Research Article

Relating Fire-Caused Change in Forest Structure to Remotely Sensed Estimates of Fire Severity

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ABSTRACT

Fire severity maps are an important tool for understanding fire effects on a landscape. The relative differenced normalized burn ratio (RdNBR) is a commonly used severity index in California forests, and is typically divided into four categories: unchanged, low, moderate, and high. RdNBR is often calculated twice—from images collected the year of the fire (initial assessment) and during the summer of the year after the fire (extended assessment). Both collection times have been calibrated to field measurements, but field data with both pre-fire and post-fire observations of matched plots are typically not available. This study uses a large network of field plots (n = 175) that was surveyed the year of and one year after a large wildfire in the central Sierra Nevada, USA, to quantify forest structure, mortality, and fire effects within

RESUMEN

Los mapas de severidad del fuego son una herramienta importante para comprender los efectos del fuego sobre el paisaje. La diferencia relativa del rango de quema normalizado (RdNBR) es usado comúnmente como un índice de severidad en bosques de California, y es típicamente dividido en cuatro categorías: sin cambios, bajo, moderado, y alto. El RdNBR es calculado frecuentemente dos veces—en imágenes colectadas el año de ocurrencia del fuego (determinación inicial) y luego durante el verano del año posterior al incendio (determinación extendida). Ambas determinaciones se calibran con datos de campo, aunque esos datos pre fuego y post fuego de parcelas superpuestas no siempre están disponibles. En este estudio se usó una gran red de parcelas de campo (n = 175), que fue relevada el año de ocurrencia y luego el año posterior a un gran incendio ocurrido en la Sierra Nevada Central, EEUU, para cuantificar la estructura forestal, la mortalidad, y los efectos del fuego dentro de las determinaciones de categorías de severidad (RdNBR) en fire severity categories from both the initial and extended RdNBR assessments. Most plots were classified in the same severity category in both assessments, particularly when mortality was high. Comparing initial and extended assessments, plots with lower pre-fire basal area were more likely to be classified at lower severity in the extended assessment, while plots with greater tree density were more likely to be classified at higher severity. High-severity plots had significantly greater pre-fire density of small trees. The high-severity category clearly captured stand-replacing fire effects (>95% basal area mortality, >99% tree density mortality), with typically all trees exhibiting high levels of crown consumption and scorching. In other severity categories, most large-sized and intermediate-sized trees survived, and moderate-severity fire favored survival of shade-intolerant species. Results suggest that both the initial and extended RdNBR assessments give an accurate representation of forest structural change in mixed-conifer forests following fire, particularly those of high severity.

los períodos inicial y extendido. La mayoría de las parcelas fue clasificada en la misma categoría de severidad por ambas determinaciones, en particular cuando la mortalidad fue alta. Comparando las determinaciones iniciales y extendidas, las parcelas con menores áreas basales pre-fuego fueron clasificadas mayoritariamente como de baja severidad en la determinación extendida, mientras que las parcelas con mayor densidad arbórea fueron clasificadas mayoritariamente como de alta severidad. Las parcelas que mostraron una alta severidad tenían, previo al fuego, una densidad significativamente mayor de árboles de pequeño porte. La categoría de alta severidad claramente capturó los efectos de un fuego de renovación total del rodal (>95% de mortalidad del área basal, >99% de mortalidad relacionado a la densidad de los árboles), con todos los árboles exhibiendo típicamente altos niveles de chamuscado y consumo de sus coronas. En otras categorías de severidad, la mayoría de los árboles de tamaño grande a intermedio sobrevivieron, y una severidad moderada favoreció la sobrevivencia de especies intolerantes a la sombra. Los resultados sugieren que la determinación del RdNBR, tanto inicial como extendido, proporciona una representación certera de los cambios estructurales en bosques mixtos de coníferas después de un incendio, particularmente en aquellos de alta severidad.

Keywords: fire effects, fire severity, initial severity assessment, mixed-conifer forest, RdNBR, Rim Fire

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INTRODUCTION

Fire severity maps depicting the spatial distribution of fire-caused change to vegetation are an important tool for understanding fire effects on a landscape (Key and Benson 2006). Vegetation fire severity maps are commonly used by land managers to aid in prioritizing post-fire management actions such as reforestation (Miller and Quayle 2015). These maps are also widely used by researchers to study a variety of fire effects, including spatial patterns of fire severity (Collins *et al.* 2007, Cansler and McKenzie 2013), interactions with previous fire and fuel treatments (Wimberly *et al.* 2009, Holden *et al.* 2010, Prichard and Kennedy 2013, Parks *et al.* 2015), fire effects on vegetation (Kane *et al.* 2013, Higgins *et al.* 2015), trends in fire severity over time (Miller *et al.* 2009*b*, Miller and Safford 2012, Mallek *et al.* 2013), and effects on streamflow and habitat (Arkle *et al.* 2010) and carbon pools (Meigs *et al.* 2009, Rose *et al.* 2016).

The use of satellite images to estimate fire severity has become a standard practice in forestry. Remotely sensed images are widely available at moderate (30 m) spatial resolution, enabling visualization of fire effects throughout a fire perimeter. Commonly used fire severity indices derived from Landsat images include the differenced normalized burn ratio (dNBR; Key and Benson 2006) and related measures that adjust for the amount of pre-fire vegetation such as the relative differenced normalized burn ratio (RdNBR; Miller and Thode 2007) and, more recently, the relativized burn ratio (RBR; Parks *et al.* 2014). Each of these indices incorporate wavelengths that are primarily sensitive to pre-fire to post-fire changes in chlorophyll and ash cover (Key and Benson 2006, Miller and Thode 2007). The dNBR incorporates an absolute difference between pre-fire and post-fire values, which directly relates to total change in vegetation and may be more appropriate in areas with somewhat homogeneous pre-fire vegetation cover (Cansler and McKenzie 2012). RdNBR and RBR both adjust for the amount of pre-fire vegetation by dividing dNBR by a function of the pre-fire image. In California, USA, forests, RdNBR is commonly used as it has been shown to perform better than dNBR in heterogeneous vegetation that includes areas of both low and high cover, particularly for high-severity fire (Miller and Thode 2007). Many applications of RdNBR typically involve classifying the continuous data into discrete categories (e.g., Dillon *et al.* 2011, Miller *et al.* 2012, Mallek *et al.* 2013). Often four severity categories are used: unchanged, low, moderate, and high (Table 1). This classification is based on the relationship between RdNBR and the composite burn index (CBI), a field based protocol that combines ocular estimates of fire effects on soil and vegetation in several height strata (Key and Benson 2006, Miller and Thode 2007). The unchanged class represents pixels in which spectral differences between pre-fire and post-fire images are too small for detection, which can occur in both burned and unburned areas (Miller and Thode 2007, Kolden *et al.* 2012, Mallek *et al.* 2013). RdNBR has also been calibrated to field measurements of tree basal area change and change in canopy cover after fire (Miller *et al.* 2009*a*, Miller and Quayle 2015).

The most robust calculation of satellite-image-derived burn ratio indices uses post-fire images acquired during the middle of the summer when solar elevation angles are maximized and topographic and tree shadows are minimized. Because containment dates of many fires in the western US occur after the fall equinox, the best images for minimizing shadows can only be acquired during the summer of the year after the fire. Therefore, the

Table 1. Composite burn index (CBI) and relative differenced normalized burn ratio (RdNBR) values for each severity category.

Severity category	CBI	Initial RdNBR	Extended RdNBR
Unchanged	0.00 to 0.10	<79	<69
Low	0.10 to 1.24	79 to 360	69 to 315
Moderate	4.25 to 2.24	361 to 732	316 to 640
High	2.25 to 3.0	≥733	≥641

fire severity mapping methodologies evolved using these "extended" assessments created from post-fire images acquired during the summer after the fire (Key and Benson 2006). Additional benefits of extended assessments include reduction of ash-related reflectance, and they allow for one season of delayed mortality or flushing of new growth on defoliated trees. These factors may lead to more accurate representations of forest structural change in some situations. However, post-fire management actions (e.g., salvage harvesting), post-fire regrowth of herbaceous vegetation, and sprouting of shrubs before image acquisition can cause confusion when interpreting the images (Crotteau *et al.* 2013, Miller and Quayle 2015, Safford *et al.* 2015). Since 2007, management requirements for more immediate estimates of fire effects to guide post-fire response has given rise to the production of initial assessments, which use post-fire images collected 30 to 45 days after fire containment (Miller and Quayle 2015). These initial assessments, however, can be adversely affected by shadows, depending upon topographic complexity and how late in the year the post-fire image is acquired. For example, a sun elevation angle of 40°, which occurs at the latitude of our study area in mid-October, means that north-facing slopes >40° will be in complete shadow. As a result, in non-hazy clear sky conditions, which are typical in our study area, satellite reflectance values for areas in complete shadow will be greatly reduced to near zero regardless of whether live vegetation exists or not (Chavez 1988). Additionally, when the fire's containment date is very late in the year, it may be necessary to use an image acquired while the fire is still active to avoid cloud cover, which blocks the satellite's view of the earth's surface.

While the accuracy of initial and extended assessments have been validated with extensive field data, those field data were only collected during the summer one year after the fire (Miller and Thode 2007, Miller *et al.* 2009*a*, Miller and Quayle 2015). Therefore, fire-caused change relied on reconstructed pre-fire vegetation conditions based on post-fire observations. Given the potential difficulties in identifying what was alive prior to the fire and the fact that there is outright consumption of some vegetation, pre-fire reconstructions based only on post-fire observations contain some uncertainty. In this study, we took advantage of a unique opportunity to use a large network of field plots (n = 175) with repeat measurements collected 2 to 6 weeks prior to, and one year following, a large Sierra Nevada wildfire, the Rim Fire. Our objective was to quantify fire-caused change in forest structure within commonly used RdNBR fire severity categories. Additionally, we compared this change within mapped severity categories between initial and extended assessments to explore potential inconsistencies between them. Our intent with these objectives was to both robustly describe the range of forest structural change in severity categories and independently evaluate the classification scheme.

METHODS

The study area is located in Stanislaus National Forest in the Sierra Nevada of California, USA. The climate is mediterranean, with average annual precipitation (Oct trhough Sep) of 60 cm. Average January daily minimum temperature is 1 °C, while average July daily maximum temperature is 25 °C (2000 to 2015; http://www.wrcc.dri.edu/; Crane Flat Remote Automated Weather Stations). Precipitation falls in winter as a mix of rain and snow. Low-severity to moderate-severity fires were a common ecosystem process prior to the twentieth century, based on a nearby fire history study that used fire scars, tree cores, and tree age structure and partially overlaps the site (Scholl and Taylor 2010). Pre-fire field data were collected in 2013. Plots were located in mixed conifer forest, ranging in elevation from 1187 m to 1609 m. Principal conifer species included incense-cedar (*Calocedrus decurrens* [Torr.] Florin), ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson), Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), white fir (*Abies concolor* [Gord. & Glend.] Lindl. ex Hildebr.), and sugar pine (*Pinus lambertiana* Douglas), in order of abundance. Jeffrey pine (*Pinus jeffreyi* Balf.) was also present. Black oak (*Quercus kelloggii* Newberry) and canyon live oak (*Quercus chrysolepis* Liebm.) were common hardwood species, and Pacific dogwood (*Cornus nuttallii* Audubon ex Torr. & A. Gray), big leaf maple (*Acer macrophyllum* Pursh), California bay laurel (*Umbellularia californica* [Hook. & Arn.] Nutt.), and white alder (*Alnus rhombifolia* Nutt.) were present in smaller numbers.

Field plots were initially established to remeasure areas covered by timber surveys that were conducted in 1911. Contemporary forest structure data were collected in 209 plots located within 55 of the survey transects from 1911, which spanned the midline of quarter-quarter sections designated by the Public Land Survey System (Collins *et al.* 2015). In 2013, three to four 0.1 ha circular plots (radius = 17.84 m) were randomly placed within each 1911 sampling strip, with at least 60 m between plots. All trees and snags ≥5 cm diameter at breast height (dbh) were recorded by diameter, species, and crown class (suppressed, intermediate, codominant, dominant; Avery and Burkhart 2015). For trees and snags with multiple stems, each stem ≥5 cm dbh was counted individually. Shrub cover was visually estimated by species. All plots burned in the Rim Fire between 21 and 29 August 2013 with a range of burn severities (Figure 1). Plots were revisited in summer of 2014. Status (live or dead) was assessed for each tree present in 2013 and shrub cover was remeasured. Hardwoods that were top-killed but were sprouting from the base were included with dead trees in our analysis. Minimum and maximum bole char height, heights of leaf scorch and consumption, percent crown scorch, and percent crown volume consumed were measured on all trees within 5.64 m of the plot center. Post-fire data were collected for 182 plots; 27 plots were not relocated or were omitted due to post-fire management actions. For analyses of forest structure change, an additional seven plots were omitted because the 2013 tree status was not recorded, leaving a sample size of 175 plots from 50 quarter-quarter sections. Plot steepness ranged from 0° to 37°, with a median of 9°.

Fire severity for each plot was estimated for both the initial and extended RdNBR assessments. The image for the initial severity assessment was acquired on 13 October 2013, one month prior to the official fire containment. However, all of the fire activity that occurred after image acquisition was not in the vicinity of the field plots. The image for the extended analysis was acquired on 1 July 2014, approximately eight months after fire containment. RdNBR values for each plot were extracted using bilinear interpolation of 30 m raster datasets for both assessments. This method uses a distance-weighted average of the four closest pixels to a plot's center to calculate its RdNBR value, and is therefore a better representation of fire severity within 0.1 ha plots, particularly when plot centers do not align perfectly with pixel centers (Cansler and McKenzie 2012, Coppoletta *et al.* 2016). Plots were assigned to a severity category for each assessment using thresholds developed in previous work (Table 1). The thresholds for extended assessment RdNBR classes were based on the calibration of RdNBR to field-measured CBI values acquired in fires in the Sierra Nevada (Miller and Thode 2007). RdNBR initial assessment calibrations were derived by Miller and Quayle (2015) by adjusting the extended assessment calibrations to account for changes in ash cover using the relationship between extended and initial RdNBR values in severely burned areas in fires in the Sierra Nevada.

We used conditional inference tree analysis (Hothorn *et al.* 2006) to explore factors that

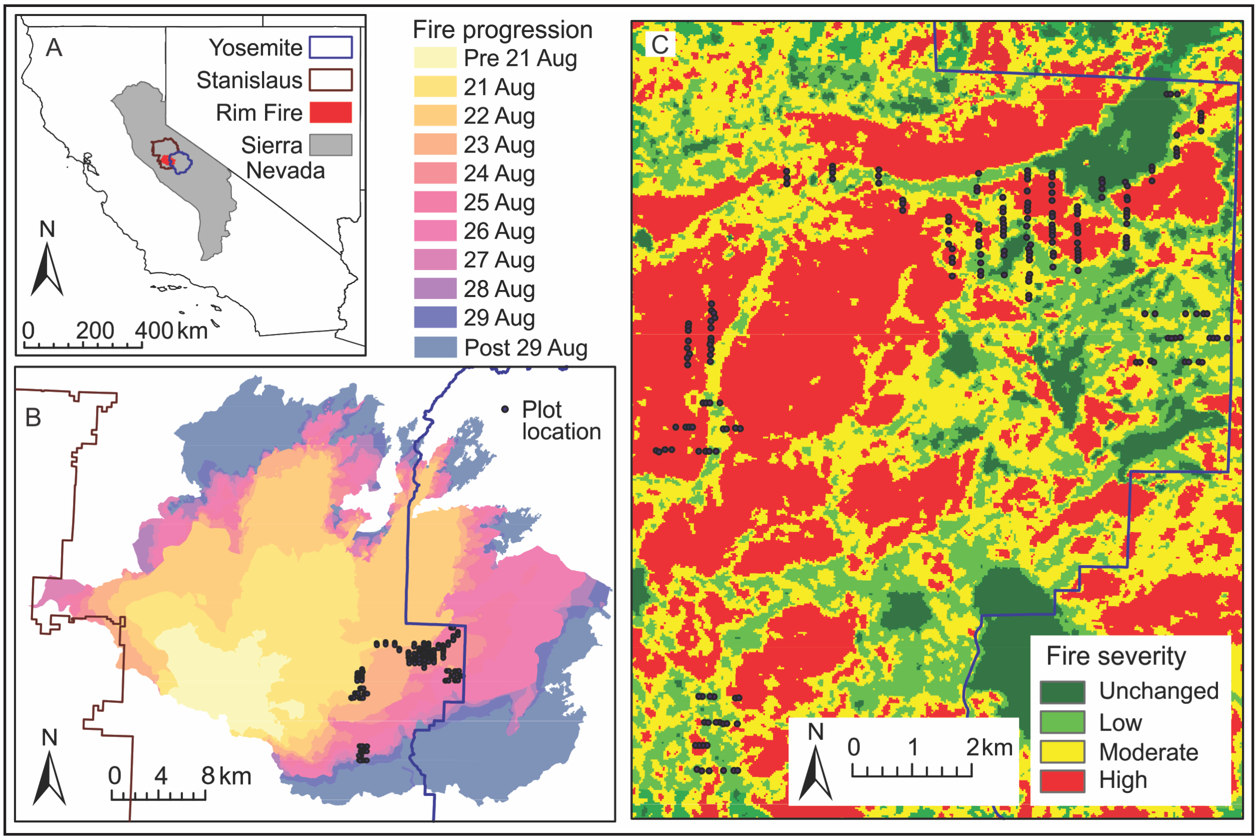

Figure 1. Maps of study area. (A) Location of Rim Fire burn area, Stanislaus National Forest, and Yosemite National Park within the Sierra Nevada ecoprovince in California, USA. (B) Rim Fire progression map showing location of study plots. All dates are in August 2013. Dates prior to or after plot burn dates are shown in one color for simplification. (C) Fire severity map, based on the extended RdNBR assessment, showing location of study plots.

contributed to plots being assigned different severity categories in the extended assessment as compared to the initial assessment. Conditional inference tree analysis is a nonparametric method in which recursive binary splits divide the data by choosing the covariate with the strongest relationship to the dependent variable based on Monte Carlo derived significance values. Recursive splitting continues until the observations in a given node have no significant relationship between the dependent variable or any of the covariates. We used a significance threshold of 0.05 to determine the final decision tree nodes. Plots were divided into three groups: those that were classified at increased severity, those that were classified at decreased severity, and those that remained in the same severity category. Plot membership within those groups was used as the response variable in a classification tree with slope, aspect, solar radiation, pre-fire density and basal area, pre-fire quadratic mean dbh, total and percent change in density and basal area, pre-fire and post-fire shrub cover, bole char, leaf scorch and leaf consumption heights, and percentage crown scorch and consumption as the predictor variables. Slope, aspect, and solar radiation were derived in ArcMap 10.1 (ESRI Inc. 2012) from a 10 m digital elevation model. Solar radiation was calculated for 13 October 2013, the day images were collected for the initial RdNBR assessment. Conditional inference tree analysis was performed using the party package of R software (Hothorn *et al.* 2006, R Core Team 2014).

We used a mixed model ANOVA to assess differences in forest structure pre-fire and post-fire, as well as for differences between severity categories from the extended assessment. Quarter-quarter section and plot identification were included as random factors to account for the spatial dependence of the data and the repeated measurements. A power spatial covariance structure was applied to quarter-quarter sections. Rather than treating all plots as independent replicates, this model explicitly includes spatial autocorrelation between quarter-quarter sections that are geographically closer to each other by adjusting the standard error used to determine significant differences between means. In addition to using a spatial covariance structure in the mixed model, the variable burn conditions present at our site likely help to minimize spatial autocorrelation as well (van Mantgem and Schwilk 2009).

Comparisons of forest structure were made between least squares means of pre-fire and post-fire within each severity category (α = 0.05), and between the four severity categories for each time point using a significance value adjusted by the Bonferroni correction (α = 0.0083). Comparisons included change in live basal area, both total and by tree species grouping (hardwood, shade-intolerant conifers, and shade-tolerant conifers), and change in live tree density, both total and by diameter class (dbh <15.2 cm, 15.2 cm to 30.4 cm, 30.5 cm to 61.0 cm, 61.1 cm to 91.4 cm, and >91.4 cm). The shade-intolerant species group included Jeffrey pine, ponderosa pine, and sugar pine. The shade-tolerant species group included Douglas-fir, white fir, and incense-cedar. The hardwood species group consisted mainly of black oak and canyon live oak but also included Pacific dogwood, big leaf maple, California bay laurel, and white alder. We checked that model assumptions were met by examining graphs of residual versus predicted response of observations, residual quantile, and residual distribution. A square root transformation was used on all forest structure variables to improve conformation to model assumptions. A similar mixed-model ANOVA with a power spatial covariance structure based on plot coordinates was used to compare average percentage crown scorch and crown consumption of co-dominant and dominant trees between severity categories. Means were compared using a Games-Howell test (α = 0.05), which does not require homogeneous variances (Games and Howell 1976). ANOVAs were performed with SAS version 9.4 (SAS Institute, Inc. 2014).

RESULTS

Initial Versus Extended Severity Assessment

There was less overlap in the interquartile distribution of percent change in basal area and stem density for the four severity categories in the extended assessment compared to the initial assessment, indicating better distinction between severity categories in the extended assessment (Figure 2). Twenty-two plots increased by one severity category level from initial to extended assessment, while 17 plots decreased by one severity category level and 143 plots remained in the same severity category (Table 2). While some areas such as steep south facing slopes tended to have greater concentrations of pixels that changed severity class, the plots were located in areas in which pixels that changed severity class between assessments tended to be more scattered in their distribution (Figure 3). Plots in the southeast of the study area were located near a greater number of pixels that increased in severity, while plots on the west side of the study area were located near a greater number of pixels that decreased in severity.

Several forest structure variables were associated with changes in fire severity category between assessments. The plots with the lowest pre-fire basal area were most likely to show a lower severity in the extended assessment as

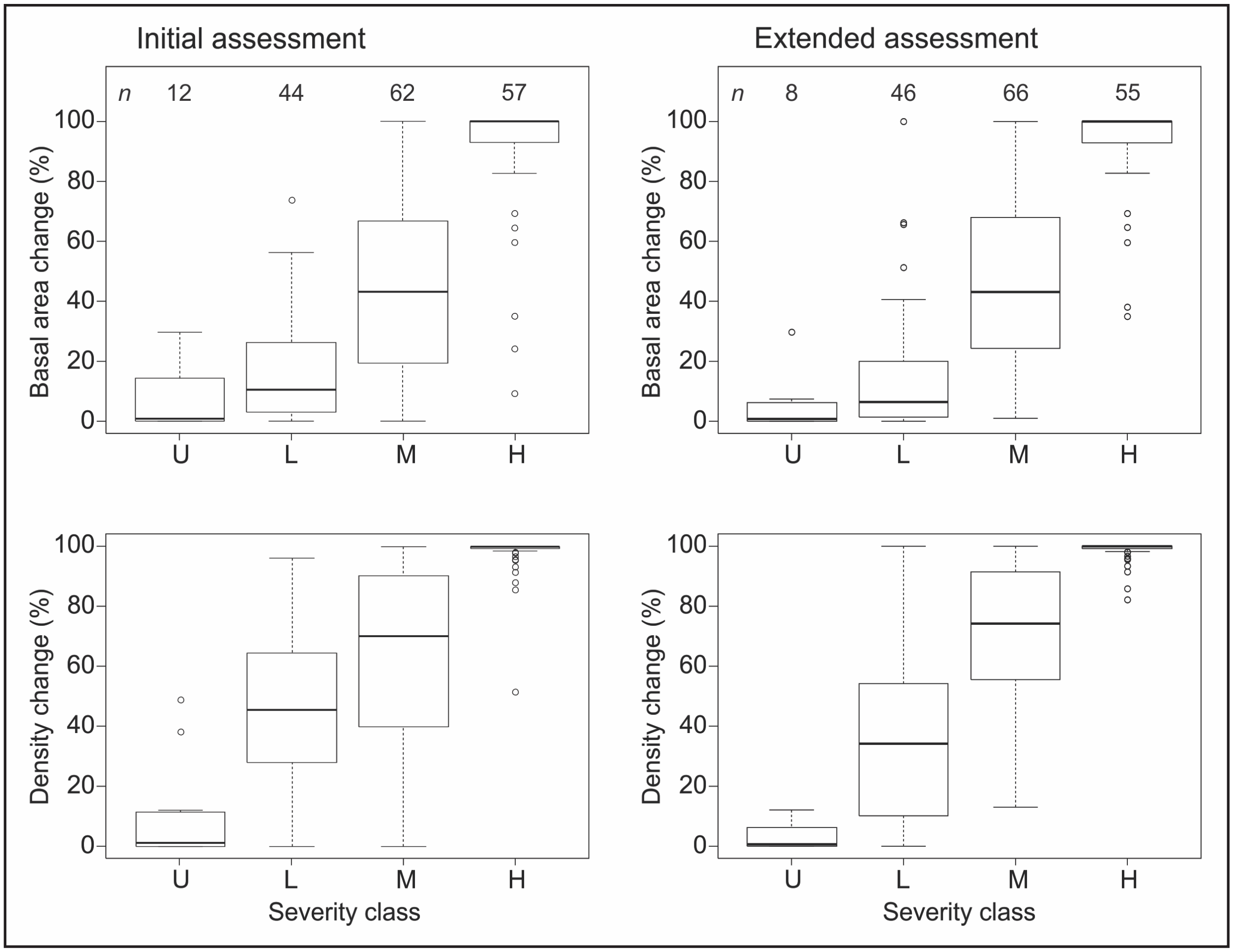

Figure 2. Change in live basal area and stem density pre and post Rim Fire for initial and extended RdNBR assessments. Severity categories are based on RdNBR values. Box and whisker plots depict median (horizontal band), interquartile range (white bar), range of data within 1.5 interquartile range of the lower and upper quartiles (vertical dashed lines), and outliers (points).

Table 2. Number of plots by severity class, in the initial and extended RdNBR assessment of the Rim Fire for 182 plots in Stanislaus National Forest, USA. An increase in severity category is indicated by (+) and a decrease is indicated by (–). U is unchanged, L is low severity, M is moderate severity, and H is high severity.

	U (extended)	L (extended)	M (extended)	H (extended)
U (initial)	7	5 (+)	0	0
L (initial)	1 (–)	29	14 (+)	0
M (initial)	0	12 (–)	49	3 (+)
H (initial)	0	0	4 (–)	58

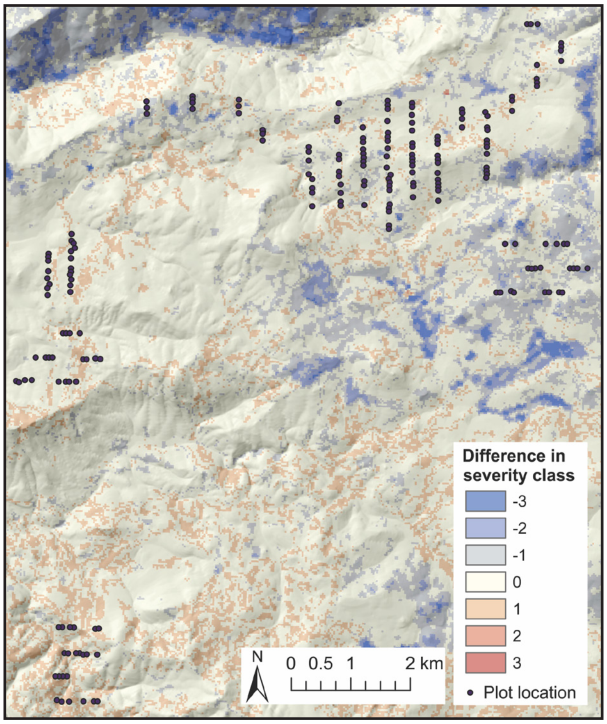

Figure 3. Map depicting degree of fire severity change between the initial and extended RdNBR assessments for all pixels in the study area. Positive values indicate an increase in severity and negative values indicate a decrease. The severity change is superimposed on a hillshade with an illumination angle of 315°.

compared to the initial assessment (Figure 4). In contrast, plots were most likely to show an increase in severity when fire-caused mortality was low and pre-fire tree density was high. Plots with greater fire-caused mortality tended not to change severity category between the two assessments. Plots were also more likely to stay within the same severity category when basal area mortality was low if pre-fire stem density was relatively low (≤830 ha^{-1}). Although variability in shrub cover was high and did not come out as a significant variable in the classification tree, plots that decreased in severity tended to have greater shrub cover on average than those that increased in severity (Figure 5).

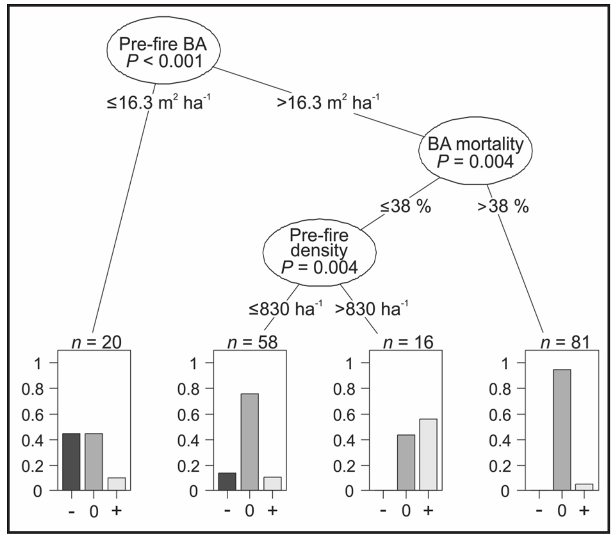

Figure 4. Classification tree depicting the relationships between initial and extended assessment severity categories for the 2013 Rim Fire in Stanislaus National Forest, USA. Minus (plus) sign represents plots that were classified at a lower (higher) severity level in the extended assessment as compared to the initial assessment, and 0 represents plots with no change in severity category. The *y*-axis shows proportion of plots in each tree node. BA is basal area.

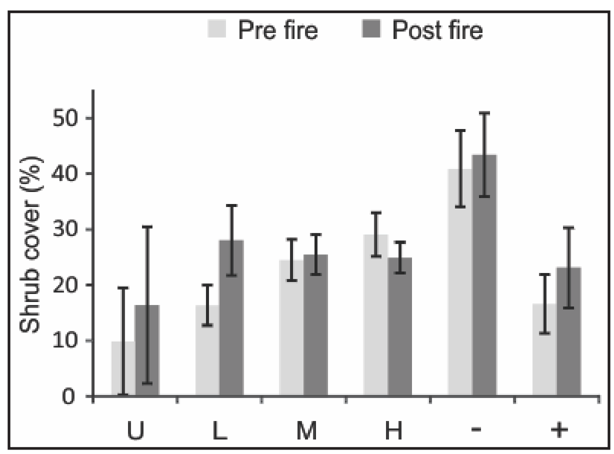

Figure 5. Average pre-fire and post-fire shrub cover for plots with the same fire severity category in both the initial and extended RdNBR assessment for the Rim Fire by severity category: U (unchanged), L (low), M (moderate) and H (high); and for plots that decreased (–) or increased (+) their severity category. Error bars show the standard error.

Pre-Fire and Post-Fire Forest Structure

Among plots classified as unchanged, there were no significant differences in pre-fire and post-fire forest structure, while those classified as moderate or high severity had significantly lower basal area and tree density for all species types and size classes (Figure 6). For moderate-severity plots, there was a significant basal area reduction in all three species groups, although the magnitude of change was less pronounced for the shade-intolerant group (21 %) than it was for the shade-tolerant (53 %) and hardwood (61 %) groups. Among plots classified as low severity, only tree density in the two smallest size classes and hardwood basal area were significantly lower post fire, with the greatest reduction being in trees <15.2 cm dbh (60 %).

Pre-fire forest structure varied between severity categories, although the small sample size of the unchanged group (n = 8) probably limited our ability to determine significant differences for that group. There were fewer significant differences in species composition than there were in tree size class distributions (Figure 6). The only significant difference was for pre-fire hardwood basal area, which was greater in plots that burned at moderate and high severity compared to low severity. Pre-fire tree size classes showed a distinct pattern among severity categories. Small-tree density

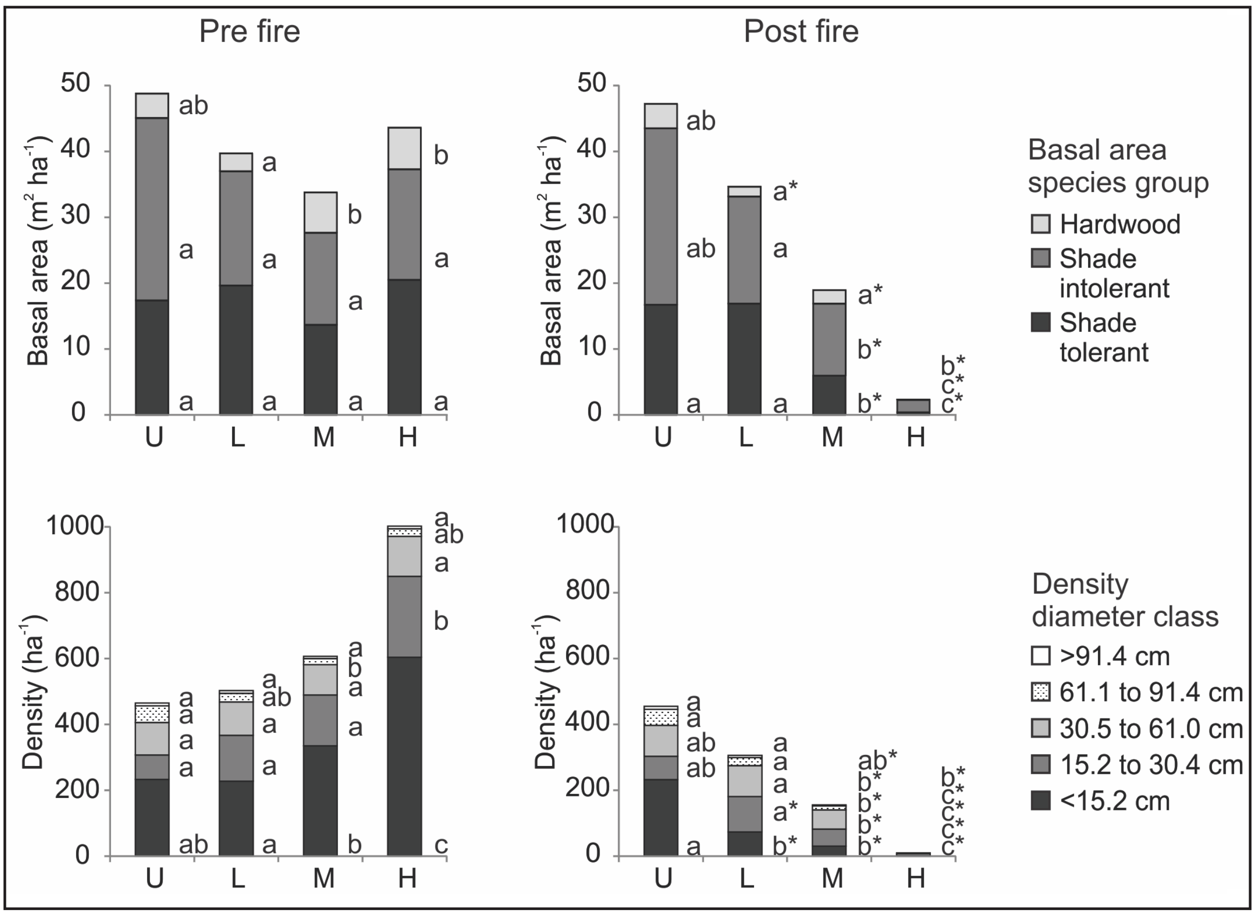

Figure 6. Live basal area by species group and live stem density by size dbh class pre and post Rim Fire. Statistical comparisons were made across time periods (pre-fire to post-fire) for a given severity category (asterisks denote significant differences) as well as within a time period across severity categories (different letters denote significant differences). Severity categories are based on the extended RdNBR assessment; U is unchanged, L is low severity, M is moderate severity, and H is high severity.

tended to be initially higher in plots that burned with greater fire severity (Figure 6). The density of trees in the two smallest size classes was significantly greater pre fire in the plots classified as high severity than in all other severity categories. In contrast, pre-fire density of larger trees tended to be similar among categories or be less at higher fire severities. While the unchanged plots had the highest mean density of trees in the two largest size classes, the only significant difference was for those in the 61.1 cm to 91.4 cm dbh category, which had a greater density in plots classified as unchanged compared to those classified as moderate.

In general, post-fire forest structure exhibited more significant differences between severity categories than did pre-fire forest structure. Unsurprisingly, tree density and basal area decreased with increasing severity (Figure 6). In plots classified as high severity, all post-fire forest structure variables were significantly lower compared to all other severity categories, with the exception of two comparisons that were marginally insignificant. The two exceptions were hardwood basal area, which was not significantly different from the unchanged group ($P = 0.0152$), and density of trees >91.4 cm dbh, which was not significantly different from the moderate group ($P = 0.0087$). Remaining live tree density and basal area were so low in plots classified as high severity that all least squares means estimates of post-fire forest structure variables were not significantly different from zero. Between plots classified as unburned, low, and moderate severity, there was no significant difference in density of trees >91.4 cm dbh. In contrast, trees <15.2 cm dbh were significantly lower in the low severity than unchanged plots.

Fire Effects Measurements

Average heights of leaf scorch, leaf consumption, and minimum and maximum bole char all tended to be greater with increasing severity category (data not shown). Percentage crown scorch and crown consumption of dominant and co-dominant trees also were greater in higher severity categories (Figure 7). For crown scorch, means of all categories

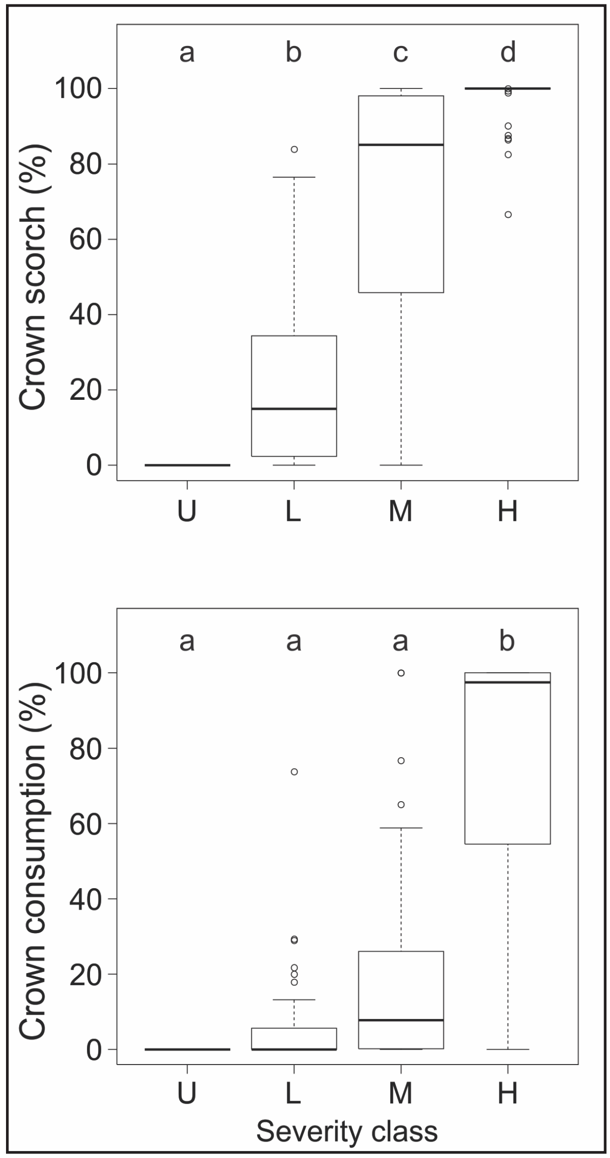

Figure 7. Distribution of average percent crown scorch and consumption for dominant and co-dominant trees by severity category from the extended assessment of the Rim Fire. U is unchanged, L is low severity, M is moderate severity, and H is high severity. Letters across the top of each chart refer to Games-Howell statistical comparisons, with different letters corresponding to significant differences between severity categories.

were significantly different. For crown consumption, only the high-severity group was significantly greater.

DISCUSSION

The observed changes in forest structure within each severity category were within the expected range of fire effects, demonstrating that the commonly used RdNBR fire severity classification (CBI based) is an accurate representation of forest structural change in mixed-conifer forests following fire. Most plots (79 %) remained within the same severity category in both extended and initial RdNBR assessments, suggesting that the initial assessment also gives a fairly accurate representation of fire severity. However, it is clear from our results that the extended assessment provided better distinction between categories based on vegetation changes measured one year post fire. The significant differences in crown scorch between all groups further supports that these categories are fairly distinct.

The lack of agreement in severity categories between initial and extended RdNBR assessments for just over one fifth of the plots warrants further attention. Plots classified at a higher severity in the extended assessment tended to have greater basal area and stem density but lower shrub cover, while the opposite trend occurred in plots that decreased in severity. Increasing severity in some cases may be attributed to the timing of the post-fire images. For the Rim Fire, the initial assessment post-fire image was acquired on 13 October 2013, and for the extended assessment it was acquired on 1 July 2014. When images are acquired after the equinox, low sun angles will cause more shading effects compared to mid-summer images. As a consequence, the increase in severity from unchanged or low to low or moderate categories may be a function of better illumination in the extended assessment. This effect would be expected to be more noticeable on steep slopes and in dense plots with a lower percent mortality. Our study did find that high tree density combined with lower mortality was associated with an increase in severity classification between assessments, but we did not find a significant effect of steepness or aspect (Figure 4). Therefore, shading from trees appears to have more of an influence on reflectance across the range of topographic conditions captured in our plots.

An increase in severity from initial to extended assessments could also reflect delayed mortality. Mortality following wildfire or prescribed fire typically takes place over several years (Hood *et al.* 2010, van Mantgem *et al.* 2011, Collins *et al.* 2014), so it is likely that additional tree death occurred during the eight months between image acquisition for the initial and extended assessments at our study site. A decrease in severity between assessments would be more likely in plots with low tree density, due to greater visibility of the ground and understory, as occurred in our study (Figure 4). Resprouting of shrubs in pixels with a higher percentage of shrub cover compared to tree cover can lead to decreased severity between assessments when overstory mortality is high or low. The high reflectance of ash present immediately after fire can also affect reflectance in the initial assessment; however, the recent calibration for initial assessments developed by Miller and Quayle (2015) and used in this analysis minimizes this effect. Despite discrepancies in severity category between assessments for some plots, previous work has found that RdNBR tends to be particularly accurate for high severity, with little classification difference between initial and extended assessments (Miller and Quayle 2015, Safford *et al.* 2015). Our results agree with this finding; we found that only 6 % of plots that were classified as high severity in the initial assessment changed severity level in the extended assessment compared to 42 %, 34 %, and 23 % for the unchanged, low, and moderate severity categories, respectively (Table 2). In addition, plots with greater percent basal area mortality tended to stay within the same severity category between assessments (Figure 4). It should be noted that net changes in severity classes between initial and extended assessments, which account for both movement into and out of a severity class, were below 5% for all classes except the unchanged. This suggests that, when aggregated across a fire or multiple fires, initial assessments capture overall proportions among severity classes reasonably well.

Fire severity tended to increase with greater pre-fire density of small trees. In contrast, overall basal area was not significantly different prior to fire, suggesting that tree demographics are more important than biomass present. Trees <15 cm dbh were particularly abundant in plots that burned at high severity. Tree density in this category averaged over 600 ha^{-1}, similar to or exceeding average total tree density in plots that burned at lower severity; the maximum density observed was 1690 ha^{-1}. The association between high numbers of small trees and high potential fire behavior is well established (Agee and Skinner 2005) and is a major focus of forest management in forests that have been subject to fire exclusion and past large tree harvesting. Increases in small-tree density are a major ecosystem change attributed to removal of fire from historically frequent-fire forests. The shift to a forest dominated by small trees is associated with homogenization of forest structure (Lydersen *et al.* 2013) that can lead to large patches of high-severity fire (Mallek *et al.* 2013). In resulting stand-replacing patches, lack of natural regeneration can be a concern (Collins and Roller 2013) along with the potential for future fires to reburn at high severity (Coppoletta *et al.* 2016).

The majority of trees >30 cm dbh survived unless a plot burned at high severity. However, mortality was somewhat greater for trees >91 cm dbh than for intermediate sized trees. For example, in plots that burned at moderate severity, the survival rate of large trees was 49% compared to 68% for trees 61 cm to 91 cm, and 63% for trees 31 cm to 61 cm. Similarly, survival of trees >91 cm dbh in low-severity plots was 79%, but 97% and 92% for trees 61 cm to 91 cm and 31 cm to 61 cm dbh, respectively. Large trees have been found to be declining in nearby Yosemite (Lutz *et al.* 2009) and worldwide (Lindenmayer *et al.* 2012). Recent work has attributed the decline of large trees in California to increasing climatic water deficit (McIntyre *et al.* 2015). Large trees in areas where fire has been excluded for long periods of time may also be more vulnerable due to large accumulations of fuel at their base, leading to longer burn durations and cambium damage (Kolb *et al.* 2007, Nesmith *et al.* 2010). This is a possible mechanism of large tree death at our site, although factors contributing to mortality among size classes were not investigated. Regardless of the cause, loss of large trees is problematic due to the associated decrease in ecosystem carbon (Fellows and Goulden 2008) and potential negative impact on wildlife (Tempel *et al.* 2014).

Moderate severity had the greatest range of percent change in basal area and, along with low severity, a large range in percent change in stem density (Figure 2). The large range in change in stem density for the low-severity plots likely reflects that some plots had a large percentage of small trees, which may contribute little to the change in vegetation cover as viewed from above, especially when large trees are present or understory is dense. Regarding the moderate-severity category, the large range in both basal area and stem density change suggests that it may be a “catch all” grouping that captures everything spanning from little overstory change to nearly complete overstory mortality. Having a single category that includes such a range can be problematic, particularly with respect to informing post-fire restoration planning. Another consideration is that moderate severity is also the most difficult to precisely locate on the ground because it often forms a narrow ring (2 pixels to 4 pixels wide) around high severity. Miller and Quayle (2015) inferred that this may reflect the transition between surface and crown fire. Edges and narrow bands are difficult to quantify because pixels do not perfectly align with edges, leading to "mixed" pixels. Image miss-registration (sometimes up to one pixel in width) can also contribute to uncertainty.

Management Implications

Fire can be used as a tool to restore forest structure to a state more resilient to future disturbance. At our site, low-severity fire substantially reduced the number of trees <30 cm dbh, particularly those <15 cm, while having no significant effect on larger tree densities. Fewer small trees could make those areas less prone to high-severity fire in the future (Figure 6), assuming that the fire-killed trees do not create an exacerbated surface fuel problem. There was no appreciable effect on species composition due to low-severity fire, with the exception that hardwood basal area was reduced. While low-severity fire was effective at reducing small-tree densities, moderate severity reduced tree density closer to historical values, a finding also demonstrated by Collins *et al.* (2011) in a nearby study area. Total post-fire basal area averaged 19 m^2 ha^{-1}, which is fairly close to the average basal area of 16 m^2 ha^{-1} found in forested transects in 1911 and falls within the range observed in five of eight historical forest vegetation groups (Collins *et al.* 2015). Moderate-severity fire also favored survival of pines over shade tolerant species, which is a common management objective associated with forest restoration. However, the range of forest structural change in the moderate-severity category was too great to make the claim that fire effects for the category as a whole were desirable from a restoration standpoint. In contrast to moderate severity, average basal area following low-severity fire was 35 m^2 ha^{-1}, which is greater than all but the highest basal area group in 1911. Perhaps a combination of low-severity and moderate-severity fire, ranging from 5% to 70% basal area mortality, would provide the best means of restoring landscape heterogeneity that can meet diverse habitat requirements and management objectives.

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 (Figure 2) and was further distinguished by the majority of trees experiencing crown fire (Figure 7). On average, post-fire live basal area was 2 m^2 ha^{-1} with a median of zero, which falls clearly outside the historical range of variability for a large portion of this landscape (Collins *et al.* 2015). The association between pre-fire density of small trees and high-severity fire at our site suggests that reduction of small-tree density down to a level similar to that of the other plots would likely have reduced the spatial extent of high-severity fire, and therefore preserved large trees that disproportionately contribute to ecosystem services such as wildlife habitat and carbon sequestration.

The two severity assessments provide complementary information. When image dates are late in the year, initial assessments should be considered as an initial (draft) estimate. But when severity data are used to assess fire behavior and effects in vegetation that vigorously resprouts, or when post-fire management actions occur before the extended assessment images are acquired, then the initial assessment data may be preferred.

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