

# Vegetation and weather explain variation in crown damage within a large mixed-severity wildfire

Jonathan R. Thompson<sup>a,\*</sup>, Thomas A. Spies<sup>b,1</sup>

<sup>a</sup> Department of Forest Science, Oregon State University, Corvallis, OR 97331, United States

<sup>b</sup> USDA Forest Service, Pacific Northwest Research Station, Corvallis, OR 97330, United States

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## ABSTRACT

The 2002 Biscuit Fire burned through more than 200,000 ha of mixed-conifer/evergreen hardwood forests in southwestern Oregon and northwestern California. The size of the fire and the diversity of conditions through which it burned provided an opportunity to analyze relationships between crown damage and vegetation type, recent fire history, geology, topography, and regional weather conditions on the day of burning. We measured pre- and post-fire vegetation cover and crown damage on 761 digital aerial photo-plots (6.25 ha) within the unmanaged portion of the burn and used random forest and regression tree models to relate patterns of damage to a suite of 20 predictor variables. Ninety-eight percent of plots experienced some level of crown damage, but only 10% experienced complete crown damage. The median level of total crown damage was 74%; median damage to conifer crowns was 52%. The most important predictors of total crown damage were the percentage of pre-fire shrub-stratum vegetation cover and average daily temperature. The most important predictors of conifer damage were average daily temperature and “burn period,” an index of fire weather and fire suppression effort. The median level of damage was 32% within large conifer cover and 62% within small conifer cover. Open tree canopies with high levels of shrub-stratum cover were associated with the highest levels of tree crown damage, while closed canopy forests with high levels of large conifer cover were associated with the lowest levels of tree crown damage. Patterns of damage were similar within the area that burned previously in the 1987 Silver Fire and edaphically similar areas without a recent history of fire. Low-productivity sites on ultramafic soils had 92% median crown damage compared to 59% on non-ultramafic sites; the proportion of conifer cover damaged was also higher on ultramafic sites. We conclude that weather and vegetation conditions — not topography — were the primary determinants of Biscuit Fire crown damage.

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## 1. Introduction

Mixed-severity fire regimes — characterized by variable fire frequencies and heterogeneous effects within and between fires — structure temperate forest ecosystems worldwide. Despite their prevalence, the dominant controls over fire effects within mixed-severity regimes remain poorly understood (Agee, 2005). Unlike high severity regimes, where extreme weather tends to override other influences on fire behavior (Bessie and Johnson, 1995; Turner et al., 1997), and low severity regimes where fuels are a primary

determinant of fire behavior even during extreme weather (Agee, 1997; Finney et al., 2005), few generalities have been made about the relative importance of weather, fuel, and topography (i.e. the fire environment) for determining fire effects in mixed-severity regimes (Schoennagel et al., 2004). We examined the pattern of crown damage created by the 2002 Oregon Biscuit Fire in relation to its fire environment. The Biscuit Fire encompassed more than 200,000 ha of mixed-conifer/evergreen hardwood forests, whose structure and composition have been strongly influenced by a historically mixed-severity regime (Agee, 1993). The remarkable size of the fire and the diversity of conditions through which it burned provided an opportunity to assess the factors that gave rise to the mosaic of crown damage. Using pre- and post-fire digital aerial photography, we measured patterns of crown damage among several vegetation cover classes in relation to daily weather conditions, topography, vegetation cover, edaphic setting, and recent fire history. We structured our study around three research questions.

\* Corresponding author. Current address: Harvard Forest, Harvard University, 324 N. Main Street, Petersham, MA 01366, United States. Tel.: +1 978 756 6159; fax: +1 978 724 3595.

E-mail addresses: [jthomps@fas.harvard.edu](mailto:jthomps@fas.harvard.edu) (J.R. Thompson), [tspies@fs.fed.us](mailto:tspies@fs.fed.us) (T.A. Spies).

<sup>1</sup> Tel.: +1 541 750 7354; fax: +1 541 750 7329.

*Question 1: What was the relative importance of daily regional weather conditions, topography, and vegetation cover for predicting patterns of crown damage?*

Variation in regional weather conditions can have a dramatic influence on fire behavior, but quantifying its relationship to fire effects can be difficult post hoc. By consuming oxygen and releasing heat, combustion circulates air and creates its own weather that is site-specific and impossible to reconstruct (Pyne et al., 1996). Consequently, most retrospective studies of fire effects exclude the influence of weather (e.g. Weatherspoon and Skinner, 1995; Lentile et al., 2006). However, the few studies that have related variation in regional weather to patterns fire effects have found average daily temperature and wind speed to be important predictors (Collins et al., 2007, 2009).

Topographic variation can impose important direct and indirect controls on patterns of fire effects. For example, greater solar radiation on southwesterly aspects can result in drier conditions and smaller vegetation, which can lead to higher levels of fire damage (Kushla and Ripple, 1997; Taylor and Skinner, 2003). The relationship between fire effects and elevation is more variable. Higher elevations have been associated with lower severity in some fires, presumably due to cooler temperature and higher humidity (Weatherspoon and Skinner, 1995); however, this pattern may be reversed when vegetation found at higher elevations is more susceptible to damage either due to the species' vulnerability or greater fuel accumulation associated with lower fire frequency (Agee, 1991). Finally, dendrochronological research has linked increasing fire effects with upper topographical positions (Taylor and Skinner, 1998), which have a higher probability of being burned by an intense heading fire.

Vegetation cover type (e.g. evergreen hardwood, conifer, low stature shrub, etc.), while not a direct measure of fuel conditions, is often related to patterns of fire damage (Weatherspoon and Skinner, 1995). Further, because vegetation is the only component of the fire environment that can be managed, and because crown cover is often all that is known over broad regions, understanding its relationship to fire effects is of particular importance. The role of vegetation cover in controlling fire effects varies widely. Clearly, some cover types, such as low-stature shrub vegetation are vulnerable to fire damage regardless of the weather and topographical conditions. Within forested areas, however, the importance of cover type on patterns of fire effects, relative to the rest of the fire environment, is not well understood, particularly in mixed-severity regimes. We measured crown damage within four forested cover types (small, large, and mixed-sized conifers, and evergreen hardwood) and one non-forested cover types (low "shrub-stature" vegetation). Not surprisingly, several studies have found lower rates of damage in large conifers compared to small (Alexander et al., 2006; Lentile et al., 2006). But, whether mixed-sized conifers are at an intermediate level of vulnerability is not clear. There has been concern that large trees in fire-dependent forests may be at increased risk of damage due to the encroachment of small conifers in the understory resulting from decades of fire suppression (Spies et al., 2006). Patterns of fire damage within evergreen hardwood forests have received little attention. However, Raymond and Peterson (2005) did report high levels of overstory mortality of tanoak (*Lithocarpus densiflora*) within field plots in the Biscuit Fire, apparently owing to their low crown-base-heights, relatively thin bark, and flammable leaves.

*Question 2: Did the pattern of crown damage differ between areas with and without a recent history of fire?*

The 2002 Biscuit Fire re-burned a large area (>38,000 ha) that had burned previously during the 1987 Silver Fire, which provided a

unique opportunity to compare fire effects in an area with a recent history of mixed-severity fire to one where fire has been removed for many decades. Prolonged periods of fire exclusion has elevated the hazard within many dry forests types and prompted calls for widespread landscape restoration (Stephens and Ruth, 2005; Spies et al., 2006). It is unclear whether this strategy is appropriate for mixed-severity regime forests, particularly those in the Biscuit Fire region, which are seasonally dry but have relatively high forest productivity and, thus, do not fit the idealized model for restoring fuel-limited forests (e.g. Covington, 2000). Nevertheless, several studies have shown that fire frequency has decreased from historical levels within the region (Agee, 1991; Taylor and Skinner, 1998, 2003), which has coincided with increased forest density and decreased spatial complexity (Skinner, 1995; Taylor and Skinner, 1998). An earlier study that examined fire effects exclusively within the reburn area showed that places where overstory crown damage was severe during the Silver Fire — and had regenerated to low shrubs and young trees — experienced severe crown damage during the Biscuit Fire (Thompson et al., 2007). In contrast, places with low levels of overstory crown damage during the Silver Fire were the least likely to experience overstory damage in the Biscuit Fire. Based on these findings, one might expect that the twice-burned landscape would have more abundant shrubs and regenerating trees, and thus, higher levels of overall Biscuit Fire crown damage than the area outside the Silver Fire. Alternatively, the Silver Fire may have decreased surface fuels and vertical continuity within the bulk of the landscape that burned as a surface fire in 1987, thereby resulting in lower levels of crown damage, which is consistent with the conventional wisdom that fire suppression has increased the fire hazard (Taylor and Skinner, 2003).

*Question 3: Did the pattern of crown damage differ between ultramafic and non-ultramafic soils?*

Vegetation patterns within the Biscuit Fire region are heavily influenced by largest exposure of ultramafic soils in North America (Kruckeberg, 1984). Approximately one-third of the fire burned over unproductive soils formed on peridotite and serpentinite parent materials. Sparse vegetation on these sites is commonly juxtaposed by dense stands of conifers and evergreen hardwoods on highly productive metamorphic and igneous parent materials (Whittaker, 1960). We are not aware of any studies that have quantified fire effects in serpentine forest vegetation. Conventional wisdom suggests that ultramafic sites do not readily carry fire owing to their low fuel loads (Whittaker, 1960; Taylor and Skinner, 2003). That notwithstanding, these areas tend to support more low shrub-stature vegetation and small trees, which may be more susceptible to fire damage.

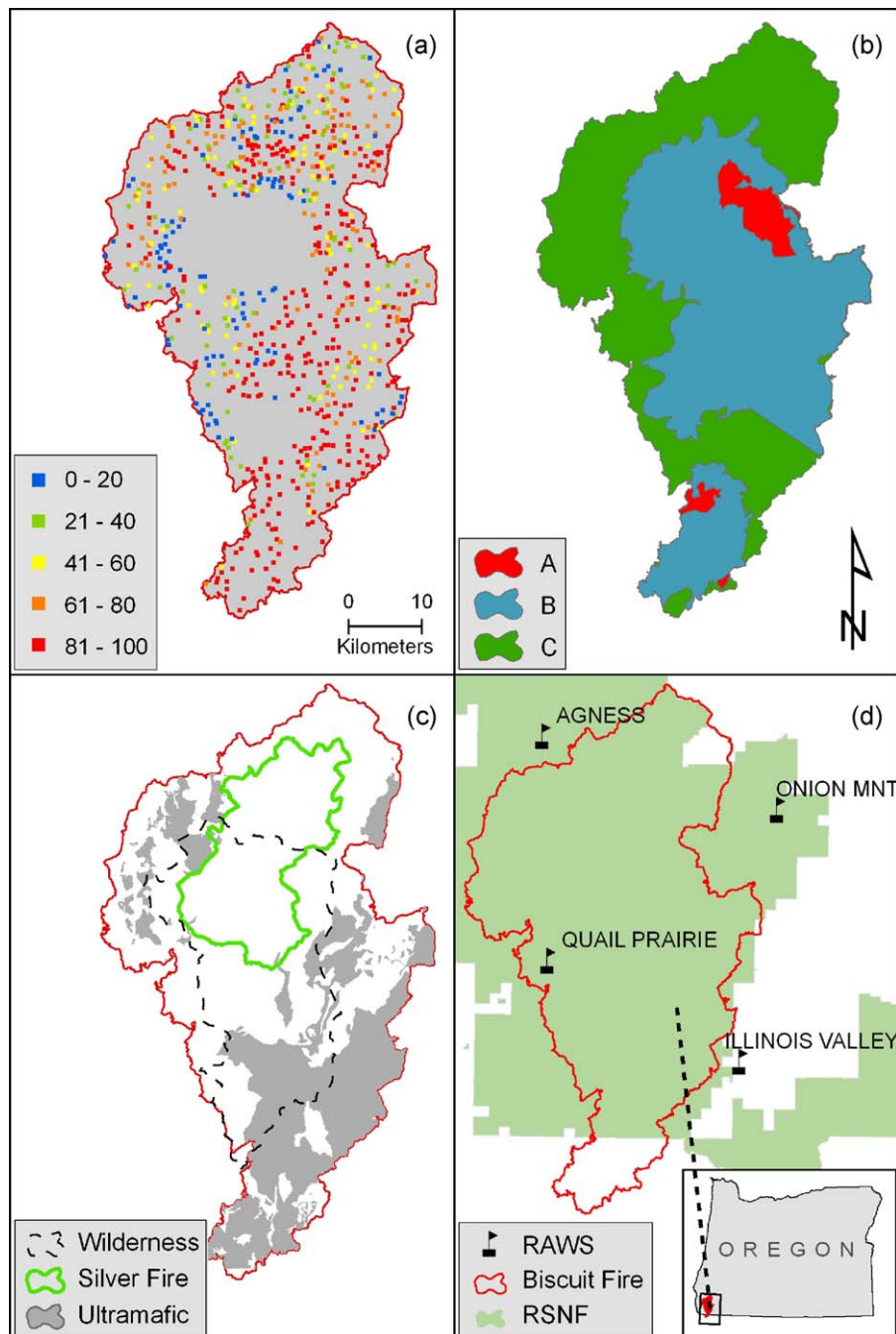
## 2. Methods

### 2.1. Study area

The study area was the region burned by the 2002 Biscuit Fire, centered at 123°91'W, 42°29'N (Fig. 1). The fire began as five separate lightning ignitions between July 13th and 15th, 2002, which combined to become the Biscuit Fire (GAO, 2004). On September 6th, the fire was contained at 202,168 ha. Ninety four percent of the fire was on land managed by the Rogue Siskiyou National Forest (RSNF) in southwestern Oregon, 5% was on the Six Rivers National Forest in northwestern California, and 1% was on Bureau of Land Management land (USDA-USDI, 2004). The area contains a range of management histories and designations, including the 73,000 ha Kalmiopsis Wilderness as well as roaded and logged areas. Even-aged conifer plantations make up ~5% of the Biscuit Fire region and those areas were excluded from this

analysis (USDA-USDI, 2004). Topography is steep and complex with no consistent directional trends. Elevation ranges from 50 to 1550 m. Sixty-eight percent of the burn area is underlain by igneous, meta-sedimentary, and metamorphic soil parent materials. Forests on these soils are dominated by conifer species such as Douglas-fir (*Pseudotsuga menziesii*), sugar pine (*Pinus lambertiana*), and white fir (*Abies concolor*). Dominant evergreen hardwoods include tanoak, Pacific madrone (*Arbutus menziesii*), and canyon live-oak (*Quercus chrysolepis*). Manzanita (*Arctostaphylos* sp.), and Sadler oak (*Q. sadleriana*) are common shrubs. The remaining 32% of the study area is underlain by ultramafic parent material with distinct flora dominated by conifer species such as Jeffery pine (*P. jeffreyi*), Douglas-fir, sugar pine, and incense-cedar (*Calocedrus*

*decurrens*). Common shrubs include huckleberry oak (*Q. vacciniifolia*), manzanita, and snowbrush (*Ceanothus velutinosus*). The climate is Mediterranean. Mean January temperature is 6 °C. Mean July temperature is 16 °C. Mean annual precipitation is 290 cm, with >90% occurring in winter (Daly et al., 2002). Fires were common throughout pre-Euro American history with a large portion of them burning with low to mixed-severity (Agee, 1991, 1993). Estimated historical return intervals lengthen along east to west and low to high elevational gradients and range between 5 and 100 years (Agee, 1991). Since 1945, fire has been largely excluded with the exception of the 1987 Silver Fire that encompassed >38,000 ha of forest on non-ultramafic soil (RSNF, 2004).



**Fig. 1.** Maps of the Biscuit Fire in southwestern Oregon and northwestern California, USA. (a) Distribution of 761 randomly placed aerial photo-plots color coded to show average percent crown damage within each plot. (b) Location of the three burn periods. (c) Location of ultramafic soils, the 1987 Silver Fire and the Kalmiopsis wilderness. (d) Locations of four remote automated weather stations (RAWS) and the Rogue Siskiyou National Forest (RSNF).



## 2.2. Digital aerial photo processing and interpretation

We interpreted pre- and post-fire vegetation and fire damage within 761 aerial photo-plots (6.25 ha) randomly distributed across the portion of the Biscuit Fire that had no record of forest management and had pre- and post-fire photo coverage (~80% of the fire). The best available pre-Biscuit photos (August 2000) were digital orthoquads (DOQs) taken as part of the USDA National Agriculture Imagery Program. They were panchromatic with a 1 m grain size, and dictated the resolution of vegetation data that we could reliably interpret. The post-Biscuit Fire photos were taken on September 24, 2002; they were scanned directly from diapositives at 20  $\mu$ m. Photo-plots were five-by-five polygon grids of 50 m cells (1 plot = 6.25 ha) constructed in a geographic information system (GIS) and overlain onto digital aerial photos and other GIS layers. Plots were distributed such that no portion of a road, management unit, or stream was included. Photos were spatially co-registered using approximately fifteen ground control points (GCP) to link the pre- to the post-fire photos. GCPs were concentrated in and around the plot. A first-order polynomial transformation was used to georectify the post-fire photos resulting in a 30 cm grain size.

To quantify fire damage we measured the percent of overstory vegetation scorched or consumed by fire. Crown damage is a one of the major determinants of tree damage and mortality, results in changes in forest structure, the light environment, and affects numerous other ecosystem components (Weatherspoon and Skinner, 1995). We measured crown damage from a planer view of the landscape, which is not strictly equivalent to the proportion of the crown volume damaged as measured in the field. Ideally, fire effects would be quantified through pre-fire field measurements of fuel conditions coupled to post-fire measures of fire-effects on above- and below-ground resources. However, the expense of field sampling and the inability to forecast wildfire locations limit the applicability of this approach. Consequently, for studies of whole fires, satellite-based measures are typically used—most frequently, the differenced normalized burn ratio (dNBR; Key and Benson, 2004; Finney et al., 2005; Wimberly and Reilly, 2007). While useful, this approach relies entirely on changes in spectral reflectance, and, thus, lumps multiple fire effects—crown damage, soil damage, ash color—into a single synthetic metric (Key and Benson, 2004; Kokaly et al., 2007). By interpreting vegetation condition in pre- and post-fire digital photos, we are able to attain some of the ecological resolution of ground plots but with the data collection facility of remote sensing. This allowed us to first calculate a measure of total crown damage across all cover types—which was roughly equivalent to dNBR—then calculate damage within shrub-stature vegetation, conifer and hardwood crowns independently. Making the distinction between cover types was important, particularly in this heterogeneous landscape, because damage in the shrub-stratum is clearly not ecologically equivalent to damage in tree crowns; moreover, crown damage in hardwoods, which will quickly sprout back, is not ecologically equivalent to damage in conifer crowns. (In a separate assessment, we compared total crown damage as measured in our aerial photo-plots to LANDSAT-derived dNBR and to a relativized version of dNBR designed for heterogeneous landscapes, RdNBR (Miller and Thode, 2007). Polynomial regressions described the relationships well:  $r$ -squared values were 0.93 and 0.92 for the dNBR and RdNBR, respectively (Thompson, 2008).

To conduct photo interpretation, we overlaid the photo-plot polygons onto the geo-referenced aerial photos in a GIS and interpreted vegetation conditions before and after the fire. We estimated the percent cover of conifer, hardwood, shrub-stature vegetation, and bare ground/grass in every cell in every plot at both points in time. We made no attempt to quantify specific fuel loads from aerial photos. Percent crown scorch or consumption was

estimated for every cell in the post-fire photo-plots. Areas of topographic shadow were subtracted from the effective area of the plot (<1% of the total area). Pre-fire conifer cover in each cell was assigned a size class: small, large, or mixed. Cover estimates summed to 100% in each cell. Cell-level cover estimates were averaged to obtain plot-level values. We used the standard deviation of pre-fire cover estimates for each cover type as a measure of compositional and structural complexity. Because it was impossible to reliably discern grass from bare ground in the pre-fire photos, and because bare ground does not burn, we included a constraint that forced the percent bare/grass to be equal in 2002 and 2000. To ensure consistency and reduce error, a single researcher (Thompson) conducted all photo interpretation. All photo interpretation was conducted by a single researcher (Thompson) to ensure consistency and reduce error. At the onset of the research, we developed a catalog of paired oblique-to-aerial photos for use as a training manual and later informally ground-truthed a subset of photo-plots, which revealed excellent correspondence between post-fire field conditions and photo measurements.

## 2.3. Topographic, edaphic, climatic, and weather data

Using a 10-m digital elevation model (DEM), we calculated average elevation, percent slope, Beers' transformed aspect (Beers et al., 1966), and topographic position (TP) for each photo-plot. We calculated an index of 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, while "TP-Coarse" uses an annulus 850–1000 m from the plot. We identified plots on ultramafic soil parent material using the USDA Soil Survey Geographic (SSURGO) Database (USDA, 2008). To capture regional gradients in productivity associated with moisture availability, we assigned the average local annual precipitation for the climatological period spanning 1971–2000 to each plot based on the PRISM model (Daly et al., 2002).

The RSNF provided a map showing the daily progression of the fire, which we used to assign weather data to each photo-plot based on the day it burned. This technique, though temporally and spatially coarse, has been successfully used in other reconstructions of fire effects (e.g. Collins et al., 2007). Average daily values for temperature, relative humidity, wind speed, and cosine transformed wind direction between 10:00 and 17:00 for each day of the burn were calculated from four remote automated weather stations (RAWS) that surround the burn (Fig. 1). The RAWS span large geographical and elevational gradients and, although data were moderately correlated between stations (Pearson correlation  $\approx$ 0.3–0.8) each provided some unique information. We assigned a weighted average of each weather variable to each plot, where the weights were based on the inverse of the squared Euclidian distance between each plot and each RAWS station. We also created a variable that divided the burn area into three "burn periods," which correspond 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 and includes the region that burned from July 13 to July 26 with comparatively little suppression effort and mild weather conditions (Table 1). Period B includes the region that burned from July 27 to August 4. Fifty percent of the Biscuit Fire burned in this 9-day period, which was characterized by comparatively low relative humidity and strong north-northeasterly winds, which dramatically increased spread rates. Suppression resources increased during this period but were largely unsuccessful in preventing fire spread (GAO, 2004). Period C represents the remaining 45% of the Biscuit Fire that burned from August 5 to September 06. Fire suppression activities were extensive throughout Period C. The fire continued

**Table 1**

Dates, area, and weather information for burn periods describing the spread of fire and the resources used for fire suppression.

Burn period	Start–stop	No. of days	Hectares (% total)	Temperature (°C)	Relative humidity (%)	Wind speed (km/h)	Wind direction	Suppression effort
A	7/13–7/26	14	8,995 (5)	26.2	36.1	11.8	0.03	Low
B	7/27–8/04	9	102,723 (50)	26.6	32.4	12.5	0.42	Moderate
C	8/05–9/06	30	91,480 (45)	28.4	25.4	10.9	0.52	High

Weather variables are averages of the daily average between 10:00 and 17:00 within the burn period. 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.

to spread during extreme weather and northeasterly winds but had a higher potential to be influenced by fire fighters.

#### 2.4. Data analysis

To summarize fire effects on vegetation, we plotted empirical cumulative distributions of total canopy damage, conifer damage, hardwood damage, and shrub-stratum damage. We compared median values and distributions of crown damage within each cover type between ultramafic and non-ultramafic plots and between plots that burned during the 1987 Silver Fire and edaphically similar areas (non-ultramafic) without any recent history of fire. We compared medians and distributions but did not report  $p$ -values because spatial autocorrelation prevented us from setting a meaningful level for  $\alpha$  (see below).

We took a two-stage approach to modeling relationships between three response variables (total crown damage, conifer damage, and hardwood damage) and 20 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 examine the nature of relationships between the response and important predictor variables. These non-parametric methods are ideally suited to the analysis of high dimensional ecological data with hierarchical and complex relationships among the predictor variables (i.e. collinearity) and between predictor and response variables (De'ath and Fabricius, 2000; Cutler et al., 2007). RFA is an ensemble learning algorithm that averages predictions over

multiple bootstrapped regression trees; it consistently out-performs other statistical methods, including RTA, for prediction accuracy and ranking predictor importance (Lawler et al., 2006; Prasad et al., 2006; Cutler et al., 2007). We used Liaw and Wiener's (2002) implementation of RFA within the R statistical language (R Development Core Team, 2006). The algorithm, as applied to these data, was as follows: (1) Select 1500 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 with regard to the

**Table 2**

Summary statistics for response and predictor variables used in the random forest and regression tree analysis of unmanaged stands within the Biscuit Fire.

	Median	Mean	Min	Max
Response variables				
All crown damage	73.9	64.8	0	100
Relative conifer damage	53.2	52.3	0	100
Relative hardwood damage	88.1	74.3	0	100
Predictor variables				
Large conifer cover	4.9	17.1	0	100
Small conifer cover	8.1	13.3	0	85.4
Mixed-size conifer cover	6.8	11.8	0	83.2
Hardwood cover	22.7	28.1	0	92.8
Shrub cover	14.6	23.4	0	92.8
Bare/grass cover	2.8	6.2	0	80.6
Shannon diversity	0.64	0.61	0	0.95
Elevation (m)	781	775	92	1476
Topographic position (fine)	1.7	1.45	−58.4	55.6
Topographic position (coarse)	3.8	2.7	−271.8	275.6
Slope (%)	49.8	49.9	9.5	92.3
Beer's aspect	0.02	0.02	−0.97	0.98
Average annual precipitation (cm)	279	284	160	424
Temperature (°C)	28.7	27.4	15.2	34.9
Relative humidity (%)	28.5	29.3	9.3	53.6
Wind speed (km/h)	11.6	11.7	5.1	19.1
Wind direction*	0.54	0.43	−0.58	0.91
Burn period		A = 8%, B = 44%, C = 48%		
Ultramafic		Ultramafic = 68%, non-ultramafic = 32%		
Inside silver fire		Inside silver = 23%, outside silver = 77%		

Plots with <5% pre-fire cover of a response variable were excluded from that analysis (see text).

\* Cosine transformed.

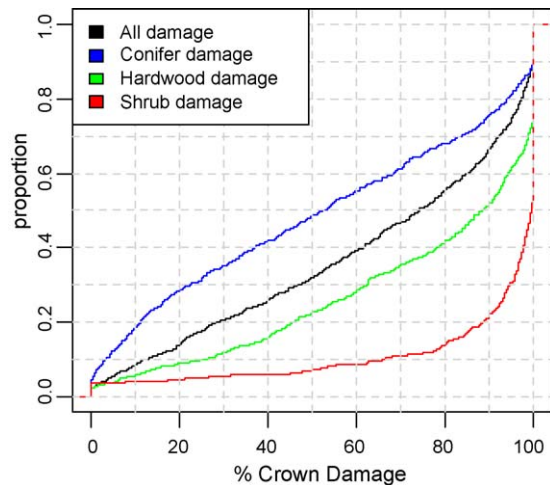


Fig. 2. Empirical cumulative distributions for crown damage in photo-plots (6.25 ha) within the 2002 Biscuit Fire.

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 data (De'ath and Fabricius, 2000). We used an implementation of RTA called conditional inference trees, which requires a statistically significant difference ( $p < 0.001$ ), as determined from a Monte Carlo randomization, in order to partition the data, which minimizes bias and prevents over-fitting and the need for pruning (Hothorn et al., 2006).

Measures of fire effects are positively spatially autocorrelated, which can bias statistical comparisons and increase the occurrence of Type-I errors (Legendre, 1993). Ideally, samples should be spaced beyond the range of autocorrelation. In the Biscuit Fire, however, significant spatial autocorrelation in crown damage existed beyond 4500 m, making it impossible to collect a sufficient sample at an adequate spacing. Given this constraint, we took several steps to examine the level of autocorrelation and limit exposure to its consequences. We selected RTA and RFT, in part,

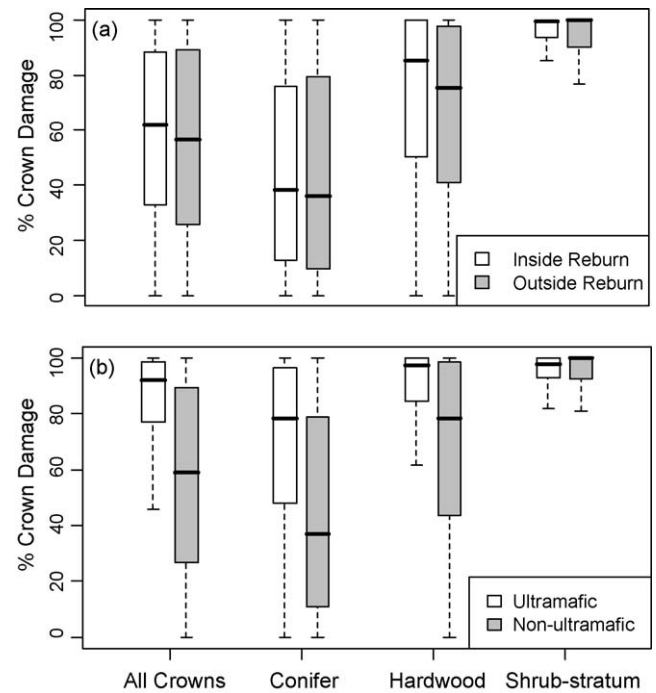


Fig. 3. Distributions of total, shrub, hardwood, and conifer damage (a) inside and outside Silver Fire reburn area and (b) on and off ultramafic soils.

because residuals from these models often have low levels of autocorrelation when the predictors are themselves spatially structured (McDonald and Urban, 2006). In addition, to guard against Type-I errors within the RTA, which required a criterion for partitioning, we set  $\alpha$  conservatively to 0.001. We assessed autocorrelation in model residuals using semivariograms.

### 3. Results

#### 3.1. Overall patterns of crown damage

Ninety-seven percent of plots experienced >1% crown damage (Fig. 2). Ten percent of plots experienced 100% crown damage. The median level of overall crown damage within a plot was 74% (Fig. 2). Median crown damage was highest in shrub-stratum cover

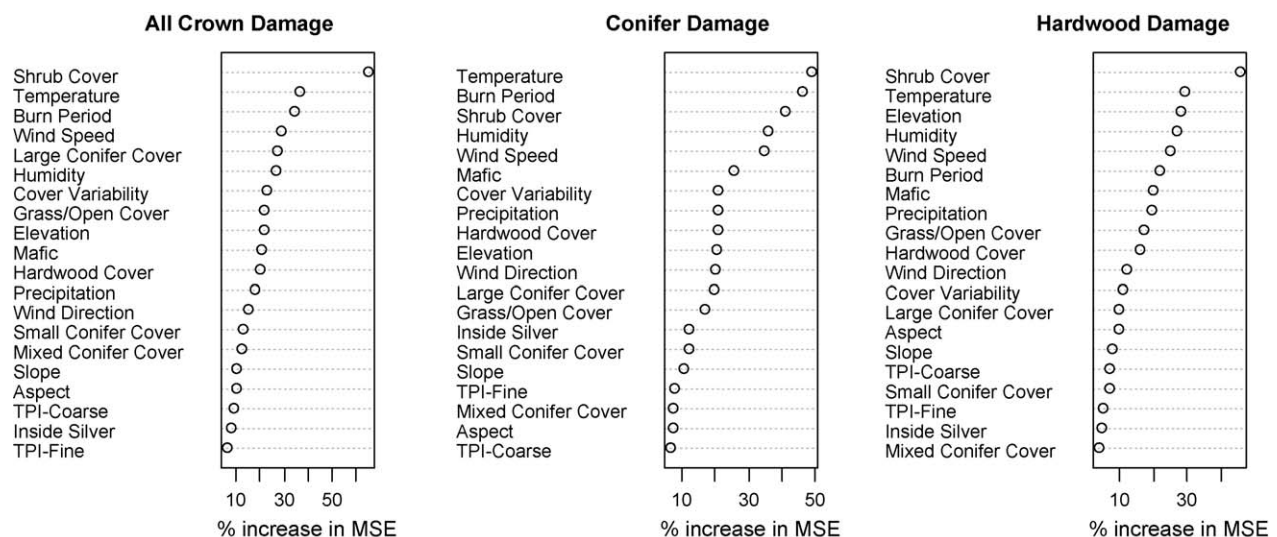
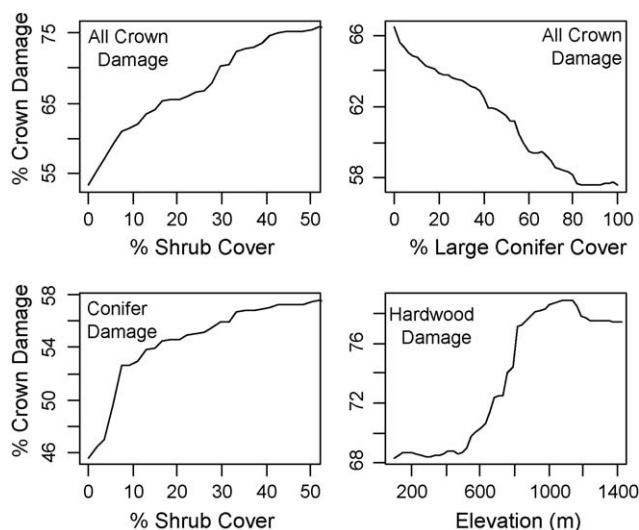


Fig. 4. Variable importance plots for predictor variables from random forests models for: total crown damage, conifer damage, and hardwood damage. Predictor variables are along the y-axis and the average increase in the mean square error when data for that variable is permuted while all others are left unchanged is on the x-axis.



**Fig. 5.** Partial dependence plots from random forest predictions of total crown damage on percent shrub cover; total damage on large conifer cover; conifer damage on percent shrub-stratum cover, and hardwood damage on elevation. Partial dependence is the predicted value of the response based on the value of one predictor variable after averaging out the effects of the other predictor variables in the model.

(96%) intermediate in hardwood cover (88%), and lowest in conifer cover (53%; Fig. 2). Seventy-five percent of plots retained more than 10% of their live pre-fire conifer cover; 52% of plots retained more than 10% of their pre-fire hardwood cover (Fig. 2). Median damage in large conifer cover (32%) was lower than in mixed-size conifer cover (53%), which was lower than in small conifer cover (62%).

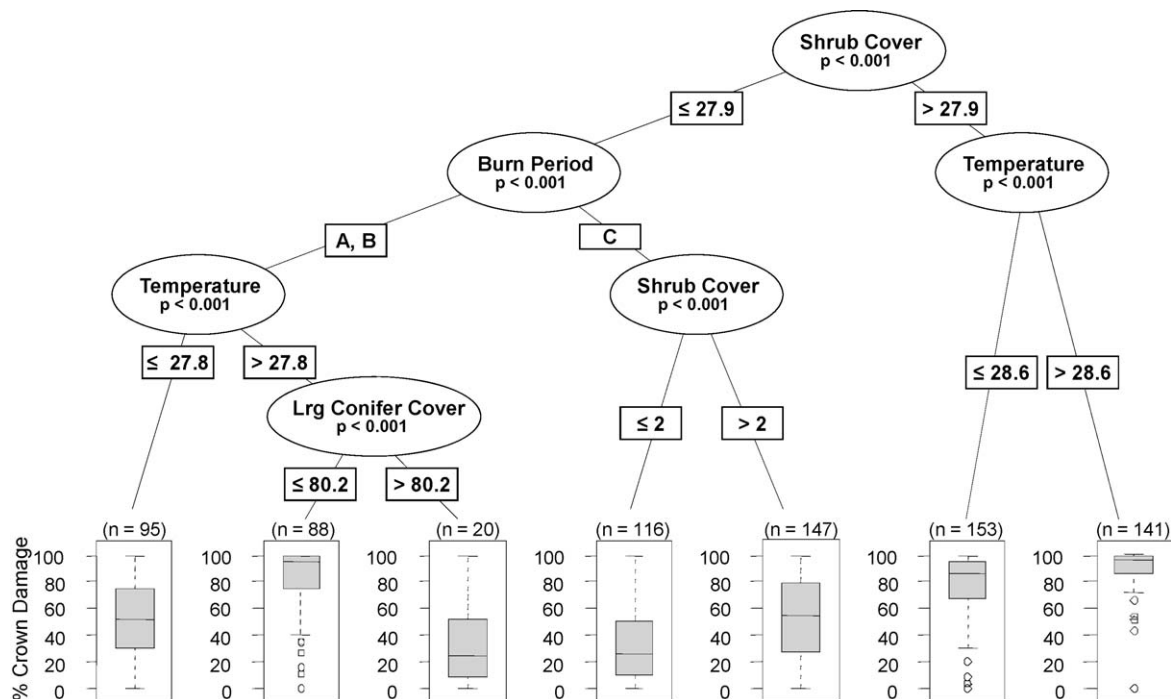
Plots that had burned previously, during in 1987 Silver Fire, had higher median pre-fire shrub-stratum cover (11% vs. 4%) and large conifer cover (32% vs. 10%), but lower pre-fire median hardwood

cover (8% vs. 40%), small conifer cover (0.4% vs. 7%) and mixed-size conifer cover (0% vs. 10%), than did edaphically similar areas (non-ultramafic) outside the Silver Fire (Appendix A). Median total crown damage was similar inside and outside the Silver Fire (62% and 57%, respectively; Fig. 3). Median relative damage to the individual cover types was also similar (Fig. 3).

Ultramafic plots had higher median pre-fire shrub-stratum (46% vs. 6%), small conifer (13% vs. 5%), and bare/grass cover (6% vs. 1%), but lower hardwood (17% vs. 30%), mixed-size conifer (4% vs. 8%) and large conifer cover (0% vs. 12%) than did non-ultramafic plots (Appendix A). Ultramafic plots experienced higher total crown damage (92% vs. 59%; Fig. 3). Ultramafic areas had similarly high median damage to the shrub-stratum (95% vs. 97%), but higher median damage to hardwood (95% vs. 76%), and conifer cover (78% vs. 37%; Fig. 3).

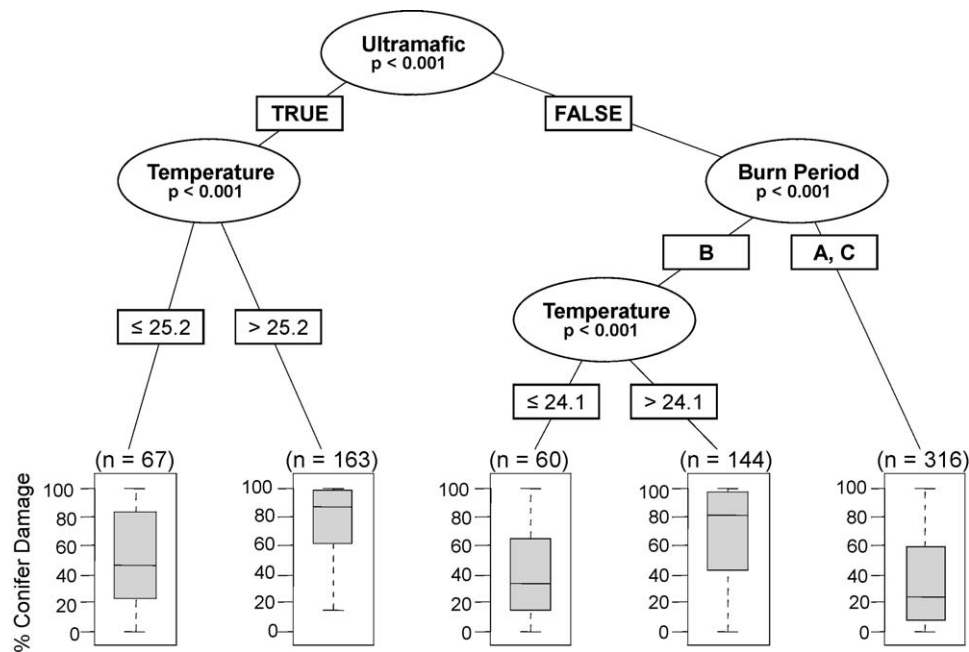
### 3.2. Total crown damage models

RFA explained 45% of variation in total crown damage. Shrub-stratum cover was, by far, the most important predictor variable (Fig. 4); increasing shrub-stratum cover was associated with increasing crown damage (Fig. 5). Average temperature and burn period were similarly important and were ranked second and third, respectively. Large conifer cover was ranked fourth and was associated with decreasing total damage. The RTA of total crown damage produced 7 terminal nodes (Fig. 6). The first partition was based on whether shrub-stratum cover was  $>28\%$ ; when that criterion was met median crown damage was  $>85\%$ . Lower levels of total damage were generally associated with lower levels of shrub-stratum cover (i.e. closed canopy forest), particularly during period C when shrub-stratum cover was below 2%. Low levels of total crown damage were also associated with large conifer cover above 80% during periods A and B. Semivariograms indicated high levels of spatial autocorrelation in the crown damage data to lag distances greater than 4500 m, but that model residuals had low



**Fig. 6.** Regression tree for total crown damage using the six most important predictor variables as determined by the random forest analysis (see Fig. 4). Descriptions of Burn Periods A, B, and C are given in Table 1.  $p$ -Values at each node are from a Monte Carlo randomization test. In order for a split to occur the  $p$ -value must be  $<0.005$ . Box plots at terminal nodes show the distribution of the data within that branch of the tree. Boxes represent inner-quartile range; horizontal lines within the boxes represent median values; whiskers extend to the most extreme data point that is no more than 1.5 times the inner-quartile range. Dots above and below whiskers represent more extreme data points.





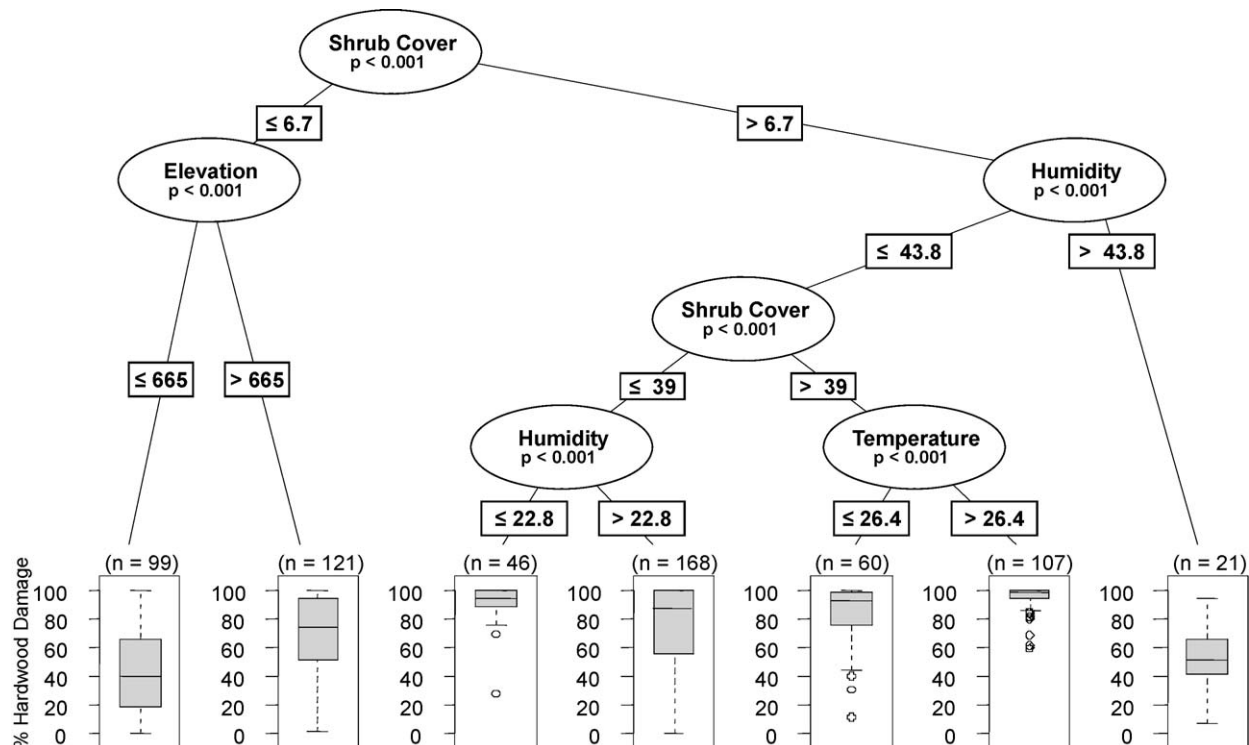
**Fig. 7.** Regression tree for conifer crown damage using the six most important predictor variables as determined by the random forest analysis (see Fig. 4). Plot layout follows Fig. 6.

levels of autocorrelation across all response variables (Appendix B).

### 3.3. Conifer damage models

RFA explained 38% of variation in relative conifer damage. Average daily temperature, burn period and shrub-stratum cover were ranked as the first, second and third most important predictors but permuting the values of any resulted in similar

increases in the MSE (Fig. 4). Increasing shrub-stratum cover, particularly between 0% and 10%, was associated with a sharp increase in damage to the available conifer cover (Fig. 5). The RTA of conifer damage produced 5 terminal nodes (Fig. 7); the first split partitioned the data based on the presence or absence of ultramafic soils. The lowest levels of conifer damage occurred on non-ultramafic soils during periods A and C. The highest levels of conifer damage occurred on ultramafic soils when the average temperature was  $>25^{\circ}\text{C}$ .



**Fig. 8.** Regression tree for hardwood crown damage using the six most important predictor variables as determined by the random forest analysis (see Fig. 4). Plot layout follows Fig. 6.



### 3.4. Hardwood damage models

RFA explained 37% of the variation in relative hardwood damage. Shrub-stratum cover was, by far, the most important predictor, followed by temperature, elevation, and relative humidity (Fig. 4). Increasing elevation was associated with increasing damage to the available hardwood cover (Fig. 5). The RTA of hardwood damage produced 7 terminal nodes (Fig. 8); the first split partitioned the data based on whether shrub-stratum cover was >7%. High levels of hardwood damage were associated with low humidity and high shrub-stratum cover. The lowest hardwood damage occurred at elevations below 666 m when shrub-stratum was >7%.

## 4. Discussion and conclusion

### 4.1. Overall pattern of Biscuit Fire damage

Large, post-fire fire burn mosaics typically include a substantial component of unburned patches (Agee, 1993; Turner and Romme, 1994). For instance, unburned patches made up over 25% of the area within the 1988 Yellowstone Fires (Turner et al., 1994) and over 15% of the 2002 Hayman Fire (Graham, 2003). In this respect, the Biscuit Fire was unique; we observed evidence of burn damage – at least within the shrub-stratum – on some portion of nearly every plot (97%). This finding is supported by an examination of 180 inventory field plots within the Biscuit Fire perimeter where 178 had evidence of a surface fire (Campbell et al., 2007) and by an analysis of riparian areas after the Biscuit Fire where 90% had evidence of fire (Halofsky and Hibbs, 2008). However, while fire damage was nearly universal on the surface, it was quite variable within the tree canopy. Indeed, just 10% of plots experienced total crown damage and almost half of the conifer cover was undamaged. We discuss the pattern of crown damage using our three research questions as a guide.

### 4.2. What was the relative importance of weather, topography, and vegetation cover for predicting patterns of crown damage?

Overall, topographic variables were less important predictors of crown damage than were weather or vegetation cover. While many analyses of mixed-severity fire effects have reported greater levels of damage on southwesterly aspects (e.g. Weatherspoon and Skinner, 1995; Alexander et al., 2006), aspect was not an important predictor of crown damage in the Biscuit Fire. It is possible that countervailing effects of dry winds out of the northeast, greater solar radiation in the southwest, and a maritime climate influence on west facing slopes confounded any relationship between aspect and crown damage. Similarly, elevation and TP were not important predictors of total crown damage or conifer damage. However, higher elevations were associated with greater hardwood damage. Hardwood trees tend to be smaller at higher elevations within the region and may have been more vulnerable to damage.

Weather variables were among the most important predictors for all three response variables. Higher temperatures and lower humidity correspond with lower fine fuel moisture and less energy required for pre-heating (Pyne et al., 1996). Therefore, it was not surprising, even given our coarse measures of regional daily weather, that higher temperatures and lower relative humidity were consistently associated with greater levels of damage. Burn period was also among the top predictors for all response variables, and, by all measures, crown damage was most severe during the 9 days that constituted period B, when wind speeds were highest and predominantly out of the northeast. This finding is consistent with accounts of widespread torching, crowning, running, and spotting during this period reported by Forest Service personnel

(USDA, 2002). It is impossible to confidently attribute differences in fire effects between burn periods to changing weather or to increasing fire suppression efforts. The 2002 fire season was the nation's second largest on record (NIFC, 2008) and in mid July (period A), inter-agency fire fighting resources were spread throughout the country and unable to converge on the Biscuit Fire (GAO, 2004). By August 5 (the start of period C), however, the Biscuit Fire had become the region's highest priority fire and extensive resources were dedicated to its suppression (\$153 million was spent on suppression) (GAO, 2004). Throughout the duration of the fire, but mostly during Period C, fire fighters frequently ignited fires, called "burn-outs," to reduce available fuels between a control point or fire-line and the fire itself (USDA, 2002). There are no official records describing their location or severity, but they are believed to be widespread. It is impossible to know how many plots were within burn-outs, though, undoubtedly, many were. Like local weather and specific fuel conditions, the influence of fire suppression was a source of unexplained variance within the models.

Despite the importance of weather for predicting patterns of Biscuit Fire damage, and the propensity for extreme weather to override other aspects of the fire environment (Bessie and Johnson, 1995; Agee, 1997), vegetation conditions were also among the important predictors of damage. Not surprisingly, shrub-stratum cover experienced the highest levels of damage within the Biscuit Fire. Median damage to shrub-stratum cover was 96% and, accordingly, increasing pre-fire cover of shrub-stratum vegetation corresponded to increased total crown damage. Within the tree stratum, hardwoods experienced greater crown damage than conifers. However, it is likely that actual fire-related mortality was lower in hardwood trees compared to conifers. This is because most hardwoods in this region are aggressive basal sprouters that quickly reoccupy sites after disturbance (Hobbs et al., 1992). Lacking the ability to sprout, most conifers in the region have evolved a "resister strategy" for dealing with fire (with the notable exception of serotinous knobcone pine (*P. attenuata*) (Agee, 1993). Furthermore, the ability of conifers to resist fire damage increases with age, as the height to the base of the crown rises and the insulating capacity of the bark increases. This is consistent with the fact that, within the Biscuit Fire, median crown damage within large conifer cover was 32%, compared to 62% within small conifer cover. Damage to both hardwood and conifer increased with the amount of shrub cover within the plot. A similarly strong relationship between shrub consumption and tree mortality has also been documented within the conifer forests and shrublands of the Californian floristic province within Baja Mexico (Stephens et al., 2008). We found little evidence that the presence of hardwood cover or small conifer cover in the plot had an impact on damage to other cover types. The RFA of conifer damage ranked hardwood cover 9th and small conifer cover 14th for relative importance out of 20 predictor variables (Fig. 4). In addition, mixed-sized conifer cover experienced levels of damage that were intermediate between small and large (median = 52%), which suggests that multi-storied conifer stands did not increase the level of damage by increasing vertical fuel continuity. Instead, it seems likely that the small tree component of the mixed-sized stands was damaged, while the large tree component was not.

### 4.3. Did the pattern of crown damage differ between areas with and without a recent history of fire?

When approaching this question, plausible arguments could be made in support of higher, lower, or no difference in crown damage between the once and twice burned portion of the Biscuit Fire burn mosaic. We found that Biscuit Fire crown damage within the twice-burned (within the past 15 years) landscape was similar to

edaphically comparable (i.e. non-ultramafic) areas without a recent history of fire. In fact, RFA ranked the variable for “Inside Silver Fire” among lowest predictors for all response variables considered (Fig. 4). The similarity in total damage between the once and twice-burned landscapes was partially the result of different pre-fire cover types canceling each other out. The 1987 Silver Fire burned later in the season during comparatively mild weather conditions and resulted in lower levels, and more variable patterns, of crown damage at the plot-scale than did the Biscuit Fire (Thompson, 2008). This produced a complex legacy of vegetation conditions at the time of the Biscuit Fire. As expected, the level of pre-Biscuit fire shrub-stratum cover was higher in the landscape with a history of recent fire, but, because the Silver Fire was not particularly severe and because tree crowns filled in some of the damaged overstory during the intervening years, the difference in pre-Biscuit shrub-stratum cover was not too great (median = 11% vs. 3%). If this were the only difference, the twice-burned landscape may have had greater total crown damage than the once-burned landscape. However, presumably as a result of damage during the Silver Fire, the landscape with a history of recent fire had lower pre-fire overstory hardwood cover. The effect of greater hardwood cover — which was more vulnerable to damage — outside the Silver Fire effectively increased levels of total damage such that difference between median total crown damage was <5%. Interestingly, the landscape without a history of recent fire also had higher levels of pre-fire small and mixed-size conifer cover, while the Silver Fire area had considerably more pre-fire large conifer cover. The fact that the legacy of the Silver Fire did not have a landscape-scale effect on the Biscuit Fire suggests that using fire intervals to assess fire hazard in this region may be overly simplistic (e.g. Fire Regime Condition Class). Moreover, it may be that 15 years between fires is a sufficient time for surface fuels to accumulate such that the subsequent fire is unaffected by any fuels reduction that resulted from the previous fire.

Based on these findings and those of Thompson et al. (2007) and Thompson (2008), we conclude that, at a plot-scale, increasing Silver Fire damage led to increasing shrub-stratum cover by 2002, which, in turn, led to high levels of crown damage on those sites. But, total crown damage during the Silver Fire was comparatively low, and tree-stratum damage during the Biscuit Fire was largely independent of the Silver severity mosaic. Therefore, the legacy of the Silver Fire had little effect on the overall landscape pattern of Biscuit Fire damage.

#### 4.4. Did the pattern of crown damage differ between ultramafic and non-ultramafic soils?

Due to their sparse and patchy fuel environment, conventional wisdom suggests that ultramafic sites do not typically experience high severity fire (Whittaker, 1960; Kruckeberg, 1984). The Biscuit Fire was an exception. Ultramafic areas had higher total crown damage and higher levels of damage to conifer and hardwood cover on these sites. Several characteristics of ultramafic sites may help explain this pattern: First, “ultramafic” as a plot descriptor ranked 10th out of 20 variables for predictive importance of total crown damage (Fig. 4), while shrub-stratum cover, which was more than eight times higher on ultramafic sites, ranked first. Higher shrub-stratum cover in ultramafic plots may largely account for the difference in total crown damage. The ultramafic plots also had higher damage in the tree-stratum. The RFA variable importance rankings show that average temperature and burn period were the most important predictors of conifer damage, while the indicator for ultramafic sites ranked sixth. And, indeed, ultramafic areas happened to burn disproportionately during more extreme fire weather and during period B, when damage was highest. Additionally, higher damage to the tree-

stratum on ultramafic soils may be due to the relatively small, open-grown, low canopy, conifer trees that occupied these sites and are more vulnerable to damage from a surface fire (Van Wagner, 1973). Open conditions may have also resulted in hotter and drier microclimatic conditions on the surface, which can increase surface fire intensity, spread rates, and crown scorch (Van Wagner, 1977). Finally, higher wind velocity at the surface may have lowered fuel moisture and increased fire intensity and spread rates.

#### 4.5. Ecological and management implications

Managers on the RSNF will be dealing with the legacy of the Biscuit Fire for years to come. Biomass accumulation, mainly in the form of sprouting hardwoods and shrubs, is rapid in the wake of fires in this region (Shatford et al., 2007). High levels of competition in this early seral environment can result in protracted rates of succession to a tree-stratum (Hobbs et al., 1992; Shatford et al., 2007). In the interim, early seral, shrub-stratum vegetation is vulnerable to repeated high severity fire (Thompson et al., 2007). In the decades following the Biscuit Fire, the hazard presented by large areas of low, regenerating shrubs and trees with low crown base heights, small stem diameters and thin bark, and associated surface fuels (which we unable to measure) will be a persistent management concern. Forest managers have few options for reducing fire risk associated with this vegetation condition. Evidence from within the Silver Fire suggests that traditional silviculture methods (i.e. salvage logging and planting) do not reduce the hazard associated with early seral vegetation in these forest types—at least in the short term (Thompson et al., 2007). It is possible that tree planting may accelerate the transition from shrub patches to taller more fire resistant forests. Strategically placed fuel treatments might slow the spread of future fires enabling protection of key structures and habitat conditions (e.g. spotted owl habitat areas) within the landscape (Ager et al., 2007), and strategically placed fuel management zones can provide defensible spaces from which to manage future fires.

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#### Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2009.07.031.

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