severity can lead to mixed effects on subsequent fire, ranging from exacerbated to mitigated reburn severity. Vegetation and fuel dynamics following initial moderate severity influenced the character of the reburn. The moderate severity category is inherently messy because it encompasses such a range of overstory mortality (see Lydersen

et al. 2016). Refinement of this category may be necessary to better characterize effects on forest structure.

Literature Cited

Agee JK, Skinner CN (2005) Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* **211**, 83-96.

Barnett K, Parks SA, Miller C, Naughton HT (2016) Beyond fuel treatment effectiveness: Characterizing interactions between fire and treatments in the US. *Forests* **7**, 237.

Bischl B, Lang M, Kotthoff L, Schiffner J, Richter J, Studerus E, Casalicchio G, Jones ZM (2016) mlr: Machine Learning in R. *The Journal of Machine Learning Research* **17**, 5938-5942.

Borcard D, Legendre P (2002) All-scale spatial analysis of ecological data by means of principal coordinates of neighbour matrices. *Ecological Modelling* **153**, 51-68.

Cansler CA, McKenzie D (2013) Climate, fire size, and biophysical setting control fire severity and spatial pattern in the northern Cascade Range, USA. *Ecological Applications* **24**, 1037-1056.

Collins BM, Kramer HA, Menning K, Dillingham C, Saah D, Stine PA, Stephens SL (2013) Modeling hazardous fire potential within a completed fuel treatment network in the northern Sierra Nevada. *Forest Ecology and Management* **310**, 156-166.

Collins BM, Lydersen JM, Everett RG, Stephens SL (2018) How does forest recovery following moderate-severity fire influence effects of subsequent wildfire in mixed-conifer forests? *Fire Ecology* **14**, 3.

Finney MA, Bartlette R, Bradshaw L, Close K, Collins BM, Gleason P, Hao WM, Langowski P, McGinely J, McHugh CW, Martinson EJ, Omi PN, Shepperd WD, Zeller K (2003) Fire behavior, fuel treatments, and fire suppression on the Hayman Fire. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station General Technical Report RMRS-GTR-114. (Ogden, UT).

Harris L, Taylor A (2015) Topography, fuels, and fire exclusion drive fire severity of the Rim Fire in an old-growth mixed-conifer forest, Yosemite National Park, USA. *Ecosystems* **18**, 1192-1208.

Harvey BJ, Donato DC, Turner MG (2016) Drivers and trends in landscape patterns of stand-replacing fire in forests of the US Northern Rocky Mountains (1984–2010). *Landscape Ecology* **31**, 2367-2383.

Johnson M, Crook S, Stuart M, Romero M, 2013. Rim Fire—Preliminary fuel treatment effectiveness report. USDA Forest Service Rep. 7 p.

Kane VR, Cansler CA, Povak NA, Kane JT, McGaughey RJ, Lutz JA, Churchill DJ, North MP (2015) Mixed severity fire effects within the Rim fire: Relative importance of local climate, fire weather, topography, and forest structure. *Forest Ecology and Management* **358**, 62-79.

Kennedy MC, Johnson MC (2014) Fuel treatment prescriptions alter spatial patterns of fire severity around the wildland–urban interface during the Wallow Fire, Arizona, USA. *Forest Ecology and Management* **318**, 122-132.

Lutz JA, van Wagtendonk JW, Thode AE, Miller JD, Franklin JF (2009) Climate, lightning ignitions, and fire severity in Yosemite National Park, California, USA. *International Journal of Wildland Fire* **18**, 765-774.

Lydersen JM, Collins BM, Brooks ML, Matchett JR, Shive KL, Povak NA, Kane VR, Smith DF (2017) Evidence of fuels management and fire weather influencing fire severity in an extreme fire event. *Ecological Applications* **27**, 2013-2030.

Lydersen JM, Collins BM, Knapp EE, Roller GB, Stephens SL (2015) Relating fuel loads to overstorey structure and composition in a fire-excluded Sierra Nevada mixed conifer forest. *International Journal of Wildland Fire* **24**, 484-494.

Lydersen JM, Collins BM, Miller JD, Fry DL, Stephens SL (2016) Relating fire-caused change in forest structure to remotely sensed estimates of fire severity. *Fire Ecology* **12**, 99-116.

Lydersen JM, North MP, Collins BM (2014) Severity of an uncharacteristically large wildfire, the Rim Fire, in forests with relatively restored frequent fire regimes. *Forest Ecology and Management* **328**, 326-334.

Miller JD, Safford HD (2012) Trends in wildfire severity 1984-2010 in the Sierra Nevada, Modoc Plateau and southern Cascades, California, USA. *Fire Ecology* **8**, 41-57.

Miller JD, Thode AE (2007) Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). *Remote Sensing of Environment* **109**, 66-80.

Peterson DA, Hyer EJ, Campbell JR, Fromm MD, Hair JW, Butler CF, Fenn MA (2015) The 2013 Rim Fire: Implications for predicting extreme fire spread, pyroconvection, and smoke emissions. *Bulletin of the American Meteorological Society* **96**, 229-247.

Safford H, Stevens J, Merriam K, Meyer M, Latimer A (2012) Fuel treatment effectiveness in California yellow pine and mixed conifer forests. *Forest Ecology and Management* **274**, 17-28.

Scholl AE, Taylor AH (2010) Fire regimes, forest change, and self-organization in an old-growth mixed-conifer forest, Yosemite National Park, USA. *Ecological Applications* **20**, 362-380.

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

Tinkham WT, Hoffman CM, Ex SA, Battaglia MA, Saralecos JD (2016) Ponderosa Pine Forest Restoration Treatment Longevity: Implications of Regeneration on Fire Hazard. *Forests* **7**, 137.

Werth PA, Potter BE, Alexander ME, Clements CB, Cruz MG, Finney MA, Forthofer JM, Goodrick SL, Hoffman C, Jolly WM (2016) Synthesis of knowledge of extreme fire behavior: volume 2 for fire behavior specialists, researchers, and meteorologists. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station General Technical Report PNW-GTR-891. (Portland, OR).

Appendix A: Contact Information for Key Project Personnel

Brandon Collins, Center for Fire Research and Outreach, University of California, 130 Mulford Hall, MC #3114, Berkeley, CA, 94720; bcollins@berkeley.edu; 510-664-7027

Matt Brooks, U.S. Geological Survey, Western Ecological Research Center, Yosemite Field Station, 40298 Junction Dr, Suite A, Oakhurst, CA 93644; matt_brooks@usgs.gov; 559-240-7622

Gus Smith, Superior National Forest, Kawishiwi Ranger District, USDA Forest Service, 1393 Highway 169, Ely, MN 55731; douglasfsmith@fs.fed.us; 218-365-7603

Jamie Lydersen, Ecosystem Sciences Division, Department of Environmental Science, Policy, and Management, University of California, 130 Mulford Hall, MC #3114, Berkeley, CA, 94720; jmlydersen@berkeley.edu; 510-642-4934

Van R. Kane, School of Environmental and Forest Sciences, University of Washington, Seattle, WA, 98195; vkane@uw.edu; 206-543-1464

Nicholas Povak, Wenatchee Forestry Sciences Lab, USDA Forest Service, 1133 N Western Ave., Wenatchee, WA, 98801; npovak@fs.fed.us; 608-347-7629

Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

Articles in peer-reviewed journals

Povak, N.A., Kane, V.R., Kane J.T., Collins, B.M., Lydersen, J.M. (In prep) Decomposing multiscaled drivers of Rim Fire severity patterns across land ownerships. Target journal: Forest Ecology and Management.

Collins, B. M., J. M. Lydersen, R. G. Everett, and S. L. Stephens. 2018. How does forest recovery following moderate severity fire influence effects of subsequent wildfire in mixed-conifer forests? Fire Ecology 14:3.

Lydersen, J.M., Collins, B.M., Brooks, M.L., Matchett, J.R., Shive, K.L., Povak, N.A., Kane, V.R. and Smith, D.F., 2017. Evidence of fuels management and fire weather influencing fire severity in an extreme fire event. Ecological applications, 27(7), pp.2013-2030.

Lydersen, J.M., Collins, B.M., Miller, J.D., Fry, D.L. and Stephens, S.L., 2016. Relating fire-caused change in forest structure to remotely sensed estimates of fire severity. Fire Ecology, 12(3), pp.99-116.

Kane, V.R., Cansler, C.A., Povak, N.A., Kane, J.T., McGaughey, R.J., Lutz, J.A., Churchill, D.J., North, M.P. 2015b. Mixed severity fire effects within the Rim fire: Relative importance of local climate, fire weather, topography, and forest structure. Forest Ecology and Management. 358, 62–79.

Conference or symposium abstracts

Kane, V.R., Povak, N.A., Kane, J.T., Collins, B. 2018. Local biophysical patterns interacting with fire weather best explain burn severity patterns in the central Sierra Nevada, California. Association for Fire Ecology and International Association of Wildland Fire Fire Continuum Conference.

Kane, V.R. Predicting Burn Severity Patterns in Yosemite National Park and the Douglas Complex Fires in Oregon. 2017. USDA Forest Service Rocky Mountain Research Station Missoula Fire Sciences Laboratory Seminar Series.

Kane, V.R., Povak, N., Brooks, M., Collins, B., Smith, D., Churchill, D. 2015. Relative influence of top-down and bottom-up controls on mixed severity burn patterns in Yosemite National Park, California, USA. American Geophysical Union Fall Conference.

Collins, B. M. 2015. Moderate severity, what does it mean and what is its fate when reburned by a large wildfire? Association for Fire Ecology 6th International Fire Congress, Advancing Ecology in Fire Management, November 16-20, 2015, San Antonio, Texas. Contributed Presentation.

Lydersen, J.M., Collins, B.M. 2015. Landscape interaction of previous fire and fuel treatments and Rim Fire severity. Association for Fire Ecology 6th International Fire Congress, Advancing Ecology in Fire Management, November 16-20, 2015, San Antonio, Texas.

Kane, V.R., Cansler, C.A., Povak, N.A., Churchill, D., North, M., Smith, D.F., Lutz, J.A. 2014. Biophysical controls on forest structure and fire severity in Yosemite National Park. 99th Ecological Society of America Annual Meeting.

Field demonstration/tour summaries

Lydersen, J.M. 2016. Fire Science Retreat in Yosemite National Park. Invited presentation.

Collins, B. M. 2015. Joint Fire Sciences Program Governing Board Field Tour. Landscape fuel treatment effectiveness in the 2013 Rim Fire. June 10, 2015, Tuolumne County, California. Invited Presentation.

Brooks, M. 2015. Yosemite Rim Fire field trip for congressional staffers.

Collins, B. M. 2014. The Northern California & Southern California Society of American Foresters Joint Summer Meeting, Rim Fire Field Tour. August 22-23, 2015, Tuolumne County, California. Invited Presentation.

Webinars and other outreach

Lydersen, J.M., Collins, B. 2017. Effect of fuels management, previous wildfire and fire weather on Rim Fire severity. California Fire Science Consortium. http://www.cafiresci.org/events-webinars-source/category/effect-of-fuels-management-previous-wildfire-and-fire-weather-on-rim-fire-severity

Lydersen, J.M., Collins, B.M. 2017. Influence of fuels management and fire weather on the Rim Fire: Research Brief. http://www.cafiresci.org/research-publications-source/category/influence-of-fuels-management-and-fire-weather-on-the-rim-fire-research-brief

Appendix C: Metadata

Lydersen, Jamie M.; Collins, Brandon M.; Brooks, Matthew L.; Matchett, John R.; Shive, Kristen L.; Povak, Nicholas A.; Kane, Van R.; Smith, Douglas F. 2017. Fuel treatment and fire history within the Rim Fire in California. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2017-0020.

This data publication contains a geospatial file in raster format of wildfires and fuels treatments that occurred between 1995 and 2013 on Stanislaus National Forest and Yosemite National Park in California within the area burned by the 2013 Rim Fire, excluding the outer 500 meters of the fire perimeter. Tabular data are provided for three sets of circular sample windows of size 500 acres (ac), 2500 ac and 5000 ac within the same geospatial extent. Variables included for the sample windows are proportion burned at high severity in the Rim Fire; proportion treated/burned prior to the Rim Fire; mean values for actual evapotranspiration, water deficit, energy release component, and burning index; and proportion in shrubland, riparian, hardwood, conifer, and grassland LandFire vegetation classes. Tabular data are also provided for a set of transects within the same geographic extent that are placed along radial lines centered on the Rim Fire's origin point.