Factors influencing fire severity under moderate burning conditions in the Klamath Mountains, northern California, USA

BECKY L. ESTES,[1,4],† ERIC E. KNAPP,[1] CARL N. SKINNER,[1] JAY D. MILLER,[2] AND HAIGANOUSH K. PREISLER[3]

[1]Pacific Southwest Research Station, USDA Forest Service, Redding, California 96002 USA
[2]Pacific Southwest Region, Fire and Aviation Management, USDA Forest Service, McClellan, California 95652 USA
[3]Pacific Southwest Research Station, USDA Forest Service, Albany, California 94710 USA

Abstract. Topography, weather, and fuels are known factors driving fire behavior, but the degree to which each contributes to the spatial pattern of fire severity under different conditions remains poorly understood. The variability in severity within the boundaries of the 2006 wildfires that burned in the Klamath Mountains, northern California, along with data on burn conditions and new analytical tools, presented an opportunity to evaluate factors influencing fire severity under burning conditions representative of those where management of wildfire for resource benefit is most likely. Fire severity was estimated as the percent change in canopy cover (0–100%) classified from the Relativized differenced Normalized Burn Ratio (RdNBR), and spatial data layers were compiled to determine strength of associations with topography, weather, and variables directly or indirectly linked to fuels, such as vegetation type, number of previous fires, and time since last fire. Detailed fire progressions were used to estimate weather (e.g., temperature, relative humidity, temperature inversions, and solar radiation) at the time of burning. A generalized additive regression model with random effects and an additional spatial term to account for autocorrelation between adjacent locations was fitted to fire severity. In this fire year characterized by the relative absence of extreme fire weather, topographical complexity most strongly influenced severity. Upper- and mid-slopes tended to burn at higher fire severity than lower-slopes. East- and southeast-facing aspects tended to burn at higher severity than other aspects. Vegetation type and fire history were also important predictors of fire severity. Shrub vegetation was more likely to burn at higher severity than mixed hardwood/conifer or hardwood vegetation. As expected, fire severity was positively associated with time since previous fire, but the relationship was non-linear. Of the weather variables analyzed, temperature inversions, common in the complex topography of the Klamath Mountains, showed the strongest association with fire severity. Inversions trapped smoke and had a dampening effect on severity within the landscape underneath the inversion. Understanding the spatial controls on mixed-severity fires allows managers to better plan for future wildfires and aide in the decision making when managing lightning ignitions for resource benefit might be appropriate.

Key words: fire severity; Klamath Mountains; temperature inversions; topography; weather.

[4] Present address: Pacific Southwest Region, USDA Forest Service, Eldorado National Forest, Placerville, California 95667 USA.
† **E-mail:** bestes@fs.fed.us

INTRODUCTION

Fire is an important ecological process in many forested landscapes, with variation in the intensity and resulting severity strongly influencing forest structure and shaping habitat for a diversity of species. Fire regimes vary greatly among ecosystems, ranging from predominantly low-severity surface fire, where intensity causes little change to the overstory vegetation, to stand-replacing crown fire. The fire regime in forested areas of northwestern California lies somewhere between these extremes, with still relatively frequent but commonly mixed-severity effects (Perry et al. 2011). Patterns of fire severity are influenced by factors that drive fire behavior, namely topography, weather, and fuels. Our understanding of the degree to which each contributes to the spatial patterns of ecological change (fire severity) across a diversity of forested landscapes and under different burning conditions is improving (e.g., Alexander et al. 2006, Collins et al. 2007, Lentile et al. 2007, Holden et al. 2009, Thompson and Spies 2009, Bradstock et al. 2010, Miller et al. 2012*a*, Prichard and Kennedy 2014) but many details remain inadequately understood. Adding to the complexity are a warming climate and increasing fuel loading and continuity as a result of fire exclusion, all of which can influence fire frequency and severity (Miller and Urban 1999, Westerling et al. 2006, Cansler and McKenzie 2014).

Topography (e.g., elevation, slope, aspect, complexity) influences fire behavior directly, with rate of spread greatest on steeper slopes (Rothermel 1972), and heading fire more probable on upper-slope than on lower-slope positions (Skinner et al. 2006). Topography also influences biophysical gradients such as solar radiation and topographic moisture, thereby altering fuel composition and availability for consumption (Holden et al. 2009). Annual and daily meteorological patterns can heavily influence fire behavior (Martín and Birk 2010) in any given fire season (climate) or day (temperature, relative humidity, wind). Fuel, a factor that can be manipulated through management, is a function of vegetation, which is controlled by topographic gradients, climate, and modified by time since previous fire or the severity of previous fire(s) (Collins et al. 2008, Holden et al. 2009).

The degree of influence of topography on fire severity is often related to the degree of topographic complexity of the landscape. Strong relationships between topography and fire severity have been reported in the Klamath-Siskiyou region (Weatherspoon and Skinner 1995, Taylor and Skinner 1998, Jimerson and Jones 2003), as well as in other mixed fire severity regimes in the Mediterranean (Oliveras et al. 2009), Australia (Bradstock et al. 2010), and southern Appalachian mountains (Wimberly and Reilly 2007). Conversely, other studies have found little association between topography and fire severity patterns. For example, following a lightning-ignited wildfire in a frequently burned Sierra Nevada forest, Collins et al. (2007) found only a weak relationship between topography and fire severity, and Turner et al. (1999) reported severity in the 1988 Yellowstone fires, which burned across a relatively gentle landscape, to be unrelated to topography.

Weather parameters at the time of burning are often difficult to obtain or estimate (Collins et al. 2007, Thompson and Spies 2009). The increasing availability of daily fire progression maps linked to weather recorded at nearby remote automated weather stations (RAWS) can provide a rough index of weather at the time of burning. However, progressions are usually only created for large fires and are often only created daily under times of highest spread. At times of reduced fire behavior (low spread), fire progression maps may only be produced every few days. Still, weather variables linked to progression maps do provide a coarse index of fire weather conditions among burning periods for a fire.

Neglecting to include weather variables may lead to spurious conclusions about the relative importance of factors contributing to fire severity. In addition, the contribution of weather, relative to other factors, may vary greatly over different burning conditions within fires. For example, during benign weather conditions, severity may be influenced more strongly by variability in topography and fuels (Bradstock et al. 2010), whereas extreme conditions may overwhelm the effects of non-weather variables on severity (Bigler et al. 2005, Nunes et al. 2005). For example, Thompson and Spies (2009), evaluating the large Biscuit fire in the topographically complex Klamath-Siskiyou region, found that severity patterns were not closely tied to topography, presumably because a

severe wind event was responsible for nearly half of the total area burned. Another weather-related factor potentially having considerable effect on fire behavior is temperature inversions. Temperature inversions reduce lift of the smoke plume and trap smoke near the surface, leading to lower surface temperatures and higher relative humidity, thereby substantially suppressing fire activity (Robock 1988, Weatherspoon and Skinner 1995, Skinner et al. 2006, Sharples 2009). To date, no research has been conducted to approximate the location of temperature inversions and quantify effects of temperature inversions on fire severity.

The 2006 fire season in the Klamath Mountains of Northwest California provides an opportunity to assess the mechanisms driving severity of fires burning under average conditions following a period of wetter than normal fall/winter/spring precipitation. These or similar conditions are ones most optimal for management of wildfires to achieve resource benefits, and modeling the controls on fire severity will provide managers tools to better understand effects of such wildfires. We employed new data sources and techniques to address shortfalls that have limited a better understanding of mechanisms regulating fire severity in the past. A complete data set spanning multiple fires greater than 400 ha primarily in wilderness land allocation on the Klamath and Six Rivers National Forests was developed to explore a wide range of biotic and abiotic relationships with patterns of fire severity. One advantage of these fires for studying controls on severity was the long burning period (July–October), which captured a large range of weather conditions. We also considered the effect of temperature inversions on fire severity patterns for the first time, and used robust statistical analyses to control for spatial autocorrelation, which can otherwise interfere with or confound relationships between variables of interest and fire severity.

METHODS

Study area

The Klamath Mountains cover approximately 225,000 km^2 between the California Coast Ranges and the Cascade Ranges in northern California (Fig. 1). The climate is Mediterranean with long, hot summers and cool, wet winters. The Klamath Mountains are characterized by complex topography with steep canyons and tall peaks over a broad range of elevations (30–2775 m), which heavily influences the structure and composition of vegetation (Skinner et al. 2006). The vegetation can be classified into three zones with the lower elevation dominated by a mix of conifers with *Pseudotsuga menzesii* Mirbel (Douglas-fir) being the most important, along with hardwoods such as *Quercus garryana* Douglas ex Hook. (Oregon white oak) and *Quercus kelloggi* Newberry (black oak). The mid-elevation contains a mix of hardwoods and a diverse array of conifer species including *Pinus ponderosa* C. Lawson (ponderosa pine), *Pinus lambertiana* Douglas (sugar pine), and *Calocedrus decurrens* (Torr.) Florin (incense cedar). At higher elevations, *Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr. (white fir) and *Abies × shastensis* (Lemmon) Lemmon [*magnifica × procera*] (Shasta red fir) replace the pines (Skinner et al. 2006). Prior to extensive Euro-American influence, lower- to mid-elevation mixed conifer/hardwood forests of the Klamath Mountains historically burned every 5–19 yr (Taylor and Skinner 1998, 2003, Fry and Stephens 2006), with riparian areas and higher-elevation forests burning somewhat less frequently (Stuart and Salazar 2000, Skinner 2003). However, due to fire suppression as well as the reduction in Native American fire use, most areas have burned less frequently in the recent recorded history and some not at all since 1908 (Miller et al. 2012*b*). As a result, fuel levels are elevated compared to historical conditions.

Fire characteristics

Five lightning-ignited fires that burned on the Klamath and Six Rivers National Forests during the summer and fall of 2006 were selected for this study (Table 1, Fig. 1). The 2006 fire season followed a fall/winter/spring where precipitation was 50% above average (based on monthly precipitation values from 1936 to 2016 from three of the closest weather stations with long-term precipitation records (Happy Camp, Fort Jones, and Orleans; California Data Exchange Center). The 2006 water year was the fourth or fifth wettest during this time period—years with precipitation equaling or exceeding these amounts happen on average every 16–20 yr. As a result, the fire season started slowly, with burning index (BI: an index of potential fire intensity used by fire management agencies that integrates variables controlling the
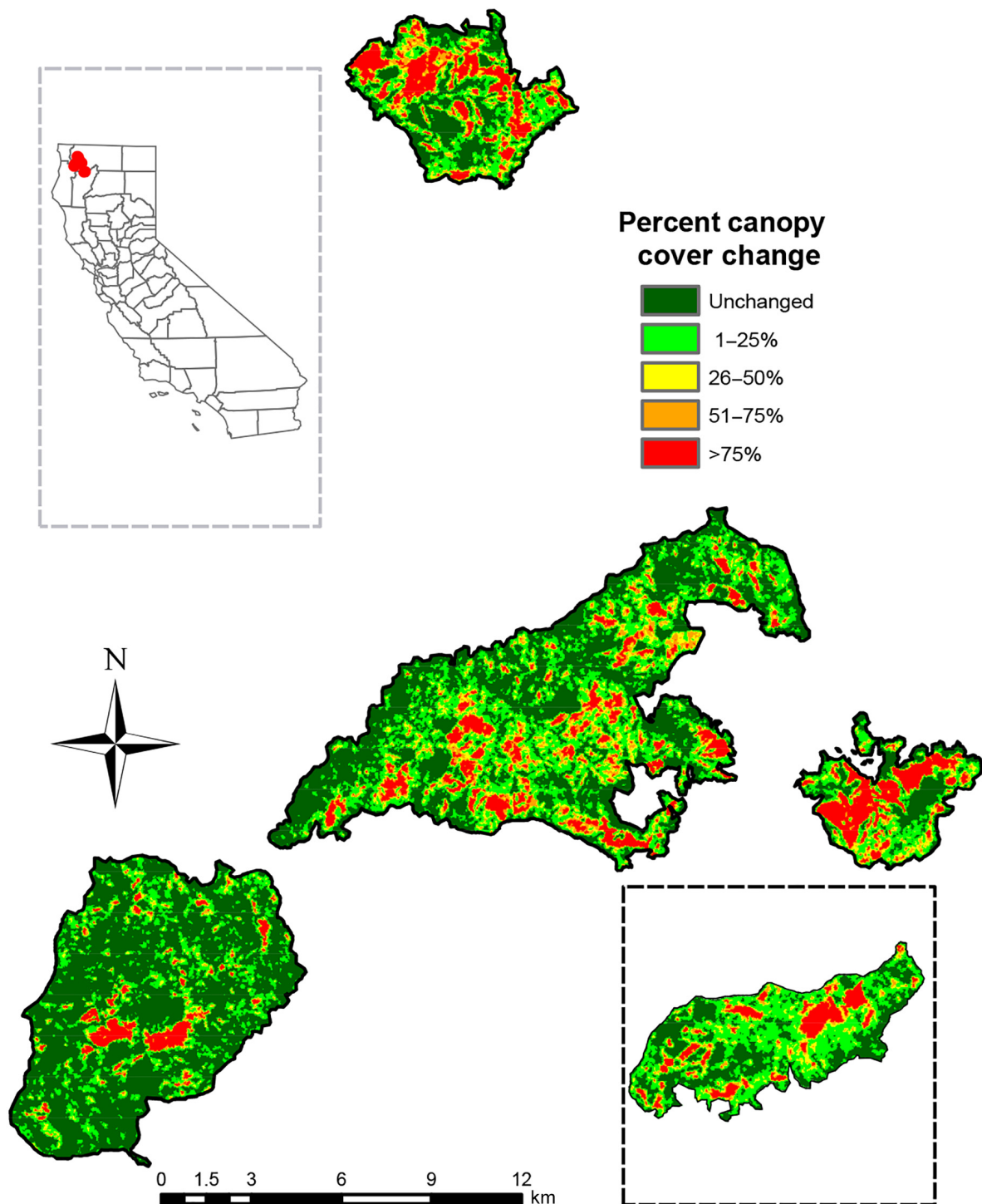
Fig. 1. Study area showing the perimeter and one year post-fire severity within the Titus, Hancock, Uncles, and Somes Fires (from north to south). The Rush Fire (inset) occurred off the map, southeast of the Uncles Fire. All fires are located in the Klamath Mountains of California and burned during the summer and fall of 2006.

Table 1. Fire name, location, ignition date, control date, total hectares burned, and percentage of vegetated acres burned at low to moderate and high severities (high severity defined as ≥75% canopy cover change) in the 2006 lightning fires in the Klamath Mountains, California, USA.

Fire name	Location	Ignition date	Control date	Total hectares	Low to moderate severity (%)	High severity (%)
Hancock	123°27′7″, 41°18′57″	23 July	23 October	8972	82	18
Rush	123°2′6″, 41°7′43″	23 July	2 October	2080	80	20
Somes	123°27′38″, 41°20′27″	24 July	8 November	6323	92	8
Titus	123°21′4″, 41°36′41″	23 July	24 September	2538	68	32
Uncles	123°10′35″, 41°24′1″	23 July	23 October	7142	61	39

forward spread of a fire, such as wind speed, and fuel consumption, such as fuel moisture) values mostly below average through June, near average in July and August, and somewhat above average for a few time periods in September and October as the fire season shifted down from its peak (Fig. 2). Overall, the fire season was about average with the BI exceeding the 97th percentile on only five days (Fig. 2). These would be the conditions under which the most extreme fire behavior might be expected, should weather be a major controlling factor. Thunderstorms, some accompanied by copious rainfall, in late July resulted in numerous fire ignitions, some of which burned until the fall rains in late September and October. Approximately 69,000 ha of the Klamath Mountains burned during this period. Fires occurred primarily in wilderness but also burned managed private
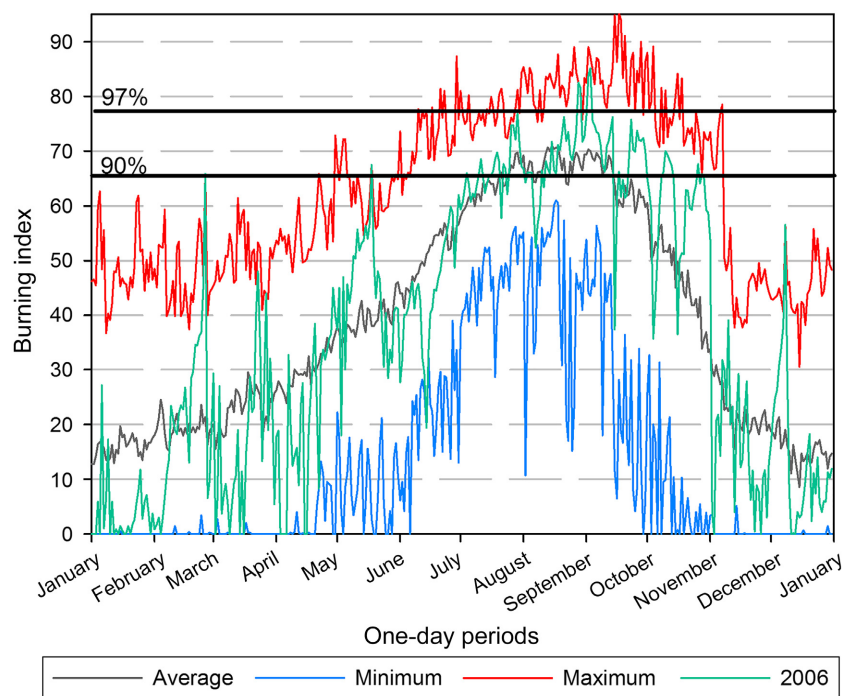

Fig. 2. Burning index (BI) values over the course of the 2006 fire year for the western Klamath National Forest, compared to 18-yr (1997–2015) minimum, maximum, and average values for the same dates. The BI is a measure of potential fire behavior/difficulty of control used by fire management agencies which integrates variables associated with the forward rate of spread of a fire (e.g., wind speed) and consumption of fuel (e.g., fuel moisture). The BI was calculated using data from nine weather stations located in or near the western half of the Klamath National Forest, using the program Fire Family Plus.

and Forest Service land across a broad range of elevations and vegetation types. The Bar/Pigeon complex (40,636 ha), which burned predominantly on the Shasta-Trinity National Forest, was not included because the Pigeon Fire was human-caused and started adjacent to a major highway. While the Pigeon Fire eventually burned together with the lightning-ignited Bar Fire, the human cause and greater proximity to infrastructure led this fire to be managed differently with a larger proportion of the area within the fire perimeter potentially being influenced by fire management tactics, such as burnout operations.

Fire progression maps for the periods between 25 July 2006 and 4 October 2006 were obtained for all five fires from the Klamath National Forest and the National Interagency Fire Center. These maps show the daily progression of each fire during the more active fire periods and the multi-day progression during periods with less-active fire spread. The fire progression maps allowed fire weather variables and solar radiation grids to be linked spatially and temporally, producing average fire weather and solar radiation for each day.

Fire severity

Fire severity is defined as the magnitude of ecological effect of fire (Sugihara et al. 2006) usually described as amount of physical change (Sousa 1984) and is a function of biological and physical variables that influence fire behavior. The differenced Normalized Burn Ratio (dNBR), a measure of absolute change between pre- and post-fire Landsat satellite images, is commonly used to map severity (Key and Benson 2006). However, dNBR is correlated with pre-fire vegetation conditions, and categorical maps developed from dNBR have been shown to underrepresent high-severity fire (Miller and Thode 2007, Kolden et al. 2015, Whittier and Gray 2016). To avoid biasing by pre-fire conditions, we used a Relativized dNBR (RdNBR) computed by dividing dNBR by a function of the pre-fire image (Miller and Thode 2007).

Containment dates of the fires in our study occurred in late October and early November (Table 1). Therefore, immediate post-fire satellite images could not be used because steep north-facing slopes at this latitude are obscured by shadows due to low sun angles this late in the calendar year. Therefore, RdNBR data were derived from an image acquired 13 August 2007,

the first summer after the fires occurred. Fire effects recorded with one year post-fire images can include immediate as well as delayed effects, such as conifer mortality or resprouting of shrubs (Key 2006). Areal extent of stand-replacing fire can consequently be underestimated, especially where species that respond by resprouting dominate. In forested environments, Landsat images are primarily correlated with variables describing the upper tree canopy, because effects to the understory are obscured (Cohen and Spies 1992, De Santis and Chuvieco 2007). Percent change in canopy cover, herein termed "fire severity," was used as the measure of the effects of fire on vegetation in this study (Table 2). The RdNBR raster data were transformed into a continuous measure of percent change in canopy cover (0–100%) using calibrations previously derived using plot-level data acquired in part within the perimeters of the same five 2006 fires (Miller et al. 2009).

Topographic data layers

Topography quantitatively describes the terrain of a landscape using different components (elevation, aspect, slope percent, and slope position; Table 2). These variables have different effects on behavior as fire moves across the landscape. Elevation can explain changes in temperature following the adiabatic lapse rate, especially in topographically complex terrain. Aspect influences the amount of solar radiation and moisture availability, which contribute to fire behavior directly, as well as indirectly through differences in vegetation composition and density. Slope percent is a key factor influencing fire intensity, with steeper slopes leading to greater preheating of fuels and increased rate of spread when fire is moving upslope. The probability of fire moving uphill or backing downhill is influenced by slope position, with lower-slope positions more likely to experience lower flame lengths and lower rates of spread in a backing fire. Slope position and elevation are also indicators of vegetation type, with upper slopes tending to contain more sclerophyllous vegetation and lower slopes dominated by more mesic vegetation.

The amount of solar radiation reaching a specific location is a function of the topographic elevation, aspect, and slope (Table 2). We calculated potential solar radiation (kJ·m^{-2}·d^{-1}) by taking into account both direct and diffuse radiation and

Table 2. Variables analyzed in the regression models explaining patterns of fire severity in the Klamath Mountains, California, USA.

Variables	Source	Type	Description
Vegetation fire severity	Remote Sensing Lab, USDA Forest Service, Pacific Southwest Region	Continuous	0–100%
Elevation	Raw elevation from DEM	Continuous	155–2175 m
Slope position	Generated from a 30-m DEM utilizing David Hatfield's (Digital Visions Enterprise) slope position model	Categorical	Lower 1/3, middle 1/3, upper 1/3
Aspect class	Derived from DEM using ArcGIS Spatial Analyst	Categorical	N (337.5°–22.5°), NE (22.5°–67.5°), E (67.5°–112.5°), SE (112.5°–157.5°), S (157.5°–202.5°), SW (202.5°–247.5°), W (247.5°–292.5°), NW (292.5°–337.5°), F (flat)
Slope (%)	Derived from DEM using ArcGIS Spatial Analyst	Continuous	0–171%
Potential solar radiation	Modeled using shortwave models (Kumar et al. 1997) with elevation, slope, aspect, shading, the time interval during each fire progression perimeter, and latitude.	Continuous	$(kJ \cdot m^{-2} \cdot d^{-1})$ 0–28,246
Inversion × Elevation	Temporal occurrence of an inversion layer categorized by elevation	Continuous	Above 1300 m: no inversion; below 1300 m: no inversion or evidence of inversion on this date.
Temperature and relative humidity	Weather variables were calculated from RAWS data located above or below the inversion and summarized using Fire Family Plus	Continuous	14.5°–29.3°C 27.4–61.4%
Vegetation cover	CalVeg Cover 2004	Categorical	Hardwood, conifer, mixed, herbaceous
Time since last fire	Time since the last recorded fire; this information is used as an indication of fuel loading across the landscape.	Continuous	6–93
Number of fires	Number of fires between 1908 and 2006 derived from the California fire history database.	Categorical	0–4

Note: DEM, Digital Elevation Model; RAWS, Remote Automated Weather Stations.

using latitude, elevation, slope, aspect, and shading in homogeneous clear sky conditions. In order to model the temporal changes during the fires, average solar radiation was calculated for each period during which fire progressions were available. Solar radiation was calculated using the shortwave models developed by Kumar et al. (1997; Table 2).

National fire danger rating indices and weather variables

Hourly weather variables were obtained from six Remote Automated Weather Stations (RAWS) within the Klamath National Forest, California. Mean, minimum, and maximum temperature and relative humidity were calculated for each period during which fire progressions were available in order to model the temporal changes during the fire (Table 2).

Of particular interest are temperature inversions that frequently occur during widespread fire events in this landscape (Robock 1988, Skinner et al. 2006). Observations from the fire line suggest that inversions have a considerable effect on fire behavior. The multiple fires burning in the Klamath Mountains in 2006 generated significant amounts of smoke. The ignition of these fires was followed by several periods with stable atmospheric conditions characterized by subtropical highs. These weather conditions led to subsidence inversions that trapped smoke and reduced mixing, leading to lower surface temperatures and higher relative humidity that substantially suppressed fire activity (Robock 1988, Weatherspoon and Skinner 1995, Skinner et al. 2006, Sharples 2009). Fire severity above the inversion has been observed to be similar to or greater than below the inversion due to lower relative humidity and higher temperatures (Robock 1988). When the inversions dissipate, either by a changing air mass or higher winds, fire spread can increase dramatically, often leading to large patches

of high fire severity such as seen in the 1999 Megram, 2008 Motion, and 2008 Panther fires. To quantify the presence or absence of inversions on a specific progression day, the Absorbed Photosynthetically Active Radiation (APAR; watts/m^2), obtained from the RAWS, was analyzed. During inversions, APAR should be reduced at weather stations located below the smoke layer relative to stations above, and this decrease in APAR provides quantitative evidence of the temporal extent of an inversion layer. Observations by fire management personnel suggest that inversions in the Klamath Mountains often set up at an elevation of approximately 1300 m. Utilizing the six RAWS across the Klamath Mountains bioregion (three below and three above 1300 m), APAR was compiled from 0600 to 2000 Pacific Daylight Savings Time. The hourly APAR was differenced to capture hours when sunlight was not fully penetrating the smoke inversion layer. A non-parametric Wilcoxon signed rank test was employed to determine whether a significant daily difference existed between the RAWS above and below the inversion using a *P*-value of 0.01. Moderate-Resolution Imaging Spectroradiometer (MODIS) images were visually examined to provide further validation of days when strong smoke-trapping inversions were present (NASA EOSDIS Land Processes Distributed Active Archive Center [LP DAAC], USGS/Earth Resources Observation and Science [EROS] Center, Sioux Falls, South Dakota, USA). Presence or absence of an inversion was then spatially linked to the daily fire progressions for each fire. In addition, the inversion was modeled as an interaction with elevation in the final output.

Vegetation and previous fire history

Vegetation types differ in the structure and rate of development of fuels, and the number of fires and time since last fire provide a rough indication of fire-related effects to vegetation that might have occurred as well as potential surface fuel availability. For example, because lightning-ignited fires in this landscape typically produce low- to moderate-severity effects over the majority of acres burned (Miller et al. 2012*b*), areas burned numerous times would be expected to have, on average, less-abundant ladder fuels and areas burned most recently would be expected to have, on average, less surface fuel. The vegetation types within the 2006 fires were classified as shrub, herbaceous, conifer, mixed conifer/hardwood, or hardwood, based on vegetation maps developed by the USDA Forest Service, Pacific Southwest Region's Remote Sensing Lab (CALVEG 2004; Table 2). The number of fires since 1908 (range = 0–4) and time since the previous fire (range = 0–93 yr) were calculated for areas that occurred within the perimeters of the 2006 fires, using the interagency California digital fire history database which contains fire perimeters for fires beginning in 1908 through the present (available online at http://frap.fire.ca.gov/data/frapgisdata-sw-fireperimeters_download; Table 2). Locations within the fire perimeters with no record of fire since 1908 were assumed to have burned during the previous large fire year (1896; ≈110 yr since the previous fire). This database is the most complete compilation of perimeters of fires >4 ha for the state, but perimeters for many small fires <40 ha prior to 1970 are likely missing.

Spatial data analyses

Analysis was conducted on the full set of data with 226,110 pixels/observations in all five of the fires (Table 3). A generalized additive regression model (GAM) with random effects was fitted to the square root of percent canopy cover change (CC) with smooth spline functions of the continuous covariates. Although other methods exist to

Table 3. Number of pixels analyzed (*n*) and summary statistics (mean, range) for topographic, fire history, and weather variables observed in the Klamath 2006 fires.

Fires	Elevation (m)	Slope (%)	Solar radiation (kJ·m^{-2}·d^{-1})	Time since fire (yr)	Mean daily temperature (°C)	Mean daily relative humidity (%)
Hancock (*n* = 95,998)	1063 (216–2054)	63 (0–171)	17,001 (0–28,185)	35 (7–93)	19 (14–27)	44 (27–58)
Rush (*n* = 21,523)	1490 (889–2146)	45 (0–117)	25,510 (14,056–28,246)	93 (29–93)	22 (18–29)	45 (39–61)
Somes (*n* = 67,112)	776 (155–1772)	63 (0–162)	20,928 (0–28,162)	79 (6–93)	21 (17–29)	45 (36–61)
Titus (*n* = 25,006)	1444 (666–1982)	49 (0–136)	21,750 (1254–28,230)	19 (19–19)	22 (17–29)	40 (33–55)
Uncles (*n* = 16,471)	1623 (1058–2175)	52 (1–123)	23,846 (4477–28,245)	82 (12–93)	24 (18–29)	40 (27–58)

model spatially explicit data, these are often limited to linear relationships. Generalized additive regression models allowed the flexibility of modeling non-linear relationships present in the data set. We were able to take advantage of the flexibility in GAM in particular because there was no remaining autocorrelation in the residuals from the fitted models (Fig. 3).

The regression model was

$$Y_{ij} = \alpha + \sum_{k} \delta(X_{kj}) + \sum_{m} s(X_{mj}) + s(x\text{loc}_j, y\text{loc}_j)$$
$$+ \tau_i + \varepsilon_{ij}$$

where $Y_{ij} = \sqrt{(CC)}$ for the jth sample point in the ith fire; α = intercept, $\delta(X_{kj})$ = step function for the kth categorical variable; $s(X_{mj})$ = smooth spline function of the mth continuous variable; $s(x\text{loc}_j, y\text{loc}_j)$ = two-dimensional spline function (surface) of location of each 30-m pixel; τ_i = random effect of ith fire; and ε_{ij} = random error term.

The spatial term $s(x\text{loc}_j, y\text{loc}_j)$, in the regression equation above, was included to account for spatial autocorrelation between adjacent locations not accounted for by the other spatially explicit variables in the model (e.g., elevation). The square root of CC was used as the dependent variable because the histogram of the latter was more symmetric than the untransformed data. The independent/explanatory variables were composed of continuous and categorical variables (e.g., past fire history, vegetation type; Table 2). The random fire effect (the five individual fires) was not significant (SE of the random fire effect was $\hat{\tau} = 1.2 \times 10^{-5}$ as
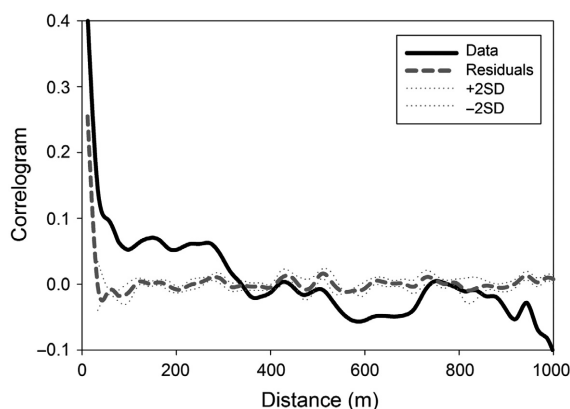

Fig. 3. Correlogram demonstrating the raw data and residuals from the fitted model with a two-dimensional spline function (surface) of distance between pixels.

compared to the SE of the residuals $\hat{\sigma} = 5.498$). Therefore, the final model was fitted without a random fire effect. All spatial analyses were performed in R 3.0.2 (R Development Core Team 2016) using the "mgcv" libraries (Wood 2011). Significance of each categorical variable was determined using the intercept and the associated estimated value at the corresponding level. In order to assess the contribution of each of the predictor variables (continuous and categorical) in the final model, the percentage of relative importance was assessed based on (1) the F value and (2) the SE and range of the partial residuals of each predictor. Spatial autocorrelation was determined by generating correlograms for the raw data and for the residuals from the final model using the "gstat" library in R 2.15.2 (Pebesma 2004).

RESULTS

Fire severity, topography, previous fire history, and weather

Of the acres burned in the five fires, 77% burned at low to moderate severities and 23% burned at high severity (Table 1). The Uncles and Titus Fires had the largest percentage burned at high severity fire followed by the Rush, Hancock, and Somes Fires (Table 1, Fig. 1). Elevation within the fire perimeters ranged from 155 to 2175 m with the lowest mean elevation in the Somes Fire and the highest in the Uncles Fire (Table 3). Slope (%; Table 3) and slope position (Fig. 4a) were fairly equally distributed across all five fires. A greater proportion of the landscape within the Somes Fire occurred on north-facing aspects, while a greater proportion of the Rush and Uncles Fires occurred on south-facing aspects (Fig. 4b). The Hancock and Titus Fires burned approximately equal proportions of north- and south-facing aspects (Fig. 4b).

The majority of acres within the perimeter of the Rush, Somes, and Uncles Fires had no prior record of fire, according to the California fire history database (Fig. 4c). The Hancock Fire had a mean time since fire of 35 yr with numerous locations having burned one, two, or three times prior to 2006. The entire area of the Titus Fire previously burned in the 1987 King Titus Fire (Table 3). Less than 1% of the total hectares in the 2006 fires analyzed burned three or more times since 1908 (Fig. 4c).
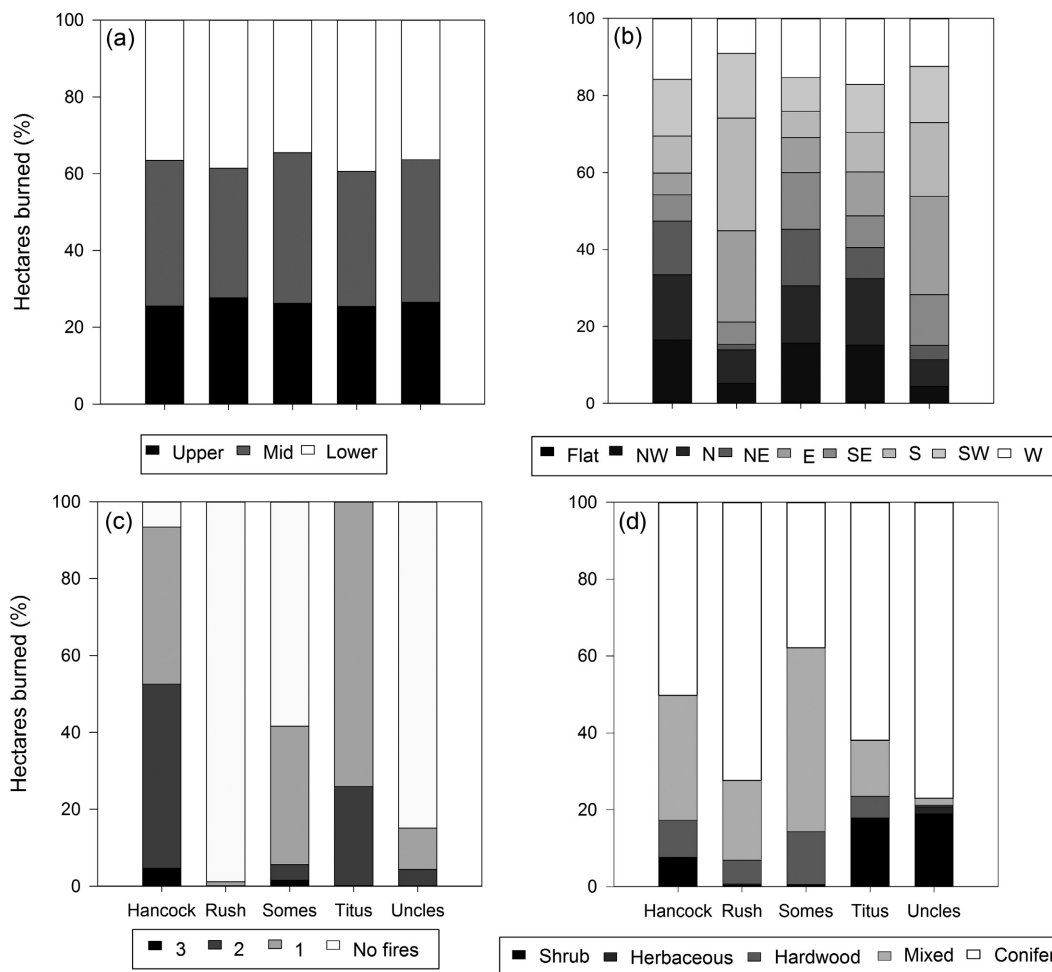
Fig. 4. Distribution (percentage of hectares burned) for categorical variables (a) slope position, (b) aspect class, (c) number of fires, and (d) vegetation cover type in five fires that burned in the Klamath Mountains during the summer and fall of 2006.

Vegetation cover type prior to the 2006 fires was classified as mostly conifer and mixed hardwood/conifer (>80%). Approximately 15% of the area within both the Titus and Uncles Fires consisted of shrubs, with lesser amounts in the remaining three fires (Fig. 4d). Hardwood and mixed hardwood/conifer vegetation dominated the area burned by the Somes Fire, while the majority of forest vegetation within the other four fires was conifer (Fig. 4d). Little area within the 2006 fire perimeters was classified as herbaceous.

The highest mean daily rates of solar radiation were recorded within the Rush (25,510 kJ·m^{-2}·d^{-1}) and Uncles (23,846 kJ·m^{-2}·d^{-1}) Fires (Table 3).

Average daily temperature ranged from a low of 14°C to a high of 29°C, and mean daily relative humidity ranged from a low of 27% to a high of 61% (Table 3).

Influence of inversions

During an inversion, sunlight was absorbed by the thick smoke layer, reducing APAR at the RAWS below 1300 m. A significant difference between APAR above and below the inversion layer was observed on 20 of 45 d analyzed during the 2006 burn period (Figs. 5, 6). On these days, differences between RAWS above and below the inversion ranged from 3.1 to 8.2 watts/m^2.
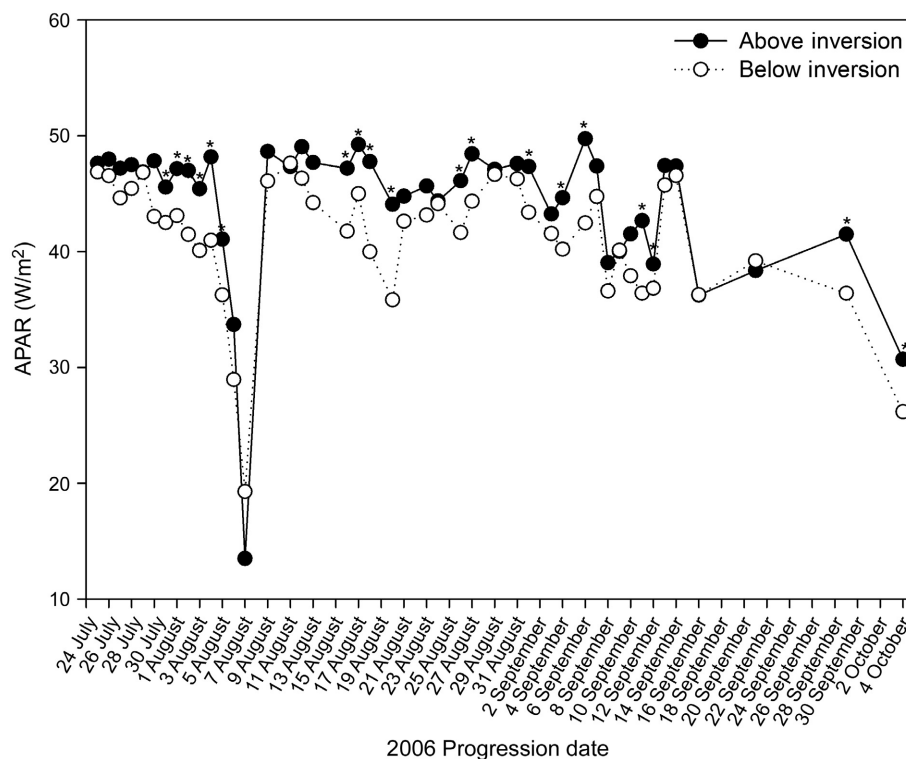
Fig. 5. Absorbed photosynthetically active radiation (APAR; watts/m^2) by progression date comparing RAWS above and below the inversion layer (approximately 1300 m) through the 2006 burn period. Comparison dates that have significant differences are indicated with an asterisk.

Generalized additive model

The predictor variables in the final model (significant at $P < 0.001$; a conservative P was used due to the high statistical power achieved by including all pixels within the fire perimeters) were vegetation type, slope position, aspect class, the number of fires, inversion day by elevation, average temperature, average relative humidity, solar radiation, time since fire, and slope percent (Table 4). The data exhibited a positive spatial correlation up to a distance of approximately 250 m, meaning that locations 250 m apart or less were more likely to have similar fire severities (Fig. 3). In the full model that included spatially explicit covariates (e.g., elevation, aspect, and a function of longitude, longitude referred to as spatial term), the residuals were no longer spatially correlated (Fig. 3). The spatial term in the model is a surrogate for other, unobserved, spatially explicit variables with potential effects on burn severity. The model with all variables, including the spatial variable, explained 26% of the variance in fire severity.

Variables included in final model

Fire severity was highest on east-facing aspects (east, northeast, and southeast), regardless of dominant vegetation class (Table 5). Alternatively, west- and northwest-facing aspects exhibited reduced fire severity (Table 5). Both the mid- and upper slopes had higher fire severity than the lower slopes (Table 5). Lower fire severity was noted on the steepest slopes (>100%), but percent slope had little effect on fire severity overall (Fig. 7a).

For vegetation types, the highest severity occurred where shrubs dominated, and the lowest severity occurred where conifers dominated (Table 5). Hardwood vegetation burned at severities intermediate between shrub and conifer vegetation, and mixed hardwood/conifer vegetation burned at severities intermediate between mixed hardwood and conifer vegetation (Table 5).

Number of fires since 1908, while statistically significant, did not explain much of the variation in fire severity (Table 4). Areas that had burned
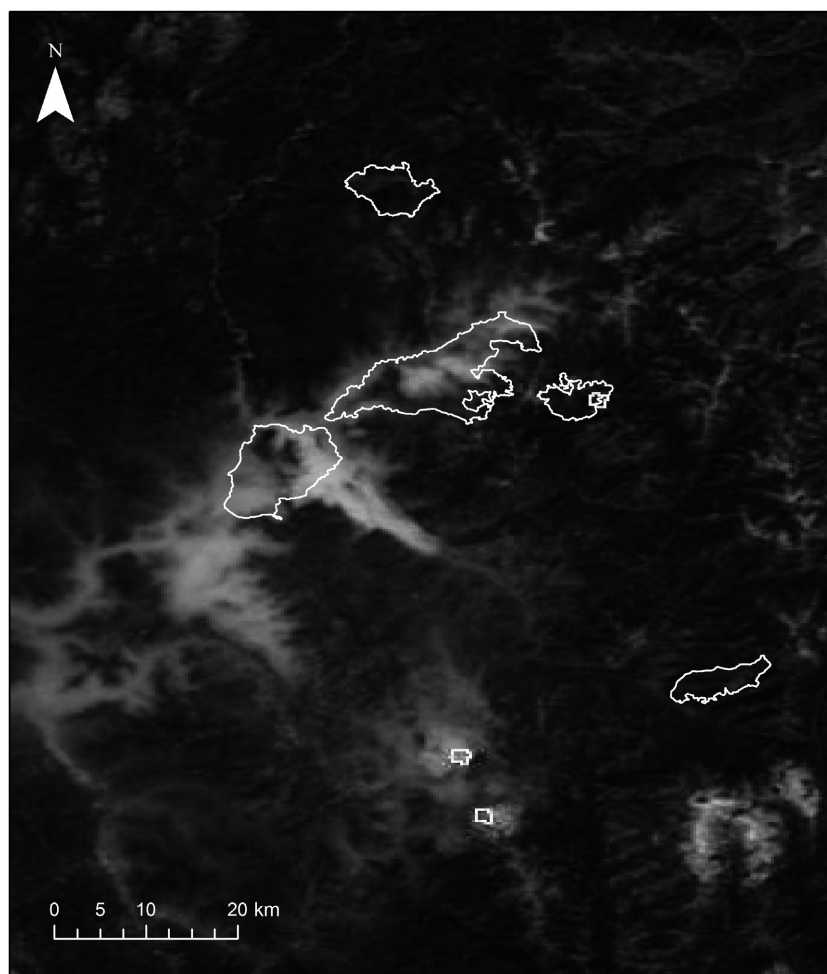
Fig. 6. Moderate-resolution imaging spectroradiometer image from 18 August 2006, illustrating a stagnant smoke layer trapped in valleys of the Klamath Mountains below 1300 m in elevation.

once or twice previously since 1908 had higher fire severity as compared to areas that had burned zero or three times (Table 5). The few areas that burned four times were generally associated with shrub-dominated vegetation (Table 5). Fire severity was lower in areas that had burned less than 20 yr prior (Fig. 7b). Severity tended to be somewhat greater for areas burned within the past 25–35 yr, but was lower again for areas that had not experienced fire for 40–80 yr (Fig. 7b). Severity was highest in areas that had not burned in over 80 yr (Fig. 7b). Areas that burned during periods of low solar radiation ($<$15,000 kJ·m^{-2}·d^{-1}) showed lower fire severity, while severity slowly increased as average daily solar radiation increased above this threshold (Fig. 7c).

In addition to topography and fire history, dominant weather patterns also helped to explain variation in fire severity (Table 4). Fire severity was lower when mean temperatures recorded at RAWS were low (Fig. 7d). Similarly, fire severity was lower when mean relative humidity was high (Fig. 7e). Severity was highest when average temperature exceeded 22°C and average relative humidity dropped below 35% (Fig. 7e).

On days when no inversion was present, the estimated partial effects indicated a positive association between fire severity and elevation (Fig. 8a).

Table 4. The variables used in the final generalized additive model listed according to their importance as indicated by the F statistic.

Dependent variables	df	F	P-value
(A) Categorical variables			
Vegetation type	4	1754.83	<0.001
Slope position	2	680.95	<0.001
Aspect class	8	285.55	<0.001
Number of fires	4	29.51	<0.001
(B) Continuous variables			
No inversion day by elevation	2	1452.60	<0.001
Inversion day by elevation	2	1035.00	<0.001
Average temperature	2	517.90	<0.001
Average relative humidity	2	474.50	<0.001
Location (X, Y)	24	367.70	<0.001
Solar radiation	4	181.30	<0.001
Time since fire	4	137.70	<0.001
Slope percent	4	60.80	<0.001

On days when an inversion was present, all locations burned at similar average severities below the inversion, whereas fire severity increased linearly with elevation above the inversion (Fig. 8b).

DISCUSSION

A better understanding of the drivers of ecological change resulting from wildfire would assist managers in making informed choices for fires where effects to habitat are an important factor in decision making. Wildfires in the Klamath Mountains in 2006 present one set of conditions fires burn under in this landscape. Because the fire season followed a significantly wetter than average winter, both live and dead and down fuels were likely at least initially moister than they might otherwise be during the summer through early fall burning period. In addition, average burning conditions prevailed with relatively stable atmospheric conditions and a lack of strong winds enhanced the likelihood that fire would produce beneficial ecological effects (Fig. 2). This analysis provides managers an idea of the relative strength of different factors controlling fire severity under such burning conditions.

Table 5. The coefficient estimates and significance of each class in the categorical variables used in the final general additive model.

Variables	Estimate	Standard error	T-value	P-value
Intercept	−0.308	0.244	−1.260	0.208
Vegetation type				
Shrub	3.961	0.216	18.343	<0.001
Hardwood	2.643	0.216	12.240	<0.001
Conifer	1.722	0.215	8.025	<0.001
Mixed/hardwood conifer	2.097	0.215	9.749	<0.001
Slope position				
Middle	0.572	0.016	35.103	<0.001
Upper	0.638	0.021	29.996	<0.001
Aspect				
N	−0.063	0.110	−0.570	0.569
NE	0.349	0.111	3.153	0.002
E	0.686	0.112	6.109	<0.001
SE	0.557	0.115	4.855	<0.001
S	0.039	0.116	0.335	0.738
SW	−0.155	0.114	−1.358	0.174
W	−0.252	0.112	−2.261	0.024
NW	−0.171	0.110	−1.548	0.122
Number of fires				
One	0.452	0.069	6.582	<0.001
Two	0.525	0.073	7.214	<0.001
Three	0.099	0.083	1.190	0.234
Four	2.488	1.200	2.074	0.038

Notes: The coefficients are the values to be added to the intercept (−0.308) for each level of the categorical variable. For each variable, one of the levels is randomly assigned an estimated effect of zero to be added to the intercept (e.g., vegetation type, herbaceous; slope position, lower; aspect, flat; and number of fires, zero).
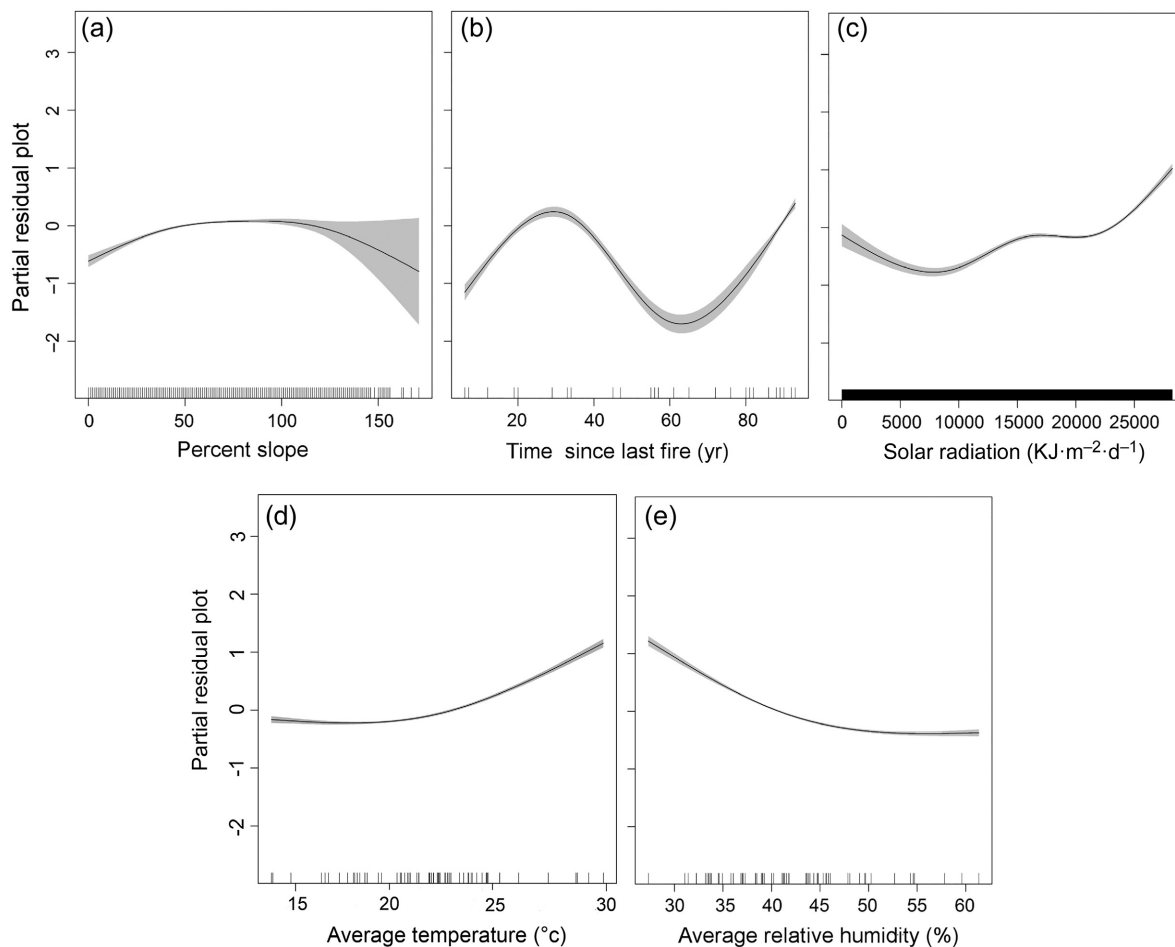
Fig. 7. Estimated partial effects of smoothed terms: (a) percent slope, (b) time since last fire, (c) solar radiation, (d) average temperature, (e) average relative humidity on fire severity (percent change in canopy cover). The zero line provides the average response level, and the shaded area indicates 95% confidence bounds. The vertical lines on the x-axis represent each observation.

Topography: an important driver of fire severity in the Klamath Mountains

Slope position and aspect were the most important topographic drivers of fire severity in these fires. Both mid- and upper-slope positions experienced higher fire severities compared to lower-slope positions including canyon bottoms. One likely cause is that wind speeds are often greater on upper-slope positions (Bradstock et al. 2010). In addition, in part because lightning ignitions tend to occur at higher elevations, lower slopes and canyon bottoms would on average experience a greater percentage of more slowly spreading backing and flanking fire, with faster spreading heading fire more likely on upper

slopes (Agee 1993). Differences in vegetation structure between upper- and lower-slope positions may also contribute to this pattern. The tallest trees are typically found along streams in canyon bottoms due to deeper soils and access to moisture. If effects to trees are the result of crown scorch, when trees are taller the same intensity fire would tend to produce lower-severity effects. We found higher severity on east- and southeast-facing aspects throughout the fires, a pattern similar to that observed by Weatherspoon and Skinner (1995) for a series of lightning-ignited fires burning in the same landscape in 1987. Based on total solar radiation, one might expect to see more high-severity fire on west-facing than
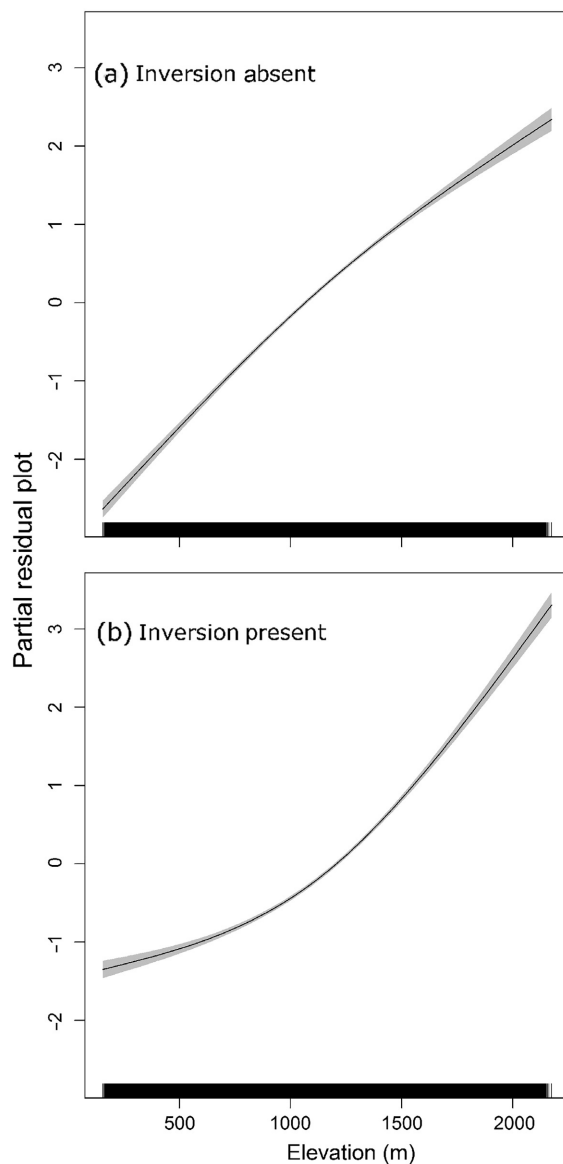
Fig. 8. Estimated partial effects of the (a) interaction between elevation and no inversion presence and (b) interaction between elevation and inversion presence on fire severity (percent change in canopy cover). The zero line provides the average response level, and the shaded area indicates 95% confidence bounds. The vertical lines on the x-axis represent each observation.

on east-facing aspects (Taylor and Skinner 1998). It is therefore possible that the stronger influence on fire severity, in this case, was earlier warming of fuels on east- to southeast-facing aspects. Additionally, east- and southeast-facing aspects

tended to be dominated by hardwood vegetation that is often completely consumed in a fire, a possible consequence of past fire severity influencing vegetation composition and therefore future fire severity—fire perpetuating a vegetation type more likely to burn at high severity.

While fire spreads faster on steeper slopes (Rothermel 1972), slope steepness was only a minor predictor of fire severity, likely because it was confounded by other factors. In the Klamath Mountains, the steepest slopes tend to also be rocky, have lower moisture availability, and therefore less available fuel (Weatherspoon and Skinner 1995). This is consistent with the trend of decreasing severity noted on slopes greater than 100% in this study. The low importance of slope percent relative to other variables may also be due to most of the landscape of the Klamath Mountains being very steep—lack of variation (Table 4).

Vegetation and previous fire history as predictors of fire severity

Vegetation type was the strongest predictor of fire severity in the final model. Highest severity was observed in areas dominated by shrubs and hardwoods. These vegetation types are typically lower statured and thus are expected to experience higher severity at a given level of fire intensity than taller-statured mature conifer vegetation types. Positions on the landscape most likely to burn at high severity tend to favor plants with adaptations that allow them to persist with such a fire regime. For example, seeds of common shrub genera such as *Arctostaphylos* Adans. (manzanita) and *Ceanothus* L. are stimulated to germinate by fire (Keeley et al. 2005), and many shrub and hardwood species resprout vigorously after high-severity fire (Cocking et al. 2014). The renowned diversity of vegetation in the Klamath Mountains, containing vegetation types favored by both high- and low-severity fire at the stand to landscape scales, points to the importance of mixed-severity fire in shaping vegetation in this region (Skinner et al. 2006, Perry et al. 2011).

Fire history (time since last fire, number of fires) prior to the 2006 fires had low relative importance in the final model, possibly because the effect of fire on future fuels is complex. Fire both consumes fuel and creates fuel, with more of the latter the more severe the previous fire(s). Fire severity was lowest in areas that had experienced a fire in the

past 20 yr, likely because accumulated fine dead surface fuels were consumed and require years to build up again to levels similar to or exceeding those found prior to the fire. Both Collins et al. (2007) and Bradstock et al. (2010) found reduced severity when time since the previous fire was less than 17 and 10 yr, respectively. Severity in this study gradually increased when the time since fire ranged from 30 to 50 yr. One possible explanation is that larger woody fuels created by the death of stems from the previous fire would have become rotten and likely fallen to the ground by this time. Large rotten wood is readily ignited and consumed by fire, and too much can lead to extreme fire behavior and more extreme fire effects (Barker 2008). Severity decreased again between 50 and 80 yr since previous fire and then increased beyond 80 yr. It is not clear why a decrease was found during the 50- to 80-yr interval post-fire, but the increase following 80+ without fire is consistent with accumulating fuels over time (often accompanied by forest densification) in the absence of fire. The number of fires that occurred prior to the 2006 fires reduced fire severity only when more than three fires had occurred. Recurring fire creates a patchy mosaic of vegetation and fuels which can influence the rate of spread and extent of subsequent fires (Collins et al. 2008). Multiple fires may also be necessary to both thin the forest and then consume the dead material killed by the initial fire(s).

Weather and inversions as predictors of fire severity

Severity tended to be less during periods of lower average daily temperature and higher average daily relative humidity, as would be expected, but weather explained little of the variation in the final model. Generally, moderate weather conditions prevailed throughout the 2006 fire season with relatively narrow ranges of mean temperature and relative humidity (Table 3). Other studies have found a much stronger relationship between daily variation in relative humidity and fire severity. For example, Collins et al. (2007) saw a strong effect of relative humidity on patterns of severity in Yosemite National Park, and both higher temperatures and lower relative humidity were associated with higher rates of damage in the Biscuit Fire, which burned nearby in southern Oregon and northern California (Thompson and

Spies 2009). The Biscuit Fire burned under more extreme weather conditions, leading to weather dominating over local variation in fuels and topography in shaping the patterns of fire severity. Elevated influence of weather-related factors under extreme weather conditions has also been reported by others (Oliveras et al. 2009, Bradstock et al. 2010). Instead of extreme temperatures, relative humidity, or wind, the 2006 Klamath fires were most heavily influenced by the inversions that were common throughout the summer months. The topographic complexity of the Klamath Mountains supports development of inversions that can persist for days or weeks, and are known to have a suppressing effect on fire behavior especially during large fire events, or when multiple fires are burning at the same time, trapping large quantities of smoke. Additionally, a thermal belt in the warm air above the inversion can cause fire behavior on the mid- to upper slopes to exceed that on the lower slopes (Sharples 2009). These results corroborate the findings of Miller et al. (2012b), who reported a lower proportion of high-severity fire occurring in years with many lightning starts, when total area burned was high and the fires burned over a long time span. They hypothesized that the lower severity was due in part to lengthy inversions that trapped smoke from multiple fires.

Because this was the first attempt to quantify the effects of temperature inversions on patterns of fire severity, there were a number of limitations to this analysis. The actual effect of smoke-trapping temperature inversions may have been stronger than we were able to show because we used RAWS data to predict the presence of inversions, but this does not actually identify the location of the smoke layer. A temperature inversion in (relatively) clear air without the presence of smoke should have less of an effect on fire severity. Second, determining the elevation at which the smoke layer becomes stagnant is important to understanding the threshold where fire behavior is altered and where differential potential effects on vegetation are hypothesized to occur. In this study, the location of the inversion layer was assumed to be 1300 m based on multiple field observations by fire personnel. Future research may wish to utilize a combination of MODIS and multi-angle imaging spectroradiometer images that have the capability to capture the location

and altitude of the smoke clouds to better assess temporal as well as spatial aspects of smoke trapped by the inversions.

Spatial model

The generalized additive model used in this study explained only a moderate amount of variation in fire severity, despite incorporating an extensive spatially representative data set. Other studies using varying analysis techniques have been able to explain higher percentages (Wimberly and Reilly 2007, Holden et al. 2009, Prichard and Kennedy 2014). Reasons for the relatively low explanatory power may lie in the topographic complexity, difficulty in quantifying weather, uncertainty in the timing and extent of smoke-trapping inversions, varying fire management techniques, and the fact that we analyzed data from multiple fires in the same statistical model. In addition, the topographic complexity of the Klamath Mountains landscape means that localized variation driving patterns in fire severity may not be adequately captured with standard variables. Defining vegetation structure and topographic complexity at an appropriate scale may help to further refine models to strengthen predictive power.

Variation in fire severity is perhaps easier to explain for fires burning under a greater range of weather conditions, including periods of extreme fire weather. In addition, daily averages capture warming and drying trends, but diurnal variation is often much greater and has a major influence on fire behavior. For example, areas burning at night would be expected to experience much reduced severity, even during periods of warmer average temperature or lower average relative humidity. Because progression maps are created at most once per day, the effect of diurnal variation is not captured. Some weather variables that are often important for explaining fire behavior, such as wind speed and direction, were not in the model, because daily averages would not be very informative.

Finally, the role of fire management actions is often difficult to assess after a fire. While we studied fires that burned primarily in wilderness, some portions of these fires were subject to burn-out operations and other forms of fire management that were not quantified. It is widely known that differences in fire management can have considerable effects on the natural fire spread.

Consequences for fire management and future directions

Despite several major fire years in recent times (1987, 1999, 2006, 2008), the fire rotation in this landscape is still much higher than it was historically (Miller et al. 2012b). With less fire, fuels that have accumulated in many areas have increased the susceptibility to higher-severity fire (Agee and Skinner 2005). Mechanical treatments for treating fuels and reducing fire hazard are impractical in many areas of the Klamath Mountains, due to the steepness of the landscape, and may not meet objectives unless accompanied by a reduction in surface fuels. Prescribed fire, while effective for reducing surface fuels, has not kept pace with the need for many reasons (Quinn-Davidson and Varner 2012, Ryan et al. 2013). Allowing some lightning-ignited fires to burn, particularly those occurring under conditions likely to produce the most desirable effects, may be the best way to restore fire at a scale necessary to substantially influence fire hazard and pre-empt fires burning under more extreme conditions (North et al. 2012).

The decision of allowing at least some portions of wildfires to burn for resource and future fuels benefits often boils down to the level of short-term risk one is willing to accept. While potential effects to human life and property often factor more highly in the risk avoidance equation, effects to resources are also an important consideration. Without good information on the conditions that lead to fire with desired ecological outcomes, many potentially beneficial wildfires are suppressed. This research provides concrete evidence about the relative importance of topographic, weather, and fire history-related factors in shaping fire severity during the 2006 fire season. Findings also illustrate fire severity patterns that might be expected for fires burning under these or similar conditions in this landscape, and could be used for decisions on appropriate response to wildfire. Managers may need to recognize that higher levels of fire severity (tree mortality) are likely to occur on upper slopes and ridgelines and to a lesser degree on middle slopes and east-/southeast-facing aspects, even during wetter than during normal precipitation years. Additionally, shrub-dominated habitats that are often associated with certain positions on the landscape may be vulnerable to reburning at high severity, maintaining them as self-reinforcing vegetation community

types (Peterson 2002, Skinner et al. 2006). Finally, temperature inversions that are common in landscapes with complex topography (Sharples 2009) can have a significant influence on prevailing weather below the elevation where the inversion is present. Even though trapped smoke represents a challenge for the human communities living in this landscape (Mott et al. 2002), there are also potential benefits to exploiting such conditions in fire management decisions, if reducing fire severity is the goal. As our understanding about the controls to spatial and temporal patterns of fire severity improves, it may one day be possible to develop a predictive model for the Klamath Mountains, similar to one developed by Holden et al. (2009), for the Gila Wilderness and surrounding National Forest, that could output ranges of fire severity on a particular landscape under varying weather scenarios for use in fire management decision support. Such a model would require data from a range of burning conditions much broader than those studied here. Multiple fire seasons across multiple regions burning under different weather and climatic conditions would be needed to predict landscape-scale fire severity at multiple spatial and temporal scales, and to develop localized variants. In addition, in order for models to explain more of the variance in fire severity, new variables that more closely capture fuel type, structure, and condition will need to be developed, along with the means to better locate and quantify smoke-trapping temperature inversions and weather conditions at finer temporal scales.

Acknowledgments

Literature Cited

Agee, J. K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C., USA.

Agee, J. K., and C. N. Skinner. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management 211:83–96.

Alexander, J. D., N. E. Seavy, C. J. Ralph, and B. Hogoboom. 2006. Vegetation and topographical correlates of fire severity from two fires in the Klamath-Siskiyou region of Oregon and California. International Journal of Wildland Fire 15:237–245.

Barker, J. S. 2008. Decomposition of Douglas-fir coarse woody debris in response to differing moisture content and initial heterotrophic colonization. Forest Ecology & Management 255:598–604.

Bigler, C., D. Kulakowski, and T. T. Veblen. 2005. Multiple disturbance interactions and drought influence fire severity in Rocky Mountain subalpine forests. Ecology 86:3018–3029.

Bradstock, R. A., K. A. Hammill, L. Collins, and O. Price. 2010. Effects of weather, fuel and terrain on fire severity in topographically diverse landscapes of south-eastern Australia. Landscape Ecology 25:607–619.

CALVEG. 2004. Existing vegetation – CALVEG, [ESRI personal geodatabase]. USDA-Forest Service, Pacific Southwest Region, McClellan, California, USA [2009].

Cansler, C. A., and D. McKenzie. 2014. Climate, fire size, and biophysical setting control fire severity and spatial pattern in the northern Cascade Range, USA. Ecological Applications 24:1037–1056.

Cocking, M. L., J. M. Varner, and E. E. Knapp. 2014. Long-term effects of fire severity on oak-conifer dynamics in the southern Cascades. Ecological Applications 24:94–107.

Cohen, W. B., and T. A. Spies. 1992. Estimating structural attributes of Douglas-fir/Western hemlock forest stands from Landsat and SPOT imagery. Remote Sensing of Environment 41:1–17.

Collins, B. M., M. Kelly, J. W. van Wagtendonk, and S. L. Stephens. 2007. Spatial patterns of large natural fires in Sierra Nevada wilderness areas. Landscape Ecology 22:545–557.

Collins, B. M., J. D. Miller, A. E. Thode, M. Kelly, J. W. van Wagtendonk, and S. L. Stephens. 2008. Interactions among wildland fires in a long-established Sierra Nevada natural fire area. Ecosystems 12:114–128.

De Santis, S., and E. Chuvieco. 2007. Burn severity estimation from remotely sensed data: performance of simulation versus empirical models. Remote Sensing of Environment 108:422–435.

Fry, D. L., and S. L. Stephens. 2006. Influence of humans and climate on the fire history of a ponderosa pine-mixed conifer forest in the southeastern Klamath Mountains, California. Forest Ecology and Management 223:428–438.

Holden, Z. A., P. Morgan, and J. S. Evans. 2009. A predictive model of burn severity based on 20-year satellite-inferred burn severity data in a large southwestern US wilderness area. Forest Ecology and Management 258:2399–2406.

Jimerson, T. M., and D. W. Jones. 2003. Megram: blow-down, wildfire, and the effects of fuel treatment. Pages 55–59. Fire Conference 2000: The first national congress on fire ecology, prevention, and management. Tall Timbers Research Station, Tallahassee, Florida, USA.

Keeley, J. E., T. W. McGinnis, and K. A. Bollens. 2005. Seed germination of Sierra Nevada postfire chaparral species. Madroño 52:175–181.

Key, C. H. 2006. Ecological and sampling constraints on defining landscape fire severity. Fire Ecology 2:34–59.

Key, C. H., and N. C. Benson. 2006. Landscape assessment: ground measure of severity, the composite burn index, and remote sensing of severity, the normalized burn ratio. Pages LA25–LA41 *in* D. C. Lutes, R. E. Keane, J. F. Caratti, C. H. Key, N. C. Benson, and L. J. Gangi, editors. FIREMON: fire effects monitoring and inventory system. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Kolden, C. A., A. M. Smith, and J. T. Abatzoglou. 2015. Limitations and utilization of Monitoring Trends in Burn Severity products for assessing wildfire severity in the USA. International Journal of Wildland Fire 24:1023–1028.

Kumar, L., A. K. Skidmore, and E. Knowles. 1997. Modelling topographic variation in solar radiation in a GIS environment. International Journal of Geographical Information Science 11:475–497.

Lentile, L. B., P. Morgan, A. T. Hudak, M. J. Bobbit, S. A. Lewis, A. M. S. Smith, and P. R. Robichaud. 2007. Post-fire burn severity and vegetation response following eight large wildfires across the western United States. Fire Ecology 3:91–108.

Martín, S. D., and E. L. Birk. 2010. The singular role of the atmospheric stability in forest fires. Atmósfera 23:129–139.

Miller, J. D., B. M. Collins, J. A. Lutz, S. L. Stephens, J. W. van Wagtendonk, and D. A. Yasuda. 2012*a*. Differences in wildfires among ecoregions and land management agencies in the Sierra Nevada region, California, USA. Ecosphere 3:1–20.

Miller, J. D., E. E. Knapp, C. H. Key, C. N. Skinner, C. J. Isbell, R. M. Creasy, and J. W. Sherlock. 2009. Calibration and validation of the relative differenced normalized burn ratio (RdNBR) to three measures of fire severity in the Sierra Nevada and Klamath Mountains, California, USA. Remote Sensing of Environment 113:645–656.

Miller, J. D., C. N. Skinner, H. D. Safford, E. E. Knapp, and C. M. Ramirez. 2012*b*. Trends and causes of severity, size, and number of fires in northwestern California, USA. Ecological Applications 22:184–203.

Miller, C., and D. L. Urban. 1999. Interactions between forest heterogeneity and surface fire regimes in the southern Sierra Nevada. Canadian Journal of Forest Research 29:202–212.

Miller, J. D., and A. E. Thode. 2007. Quantifying burn severity in a heterogeneous landscape with a relative version of the delta normalized burn ratio (dNBR). Remote Sensing of Environment 107:66–80.

Mott, J. A., P. Meyer, D. Mannio, S. C. Redd, E. M. Smith, C. Gotway-Crawford, and E. Chase. 2002. Wildland forest fire smoke: health effects and intervention evaluation, Hoopa, California, 1999. Western Journal of Medicine 178:157–162.

North, M., B. M. Collins, and S. L. Stephens. 2012. Using fire to increase the scale, benefits, and future maintenance of fuels treatments. Journal of Forestry 110:392–401.

Nunes, M. C. S., M. J. Vasconcelos, J. M. C. Pereira, N. Dasgupta, R. J. Alldredge, and F. C. Rego. 2005. Land cover type and fire in Portugal: Do fires burn land cover selectively? Landscape Ecology 20:661–673.

Oliveras, I., M. Gracia, G. More, and J. Retana. 2009. Factors influencing the pattern of fire severities in a large wildfire under extreme meteorological conditions in the Mediterranean basin. International Journal of Wildland Fire 18:755–764.

Pebesma, E. J. 2004. Multivariable geostatistics in S: the gstat package. Computers and Geosciences 30:683–691.

Perry, D., P. F. Hessburg, C. N. Skinner, T. A. Spies, S. Scott, A. H. Taylor, J. F. Franklin, B. McComb, and G. Riegel. 2011. The ecology of mixed fire severity regimes in Washington, Oregon, and Northern California. Forest Ecology and Management 262:703–717.

Peterson, G. D. 2002. Contagious disturbance, ecological memory, and the emergence of landscape pattern. Ecosystems 5:329–338.

Prichard, S. J., and M. C. Kennedy. 2014. Fuel treatments and landform modify landscape patterns of burn severity in an extreme fire event. Ecological Applications 24:571–590.

Quinn-Davidson, L. N., and J. M. Varner. 2012. Impediments to prescribed fire across agency, landscape, and manager: an example from northern California. International Journal of Wildland Fire 21:210–218.

R Development Core Team. 2016. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Robock, A. 1988. Enhancement of surface cooling due to forest fire smoke. Science 242:911–913.

Rothermel, R. C. 1972. A mathematical model for predicting fire spread in wildland fuels. Page 40. U.S. Department of Agriculture, Intermountain Forest and Range Experiment Station, Ogden, Utah, USA.

Ryan, K. C., E. E. Knapp, and J. M. Varner. 2013. Prescribed fire in North American forests and woodland: history, current practice and challenges. Frontiers in Ecology and the Environment 11:e15–e24.

Sharples, J. J. 2009. An overview of mountain meteorological effects relevant to fire behaviour and bushfire risk. International Journal of Wildland Fire 18:737–754.

Skinner, C. N. 2003. A tree-ring based fire history of riparian reserves in the Klamath Mountains. Pages 116–119 in California Riparian Systems: Processes and Floodplains Management, Ecology, and Restoration. Riparian Habitat and Floodplains Conference Proceedings. Riparian Habitat Joint Venture, Sacramento, California, USA.

Skinner, C. N., A. H. Taylor, and J. K. Agee. 2006. Klamath Mountain bioregion. Pages 170–194 in N. G. Sugihara, J. W. van Wagtendonk, K. E. Shaffer, J. Fites-Kaufman, and A. E. Thode, editors. Fire in California's ecosystems. The University of California Press, Berkeley, California, USA.

Sousa, W. P. 1984. The role of disturbance in natural communities. Annual Review of Ecology and Systematics 15:353–391.

Stuart, J. D., and L. A. Salazar. 2000. Fire history of white fir forests in the coastal mountains of northwestern California. Northwest Science 74:280–285.

Sugihara, N. S., J. W. van Wagtendonk, K. E. Shaffer, J. Fites-Kaufman, and A. E. Thode. 2006. Fire in California's ecosystems. University of California Press, Berkeley, California, USA.

Taylor, A. H., and C. N. Skinner. 1998. Fire history and landscape dynamics in a late-successional reserve, Klamath Mountains, California, USA. Forest Ecology and Management 11:285–301.

Taylor, A. H., and C. N. Skinner. 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. Ecological Applications 13:704–719.

Thompson, J. R., and T. A. Spies. 2009. Vegetation and weather explain variation in crown damage within a large mixed-severity wildfire. Forest Ecology and Management 258:1684–1694.

Turner, M. G., W. H. Romme, and R. H. Gardner. 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.

Weatherspoon, C. P., and C. N. Skinner. 1995. An assessment of factors associated with damage to tree crowns from the 1987 wildfires in northern California. Forest Science 41:430–451.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313:940–943.

Whittier, T. R., and A. N. Gray. 2016. Tree mortality based fire severity classification for forest inventories: a Pacific Northwest national forests example. Forest Ecology and Management 359:199–209.

Wimberly, M. C., and M. J. Reilly. 2007. Assessment of fire severity and species diversity in the southern Appalachians using Landsat TM and ETM+ imagery. Remote Sensing of Environment 108:189–197.

Wood, S. N. 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. Journal of the Royal Statistical Society 73:3–36.