

The importance of small fire refugia in the central Sierra Nevada, California, USA



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ABSTRACT

Fire refugia – the unburned areas within fire perimeters – are important to the survival of many taxa through fire events and the revegetation of post-fire landscapes. Previous work has shown that species use and benefit from small-scale fire refugia (1–1000 m²), but our understanding of where and how fire refugia form is largely limited to the scale of remotely sensed data (i.e., 900 m² Landsat pixels). To examine the causes and consequences of small fire refugia, we field-mapped all unburned patches ≥ 1 m² within a contiguous 25.6 ha forest plot that burned at generally low-to-moderate severity in the 2013 Yosemite Rim Fire, California, USA. Within the Yosemite Forest Dynamics Plot (YFDP), there were 685 unburned patches ≥ 1 m², covering a total unburned area of 12,597 m² (4.9%). Small refugia occurred in all fire severity classifications. Random forest models showed that the proportion of unburned area of 100 m² grid cells corresponded to pre-fire density and basal area of trees, distance to the nearest stream, and immediate fire mortality, but the relationships were complex and model accuracy was variable. From a pre-fire population of 34,061 total trees ≥ 1 cm diameter at breast height (1.37 m; DBH) within the plot (1330 trees ha⁻¹), trees of all five of the most common species and those DBH < 30 cm had higher immediate survival rates if their boles were wholly or partially within an unburned patch ($P \leq 0.001$). Trees 1 cm \leq DBH < 10 cm that survived were located closer to the center of the unburned patch than the edge (mean 1.1 m versus 0.6 m; ANOVA; $P \leq 0.001$). Four-year survival rates for trees 1 cm \leq DBH < 10 cm were 58.8% within small refugia and 2.7% in burned areas ($P \leq 0.001$). Species richness and the Shannon Diversity Index were associated with unburned quadrats in NMDS ordinations 3 years post-fire. Burn heterogeneity in mixed-conifer forests likely exists at all scales and small refugia contribute to diversity of forest species and structures. Thus, managers may wish to consider scales from 1-m² to the landscape when designing fuel reduction prescriptions. The partial predictability of refugia location suggests that further work may lead to predictive models of refugial presence that have considerable potential to preserve ecological function or human habitation in fire-frequent forests.

1. Introduction

Fire is a principal disturbance process in the dry forests of western North America, and there is widespread evidence that fire activity is increasing (Westerling et al., 2006; Miller and Safford, 2012; Dennison et al., 2014). High severity fires and the total area burned have received considerable media attention, depicting an overly simplistic view of fire activity that omits natural variability in fire effects. Within fire perimeters, the distribution of burn severity (i.e., the degree of environmental change following a fire; Key and Benson, 2006; Keeley, 2009) is heterogeneous. Fire mosaics consist of myriad burn severities, including areas that experienced little or no burning. A critical outcome of this heterogeneity is the formation of fire refugia—unburned or lightly

burned areas in the burned matrix that are functionally unaltered by fire. Fire refugia are important but largely understudied landscape components that preserve ecological function in the immediate aftermath of the fire and may reduce vulnerability to future disturbance (Meddens et al., 2018b). Scientific understanding is particularly limited in the study of small-scale fire refugia (1–900 m²), which are known to benefit forest organisms (Robinson et al., 2013), but cannot be reliably detected with most remote-sensing techniques.

Fire refugia influence forest recovery and succession. By buffering lethal temperatures, refugia facilitate the survival and persistence of many taxa during and after a fire event (Gasaway and DuBois, 1985; Robinson et al., 2013). Remnant vegetation provides immediate post-fire habitat for faunal species, expediting recolonization of burned areas

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(e.g., Banks et al., 2011). Islands of unburned forest preserve patches of different successional stages (Turner et al., 1997; Kane et al., 2010), thus increasing overall diversity of habitats and forest structure. Patches of surviving mature vegetation act as barriers to erosion and influence immediate successional processes by providing seed sources to repopulate gaps created by the disturbance (Turner et al., 1998). Fire refugia, therefore, are associated with both immediate and long-term benefits to forest organisms.

The study of relatively large fire refugia (≥ 1 ha) has increased in recent decades with the aid of remote sensing (e.g. Meddens et al., 2016, 2018a). Most recent studies have utilized satellite-derived indices based on 30 m \times 30 m Landsat pixels; the resolution of the Landsat instrument is well-suited for analysis of landscape-scale patterns and trends in burn severity and fire size. Fire refugia in this type of study are identified as pixels with an unchanged surface reflectance between pre- and post-fire scenes, which could include several surface conditions (e.g., unburned forest, a sub-canopy burn not reflected in the overstory, or a burn followed by rapid vegetative regrowth; Kolden et al., 2012). Previous work has described the spatial characteristics and environmental predictors of large fire refugia, as well as differences between remnant vegetation and the surrounding forest. Kolden et al. (2012) found that characteristics such as patch size, density, and shape complexity vary with forest type. Other studies have successfully predicted the presence of large fire refugia based on environmental factors such as terrain ruggedness, soil moisture, aspect, and slope (Román-Cuesta et al., 2009; Krawchuk et al., 2016; Haire et al., 2017). Patches of remnant forest and the surrounding matrix of young forest have exhibited differences in structure, composition, and regeneration (DeLong and Kessler, 2000).

Although large fire refugia have been the subject of much interest, small fire refugia have been less studied. Small fire refugia can be characterized by size or lack of change in vertical forest strata (or both). Landsat 30-m reflectance data has been the primary source for refugia classification (e.g. Meddens et al. 2016), but Landsat data can confuse classification of cover and change at the sub-pixel level due to spectral mixing; a fire refugium that dominates a pixel may be classified as “unchanged” while a small refugium surrounded by char and ash may be classified as burned (Kolden and Rogan, 2013). Similarly, as spectral indices are predominantly sensitive to changes in forest canopy cover (McCarley et al., 2017), fire refugia in the understory or organic soil/duff layers that are obscured by unchanged forest canopy have not yet been reliably quantified with remote sensing techniques (Kolden et al., 2012), although active remote sensing approaches, such as multi-temporal Lidar acquisitions, may provide feasible high-resolution alternatives to Landsat for characterizing fire-induced changes in the vertical strata (McCarley et al., 2017). The unburned patches examined here meet both of these criteria, but we characterize them as “small fire refugia” specifically to acknowledge their size of less than 0.09 ha (900 m²; one Landsat pixel) and to contrast them with pixel-based refugia defined by other studies based on an “unchanged” classification from Landsat data.

Small fire refugia have been exclusively studied in the context of a specific study organism, involving ground-based measurements of unburned forest floor, and have been shown to be important mechanisms of survival for both individual species (Brennan et al., 2011; Robinson et al., 2013; Meddens et al., 2018b) and plant communities (Schwilk and Keeley, 2006; Hylander and Johnson, 2010). Rodent populations have been shown to shift to use small unburned drainages, possibly to avoid predation (Banks et al., 2011) or to use post-fire areas with higher levels of burn heterogeneity, including unburned areas (Roberts et al., 2008). Other studies have shown that forest-floor-dwelling invertebrates survive fire in unburned patches (Zaitsev et al., 2014) and that unburned microhabitats near residual trees and other vegetation correlate positively with beetle diversity (Gandhi et al., 2001). Tree seedlings and saplings can survive in unburned patches, creating structural diversity that provides more habitat for forest fauna and

increases overall forest resilience to disturbances (North et al., 2009).

There is a considerable knowledge gap in our spatial and predictive understanding of small fire refugia. It is unknown how the distribution and formation of small fire refugia compare with studies conducted at a coarser scale, a question relevant to managing forests with fire refugia—of all scales—in mind. It is important, additionally, to understand the relationship between small fire refugia and remotely sensed burn severity. Although, spaceborne remote sensing techniques are unlikely to identify all unburned areas relevant to biota, these methods may help estimate spatial attributes of small refugia in relation to burn severity.

To examine the causes and consequences of small refugia, we field mapped all unburned areas ≥ 1 m² within a 25.6 ha study area. Our objectives were to: (1) characterize the fine-scale spatial distribution of unburned patches, including their sizes, distributions, and correlations with Landsat-derived burn severity; (2) determine the environmental variables predictive of small fire refugia; and (3) compare vegetation in unburned patches and burned areas, including understory community composition and post-fire tree survival. We hypothesized that the spatial distribution of small unburned patches would be aggregated in areas that inhibit fire spread; for example, riparian areas less likely to burn due to the high soil moisture content (Dwire and Kauffman, 2003). Similarly, if the same processes that drive large fire refugia formation also apply to small fire refugia, then abiotic factors such as topography and aspect may be predictive of patch presence (Krawchuk et al., 2016; Haire et al., 2017). We expected that small unburned patches would increase tree survival and have distinct understory communities relative to burned areas.

2. Methods

2.1. Study area

We conducted this study in the Yosemite Forest Dynamics Plot (YFDP, 37.77°N, 119.92°W; Lutz et al., 2012), a 25.6 ha plot in the lower-montane forest zone (1774–1911 m) of Yosemite National Park (Yosemite; Fig. 1). The climate at the YFDP is Mediterranean, characterized by hot, dry summers and cool, wet winters. Between 1981 and 2010 the annual mean monthly minimum and maximum temperatures were 6 °C and 16 °C respectively; annual precipitation was 1070 mm with most precipitation falling as snow between December and March (Lutz et al., 2010; Prism Climate Group, 2017). The YFDP is located in primary *Abies concolor*-*Pinus lambertiana* (white fir-sugar pine) forest of the White Fir Superassociation (Keeler-Wolf et al., 2012), with some trees older than 500 years. The five most abundant tree species are (in decreasing abundance): *Abies concolor* (white fir), *Pinus lambertiana* (sugar pine), *Cornus nuttallii* (Pacific dogwood), *Calocedrus decurrens* (incense-cedar), and *Quercus kelloggii* (California black oak). Plant nomenclature follows Flora of North America (1993+).

2.2. Fire regime

The fire regime in dry mixed-conifer forests of the Sierra Nevada prior to European settlement was characterized by a mean fire return interval of 11 years (van de Water and Safford, 2011), consistent with an interval of 10–13 years found by Scholl and Taylor (2010) approximately 10 km north of the YFDP. However, the mean fire return interval in the YFDP itself was 29.5 years (Barth et al., 2015), possibly due to the northerly aspect of the plot (Lutz et al., 2017). The last widespread fire in the YFDP occurred in 1899, followed by a period of fire exclusion from 1900 to 2012 (Scholl and Taylor, 2010; Barth et al., 2015). In Yosemite as a whole, the reintroduction of fire since the 1970 s has resulted in mixed- and high-severity fires (van Wagtenonk, 2007; van Wagtenonk and Lutz, 2007; Lutz et al., 2009).

The Rim Fire burned 104,131 ha of mostly forested land in August–September 2013 (Kane et al., 2015a; Stavros et al., 2016), including

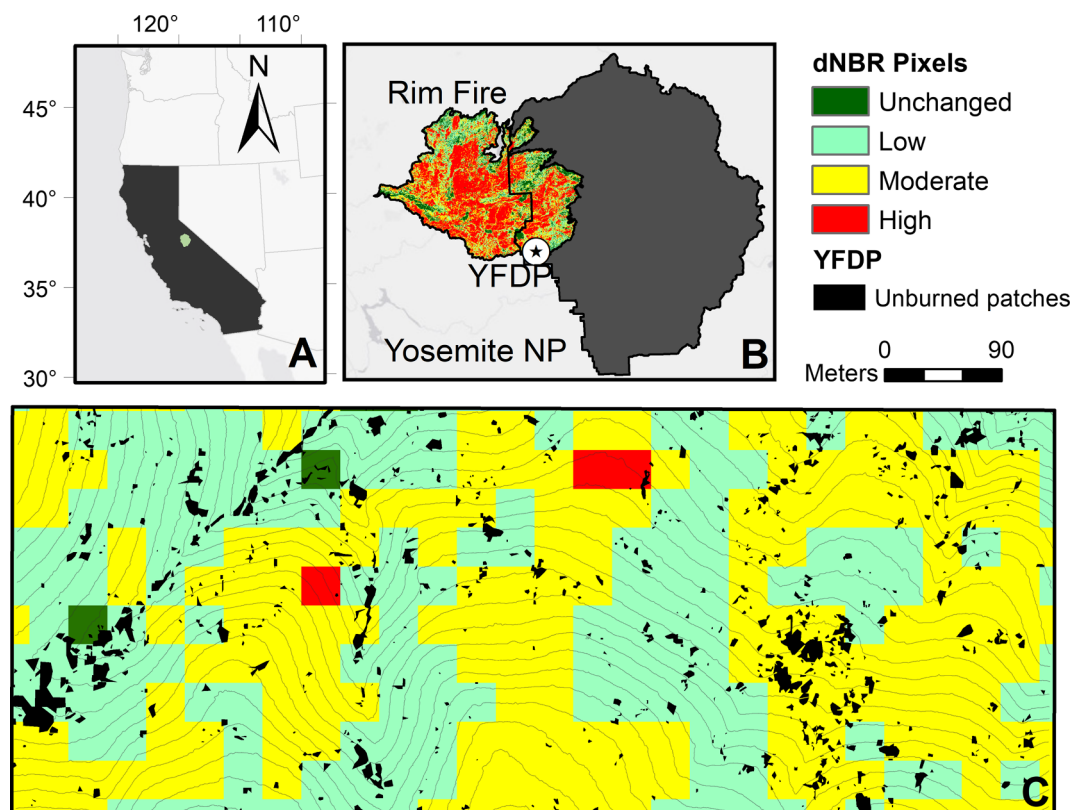


Fig. 1. Location of the Yosemite Forest Dynamics Plot (C) within Yosemite National Park (B), California (A). The footprint of the Rim Fire of 2013 had large contiguous portions that burned at high-severity (B), but within the YFDP, the Rim Fire burned at low- to moderate-severity (C). There were 260 Landsat pixels completely within the YFDP and 336 pixels that intersected the YFDP (C). Small fire refugia ($\geq 1 \text{ m}^2$) were present in all burn severity classes (black shading within C). Differenced Normalized Burn Ratio (dNBR) categorical classifications follow [Miller and Thode \(2007\)](#): unchanged, < 41 ; low, 41–176; moderate, 176–366; high, ≥ 367 . Contour intervals are at 5 m.

32,079 ha within Yosemite. The YFDP was contained entirely within the fire perimeter ([Fig. 1](#)). The YFDP burned on September 1st and 2nd in a management-ignited backfire intended to control the spread of the Rim Fire. The fire was started 1 km away from the YFDP and unmanaged thereafter, with portions of the plot burning in a backing fire at night and the rest burning upslope the following day ([Lutz et al., 2017](#)). Unlike portions of the Rim Fire in the Stanislaus National Forest that burned at high severity in plume-dominated fire behavior ([Lydersen et al., 2014](#)), the YFDP burned at generally low- to moderate-severity ([Fig. 1](#)). Pre-fire surface fuel loading was 334.8 Mg ha^{-1} ([Larson et al., 2016](#)), with high values for litter (63.9 Mg ha^{-1}) and duff (188.8 Mg ha^{-1}). Surface fuel consumption was 95% for litter, 93% for duff, and 90% for 1-hour fuels ([Larson et al., 2016](#)).

2.3. Field methods

The YFDP is a contiguous, rectangular plot comprised of 640, $20 \text{ m} \times 20 \text{ m}$ quadrats, within which all trees $\geq 1 \text{ cm}$ DBH were identified, tagged, and mapped in 2009 and 2010 following the methods of the Smithsonian ForestGEO network ([Anderson-Teixeira et al., 2015](#), [Lutz, 2015](#)). Each tree was revisited annually between 2011 and 2017 and its status tracked (e.g., live or dead). In 2010 all shrub species $\geq 2 \text{ m}^2$ at 40% cover were identified and mapped using the methods of [Lutz et al. \(2014\)](#). In June 2014 (eight months post-fire), we mapped unburned patches $\geq 1 \text{ m}^2$ in the YFDP. Unburned patches were defined by an intact litter and duff layer (i.e. canopy conditions were not evaluated in patch delineation). We mapped the unburned patches as polygons following the methods of [North et al. \(2002\)](#), by traversing each quadrat to identify patches. We used ocular estimation to delineate patch vertices in relation to features on field maps (e.g., trees

and quadrat grid corners; [Figs. S1 and S2](#)). The unburned patch edges were measured using meter tapes, and the datasheets included a representation of a 1-m grid to increase mapping accuracy. Field technicians recorded spatial references to nearby features which were individually verified during digitization (ArcMap 10.3 georeferencing toolbar; [Fig. S1](#)). The position of nearby trees was recorded as outside, intersecting, or within an unburned patch.

We established 63, 1-m^2 square subplots on a defined grid, 54 of which were burned ($> 95\%$ surface fuel consumption). We measured understory vegetation percent cover by species, seedling abundance, in the early growing season (May, June) and after the growing season (August–November) in 2015 through 2017. In order to compare vegetation between burned and unburned areas, in 2016 we installed 40 additional 1-m^2 subplots within unburned patches that ranged in size from 16 m^2 to 40 m^2 . In 2016, we measured litter cover and litter and duff depth in the center of each of the four sides of the 103 1-m^2 subplots; the mean of these measurements was used in analysis.

2.4. Ancillary data

To calculate burn severity of the Rim Fire, we used Landsat 8/OLI Level 1T surface reflectance pre-fire (July 14, 2013) and post-fire (July 1, 2014) scenes (path 43 row 34) downloaded from the Earth Resources Observation and Science (EROS) Center Science Processing Architecture (ESPA) web portal. We selected the scene pair after examining all available scenes from the growing seasons of 2013 and 2014 for optimal sun angle, phenology, and low cloud cover ([Key, 2006](#)). We calculated the differenced normalized burn ratio (dNBR) according to [Key and Benson \(2006\)](#). We calculated the dNBR offset (following [Meddens et al., 2016](#)) from 780 pixels of unburned forest of

the same type located approximately 2 km south of the YFDP. Categorical burn severity classification was based on dNBR thresholds from Miller and Thode (2007): unchanged, < 41; low, 41–176; moderate, 177–366; high, ≥ 367. There were 260 contiguous Landsat pixels completely within the boundaries of the YFDP and 336 Landsat pixels that intersected at least a portion of the area of the YFDP.

2.5. Patch summary statistics

We calculated patch metrics (patch size, patch density, and nearest neighbor) for the total area occupied by each dNBR burn severity category (unchanged, low, moderate, high), and for the entire plot. To calculate distance to nearest patch neighbor the unburned polygons were rasterized using the raster package version 2.6–7 (Hijmans, 2016) in R version 3.4.3 (R Core Team, 2017). The raster cell size that maintained the same total of unburned polygon units was 0.25-m. The nearest patch neighbor was determined as Euclidean distance from the cell center of the focal patch to the cell center of the neighboring patch.

2.6. Random forest modeling of the unburned fraction

We used a random forest model (randomForest package version 4.6–12; Liaw and Wiener, 2002) to determine the environmental variables most predictive of unburned patch presence and proportion within contiguous 10 m × 10 m grid cells ($n = 2723$). All variables were calculated at the scale of the 10-m grid, which was oriented with the 2013 USGS 1/3 arc second (10 m) digital elevation model (DEM). We initially set up the response as the proportion unburned within a 10 m × 10 m cell, however, the response was heavily weighted with zero values as the majority of the plot surface burned in the fire (> 95%). We therefore used a zero-inflated model approach involving two steps: (1) a model with a binary response variable indicating unburned patch presence/absence, and (2) a model consisting of the non-zero observations with a continuous response variable. At the first step we assessed accuracy metrics (listed in Table 3) to determine if unburned patch presence could be distinguished from burned areas. Based on the prediction accuracy we justified proceeding to the second step, in which we assessed the variables predictive of the proportion

unburned. The final random forest regression model was developed using 500 classification trees.

The predictor variables (Table 1, Table S1) were a combination of abiotic and biotic factors hypothesized to influence fire behavior based on previous studies at larger spatial scales (Kane et al., 2013, 2014, 2015b). We calculated the topographic position index (TPI), terrain ruggedness index (TRI), roughness, and slope using the terrain function in the raster package (Hijmans, 2016; Wilson et al., 2007). We calculated insolation using the solar radiation toolset in ArcGIS version 10.3 (ESRI, 2011). Distance to water was the minimum Euclidean distance from each grid cell center to the nearest vernal stream course. Shrub cover was assessed (total cover, and separated by guild) using polygons and guild classifications from Lutz et al. (2017). Mortality-based metrics were defined based on pre-fire live trees that died in the first year following the fire. We first included all predictor variables (Fig. S3), and then developed a final model with the ten variables with highest importance by iteratively removing variables of lowest importance (Fig. S4).

2.7. Tree mortality

To analyze the effect of unburned patches on tree survival, we calculated mortality rates in burned and unburned areas by species and diameter class. Trees were considered to be in an unburned patch if they were completely within the unburned patch or if their boles intersected the perimeter of a patch. We tested for significance ($\alpha = 0.05$) using χ^2 tests under the null hypothesis of equal proportion of mortality in burned and unburned areas and used a Bonferroni correction to account for multiple tests. We assessed the relationship of immediate post-fire tree mortality and tree location relative to unburned patch edge. We analyzed trees in unburned patches and trees within burned areas for both burned and unburned trees. We used ANOVA ($\alpha = 0.05$) to test the response of distance to patch edge and the two predictors, diameter class and post-fire status (live, dead). We calculated the distances between features using the gDistance function in the rgeos package version 0.3–26 (Bivand et al., 2017). We used logistic regression to predict post-fire status and validated model accuracy using ten-fold cross-validation.

Table 1

Model predictors used to predict the presence and proportion of unburned areas. The predictor variables were derived from the US Geological Survey 1/3 arc-second (10 m) digital elevation model (DEM), the National Hydrological Database (NHD), Landsat 8, and the Yosemite Forest Dynamics Plot (YFDP) tree and mortality data. The satellite-derived burn severity index used was the differenced normalized burn ratio (dNBR). Shrub cover was separated by species into three guilds: montane, generalist, and riparian according to the classifications of Lutz et al., (2017). The descriptions for the terrain variables (roughness, topographic position, and topographic ruggedness) are based on descriptions from Hijmans 2016.

Variable Name	Variable description	Units	Source
<i>Abiotic factors</i>			
Distance to water	Minimum distance from unburned patch centroid to water source	Meters	NHD
Roughness	The difference between the range of a cell and its surrounding cells	Relative index	DEM
Slope	Steepness of landscape	Degrees	DEM
Solar incidence	Total amount of solar energy hitting a pixel surface on the day of the fire	W/m ²	DEM
Topographic position	The difference between a focal cell and the mean of the surrounding cells	Relative index	DEM
Topographic ruggedness	The mean of the absolute differences of a focal cell and the surrounding cells	Relative index	DEM
<i>Biotic factors</i>			
Basal area	Area occupied by tree stems	m ² ha ⁻¹	YFDP
dNBR	Satellite-derived index of environmental change caused by fire	Relative index	Landsat
Mortality basal area	Proportion of basal area that experienced immediate fire-related mortality	Percent	YFDP
Mortality tree density	Proportion of live trees that experienced immediate fire-related mortality	Percent	YFDP
Shrub cover	Cover occupied by shrub species (all guilds)	m ²	Lutz et al. 2017
Shrub cover by guild	Shrub cover separated into guilds: generalist, montane, and riparian	m ²	Lutz et al. 2017
Tree density	Number of tree stems	stems ha ⁻¹	YFDP
Tree density (1 to 10 cm)	Number of tree stems 1 cm ≤ DBH < 10 cm	stems ha ⁻¹	YFDP
Tree density (10 to 30 cm)	Number of tree stems 10 cm ≤ DBH < 30 cm	stems ha ⁻¹	YFDP
Tree density (30 to 60 cm)	Number of tree stems 30 cm ≤ DBH < 60 cm	stems ha ⁻¹	YFDP
Tree density (60 to 90 cm)	Number of tree stems 60 cm ≤ DBH < 90 cm	stems ha ⁻¹	YFDP
Tree density (≥ 90 cm)	Number of tree stems DBH ≥ 90 cm	stems ha ⁻¹	YFDP

Table 2

Spatial attributes of small fire refugia in the Yosemite Forest Dynamics Plot (YFDP), categorized by differenced Normalized Burn Ratio (dNBR) severity classes. Burn severity classifications follow [Miller and Thode \(2007\)](#): unchanged, < 41; low, 41–176; moderate, 176–366; high, ≥ 367 . The nearest neighbor metric is the mean of the nearest neighbor distances for each burn severity class.

Burn severity (dNBR)	Unburned area (m ²)	Prop. YFDP (%)	Prop. unburned (%)	Unburned patches (n)	Density (patches ha ⁻¹)	Mean size (m ²)	Patch SD (m ²)	Nearest neighbor (m)
Unchanged	339.1	0.9	15.0	11	48.8	30.8	39.0	1.6
Low	6756.3	44.8	5.9	316	27.5	21.4	61.0	4.4
Moderate	5419.9	53.2	4.0	355	26.0	15.3	36.7	4.3
High	81.3	1.1	3.0	3	11.1	27.1	41.1	6.2
Total YFDP	12596.6	100.0	4.9	685	26.7	18.4	49.5	4.3

2.8. Understory vegetation

We used non-metric multidimensional scaling (NMDS) to compare understory plant communities in burned and unburned 1-m² quadrats in the YFDP. The community matrix consisted of percent cover data of the species occurring in greater than 5% of the quadrats, with each species relativized by the column total. The variables in the environmental matrix ([Table S1](#)) were measured while the community data were collected (2016, 2017), except for percent burned (2015) and litter depth (2016 only). We used the litter depth data in both 2016 and 2017 ordinations under the assumption changes in litter depth between these years was slight. To build the ordinations we used the metaMDS function in R (vegan package version 2.4-6; [Oksanen et al., 2013](#)), which performed a double Wisconsin standardization and square root transformation on the community matrix. The final solutions were assembled in two-dimensions (up to three-dimensions were considered) using the Bray-Curtis dissimilarity index, with 100 minimum and 500 maximum random starts. Our results display the species centroids with the 5 largest correlation coefficients labeled. To examine the correlation between environmental variables and measures of species diversity, we used the env.fit function in R ([Oksanen et al., 2013](#)) to plot the significant vectors ($\alpha = 0.05$) on to the ordination space.

3. Results

3.1. Unburned patch metrics

In the YFDP (25.6 ha), there were 685 unburned patches ≥ 1 m², with a total unburned area of 12,597 m² (4.9%; [Table 2](#)). Mean

unburned patch size was 18.4 m² (SD: 49.4 m², min: 1 m², max: 895.6 m²). Patch density varied with burn severity class ([Table 2](#)), with the highest concentration of actual unburned patches in Landsat pixels calculated as unchanged by dNBR (48.8 patches ha⁻¹). Unburned patch densities were similar in low- and moderate-severity pixels (27.5 and 26.0 patches ha⁻¹, respectively), with the lowest number of unburned patches in high-severity pixels (11.1 patches ha⁻¹). The average nearest neighbor distance between unburned patches was 4.3 m for the whole plot, with the shortest nearest neighbor distances occurring between Landsat unchanged pixels (mean: 1.6 m) and the longest nearest neighbor distances occurring between high-severity pixels (mean: 6.2 m; [Table 2](#)). The actual unburned area within individual dNBR pixels had a weak negative relationship with dNBR burn severity, whether considered categorically ([Table 2](#)) or continuously ([Fig. 2](#)).

3.2. Random forest model

The presence-absence random forest model correctly predicted observed values 73.6% of the time. The model correctly predicted unburned patch absence (i.e. completely burned areas) 88.7% of the time, compared to 46.3% for unburned patch presence. Of the rows incorrectly classified by the model (25.6%), 72.2% of these errors were unburned presence observations incorrectly predicted as absence.

The presence-only random forest model with a continuous response of proportion unburned had a mean difference between predicted and observed values of 0.63 ([Table 3](#)). The predictors that contributed the most to increase in mean square error (MSE), a measure of variable importance to model accuracy, were (in order of importance): distance to stream (m), mortality basal area (m² ha⁻¹), basal area (m² ha⁻¹),

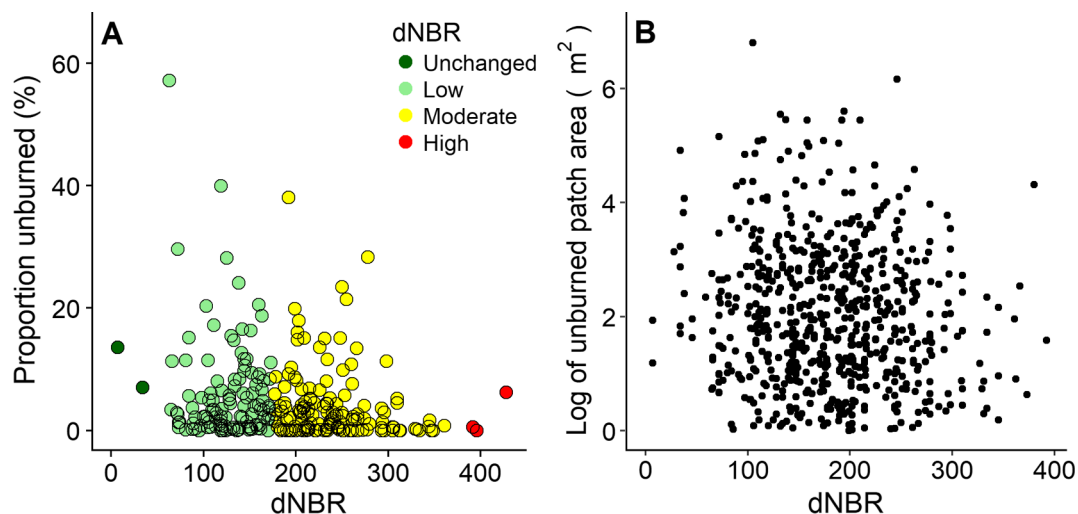


Fig. 2. Differenced Normalized Burn Ratio (dNBR) pixel values for the Yosemite Forest Dynamics Plot and the proportion of each pixel's ground surface that was observed as unburned (A). There was no relationship between the log-transformed unburned patch area and the associated dNBR values (B), suggesting factors other than satellite-derived burn severity control the size of small refugia. The dNBR severity classifications follow [Miller and Thode \(2007\)](#): unchanged, < 41; low, 41–176; moderate, 176–366; high, ≥ 367 .

Table 3

Accuracy statistics for the two random forest classification models: out of bag (OOB) error rate (a measure of overall percent incorrectly classified), sensitivity (the true positive rate), specificity (the true negative rate), and area under curve (AUC; a threshold-independent metric that combines sensitivity and specificity). Accuracy measures for the random forest regression model predicting the non-zero unburned proportion: Variation explained (%), mean difference between predicted and observed values, root mean square error (RMSE), mean absolute error (MAE), and the difference between RMSE and MAE.

Presence-absence model with binary response			
OOB Error	Sensitivity	Specificity	AUC
25.6	0.89	0.46	0.76
Presence-only model with continuous response			
Var. explained	Mean difference	RMSE	MAE
30.4	0.63	17.3	13.1

density (stems ha^{-1}), mortality density (stems ha^{-1}) and the Topographic Position Index (Fig. 3). The mean of the predicted values plotted against the observed values demonstrated the model was best at predicting unburned proportion from 0% to 35%, and less accurate for predicting larger patches (Fig. 3F).

3.3. Understory tree mortality

Total pre-fire tree density in the unburned areas of the plot was 871 stems ha^{-1} compared to 1359 stems ha^{-1} in burned areas. Immediate tree mortality rate was 26.7% within unburned patches and 72.5% in burned areas (Table 4). The greatest difference in tree mortality was in

the $1\text{ cm} \leq \text{DBH} < 10\text{ cm}$ diameter class, with mortality in burned and unburned areas of 90.5% and 30.6% respectively (χ^2 tests, $P < 0.001$). There was no mortality for trees $\geq 30\text{ cm}$ DBH located within unburned patches, compared to 11.5% mortality for trees $30\text{ cm} \leq \text{DBH} < 60\text{ cm}$ in burned areas (Table 4). *Cornus nuttallii* was the tree species with the highest proportion of its population located within unburned patches (15.8%), while *Pinus lambertiana* had the lowest proportion represented (1.5%). Differences in mortality rates between burned and unburned areas by species tended to correspond to the proportion located within unburned patches.

Four years after the fire, trees had markedly higher survival rates in unburned patches for all species and diameter classes $\leq 60\text{ cm}$ DBH (Fig. 4). The greatest difference in survival was for trees $1\text{ cm} \leq \text{DBH} < 10\text{ cm}$, where 58.8% survived in unburned patches and 2.7% survived in burned areas (χ^2 tests, $P < 0.001$). Survival rates for trees $60\text{ cm} \leq \text{DBH} < 90\text{ cm}$ did not differ between unburned and burned areas (66.7% and 62.9%; χ^2 tests, $P = 0.901$).

Trees in unburned patches survived at higher rates when they were farther from the patch edge (mean: 1.1 m, min: 0 m, max: 5.7 m), while trees in unburned patches that died were closer to the patch edge (mean: 0.6 m, min: 0 m, max: 2.9 m). The position within unburned patches of trees $1\text{ cm} \leq \text{DBH} < 10\text{ cm}$ that survived was farther from the edge than trees that died (ANOVA, $P < 0.001$), indicating that buffering from radiant and convective heat was critical to survival of small-diameter trees. Distance to patch edge did not predict survival for trees $10\text{ cm} \leq \text{DBH} < 30\text{ cm}$ (ANOVA, $P = 0.204$) or larger. Trees in burned areas that survived were closer to unburned patches (mean: 8.6 m, min: 0 m, max: 44.3 m) than trees that died (mean: 11.0 m, min: 0 m, max: 47.6 m), with significant differences (ANOVA, $P < 0.05$) for all diameter classes except for trees $\geq 90\text{ cm}$ DBH (ANOVA, $P = 0.643$).

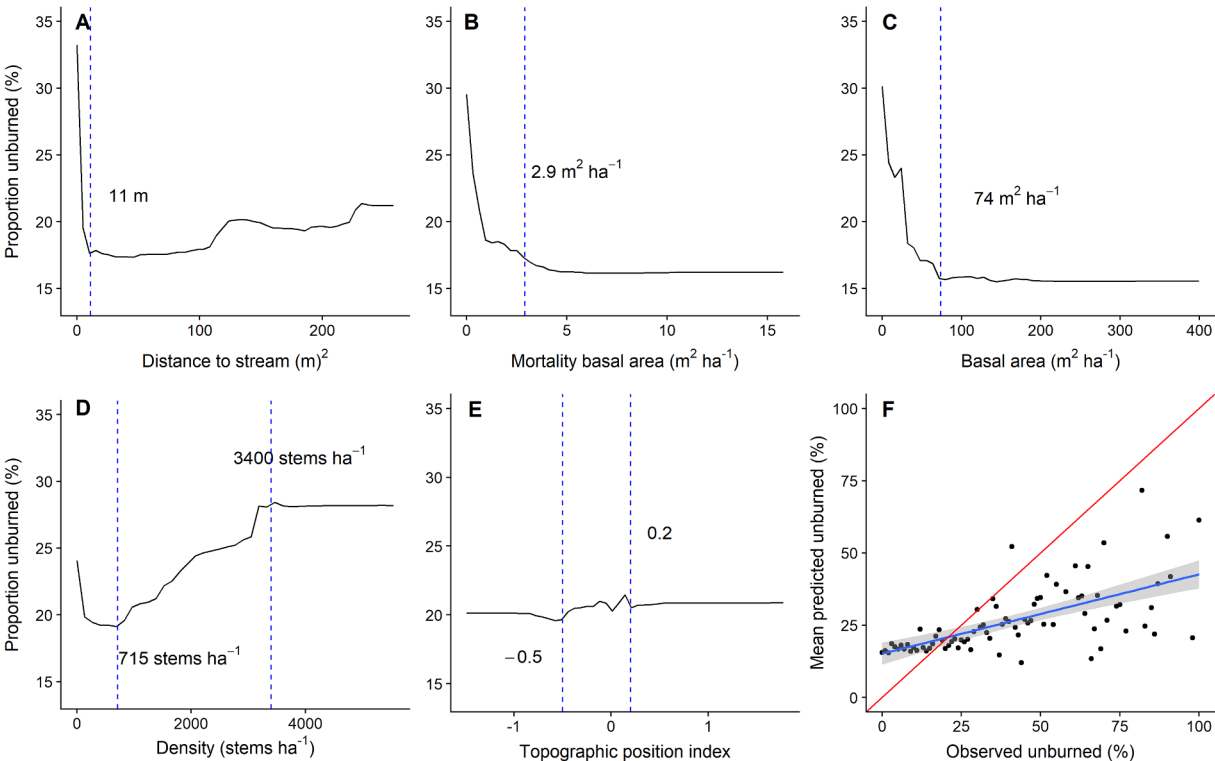


Fig. 3. Partial dependence plots of random forest model variables, listed in order of variable importance: distance to stream (A), local tree mortality as measured by basal area (B), pre-fire tree basal area (C), pre-fire tree density (D), and topographic position index (E). Panel F depicts a measure of model accuracy in aggregate: the mean of the predicted dependence variable plotted against the observed response in bins (rounded to the nearest whole number). The blue line represents the smoothed linear model of the mean predicted versus observed values with a 95% confidence interval. The red line is a linear visual aid to contrast with the slope of the plotted values. In all plots, dashed vertical lines indicate inflection points.

Table 4
Abundances and immediate (2014) mortality rates of all trees in the Yosemite Forest Dynamics Plot during the Rim fire (2013). Trees were categorized based on whether their bole was wholly or partially in an unburned patch $\geq 1 \text{ m}^2$ (unburned) or not (burned). Mortality rates for trees within unburned patches were lower for the five most abundant species and the two smallest diameter classes (χ^2 tests with a Bonferroni correction, modified $\alpha = 0.01$; $P < 0.001$ for all). Significant differences indicated in bold.

	Pre-fire live tree abundance			Post-fire mortality rates		
	Entire plot (n)	Unburned areas (n)	Burned areas (n)	Entire plot (%)	Unburned areas (%)	Burned areas (%)
Species						
<i>Abies concolor</i>	23,999	473	23,526	72.5	29.2	73.3
<i>Pinus lambertiana</i>	4616	67	4549	63.7	35.8	64.1
<i>Cornus nuttallii</i>	2701	428	2273	77.1	23.4	87.2
<i>Calocedrus decurrens</i>	1635	49	1586	63.9	24.5	65.1
<i>Quercus kelloggii</i>	1110	63	1047	63.2	14.3	66.1
Diameter class						
1 cm \leq DBH < 10 cm	21,226	890	20,336	90.5	30.6	93.1
10 cm \leq DBH < 30 cm	9415	195	9220	50.9	10.8	51.8
30 cm \leq DBH < 60 cm	2293	10	2283	11.5	0.0	11.5
60 cm \leq DBH < 90 cm	690	3	687	3.3	0.0	3.3
DBH ≥ 90 cm	621	0	621	4.0	NA	4.0
Total	34,061	1080	32,981	71.0	26.7	72.5

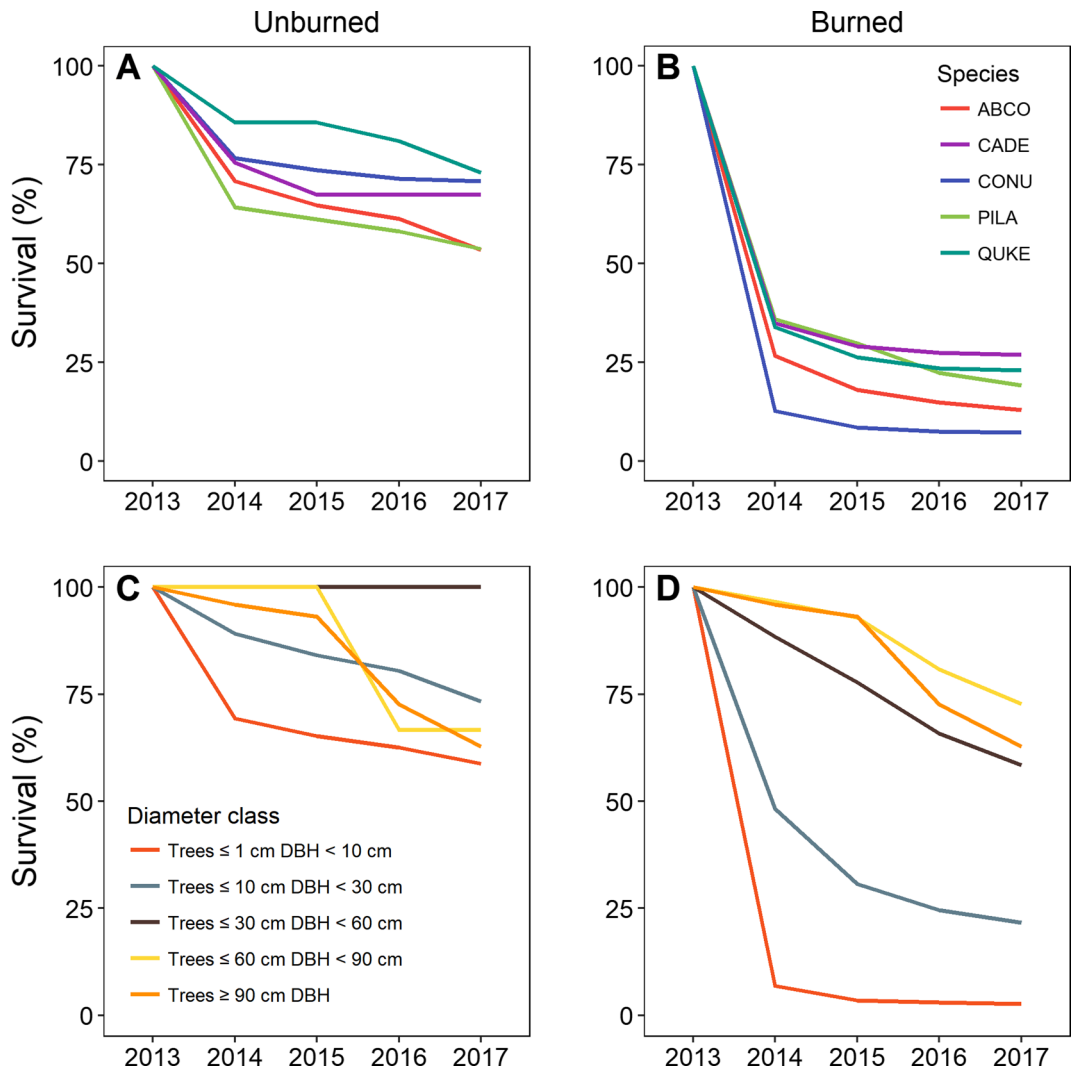


Fig. 4. Tree survival rates in the Yosemite Forest Dynamics Plot from 2014 to 2017. Trees of the five most abundant species (*Abies concolor*, *Calocedrus decurrens*, *Cornus nuttallii*, *Pinus lambertiana*, *Quercus kelloggii*) had higher survival rates if their boles were in unburned patches (A) compared to areas with burned substrate (B). Trees $\leq 30 \text{ cm DBH}$ had higher survival rates in unburned (C) versus burned (D) patches. Survival of trees $> 30 \text{ cm DBH}$ did not differ between burned and unburned substrate.

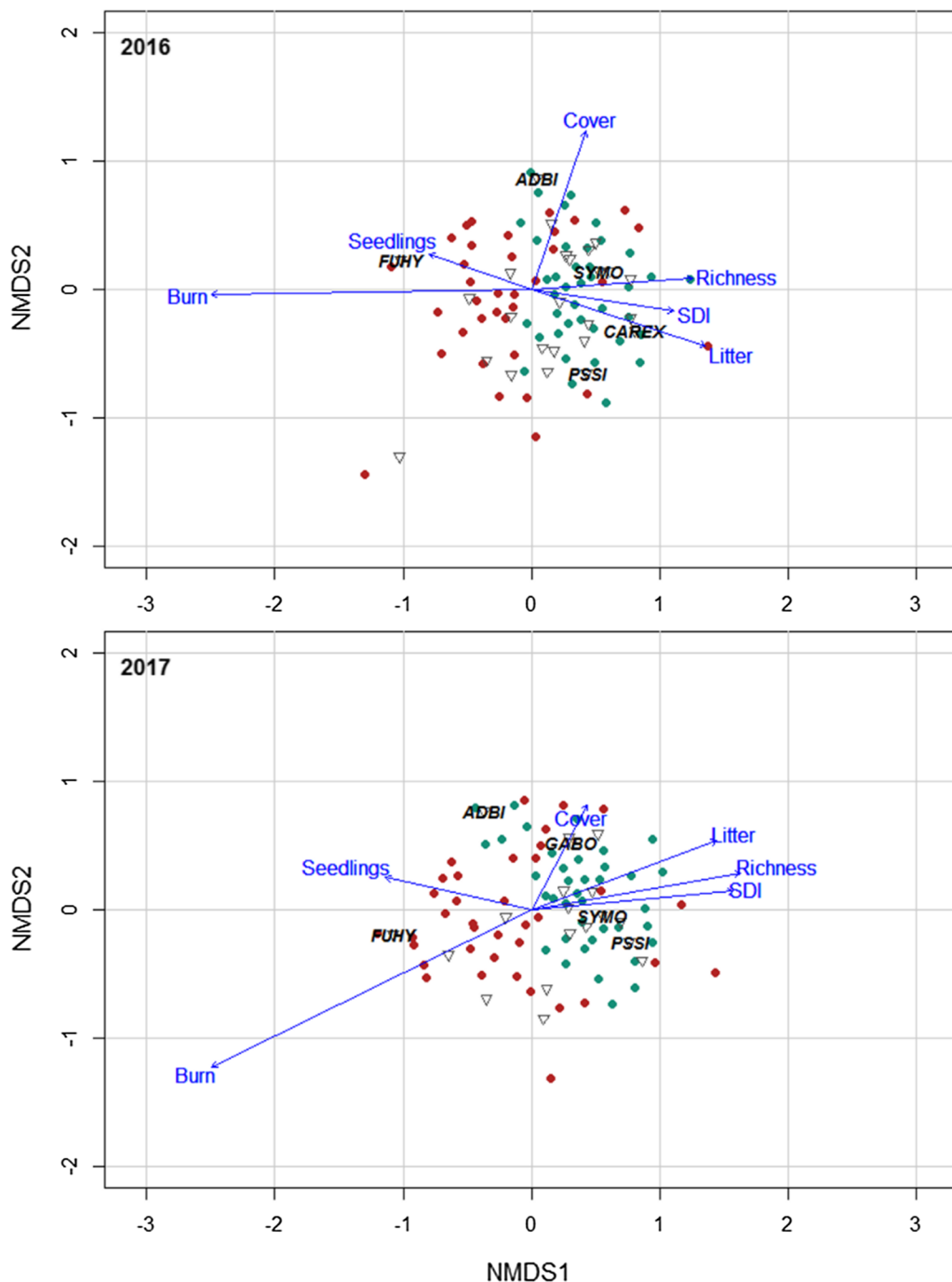


Fig. 5. Non-metric multidimensional scaling (NMDS) ordination showing understory vegetation community differences in the Yosemite Forest Dynamics Plot (YFDP) 3 and 4 years following the 2013 Yosemite Rim fire. Vegetation was measured in 1-m² quadrats in burned (represented by red circles) and unburned (represented by green circles) areas. Species centroids are represented by black triangles, wherein the species with the 5 largest correlation coefficients are labeled. ADBI = *Adenocaulon bicolor*; CAREX = *Carex* spp.; FUHY = *Funaria hygrometrica*; GABO = *Galium bolanderi*; PSSI = *Pseudostellaria sierra*; SYMO = *Symphoricarpos mollis*. Environmental variables with significant associations ($P \leq 0.05$) are represented by blue arrows. Burn = percent of 1-m² quadrat that burned; Cover = percent vegetative cover; Litter = depth (cm) of the litter layer; Richness = number of species observed at a quadrat; SDI = the Shannon Diversity Index; Seedlings = seedling abundance.

3.4. Understory vegetation

The NMDS ordinations showed a modest separation between burned and unburned quadrats for both years, suggesting these areas contain distinct understory communities (Fig. 5). The final solutions had a stress of 0.18 for both 2016 and 2017. Six vectors had significant associations ($\alpha = 0.05$) with the ordination configuration: percent burned, litter depth, seedling abundance, percent cover, species richness, and the Shannon Diversity Index (SDI). Most notably, species richness and SDI were associated with unburned quadrats (richness: $r_{2016} = 0.10$, $r_{2017} = 0.11$; SDI: $r_{2016} = 0.09$, $r_{2017} = 0.10$), indicating that small refugia include plant communities with a greater number of species and a more even distribution than those of burned areas. In addition to the diversity indices, percent cover and litter depth were correlated with unburned areas (cover: $r_{2016} = 0.10$, $r_{2017} = 0.04$; litter

depth: $r_{2016} = 0.09$, $r_{2017} = 0.10$), suggesting either that small fire refugia are places with high vegetative cover, or that recolonization of burned areas 3 to 4 years after fire does not match the cover observed in unburned areas. Seedling abundance was negatively correlated with unburned plots in 2017 ($r = 0.06$), likely because the litter layer acts as a barrier for the anchoring of seedling roots. Species composition in the burned plots was more similar to that of the unburned plots in 2017 relative to 2016, suggesting that understory recolonization four years post-fire homogenizes these two areas.

Despite community differences visible in the NMDS ordinations, mean quadrat summary metrics for all understory species (including rare species) did not differ significantly in burned and unburned areas (Table S2). Mean cover in unburned quadrats was 21.8% (SD: 22.2%, min: 0%, max: 150.8%); compared to 13.1% in burned quadrats (SD: 22.4%, min: 0%, max: 104.5%; Table S2; $P = 0.121$). Average seedling

abundance was 6 m^{-2} in burned quadrats and 2 m^{-2} in unburned quadrats ($P = 0.180$). Species richness in unburned quadrats was 6.4 m^{-2} (min: 0 m^{-2} , max: 15 m^{-2}) and 3.2 m^{-2} in burned quadrats (min: 0 m^{-2} , max: 12 m^{-2}), but the differences were not significant ($P = 0.266$).

4. Discussion

4.1. Characteristics of small fire refugia

Small fire refugia ($1\text{--}900\text{ m}^2$) were abundant throughout the study area in this low- to moderate-severity fire. The fire traversed the entire plot, with the exception of approximately 5% of the forest surface. Refugia occurred in all landscape positions and dNBR burn severity classes; it is important to note, however, that pixels classified as unchanged or high severity were very limited in the study area.

Although small fire refugia were present within pixels of all dNBR severities, they were fewer and farther apart with increasing dNBR. We posit that this pattern is influenced by soil, fuel continuity, and litter moisture (Wohlgemuth et al., 2006). Environments that tend to burn at moderate or high severity, such as steep, rocky areas, may exhibit reduced fuel continuity because of the rocky matrix and low productivity (Kolden et al., 2017). Low fuel continuity could lead some areas to remain unburned despite high flame heights associated with steep slopes. In low burn severity environments, such as drainages and riparian areas, high litter moisture and cold air pooling inhibit fire spread, possibly leading to more abundant and less dispersed unburned patches (Dwire and Kauffman, 2003).

Individual unburned patch area showed no relationship with dNBR as a continuous metric (Fig. 2), suggesting that burn severity may be entirely unrelated to unburned patch size and that many conditions associated with both high and low dNBR can give rise to small unburned patches. Stochasticity in fire behavior, such as a change in wind direction or relative humidity, may give rise to small skips in the burning of surface fuels (irrespective of burn severity). However, refugial patches were closer together in low severity pixels and farther apart in areas of high burn severity. While burn severity may not control patch size, the results suggest that burn severity potentially influences patch density and proportion of area unburned, consistent with prior studies (Kolden et al. 2015).

4.2. Limitations of dNBR

Our results highlight a consequence of the limited spatial resolution of Landsat-derived dNBR—small fire refugia cannot be reliably detected. Pixels with an unchanged surface reflectance at $30\text{ m} \times 30\text{ m}$ grain occupied 0.9% of the YFDP, much lower than the 4.9% unburned surface layer determined by field observations. This is not surprising—dNBR values primarily exhibit overstory changes because differenced Landsat scenes cannot detect surface burning when masked by the canopy (Kolden et al., 2012).

The spatial resolution of dNBR is an important consideration in the interpretation of our results regarding unburned patch distribution in relation to fire severity classifications. Landsat-derived pixels represent an average of spectral changes over a 900 m^2 area, thus dNBR values may not accurately reflect overstory conditions most proximate to field-mapped unburned patches. Areas classified as moderate burn severity, for example, could be largely unburned but contain a high severity patch in a fraction of the pixel.

4.3. Predicting small refugia

Inaccuracies in our presence-absence random forest model may be due to the presence of different types of small fire refugia in our dataset. Fire refugia include those that are persistent or ephemeral (*sensu* Meddens et al., 2018b). Predictive models might reach a high level of

accuracy for persistent refugia that are controlled primarily by their landscape position or surrounding vegetation, but it may be difficult to model ephemeral refugia, where the locations are controlled by the vagaries of fire progression, in anything other than a probabilistic sense. The relative proportion of persistent and ephemeral refugia on the landscape remains an open area of research.

In a separate analysis of the cells our presence-absence model could accurately predict, we found that the proportion of likely persistent refugia (*sensu* Meddens et al., 2018b) is considerable, and can be modeled with physiologically plausible predictors (i.e., distance to streams, proximate tree density and basal area, proximate tree mortality, and topographic position). A distance of 11 m from the nearest stream maximized the unburned proportion, and interestingly, the unburned proportion increased slightly from stream distances of 100–300 m, suggesting that the distribution of refugia responds to multiple factors (Fig. 3A). The unburned proportion was highest in areas with the lowest mortality by basal area, a measure of burn severity (Fig. 3B). Low basal area, which is often associated with low productivity areas, was also correlated with high unburned proportion (Fig. 3C). Refugia occurred in areas of both high and low stem densities (Fig. 3D), likely a reflection of the high stem densities of riparian species (i.e., *Cornus sericea* and *Cornus nuttallii*) and the low fuel continuity associated with low stem densities (Fig. 3D). Topographic Position Index had less explanatory power, but indicated unburned proportion was slightly higher in concave lower slopes and convex upper slopes (Fig. 3E).

Data limitations likely contributed to model inaccuracies in predicting small fire refugia presence. Following the abstraction of the fire behavior triangle (fuels, weather, topography), our set of predictors was incomplete. Topography was approximated through DEM-derived indices and their predictive ability was less than vegetation-related predictors. Our measures of fuel loading and consumption were indirect, as we used proxies known to contribute to the litter and duff layer (e.g., nearby tree density and basal area) or to represent fire intensity (e.g., local tree mortality). We had no measurements of fine-scale fire weather (but see Lutz et al., 2017). There was also a scale problem, wherein our predictive data did not necessarily match the spatial scale of the refugia we delineated, which influences model predictive power (Birch et al., 2015).

4.4. Impact of small refugia on tree mortality and survival

Despite our definition of refugia as entirely unburned at the surface, tree mortality still occurred in unburned areas. Our field measurements of unburned patches considered only the forest floor and root crowns when classifying an area as either burned or unburned. Radiant and convective heat from the flames, however, was often lethal for sub-canopy foliage, and many trees located within unburned patches experienced crown scorch despite having an intact litter layer. Overall, however, small refugia were a significant source of tree survival for all species and diameter classes $< 60\text{ cm DBH}$ and these higher survival rates persisted for at least four years. The deciduous species *Quercus kelloggii* and *Cornus nuttallii* were more susceptible to bole scorch mortality due to their thinner bark, and consequently these species experienced the greatest increases in survival when located in small refugia. Trees positioned deeper within unburned patches had higher survival rates, likely due to heat buffering resulting in sub-lethal fire heating (i.e., Smith et al., 2016b, 2017).

Small-diameter trees disproportionately benefited from the heat buffering effects of small refugia. After a century of fire suppression, which resulted in increased tree densities and high ground fuel accumulations, even low- to moderate-severity surface fires can be fatal to most sub-canopy trees while larger and older trees survive (Larson et al., 2015). Small refugia may be important determinants of the trees that eventually recruit into the canopy; trees $< 10\text{ cm DBH}$ that escape fire by virtue of being in refugia may be large enough to survive the

next fire, even if that subsequent fire burns near them (Becker and Lutz, 2016). By preserving a population of advanced regeneration, small refugia may be a means through which forests maintain structural diversity (Lutz et al., 2018a).

4.5. Understory vegetation in burned and unburned areas

Small fire refugia appear to host more diverse understory plant communities relative to burned areas 3 and 4 years post-fire (Fig. 5). Burned areas were dominated by colonizing species or in some cases, lacked any vegetative regrowth, while unburned areas likely maintained pre-fire species composition. We draw two conclusions from the higher understory plant diversity found in unburned areas. First, places where small fire refugia form may host different and/or more diverse understory communities than areas that burned. Alternatively, the same understory communities may have been prevalent throughout burned and unburned areas, and those surviving in small fire refugia represent starting points for post-fire recolonization of burned areas. In either case, refugial areas may be a mechanism by which forests maintain biodiversity across periods of disturbance.

4.6. Scale

The fine-scale resolution and spatial extent of this dataset allows us to address whether spatial patterns of fire refugia are maintained across scales (i.e., Lutz et al., 2018b). Previous work has examined fire refugia primarily at the landscape scale, for which the smallest unit of measure is a 900 m² Landsat pixel. Kolden et al. (2012) and Kolden et al. (2015) reported the average unburned proportion in Yosemite National Park at 20% to 25%, much higher than the 5% unburned area found in this study. Moreover, the fire in the YFDP had a substantial low-severity component (44.8%); based on the results of Kolden et al. (2012) we would expect a higher proportion of unburned area following lower severity fire. Several conditions could explain these incongruities. First, these results suggest that—at least for low- to moderate-severity fire—landscape-scale factors that give rise to large fire refugia (e.g. aspect, topography, burn history) may not apply at fine scales. Second, the methods associated with measuring small vs. large fire refugia are based on different definitions of unburned refugia. Whereas we delineated unburned patches based on the presence of an intact litter and duff layer, unchanged dNBR pixels could represent several ground conditions, including unburned forest; an undetectable low-severity burn; or regrown vegetation with an identical spectral signal to that of the pre-fire scene (Kolden et al., 2012). Given the possible surface conditions that large fire refugia could represent, it is not surprising that the unburned proportion differs between large and small scales.

5. Conclusions and management implications

The portion of the Rim Fire that was burned by the management-ignited backfire was broadly consistent in terms of mean severity and pattern with recent fires in Yosemite that have been allowed to burn (van Wagtenonk and Lutz, 2007; Lutz et al., 2011; Thode et al., 2011) suggesting that the density of small refugia found here (26.7 ha⁻¹) is representative of characteristic fire behavior, at least on north-facing slopes within the *Abies concolor* superassociation where Landsat-derived fire severity was low to moderate. In contrast, many prescribed fires ignited to reduce fuels would be expected to leave far fewer small refugia because a specific operational objective is to burn essentially the entire forest floor. Frequent-fire forests of the Sierra Nevada are renowned for their vascular plant species diversity and their structural heterogeneity (Lutz et al., 2013, 2018a), which is at least partially due to heterogeneity in fire effects and behavior (Kane et al., 2015a). We show that the small fire refugia observed after a low- to moderate-severity fire were associated with more diverse understory plant communities and may contribute to structural diversity through increased

survival of small-diameter trees relative to burned areas. To preserve these outcomes, managers conducting prescribed fires as fuel reduction treatments may wish to consider allowing some unburned patches to remain within treatment areas. Uniformly burning all surface area within a treatment block is uncharacteristic of the contemporary, unmanaged fire regime in these forests, and may stall elements of post-fire development. Fire heterogeneity in Sierra Nevada forests is likely present at all spatial scales, and therefore managers may wish to consider all scales from 1-m² to the landscape.

Better knowledge of refugia may also help create fire-resilient communities (*sensu* Smith et al., 2016a). The predictability of refugia location (albeit with limited skill) suggests that further research may lead to predictive models of refugial presence that have considerable potential to preserve ecological function or human habitation in frequent-fire forests. If characteristics associated with refugia can be better identified, these characteristics (to the extent that they are biotic in nature) can be modified by planting tree species that are associated with less intense fire behavior (e.g., Fechner and Barrows, 1976) or thinning to help protect areas of ecological or anthropogenic importance.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.foreco.2018.10.038>.

References

- Anderson-Teixeira, K.J., Davies, S.J., Bennett, A.C., Gonzalez-Akre, E.B., Muller-Landau, H.C., Joseph Wright, S., Abu Salim, K., Almeyda Zambrano, A.M., Alonso, A., Baltzer, J.L., Basset, Y., Bourg, N.A., Broadbent, E.N., Brockelman, W.Y., Bunyavejchewin, S., Burslem, D.F.R.P., Butt, N., Cao, M., Cardenas, D., Chuyong, G.B., Clay, K., Cordell, S., Dattaraja, H.S., Deng, X., Detto, M., Du, X., Duque, A., Erikson, D.L., Ewango, C.E.N., Fischer, G.A., Fletcher, C., Foster, R.B., Giardina, C.P., Gilbert, G.S., Gunatilleke, N., Gunatilleke, S., Hao, Z., Hargrove, W.W., Hart, T.B., Hau, B.C.H., He, F., Hoffman, F.M., Howe, R.W., Hubbell, S.P., Inman-Narahari, F.M., Jansen, P.A., Jiang, M., Johnson, D.J., Kanzaki, M., Kassim, A.R., Kenfack, D., Kibet, S., Kinnaird, M.F., Korte, L., Kral, K., Kumar, J., Larson, A.J., Li, Y., Li, X., Liu, S., Lum, S.K.Y., Lutz, J.A., Ma, K., Maddalena, D.M., Makana, J.R., Malhi, Y., Marthews, T., Mat Serudin, R., McMahon, S.M., McShea, W.J., Memiaghe, H.R., Mi, X., Mizuno, T., Morecroft, M., Myers, J.A., Novotny, V., de Oliveira, A.A., Ong, P.S., Orwig, D.A., Ostertag, R., den Ouden, J., Parker, G.G., Phillips, R.P., Sack, L., Sainge, M.N., Sang, W., Sringernyung, K., Sukumar, R., Sun, L.F., Sungpalee, W., Suresh, H.S., Tan, S., Thomas, S.C., Thomas, D.W., Thompson, J., Turner, B.L., Uriarte, M., Valencia, R., Vallejo, M.I., Vicentini, A., Vrska, T., Wang, X., Wang, X., Weiblen, G., Wolf, A., Xu, H., Yap, S., Zimmerman, J., 2015. CTF-forestGEO: A worldwide network monitoring forests in an era of global change. *Glob. Change Biol.* 21, 528–549.
- Banks, S.C., Dujardin, M., McBurney, L., Blair, D., Barker, M., Lindenmayer, D.B., 2011. Starting points for small mammal population recovery after wildfire: Recolonisation or residual populations? *Oikos* 120, 26–37.
- Barth, M.A.F., Larson, A.J., Lutz, J.A., 2015. A forest reconstruction model to assess changes to Sierra Nevada mixed-conifer forest during the fire suppression era. *For. Ecol. Manage.* 354, 104–118.

- Becker, K., Lutz, J.A., 2016. Low-severity fire fails to reverse overstory compositional change in montane forests of the Sierra Nevada. *Ecosphere* 7 (12), e01484.
- Birch, D.S., Morgan, P., Kolden, C.A., Abatzoglou, J.T., Dillon, G.K., Hudak, A.T., Smith, A.M.S., 2015. Vegetation, topography and daily weather influenced burn severity in central Idaho and western Montana forests. *Ecosphere* 6, art17.
- Bivand, R., Rundel, C., Pebesma, E., Stuetz, R., Hufthammer, K.O., 2017. Interface to geometry engine - open source ('GEOS'). Version 0.3-26. <http://cran.r-project.org/package=rgeos>. Downloaded 23 March 2018.
- Brennan, K.E.C., Moir, M.L., Wittkuhn, R.S., 2011. Fire refugia: The mechanism governing animal survivorship within a highly flammable plant. *Austral Ecol.* 36, 131–141.
- Delong, S.C., Kessler, W.B., 2000. Ecological characteristics of mature forest remnants left by wildfire. *For. Ecol. Manage.* 131, 93–106.
- Dennison, P.E., Brewer, S.C., Arnold, J.D., Moritz, M.A., 2014. Large wildfire trends in the western United States, 1984–2011. *Geophys. Res. Lett.* 41, 2928–2933.
- Dwire, K.A., Kauffman, J.B., 2003. Fire and riparian ecosystems in landscapes of the western USA. *For. Ecol. Manage.* 178 (1–2), 61–74.
- ESRI, 2011. ArcGIS Desktop: Release 10.3. Environmental Systems Research Institute, Redlands, California, USA.
- Fechner, G.H., Barrows, J.S., 1976. Aspen stands as wildfire fuel breaks. *Eisenhower Consortium Bulletin* 4. Department of Forestry and Wood Science, College of Natural Resources, Colorado State University, Fort Collins, Colorado, USA.
- Gandhi, K.J.K., Spence, J.R., Langor, D.W., Morgantini, L.E., 2001. Fire residuals as habitat reserves for epigeic beetles (Coleoptera: Carabidae and Staphylinidae). *Biol. Conserv.* 102, 131–141.
- Gasaway, W.C., DuBois, S.D., 1985. Initial response of moose, *Alces alces*, to a wildfire in Interior Alaska. *Canadian Field-Naturalist* 99, 135–140.
- Haire, S., Coop, J., Miller, C., 2017. Characterizing spatial neighborhoods of refugia following large fires in northern New Mexico USA. *Land* 6, 19.
- Hijmans, R.J., 2016. Raster: Geographic Data Analysis and Modeling. R package version 2.6-7. <https://CRAN.R-project.org/package=raster>. Downloaded 23 March 2018.
- Hylander, K., Johnson, S., 2010. In situ survival of forest bryophytes in small-scale refugia after an intense forest fire. *J. Veg. Sci.* 21, 1099–1109.
- Kane, V.R., Bakker, J.D., McGaughey, R.J., Lutz, J.A., Gersonde, R.F., Franklin, J.F., 2010. Examining conifer canopy structural complexity across forest ages and elevations with LiDAR data. *Can. J. For. Res.* 40, 774–787.
- Kane, V.R., Cansler, C.A., Povak, N.A., Kane, J.T., McGaughey, R.J., Lutz, J.A., Churchill, D.J., North, M.P., 2015a. Mixed severity fire effects within the Rim fire: Relative importance of local climate, fire weather, topography, and forest structure. *For. Ecol. Manage.* 358, 62–79.
- Kane, V.R., Lutz, J.A., Alina Cansler, C., Povak, N.A., Churchill, D.J., Smith, D.F., Kane, J.T., North, M.P., 2015b. Water balance and topography predict fire and forest structure patterns. *For. Ecol. Manage.* 338, 1–13.
- Kane, V.R., Lutz, J.A., Roberts, S.L., Smith, D.F., McGaughey, R.J., Povak, N.A., Brooks, M.L., 2013. Landscape-scale effects of fire severity on mixed-conifer and red fir forest structure in Yosemite National Park. *For. Ecol. Manage.* 287, 17–31.
- Kane, V.R., North, M.P., Lutz, J.A., Churchill, D.J., Roberts, S.L., Smith, D.F., McGaughey, R.J., Kane, J.T., Brooks, M.L., 2014. Assessing fire effects on forest spatial structure using a fusion of landsat and airborne LiDAR data in Yosemite national park. *Remote Sens. Environ.* 151, 89–101.
- Keeler-Wolf, T., Moore, P.E., Reyes, E.T., Menke, J.M., Johnson, D.N., Karavidas, D.L., 2012. Yosemite National Park Vegetation Classification and Mapping Project Report. Natural Resource Report NPS/YOSE/NRTR-2012/598. National Park Service, Fort Collins, Colorado.
- Keeley, J.E., 2009. Fire intensity, fire severity and burn severity: A brief review and suggested usage. *Int. J. Wildland Fire* 18, 116–126.
- Key, C.H., 2006. Ecological and sampling constraints on defining landscape fire severity. *Fire Ecol.* 2, 34–59.
- Key, C.H., Benson, N.C., 2006. Landscape assessment: Sampling and analysis methods. General Technical Report RMRS-GTR-164-CD. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado.
- Kolden, C.A., Lutz, J.A., Key, C.H., Kane, J.T., van Wagtenonk, J.W., 2012. Mapped versus actual burned area within wildfire perimeters: characterizing the unburned. *For. Ecol. Manage.* 286, 38–47.
- Kolden, C.A., Rogan, J., 2013. Mapping wildfire burn severity in the Arctic tundra from downsampled MODIS data. *Arct. Antarct. Alp. Res.* 45 (1), 64–76.
- Kolden, C.A., Abatzoglou, J.T., Lutz, J.A., Cansler, C.A., Kane, J.T., van Wagtenonk, J.W., Key, C.H., 2015. Climate contributors to forest mosaics: ecological persistence following wildfire. *Northwest Sci.* 89 (3), 219–238.
- Kolden, C.A., Bleeker, T.M., Smith, A.M.S., Poulos, H.M., Camp, A.E., 2017. Fire effects on historical wildfire refugia in contemporary wildfires. *Forests* 8, 8100400.
- Krawchuk, M.A., Haire, S.L., Coop, J.D., Parisien, M.-A., Whitman, E., Chong, G.W., Miller, C., 2016. Topographic and fire weather controls of fire refugia in forested ecosystems of northwestern North America. *Ecosphere* 7 (12), e01632.
- Larson, A.J., Cansler, C.A., Cowdery, S.G., Hiebert, S., Furniss, T.J., Swanson, M.E., Lutz, J.A., 2016. Post-fire morel (*Morchella*) mushroom abundance, spatial structure, and harvest sustainability. *For. Ecol. Manage.* 377, 16–25.
- Larson, A.J., Lutz, J.A., Donato, D.C., Freund, J.A., Swanson, M.E., HilleRisLambers, J., Sprugel, D.G., Franklin, J.F., 2015. Spatial aspects of tree mortality strongly differ between young and old-growth forests. *Ecology* 96 (11), 2855–2861.
- Liaw, A., Wiener, M., 2002. Classification and Regression by randomForest. *R News* 2, 18–22.
- Lutz, J.A., Van Wagtenonk, J.W., Thode, A.E., Miller, J.D., Franklin, J.F., 2009. Climate, lightning ignitions, and fire severity in Yosemite National Park, California USA. *Int. J. Wildland Fire* 18 (7), 765–774.
- Lutz, J.A., van Wagtenonk, J.W., Franklin, J.F., 2010. Climatic water deficit, tree species ranges, and climate change in Yosemite National Park. *J. Biogeogr.* 37, 936–950.
- Lutz, J.A., Key, C.H., Kolden, C.A., Kane, J.T., van Wagtenonk, J.W., 2011. Fire frequency, area burned, and severity: A quantitative approach to defining a normal fire year. *Fire Ecol.* 7 (2), 51–65.
- Lutz, J.A., Larson, A.J., Swanson, M.E., Freund, J.A., 2012. Ecological importance of large-diameter trees in a temperate mixed-conifer forest. *PLoS One* 7 (5), e36131.
- Lutz, J.A., Larson, A.J., Freund, J.A., Swanson, M.E., Bible, K.J., 2013. The importance of large-diameter trees to forest structural heterogeneity. *PLOS ONE* 8 (12), e82784.
- Lutz, J.A., Schwindt, K.A., Furniss, T.J., Freund, J.A., Swanson, M.E., Hogan, K.I., Kenagy, G.E., Larson, A.J., 2014. Community composition and allometry of *Leucothoe davisiae*, *Cornus sericea*, and *Chrysolepis sempervirens*. *Canadian J. For. Res.* 44 (6), 677–683.
- Lutz, J.A., 2015. The evolution of long-term data for forestry: large temperate research plots in an era of global change. *Northwest Sci.* 89, 255–269.
- Lutz, J.A., Furniss, T.J., Germain, S.J., Becker, K.M.L., Blomdahl, E.M., Jeronimo, S.A., Cansler, C.A., Freund, J.A., Swanson, M.E., Larson, A.J., 2017. Shrub communities, spatial patterns, and shrub-mediated tree mortality following reintroduced fire in Yosemite National Park, California USA. *Fire Ecol.* 13 (1), 104–126.
- Lutz, J.A., Furniss, T.J., Johnson, D.J., Davies, S.J., Allen, D., Alonso, A., Anderson-Teixeira, K., Andrade, A., Baltzer, J., Becker, K.M.L., Blomdahl, E.M., Bourg, N.A., Bunyavechewin, S., Burslem, D.F.R.P., Cansler, C.A., Cao, K., Cao, M., Cárdenas, D., Chang, L.-W., Chao, K.-J., Chao, W.-C., Chant, J.-M., Chu, C., Chuyong, G.B., Clay, K., Condit, R., Cordell, S., Dattaraja, H.S., Duque, A., Ewango, C.E.N., Fisher, G.A., Fletcher, R., Fruend, J.A., Giardina, C., Germain, S.J., Gilbert, G.S., Hao, Z., Hart, T., Hau, B.C.H., He, F., Hector, A., Howe, R.W., Hsieh, C.-F., Hu, Y.-H., Hubbell, S.P., Inman-Narahari, F.M., Itoh, A., Janik, D., Kassim, A.R., Kenfack, D., Korte, L., Král, K., Larson, A.J., Li, Y.-D., Lin, Y., Liu, S., Lum, S., Ma, K., Makana, J.-R., Malhi, Y., McMahon, S.M., McShea, W.J., Memiaghe, H.R., Mi, X., Morecroft, M., Musili, P.M., Myers, J.A., Novotny, V., de Oliveira, A., Ong, P., Orwig, D.A., Osterag, R., Parker, G.G., Patankar, R., Phillips, R.P., Reynolds, G., Sack, L., Song, G.-Z.M., Su, S.-H., Sukumar, R., Sun, I.-F., Suresh, H.S., Swanson, M.E., Tan, S., Thomas, D.W., Thompson, J., Uriarte, M., Valencia, R., Vicentini, A., Vrška, T., Wang, X., Weiblen, G.D., Wolf, A., Wu, S.-H., Xu, H., Yamakura, T., Yap, S., Zimmerman, J.K., 2018a. Global importance of large-diameter trees. *Glob. Ecol. Biogeogr.* 27 (7), 849–864.
- Lutz, J.A., Larson, A.J., Swanson, M.E., 2018b. Advancing fire science with large forest plots and a long-term multidisciplinary approach. *Fire* 1 (1), 5. <https://doi.org/10.3390/fire1010005>.
- Lydersen, J.M., North, M.P., Collins, B.M., 2014. Severity of an uncharacteristically large wildfire, the Rim Fire, in forests with relatively restored frequent fire regimes. *For. Ecol. Manage.* 328, 326–334.
- McCarley, T.R., Kolden, C.A., Vaillant, N.M., Hudak, A.T., Smith, A.M.S., Wing, B.M., Kellogg, B.S., Kreidler, J., 2017. Multi-temporal LiDAR and Landsat quantification of fire-induced changes to forest structure. *Remote Sens. Environ.* 191, 419–432.
- Meddens, A.J.H., Kolden, C.A., Lutz, J.A., 2016. Detecting unburned areas within wildfire perimeters using Landsat and ancillary data across the northwestern United States. *Remote Sens. Environ.* 186, 275–285.
- Meddens, A.J.H., Kolden, C.A., Lutz, J.A., Abatzoglou, J.T., Hudak, A.T., 2018a. Spatiotemporal patterns of unburned areas within fire perimeters in the northwestern United States from 1984 to 2014. *Ecosphere* 9 (2), e02029.
- Meddens, A.J.H., Kolden, C.A., Lutz, J.A., Smith, A.M.S., Cansler, C.A., Abatzoglou, J.T., Meigs, G.W., Downing, W.M., Krawchuk, M.A., 2018b. Fire refugia: What are they and why do they matter for global change? *Bioscience*. <https://doi.org/10.1093/biosci/biy103>.
- Miller, J.D., Thode, A.E., 2007. Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). *Remote Sens. Environ.* 109, 66–80.
- Miller, J.D., Safford, H., 2012. Trends in wildfire severity: 1984 to 2010 in the Sierra Nevada, Modoc Plateau, and southern Cascades, California, USA. *Fire Ecol.* 8, 41–57.
- North, M., Oakley, B., Chen, J., Erickson, H., Gray, A., Izzo, A., Johnson, D., Ma, S., Marra, J., Meyer, M., Purcell, K., Rambo, T., Rizzo, D., Roath, B., Schowalter, T., 2002. Vegetation and Ecological Characteristics of Mixed Conifer and Red Fir Forests at The Teakettle Experimental Forest. General Technical Report PSW-GTR-186. Page General Technical Report PSW-GTR-186. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Davis, California, USA.
- North, M., Stine, P., Hara, K.O., Zielinski, W., Stephens, S., 2009. An Ecosystem Management Strategy for Sierran Mixed- Conifer Forests. PSW-GTR-220. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Davis, California, USA.
- Oksanen, J., Blanchet, F.G., Kindt, R., Legendre, P., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Wagner, H., 2013. Vegan: community ecology package. Version 2.4-6. <http://cran.r-project.org/package=vegan>. Downloaded 23 March 2018.
- Prism Climate Group, 2017. Climatological normals, 1981–2010. Oregon State University, Oregon, USA, The PRISM Group.
- R Core Team, 2017. R: A language and environment for statistical computing. Version 3.4.3. R Core Team, R Foundation for Statistical Computing, Vienna, Austria.
- Roberts, S.L., van Wagtenonk, J.W., Kelt, D.A., Miles, A.K., Lutz, J.A., 2008. Modeling the effects of fire severity and spatial complexity on small mammals in Yosemite National Park, California. *Fire Ecol.* 4 (2), 83–104.
- Robinson, N.M., Leonard, S.W.J., Ritchie, E.G., Bassett, M., Chia, E.K., Buckingham, S., Gibb, H., Bennett, A.F., Clarke, M.F., 2013. Refuges for fauna in fire-prone landscapes: Their ecological function and importance. *J. Appl. Ecol.* 50, 1321–1329.
- Román-Cuesta, R.M., Gracia, M., Retana, J., 2009. Factors influencing the formation of unburned forest islands within the perimeter of a large forest fire. *For. Ecol. Manage.* 258, 71–80.
- Scholl, A.E., Taylor, A.H., 2010. Fire regimes, forest change, and self-organization in an old-growth mixed-conifer forest, Yosemite National Park, USA. *Ecol. Appl.* 20, 362–380.

- Schwilke, D.W., Keeley, J.E., 2006. The role of fire refugia in the distribution of *Pinus sabiniana* (Pinaceae) in the southern Sierra Nevada. *Madroño* 53 (4), 364–372.
- Smith, A.M.S., Kolden, C.A., Paveglio, T.B., Cochrane, M.A., Bowman, D.M.J.S., Moritz, M.A., Kliskey, A.D., Alessa, L., Hudak, A.T., Hoffman, C.M., Lutz, J.A., Queen, L.P., Goetz, S.J., Higuera, P.E., Boschetti, L., Flannigan, M., Yedinak, K.M., Watts, A.C., Strand, E.K., Van Wagtendonk, J.W., Anderson, J.W., Stocks, B.J., Abatzoglou, J.T., 2016a. The science of fireescapes: achieving fire-resilient communities. *Bioscience* 66, 130–146.
- Smith, A.M.S., Sparks, A.M., Kolden, C.A., Abatzoglou, J.T., Talhelm, A.F., Johnson, D.M., Boschetti, L., Lutz, J.A., Apostol, K.G., Yedinak, K.M., Tinkham, W.T., Kremens, R.J., 2016b. Towards a new paradigm in fire severity research using dose-response experiments. *Int. J. Wildland Fire* 25, 158–166.
- Smith, A.M.S., Talhelm, A.F., Johnson, D.M., Sparks, A.M., Kolden, C.A., Yedinak, K.M., Apostol, K.G., Tinkham, W.T., Abatzoglou, J.T., Lutz, J.A., Davis, A.S., Pregitzer, K.S., Adams, H.D., Kremens, R.L., 2017. Effects of fire radiative energy density dose on *Pinus contorta* and *Larix occidentalis* seedling physiology and mortality. *Int. J. Wildland Fire* 26, 82–94.
- Stavros, E.N., Tane, Z., Kane, V.R., Veraverbeke, S., McGaughey, R.J., Lutz, J.A., Ramirez, C., 2016. Unprecedented remote sensing data over the King and Rim Megafires in the Sierra Nevada Mountains of California. *Ecology* 97 (11), 3244.
- Thode, A.E., van Wagtendonk, J.W., Miller, J.D., Quinn, J.F., 2011. Quantifying the fire regime distributions for severity in Yosemite National Park, California, USA. *Int. J. Wildland Fire* 20, 223–239.
- Turner, M.G., Baker, W.L., Peterson, C.J., Peet, R.K., 1998. Factors influencing succession: Lessons from large, infrequent natural disturbances. *Ecosystems* 1, 511–523.
- Turner, M.G., Romme, W.H., Gardner, R.H., Hargrove, W.W., 1997. Effects of fire size and pattern on early succession in Yellowstone National Park. *Ecol. Monogr.* 67, 411–433.
- van Wagtendonk, J.W., 2007. The history and evolution of wildland fire use. *Fire Ecol.* 3 (2), 3–17.
- van Wagtendonk, J.W., Lutz, J.A., 2007. Fire regime attributes of wildland fires in Yosemite National Park, USA. *Fire Ecol.* 3 (2), 34–52.
- van de Water, K.M., Safford, H.D., 2011. A summary of fire frequency estimates for California vegetation before Euro-American settlement. *Fire Ecol.* 7 (3), 26–58.
- Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western U.S. forest wildfire activity. *Science* 313, 940–943.
- Wilson, M.F.J., O'Connell, B., Brown, C., Guinan, J.C., Grehan, A.J., 2007. Multiscale terrain analysis of multibeam bathymetry data for habitat mapping on the continental slope. *Mar. Geod.* 30 (1–2), 3–35.
- Wohlgenuth, P.M., Hubbert, K., Arbaugh, M.J., 2006. Fire and Physical Environment Interactions. In: Sugihara, N.G., van Wagtendonk, J.W., Shaffer, K.E., Fites-Kaufman, J., Thode, A.E. (Eds.), *Fire in California's Ecosystems*. University of California Press, Berkeley, California, pp. 75–93.
- Zaitsev, A.S., Gongalsky, K.B., Persson, T., Bengtsson, J., 2014. Connectivity of litter islands remaining after a fire and unburnt forest determines the recovery of soil fauna. *Appl. Soil Ecol.* 83, 101–108.