Forest Ecology and Management xxx (2011) xxx–xxx

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Canopy damage to conifer plantations within a large mixed-severity wildfire varies with stand age

Jonathan R. Thompson [a,*], Thomas A. Spies [b,1], Keith A. Olsen [c,2]

[a] Smithsonian Institution, Smithsonian Conservation Biology Institute, 1500 Remount Road, Front Royal, VA 22630, USA
[b] USDA Forest Service, Pacific Northwest Research Station, Corvallis, OR 97331, USA
[c] Dept. of Forest Science, Oregon State University, Corvallis, OR 97331, USA

ARTICLE INFO

Article history:
Received 4 December 2010
Received in revised form 3 March 2011
Accepted 1 April 2011
Available online xxxx

Keywords:
Biscuit Fire
Burn severity
Land use legacy
Klamath Mountains
Random Forest analysis
Geostatistical regression

ABSTRACT

The 2002 Biscuit Fire burned at mixed-severities encompassing over 200,000 ha of publicly owned forest-land, including more than 8300 ha of conifer plantations. We used pre- and post-fire digital aerial photography to examine how the level of canopy damage varied within these plantations in relation to topography, weather, vegetation-cover, and management history, with an emphasis on the age of the plantation. We examined 198 plantations that varied widely in age (5–47 years), size (1.25–47 ha), and landscape context. The average level of canopy damage within the plantations was 77%. Based on Random Forest variable importance values, plantation age was the best predictor of canopy damage. Average annual precipitation, elevation and topographic position were ranked second, third, and fourth, respectively. A model selection procedure, using geo-statistical regression models and Akaike's information criterion, corroborated the importance of plantation age relative to the other predictors tested and also suggested that the influence of age varied over time. The top ranked regression model indicated that the level of canopy damage reached its maximum around age 15 and stayed relatively high until age 25 before declining.

Published by Elsevier B.V.

1. Introduction

The legacy of past forest management can influence the mosaic of burn damage left in the aftermath of a large wildfire. Several studies have documented the persistent influence of partial harvests and fuel treatments on wildfire effects, (e.g. Finney et al., 2005; Pollet and Omi, 2002; Prichard et al., 2010; Raymond and Peterson, 2005). Equally important, though somewhat less represented in the literature, are studies that quantify the influence of even-aged silvicultural treatments on wildfire effects. Even-age plantations are a common feature of forested landscapes worldwide and there are more than 17 million hectares of conifer plantations in the US alone (FAO, 2005). The available evidence suggests that plantations experience higher levels of canopy damage than surrounding unmanaged forests (Odion et al., 2004; Thompson et al., 2007; Weatherspoon and Skinner, 1995). This is likely attributable to higher stem densities and continuous canopies, which are characteristic features of plantations and can increase vulnerability to crown fire (Kobziar et al., 2009; Stephens and Moghaddas, 2005; Graham et al., 2004). However, as trees within plantations mature, self-pruning results in higher crown base heights, self-thinning can reduce tree density, and the thickness of tree bark can increase, all of which may decrease the risk of fire damage in some forest types (Agee, 1993; Hanus et al., 2000). This pattern suggests that the increased risk of canopy damage within plantations could be reduced with the passage of time, but an extensive search of the literature produced no empirical data regarding how fire damage varies with plantation age or structure.

The 2002 Biscuit Fire burned at mixed-severities across >200,000 ha of mixed conifer and evergreen hardwood forests in southwest Oregon and northwest California. The fuel complex encountered by the Biscuit Fire was strongly affected by a legacy of forest management, including silviculture treatments of various ages, sizes, and techniques. This included >8300 ha of even-aged conifer plantations, which were established following clearcut harvesting and planted primarily with Douglas-fir (*Pseudotsuga menziesii*) and to a much lesser degree ponderosa pine (*Pinus ponderosa*) and sugar pine (*Pinus lambertiana*). The region has a long history of using even-aged silvicultural practices to achieve timber production goals, which were a dominant management objective from the 1950s until the early 1990s, when federal logging was curtailed with the adoption of the Northwest Forest Plan (Walstad, 1992). Accordingly, most plantations encountered by the Biscuit Fire

* Corresponding author. Tel.: +1 540 635 6580; fax: +1 540 635 6506.
E-mail addresses: thompsonjr@si.edu (J.R. Thompson), tspies@fs.fed.us (T.A. Spies), keith.olsen@oregonstate.edu (K.A. Olsen).
[1] Tel.: +1 541 750 7354; fax: +1 541 750 7329.
[2] Tel.: +1 541 750 7279; fax: +1 541 750 7329.

0378-1127/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.foreco.2011.04.001

range in age from approximately 10 to 50 years old. We are aware of no previous empirical studies to explicitly consider the relationship between plantation age and wildfire damage, however, Graham (2003) did note that plantations younger than 12 years experienced higher levels of burn severity (as determined from Landsat-derived burn mapping) than did older plantations during the 2002 Hayman Fire in Colorado. Similarly, Thompson et al. (2007) found high levels of canopy damage within 12- to 15-year-old management units that were salvage-logged and planted after the 1987 Silver Fire then burned again in the Biscuit Fire. Fire modeling also suggests that plantations are more vulnerable than unmanaged stands from the time they are young saplings (<5 years) at least until they reach >50 cm diameter at breast height (Stephens and Moghaddas, 2005).

Our overall objective was to develop a better understanding the factors that were associated with burn damage within the intensively managed portion of the Biscuit Fire. We used pre- and post-fire digital aerial photography to examine how the level of Biscuit Fire canopy damage varied within 198 plantations in relation to their age, topographical setting, the weather conditions on the day of burn, climate (productivity) and vegetation-cover. Ideally, fire effects should be quantified through pre-fire field measurements of fuel conditions coupled to post-fire measures of fire-effects on above- and below-ground resources. Unfortunately, the expense of field sampling and the inability to forecast wildfire locations and measure them in advance of wildfire occurrence limits the use of this approach. Instead, we interpreted vegetation conditions within pre- and post-fire digital aerial photos. By interpreting vegetation condition using digital aerial photography, we are able to attain some of the ecological resolution of ground plots but with the data collection facility of remote sensing.

Based on our previous work quantifying fire damage within the unmanaged portion of the Biscuit Fire, which showed the highest levels of canopy damage in very young and shrubby vegetation (Thompson and Spies, 2009), we hypothesized that plantation age would be negatively correlated with the level of canopy damage but that the effect of plantation age would decrease over time. Further, we hypothesized that daily fire weather conditions would also be an important predictor of canopy damage, with extreme fire weather conditions overriding all other structural or other environmental variables.

2. Methods

2.1. Study area

The study was conducted within the perimeter of the 2002 Biscuit Fire, which encompassed approximately 200,000 ha of the Klamath Mountains in southwest Oregon and northwest California. The area is primarily managed by the Rogue–Siskiyou National Forest (RSNF) and is within the mixed evergreen vegetation zone (Franklin and Dyrness, 1988). While the Biscuit region does include areas of low-productivity, ultramafic soils, those regions were excluded from this study. The plantations we examined are underlain by igneous, meta-sedimentary, and metamorphic soil parent materials. Unmanaged forests on these soils are dominated by conifer species such as Douglas-fir, sugar pine, and white fir (*Abies concolor*). Dominant evergreen hardwoods include tanoak (*Lithocarpus densiflora*), Pacific madrone (*Arbutus menziesii*), and canyon live-oak (*Quercus chrysolepis*). Manzanita (*Arctostaphylos* sp.), and Sadler oak (*Quercus sadleriana*) are common shrubs. Topography within the Biscuit Fire is steep and complex; elevations range from 100 to 1500 m. Mean January temperature is 6 °C. Mean July temperature is 16 °C. Mean annual precipitation is 270 cm, with greater than 90% occurring as a mixture of snow and rain during winter and spring (Daly et al., 2002). A detailed account of the Biscuit Fire's effect on vegetation cover within unmanaged areas can be found in Thompson and Spies (2009).

2.2. Management data

Our analysis focused on 200 even-aged plantations randomly selected from a RSNF spatial database that described the location of all significant historical logging and planting, which included a total of 652 conifer plantations (8300 ha) within the fire's perimeter. To be eligible for inclusion in this study, each unit must have been clearcut between 1960 and 1996 and have a record of successful conifer planting. Of the 200 selected units, 35 were salvage-harvests completed between 1988 and 1991 following the 1987 Silver Fire (to determine if the salvage units had a unique influence on canopy damage we analyzed our data with and without these plantations.). Two units were later removed because their positions were inaccurate within the spatial database. Records were incomplete regarding species composition and volume removed, site preparation, and planting density. However, discussions with RSNF employees indicated that some live trees were left after harvests and that planting was overwhelmingly Douglas-fir with a much lesser component of ponderosa and sugar-pine. Multiple planting dates, all clustered within 1–3 years of harvest, were often associated with individual management units. We therefore used the date of harvest as a surrogate for the plantation's establishment date, unless there was evidence that original planting had failed and the site had been reforested at a later date. Harvest date information was considered reliable by RSNF personnel (pers. comm. J. Hawkins, Gold Beach Ranger District, RSNF).

2.3. Aerial photo plots

Photo-plots were a grid of 50-by-50 meter cells overlain onto the variably-shaped harvest unit polygons supplied by the RSNF. On large harvest units (>6.25 ha), we randomly selected 25 cells to use as the plot. For management units <6.25 ha but >1.25 ha, we used all cells as the photo-plot. Management units <1.25 ha were excluded from this study. The best available pre-Biscuit Fire photos were digital orthoquads taken as part of the USDA National Agriculture Imagery Program in August 2000; they were panchromatic with a 1 m grain size. The post-Biscuit Fire photos were taken on September 24, 2002, were true color, and had a 25 cm grain size. We spatially co-registered the pre- to post-fire photo plots using approximately 15 ground control points per plot and used a first-order polynomial transformation for geo-rectification. Starting with the pre-fire photos, a single researcher (Thompson) estimated the percent cover of live vegetation and bare ground/grass cover (which were indistinguishable) in each cell in every plot. Then, using the post-fire photos, the same researcher measured the percent of the vegetation cover that was scorched or consumed (i.e. canopy damage) by the Biscuit Fire. Cell-level estimates were then averaged to obtain plot-level values. Our original intent was to separate canopy consumption from canopy scorch to infer differences in fire behavior (i.e. surface fire versus torching). Unfortunately, however, the vertical and horizontal continuum between scotch and consumption we witnessed in the photos and in field assessments revealed that any attempts to make inferences in this regard would be unreliable. Therefore, we treated scorch and consumption collectively as "canopy damage."

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. Indeed, the 25 cm resolution of the post-fire photography permitted a unambiguous interpretation of the fire's effects on tree canopies. Nonetheless, it is important to note that canopy damage measured from a planer view of the landscape (i.e. from an aerial photo) is not strictly equivalent to the proportion of the crown volume damaged as measured in the field.

2.4. Topographic and weather variables

We used a 10-m digital elevation model to calculate the average elevation, percent slope, Beers' transformed aspect (Beers et al., 1966), and topographic position for each photo-plot. To capture local and broad scale variation in topography, we calculated topographic position at two 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. The topographic index values are in units of meters, but their usefulness is chiefly in a relative sense (*c.f.* Jones et al., 2000). For example, within the TP-Fine index, a value of, say 30 m, reflects the fact that most of the area immediately around the focal site (within 150–300 m) is at a higher elevation. The RSNF provided a map that depicted 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 within the fire perimeter. To capture regional gradients in productivity associated with moisture availability, we assigned each photo plot the average local annual precipitation for the climatological period spanning 1971–2000 to each plot based on the PRISM model (Daly et al., 2002).

2.5. Data analysis

To rank the predictor variables in terms of the strength of their relationship to the response, we calculated variable importance values using the Random Forest (RF) algorithm (Liaw and Wiener, 2002) within the R statistical environment (R Development Core Team, 2006). While RF is relatively new to forestry and ecological research, its use is growing and, in simulation and comparative analyses, it has consistently out-performed other methods for prediction accuracy and ranking variable importance (Cutler et al., 2007; Lawler et al., 2006; Prasad et al., 2006). The RF algorithm (as applied to these data) selects 1500 bootstrap samples, each containing two-thirds of the photo plots. For each sample, it creates an un-pruned regression tree with modification that, at each node, it randomly selects only one-third of the predictor variables and chooses the best partition from among those variables. To assess the predictive power of the model, RF calculates an ensemble average of all the regression trees, which is used to predict the level of canopy damage for the plots not included in the bootstrap sample. The RF model is then used to calculate importance values for each of the predictor variables by calculating the percent increase in the mean squared error (MSE) in the predicted data when the values for that predictor are permuted and the others are left intact.

To further assess potential relationship between canopy damage and the predictor variables (including potential interactions) we compared a series of regression models using Akaike's information criterion, (AIC; Burnham and Anderson, 2002). We compared 11 different regression models that included the top-ranking predictors from the RF analysis (i.e. those predictors uses inclusion the model reduces the MSE by >10%) in addition to a null model that contained no predictor variables. Due to the relative importance of plantation age in the RF model and our hypothesis that the influence of age would vary over time, we also assessed whether the relationship between age and canopy damage varied over time by adding a polynomial term. Semivariograms of model residuals from an ordinary least squares (OLS) regression displayed strong positive spatial autocorrelation to distances >5 km (not shown). Due to the lack of independence of the residuals and the shape of the semivariogram we chose to fit a generalized least squares (GLS) regression models that included a spherical spatial correlation structure using the 'nlme' package (Pinheiro et al., 2009) within the R statistical environment (R Development Core Team, 2006). GLS regression relies on the distance between sample locations and the form of the correlation structure to derive a variance–covariance matrix, which is, in turn, used to solve a weighted OLS regression (Dormann et al., 2007).

3. Results

Sampled plantations ranged in age from 5 to 47 years (Fig. 1) and in size from 1.25 to 47 ha. Ninety-seven percent of the plantations (192 of 198) had >1% canopy damage. The average level of canopy damage within photo plots was 77% (SD = 20.1; Table 1). The RF model explained 34% of variability in canopy damage and identified plantation age as the most important predictor variable (Fig. 2), with older plantations experiencing lower levels of canopy damage. Average annual precipitation had a generally negative relationship with canopy damage and was ranked second by the RF model. Elevation and topographic position both had a positive relationship with canopy damage and were ranked third and fourth, respectively. No other predictor variable included within the RF model reduced the MSE by >10%.

Based on the RF results, we compared 11 different GLS regression models (Table 2). The top ranked model included plantation age and a polynomial term that allowed the effect of age on canopy damage to vary. This model was significant at $P < 0.0001$ and had a pseudo-R^2 of 0.30 (Fig. 3). Modeled percent canopy damage reached its maximum (91%) in plantations that were around age 15 and stayed relatively high (above 80%) within plantations that were between 15 and 25 years old before declining in older plantations. Based on conventions of the information theoretic approach (whereby models whose AIC statistics are within two units of the highest ranked model are considered equal (Burnham and Anderson, 2002)), no other model fit the data as well. However, it is important to note that, while modeled canopy damage does decline after plantations reach age 25, there is considerable variability in the data, and some plantations >25 years did experience high levels of damage. These results were not qualitatively different when we removed those plantations that were created after post-fire salvage logging from 1988 to 1990 then reran the analyses.

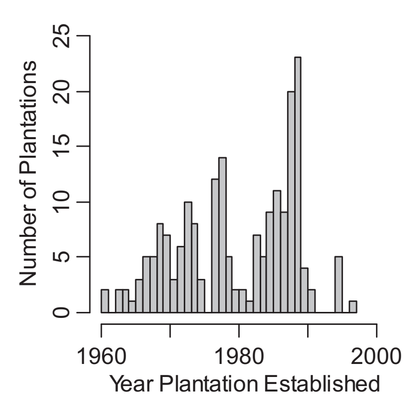

Fig. 1. The distribution of sampled plantation ages.

Please cite this article in press as: Thompson, J.R., et al. Canopy damage to conifer plantations within a large mixed-severity wildfire varies with stand age. Forest Ecol. Manage. (2011), doi:10.1016/j.foreco.2011.04.001

Table 1
Summary statistics for response and predictor variables used in the Random Forest analysis of crown damage within conifer plantations in the 2002 Biscuit Fire (DOB = day of burn).

Variables	Mean	Standard deviation	Minimum	Maximum
Response variable				
Percent crown damage	77.8	20.1	0	100
Predictor variables				
Age (years)	22	8.4	5	42
Harvest size (ha)	14.1	15.3	1.25	47
Vegetation cover (%)	89.8	10.7	47	100
Bare/grass cover (%)	10.3	10.0	0	53
Elevation (m)	885	227	265	1346
Topographic position (fine)	3.4	13.1	−25.7	49.4
Topographic position (coarse)	26.8	77.0	176.4	203.3
Slope (%)	40	13.6	12	79
Beer's aspect	−0.2	0.5	−0.97	0.99
Average annual precipitation (cm)	320	71	171	439
Temperature on DOB (C)	26.6	4.9	16.6	35.8
Relative humidity on DOB (%)	31	15	10	65.5
Wind speed on DOB (km/h)	9	2.1	4.2	18.2
Wind direction on DOB (cosine transformed)	0.24	0.44	−0.3	0.75

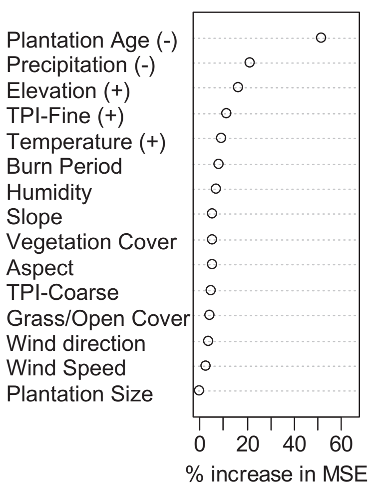

Fig. 2. Variable importance plots for predictor variables from a Random Forests model of canopy damage within conifer plantations. Predictor variables are along the *y*-axis and the average increase in the mean square error when data for that variable are permuted and all other are left unchanged is on the *x*-axis. The direction of the relationship is given in parentheses for predictor variables whose Pearson's correlation were significant at $p < 0.05$; however, we urge caution in this interpretation as Random Forest variable importance values are not based on linear relationships alone.

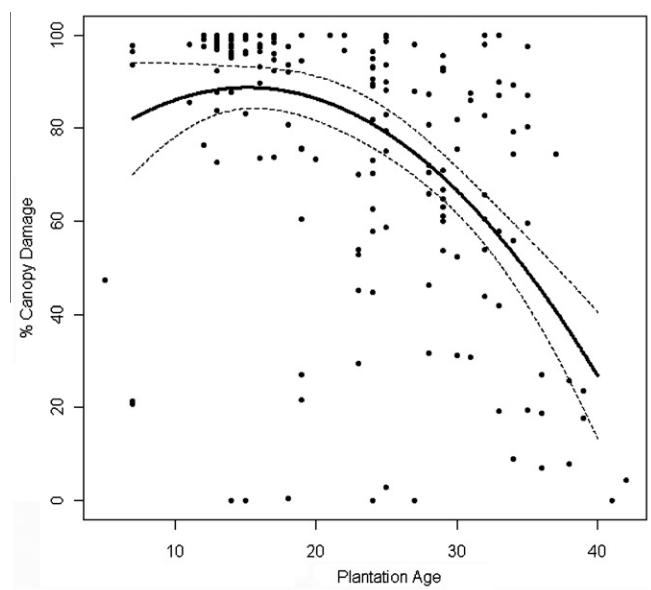

Fig. 3. Relationship between plantation age and percent canopy damage used to fit a generalized least squares regression model with a spatial spherical correlation structure to accommodate positive spatial autocorrelation. Dashed lines represent 95% confidence intervals.

Table 2
Comparison of geo-statistical regression models based on Akaike information criteria (AIC; interaction terms implicitly include their associated additive term).

Rank	Model Form	AIC	Δ AIC	ω_i
1	AGE + AGE^2	1713.9	0	0.907
2	AGE + AGE^2 + TPI	1719.3	5.4	0.061
3	AGE + AGE^2 + ELEV	1721.3	7.4	0.022
4	AGE + AGE^2 + PRECIP	1723.8	9.9	0.006
5	AGE + AGE^2 + PRECIP + TPI	1726.7	12.8	0.002
6	AGE	1727.6	14.1	0.001
7	AGE + AGE^2 + PRECIP + ELEV	1729.2	15.3	0.000
8	AGE * TPI	1738.5	24.6	0.000
9	AGE * ELEV	1748.8	34.9	0.000
10	AGE * PRECIP	1753.9	40.0	0.000
11	NULL MODEL	1760.2	46.3	0.000

4. Discussion

Given the absence of controlled experiments within large wildfires, long-term records of forest management type, location, and intensity are important for retrospectively assessing wildfire effects. Unfortunately, with the exception of plantation age and its status as a "successful" reforestation effort, we had no reliable and consistent records documenting the plantations' specific management history or composition at the time of the fire. The lack of site information is important limitation of this study. Indeed, site preparation has been shown to be an important predictor of plantation canopy damage, for example, where broadcast burned sites experienced significantly less damage than untreated or piled-and-burned sites (Weatherspoon and Skinner, 1995). Similarly, in a fortuitous experiment regarding fire effects after thinning in 90–120 year old unmanaged stands within the Biscuit Fire, tree mortality was lowest (5%) on sites that were thinned in 1996 then broadcast burned in 2001, just 1 year before the fire, intermediate in unmanaged sites (53–54%), and highest in sites that were thinned in 1996 but not broadcast burned (80–100%; Raymond and Peterson, 2005). Nonetheless, we were able to look back over 40 years of even-age forest management and document a relatively strong relationship between plantation age and the level of canopy damage. To our knowledge, no similar empirical information documenting this relationship exists.

Of the 15 predictor variables we examined, we found that level of canopy damage in plantations was most strongly related to its age. Indeed, the variable describing the age of plantations reduced the error in the model by more than twice as much as any of the other predictors (Fig. 2). The shape of the best-fitting geo-statistical regression model suggested that the level of canopy damage reached its maximum around age 15 and stayed relatively high until age 25 before declining (Fig. 3). This pattern is consistent with what is known about the fire ecology of Douglas-fir forests, whether planted or naturally regenerated (Starker, 1934; Agee, 1993). The fire resistance of Douglas-fir increases with age due to a continually thickening layer of protective bark and due to increasing height-to-crown, which is associated with reduced likelihood of torching or crown fires (Scott and Reinhardt, 2001; Graham et al., 2004). In effect, as Douglas-fir matures it transitions from an "avoider" (a species that is vulnerable to low intensity fires) to a "resister" (a species that has adaptations that increase the probability of survival during low intensity fires; Agee, 1993, pp. 206 and 285). Empirical growth curves show that by the time a Douglas-fir plantation in southwest Oregon is 25 years old an average tree is typically between 8 and 16 m tall and have crown base heights >3 m off the ground, depending on site class and stem density (Hann and Scrivani, 1987; Hanus et al., 2000). The combination of bark thickness and a sufficiently high crown-base-height is the likely explanation for, on average, decreasing canopy damage in the older plantations. However, given the data available to us in this study it is impossible to know exactly which fire resistance strategy (or combination of strategies) was responsible for the pattern of decreasing canopy damage with plantation age.

Our previous research in the unmanaged portion of the Biscuit suggested that weather conditions on the day of the burn were an important correlate of canopy damage (Thompson and Spies, 2009). Therefore, it was surprising that the predictor variables describing daily weather conditions were comparatively unimportant (Fig. 2 and Table 2). There are at least two possible explanations for the difference. In the study of unmanaged forests, we did not have explicit information on the age or structure of the stands, but most were mature mixed-conifer >50 years old. It is possible that fire weather is a better predictor of canopy damage in older stands where extremes in wind and fuel moisture are necessary to transition from a surface fire to torching the canopy or running as a crown fire (Van Wagner, 1977). Another possible reason for the difference relates to differences in the sampling extent and intensity. The study of unmanaged forest had many more plots that encompassed a much larger area and burned over a longer period of time spanning a greater range of variability in weather conditions. Average annual precipitation was ranked as the second most important predictor of canopy damage within the plantation and had a generally negative correlation. In this landscape, precipitation in correlated with productivity (Coops and Waring, 2001). Given the much stronger relationship between canopy damage and plantation age, the weak negative relationship with precipitation may suggest that greater moisture and productivity accelerated stand development and, in turn, decreased the age at which fire resistance is reached.

Given the ubiquity of plantations within fire-prone landscapes, it is perhaps surprising that so little research has been done regarding fire behavior in even-aged conifer plantations. The existing empirical research suggests that when compared to more heterogeneous unmanaged forests, plantations are associated with elevated fire damage (Weatherspoon and Skinner, 1995; Odion et al., 2004). While the intent of this study was not to compare unmanaged stands to plantations, it is worth noting that, in a separate examination of Biscuit Fire effects (Thompson and Spies, 2009), the average level of canopy damage within unmanaged forest with variable stand histories was lower than is was the within the plantations measured herein (65% in the previous study of unmanaged forests versus 78% in the present study). Given the relationship between plantation age and canopy damage, the difference in canopy damage between unmanaged and unmanaged stands may have more to do with the fact that most of the unmanaged stands were >50 years old, than with their origin as "unmanaged" (i.e. naturally regenerated).

With the clear proviso that our study was observational and only describes Douglas-fir plantations burned within the Biscuit Fire, for the sake of context it is also worth noting that fire modeling studies in other regions that have examined fire behavior and tree mortality within a range of silvicultural treatment types and ages have found a similar trends of decreasing fire damage with increasing age (e.g. Kobziar et al., 2009; Stephens and Moghaddas, 2005). For example, in Sierra Nevadan ponderosa pine plantations, high rates of mortality were predicted for untreated conifer plantations (when compared to young growth reserves (80–100 years)) across all diameter classes up to 50 cm DBH, regardless of weather conditions (Stephens and Moghaddas, 2005). In the Biscuit Fire, young (<15 years) Douglas-fir stands tended experience high levels of canopy damage whether they were plantations or naturally regenerated stands. This was demonstrated through a separate examination of the areas that burned at high severity in the 1987 Silver Fire and were subsequently re-burned by the Biscuit Fire (Thompson and Spies, 2010).

5. Conclusion

In this paper, we utilized pre- and post-fire digital aerial photography to assess fire-related canopy damage within Douglas-fir plantations in southwest Oregon. We used parametric and non-parametric modeling approaches to examine the level of canopy damage in relation to several variables describing the vegetation-cover, topographic setting, weather conditions on the day a site burned, and the time since the plantations were established (i.e. the plantations' age). We found that age of a plantation was the best predictor of the level canopy damage and that the other variables were comparatively poor predictors. The best fitting geostatistical regression model indicated that the level of canopy damage reached its maximum around age 15 and stayed relatively high until age 25 before declining. Based on a previous analysis of unmanaged vegetation (Thompson and Spies, 2009), we had hypothesized that daily weather conditions would be important predictor variables within the models. However, the data did not support this hypothesis. Our findings, while observational and thus not generalizable, offer managers and forest scientists a rare empirical perspective on patterns fire damage within even-age conifer plantations, which are a common landscape feature throughout the western North America. At least in this case, the data suggest that young plantations were vulnerable to canopy damage regardless of their environmental setting.

Acknowledgements

This research was funded by the Joint Fire Science Program. We thank Duck Creek Inc., for technical help and W. Cohen, T. Atzet, and R. Miller for helpful reviews.

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