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RESEARCH ARTICLE

# Factors associated with crown damage following recurring mixed-severity wildfires and post-fire management in southwestern Oregon

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**Abstract** Wildfires and post-fire logging and planting have a lasting influence on the quantity and arrangement of live and dead vegetation, which can, in turn, affect the behavior of future fires. In 2002, the Biscuit Fire re-burned 38,000 ha of mixed-conifer/evergreen hardwood forest in southwestern Oregon that had burned heterogeneously during the 1987 Silver Fire and then was subject, in part, to post-fire logging and planting. We measured vegetation cover and crown damage from at temporal sequence (1987, 2000, and 2002) of digital aerial photo-plots (plot size = 6.25 ha) within managed and unmanaged portions of the twice-burned landscape. We estimated the strength and nature of relationships between crown damage in the two fires while also accounting for the influence of several vegetation, topographic, weather, and management variables. On average, unmanaged plots within the reburn area had 58% of their live crown cover scorched or consumed by the Biscuit Fire (median = 64%). The level of re-burn crown damage was strongly related to the level of crown damage during the Silver Fire. Typically, the areas that burned severely in the Silver Fire succeeded to a mix of shrubs and tree regeneration (i.e. shrub-stratum vegetation), which then experienced high levels of Biscuit Fire damage. In contrast, the level of tree-stratum damage in the Biscuit Fire was largely independent of Silver Fire damage. Within plots that were salvage-logged then planted after the Silver Fire, on average 98% of the vegetation cover was damaged by the Biscuit Fire (median = 100%). Within the plots that experienced complete crown damage in the Silver Fire but were left unmanaged, on average 91% of the vegetation cover was damaged by the Biscuit Fire (median = 95%). Our findings suggest that in productive fire-prone landscapes, a post-fire mosaic of young regenerating vegetation can influence the pattern of crown damage in future wildfires.

**Keywords** Burn mosaic · Reburn · Salvage logging · Burn severity · Biscuit Fire

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## Introduction

Wildfire is a dominant disturbance shaping forest ecosystems (Agee 1993). Individual wildfires have variable effects on vegetation and tend to increase the spatial and structural heterogeneity of live and dead fuels (Turner et al. 2003; Baker et al. 2007), which

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can in turn influence the behavior of subsequent wildfires (Peterson 2002; Agee 2005). This pathway may be affected further by post-fire forest management (McIver and Ottmar 2007; Thompson et al. 2007). Although the effects of compounding disturbances remain relatively unstudied, it is often assumed that severe forest disturbances, recurring over short time periods relative to their rate of recovery, can have qualitatively different ecological consequences than do isolated disturbances (Paine et al. 1998). We examined patterns of crown damage following two recurring mixed-severity wildfires in southwestern Oregon: the 1987 Silver Fire and the 2002 Biscuit Fire.

The "ecological memory" of past wildfires (sensu, Peterson 2002) ranges from strong (Minnich 1983) to non-existent (Bessie and Johnson 1995). In some low severity regimes, frequent surface fires reduce available fuels and the risk of crown fires (Covington and Moore 1994). Similarly, in some high severity regimes, fires can reduce short term fire hazard if regenerating vegetation is less flammable than older vegetation (Despain and Sellers 1977; Romme 1982). In contrast, in other high-severity regimes, stand replacing fires elevate fuel-loads (Agee and Huff 1987) and can lead to repeated high severity fires in rapid succession (Gray and Franklin 1997). In mixed-severity regimes, characterized by variable fire frequencies and heterogeneous effects within and between fires, the post-fire legacy of live and dead fuels is variable over time and space and is comparatively not well understood (Schoennagel et al. 2004; Agee 2005). Simulations suggest that the patch mosaic created by a mixed-severity fire can structure and reinforce the severity pattern within future fires (Peterson 2002; Wimberly and Kennedy 2008). In Sierra-Nevadan mixed-conifer forest, frequent fires with fire-free intervals <9 years appeared to limit the extent of recurring fires (Collins et al. 2009). In the more productive mixed-conifer/mixed-evergreen hardwood forests of southern Oregon and northern California, where the Silver and Biscuit Fires occurred, the post-fire landscape is typically a mosaic of high and low severity patches that vary widely in size (Agee 1991; Skinner 1995; Taylor and Skinner 2003). Within severely burned patches, most biomass remains on site but is converted from live to dead, while fine surface fuels and the forest floor are largely consumed (Campbell et al. 2007; Bormann et al. 2008). Dead aerial fuels gradually fall to the surface and decompose over time. Within a few years, live surface fuels increase dramatically, as shrubs, hardwoods and conifer trees regenerate, often at high densities (Shatford et al. 2007; Donato et al. 2009).

The risk of recurring high severity fires is just one of many competing concerns that managers must consider in the aftermath of a fire. Post-fire logging (i.e. salvage logging) has long been a management choice, motivated primarily by interest in economic returns and a perceived reduction in the risk of future severe fires resulting from lower fuel loads (Poff 1989; Brown et al. 2003; Sessions et al. 2004; Gorte 2006). Some recent studies have found, however, that post-fire logging can increase short-term fire hazard by increasing the availability of fine fuels (Donato et al. 2006; McIver and Ottmar 2007). Planting conifers has also been widely employed in the aftermath of wildfires to expedite the return of desired tree species and hasten the return of fire resistant forests (Sessions et al. 2004). This practice, too, may elevate short-term fire hazard if planting increases the availability and continuity of fine fuels (Stephens and Moghaddas 2005). Several observational and modeling studies have documented the high severity fire within plantations (Weatherspoon and Skinner 1995; Odion et al. 2004; Thompson et al. 2007; Kobziar et al. 2009), even when conifers are planted at low densities (Roloff et al. 2004).

We capitalized on a unique arrangement of disturbances to address questions of re-burn severity and post-fire management. We examined a landscape in southwest Oregon that burned heterogeneously during the 1987 Silver Fire, and then was subject to some salvage logging and planting before re-burning in the 2002 Biscuit Fire. In an earlier analysis of the same landscape, Thompson et al. (2007) used the Landsat-based differenced normalized burn ratio (dNBR, Lutes et al. 2004), and found that areas that burned at high severity in 1987 tended to re-burn severely in 2002. Conversely, areas that burned at low severity in 1987 tended to reburn at the lowest severities. Further, they found that areas that were salvage-logged and planted after the Silver Fire burned somewhat more severely in the Biscuit Fire than did areas that burned severely in the Silver but were left unmanaged. dNBR is correlated with vegetation damage (Lutes et al. 2004) and is commonly used for quantifying landscape-scale burn effects (Miller and Yool 2002; Bigler et al. 2005; Finney et al. 2005; Wimberly and Reilly 2007). However, dNBR cannot effectively distinguish between the type or structure of burned vegetation. At high levels of dNBR, changes in the index may be more associated with surface soil features (e.g., ash, soil color) than with canopy mortality, which reaches 100% before the maximum level of dNBR is reached (Kokaly et al. 2007). In this analysis, we increased ecological resolution far beyond dNBR by using a temporal sequence of digital aerial photography to document the layering of disturbances and the pattern of vegetation damage among the three dominant cover types: conifers, hardwoods, and low stature vegetation [a mix of shrubs and small trees, hereafter called the shrub-stratum, sensu Sandberg et al. (2001)]. We examined the relationship between 1987 Silver Fire severity and post-Silver management with Biscuit Fire severity. Additionally, we estimated the relative importance and the nature of relationships between Biscuit Fire crown damage and several aspects of its fire environment and management history. Our objectives were:

1. To characterize the relative importance of weather, topography, and the legacy of the 1987 Silver Fire on patterns of crown damage created by the 2002 Biscuit Fire.
2. To compare patterns of crown damage between areas that were salvage-logged and planted after the Silver Fire to areas that experience stand-replacing fire but were unmanaged, with respect to weather, topography, and vegetation structure.

## Methods

### Study area

The analysis was limited to the 21,000 ha that make up the northern half of the 1987 Silver Fire, centered at 123°89′W latitude 42°49′N longitude (Fig. 1), where an adequate aerial photo record was available. At >38,000 ha, the Silver Fire was the largest of more than 1,600 fires ignited by lightning in northwest California and southwestern Oregon on August 30, 1987 (Reider 1988). The Biscuit Fire burned through and completely encompassed the region of the Silver Fire beginning on July 17, 2002 and continuing through August 18, 2002.

The study area is managed by the Rogue-Siskiyou National Forest (RSNF) and is within the mixed evergreen zone (Franklin and Dyrness1988). It is dominated by conifer species such as Douglas-fir (*Pseudotsuga menziesii*), sugar pine (*Pinus lambertiana*), and white fir (*Abies concolor*). Dominant evergreen hardwoods include tanoak (*Lithocarpus densiflorus*), and Pacific madrone (*Arbutus menziesii*). Dominant shrubs species include manzanita (*Arctostaphylos* sp.) and snowbrush (*Ceanothus velutinus*). In older stands, the sclerophyllous hardwood trees often form lower strata under the conifer overstory (Franklin and Dyrness 1988).

Soil parent materials in the study area include igneous, meta-sedimentary, and metamorphic types. Less than 5% of the study area has ultramafic soils. These areas are floristically distinct and presented an unrepresentative fuel environment (Thompson and Spies 2009), so were excluded from this analysis. Topography in the region is steep and complex; the area is sometimes referred to as “Klamath Knot,” a reference to the lack of directionality to the mountains and the multifarious geology. Elevations range from 100 to 1,500 m. Mean January temperature is 6°C. Mean July temperature is 16°C. Mean annual precipitation is 270 cm, with greater than 90% occurring in winter (Daly et al. 2002).

### Image processing and interpretation

We overlaid and manually interpreted a temporal sequence of digital aerial photo plots taken at three points in time: Post-Silver Fire (October 15, 1987, color, 30 cm grain size), Pre-Biscuit Fire (August 2000, panchromatic, 1 m grain size) and Post-Biscuit Fire (September 24, 2002, color, 30 cm grain size). We interpreted vegetation condition and fire effects within 181 randomly located photo-plots and 35 management units randomly selected from a database acquired from the RSNF. Unmanaged photo-plots were square, five-by-five polygon grids of 50 m cells, covering 6.25 ha. Plots were discarded if they contained any portion of a road, management unit or a large stream or river. To construct management plots, we overlaid a polygon grid of 50 m cells onto the variably shaped management units. If the unit was larger than 6.25 ha, then 25 cells were randomly selected and used as the plot. If the units was smaller than 6.25 ha, then all cells were used. Management units <1.25 ha were excluded. We

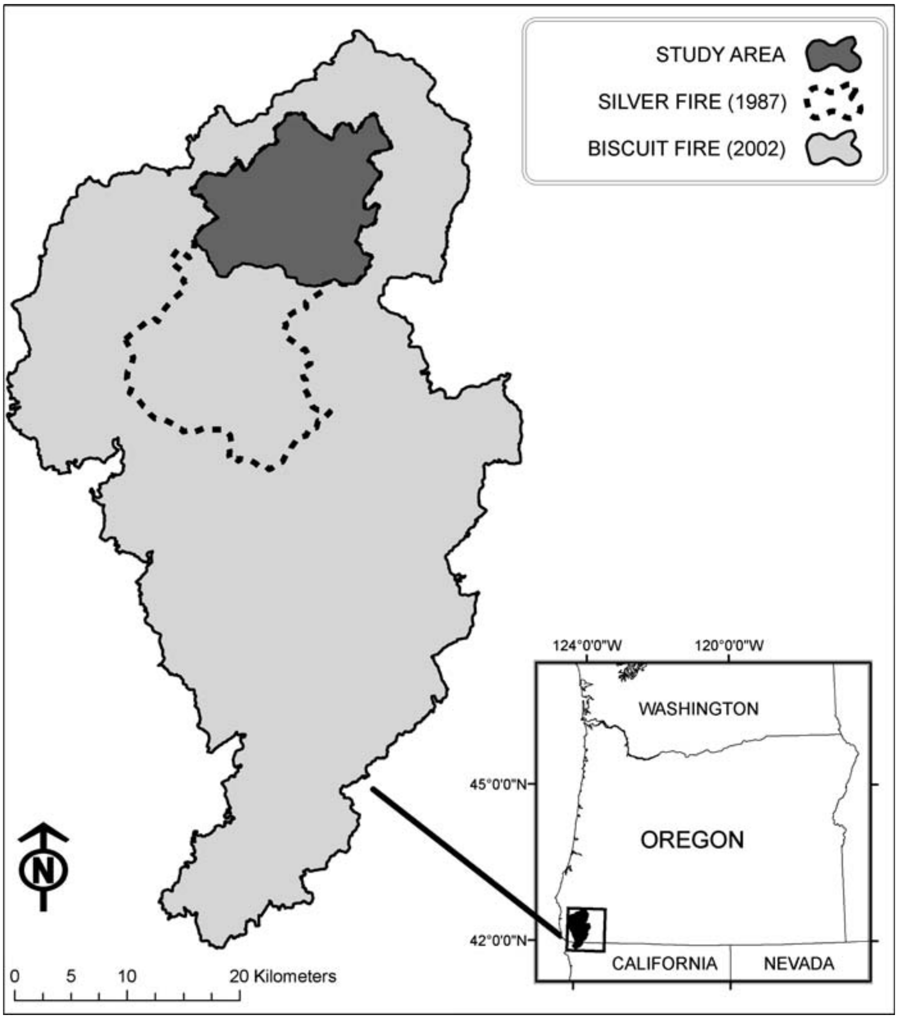



**Fig. 1** Map of the study area in context of the Silver and Biscuit Fires

spatially co-registered each photo-plot using approximately 15 ground control points and used a first-order polynomial transformation for rectification, which resulted in a 30 cm grain size.

To quantify Silver and Biscuit fire effects, we measured the percent of overstory vegetation scorched or consumed (i.e. crown damage) by each fire within each cell of each photo-plot. In addition to measuring the percent of crown damage across all cover types we also independently measured the percent of pre-Biscuit Fire (year 2000) shrub-stature, conifer, and hardwood cover that was damaged by the Biscuit Fire (year 2002). The distinction between damage in each cover class proved necessary to understand the patterns of recurring fires. It is important to note that the percent of crown cover damaged as measured from a planar view of the landscape is not necessarily equivalent to the proportion of the crown volume damaged when measured in the field and, thus, these two measures of "crown damage" should not be directly compared. Also, while field measurements of pre-fire fuel conditions and post-fire burn effects may be ideal, the retrospective nature of this study and the spatial layering of multiple disturbances dictated a remote sensing approach.

We measured percent cover of conifer, hardwood, shrub-stature vegetation, bare ground/grass in every cell within each photo-plot at each point in time, and measured percent crown damage to the conifer, hardwood and shrub-stratum for each cell in 1987 and 2002. We subtracted areas obscured by topographic shadow from the effective area of the photo plot (which cumulatively represented <0.5% of the sampled area).

Pre-fire conifer cover in each cell was further assigned a size class: small, (<50 cm DBH), large (>50 cm DBH), or mixed. DBH estimates were verified with a post hoc comparison of conifers in photo photos to 70 co-located Forest Service inventory plots measured before the Biscuit Fire. Cover estimates summed to 100% in each cell. We averaged cell-level cover estimates to obtain plot-level values. As a metric of structural complexity for each plot, we calculated the standard deviation of the different cover types measured in 1987. To ensure consistency and reduce error all photo interpretation was conducted by a single researcher (Thompson). To calibrate interpretation, we began by developing a catalog of paired oblique-to-aerial photos for use in training then, later, informally ground-truthed a subset of photo-plots, which revealed excellent correspondence.

## Topographic and weather variables

Using a 10-meter digital elevation model (DEM), we calculated average photo-plot elevation, percent slope, Beers' transformed aspect (Beers et al. 1966), and topographic position (TP) for each photo-plot. We calculated TP at two spatial scales: "TP-Fine" is the difference between the mean plot elevation and the mean elevation in an annulus 150–300 m from the plot; "TP-Coarse" uses an annulus 850–1,000 m from the plot.

The RSNF provided a map showing the daily progression of the Biscuit Fire, which we used to assign weather data to each photo-plot based on the day it burned. We assigned the average temperature, relative humidity, wind speed, and cosine transformed wind direction between 10:00 and 19:00 for each day as calculated from the Quail Prairie Remote Automated Weather Station, located approximately 25 km south of the study area. We also created a variable that divided the reburn area into three "Burn Periods," which corresponded to the spread of the Biscuit Fire and fire suppression effort during each period (USDA 2002; GAO 2004). Period A represents 5% of the total Biscuit Fire area (7% of the study area) and includes the region that burned from July 13 to July 26. There was comparatively little suppression effort and mild weather conditions during the time this area burned (Table 1). Period B includes the region that burned from July 27 to Aug 04; 50% of the Biscuit Fire burned in this 9 days period (46% of the study area), which was characterized by strong north-northeastern winds and low relative humidity. Suppression resources increased during this period but were largely unsuccessful in preventing fire spread. Period C represents the remaining 45% of the Biscuit Fire (47% of study area) that burned from August 5 to 18 Fire suppression activities were extensive throughout Period C. The fire continued to spread during extreme weather but had a higher potential to be influenced by fire fighting activities, including burn-outs. While there are no official records describing burn-out locations or severity, the practice was widely used during the suppression campaign, particularity in areas close to towns and private land at the very north and west margins of the Biscuit Fire perimeter. These areas are primarily outside of the re-burn study area which is in the central and more remote regions of the fire. Therefore, we are confident that burn outs did not have a large effect on the crown damage estimates we report here. However, like local weather and specific fuel conditions, the influence of fire suppression was a source of unexplained variance within our analyses.

**Table 1** Dates, area, and weather information for burn periods distinguished by the spread of fire and the resources used for fire suppression

| Burn period | Start-stop | No. days | Hectares (% total) | Temperature (°C) | Relative humidity (%) | Wind speed (km/h) | Wind direction | Suppression effort |
|---|---|---|---|---|---|---|---|---|
| A | 7/13 to 7/26/2002 | 14 | 1,485 (7) | 23.3 | 43 | 13.0 | 0.08 | Low |
| B | 7/27 to 8/04/2002 | 9 | 9,731 (46) | 25.5 | 35 | 13.1 | 0.63 | Moderate |
| C | 8/05 to 8/18/2002 | 14 | 9,761 (47) | 27.2 | 22 | 9.8 | 0.66 | High |
| Silver Fire | 8/31 to 10/15/1987 | 46 | 20,977 (100) | 22.7 | 37 | 7.9 | 0.02 | Unknown |

Weather variables are averages of the daily average between 10:00 and 19:00 within each Biscuit Fire burn period, or within the duration of Silver Fire. Wind direction has been cosine transformed such that a value of −1 is associated with southwesterly winds and a value of +1 is associated with northeasterly winds

### Management data

All the management units included in the study were salvage logged in the 3 years following the Silver Fire, then planted with conifers (primarily Douglas-fir) and later certified as "successful plantations" by the RSNF. The Silver Fire salvage logging guidelines set by the Forest Service required that, within harvest units, 12–18 standing snags >60 cm diameter and >12 m tall, along with 2.8 $m^3$ of down wood be retained per hectare. No documentation describing post-logging fuel treatment was available. Plantations were deemed successful if, 3–5 years after planting, conifers exceeded 370 stems per hectare and were considered healthy enough to survive competition with shrubs and hardwood trees. Though post-Silver Fire records from the RSNF are not complete, they indicate that some certified plantations had undergone mechanical treatment to suppress competing vegetation and that conifer stocking typically ranged from approximately 600–1,100 trees per hectare. All areas logged and planted prior to the Silver Fire were excluded from our analyses.

### Data analysis

#### *Unmanaged plots*

To illustrate the differences in patterns of crown damage between the two fires, we plotted empirical cumulative distributions of total crown damage measured in the photo-plots after each fire. To assess the pattern of re-burn damage as it related to the level of Silver Fire damage, we summarized the proportion of conifer, hardwood, and shrub-stratum damage at 5% increments of Silver Fire crown damage. To estimate the importance of the predictor variables (Table 2) on re-burn severity, we structured three response variables that describe different aspects of crown damage during the Biscuit Fire: total crown damage across all cover types, relative conifer damage (i.e. (2000 Conifer Cover—2002 Conifer Cover)/2000 Conifer Cover), and relative hardwood damage. When modeling relative hardwood damage, we subset the data to include only those plots with greater than 5% pre-fire hardwood cover ($n = 107$). We used a two-stage approach to analyzing relationships between the three response variables and the suite of 18 predictor variables (Table 2). We first used random forest analysis (RFA; Breiman 2001) to estimate and rank the importance of predictors, and then used regression tree analysis (RTA; De'ath and Fabricius 2000) to illustrate the nature of relationships between the response and the top ranked predictor variables. These nonparametric methods are ideally suited for the analysis of high dimensional ecological data with hierarchical and non-linear relationships among predictor variables and between predictor and response variables (De'ath and Fabricius 2000; Cutler et al. 2007).

We used Liaw and Wiener's (2002) implementation of RFA within the R statistical environment (R Development Core Team 2006). The algorithm, as applied to these data, was as follows: (1) Select 1,500 bootstrap samples each containing two-thirds of the data; (2) For each bootstrap sample, grow an un-pruned regression tree with the modification that at each node, rather than implementing the best split among all predictors (as is typical in regression trees), randomly select one-third of the predictor variables and choose the best split from among those variables; (3) At each bootstrap iteration, predict the response value for data not included in the bootstrap sample—the so-called Out-Of-Bag or OOB data—and average those response values over all trees; (4) Calculate importance values for each predictor by calculating the percent increase in mean squared error when OOB data for each variable are permuted while all others are unchanged. We used RFA variable importance values to rank predictors in terms of the strength of their relationship to the response and partial dependence plots to show the effect of changing individual predictors while holding all other predictors at their average.

After identifying important predictor variables with RFA, we used RTA to better understand the nature of relationships between the six top-ranked predictors and each response variable. RTA is a non-parametric technique that recursively partitions a dataset into subsets that are increasingly homogeneous in terms of the response (De'ath and Fabricius 2000). RTA produces a set of decision rules on predictor variables that are easily interpreted as a dendrogram. Most implementations of RTA have a selection bias towards predictors with many possible splits and tend to overfit to a given dataset by creating splits that do not significantly reduce the variance (Hothorn et al. 2006). Trees are typically pruned back to include only those partitions assumed to be valuable beyond the sample

**Table 2** Summary of response and predictor variables used in the random forest and regression tree analysis of unmanaged stands

| | Median | Mean | Min | Max |
|---|---|---|---|---|
| Response variables | | | | |
| All crown damage | 62.6 | 58.4 | 0.0 | 100.0 |
| Relative conifer damage | 38.6 | 45.8 | 0.0 | 100.0 |
| Relative hardwood damage | 85.3 | 72.9 | 0.0 | 100.0 |
| Predictor variables | | | | |
| 1987 crown damage (silver fire) | 16.4 | 28.3 | 0.0 | 100.0 |
| 1987 Large conifer cover | 29.0 | 36.6 | 0.0 | 100.0 |
| 1987 Small conifer cover | 1.2 | 6.1 | 0.0 | 82.8 |
| 1987 Mixed-size conifer cover | 2.2 | 9.2 | 0.0 | 82.2 |
| 1987 Hardwood cover | 6.2 | 15.8 | 0.0 | 77.2 |
| 1987 Shrub cover | 0.0 | 2.1 | 0.0 | 52.0 |
| 1987 Bare/grass cover | 0.0 | 1.9 | 0.0 | 44.0 |
| 1987 Cover variability (SD) | 21.1 | 22.0 | 9.2 | 35.4 |
| Elevation (m) | 700.0 | 701.9 | 136.8 | 1,476.0 |
| Topographic position (Fine) | −0.9 | −1.1 | −58.5 | 53.8 |
| Topographic position (Coarse) | −6.1 | −2.5 | −271.0 | 275.6 |
| Slope (%) | 57.6 | 57.0 | 21.7 | 92.4 |
| Beer's aspect | 0.1 | 0.1 | −1.0 | 1.0 |
| Temperature (C) | 27.2 | 25.6 | 16.6 | 35.0 |
| Relative humidity (%) | 28.3 | 29.3 | 11.4 | 53.6 |
| Wind speed (km/h) | 15.0 | 14.1 | 6.2 | 19.1 |
| Wind direction (cosine transformed) | 0.6 | 0.5 | −0.3 | 0.8 |
| Burn period | A (9%), B (49%), C (42%) | | | |

See "Methods" and Table 1 for information regarding the different burn periods

data. We used an implementation of RTA called conditional inference trees, which establishes partitions based on the lowest statistically significant *P*-value that is obtainable across all levels of all predictor variables, as determined from a Monte Carlo randomization test. This minimizes bias and prevents over-fitting and the need for pruning (Hothorn et al. 2006). To guard against Type-I errors resulting from spatial autocorrelation, we set $\alpha$ conservatively to 0.005. We assessed autocorrelation in RFA and RTA model residuals using semivariograms.

### *Management data*

To determine whether salvage logging and planting after the Silver Fire influenced the level of crown damage in the Biscuit Fire, we compared the management plots ($n = 35$) with the portion of unmanaged plots (or contiguous portions of unmanaged plots >1.25 ha) that experienced complete overstory mortality during the Silver Fire ($n = 35$). By using only those unmanaged plots that burned severely during the Silver Fire we ensured that our comparison was between two stand-replacing events. We compared medians and distributions of the percent of crown damage in the managed and unmanaged plots, but did not report *P*-values because spatial autocorrelation prevented us from setting a meaningful level for $\alpha$. We then pooled these data ($n = 70$) and used RFA and RTA to examine relationships between the predictor variables (Table 2) and crown damage, while also including an indicator variable for management history as a potential predictor.

## Results

### Level of overall crown damage

Ninety percent of the unmanaged plots experienced some level of crown damage (i.e. >1% of the plot area) during the Silver Fire, while 99% experienced some level of crown damage during the Biscuit Fire (Fig. 2). On average, unmanaged plots had 28% of

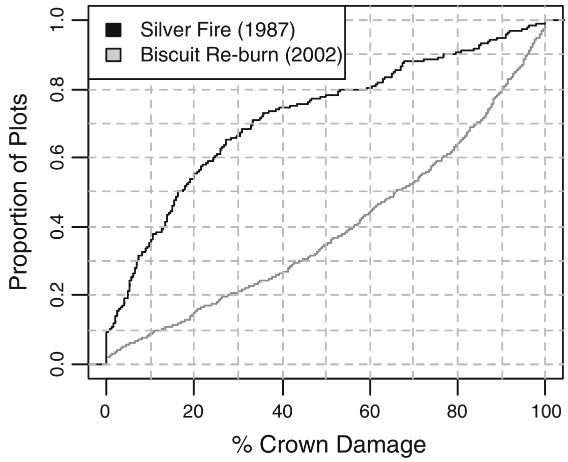



**Fig. 2** Empirical cumulative distribution of crown damage in the 1987 Silver Fire and re-burn portion of the 2002 Biscuit Fire

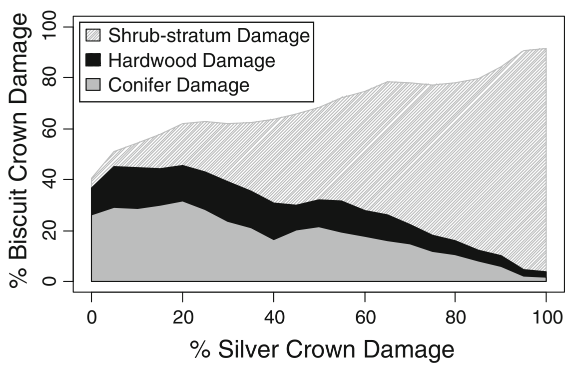



**Fig. 3** Percent Biscuit Fire crown damage to the shrub-stratum, hardwood, and conifer crowns in relation to the overall percent crown damage during the 1987 Silver Fire

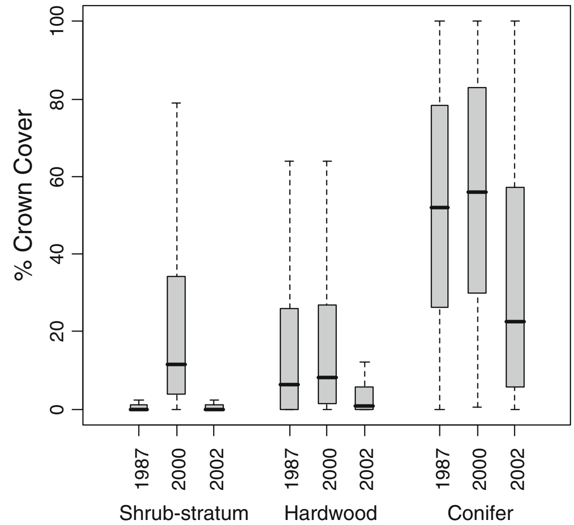



**Fig. 4** Percent crown cover of shrub-stratum, hardwood, and conifer cover in 1987 (immediately after the Silver Fire), in 2000 (2 years before the Biscuit Fire), and in 2002 (immediately after the Biscuit Fire). *Black lines* correspond to median values; *boxes* correspond to the inner quartile range; *whiskers* correspond to the range of the data

their crown cover damaged by the Silver Fire (median = 16%), while the average level of crown damage from the Biscuit Fire, across all cover types, was 58% (median = 64%; Table 2). Within-plot burn variability was higher in the Silver Fire than the Biscuit Fire (coefficient of variation = 1.05 vs. 0.6, respectively). Plots with the highest levels of crown damage in the Silver Fire also had the highest levels of crown damage within the Biscuit Fire (Fig. 3). By the year 2000, plots that had been severely burned by the Silver Fire had largely succeeded to shrub-stratum cover and contained low levels of tree-stratum cover. Consequently, the highest levels of absolute (as opposed to relative) tree-stratum crown damage (conifer and hardwood) during the Biscuit Fire were in areas that had sustained the lowest levels of Silver Fire damage (Fig. 3). Of the three cover types considered, the shrub-stratum experienced the largest proportional damage (95%; Fig. 4). Of the tree-strata cover types, hardwoods experienced a greater proportional loss of canopy than did conifers (85 vs. 39%, respectively; Table 2).

## Overall crown damage models

The RFA model explained 46% of the variability in overall crown damage (unmanaged plots only). Silver Fire damage and large conifer cover were the most important predictor variables (Fig. 5). Increasing Silver Fire damage was associated with increasing Biscuit crown damage, while increasing large conifer cover was associated with decreasing crown damage in the Biscuit.

RTA of total crown damage resulted in five terminal nodes (Fig. 6). The first partition was based on whether Silver Fire crown damage was >39%; when it was, Biscuit Fire damage was generally >90%. When Silver Fire damage was <39%, areas that burned during period B, and when the average

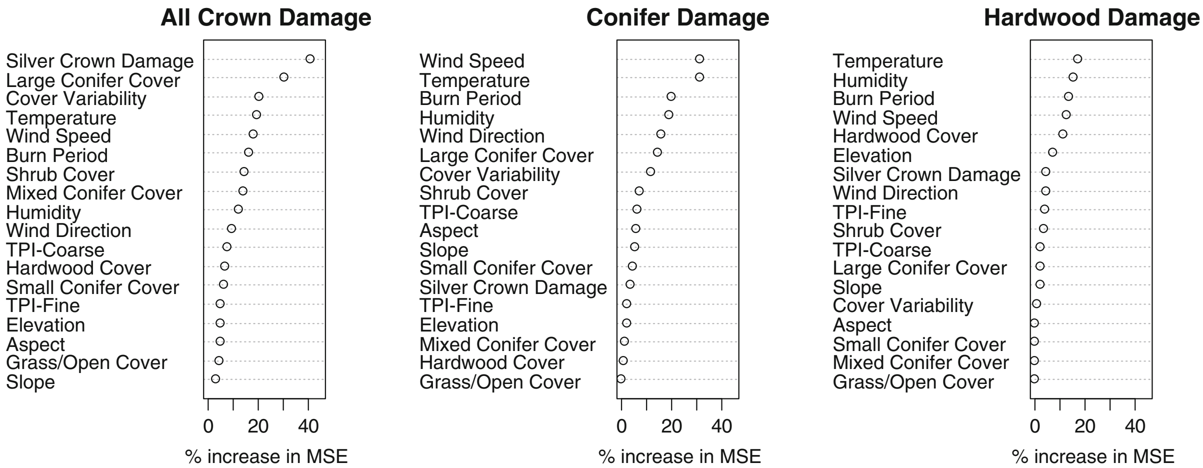
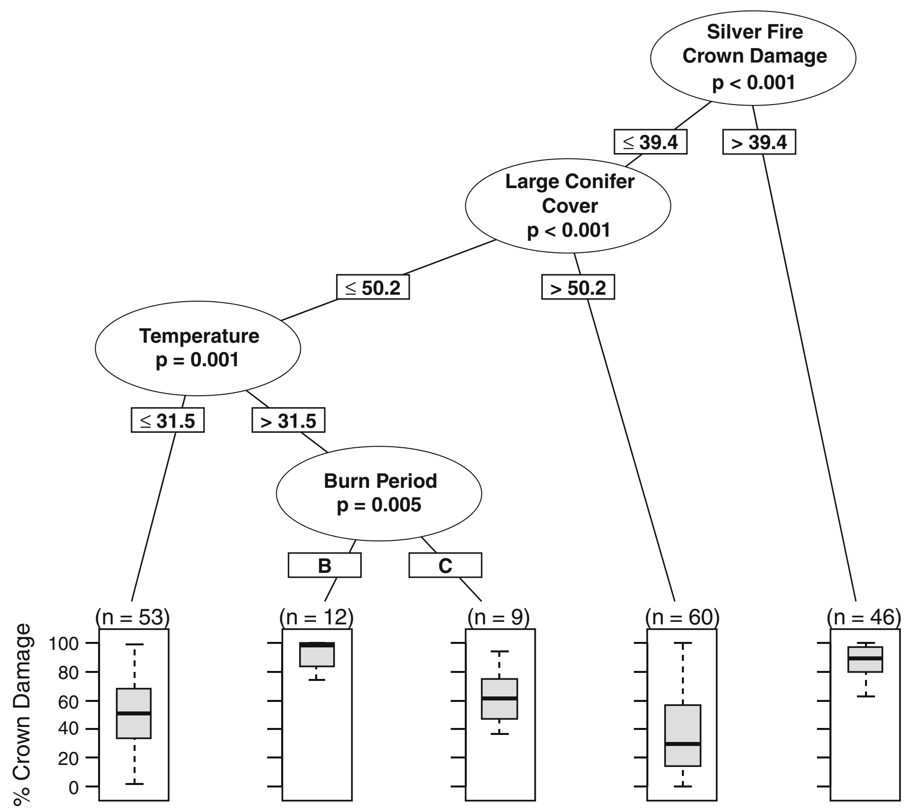



**Fig. 5** Variable importance plots for predictor variables from random forests models for overall crown damage, relative conifer damage, and relative hardwood damage. Predictor variables are along the *y*-axis and the average increases in the mean square error when data for that variable are permuted and all other are left unchanged are on the *x*-axis. TPI = Topographic position index; see "Methods" section for details

**Fig. 6** Regression tree for total Biscuit Fire crown damage based on the top six predictor variables from the random forest analysis (see Fig. 5). *Box-plots* at terminal nodes show the distribution of the data within that branch of the tree




temperature was greater than 31°C, had very high levels of crown damage. In contrast, the lowest levels of crown damage were in areas with >50% large conifer cover.

## Conifer and hardwood damage

The RFA models explained 32 and 18% of the variability in relative conifer and hardwood damage,

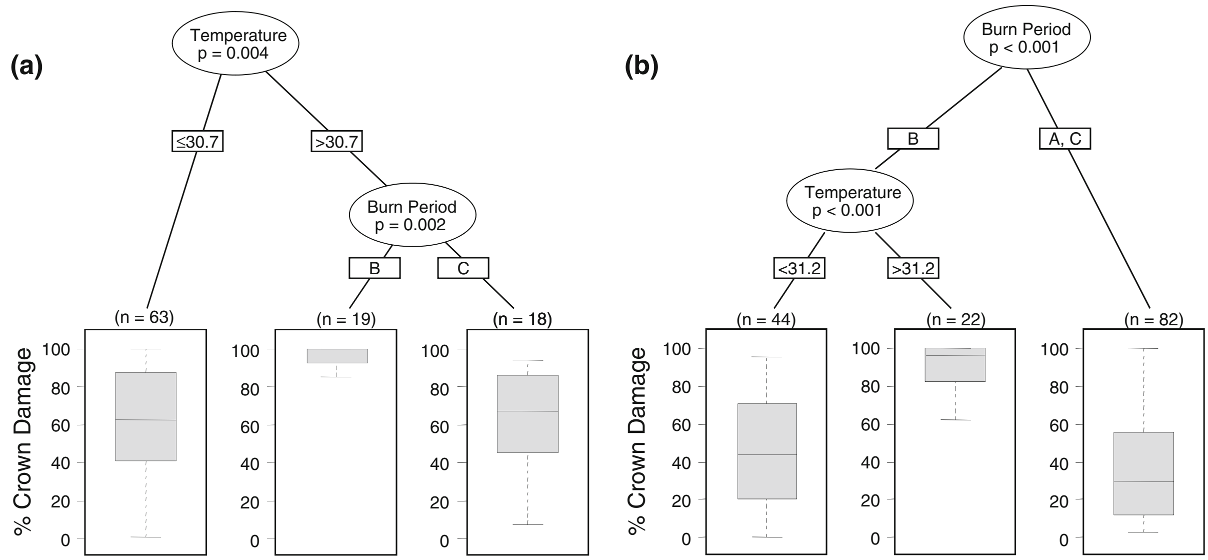



**Fig. 7** Regression trees of **a** relative conifer and **b** hardwood crown damage during the Biscuit Fire using the top six predictor variables from the random forest analysis (see Fig. 5)

respectively (Fig. 5). Weather variables and burn period were ranked as most important predictor variables in both cases. The first split in the regression tree of relative conifer damage was burn period and indicated lower levels of damage during burn periods A and C (Fig. 7). Conifer damage was highest during period B when the average temperature was above 31°C. The first split in the RTA for hardwood damage was related to average daily temperature, but overall, patterns were similar to those in relative conifer damage (Fig. 7).

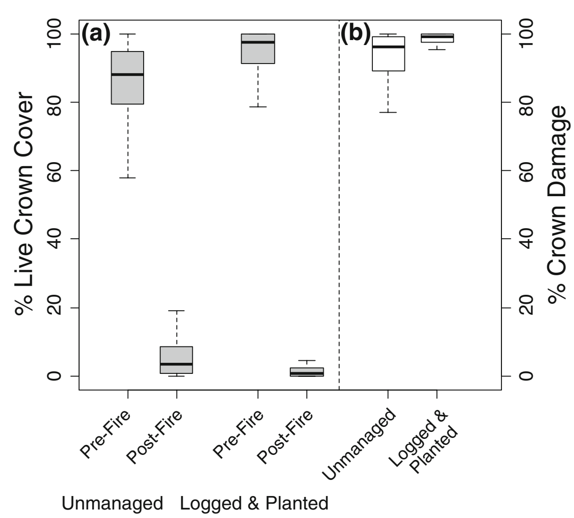



**Fig. 8** Distribution of **a** vegetation cover and **b** percent crown damage within areas that were severely burned in the Silver Fire and either left unmanaged or were salvage logged and planted with conifers

## Management history

The average level of pre-Biscuit Fire (year 2000) live shrub-stratum cover was 95% in the salvage-logged and planted plots (i.e. managed plots) and was 86% in the plots that experienced complete crown damage in the Silver Fire but were left unmanaged (Fig. 8). Within the managed plots, on average 98% of the vegetation cover was damaged by the Biscuit Fire (median = 100%). Within the plots that experienced complete crown damage in the Silver Fire but were left unmanaged, on average 91% of the vegetation cover was damaged by the Biscuit Fire (median = 95%).

With those managed and unmanaged plot data pooled, the RFA model explained 37% of the variability in crown damage. The two measures of topographic position and management history were the most important predictors of damage (Fig. 9). Higher topographic position and management was associated with higher crown damage. Consistent with this finding, the first split in the regression tree was on TP-Fine; plots on lower topographic positions had median crown damage of 93% and included only unmanaged plots (Fig. 10). Among plots with higher topographic

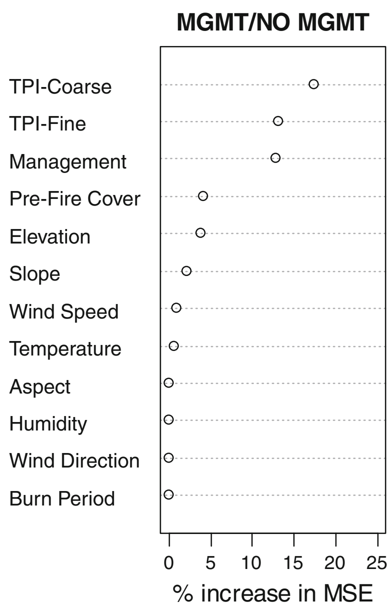



**Fig. 9** Variable importance plot from the random forests analysis of crown damage within areas that were severely burned in the Silver Fire and either left unmanaged or were salvage logged and planted with conifers. TPI = Topographic position index; see "Methods" section for details. (See Fig. 5 for further explanation of axes)

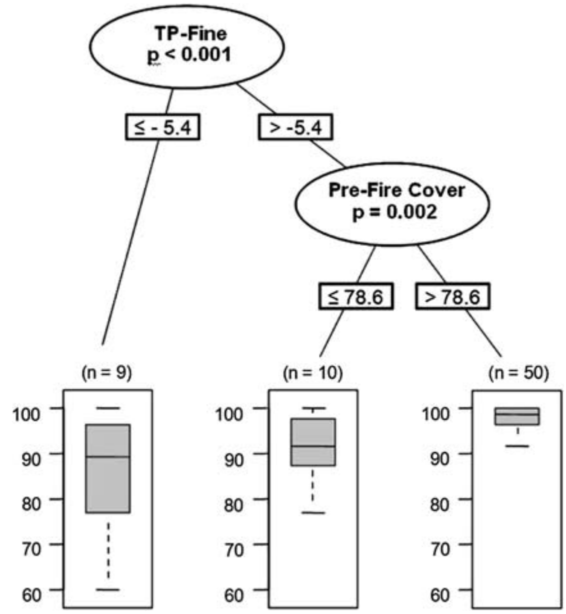



**Fig. 10** Regression tree of canopy damage for areas that experienced 100% crown damage during the Silver Fire and were either left unmanaged or were salvage logged and planted with conifers. Note that when the pre-fire cover variable was held out of this analysis, the indicator for management entered as a significant variable at the same place on the regression tree with $P = 0.026$

positions, an additional split was based on whether shrub-stratum cover was above 79%.

## Discussion

While the Biscuit Fire resulted in higher levels of canopy damage than the Silver Fire, this was not exclusively related to it being a re-burn. In fact, Biscuit-related crown damage outside of the re-burn area also exceeded the level of damage in the Silver Fire (Thompson and Spies 2009). Differences in overall damage between the two fires were largely attributable to more extreme weather conditions at the time of the Biscuit Fire (see temperature and wind speed data in Table 1). Nonetheless, the legacy of the Silver Fire was strongly associated with the pattern of overall Biscuit Fire crown damage. Consistent with Thompson et al. (2007), we found a trend of increasing overall Biscuit Fire damage with increasing Silver Fire damage (Fig. 3). What the current analysis shows—and what the previous analysis was unable to show—is that damage to the regenerating shrub-stratum vegetation drove this correlation and that damage in the tree-stratum was largely independent of patterns of damage in the Silver Fire. Early successional pathways in the Klamath-Siskiyou region are characterized by aggressive colonization of sprouting hardwoods and shrubs (Hobbs et al. 1992; Stuart et al. 1993), and although conifers will eventually succeed (Shatford et al. 2007), the period during which most live biomass remains in the shrub-stratum may be protracted over several decades. Shrub-stratum vegetation is available to surface fires and, depending on the species composition, can be associated with flashy and sometimes intense fire (Anderson 1982; Weatherspoon and Skinner 1995). As such, it not surprising that areas that burned severely in the Silver Fire and were characterized by a dominant shrub layer, re-burned severely in the Biscuit Fire. In contrast, the areas that retained large conifers through the Silver Fire were the areas that had the lowest levels of damage during the Biscuit Fire (Fig. 6).

Absolute (as opposed to relative) tree crown damage of hardwoods and conifers was highest in areas that burned with low levels of crown damage during the Silver Fire (Fig. 3). This simply reflects the fact that areas that did not experience crown fire in the Silver Fire still had trees canopies available to burn in the Biscuit Fire. Damage in the tree-stratum relative to pre-fire abundance was related primarily to weather and burn period. Interestingly, Silver Fire crown damage was not an important predictor of Biscuit Fire relative tree crown damage, further suggesting that the legacy of the Silver Fire was limited to the severely burned patches.

Results of this study suggest that the mosaic of crown damage in these productive, fire-prone forests can influence future burn mosaics. Once an area experiences a stand replacing burn, it can be caught within a positive feedback of repeated severe fires. Lightning strikes are ubiquitous in this region, and can ignite wildfires that repeatedly reset succession, resulting in enduring shrub-fields (Agee 1993). After each burn, shrubs, hardwoods, and conifers regenerate vigorously, setting the stage for the next severe burn. Clearly, this cycle does not continue indefinitely, as is evidenced by abundant old-growth forests that were present in this landscape before the recent fires. Periodically, the fire-free interval must be sufficiently long to allow a tree stratum to develop. This relatively fire-resistant patch type would be characterized by dense tree canopies that suppress shrub fuel ladders, increasing heights to the base of the canopies and larger bole diameters that are progressively more resistant to fire over time. This comparatively fire-resistant patch type may endure until a high intensity fire, such as the Biscuit Fire, shifts the vegetation back to an early-seral condition.

### Relationship between crown damage and post-fire management

Shrub-stratum vegetation experienced high rates of crown mortality throughout the reburn area regardless of management history. Median crown damage was five-percent higher in areas that had been logged and planted after burning severely in the Silver Fire. The direction of this effect was consistent with Thompson et al. (2007), in that the managed stands burned more completely than comparable unmanaged stands. However, the magnitude of difference was much lower in the present study (5% difference in crown damage versus a 16–61% difference in dNBR). The reason for the difference may be due to the fact that maximum dNBR is not reached at 100% crown damage (Lutes et al. 2004; Miller and Thode 2007). Or, it may be because dNBR is a synthetic measure of multiple fire effects, and while it is primarily related to crown damage, it also corresponds to changes in soil moisture and color, ash color and content, and consumption of down wood (Lutes et al. 2004). The Biscuit Fire resulted in sharp reductions in mineral soil and changes in soil structure (Bormann et al. 2008) that may have been represented by the dNBR measure. In this respect, two estimates simply measure different aspects of "fire severity," a term that often means different things to different people (Jain et al. 2004). The difference in *crown damage*—a far more interpretable, though still imperfect, measure of fire effects—between the managed and unmanaged stands was small, and the degree to which this difference might affect subsequent ecological processes is unknown. It may make no difference, whatsoever. Or, the small initial differences in heterogeneity of shrubs and trees could affect longer term successional pathways and structural diversity. Plantations that were consumed by the Biscuit Fire were immediately replanted by managers (RSNF 2004). If these areas had not been replanted, it seems likely that their successional trajectories would be distinct from the high severity burned areas that had pre-fire abundance of sprouting shrubs and trees.

The RFA analysis ranked the predictor variable for management above the predictor describing the cover of pre-fire shrub-stratum vegetation. In contrast, RTA included pre-fire vegetation—but not management history—as a partition in the tree. This difference illustrates the strengths and weaknesses of the two approaches. The importance ranking from RFA indicates that, all other predictors being held constant, the management history explained more variability than did the level of pre-fire shrub-stratum cover. In contrast, interpretation of each node in the regression tree is conditional on the nodes above it. In our analysis, pre-fire vegetation cover is included as a split in the tree, only after accounting for topographic position. Further, RTA selects the best possible partition, but, unlike RFA, offers no information regarding other variables that may have reduced deviance almost as much as the chosen variable. Indeed, when we re-ran the RTA without the pre-fire cover variable, the indicator for management entered as a significant variable on the same branch of the regression tree with $P = 0.026$.

Our analyses suggest that the difference in crown damage between managed and unmanaged stands was related to topographic position and pre-fire vegetation cover. Although Thompson et al. (2007) controlled for topographic position within a regression framework, they were not able to adequately account for pre-fire cover. Higher cover in managed stands was presumably a result of planting. Young, evenly-spaced dense conifers have been hypothesized to have fuel properties more conducive to fire spread than shrubs and young broadleaf hardwoods (Perry 1994), but we are aware of no empirical research that supports or refutes this. However, several studies have documented high burn severity within conifer plantations (Weatherspoon and Skinner 1995; Odion et al. 2004; Roloff et al. 2004), particularly when young (Graham 2003; Stephens and Moghaddas 2005).

## Conclusions

Our analysis extends beyond Thompson et al. (2007), who used a synthetic metric of burn "severity" (Landsat-based dNBR) and focused on two narrow questions (Q1: First, was severity in the Biscuit Fire associated with severity in the Silver Fire in unmanaged areas? Q2: Did areas that were salvage-logged and planted with conifers after the Silver Fire burn more or less severely in the Biscuit Fire than comparable unmanaged areas?) By interpreting changes in vegetation cover through a time series of aerial photos, we were able to learn more about the ecological relationships that were uncovered in the first study that used only satellite imagery. We found that areas that burned severely in the 1987 Silver Fire reburned severely in the 2002 Biscuit Fire, but that these areas contained primarily shrub-stratum vegetation. Relative damage within the tree stratum was largely independent of the legacy of the Silver Fire. Areas that were salvage logged and planted after the Silver Fire experienced high rates of crown damage during the Biscuit Fire. The plantations had somewhat higher vegetation cover than the unmanaged stands, suggesting that higher live and dead fuel continuity in plantations may play a role creating more flammable vegetation types. Additional research is clearly needed to judge if these findings are generalizable to other mixed-severity reburns and to quantify the differences in reburn severity with longer and shorter intervals between fires.

The Biscuit Fire burned more than 75% of the overstory on almost 100,000 ha across the RSNF (Thompson and Spies 2009). In the short term (10–20 years), managers may not be able to reduce the likelihood of recurring high severity fire in these cover types through traditional silvicultural practices. Our findings suggest that the type of post-fire management practiced after the Silver Fire did not reduce fire hazard at 15 years and may increase it compared to early-seral unmanaged areas. Research done elsewhere within the Biscuit Fire has shown that thinning in mature (90- to 120-year-old) green forests followed by prescribed fire can be an effective way to reduce fire severity in the first few years after treatment, but that thinning without treating logging slash can increase severity compared with unmanaged stands (Raymond and Peterson 2005). Managers may consider strategically placing thinning and burning treatments in configurations that might slow the spread of future fires enabling protection of key structures and habitat conditions (e.g. spotted owl habitat areas) with the landscape (RSNF 2004; Ager et al. 2007).

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