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Vegetation and topographical correlates of fire severity from two fires in the Klamath-Siskiyou region of Oregon and California

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Abstract. We used vegetation data collected in areas before they were burned by the 2500 ha Quartz fire in southern Oregon and the 50 600 ha Big Bar complex in northern California to evaluate the ability of vegetation and topographic characteristics to predict patterns of fire severity. Fire severity was characterized as high, moderate, or low based on crown scorch and consumption, and changes in soil structure. In both fires, vegetation plots with southern aspects were more likely to burn with high severity than plots with eastern, northern, or western aspects. This was the only consistent predictor across both fires. In the Quartz fire, we found that plots at higher elevations and with larger diameter trees were more likely to burn with low or moderate severity. These correlations may have been influenced in part by the effects of unmeasured weather conditions. We found few strong correlates in the Big Bar complex, owing in part to the fact that most (75%) of our plots were in the low-severity category, providing relatively little variation. These results, in combination with previous studies of fire severity in the Klamath-Siskiyou region, suggest that areas with southern aspects tend to burn with greater severity than those of other aspects, areas with large trees burn less severely than those with smaller trees, and that correlates of fire severity vary extensively among fires.

Additional keywords: classification trees; topography; vegetation structure; wildfire.

Introduction

Weather, topography, and fuels influence fire behavior through multiple pathways and at multiple spatial scales (Agee 1993; Heyerdahl *et al*. 2001). At large spatial scales, long-term climatic fluctuations are correlated with the probability of fire ignition and spread (Swetnam and Betancourt 1990; Whitlock *et al*. 2003; Whitlock 2004). At a local scale, weather conditions, especially wind, temperature, and humidity, influence fire behavior (Byram 1959; Finney *et al*. 2003). Topography is also an important correlate; in the Northern Hemisphere, south-facing stands often burn with greater severity than stands with other aspects (Weatherspoon and Skinner 1995).

The third major factor is fuels (Agee 1993). The volume and spatial structure of both living and dead vegetation are often associated with fire behavior (Agee 1993). Areas with larger trees and mature forest conditions often have lower fire risk (Jackson 1968; Odion *et al*. 2004*a*), though their natural fire regime may be infrequent stand-replacing fire (e.g. Douglas-fir forest in the Oregon Coast Range [Agee and Huff 1987] or wet temperate forests of Tasmania [Jackson 1968]). The volume of shrub strata vegetation is also important, as there are often many small-diameter twigs that can be highly flammable and may act as 'ladder fuels'. Ladder fuels are shrubs, saplings, seedlings, and the lower dead branches of trees that provide connectivity between ground level fuels and the forest canopy of large-diameter trees. When trees are tall and have few lower branches, ladder fuels are minimized. When the height of the canopy base is reduced, or the height of the shrub strata (including understory trees) increased, these two stratum may overlap, increasing ladder fuel characteristics. Structural characteristics of fuels may be influenced by disturbance history, including fire, insect damage, wind, and management activities.

Most fire behavior models incorporate these three factors (Rothermel 1983; Andrews *et al*. 2003), but because these models have focused on predicting fire intensity (e.g. rate of heat output or flame lengths), they do not necessarily provide good predictions of fire severity (also called 'burn severity', generally a measure of the degree to which fire

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affects ecosystem characteristics [Andrews 1986], and see Jain [2004] for definitions of burn severity). The relative importance with which these factors contribute to fire severity is critical information for land managers of fire-prone landscapes (Graham *et al*. 2004). In landscapes with high-severity fire regimes, such as sub-alpine forests (Bessie and Johnson 1995; Schoennagel *et al*. 2004) and chaparral (Moritz *et al*. 2004), fuel characteristics are thought to be less important than the opportunity for ignition; these flammable vegetation types burn with high severity regardless of the structural characteristics of the fuels. In contrast, in landscapes with low-severity fire regimes, such as mature ponderosa pine (*Pinus ponderosa*) forests (Pollet and Omi 2002; Schoennagel *et al*. 2004), fuel characteristics appear to dictate fire severity, even when weather conditions are extreme. However, in many mixed-conifer forests, fire severity exhibits considerable spatial variation within a single fire event (Agee 1993). The degree to which such mixed-severity fires are a result of fuels, topography, and weather remains poorly understood (Schoennagel *et al*. 2004). As fuels are the only factor that can be addressed by land management, quantifying the influence of fuels on fire severity has been identified as a research priority (Schmoldt *et al*. 1999).

In the present paper, we use pre-fire vegetation data from two wildfires in the Klamath-Siskiyou Region of northern California and southern Oregon to evaluate the degree to which topographic and vegetation characteristics can be used alone or in combination to predict fire severity. Fire severity is related to the financial cost of post-fire recovery efforts. One measure of this aspect of fire severity is the categorical assignment (low, moderate, or high) based on crown scorch, canopy consumption, and changes in soil structure. Such categories are a critical component of the Burned Area Emergency Rehabilitation (BAER) reports used by federal agencies to evaluate the risk of soil erosion and prioritize areas for post-fire recovery efforts. Thus, this measure of fire severity is directly related to financial costs of post-fire recovery efforts. Identifying fuel characteristics associated with patterns of fire severity as described in BAER assessments may provide forest managers with information that can decrease the financial cost of post-fire recovery.

Methods

Study sites and sampling design

The two fires selected for the present study were chosen because they burned in areas where vegetation data had been collected before the fires. The Quartz fire burned in the Little Applegate Valley in Jackson County, ∼18 km southwest of Ashland, Oregon (524000E, 4671000N, Universal Transverse Mercator [UTM] zone 10, North American Datum [NAD] of 27). This fire burned between 9 August and 31 August 2001, encompassing a total of 2500 ha. Elevation of the fire ranged from 770 to 1920 m. The valley faces to the north and slopes in the fire area range from 0 to 63 degrees. Sixty-seven stations where vegetation data had been collected in the spring of 2001 opportunistically fell within the fire perimeter (Fig. 1).

The Big Bar complex burned over several watersheds of the Klamath-Trinity river system in Humboldt and Trinity counties of northern California, ∼20 km north-east of Willow Creek (446900E, 4532000N in UTM zone 10, NAD27). The complex burned 50 590 ha between 23 August and 5 November 1999. Elevation of the fire ranged from 290 to 2090 m. Slopes in the fire area range from 0 to 73 degrees. Eighty-two stations where vegetation data had been collected in 1992, 1994, 1995, or 1998 were within the fire perimeter (Fig. 1). Based on USA Forest Service fire progression maps, these points burned between 5 September and 30 October.

The forest vegetation in the area of these fires is diverse (Whittaker 1960) and includes both conifer and hardwood species. Dominant conifers include Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*), incense-cedar (*Calocedrus decurrens*), and white fir (*Abies concolor*). Dominant hardwoods include tanoak (*Lithocarpus densiflorus*), Pacific madrone (*Arbutus menziesii*), canyon live oak (*Quercus chrysolepis*), California black oak (*Q. Kellogii*), Oregon white oak (*Q. garryana*), and big-leaf maple (*Acer macrophyllum*). The relative composition of these species varies with elevation, aspect, and soils. Generally, these forests correspond to the Douglas-fir, Mixed Evergreen Hardwood, or White Fir Zones described by Franklin and Dyrness (1973) or Types described by Huff *et al*. (2005). Fire-related studies in these vegetation types show a mix of fire severities, frequencies, and sizes typically characteristic of low- and moderate-severity fire regimes (Agee 1991; Wills and Stuart 1994; Taylor and Skinner 1998, 2003). Over time, such mixed-severity fires create forests with multiple age classes, often with Douglas-fir or ponderosa pine as an emergent canopy above various hardwoods.

Vegetation data were collected before the fires burned as part of the Klamath Demographic Monitoring Network, a project that collects data on bird populations throughout southern Oregon and northern California (Alexander *et al*. 2004). As part of this effort, extensive surveys of bird abundance and vegetation composition and structure have been conducted throughout the region. These surveys are performed as groups of 12 to 30 stations that are spaced every 250 m, usually along secondary roads and trails (Ralph *et al*. 1993).

Data collection

For each station, we generated three topographical measurements, elevation (m), slope (degrees), and aspect (degrees) using a digital elevation map (DEM) and UTM coordinates of stations in GIS. Aspect was converted to a categorical variable defining aspect as north (315–44 degrees), east (45–134 degrees), south (135–224 degrees), or west (225–314 degrees). Elevation and slope measurements were also generated using all of the $10\,\text{m} \times 10\,\text{m}$ cells within the fire boundaries to characterize the entire burned landscapes.

Vegetation data were collected at each station using a relevé method (Ralph *et al*. 1993), on variable radius plots (20–50 m). Total cover and height for the tree stratum (all vegetation $\geq$5 m) and shrub stratum (all vegetation $\geq$0.5 m and $<$5 m) were estimated using 5 cover classes (0–5, 5–25, 25–50, 50–75, and 75–100%). Maximum diameter at breast height (dbh) of trees in the tree layer was visually estimated. We also estimated the height of the lower boundary of the tree canopy (usually $>$5 m).

Whereas ladder fuels are believed to play an important role in fire behavior, they are not always measured as a distinct fuel component (Cruz *et al*. 2003). Perhaps as a result, researchers have used a variety of measurements such as tree height, tree diameter, and proximity of fuels to the ground as means to quantify fuel characteristics that increase vertical fuel continuity. We developed a unique method of using our relevé data to quantify ladder fuels that considered both vertical and horizontal fuel continuity between the shrub and tree layer. We generated a ladder fuels index by first multiplying the height of the shrub layer by the shrub stratum cover score; the height of the shrub layer remained

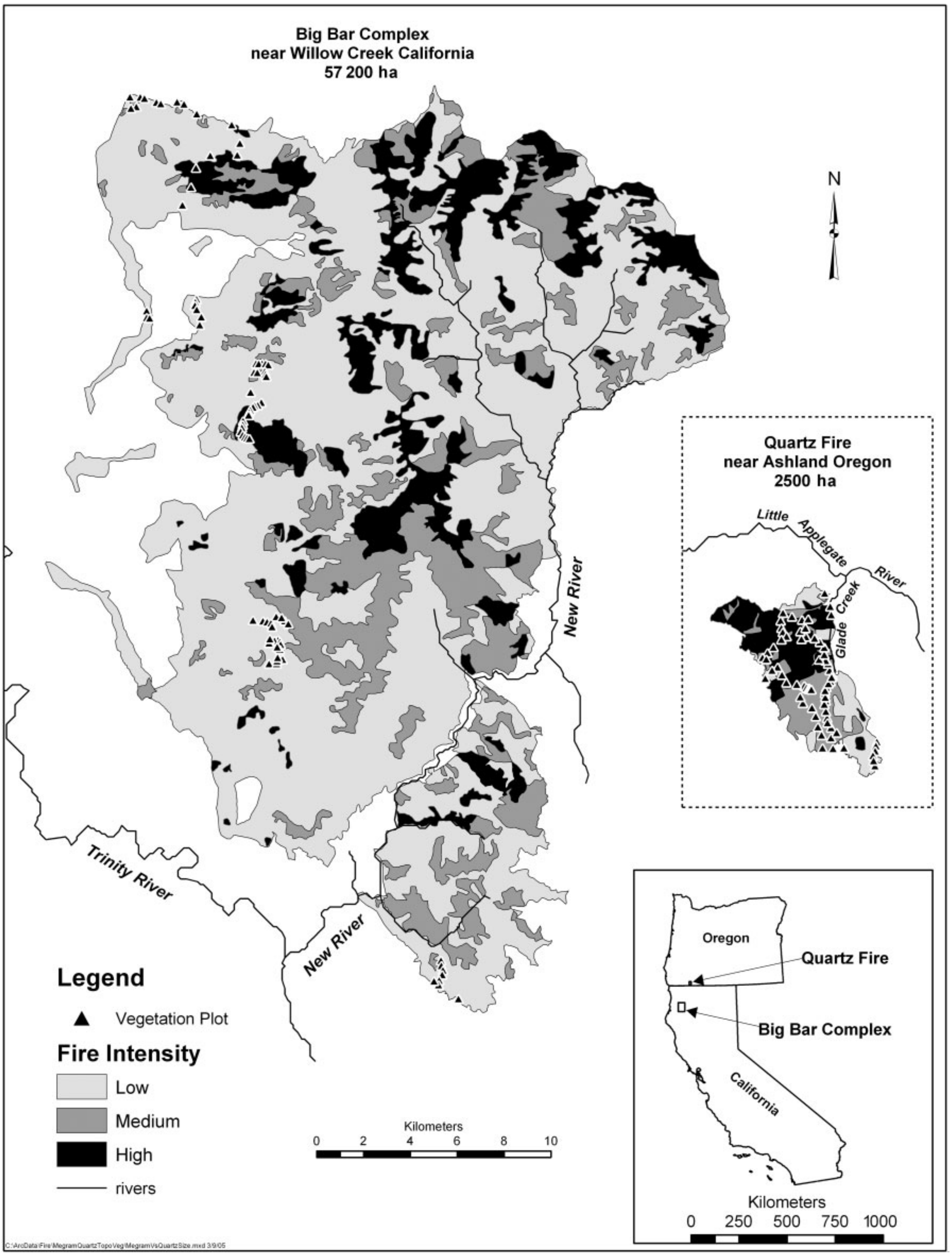

Fig. 1. Map of Quartz fire in the Little Applegate Valley, Oregon, and the Big Bar complex in California. Triangles are vegetation stations surveyed in 2001 (Quartz fire) and 1992, 1994, 1995, or 1998 (Big Bar complex).

nearly unchanged when cover was high, but was reduced when cover was low, accounting for a measure of fuel continuity. We then subtracted this adjusted height of the shrub layer from the height of the lower boundary of the tree canopy; when the canopy base height overlapped the shrub layer, the ladder fuels variable was negative, indicating high ladder fuels. Positive values of ladder fuels represented a gap between the shrub stratum and canopy base, an indication of reduced ladder fuels.

Fire severity at each station was evaluated using maps generated by BAER assessments conducted by the United States Forest Service (USFS; Fig. 1). These maps identified severity as low, medium, or high, based on post-burn aerial photography and observations from the field. In areas categorized as low severity, the fire probably spread rapidly but residence time was short, or the fire may have skipped over these areas altogether. In this category, soil cover is not significantly reduced and soil structure is minimally altered. Vegetation is at most lightly scorched and tree mortality is minimal. The effects of the fire in areas categorized as moderate severity were typically more extreme; soil structure remains intact but fine fuels near the ground are mostly consumed and 40 to 80% of trees are killed, but retain brown needles that later fall to the forest floor. In areas of high fire severity, fire and heat residence times are longer and ground cover may be completely consumed. Soil structure is often altered because soil organic matter is consumed. Because tree crowns are completely consumed, few leaves or needles remain on trees and mortality is often 100%.

Our analysis was limited to the influence of vegetation and topography. To the best of our knowledge, none of our stations had burned within the last five decades. In addition, information on weather conditions and suppression activities (e.g. backfires) during the fires was difficult to reconstruct. Thus, weather and suppression activities represent an unmeasured, but important, variable, which increased variance in the observed patterns. Previous studies of fuel structure correlates of fire severity at the stand level have been able to identify significant relationships, even when weather has not been considered (e.g. Weatherspoon and Skinner 1995; Jimerson and Jones 2003; Odion *et al*. 2004*a*).

Statistical analyses

We began by using univariate analyses to investigate the relationships between individual categorical predictor variables (e.g. aspect and cover values) and fire severity using Pearson chi-square tests. These evaluated the null hypothesis that the proportion of points in the three severity classes was independent of predictor variables. However, because the sample size was small and many cells contained <5 expected counts, we used the EXACT option within PROC FREQ of SAS (version 9.0; SAS Institute, Cary, NC, USA) to generate Monte Carlo (10 000 samples) estimates of exact *P*-values. For continuous predictor variables, we used multicategory logit models (Agresti 1996) to test associations with fire severity categories. Multicategory logit models are an extension of logistic regression that can be used to estimate the probabilities for more than two mutually exclusive outcomes (e.g. high, moderate, or low severity) as a function of one or more explanatory variables. We have presented the results of these models by plotting the predicted probability of high, moderate, and low severity classification as a function of the continuous predictor variable.

We investigated correlations among predictor variables with Spearman rank correlation tests when both variables were continuous, or Kruskal–Wallis tests when comparing categorical and continuous measures (e.g. aspect and maximum tree dbh). All univariate tests were conducted in SAS (version 9.0) and we rejected null hypotheses of no association when $P < 0.05$. We have assumed that each station is an independent sample; if there is strong spatial autocorrelation, this assumption is violated, potentially raising the risk of type 1 error (Legendre *et al*. 2004). In the absence of a formal spatial analysis, our results should be interpreted cautiously.

The application of traditional multiple regression techniques to these data is problematic because the relationships between variables may be complex and non-linear, the unplanned nature of wildfire events results in highly unbalanced datasets (e.g. some categorical predictors may have few, if any observations), and our sample size was relatively small. As a result, we wanted to use a method that could examine all of the predictor variables concurrently to describe the strongest relationships with fire severity. We chose to use 'classification tree' methods (Breiman *et al*. 1984) to summarize the association of multiple predictor variables on fire severity. Classification tree analysis is a non-parametric method of explaining the variation of a response variable by repeatedly splitting the data into subgroups, with each split based on a single explanatory variable. The goal of the technique is to identify a series of variables that can be used to split the dataset into groupings with homogeneous values of the response variables. This method provides a simple and effective way of describing complex relationships between a response variable and multiple predictor variables (De'ath and Fabricius 2000).

We used the RPART package in R (R Development Core Team 2003) to construct and evaluate classification trees. To build classification trees, we used fire severity (low, moderate, and high) as a categorical response variable, and elevation, slope, aspect, maximum tree dbh, shrub cover, and ladder fuel index as predictor variables. We used 10-fold cross validation, with >5 observations in a node to split, and then evaluated misclassification rate as a function of tree size. Following Breiman *et al*. (1984), we selected the smallest tree with an error rate that was within 1 standard error of the minimum error rate as the best tree.

Results

Severity, topographic, and vegetation characteristics by fire

The proportion of our stations in the three severity classes varied between the Big Bar complex and Quartz fire. In the Big Bar complex, most stations (76%) were in the low-severity category, with relatively few in the moderate- (8%) or high- (16%) severity categories. In contrast, points in the Quartz fire were more evenly distributed among low (17%), moderate (54%), and high (29%) severity.

Elevations at stations within each fire were similar to those that characterized the entire burned areas; however stations within the Big Bar complex represented a narrower elevation band than was affected by that event (Table 1). Stations tended to occur on shallower slopes than those of the burned areas in general, with this difference being more pronounced in the Big Bar complex than in the Quartz fire (Table 1).

Topographic characteristics of stations in the Quartz fire and Big Bar complex were similar, though those in the Quartz fire occurred at slightly higher elevations and on slightly steeper slopes than those in the Big Bar complex (Table 1). Shrub cover was greater in the Quartz fire (Table 1). In the Quartz fire, most of the 67 stations were classified with shrub cover from 50 to 100%; only five stations had shrub cover of <50%. In the Big Bar complex, approximately half of the 82 stations were classified with shrub cover from 50 to 100%.

Of the relationships between vegetation and topographic characteristics we investigated, only aspect showed a significant relationship with vegetation characteristics. Maximum tree dbh was smallest on south-facing stations of the Quartz fire (Kruskal–Wallis, $X^2_3 = 14.032$, $P = 0.003$, Fig. 2), but there was no apparent pattern with aspect and maximum dbh in the Big Bar complex (Kruskal–Wallis, $X^2_3 = 5.41$, $P = 0.144$). We found no evidence for a relationship between elevation and maximum tree dbh in either the Quartz fire (Spearman correlation, $R = 0.161$, $P = 0.193$), or the Big Bar

Table 1. Mean characteristics of vegetation survey plots for the Quartz fire in southern Oregon and the Big Bar complex in northern California

dbh, diameter at breast height; shrub cover (0.025, 0–5%; 0.15, 5–25%; 0.375, 25–50%; 0.625, 50–75%; 0.875, 75–100%); herb cover (0.025, 0–5%; 0.15, 5–25%; 0.375, 25–50%; 0.625, 50–75%; 0.875, 75–100%); ladder fuels index (height of shrubs × shrub cover subtracted from bottom height of canopy; see text for more information)

Data	Quartz fire ($n = 67$)			Big Bar complex ($n = 82$)		
	Range	Mean	s.d.	Range	Mean	s.d.
Elevation	958–1842	1252	223	785–1578	1332	200
Landscape elevation (m)	771–1919	1258	219	291–2087	1183	227
Slope (degrees)	3–32	16	6.6	2–33	15	8.3
Landscape slope (degrees)	0–63	21.5	8.8	0–72	27	10.2
Maximum tree dbh (cm)	22–123	60	27	23–170	72	38
Shrub cover	0.150–0.875	0.752	0.178	0.025–0.875	0.506	0.317
Herb cover	0.150–0.875	0.801	0.149	0.025–0.875	0.493	0.377
Ladder fuels index	−2.1–16.6	3.87	4.01	−3.5–39.25	4.86	7.25

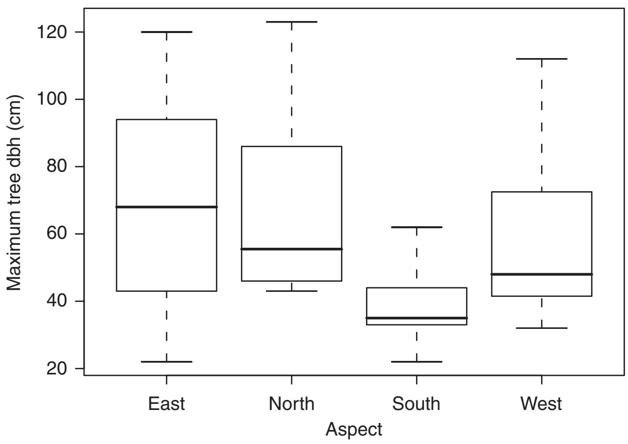

Fig. 2. Maximum tree diameter at breast height (dbh) across four aspect categories in the Quartz fire of southern Oregon. Bars are medians, boxes are defined by the upper and lower quartiles, and whiskers are maximum and minimum values.

Table 2. Statistical relationships between topographical and vegetation predictors and fire severity

Data definitions: aspect (north, 315–44 degrees; east, 45–134 degrees; south, 135–224 degrees; west, 225–314 degrees); elevation (m); slope (degrees); maximum tree diameter at breast height (dbh) (cm); shrub cover (0.025, 0–5%; 0.15, 5–25%; 0.375, 25–50%; 0.625, 50–75%; 0.875, 75–100%); ladder fuels index (height of shrubs × shrub cover subtracted from bottom height of canopy; see text for more information)

Data	Quartz fire ($n = 67$)	Big Bar complex ($n = 82$)
Aspect[A]	$X^2_6 = 19.64, P = 0.003$	$X^2_6 = 19.86, P = 0.017$
Elevation[B]	$X^2_2 = 13.30, P = 0.001$	$X^2_2 = 4.74, P = 0.094$
Slope[B]	$X^2_2 = 0.62, P = 0.735$	$X^2_2 = 7.83, P = 0.020$
Maximum tree dbh[B]	$X^2_2 = 8.09, P = 0.018$	$X^2_2 = 2.27, P = 0.322$
Shrub cover[A]	$X^2_2 = 3.900, P = 0.160$	$X^2_2 = 2.653, P = 0.301$
Ladder fuels index[B]	$X^2_2 = 3.78, P = 0.151$	$X^2_2 = 5.36, P = 0.069$

[A]X_2 and P values from Pearson chi-square tests.
[B]X_2 and P values from multicategory logit models.

complex ($R = 0.150$, $P = 0.179$). Similarly, there was no evidence for a relationship between slope and maximum tree dbh for either the Quartz fire (Spearman correlation, $R = -0.027$, $P = 0.830$) or Big Bar complex ($R = -0.063$, $P = 0.574$). There was a significant correlation between maximum tree dbh and the ladder fuels index in the Quartz fire (Spearman correlation, $R = 0.299$, $P = 0.0139$), but not in the Big Bar complex ($R = 0.113$, $P = 0.320$).

Univariate analyses of topographic and vegetation characteristics with fire severity

Of the topographic characteristics we examined, only aspect was consistently associated with fire severity in both the Quartz fire and Big Bar complex (Table 2). In the Quartz fire, more stations with southern aspects were classified as high severity than those with other aspects (Fig. 3), and in the Big Bar complex, more stations with southern and western aspects were classified as high severity than those with northern and eastern aspects (Fig. 3). In contrast, associations of elevation and slope with fire severity varied between the two fires. In the Quartz fire, stations at low elevations were more likely to burn at high severity than those at higher elevations, whereas there was no evidence of association with elevation in the Big Bar complex (Table 2). In the Quartz fire, slope and fire severity had no significant relationship, but stations on gentle slopes of the Big Bar complex were more likely to burn with moderate severity, and the probability of burning with low and high severity increased as slope increased.

Of the vegetation characteristics we investigated, only maximum tree dbh was associated with fire severity, and this association was not consistent across fires (Table 2). In the Quartz fire, stations with greater maximum tree dbh were less likely to burn with high severity, whereas the probability of burning with high severity increased as maximum tree dbh decreased (Fig. 4), but a similar association with maximum

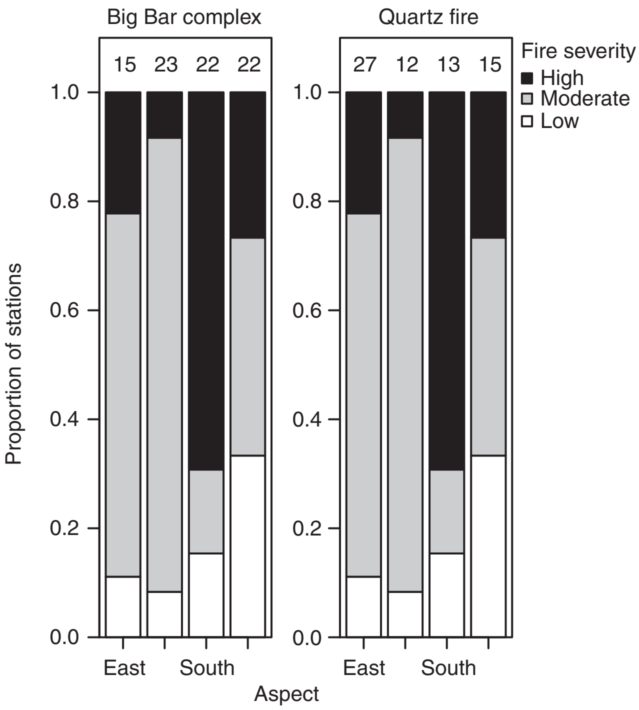

Fig. 3. Proportion of points in three fire severity classes relative to aspect categories of the Quartz fire in southern Oregon and the Big Bar complex in northern California.

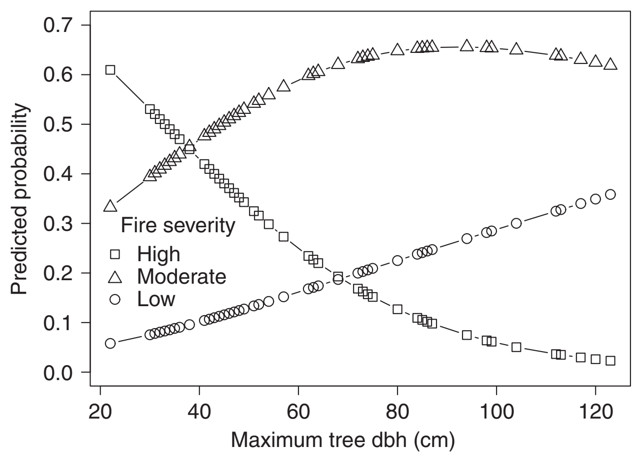

Fig. 4. Predicted probabilities of fire severity as a function of maximum tree diameter at breast height (dbh) in the Quartz fire, southern Oregon. The probability of a point being categorized as high severity decreased as maximum tree dbh increased. In contrast, the probability of a point being categorized as low severity increased as maximum tree dbh increased. Predicted probabilities were generated from a generalized logit model where the parameters for moderate/low were estimated as intercept = −3.46 and dbh = 0.051, and for high/low as intercept = −1.46 and dbh = 0.039.

tree dbh was not apparent in the Big Bar complex. In neither the Quartz fire nor Big Bar complex was there a significant relationship between ladder fuels index or shrub cover and fire severity.

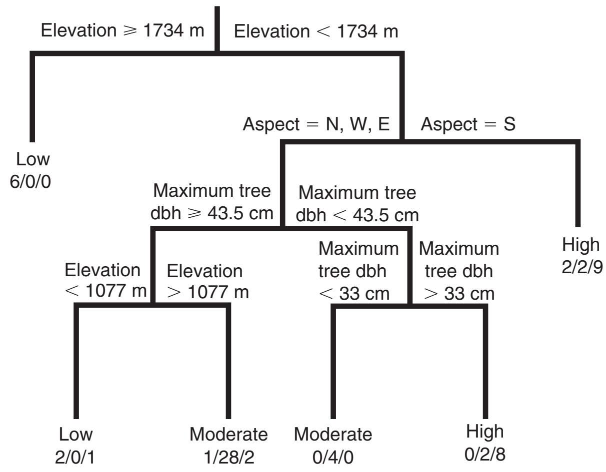

Fig. 5. Classification tree relating fire severity categories (1 = low, 2 = moderate, 3 = high) to three explanatory variables (elevation, aspect, and maximum tree diameter at breast height [dbh]) for vegetation plots in the Quartz fire, southern Oregon. Numbers at the ends of terminal nodes represent the predicted severity classification. Values below predicted classification are the number of stations in each severity category (low/moderate/high) for each group.

Classification tree analysis

For the Quartz fire, cross-validation results suggested that the smallest classification tree which could be fitted without increasing the misclassification error rate was one with six groups. This tree used three predictors (elevation, aspect, and maximum tree dbh) to correctly classify 88% of the stations. The first split was based on elevation; at elevations above 1734 m, fire severity was always low, whereas below this elevation, fire severity was more often moderate or high (Fig. 5). For stations below 1734 m, the next split was based on aspect; south-facing stations more commonly burned with high severity than those with other aspects (Fig. 5). For stations with these other aspects, maximum tree dbh was important; stations with a maximum tree dbh greater than 44 cm tended to burn less severely than those with a maximum tree dbh less than 44 cm (Fig. 5). When stations had a maximum tree dbh greater than 44 cm, elevation was again important; stations below 1077 m were more likely to burn with low severity than those at elevations above 1077 m. However, when maximum tree dbh was <44 cm, then the next split was again based on maximum tree dbh; when maximum tree dbh was greater than 33 cm, most stations burned with high severity, whereas stations with maximum tree dbh <33 cm burned with moderate severity (Fig. 5). For the Big Bar complex, cross-validation results suggested that a simple classification tree with only a single grouping was able to perform as well as more complex trees with multiple groups. This resulted from the large proportion (75%) of points categorized as low severity; there was little heterogeneity to be explained by the explanatory variables. However, we were able to use these data as an independent test of the classification tree model developed in the case of the Quartz fire. Using the Quartz fire model, 67% of the Big Bar stations were predicted to burn with moderate severity, 29% with high severity, and 4% with low severity, resulting in the correct classification of only 15 of the 62 Big Bar stations.

Discussion

Fire behavior modeling (Stephens 1998; Omi and Martinson 2002) and empirical evidence (Pollet and Omi 2002) have shown that fire intensity and severity may be reduced in some situations by modifying fuel structure. These results have kindled widespread interest in fuels reduction treatments in landscapes with low- and mixed-severity fire regimes. Our results support the link between fuel structure and fire severity, but they also suggest that the ability of fuels treatments to achieve the desired results of reduced fire severity may be limited.

Patterns of fire severity were associated with aspect in both the Big Bar complex and Quartz fire, a result that was supported by the classification tree for the Quartz fire (Fig. 5). These results corroborate the finding of Weatherspoon and Skinner (1995), suggesting that south-facing slopes tend to burn with greater severity than other aspects. This pattern may result from multiple mechanisms. First, because southern aspects receive more solar radiation, there is generally less moisture available (Stage 1976), resulting in drier fuels and smaller diameter trees (Fig. 4), which may burn with greater severity. Second, these environmental conditions and their associated disturbance regimes may favor sclerophyll vegetation, which combusts relatively easily and releases high amounts of energy (Agee 1993; Odion *et al*. 2004*b*).

In the Quartz fire, stations at low elevations were more likely to burn with high severity than those at higher elevations, a result supported by both the univariate and classification tree analyses. This pattern is consistent with that from a study of the 1987 Hayfork fire (Weatherspoon and Skinner 1995). These authors suggested that this pattern may be driven by cooler, moister conditions at higher elevations and vegetation characteristics that are less flammable.

Although these factors may have been important in the Quartz fire, an alternative explanation is that elevation may have acted as a statistical surrogate for weather conditions. The Quartz fire was ignited at a low elevation, then burned up slope over a period of nearly 3 weeks. During the early days of the fire, the weather was hot and dry and then shifted toward cooler and moister conditions toward the end of August. In Medford, Oregon, 25 km to the north of the Quartz fire, the maximum daytime temperatures were higher during the first week (mean = 37.2°C, range = 35.6–40.6°C) while the fire was burning at lower elevations, than during the rest of the fire (mean = 30.6°C, range = 22.8–35.0°C).

The association between fire severity and slope was detected only in the univariate analysis for the Big Bar complex; stations on shallow slopes were more likely to burn with moderate severity, and the probability of burning with low and high severity increased as slope increased. This result is generally consistent with a previous study of the Megram fire (part of the Big Bar complex; Jimerson and Jones 2003) that found that sites with less than 20% slope burned less severely than sites with 20–65% slope. As with aspect, slope may influence moisture availability and vegetation composition and structure, thereby influencing flammability of a site (Agee 1993).

The only evidence of an association between fire severity and fuels was in the Quartz fire, where both univariate and classification tree analyses demonstrated that stations with bigger trees burned at lower severity than those with smaller trees. The classification analysis suggested that this association was most important at low elevations on sites with a southern aspect.

The association we observed between maximum dbh and fire severity may be linked to several mechanisms. Because dbh usually is correlated with thicker bark and taller trees, it has been associated with reduced fire-induced mortality (Uhl and Kauffman 1990; Agee 1993; Hely *et al*. 2003). Alternatively, fuel characteristics of plots with large trees may have been such that the fire burned less intensely. Thus, the patterns we observed may have been created by variation in fire intensity, variation in the susceptibility of trees to damage and mortality, or a combination of these factors.

This result is consistent with patterns of fire severity from the 1987 fires in the Klamath National Forest, where fire severity was lower on sites where closed forests had not been burned in the previous 70 years (Odion *et al*. 2004*a*), and the 1988 Yellowstone fires (Turner *et al*. 1999). Although we found no evidence of such a relationship from the Big Bar complex, Jimerson and Jones (2003) reported in the Megram fire more shrub, forb and pole and early-mature seral stage stands burned with high severity than did mid-mature and late-mature seral stage stands.

Our inability to detect a stronger association of topography and fuels with fire severity in the Big Bar complex may have several explanations. One possibility is that the modest variation in fire severity (most plots burned with moderate severity) among our Big Bar plots provided little information to understand what factors were associated with the low- and high-severity categories. Alternatively, as noted for the Quartz fire, weather may have been an important and unmeasured correlate of fire behavior. The areas of the Big Bar complex where our stations were located burned later in the season than the Quartz fire, when temperatures tend to be cooler. This may explain why a greater proportion of the Big Bar stations were in the low-severity category. In Willow Creek, California, 20 km to the south-west of the Big Bar complex, the average maximum temperature was 19.4°C (range = 13.3–24.4°C) while the fire burned our stations.

Similarly, fire suppression activities, such as backburning, may have disrupted the natural patterns of fire severity that would have resulted from topography and fuels. If the effects of either of these factors were strong and variable during the time that our plots burned, they may have masked the effects of fuels and topography.

Although our classification tree model performed relatively well in the Quartz fire, it failed to accurately predict fire severity when applied to the data from the Big Bar complex. This suggests that the conclusions from a single fire event must be applied to larger domains with great caution. Although concordance of multiple studies from the Klamath-Siskiyou region supports the associations with topography and vegetation structure, these conclusions do not apply to all systems. For example, fire severity was not found to be associated with aspect or slope in the 1988 Yellowstone fires (Turner *et al*. 1999) or eucalypt forests of Australia (Chafer *et al*. 2004).

These results support the widely-held view that topography, weather, and fuels are key components of wildfire behavior (Agee 1993). These results, in combination with previous studies of fire severity in the Klamath-Siskiyou region, suggest three major conclusions with management implications:

(1) Areas with southerly aspects tend to burn with greater severity. If management activities are designed to reduce fire severity, south-facing slopes should be carefully considered with the recognition that the environmental conditions (e.g. high temperatures, dry conditions, and volatile vegetation) of these sites may limit the effectiveness of fuels reduction treatments.
(2) Areas with large trees burn less severely. Fuels management projects designed to reduce fire severity should retain and recruit large diameter trees. Such fuels reduction efforts in areas where mid- and late-seral forest conditions can be created will likely be more effective than on south-facing slopes that are dominated by sclerophyll vegetation and have less potential for supporting larger trees.
(3) Topographic and vegetation characteristics associated with fire severity may vary extensively within and among fires. As a result, it seems that even widespread treatments will provide only limited control of fire severity. Given this uncertainty, we suggest that fuels reduction projects should be implemented cautiously and with long-term interests of forest health and wildlife in mind.

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References

Agee JK (1991) Fire history along an elevational gradient in the Siskiyou Mountains, Oregon. *Northwest Science* **65**, 188–199.
Agee JK (1993) 'Fire ecology of Pacific Northwest forests.' (Island Press: Washington, DC)
Agee JK, Huff MH (1987) Fuel succession in a western hemlock/Douglas-fir forest. *Canadian Journal of Forest Research* **17**, 697–704.
Agresti A (1996) 'An introduction to categorical data analysis.' (John Wiley and Sons: New York)
Alexander JD, Ralph CJ, Hollinger K, Hogoboom B (2004) Using a wide-scale landbird monitoring network to determine landbird distribution and productivity in the Klamath Bioregion. In 'Proceedings of the Second Conference on Klamath-Siskiyou Ecology'. (Eds KL Mergenthaler, JE Williams, ES Jules) pp. 33–41. (Siskiyou Field Institute: Cave Junction, OR)
Andrews PL (1986) 'BEHAVE: Fire behavior prediction and fuel modeling system: BURN subsystem, part 1.' USDA Forest Service, General Technical Report INT-194. (Ogden, UT)
Andrews PL, Bevins CD, Seli RC (2003) 'BehavePlus fire modeling system, version 2.0: User's Guide.' USDA Forest Service, General Technical Report RMRS-GTR-106WWW. (Ogden, UT)
Bessie WC, Johnson EA (1995) The relative importance of fuels and weather on fire behavior in subalpine forests. *Ecology* **76**, 747–762.
Breiman L, Friedman JH, Olshen RA, Stone CG (1984) 'Classification and regression trees.' (Wadsworth International Group: Belmont, CA)
Byram GM (1959) Combustion of forest fuels. In 'Forest fire control and use'. (Ed. KP Davis) pp. 61–89. (McGraw-Hill: New York)
Chafer CJ, Noonan M, MacNaught E (2004) The post-fire measurement of fire severity and intensity in the Christmas 2001 Sydney wildfires. *International Journal of Wildland Fire* **13**, 227–240. doi:10.1071/WF03041
Cruz MG, Alexander ME, Wakimoto RH (2003) Assessing canopy fuel stratum characteristics in crown fire prone fuel types of western North America. *International Journal of Wildland Fire* **12**, 39–50. doi:10.1071/WF02024
De'ath G, Fabricius KE (2000) Classification and regression trees: a powerful yet simple technique for ecological data analysis. *Ecology* **81**, 3178–3192.
Finney MA, Bartlette R, Bradshaw L, Close K, Collins BM, *et al.* (2003) Fire behavior, fuels treatments, and fire suppression on the Hayman Fire. In 'Hayman fire case study'. (Ed. RT Graham) pp. 59–96. USDA Forest Service, General Technical Report RMRS-GTR-114. (Ogden, UT)
Franklin JF, Dyrness CT (1973) 'Natural vegetation of Oregon and Washington.' USDA Forest Service, General Technical Report PNW-GTR-8. (Portland, OR)
Graham RT, McCaffrey S, Jain TB (2004) 'Science basis for changing forest structure to modify wildfire behavior and severity.' USDA Forest Service, General Technical Report RMRS-GTR-120. (Fort Collins, CO)
Hely C, Flannigan M, Bergeron Y (2003) Modeling tree mortality following wildfire in southeastern Canadian mixed-wood boreal forest. *Forest Science* **49**, 566–576.
Heyerdahl EK, Brubaker LB, Agee JK (2001) Spatial controls of historical fire regimes: a multiscale example from the interior west, USA. *Ecology* **82**, 660–678.
Huff MH, Seavy NE, Alexander JD, Ralph CJ (2005) Fire and birds in the maritime Pacific Northwest. *Studies in Avian Biology* **30**, 46–62.

Jackson WD (1968) Fire, air, earth, and water—an elemental ecology of Tasmania. *Proceedings of the Ecological Society of Australia* **3**, 9–16.

Jain TB (2004) Tongue-tied. *Wildfire* **July/August**, 22–26.

Jimerson TM, Jones DW (2003) Megram: blowdown, wildfire, and the effects of fuel treatment. In 'Proceedings of fire conference 2000: The first national congress on fire ecology, prevention, and management'. (Eds KEM Galley, RC Klinger, NG Sugihara) pp. 55–59. (Tall Timbers Research Station: Tallahassee, FL)

Legendre P, Dale MRT, Fortin MJ, Casgrain P, Gurevitch J (2004) Effects of spatial structures on the results of field experiments. *Ecology* **85**, 3202–3214.

Moritz MA, Keeley JE, Johnson EA, Schaffner AA (2004) Testing a basic assumption of shrubland fire management: does the hazard of burning increase with the age of fuels? *Frontiers in Ecology and Environment* **2**, 67–72.

Odion DC, Frost EJ, Strittholt JR, Jiang H, DellaSala DA, Moritz MA (2004*a*) Patterns of fire severity and forest conditions in the western Klamath Mountains, California. *Conservation Biology* **18**, 927–936. doi:10.1111/J.1523-1739.2004.00493.X

Odion DC, Frost EJ, DellaSala DA, Strittholt JR, Jiang H, Moritz MA (2004*b*) Fire and vegetation dynamics in the western Klamath Mountains. In 'Proceedings of the Second Conference on Klamath-Siskiyou Ecology'. (Eds KL Mergenthaler, JE Williams, ES Jules) pp. 71–80. (Siskiyou Field Institute: Cave Junction, OR)

Omi PN, Martinson EJ (2002) 'Effects of Fuels Treatment on Wildfire Severity.' Final Report submitted to the Joint Fire Sciences Governing Board. Available at http://www.cnr.colostate.edu/frws/research/westfire/FinalReport.pdf [Verified 20 March 2006]

Pollet J, Omi PN (2002) Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *International Journal of Wildland Fire* **11**, 1–10. doi:10.1071/WF01045

R Development Core Team (2003) 'R: A language and environment for statistical computing. R Foundation for Statistical Computing.' (Vienna, Austria) Available at http://www.R-project.org [Verified 20 March 2006]

Ralph CJ, Guepel GR, Pyle P, Martin TE, Desante DF (1993) 'Handbook of field methods for monitoring landbirds.' USDA Forest Service, General Technical Report PSW-GTR-144. (Albany, CA)

Rothermel RC (1983) 'How to predict the spread and intensity of wildfires.' USDA Forest Service, General Technical Report INT-143. (Ogden, UT)

Schmoldt DL, Peterson DL, Keane RE, Lenihan JM, McKenzie D, Weise DR, Sandberg DV (1999) 'Assessing the effects of fire disturbance on ecosystems: a scientific agenda for research and management.' USDA Forest Service, General Technical Report PNW-GTR-455. (Portland, OR)

Schoennagel T, Veblen TT, Romme WH (2004) The interaction of fire, fuels, and climate across Rocky Mountain forests. *Bioscience* **54**, 661–676.

Stage AR (1976) An expression for the effect of aspect, slope, and habitat type on tree growth. *Forest Science* **22**, 457–460.

Stephens SL (1998) Evaluation of the effects of silviculture and fuels treatments on potential fire behavior in Sierra Nevada mixed conifer forests. *Forest Ecology and Management* **105**, 21–35. doi:10.1016/S0378-1127(97)00293-4

Swetnam TW, Betancourt JL (1990) Fire–southern oscillation relations in the southwestern United States. *Science* **249**, 1017–1020.

Taylor AH, Skinner CN (1998) Fire history and landscape dynamics in late-successional reserve, Klamath Mountains, California, USA. *Forest Ecology and Management* **111**, 285–301. doi:10.1016/S0378-1127(98)00342-9

Taylor AH, Skinner CN (2003) Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. *Ecological Applications* **13**, 704–719.

Turner MG, Romme WH, Gardner RH (1999) Prefire heterogeneity, fire severity, and early post-fire plant reestablishment in subalpine forests of Yellowstone National Park, Wyoming. *International Journal of Wildland Fire* **9**, 21–36. doi:10.1071/WF99003

Uhl C, Kauffman JB (1990) Deforestation, fire susceptibility, and potential tree responses to fire in the eastern Amazon. *Ecology* **71**, 437–449.

Weatherspoon CP, Skinner CN (1995) An assessment of factors associated with damage to tree crowns from the 1987 wildfires in northern California. *Forest Science* **41**, 430–451.

Whitlock C (2004) Forest, fires, and climate. *Nature* **432**, 28–29. doi:10.1038/432028A

Whitlock C, Shafer SL, Marlon J (2003) The role of vegetation change in shaping past and future fire regimes in the north-west US and the implications for ecosystem management. *Forest Ecology and Management* **178**, 5–21. doi:10.1016/S0378-1127(03)00051-3

Whittaker RH (1960) Vegetation of the Siskiyou Mountains, Oregon and California. *Ecological Monographs* **30**, 279–338.

Wills RD, Stuart JD (1994) Fire history and stand development of a Douglas-fir/hardwood forest in northern California. *Northwest Science* **68**, 205–212.