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Landscape-scale effects of fire severity on mixed-conifer and red fir forest structure in Yosemite National Park

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ABSTRACT

While fire shapes the structure of forests and acts as a keystone process, the details of how fire modifies forest structure have been difficult to evaluate because of the complexity of interactions between fires and forests. We studied this relationship across 69.2 km^2 of Yosemite National Park, USA, that was subject to 32 fires $\geqslant$40 ha between 1984 and 2010. Forests types included ponderosa pine (*Pinus ponderosa*), white fir-sugar pine (*Abies concolor*/*Pinus lambertiana*), and red fir (*Abies magnifica*). We estimated and stratified burned area by fire severity using the Landsat-derived Relativized differenced Normalized Burn Ratio (RdNBR). Airborne LiDAR data, acquired in July 2010, measured the vertical and horizontal structure of canopy material and landscape patterning of canopy patches and gaps. Increasing fire severity changed structure at the scale of fire severity patches, the arrangement of canopy patches and gaps within fire severity patches, and vertically within tree clumps. Each forest type showed an individual trajectory of structural change with increasing fire severity. As a result, the relationship between estimates of fire severity such as RdNBR and actual changes appears to vary among forest types. We found three arrangements of canopy patches and gaps associated with different fire severities: canopy-gap arrangements in which gaps were enclosed in otherwise continuous canopy (typically unburned and low fire severities); patch-gap arrangements in which tree clumps and gaps alternated and neither dominated (typically moderate fire severity); and open-patch arrangements in which trees were scattered across open areas (typically high fire severity).

Compared to stands outside fire perimeters, increasing fire severity generally resulted first in loss of canopy cover in lower height strata and increased number and size of gaps, then in loss of canopy cover in higher height strata, and eventually the transition to open areas with few or no trees. However, the estimated fire severities at which these transitions occurred differed for each forest type. Our work suggests that low severity fire in red fir forests and moderate severity fire in ponderosa pine and white fir-sugar pine forests would restore vertical and horizontal canopy structures believed to have been common prior to the start of widespread fire suppression in the early 1900s. The fusion of LiDAR and Landsat data identified post-fire structural conditions that would not be identified by Landsat alone, suggesting a broad applicability of combining Landsat and LiDAR data for landscape-scale structural analysis for fire management.

1. Introduction

Fire is a dynamic keystone process that influences ecosystem function and the structural and compositional heterogeneity of forests throughout the world (Bond et al., 2005; Swetnam, 1993; Whitlock et al., 2003; Wright and Bailey, 1982). However, fire does not act alone, and the interplay between fire and vegetation over space and time – encompassed in the concept of fire regime (Sugihara et al., 2006) – is what ultimately affects many of the biological and physical characteristics of the forested landscape. When characteristics of either the fire regime or vegetation are altered, the effects can be far-reaching.

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In the frequent-fire forests of the western United States, decades of fire exclusion has altered the fire regime and led to a shift from a patchy, open forest structure to a more homogeneous one (Hessburg et al., 2005). Prior to Euro-American settlement in the early 1900s, these forests experienced frequent, low severity fires that removed many smaller diameter trees and reduced ladder fuels that would otherwise facilitate fire spread from surface to canopy fuels (Scholl and Taylor, 2010; van Wagtendonk, 2007). Stands often comprised assemblages of individual larger trees and small clumps of trees with a high proportion of open space in the understory (Larson and Churchill, 2012). Currently, many of these forests have substantially higher densities of small-diameter trees providing both horizontal and vertical fuel continuity. Gaps, which both moderate fire behavior and serve as regeneration sites for shade-intolerant species, are less prevalent than they were a century ago (Hessburg et al., 2005; Lutz et al., 2012; Scholl and Taylor, 2010). Forest managers often seek to return vegetation, fire regime, and other forest characteristics to conditions that prevailed prior to fire exclusion (Larson and Churchill, 2012), and to do that they need to understand the effects of fires on forest structure (Miller et al., 2012).

Understanding how fire modifies forest structure can be difficult because of the inherent complexity of the interaction between fires and forests. Fires interact with the existing vegetation, fuel bed, and forest structure. The resulting tree mortality and post-fire vegetation depend on the stochastic combination of fire effects, post-fire propagule availability, and the post-fire climate. Fire could act to perpetuate a vegetation type or mediate forest change (Pyne et al., 1996). Individual trees, tree patches, and forest stands are continually restructured by fires that burn at less than stand-replacing severity (Agee, 1998; Romme, 1982; Turner and Romme, 1994; Turner et al., 1994). Mosaics of unburned and burned patches are particularly complex in areas where fires burn with mixed severities, and where severities differ from fire to fire and across the landscape, such as in the forests of the Sierra Nevada Mountains in California, USA (Collins et al., 2007; Lutz et al., 2009).

Fire regimes are controlled by a mixture of regional controls such as prevailing climate and local controls such as dominant vegetation, topography, and pre-existing forest structure (McKenzie et al., 2011). The post-fire landscapes of mixed severity fires are characterized by many small patches, within which burn severity was similar, and relatively few large patches (Collins and Stephens, 2010; Hessburg et al., 2005, 2007; Moritz et al., 2011; Perry et al., 2011). The complex spatial patterns of mixed severity fires are largely due to heterogeneity in the fuel bed, forest structure, and topography (Collins and Stephens, 2010; Collins et al., 2007; McKenzie and Kennedy, 2011). Pre-fire forest structure such as the size and arrangement of trees and fuel laddering is a particularly important factor leading to mixed severity fires (Moritz et al., 2011; Perry et al., 2011). However, the relationship between fire and pre-fire forest structure has rarely been quantified because of the lack of information on both pre- and post-fire structures. Quantifying fire-mediated changes in both the vertical structure of the forest and the arrangement of patches and gaps across a heterogeneous landscape would greatly improve our ability to manage the reintroduction of fire to these landscapes as well as providing a mechanism to assess likely post-fire forest development.

A better understanding of the interaction between fire severity and forest structure in mixed severity regime forests would also improve our understanding of post-fire conditions for herbaceous and vertebrate taxa of concern to managers for many forests. The post-fire forest structure influences plant establishment and community composition (Donato et al., 2009; Turner et al., 1997) as well as vertebrate abundance (Roberts et al., 2008). Gaps between patches of contiguous tree canopy are especially important regeneration sites for shade-intolerant species (Graham, 1990; Kinloch and Scheuner, 1990; Oliver and Ryker, 1990). However, exceedingly large gaps or limited connectivity between forest patches could reduce progagule dispersal into the middle of the gaps, potentially leading to a post-fire vegetation change (i.e., from forest to shrub) (Kolden et al., 2012; Turner et al., 1997).

Determining how fire restructures forests requires the ability to map both fire severity and forest structure with high resolution and fidelity. The development of burn severity indices that relate Landsat satellite images to estimated changes in vegetation following fire has allowed quantitative estimation of severity of fires that burned since 1984 at 0.09 ha resolution (Key, 2006; Key and Benson, 2006; Thode et al., 2011; White et al., 1996). For example, Thode et al. (2011) used Landsat-derived burn severity records to assign fire regimes to the major vegetation types within and around Yosemite National Park. Collins and his colleagues used fire severity maps to explore the relationship between dominant vegetation type, weather during the fire, time since last fire, and slope position to patterns of fire severity (Collins and Stephens, 2010; Collins et al., 2007, 2009).

To date, we have lacked corresponding high fidelity landscape-scale measurements of forest structure. Measurements from satellites lack the required spatial resolution to accurately map changes in structure following fire (Bergen et al., 2009; Frolking et al., 2009). Post-fire monitoring plots, such as those used for the Composite Burn Index (Key, 2006) can sample only small areas and, therefore may under sample the heterogeneity in fire severity and structure across the landscape. Furthermore, researchers measuring trees from the ground typically make only coarse summary measurements of vertical canopy structure.

Airborne Light Detection and Ranging (LiDAR) provides high resolution measurement of forest structure over large areas (Hudak et al., 2009; Lefsky et al., 2002; Reutebuch et al., 2005). As scientists have gained experience with this technology, research has moved from validation of the LiDAR measurements for forest studies (e.g., Lefsky et al., 1999; Naesset and Okland, 2002), to estimations of continuous variables such as basal area and biomass (e.g., Andersen et al., 2005; Gobakken and Naesset, 2004), and to studies of forests across very large areas (e.g., Asner et al., 2011). Increasingly, LiDAR data have been used to quantify and study canopy gaps (Kellner and Asner, 2009; Vepakomma et al., 2008) and patch dynamics (Kane et al., 2011) within forests. Several researchers have used LiDAR data to develop regressions for estimating specific fuel parameters such as crown bulk density or height to live crown for use in fire behavior models (Agca et al., 2011; Andersen et al., 2005; Erdody and Moskal, 2010; Riano et al., 2004).

LiDAR instruments measure the heights of vegetation surfaces that lie between the instruments mounted on the plane and the ground. LiDAR's strength is the high resolution (typically several measurements per square meter) and consistent measurement of forest structure over large areas with greater fidelity to structural attributes than possible with satellite images (Asner et al., 2011; Hummel et al., 2011). Most LiDAR returns measure the 3-D position of canopy material (foliage and living and dead branches) rather than the boles. This is the reverse of many field studies that focus on measurements of boles with no or few measurements of canopy structure. However, just as field measurements of tree diameters have been regularly used to estimate canopy conditions such as canopy bulk density using allometric equations (Scott and Reinhardt, 2001), LiDAR measurements of canopy structure have been used to estimate values such as mean diameter and tree height (Naesset, 2002; Reutebuch et al., 2005).

In this study, we combined Landsat estimations of burn severity with airborne LiDAR measurements of forest structure to evaluate relationships between fire and forest structure. We quantified the vertical distribution of canopy material and spatial characteristics of canopy patches and gaps in unburned forests and in burned patches of varying severity. We used a 69.2 km^2 study area that experienced 32 mixed severity fires $\geqslant$40 ha in size between 1984 and 2010 that contained large areas of three forests types that are widely distributed throughout the Sierra Nevada. By including only areas that were unburned or that experienced a single fire in our study, we sought to isolate the impact of a single fire severity on forest structure in each forest patch. We then used these data to address four questions:

1. What is the post-fire patch structure associated with different fire severities in three common Sierra Nevada forest types?
2. How does fire severity influence the vertical structure of each forest type with respect to canopy height, canopy cover, and variability in height and cover?
3. How does fire severity alter the horizontal structure of each forest type in terms of canopy patches and gaps?
4. Are observed differences in forest structure across severity classes most likely caused by fire or are they most likely reflective of pre-fire conditions?

2. Methods

2.1. Overview

Preliminary analysis of fire severity data derived from Landsat and forest structure data measured by LiDAR showed that fire changed the forest landscape in three dimensions and at multiple scales: vertically within clumps of trees (few tens of meters) and horizontally by the distribution of canopy patches and gaps (10 square meters to hundreds of hectares). As a result, we selected methods to look at structure at multiple scales in combination with two explanatory factors. In this subsection, we preview our methods so that the individual details presented in the following sections can be read in context.

We conducted our study in Yosemite National Park, USA (Subsection 2.2 and Fig. 1) in an area that experienced a number of fires over a 24 year period while retaining substantial unburned areas outside of fire perimeters for comparison (Subsection 2.3). We stratified our study area by three forest types common in the Sierra Nevada range. In parallel, we stratified the study area into patches unburned during the study period and into patches of four fire severities estimated using Landsat data (Subsection 2.4). We then combined the two stratifications into combinations of forest type and fire severities that were our basic unit of analysis (Fig. 2). For example, all patches of ponderosa pine that burned at low severity were combined for analysis of this forest type-fire severity combination.

We arranged for the canopy structure of the area to be measured by airborne LiDAR (Subsection 2.4). To analyze vertical structure within clumps of trees, we processed the LiDAR data to measure height distributions and canopy cover within 30 m (0.09 ha) grid cells across the study area (Subsection 2.5). To analyze patterns of canopy patches and gaps, we mapped these structures across the study area with a minimum mapping unit of 1 m with results reported for patches and gaps as small as 0.001 ha (10 m^2) and as large as found in the study area. All results for vertical structure and canopy patch and gap structure were analyzed by each forest type-fire severity combination.

2.2. Yosemite National Park

Yosemite National Park (3027 km^2) lies in the central Sierra Nevada range, California, USA. As a protected area with 94% classified as wilderness, the forests in Yosemite currently experience no pre- or post-fire logging. Some land now within park boundaries was logged in the early 20th century, but there has been limited thinning and development since the finalization of the park boundaries in 1937. As a result, Yosemite is one of the best remaining natural laboratories to evaluate the effects of fire severity on forest structure with minimal confounding influences. The western portion of Yosemite possesses a Mediterranean climate with July mean minimum and maximum temperatures of 2–13 °C at higher elevations and 16–35 °C at lower elevations. Most precipitation falls as snow with annual precipitation ranging from 800 mm to 1720 mm (Lutz et al., 2010). The forest vegetation of Yosemite comprises a mosaic of forest types, species, and structural stages (Fites-Kaufman et al., 2007; Thode et al., 2011; van Wagtendonk and Fites-Kaufman, 2006; van Wagtendonk et al., 2002). Each forest type, as well as woodlands and shrub fields, exhibits a characteristic fire severity distribution (Thode et al., 2011; van Wagtendonk et al., 2002).

Yosemite experiences multiple wildland fires each year, and since 1972 many naturally ignited fires have been allowed to burn under prescribed conditions (van Wagtendonk and Lutz, 2007). The historic fire return interval for the forested ecosystems of Yosemite ranges from 4 to 187 years, depending on the forest type (Caprio and Lineback, 1997; Caprio and Swetnam, 1995; Collins and Stephens, 2007; van Wagtendonk et al., 2002).

2.3. Study area

We selected a LiDAR acquisition area within Yosemite National Park of 10,895 ha ranging in elevation from 1290 m to 2526 m to span the lower mixed-conifer to red fir ecotone and to include a range of fire severities while providing substantial unburned areas outside the fire perimeters for comparison (Fig. 1 and Supplement Figs. 1–3). We assigned forest types within the study area based on either the 1997 park vegetation map (Keeler-Wolf et al., 2012) or the 1937 vegetation map (Walker, 2000; Wieslander, 1935). We used the 1997 vegetation map if the area was forested in 1997. We used the 1937 map for areas delineated as meadow or shrub in 1997 but delineated as forested in 1937 under the assumption that fire had caused a shift in vegetation type. We did not include areas that were delineated as meadow or shrub in both 1937 and 1997.

We located our study area to minimize the number of fires in the decades prior to our study period while maximizing the number of fires and range of fire severity during the study period. Between 1930, when comprehensive park fire records began, and the date of the LiDAR acquisition (21 July 2010), there were 327 fires of all sizes in the acquisition area (4.1 fires/year), with 40 fires $\geqslant$40 ha. We excluded from our study any area that was within the fire perimeter of a fire $\geqslant$40 ha between 1930 and 1983. Between 1984 and 21 July 2010, there were 169 fires with 32 fires $\geqslant$40 ha. In our study area, the unique area that burned at least once between 1984 and 21 July 2010, was 6857 ha of which 1082.1 ha burned two or more times (Table 1 and Supplement Table 1). We excluded from our study any area that was within the fire perimeters of two or more fires between 1984 and July 2010.

To make meaningful comparisons among forest structural classes, we limited our analysis to forest types >1000 ha within our study area: Ponderosa pine (*Pinus ponderosa*, PIPO) forest, white fir-sugar pine *(Abies concolor*/*Pinus lambertiana*, ABCO/PILA) forest, and red fir (*Abies magnifica*, ABMA) forest. While substantial stands of Jeffrey pine (*Pinus jeffreyi)* were present, they occurred on rocky outcrops where the distribution of germination sites controlled forest structure and rock barriers control the spread of fire. Preliminary analysis of *P. Jeffrey* stands showed that forest structure was primarily controlled by rock outcrops or edaphic conditions and that fire had minimal effects. We dropped this forest type from the study. The three remaining forest types totaled 6962 ha (64% of

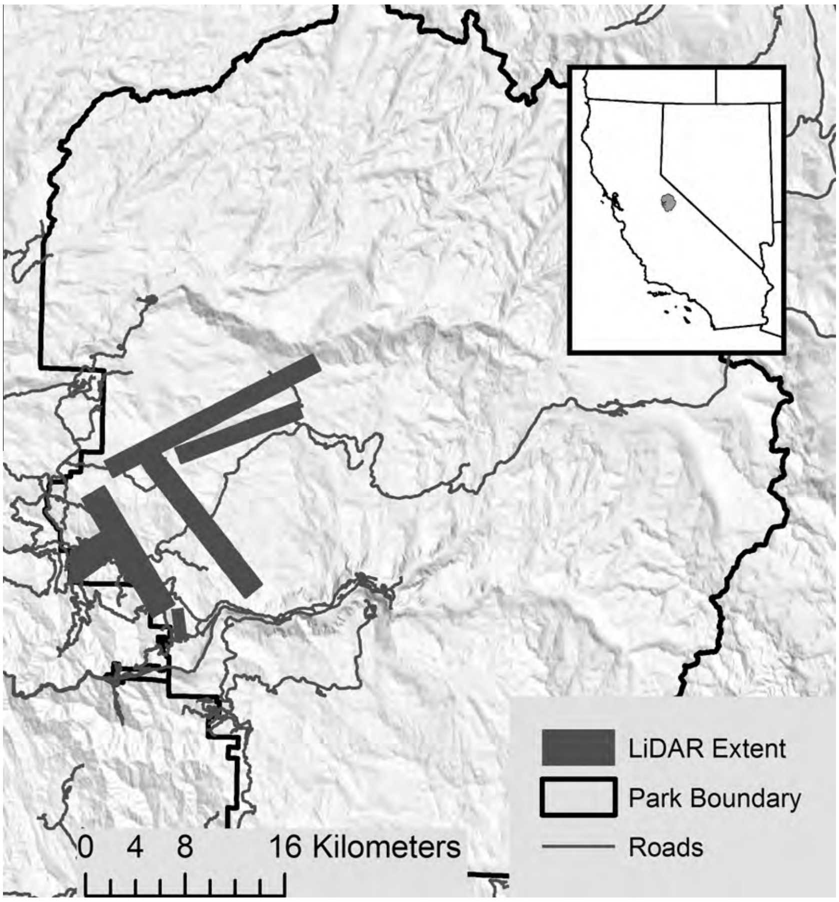

Fig. 1. Location of LiDAR data collection (bold lines) within Yosemite National Park. Insert shows location of park within the state of California. Supplement Figs. 1–4 show higher resolution maps of the study area.

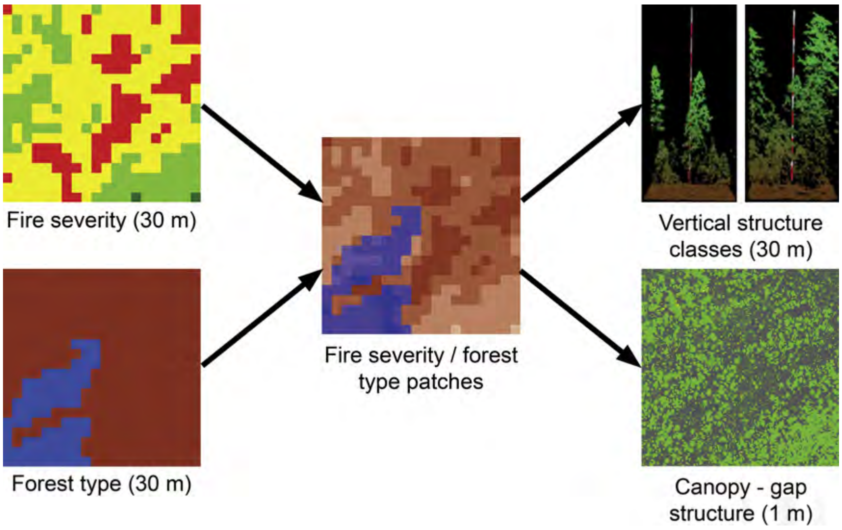

Fig. 2. This study related differences in ecological process (fire severity) with differences in ecological response (forest structure). Maps of fire severity patches were prepared by combining maps of Landsat-derived fire severity classes (unburned, undifferentiated, low, moderate, and high) with existing 30 m resolution maps of ponderosa pine, white fir/sugar pine, and red fir forest types. Then LiDAR data was used to identify and map five classes of vertical forest structure (open, sparse, shorter, multistory, and top story) and proportions of canopy patches and gaps for each combination of fire severity and forest type. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

LiDAR acquisition area) (Table 1) representing the area of these three forest types that either were unburned (outside all fire perimeters) between 1930 and July 2010 or that burned just once after 1984.

2.4. Patterns of burn severity

We used the Yosemite fire atlas assembled by Lutz et al. (2011), processed by and available from the Monitoring Trends in Burn

Table 1
Vegetation types in the study area by hectares for each RdNBR fire severity class for the study period 1984 through July 2010. Percentages refer to area within the burned area for specific RdNBR fire severity classifications or to total area burned or unburned (outside all fire perimeters between 1930 and July 2010) within the forest type during the study period within each forest type. This study used only grid cells that were unburned or had one fire. Data based on fires ⩾40 ha between 1984 and July 2010. Because of the small area in the enhanced greenness fire severity class, this class was dropped from the study.

Forest type	Total area (ha)	High severity	Moderate severity	Low severity	Landsat-undifferentiated	Enhanced greeness	Total burned (single fire)	Unburned
Ponderosa pine forest (PIPO)	1089	62.2 (9.4%)	200.9 (30.5%)	265.4 (40.2%)	130.5 (19.8%)	0.5 (0.1%)	659.5 (60.6%)	429.5 (39.4%)
White fir-sugar pine forest (ABCO-PILA)	2972.5	217.5 (13.1%)	318.6 (19.3%)	884.3 (53.5%)	232.6 (14.1%)	1.3 (0.1%)	1654.3 (55.7%)	1318.2 (44.3%)
Red fir forest (ABMA)	2900	267.9 (12.7%)	437.3 (20.7%)	1054.6 (49.8%)	350.3 (16.5%)	6.6 (0.3%)	2116.7 (73%)	783.3 (27%)
Totals	6961.5	547.6	956.8	2204.3	713.4	8.4	4430.5	2531

Severity (MTBS) project (Eidenshink et al., 2007). This atlas includes all fires ⩾40 ha from 1984 through June 2010 prior to the LiDAR acquisition, which comprised 97% of area within fire perimeters (Lutz et al., 2009). We used the Relativized differenced Normalized Burn Ratio, RdNBR, (Miller and Thode, 2007) which is an extension of the differenced Normalized Burn Ratio, dNBR (Key, 2006; Key and Benson, 2006). These severity measurements calculate Normalized Burn Ratios (NBRs) from Landsat bands 4 (near infrared) and 7 (mid infrared) to stratify estimated fire severity:

$$\mathrm{NBR} = (\mathrm{Band4} - \mathrm{Band7})/(\mathrm{Band4} + \mathrm{Band7}) \tag{1}$$

The dNBR values for each pixel were calculated by subtracting the post fire NBR from the pre-fire NBR:

$$\mathrm{dNBR} = \mathrm{prefireNBR} - \mathrm{postfireNBR} \tag{2}$$

Miller and Thode (2007) determined that the estimate of fire severity could be enhanced by calibrating severity measurements by removing the biasing of the pre-fire vegetation using the square-root of the pre-fire NBR:

$$\mathrm{RdNBR} = \mathrm{dNBR}/(\mathrm{SQRT}(\mathrm{ABS}(\mathrm{prefireNBR}/1000))) \tag{3}$$

Higher values of these satellite-derived burn indices indicate a decrease in photosynthetic materials and surface materials holding water and an increase in ash, carbon, and soil cover. Miller and Thode (2007) and Miller et al. (2009) demonstrated that RdNBR produced more accurate classifications of fire severity in Sierra Nevada forests, particularly for areas with lower pre-fire canopy cover. We classified the satellite-derived RdNBR values into standard burn severity classes originally calibrated with ground Composite Burn Index plots (Key, 2006; Key and Benson, 2006; Thode et al., 2011; Lutz et al., 2009; Miller and Thode, 2007; Miller et al., 2009).

We stratified the burned portion of the study area into the five standard MTBS fire severity classes (Table 2) using the field-validated RdNBR thresholds from Miller and Thode (2007). We classified forest patches outside of all fire perimeters for fires between 1930 and July 2010 as unburned. We found only 8.4 ha with a classification of enhanced greenness indicating a herbaceous bloom in the year following the fire, and we dropped these pixels from subsequent analysis. Areas of no detectable change were within fire perimeters, but the burn severity as measured by Landsat RdNBR was undifferentiated from unburned area. This Landsat-undifferentiated burn severity class comprises both portions of the landscape within the fire perimeter that did not burn and areas that burned as a surface fire while leaving the canopy intact (see Kolden et al. (2012) for a summary of interpretations of Landsat-undifferntiated pixels). We combined both forest type and fire severity into a landscape-scale delineation of patches, where each patch was a contiguous area having the same fire severity and forest type (Fig. 2). The minimum measuring unit was a single Landsat pixel (0.09 ha).

2.5. LiDAR data

Watershed Sciences, Inc. (Corvallis, OR) collected LiDAR data using a dual-mounted Leica ALS50 Phase II instrument on 21 and 22 July 2010 with an average pulse density of 10.9 pulses per square meter and up to four returns per pulse. Using the TerraScan v.10.009 and TerraModeler v.10.004 software packages (Terrasolid, Helsinki, Finland), Watershed Sciences used the LiDAR data to create the 1 m resolution digital terrain model (DTM). We processed the LiDAR return point cloud data to generate metrics relevant to the measurement of forest canopies using the US Forest Service's FUSION software package, beta version derived from version 3.00 (http://www.forsys.cfr.washington.edu/fusion.html). Watershed Sciences also collected true-color orthographic images with a 15 cm resolution to serve as an interpretive aid.

2.6. Analysis of vertical canopy material distribution

We estimated the vertical canopy material distribution (percentile heights, heterogeneity of heights, and canopy cover) using statistical metrics of the distribution of return heights. We calculated these metrics using all returns for 30 m grid cells to match the resolution of the fire severity and vegetation cover maps. The Fusion software had an average of 9810 returns per 30 m grid cell on which to calculate the metrics.

We normalized LiDAR return elevations to heights above ground by subtracting the elevation of the underlying ground surface model from each return height. We calculated canopy cover metrics as the proportion of returns within a height stratum, such as 2–16 m, divided by all returns in that stratum and below. We hypothesized that fire would preferentially remove canopy material in lower height strata. To test this, we initially calculated cover for five height strata: 2–4 m, 4–8 m, 8–16 m, and >16 m. Preliminary analysis showed high correlation among cover measurements in height strata below 16 m, and that the effects of fire were similar for canopy cover strata below 16 m. We therefore combined the lower three height strata into a single 2–16 m cover measurement. We did not include returns below 2 m in the calculation of height measurements, and we did not calculate cover below 2 m. This resulted in the height and cover metrics representing only the canopy of trees with canopy material >2 m in height.

We used rumple (canopy surface rugosity) as a measure of the structural heterogeneity of stand structural complexity (Birnbaum, 2001; Ishii et al., 2004; Kane et al., 2008, 2010a,b; Ogunjemiyo et al., 2005; Parker and Russ, 2004; Parker et al., 2004). We used a 1 m resolution canopy surface model (CSM) created using the maximum return height with each 1-m grid cell and smoothed with a 3 × 3 low pass filter in computing rumple. The rumple metric was measured as the ratio of the area of the 1 m CSM to the area of the underlying digital terrain model reported over the study area in 30 m grid cells.

Table 2
Fire severity classes applied to forest types. Field characteristics are from Thode et al. (2011) and associated ranges for Relativized differenced Normalized Burn Ratio (RdNBR) from Miller and Thode (2007). Areas with a classified severity of enhanced greeness class were excluded from this study because they were found only in 8.4 ha within the study area.

Severity class	Field characteristics	RdNBR ranges
Unburned	Unburned forest patches outside of fire perimeters	
Enhanced greeness	Bloom of plant growth following fire	<−150
Landsat-undifferentiated	No detected change in post-fire vegetation	−150 to 68
Low	Fine fuels removed and some scorching of understory trees	69–315
Moderate	Some fuels remain on forest floor, mortality of small trees, scorching of crowns for medium and large-sized trees	316–640
High	Near-complete combustion of ground fuels, near total mortality of small and medium-sized trees, and severe needle scorch and/or mortality of large trees	⩾641

We examined correlation among a candidate set of LiDAR metrics using Pearson correlation (Supplement Table 2) and a principal components analysis (PCA) ordination (results not shown) to find a parsimonious set of metrics that describe the heterogeneity of forest structure within our study area (Kane et al., 2010a,b; Lefsky et al., 2005). We chose five metrics calculated within 30 m grid cells to analyze vertical structure: 95th percentile return height, which corresponds to the height of dominant trees; 25th percentile return height, which is related to canopy base height (Andersen et al., 2005; Erdody and Moskal, 2010); rumple, which measures the heterogeneity of heights both vertically and horizontally (Kane et al., 2010b); canopy cover in the 2–16 m height strata; and canopy cover in the >16 m height strata (Fig. 3).

We used these five metrics to define classes of vertical forest structure based on a random sample of 10,000 grid cells (11.7% of the study area). Because of colinearity between the metrics, we used the axes of variation from a principle components analysis (PCA) to define the vertical forest structure classes. We used hierarchical clustering to classify the study area at $a \times 30 \times 30$ m (0.09 ha) resolution using the PCA axes of variation (Legendre and Legendre, 1998). We used Euclidean distances and Ward's linkage method within the "hclust" function of the R statistical package (release 2.6.1) (R Development Core Team, 2007) for this analysis. To ensure that our vertical structure classes were statistically distinct, we performed a Tukey HSD test with a Bonferroni correction for multiple tests (20) at an alpha level of 0.05 resulting in a critical value of $P < 0.002$ on the individual metrics used to define the classes. We used the classified random sample of 10,000 grid cells as training data to classify the vertical structure of all grid cells within the study area using the Random Forest algorithm (Breiman, 2001) in the yaImpute R statistical package (Crookston and Finley, 2008). The yaImpute package reported a misclassification error based on the Random Forest out of bag error assessment (Breiman, 2001) of 7.1%.

Over the 26 year period of our study, vegetation regrowth following fire could have changed the structure of forests as measured by any of the metrics we used to study vertical structure. To explore for trends for an individual metric with time since fire, we performed linear regressions using time since fire in years as the predictor variable and the structural metric value as the response variable. The regressions were repeated for each combination of metric forest type, and fire severity resulting in a total of 60 regressions. Because the area burned each year varied, we performed regressions both using the median value for each metric by year, forest type, and severity and using values for all grid cells for each metric by year, forest type, and severity. This allowed us to both examine trends with normalized (median values) and to use treat each burned grid cell as an independent sample of the interaction of fire severity and forest structure. We performed a Tukey HSD test with a Bonferroni correction for multiple tests (20) at an alpha level of 0.05 resulting in a critical P value of $P < 0$.

2.7. Analysis of canopy patch and gap structure

We analyzed post-fire canopy patch and gap structure by mapping both gaps (areas with no trees >2 m tall) and areas of canopy (areas with continuous canopy >2 m tall; canopy patches). We identified canopy patches and gaps using an unsmoothed 1 m resolution CSM with heights ⩾2 m identified as canopy and heights <2 m identified as gaps. The Fusion software assigned each 1 m CSM grid cell the height of the highest return within that grid cell. To ensure consistency between the analysis done with 30 m grid cells (see Section 2.5) and this analysis with 1 m grid cells, we ensured that the grid cells were aligned so that each 1 m grid cell fell entirely with a single 30 m grid cell.

We coded each grid cell by forest type and as either unburned or with the fire severity class experienced in that forest type. We converted the resulting 1 m resolution raster map into an ArcMap polygon file without shape simplification using ESRI ArcMap 10.0 (ESRI, Redlands, CA, USA). This preserved the resolution of the raster map and identified contiguous canopy patches or gaps as all contiguous grid cells with the same fire severity and forest type. As a consequence, we identified canopy patches and gaps that crossed the boundaries of different forest type-fire severity patches as separate canopy patches and gaps within their severity-forest combinations. We used ArcMap to calculate the area and perimeter of each canopy patch and gap (Fig. 2).

In forests prone to fires, fire-created gaps are often equated to high severity fire patches because these patches, by definition, have had most of their canopy cover removed. In our study, we followed Runkle's (1982, 1992) definition of a gap as any area without canopy cover greater than 2 m in height. This approach allowed us to include gaps caused by any condition, including edaphic factors, rock outcrops, spacing between trees caused by competition for water or other resources, or the death of individual trees caused by insects, pathogens, wind, or fire. We chose this approach based on the hypothesis that forests that experienced other than high severity fire would also show an increase in both the number and cumulative area of gaps compared to unburned patches due to direct fire mortality or delayed mortality of fire-weakened trees.

3. Results

3.1. Patterns of burn severity

The distribution of forest types and fire severity patches resulted in a mosaic landscape across the study area (Fig. 4 and Supplement Fig. 2). Unburned patches represented 27–44% of each of the three forest types (Table 1). For each forest type, the largest percentage of burned area was in the lower two severity classes: low severity patches (40–54%) and Landsat-undifferentiated patches (14–20%). Moderate (19–31%) and high (9–13%) severity patches represented smaller portions of the burned area.

Large patches >10 ha dominated (78–94%) the area of unburned forest for all three forest types (Fig. 4). With fire, however, the proportion of area in different size classes varied by both severity and forest type with no consistent trends.

3.2. Distribution of vertical canopy material

We identified an initial set of nine statistically distinct classes of vertical forest structure using hierarchical cluster analysis. We merged five of the candidate classes into two new classes based on similarities in canopy cover in the two height strata because the primary effect of increasing fire severity was to remove canopy cover. We defined the five final classes as: open, sparse, shorter, multistory, and top story (Figs. 5 and 6 and Supplement Figs. 4 and 5). The open forest class was characterized as having few or no erect trees, with trees and shrubs primarily being below 2 m in height. The sparse forest class was characterized by low densities of trees separated by relatively large areas where vegetation did not exceed 2 m in height. The shorter forest class was characterized as predominantly tree covered, but with trees of lower stature. The multistory forest class was characterized by trees of many different heights. The top story forest class was characterized by low densities of taller trees with distinct vertical separation between the tall trees and the lower forest strata.

Both ponderosa pine and white fir-sugar pine patches had a preponderance of their unburned patches in the multistory class (65% and 60% respectively) (Fig. 7). For Landsat-undifferentiated and low severity fire patches, both these forest types showed reduced area in the multistory class. However, ponderosa pine patches showed increases in the shorter class while white fir/sugar pine patches showed increases in the top story class for these two fire severity classes. Unburned red fir patches were an approximately equal mixture of the sparse, shorter, multistory, and top story classes (total of 100%). In Landsat-undifferentiated and low severity patches, the percentage of red fir area in the shorter and multistory classes decreased with corresponding increases in the sparse and the top story classes. All forest types showed an increasing percentage of area in the open and sparse structural classes within moderate and high severity fire patches.

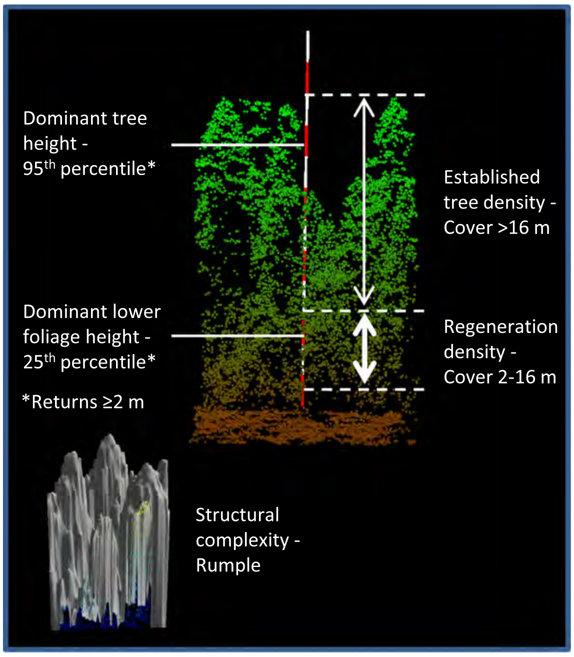

Fig. 3. LiDAR metrics used in the study to measure vertical forest structure including canopy material height, cover, and canopy complexity at a 30 m × 30 m scale. The height and cover metrics were calculated from the LiDAR return point cloud within each 30 m pixel, while the rumple value for each 30 m pixel was calculated from a 1 m canopy surface model (CSM) derived from the point cloud. Each stripe on the height pole is 5 m in length.

The changes in forest structure as measured by fire structure classes were collaborated by trends in the mean values of the LiDAR metrics used to define the classes (Table 3). Ponderosa pine stands showed loss of structure as measured by all metrics for all fire severities. The white fir-sugar pine and red fir forests, however, either showed increases in values or smaller losses than ponderosa pine stands for Landsat-undifferentiated and low severity patches for all metrics except for canopy cover in the 2–16 m stratum. All three forest types showed increasing loss of cover in the 2–16 m stratum for all fire severities. Similarly, all three forest types showed increasing loss of structure for all metrics for moderate and high severity fires.

When values for vertical structure metrics were examined by year of fire, forest type, and severity, ranges of values 95th and 25th percentile heights and rumple were usually similar for Landsat-undifferentiated and low severity fires (Supplement Figs. 8–12). Ranges for these metrics showed greater variation for moderate and high severity fires. Ranges of values for cover in the >16 m and 2–16 m strata showed considerable variation for all fire severities. Correlations between metrics and years since fire as measured by single linear regressions ($n = 25$) using median value for each metric by year, forest type, and severity were not significant ($P > 0.001$). Regressions using all grid cell values (n varied by year, forest type, and fire severity) generally either were not significant ($P > 0.001$) or had little correlation ($R^2 \leqslant 0.1$) (Table 4). All significant coefficients of determination with $R^2 \geqslant 0.1$ were for moderate and high severity patches where more recent fires had higher 95th and 25th percentile height, cover >16 m, and higher rumple values than older fires indicating a loss of structure (needles, branches, and boles) with time since fire. The exception was for ponderosa pine canopy cover 2–16 m in moderate and high severity patches, where more recent fires had lower values than older fires ($R^2 = 0.12$) indicating regrowth in this height strata with time since fire.

3.3. Analysis of canopy patch and gap structure

For all forest areas, canopy patches >1 ha (>10 ha for sugar pine-white fir forests) constituted the majority of the area and gaps generally were small inclusions within these patches (Fig. 8 and Supplement Figs. 6 and 7). With increasing fire severity, canopy patches represented an increasingly smaller proportion of the area and the patch sizes became progressively smaller on average. The trend for gaps was reversed with increasing fire severity as gaps represented an increasingly larger proportion of the area and gap sizes became progressively larger on average.

We found three archetypical patterns of canopy patches and gaps that illustrated points on a continuous range in the relative proportion of canopy patches and gaps (Fig. 9): (1) Canopy/gap patterns have the majority of their area in canopy with gaps as small breaks in the otherwise continuous canopy (the classic gap pattern found by Runkle (1982) in his eastern US study areas); (2) Patch/gap patterns have similar proportions of canopy and gap with the two interspersed across the area; (3) Open/patch patterns are the reverse of canopy-gap systems with open space essentially a continuous gap interspersed with small patches of canopy that are single trees or small tree clumps. These canopy patch and gap patterns are emergent properties that become recognizable only at scales of ~100 m or greater; they cannot be recognized at the scale of 30 m grid cells or most field plots, which sample forests at the scale of individual tree clumps or moderate-sized gaps.

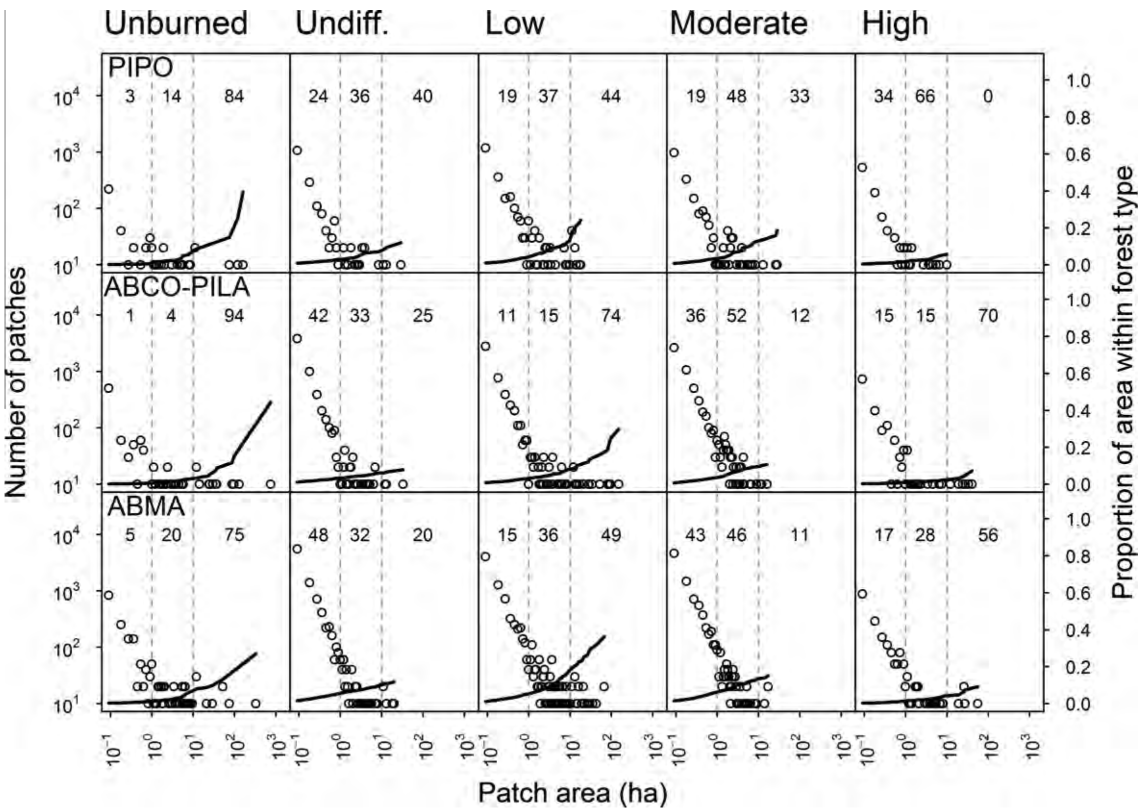

Fig. 4. Frequency of fire severity (unburned through high severity) patches by forest type – ponderosa pine (PIPO), white fir-sugar pine (ABCO-PILA), red fir (ABMA) (black circles) – and cumulative proportion of area (lines) for each fire severity and forest type. Cumulative proportions within each forest type sum to 1.0. Legend within each panel shows percentage of area within that forest type-fire severity combination in patches <1 ha, 1–10 ha, and >10 ha. A patch was defined as a contiguous area of the same fire severity class and forest type. The minimum measuring unit was a single Landsat pixel (0.09 ha).

4. Discussion

4.1. Key findings

We expected stands that had not recently experienced fire would be dominated by a single structural class, either because of species physiology and the moisture gradient (Lutz et al., 2010; Stephenson, 1998; Stephenson et al., 2006) or because a century of fire suppression had led to a homogenization of structure (Hessburg et al., 2005; van Wagtendonk and Fites-Kaufman, 2006). We expected little change in structure for areas that had burned at low severities, consistent with results from Composite Burn Index plots (Thode et al., 2011) and more extensive structural change in areas that burned at moderate or, especially, at high severity.

We were surprised on two accounts. First, each forest type showed an individual response to increasing fire severity in the vertical structure of its forests. Second, Landsat-undifferentiated and low severity patches had substantially different vertical and horizontal structure than did unburned patches. We introduce the discussion of these topics in this subsection followed by more detailed discussions of changes in vertical and horizontal structure changes in the following two subsections and conclude with a discussion of management implications.

We found changes at all three scales we examined: fire severity patches, canopy patches and gaps within fire severity patches, and clumps of trees (0.09 ha grid cells). With increasing fire severity in our study area, severity patch size shifted to increasingly smaller patches, with a partial reversal for high severity fire that increased the area in larger patches compared to moderate severity fire. Within severity patches, the proportion of area that were gaps also increased with increasing fire severity, with a transition from unburned patches dominated by canopy enclosing small gaps (canopy/gap), to approximately equal areas of canopy patch and gap (patch/gap), to open areas with scattered trees and tree clumps (open/patch). At the scale of tree clumps (our 30 m grid cells), lower fire severities removed canopy cover leading to structural shifts toward the shorter (ponderosa pine), top story (white fir-sugar pine), or top story and sparse (red fir) structural classes. With moderate and high severity, fire further removed canopy cover, leading to increases in the sparse and open structural classes.

We found differences in forest structure for all fire severities compared to the structure for unburned patches and these changes formed a pattern with increasing fire severity. Fires burned in a heterogeneous pattern creating a mosaic of canopy patches, gaps, and vertical forest structures. Fire generally thinned from below with higher fire severities resulting in the loss of canopy material in progressively higher height strata that presumably correlated with loss of progressively larger trees (Table 3 (especially trends in cover in the two height strata) and Fig. 7). (However, see the discussion in Subsection 4.2 of changes for ponderosa pine Landsat-undifferentiated and low severity for an exception to thinning from below that highlights the individual response of each forest type.) Low severity fire patches, for example, had 9–35% less cover in the >16 m stratum than unburned patches and 22–46% less cover in the 2–16 m stratum. Thinning in this manner will lead to progressively greater area in gaps and reduced canopy cover, first in the lower strata and then in higher strata.

We did not expect the degree to which Landsat-undifferentiated and low severity patches fires changed forest structure at all three scales. Thode and colleagues (2011) characterized RdNBR fire severity classes through field work in the Sierra Nevada range, and

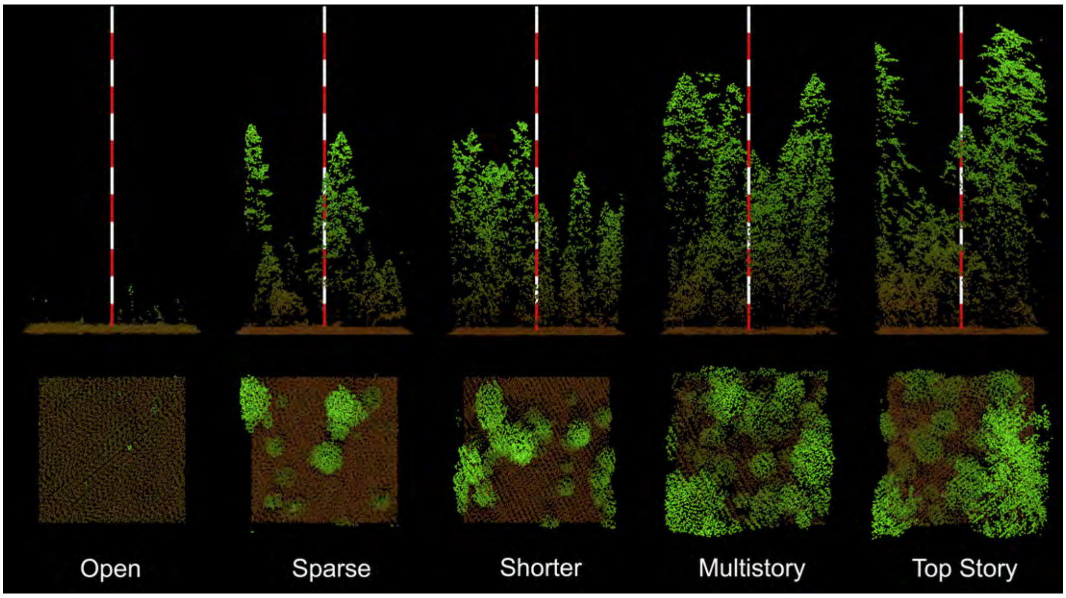

Fig. 5. Five forest structure classes derived from cluster analysis of LiDAR structural metrics. Each stripe on the height poles is 5 m in length.

they described low severity fire patches as "lightly burned with only the fine fuels removed and some scorching of the understory trees." However, we found substantial changes, such as an almost doubling to more than tripling of the proportion of area in gaps, depending on forest type, between unburned patches and the Landsat-undifferentiated and low severity patches. Our results suggest that measuring the full impact of lower severity fire may require either measurements over large areas or measurements a number of years after a fire for delayed mortality to occur.

These results suggest a more complicated relationship between tree species characteristics such as bark thickness, pre-fire structure, and fuel characteristics among other aspects than is usually considered in evaluating patterns of fire severity and resulting forest changes. Fuller exploration of these considerations will come as LiDAR becomes available for larger areas and additional forest types are analyzed (although we discuss some aspects of these issues in Subsection 4.2). In the meantime, researchers and managers should recognize that the relationship between estimates of fire severity such as dNBR and RdNBR and actual changes appears to vary among forest types.

A complication of relating differences in fire severity to changes in forest structure is that pre-fire and post-fire measures of structure near the time of a fire are rare except for prescribed fires where managers determine the timing of the fire. Collins et al. (2011), for example, attributed the differences between their low and moderate severity fire plots to the effects of fire and assumed their unburned plots represented the typical pre-fire conditions for their burned plots (the same assumption we make for our study). While this hypothesis is reasonable given the known effects of fire on forest structure, alternate explanations would be that pre-fire differences in structure caused the differences in fire severity or that the post-fire condition resembled the pre-fire condition. The large samples enabled by LiDAR can test for heterogeneity in structure within unburned patches to test for similarities between large numbers of areas that did not burn and patches that burned with different severities. Substantial differences across numerous fires in the equivalent of tens of thousands of field plots associated with different fire severities would strengthen the case for fire as the cause. The changes in vertical and horizontal structure we found across many fires and three forest types were those expected from increasing fire severities. As a result, we accept the hypothesis that fire was a dominant process creating these differences associated with different fire severity levels.

In reporting our results, we have focused on major trends to avoid both the limitations of no pre-fire structural measurements and a second concern, limitations in the accuracy of modeled fire severity. Readers should keep these limitations in mind in interpreting our results. For example, a pixel may be classified as high severity if understory shrubs were present pre-fire in a sparse stand even though no or few trees were killed if the shrubs were killed. Also, minor registration errors between pre- and post-fire images for a site with visible bare ground or rock and lead to incorrectly classified high severity pixels. In fires with little or no actual high-severity these anomalous pixels could lead to the incorrect conclusions about changes in forest structure due to high-severity fire.

4.2. Analysis of vertical canopy material distribution

We began our analysis of the impact of fire severity on forest structure by examining changes in forest structure for each of the 0.09 ha grid cells covering our three forest types. This grain of measurement captured structure at of the scale of all or a portion of clumps of trees (Larson and Churchill, 2012). Because each 0.09 ha grid cell was similar in size to the plot sizes of many field studies of fire severity (Key and Benson, 2006; Key, 2006), this portion of the study is most directly comparable to the field studies that have studied the relationships between fire severity and forest structure. Our large sample size, however, allowed us to observe variability and heterogeneity in structure that would be impractical in a field study.

We identified five statistically distinct vertical structure classes: open, sparse, shorter, multistory, and top story (Fig. 5). Height and metrics associated with taller trees (95th and 25th percentile height, rumple, and canopy cover >16 m) were the strongest differentiators in defining classes (Supplement Fig. 5). Within ranges of values for these height-related metrics, the density of cover 2–16 m was a secondary differentiator. Fire changed the aggregate vertical structure for all forest types with the amount of change increasing with increasing fire severity. Each forest type, however, showed a different pattern of change.

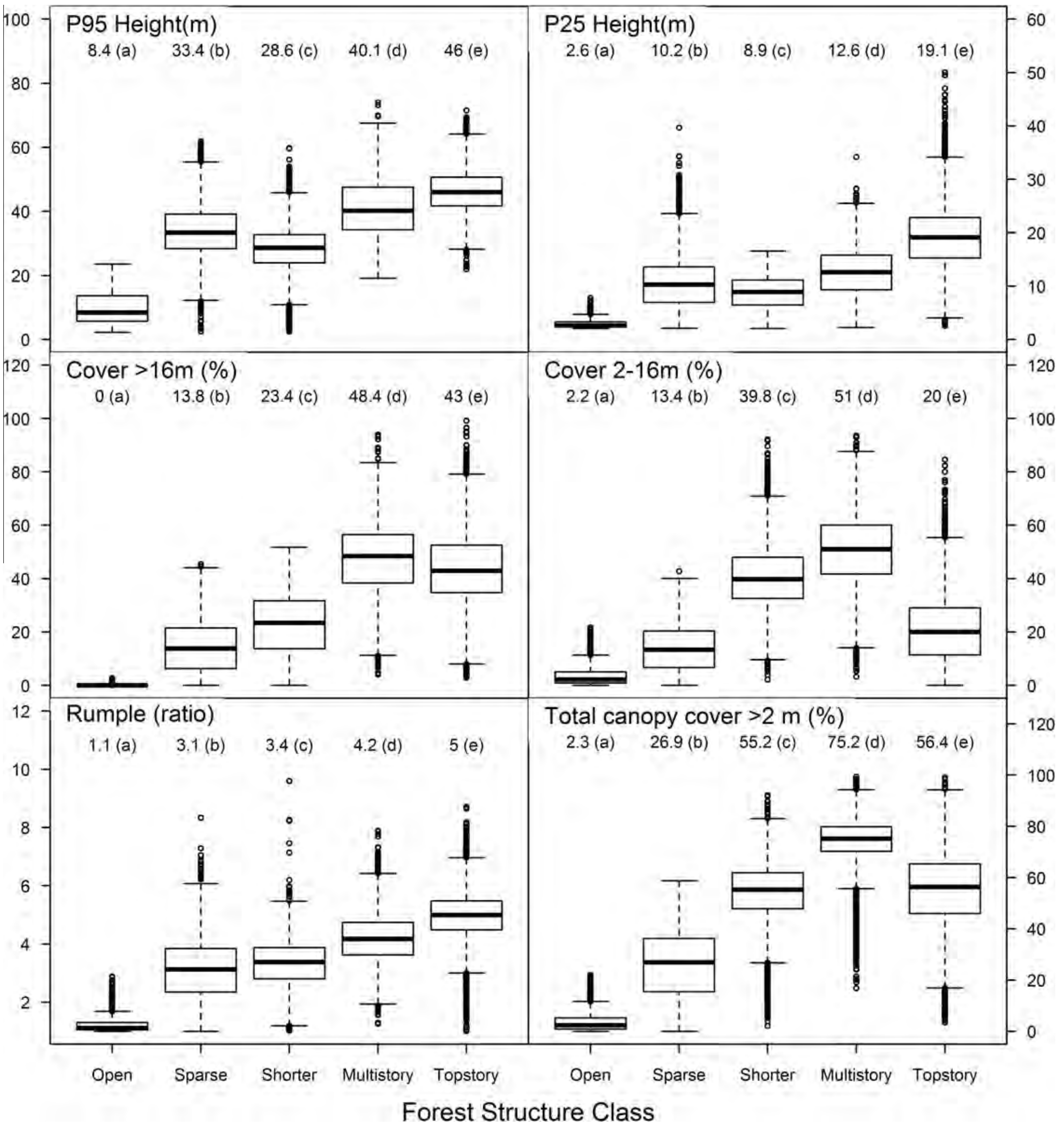

Fig. 6. Height and canopy cover characteristics of forest structural classes. Mean values and letters indicate statistically distinguishable structural classes (Tukey HSD $p \leqslant 0.002$). Total canopy cover >2 m was not used in the classification but is shown to aid in interpretation of the classes. Figure was produced with the boxplot function of the R statistical package. Bold lines show median values; the bottom and top of the boxes show the 25th and 75th percentile values; the upper and lower whiskers show either minimum and maximum values or 1.5 times the interquartile range (approximately two standard deviations), whichever is nearer to the mean; and circles show outliers.

We were surprised to see substantial differences between the ponderosa pine and white fir-sugar pine forest types in their response to Landsat-undifferentiated and low severity fires. Both the ponderosa pine and white fir-sugar pine forest types include dominant tree species that have thicker bark that are more resistant to fire (ponderosa pine and sugar pine) as well as species that have thinner bark less resistant to fire (such as white fir), especially for smaller to medium diameter trees (van Wagtendonk and Fites-Kaufman, 2006). (Red fir is less fire resistant than either ponderosa or sugar pine.) For these two lower fire severities, ponderosa pine patches showed higher levels of change in 95th and 25th percentile heights, cover in the >16 m stratum, and rumple than did white fir-sugar pine patches. (However, this pattern was reversed for cover in the 2–16 m stratum with white fir-sugar pine patches showing greater loss over than ponderosa pine patches.)

These results suggests that the lower fire severities were creating a greater loss of larger overstory trees in ponderosa pine patches than the white fir-sugar pine forest types. We would expect even low severity fires to kill a portion of less fire tolerant trees, but were puzzled by the substantial difference between the ponderosa pine and the white fir-sugar pine forest types since white fir is common in both. Several potential explanations for the apparent higher mortality for larger trees in ponderosa pine patches are plausible. One explanation may be that ponderosa pine stands tend to have less compacted ground surface fuels (needle and litter) than the other forest types leading to more intense fires and higher mortality (J. van Wagtendonk personal communication). Ponderosa pine stands also tend to be on lower productivity sites than white fir-sugar pine stands, and trees in the former may have less vigor and may be more susceptible to fire mortality (M. North, personal communication). In addition, our study period spanned an extended drought in the Sierra (1987–1992) in which a substantial proportion of large ponderosa pine trees died due to beetle outbreaks, independent of fire. The combination of fire and drought might have facilitated beetle outbreaks in larger ponderosa pine trees (N. Stephenson personal communication).

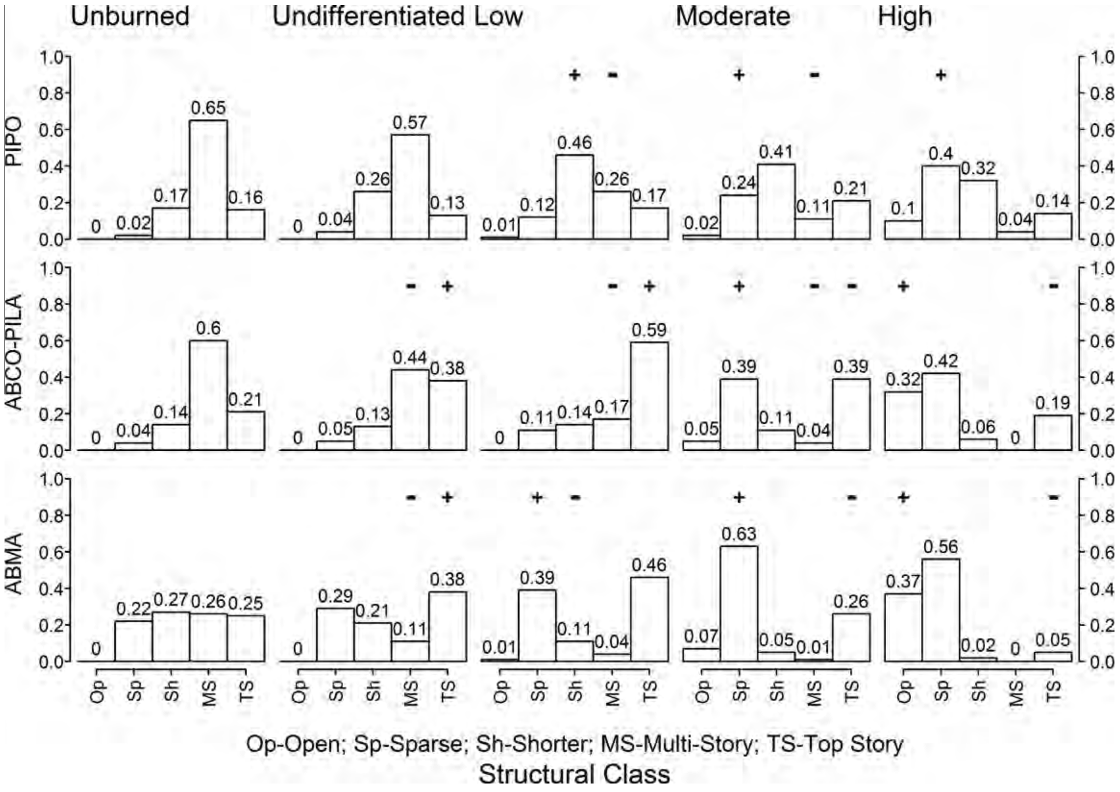

Fig. 7. Proportion of structural classes associated with forest type and fire severity (ponderosa pine (PIPO), white fir-sugar pine (ABCO-PILA), red fir (ABMA)). Differences greater or equal to an absolute difference of 0.1 compared to next lower fire severity class indicated with a plus (+) or minus (−) as an interpretive aide. Fig. 6 shows ranges of values for each metric used to define the classes.

Table 3
Mean values and change in mean values for LiDAR metrics by forest type and fire severity. First number in each entry shows the mean LiDAR metric value followed by the percentage change in that metric compared to unburned (outside all fire perimeters) value for that forest type. Species codes are ponderosa pine (PIPO), white fir-sugar pine (ABCO-PILA), red fir (ABMA).

P95 (m)	PIPO	ABCO-PILA	ABAM	P25 (m)	PIPO	ABCO-PILA	ABAM
Unburned	40.6	40.3	35.3	Unburned	11.9	13.4	11.7
Undifferentiated	37/−8.9%	40.6/0.7%	37.4/5.9%	Undifferentiated	11.4/−4.3%	15.5/15.6%	13.1/11.9%
Low	33.5/−17.5%	42.5/5.4%	39.3/11.3%	Low	10.5/−11.8%	16.7/24.6%	14.9/27.3%
Moderate	33.5/−17.5%	37.1/−8%	35.6/0.8%	Moderate	9.7/−18.5%	14.6/8.9%	13.1/11.9%
High	28.6/−29.6%	28.5/−29.3%	24.7/−30.1%	High	7.7/−20.7%	9.4/−35.7%	7.4/−43.6%
Cover >16 m (%)	PIPO	ABCO-PILA	ABAM	Cover 2–16 m (%)	PIPO	ABCO-PILA	ABAM
Unburned	42.3	45.5	32.8	Unburned	49.2	45.9	35.2
Undifferentiated	38.4/−9.3%	46.7/2.6%	31.9/−2.8%	Undifferentiated	48.1/−2.3%	36.1/−21.4%	27.3/−22.5%
Low	27.5/−28.4%	41.3/−11.6%	29.6/−7.3%	Low	38.2/−20.6%	26.3/−27.2%	19.2/−29.7%
Moderate	18.5/−51.9%	24.4/−47.8%	16.7/−47.7%	Moderate	27/−43.9%	15.8/−56.3%	10.8/−60.5%
High	9.7/−74.8%	9.9/−78.9%	4.3/−86.6%	High	17.7/−63.3%	7.7/−78.7%	4.6/−83.2%
Rumple (ratio)	PIPO	ABCO-PILA	ABAM				
Unburned	4.1	4.2	4.1				
Undifferentiated	3.8/−7.4%	4.3/2.3%	4.3/4.8%				
Low	3.5/−7.9%	4.6/6.9%	4.2/−2.4%				
Moderate	3.1/−18.5%	3.7/−14%	3.3/−23.3%				
High	2.6/−31.6%	2.6/−39.6%	2/−53.5%				

With these explanations for ponderosa pine stands, the changes in structural classes with different fire severities between forest types can be largely explained by differences in fire tolerance of dominant species (Fig. 7). Ponderosa pine patches shifted from a dominance of the multistory class for unburned patches to a dominance of the shorter class for undifferentiated and low severity classes presumably because of a loss of larger overstory trees. With moderate and high severity fire, ponderosa pine patches retained a substantial proportion of the shorter class (41–32%) with a growing dominance of the sparse class (24–40%). However, the open class with its loss of most trees remained a minor proportion of these patches (2–10%). An explanation for this pattern could be that increasing fire severity beyond low severity killed relatively few of the larger fire tolerant ponderosa pine trees. (Alternative explanations could be that the pre-fire structure of the patches were substantially different than the unburned patches we used at as reference conditions or that the severity was misclassified.)

White fir-sugar pine patches, by comparison, showed a slow decline in the proportion of area in the shorter class with increasing fire severity. Instead, this forest type showed an increase in the top

Table 4
Correlation (R^2) of structural metrics with change in metrics with years since fire based on linear regressions. Regressions were run for all grid cells for each metric by year, forest type, and severity resulting in uneven numbers of samples per year. Adjusted R^2/slope shown. Positive slope indicates metric value for more recent fires greater than for older fires; negatives slopes indicates metric value for more recent fires lower than for older fires. Correlations ⩾0.20 in bold for emphasis. Regressions that were not significant at $P < 0.001$ not shown. Species codes are: PIPO – ponderosa pine, ABCO-PILA – white fir-sugar pine, ABMA – red fir.

	Landsat-undifferentiated			Low severity		
	PIPO	ABCO-PILA	ABMA	PIPO	ABCO-PILA	ABMA
95th Percentile height					0/0	0/0
25th Percentile height		0.01/0			0/0	0/0
Rumple					0/0	
Cover >16 m					0/0	
Cover 2–16 m		0.01/0	0.01/0		0/−0.01	0/−0.01
	Moderate severity			High severity		
	PIPO	ABCO-PILA	ABMA	PIPO	ABCO-PILA	ABMA
95th Percentile height	0.11/0.69			**0.28/1.23**	**0.32/1.13**	**0.36/1.16**
25th Percentile height	0.07/0.33			**0.2/0.47**	**0.3/0.54**	0.16/0.33
Rumple	0.11/0.06			**0.43/0.12**	**0.64/0.15**	**0.32/0.08**
Cover >16 m	0.05/0.53			**0.23/0.82**	**0.51/1.16**	0.13/0.33
Cover 2–16 m	0.12/−0.98		0/−0.01	0.12/−0.77	0.17/0.4	0.03/0.12

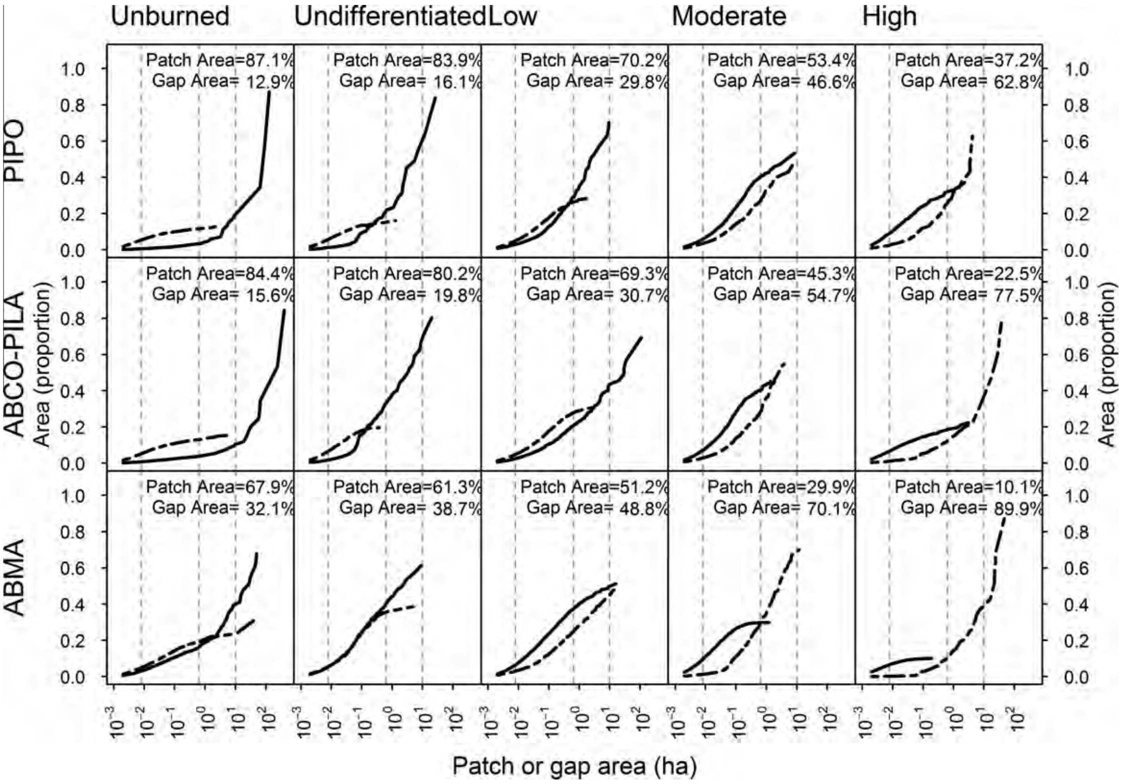

Fig. 8. Cumulative area of canopy patches (solid line) and gaps (dashed line) by size. Patch and gap cumulative areas shown in top right of each panel. A canopy patch was defined as any contiguous area with a return >2 m while gaps had no returns above this height break. Species codes are ponderosa pine (PIPO), white fir-sugar pine (ABCO-PILA), red fir (ABMA). Supplement Figs. 6 and 7 show canopy patch and gap frequency by size.

story class for undifferentiated and low severity fires. This suggests that fire was primarily killing smaller trees and opening the lower canopy, consistent with fire killing the typically smaller and less fire tolerant white fir. For high severity fire, the white fir-sugar pine patches had a similar proportion of area in the sparse class (42% versus 39%), but a larger proportion in the open class (32% versus 10%) suggesting a higher mortality of larger trees for these fire severities than for ponderosa pine patches. These results are consistent with lowered fire resistance for large sugar pines in long unburned stands due to smoldering of deep duff patches at their bases (Nesmith et al., 2010).

Red fir is less fire tolerant than either ponderosa pine or sugar pine. In red fir forests, undifferentiated and low severity fire resulted in an increase in both the sparse and top story classes, consistent with fire killing smaller trees present the unburned patches with the shorter and multistory classes. Moderate and especially high severity fire resulted in strong increases in the area of the sparse and open classes, suggesting high mortality rates for larger trees.

Following a fire, surviving trees will continue to add height, and may show an increase in growth rates in the years immediately following the fire as the result of decreased competition (Sala et al., 2005). Canopy cover will increase both from the establishment of new trees and from remaining trees extending their crowns to fill gaps created by the fire (Fites-Kaufman et al., 2006). For most metrics, we found no or weak trends in metric values with time since

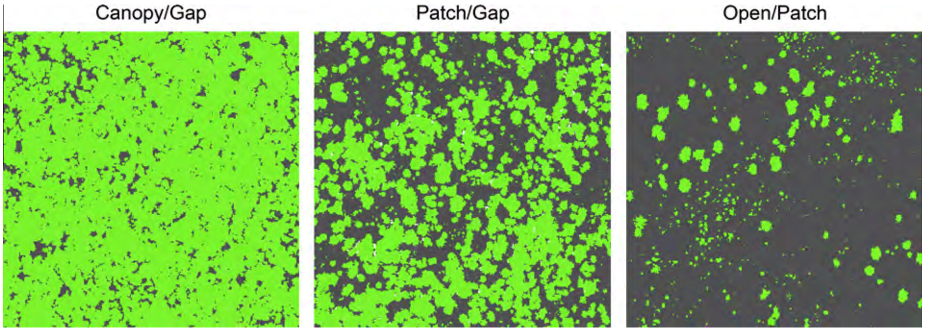

Fig. 9. Examples of the ranges of canopy patch and gap patterns present within the study area. Proportions of canopy patch and gaps for each combination of forest type and fire severity are shown in Fig. 8. Light green represents canopy and black represents gaps (no canopy greater than 2 m in height). Each example pattern is 9 ha (300 × 300 m) from the study area. Canopy and gap areas calculated from a 1 m resolution canopy surface model derived from LiDAR data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

fire (Table 4 and Supplement Figs. 8–12). In fact, the frequent wide range of values between years for the same forest type and fire severity suggests that the individual circumstances of each fire such as fire weather, topography, and pre-existing forest structure may have had substantial influence on post fire structure even for areas assigned the same Landsat estimated fire severity. However, in depth examination of trends by fire year and individual fires was beyond the scope of our study.

We did not find significant relationships ($P > 0.001$) using linear regressions with median values by year, and this likely is a consequence of the variation in results by year and the small number of years ($n = 25$). Linear regressions using all grid cell values individually (resulting in linear regressions using unequal sample numbers per year) resulted in few significant regressions and even fewer with meaningful coefficients of determination ($R^2 > 0.2$) (Table 4). However, we report the results because they suggest an important trend in forest structure change with time for moderate and high severity fire patches that can be followed up in subsequent studies. A detailed examination of these regressions showed that the pattern was one of loss of structure (needles, branches, and boles) over time that was approximately linear over time. We believe that these trends may represent both delayed mortality from fire damage and the decay of snags. Because trees can retain their needles and branches immediately following death, early mortality snags can appear to have similar structure in the LiDAR height metrics as living trees. As needles and branches drop and snags decay and eventually fall, areas of mortality should become increasingly different over time as measured by the LiDAR height metrics.

4.3. Analysis of canopy patch and gap structure

We found that canopy patch and gap patterns were not unique to any forest type, but rather were associated with different fire severity classes. The canopy-gap pattern was found predominantly in unburned, Landsat-undifferentiated, and low severity patches, although some red fir patches in these severity classes had patch/gap patterns. In these latter cases, examination of the orthographic images suggested these stands were on light-toned soils associated with granitic parent material that are generally thin and poorly developed, and the spatial structure may have been edaphically controlled. The patch/gap pattern was associated with moderate fire severity for ponderosa pine and white fir-sugar pine patches and with Landsat-undifferentiated and low fire severity patches for red fir. The open/gap pattern was associated with high severity fire for all forest types and also moderate severity fire for red fir patches.

4.4. Management implications and conclusion

Managers have been using fire as a management tool to thin forests for decades (van Wagtendonk, 2007). Our data suggest that even the low severities associated with prescribed burns (van Wagtendonk and Lutz, 2007) will thin forests and create new gaps. With our data, we can also examine the question of what level of fire severity is likely needed to return forests to structural conditions similar to those prior to fire suppression. Larson and Churchill (2012) analyzed the results of 50 studies that examined tree spatial patterns in western US pine and mixed-conifer forests that retained natural fire regimes. Their synthesis identified three structural elements in fire-frequent forests: openings, individual trees, and clumps of trees with overlapping canopies at scales of 0.0003–0.64 ha. Unfortunately, the studies they examined did not use methods to examine the spatial arrangement of these structures. Based on studies by Hessburg et al. (2005) and analysis by Larson and Churchill (2012), we believe that these structures likely were arranged in the patch-gap pattern identified in our study. If this was the case, then low severity fire would result in the creation of patch-gap structure in red fir forests while moderate severity fire would be needed for ponderosa pine and white fir-sugar pine forests to obtain the same structural goals. Collins et al. (2011) also concluded from field plot-based data that moderate severity fire would recreate pre-fire suppression vertical forest structure within Yosemite's forests.

This study was the first we are aware of to combine a multidecade history of fire severity with LiDAR-derived forest structure measurements over a large contiguous area. We employed a unique fusion of Landsat data to map fire severity patterns and LiDAR data to map forest structure. We sought dominant patterns that are likely to hold across a number of forest types, a broad range of individual fires, and local conditions of pre-fire forest structures and topographies. The fusion of LiDAR and Landsat data identified post-fire structural conditions that could not be identified by Landsat alone, suggesting a broad applicability for landscape-scale structural analysis for fire management. This approach will help create models of how fire restructures forests a multiple scales from local clumps of trees to stands and to landscapes.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2012.08.044.

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