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Project Title: A comparison of fire severity patterns in the late 19th and early 21st century in a mixed conifer forest landscape in the southern Cascades

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Key Findings

- A fire regime study (Beaty and Taylor 2001) in the mixed conifer forest landscape of the Cub Creek Research Natural Area (CCRNA) identified a strong association between fire regime parameters, topographic characteristics, and forest characteristics prior to fire suppression. Specifically, fire return intervals were shortest on south-facing slopes, longest of north-facing slopes and intermediate on west-facing slopes. Pre fire suppression fire severity patterns also varied with slope position and slope aspect. Forests on upper slopes experienced mainly high severity fire while those on lower slopes burned mainly at low severity, mid-slopes were intermediate.

- The Cub Fire in 2008 burned through the CCRNA which was never logged or actively managed. Our hypothesis was that spatial patterns of fire severity in 2008 would be strongly associated with spatial patterns of fire severity in the late 19th century. In short, there would be a strong tendency for fire severity patterns be repeated across the landscape because of strong terrain/vegetation/fuel controls on fire severity in the CCRNA landscape.

- Severity of fire effects in plots measured before the Cub Fire varied with slope aspect and slope position. Bark char height was greater on north facing than other slope aspects and basal area mortality and tree mortality was greater on north and southwest facing slopes than on other slope aspects. Bark char height, tree mortality, and basal area mortality was greater on upper slopes than lower slopes positions, and intermediate on mod-slope positions.

- Modeled fire behavior based on pre fire measurements of vegetation and fuel in the plots, and day of burn fire weather, varied by slope aspect. Rate of spread and flame length were higher on the north and southwest facing slope than on other slope aspects. Crowning index was highest on the south-facing slope. Only the crowning index varied with slope position. It was lower on upper slopes than on mid or lower slopes.

- Severity of fire effects as measured by MTBS remote sensing data also varied with topography. Areas of high severity fire were proportionally highest on upper slopes, lowest on lower slopes, and intermediate on mid-slopes. The proportion of area burned at high severity was also greater on the southwest facing slope.

- Fire type modeled by Flammap using LANDFIRE fuels and day of burn weather exhibited little spatial variability. Potential for passive crown fire was predicted for most areas in the CCRNA.

- The decreasing correspondence between observed fire effects with plot level and then landscape level modeling is probably related to low variability in fuel parameters in the LANDFIRE data.

- A general additive model using terrain, fire weather, and vegetation parameters was developed to predict fire severity as measured by MTBS data. Slope position, vegetation type in 1941 on aerial photographs, aspect, average day of burn temperature, and slope percent were the most important predictors of fire severity. The full model had an adjusted r^2 of 0.64. Fire severity was highest on southwest facing slopes regardless of vegetation type. Upper and mid-slopes were also predicted to have higher severity as well as areas that were montane chaparral in 1941. Severity was also highest with moderate temperatures. Windspeed and relative humidity were not selected by the model as important variables explaining fire severity.

- We postulate that the duration and intensity of a temperature inversion, particularly lifting of the inversion, contributed to the associations we found between topographic variables and fire severity patterns in the CCRNA.

- The analysis of plot level and landscape level measurements of fire severity effects supports our hypothesis of a strong tendency for patterns of fire severity to be repeated across a mixed conifer forest landscape. At the end of the 19th century upper slopes in the CCRNA were covered by montane chaparral and older mixed aged and mixed sized forests dominated lower slopes. The repeated severity pattern suggests that self-reinforcing feedbacks between vegetation type and fire are an important control on patterns of fire severity and that feedback effects can persist for a century or more.

- The 2008 burn severity pattern was not identical to the late 19th century pattern. Twenty percent of forest that was mixed age and mixed size forest based on the 1941 aerial photographs and field data burned at high severity in 2008. This was probably caused by an increase in forest density and forest fuels related to more than a century of fire suppression.

- In landscapes with contrasting forest structural characteristics related to fire severity, it may be advantageous for fire managers who want to reduce the likelihood of large severe fires to pattern the type and severity of treatments (prescribed fire, thinning, fuelbreaks) to historical patterns of fire severity.

INTRODUCTION

The extent and severity of fires in the United States during the last decade has been remarkable. Since 2002, there has been seven years (2002, 2004, 2005, 2006, 2007, 2011, 2012) when over 2.8 million ha have burned, more than twice the previous decade. The extent of recent fire activity has increased risks to lives and property (Cohen 2008; , biodiversity and species-at-risk (Spies et al. 2006), the timber value of forests (Butry et al. 2001) and forests as a carbon sink (Hurteau et al. 2008, 2011). Although one driver of the increase in fire extent, at least in western forests, is climate change (Westerling et al. 2006), human agency in the form of fire management has significantly contributed to the severity and extent of recent wildfires.

Since the turn of the 20th century federal forest fire policy has emphasized fire suppression and the policy has been very successful at reducing the area burned by fire until the most recent decade (Pyne 1982; Stephens and Ruth 2005; Miller et al. 2009a). The effect of fire suppression on fire activity in western forests is geographically variable and can be generalized based on knowledge of fire regimes prior to fire suppression. Fire regimes characterize the cumulative effect of temporal and spatial patterns of fire behavior and fire effects on vegetation and ecosystems over a specified period of time, usually centuries (Agee 1993; Brown 2000). Fire suppression has had little effect on fire regimes in wet or cold forests that historically burned at high severity at intervals of 200-400 years (Agee 1993; Morgan et al. 2001; Schoennagel et al. 2004). On the other hand, suppression of fire in dry pine and mixed conifer forests that once experienced frequent (every 5-30 years) low-moderate severity surface fire has led to an increase in forest density and the quantity and continuity of surface and canopy fuels (e.g. Covington and Moore 1994; Skinner and Chang 1996; Taylor 2000; Beaty and Taylor 2007; Fule et al. 2009; Skinner et al. 2006a,b; van Wagtendonk and Fites-Kaufman et al. 2006). The increase in surface and canopy fuel has increased the risk of high severity fire and high severity fire effects, and area burned at high severity has recently increased in the southern Cascades and Sierra Nevada in California (Miller et al. 2009a).The severity of recent wildfires is a concern to fire and resource managers in California and other western states (Fried et al. 2004; Fulé et al. 2004) and has led to shifts in forest management (i.e. Healthy Forest Restoration Act 2003) to emphasize reduction of surface and canopy fuels to reduce the potential for high severity fire (Agee and Skinner 2005; Schmidt et al. 2008).

Despite evidence for forest change and an increase in surface and aerial fuels there is uncertainty in whether the recent increase in high severity fire effects conform to the fire suppression-forest thickening-higher severity fire effects model. Assessment of fire severity in the Sierra Nevada and the Klamath Mountains based on remote sensing suggest that patterns of severity (i.e. high, moderate, low) for many large wildfires was consistent with the variability expected prior to the fire suppression period (Odion et al. 2004; Odion and Hanson 2006). Some, however, have questioned the appropriateness of techniques used in those analyses (Safford et al. 2008). Furthermore, fire severity assessments for fires during the same period in the Sierra Nevada and Cascade Range conclude that fire severity has increased significantly since the mid-1980s and is outside the historical range of variability. Fuel accumulation since implementation of fire suppression, and climate change were identified as the likely explanation for the fire severity increase (Safford et al. 2008). Contrasting conclusions are related, in part, to differences in protocols for identifying categories of fire severity (Safford et al. 2008). Such contrasting scientific results, however, make it a challenge for managers to making decisions for evaluating how to apply recent fire severity information to fire and fuels management planning and managing prescribed fire or wildfire for appropriate fire effects across heterogeneous landscapes.

Patterns of burn severity in pine and mixed conifer forests in California, however, are not simply related to fuel loads that have increased since fire suppression. Fire severity patterns are also influenced by topography (Weatherspoon and Skinner 1995,Taylor and Skinner 1998; Thompson et al. 2007; Beaty and Taylor 2008, Dillon et al. 2011), and the stochastic effects of weather during a fire (Collins et al, 2007; Collins and Stephens 2010; Parisien et al. 2010). These factors can amplify or attenuate the effects of fire suppression related increases in fuels and forest thickening. Moreover, there is some evidence that patterns of fire severity are related to vegetation/fuel type. For example, fires that burn in schlerophyll shrublands and mixed forest/shrublands exhibit self-reinforcing fire behavior (Odion et al. 2010). Sites with schlerophyll shrubs generally burn less frequently but more severely than conifer sites which promotes shrub development and shrubs burn severely again in subsequent fires (Odion et al. 2004; Collins and Stephens 2010).

One of the largest unknowns for fire and land managers in California in considering the severity patterns of future fires is what fire severity patterns were before fire suppression was implemented in the early 20th century. For most places, we don't know if contemporary burn severity patterns identified by remote sensing studies during the last thirty years are, or are not, within the historical range of variability (e.g. Odion, and Hanson 2006; Safford et al. 2008). Ideally, wildfire planning decisions with respect to observed and anticipated patterns of fire severity would be at least partly based on knowledge of historical fire severity patterns. One assessment approach would be to compare severity patterns for contemporary fires with reference period (pre fire suppression) severity patterns in the same or a similar landscape. This type of assessment has been limited by the paucity of tree ring based fire history studies that have quantified and mapped patterns of fire severity prior to fire suppression (i.e. Taylor and Skinner 1998; Beaty and Taylor 2001, 2008; Bekker and Taylor 2001; Scholl and Taylor 2010).

In the summer of 2008 the Cub Complex fires (21 June 2008-22 July 2008, hereafter Cub Fire) burned through the landscape of the Cub Creek Research Natural Area (CCRNA) in the Lassen National Forest, California. The CCRNA watershed is one of the few landscapes in California with a spatially explicit reference period fire history that includes mapped patterns of fire severity (Beaty and Taylor 2001). This provided the opportunity to compare severity patterns in a reference landscape with the patterns of fire severity and fire effects generated by a contemporary fire. The CCRNA was never logged or actively managed so forest harvesting and fuels treatment that are known to influence fire severity patterns in these types of forests (e.g. Weatherspoon and Skinner 1995), had no influence on patterns in the 2008 fire. Consequently, differences in fire severity patterns for the two points in time would be related to reference period fire history and vegetation structure, topography, changes in vegetation and fuels since the onset of fire suppression, and the short term influences of weather on fire behavior during the fire.

RESEARCH OBJECTIVES

This research had four objectives. First, to identify and compare fire effects to estimates of fire behavior derived from pre-fire measurements of vegetation and fuels at the plot scale.

Second, to identify landscape patterns of fire severity for the 2008 fire using remote sensing and compare the severity to simulations of landscape fire behavior using the pre-fire measurements of vegetation and fuels as input to the model.

Third, to compare the spatial patterns of fire severity and simulated fire intensity for the 2008 fires to spatial patterns of reference period fire frequency and fire severity identified by Beaty and Taylor (2001).

Fourth, to identify the relative contribution of weather, topography, and vegetation/fuels variables on severity patterns of the 2008 fire.

Our working hypothesis was that spatial patterns of fire severity in 2008 are strongly associated with the spatial patterns of severity in the late 19th century. If this hypothesis is supported, then there is a strong tendency for fire severity patterns to be repeated across a landscape because of strong terrain/vegetation controls at least in landscape types represented by the CCRNA.

SUMMARY OF MATERIALS AND METHODS

Study area

The CCRNA covers 1587 ha in the Lassen National Forest, California and includes the complete watershed of Cub Creek. Elevations range from 1136 to 2044 m. Forests grow on soils derived from Tertiary (Pliocene) aged volcanic rocks and the landscape has been deeply incised by fluvial erosion. Slopes are steep (25-30°) except for a flat bench adjacent to the north side of Cub Creek that occurs in the lower third of the drainage. Cub Creek runs southeast to northwest so the dominant slope aspects in the study area are northeast and southwest. Cliffs and rock outcrops occur in the watershed separating areas of continuous vegetation. These bare areas may serve as fuel breaks that retard the spread of fire.

Forests in the CCRNA are composed of the mixed conifer vegetation type and forest composition varies markedly with slope aspect, elevation, and potential soil moisture (Keeler-Wolf 1990; Beaty and Taylor 2001). Predominant species include white fir (*Abies concolor*), ponderosa pine (*P. ponderosa*), incense cedar (*Calocedrus decurrens*), sugar pine (*P. lambertiana*), and Douglas-fir (*Pseudotsuga menziesii*). Tree cover in some places is interrupted by patches of montane chaparral. Chaparral shrubs are usually < 2 m tall and the most common shrubs are greenleaf manzanita (*Arctostaphylos patula*), California lilac *(Ceanothus* spp.) and huckleberryoak (*Quercus vaccinifolia*). Montane chaparral species are fire adapted (post fire regeneration from fire-scarified seed, or sprouts) and chaparral occupies sites that have experienced severe fire or are too poor to support trees (Wilken 1967; Nagel and Taylor 2005).

Historical conditions and original field measurements

The objective of the original study (i.e. Beaty and Taylor 2001) was to quantify spatial variability in forest composition and structure and fire regimes before the onset of fire suppression. This was accomplished using a spatially distributed network of fire scarred trees (n=59) and forest structure plots (n=67) (Figure 1). The network was distributed by first stratifying the watershed by forest structure type, elevation, and aspect using maps and 1941 and 1993 aerial photographs. Plots and fire scar samples were then distributed among strata. Each plot was placed in an area of homogeneous species composition, structure, and environment and plot location was recorded with a GPS. Environmental characteristics (elevation, slope aspect, slope configuration, slope position) in each plot were also recorded.

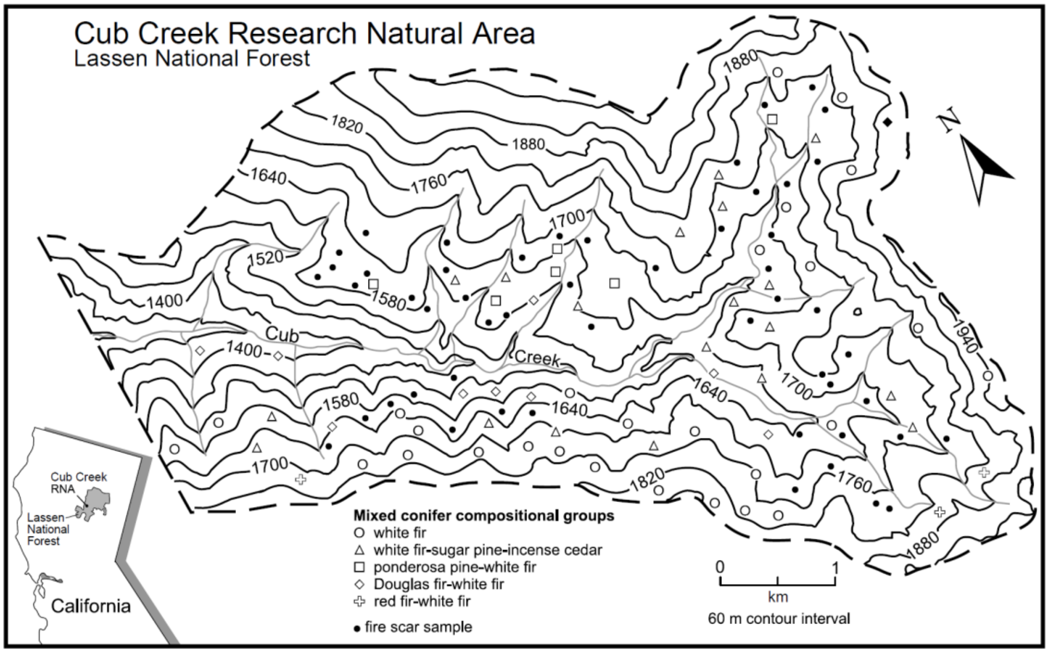


Figure 1. Location of study area, forest sample plots, and fire scar samples in the Cub Creek Research Natural Area (CCRNA), Lassen National Forest, California. The different symbols designate the forest compositional group given in Beaty and Taylor (2001).

Vegetation and fuels

Vegetation and fuels data in 1997 were collected in 400 m^2 plots. All standing live and dead tree (> 5.0 cm dbh) diameters (dbh) were measured in each plot and relative height-class (dominant, co-dominant, intermediate, suppressed) was recorded by species for each stem. Seedling (0.5-1.5 m tall) and sapling (>1.5 m tall-5.0 cm dbh) were tallied by species and understory (shrubs, forbs, grasses) and surface characteristics (litter, rock, mineral soil) were recorded by cover-class (<1%, 1-5%,6-25%, 26-50%, 51-75%, 76-100%). Surface fuel structure and load was estimated in each plot using the photo series for the southern Cascades and northern Sierra Nevada (Blonski and Schramel 1981).

Fire regimes (season, return interval, extent, fire rotation, severity) prior to fire suppression were reconstructed using dendroecology and details of the methods are provided in Beaty and Taylor (2001). Overall, there was a strong association between fire regime parameters, topographic characteristics, and forest characteristics in the CCRNA. These associations are characterized as follows. First, fire frequency varied with slope aspect ($P<0.05$) and the average period between fires was shortest on south-facing slopes (9 years), longest on north-facing slopes (34 years) and intermediate on northwest and southeast facing slopes. Second, fires were generally small (106 ha) before fire suppression and most fires burned only one or two slopes. Only one fire burned on all slope aspects during this period burning a total of 400 ha. Overall, for the period 1700-1900, larger burns were associated with dry and warm years (Taylor et al. 2008). Third, spatial patterns of fire severity varied by slope position and slope aspect. Forests that had experienced high fire severity occurred mainly on upper slopes (85%), while forests on lower slopes burned mainly at low severity (60%) and mid slopes experienced mainly low (30%) and moderate severity (47%) fire(Table 1). South and north facing slopes had similar fire severity patterns with mainly (>60%) low and moderate severity burns while NHW and SHW experienced mainly (>60%) high severity burns (Table 2).

Table 1. Percent area burned between 1883 and 1926 at low, moderate and high severity by topographic position in CCRNA.

Slope position	Low severity	Moderate severity	High severity
Lower slope	60	34	6
Middle slope	30	47	23
Upper slope	1	14	85

Table 2. Percent area burned between 1883 and 1926 at low, moderate and high severity by slope aspect in CCRNA.

Slope aspect	Low severity	Moderate severity	High severity
North (N)	33	36	31
Northwest (NHW)	18	17	65
Southwest (SHW)	14	16	70
South (S)	38	44	18

Post-fire measurements

After the Cub Fire (2008) plot level vegetation, fuel characteristics, and fire effects were re-measured in 2010 or 2011. For trees we re-measured diameter (dbh) and relative height class, and whether it was live or dead. The abundance of shrubs, forbs, and grasses was also estimated by cover class (see above). Seedlings and saplings were also tallied.

Additional measurements for each tree were made to assess damage from the 2008 fire. These measurements included total tree height (m), height to live and dead crown base (m), height to old base (m), and height to current crown base (m). We also estimated percentage of live crown relative to the total height of the tree. Fire damage to each tree was estimated by measuring the height and intensity of bark char. The height of bark char on the bole was recorded in 0.3 m sections in each of four bark char categories (1=charring of < 15 cm, 2=bark is black but not consumed and fissures are not black, 3=the entire bark, including fissures, is black but not consumed, 4=bark and fissures are black and significant bark consumption is evident-consumption smooth's the original bark profile).

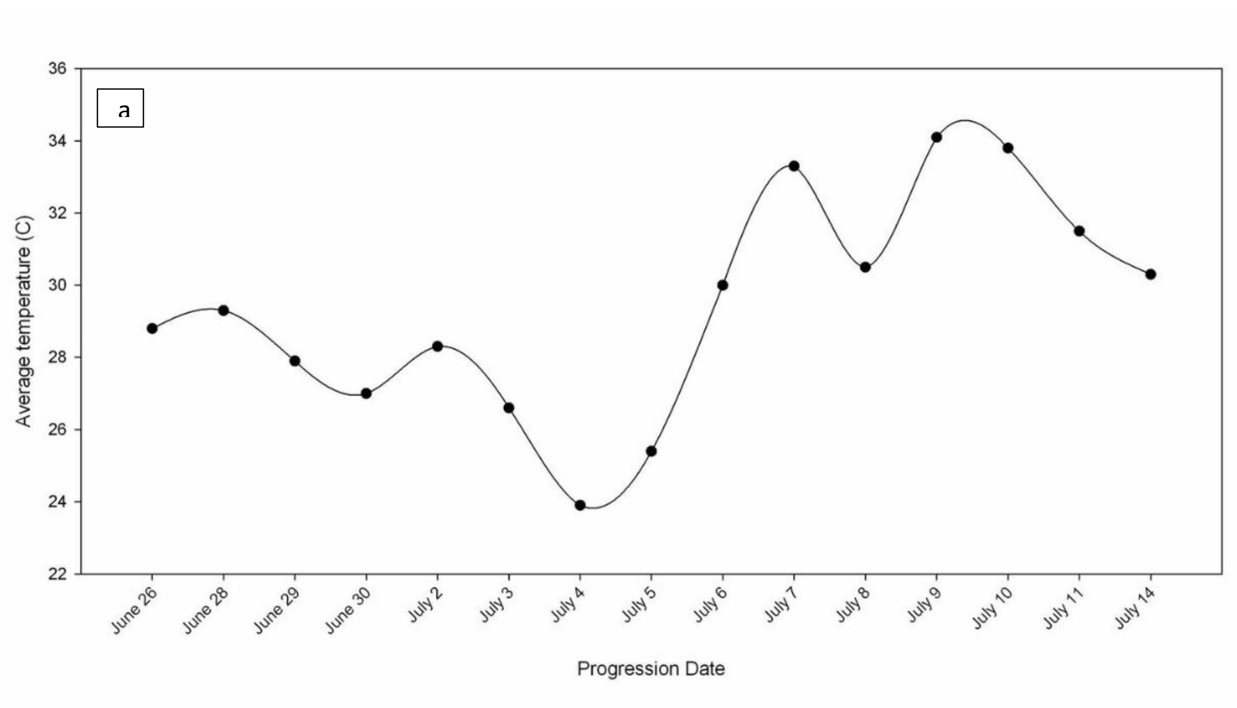
Post-fire fuel conditions and ground char characteristics were measured along three 15.15 m transects in random directions started in the plot center. Surface fuels were quantified along the transects following Brown (1974) and they were also estimated using the photo series (Blonski and Schramel 1981). The severity of ground char along each transect was evaluated by measuring the length of severity along each transect in one of four severity classes (1=unburned, 2=light char, 3) moderate char, 4) deep char).

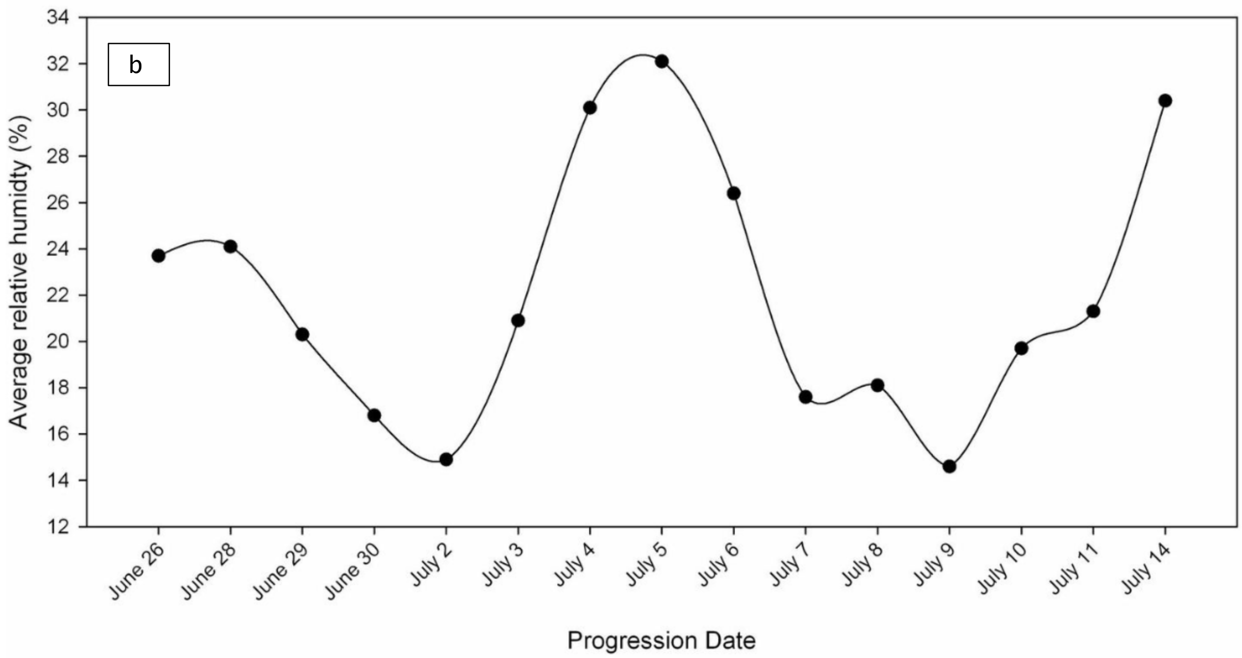
Stand level potential fire behavior

Potential stand level fire behavior for contemporary and reference forests was simulated using Crown Mass in Fuels Management Analyst (Carlton 2004). Crown Mass calculates potential fire behavior and some first order fire effects from tree lists that include tree species, dbh, tree height, crown ratio, and structural stage. Estimates of crown fuel variables in all plots were made using tree lists and the Crown Mass routine in FMA.

Surface fuel estimates for time-lag classes for each method were input to FMA which compared the similarity of the field based estimates to values for standard fuel models (i.e. Anderson 1982; Scott and Burgan 2005). We then used the FMA selected fuel model to estimate potential fire behavior. Standard surface fuel models were used to estimate potential fire behavior because we had no way to calibrate custom models with observed fire behavior under conditions similar to those simulated (Rothermel and Rinehart 1983; Burgan and Rothermel 1984).

Fire intensity depends on weather conditions and fuel moisture content (Reinhardt and Crookston 2003) so we estimated potential fire behavior for the day of the fire based on the location of each plot and the daily fire progression map (Figure 2a-d). Day of fire weather was represented by variables from the Carpenter Ridge remote automated weather station (RAWS) station.

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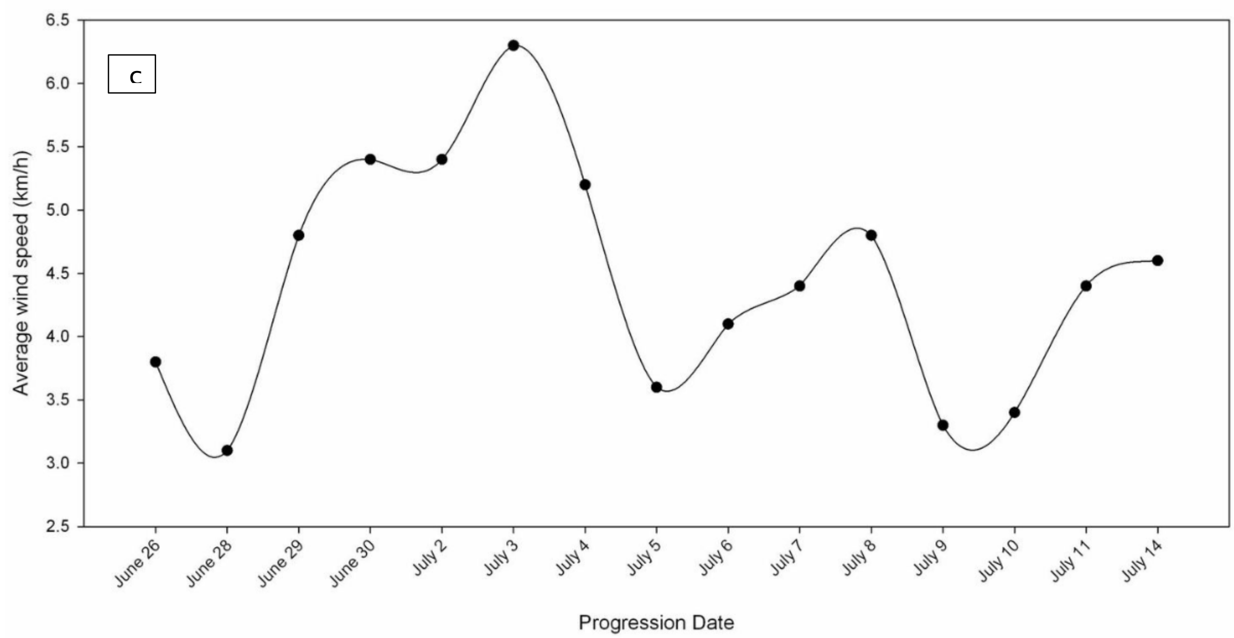
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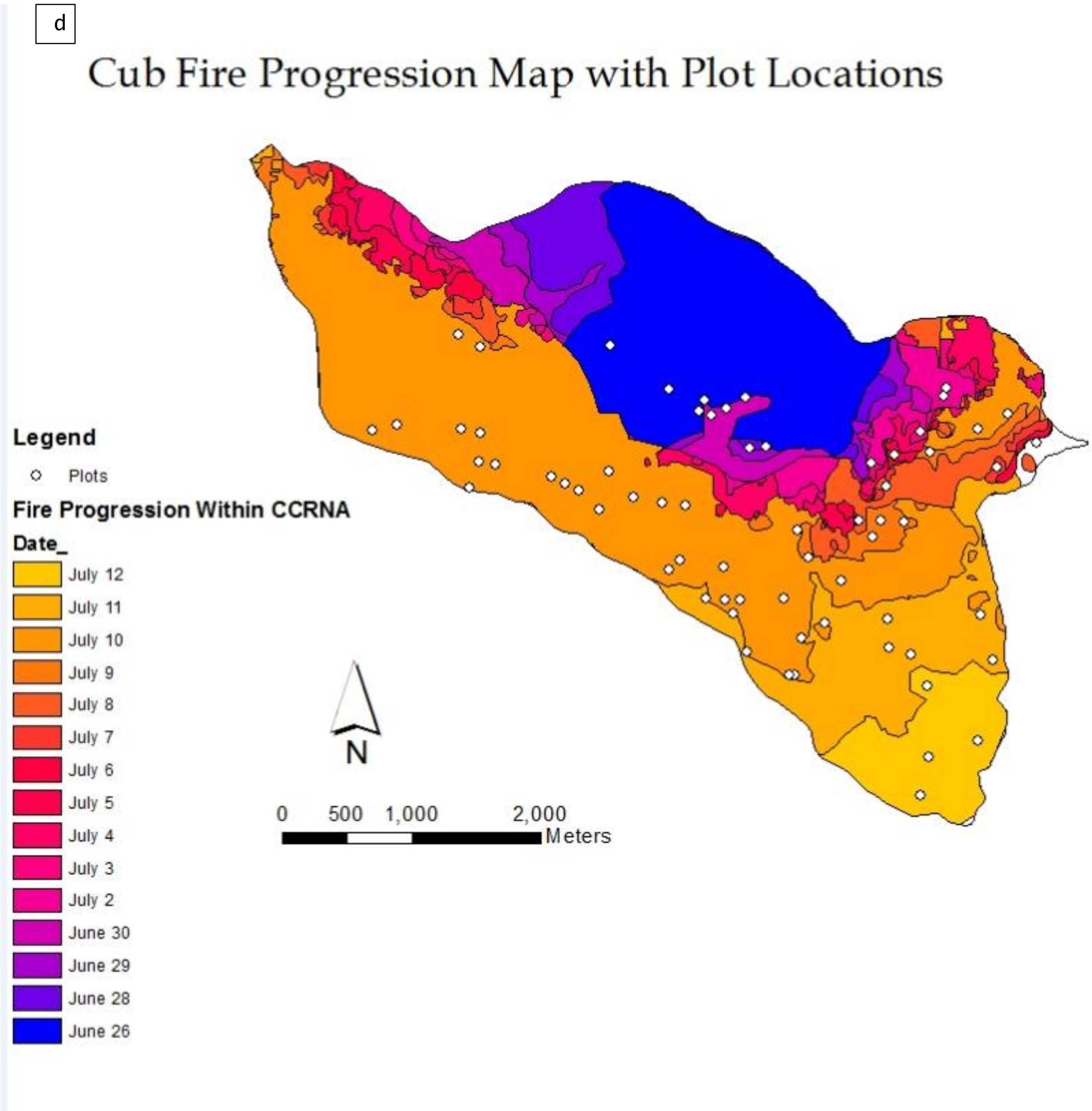

Figure 2. Average daily (a) temperature, (b) relative humidity, (c) windspeed for the Carpenter Ridge RAWS station, and daily fire progression with plot location in the CCRNA (d).

We chose four variables for the simulations to represent potential fire behavior: (1) rate of spread, (2) flame length, (3) crowning index (minimum wind speed at 6.06 m above ground level needed to support active crown fire), and (4) and torching index (wind speed at 6.06 m above the ground needed to ignite the crown).

Landscape potential fire behavior

Potential fire behavior in the CCRNA landscape was estimated using LANDFIRE maps of surface and canopy fuel variables (LANDFIRE version 1.0.5/Refresh 2001; Rollins and Frame,

2006) and FlamMap. This modeling effort produced an expected pattern of fire behavior based on pre-fire fuel and vegetation conditions. We used day of fire weather conditions (see stand level fire behavior) and the daily fire progression map to parameterize the FlamMap simulations (Figure 2). Day of fire weather was represented by the Carpenter Ridge remote automated weather station (RAWS) station and data were processed by FireFamilyPlus (Bradshaw and Brittain 1999). WindNinja was used to translate wind speeds and directions into gridded wind vectors to account for the influence of topography. Since our primary focus was on the modeled spatial patterns of fire severity in the CCRNA we output three categories of fire across the landscape: no fire, surface fire, and passive crown fire. We presumed that areas of potential passive crown fire would be potential areas of higher severity fire in 2008 as measured by post fire vegetation change from remote sensing platforms (MTBS data, see below). We developed independent maps of surface and canopy fuel variables for the landscape fire behavior modeling using our field measurements and a Random Forest classifier following the method of Pierce et al. (2012). However, there was little difference in the modeled fire behavior using the two data sets (LANDFIRE, Random Forest). Consequently, we report only the results for LANDFIRE variables because these data are widely available.

Fire severity in 2008: topography, vegetation/fuels, weather

Fire severity

We used the maps provided by Monitoring Trends in Burn Severity (MTBS) developed from Landsat imagery to represent spatial variation in fire severity for the 2008 fire (Miller and Thode 2007). We used RdNBR as our specific measure of fire severity which is calculated by dividing dNBR by a function of the pre-fire image (Miller and Thode 2007). RdNBR data was derived from imagery acquired the first summer after the fire occurred (2009). Fire effects recorded in one-year post-fire imagery can include immediate as well as delayed effects from a fire, such as delayed conifer mortality or resprouting of shrubs (Key 2006). Consequently, extent of stand-replacing fire can be underestimated where species that respond by re-sprouting dominate. Variation in Landsat imagery is primarily correlated with variation in the upper forest canopy and understory fire effects from low intensity surface fire can be obscured (Cohen and Spies 1992; De Santis and Chuvieco 2007). Therefore, percent change in canopy cover was used as the measure of fire severity on vegetation in this study . The RdNBR raster data (30 m X 30 m) was transformed into a continuous measure of percent change in canopy cover (0-100%) using calibrations derived from plot level data (Miller et al. 2009b). The percent change in canopy cover used to measure severity of fire effects were (unchanged = 0% canopy mortality, Low = 1-25% canopy mortality, Low-Moderate 25-50% canopy cover mortality, Moderate 50-75% canopy mortality, High > 75% canopy.

Topographic variables

Topography quantitatively describes the terrain of a landscape using different components such as elevation, slope, aspect, and slope position. Topographic variables have different effects on fire behavior as fire moves across the landscape. Elevation, or distance above sea level influences temperature. Slope is a key factor in fire intensity as steeper slopes can lead to greater preheating of fuels and increased rate of spread when fire is moving upslope. Aspect directly influences fire behavior due to varying the amount of solar radiation and moisture availability, as well as indirectly through contributing to variation in vegetation composition and density. Slope (%), aspect, and slope position were derived from a 30 m digital elevation model (DEM) using ArcGIS Spatial Analyst10.1. For this analysis, aspect was separated into two classes: SW (136-315°) and NE (316-135°) to contrast the fire environment on the two prevailing aspects in the CCRNA. Slope position was separated into the same three categories (upper 1/3. middle 1/3, lower 1/3) used to map 19th century fire severity. The probability of fire moving uphill or backing downhill is related to slope position, with lower slope positions more likely to experience backing fire. Slope position is also an indicator of vegetation type, particularly in areas of heterogeneous topography where upper slopes tend to be more xeric and lower slopes more mesic.

Weather variables

Hourly weather variables during the fire were obtained from the Carpenter Ridge Remote Automated Weather Stations (RAWS) located 15 km southwest of the CCRNA at an elevation of 1458 m. Weather data were imported to Fire Family Plus to calculate fire weather variables for each day of burning (mean, minimum, and maximum temperature and relative humidity, wind speed and direction) (Table 3). All variables were then associated with the daily extent of burning on the fire progression map.

Vegetation and fuels

Pre-fire vegetation and fuels in the CCRNA were represented using several spatially explicit data sets. A CalVeg map of existing vegetation with types classified by shrub, riparian, early seral coniferous forest (diameter 1-28 cm all canopy covers), grassland, barren, hardwood, mid seral (diameter 28-61 cm, all canopy covers), late seral open (diameter > 61 cm <50% cover), and late seral closed (diameter >61 cm, >50% cover) (CalVeg 2004). Relative fuel loading was represented by a 2010 California surface fuel map layer. Since we were interested in the influence of 19th century fire severity patterns on the 2008 fire we also visually classified vegetation on geo-referenced 1941 black and white aerial photographs (Fig. 3a). Vegetation was classified into four groups based on the predominance of different lifeforms in a pixel (30 m X 30 m). The vegetation groups were broadly classified into tree, shrub, barren, and areas with a mix of tree and shrubs (shrub cover or tree cover < 20%) (Fig. 3b).

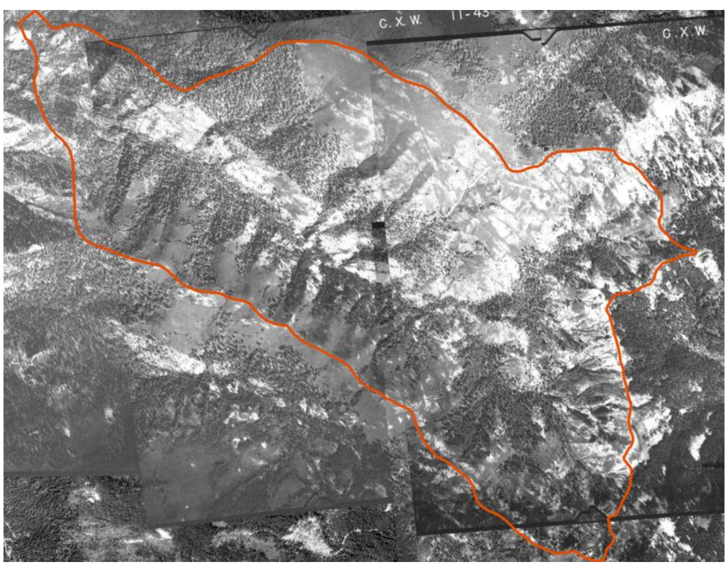

Figure 3a. Geo-referenced 1941 aerial photographs of the Cub Creek Research Natural Area, Lassen National Forest, California.

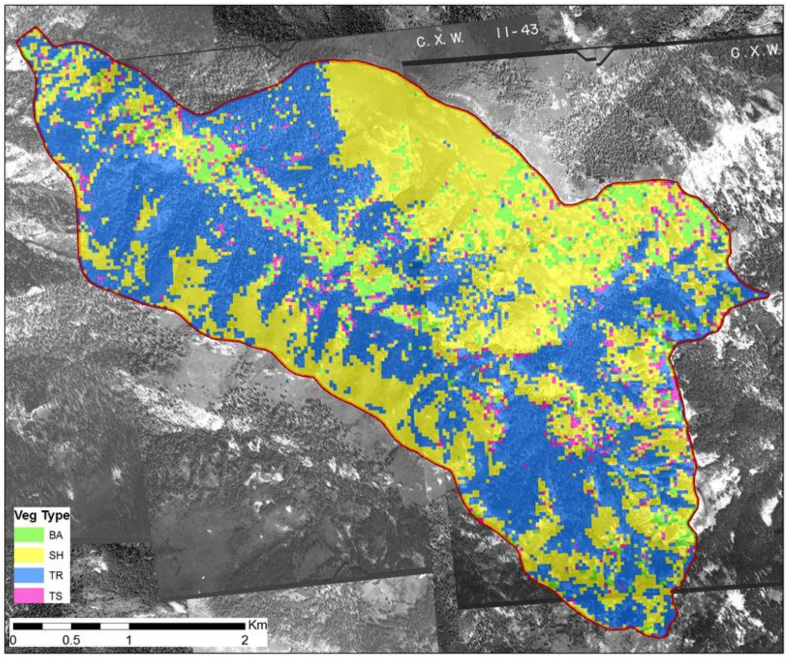

Figure 3b. Vegetation types in 1941 in the Cub Creek Research Natural Area, Lassen National Forest California. Vegetation types are BA - Bare (green), SH - Shrub (yellow), TR - Trees (blue), and TS mixed trees and shrubs (purple).

Spatial analysis of drivers of fire severity

We examined the drivers of the spatial variability in fire severity using a generalized additive regression model with random effects fit to the percent canopy cover change (MTBS data) with smooth spline functions for the continuous covariates. The general form of the regression line for a series of fires is:

$$y_{ij} = \alpha + \sum_k \delta(X_{kj}) + \sum_m s(X_{mj}) + s(xloc_j, yloc_j) + \tau_i + \varepsilon_{ij}$$

y_{ij} = percent change in canopy cover for the j^{th} sample point in the i^{th} fire,

α = intercept

$\delta(X_{kj})$= step function for the k^{th} categorical variable

$s(X_{mj})$= smooth spline function of the m^{th} continuous variable

$s(xloc_j, yloc_j)$= two dimensional spline function (surface) of location (UTM- easting, UTM-northing)

τ_i = random effect of i^{th} fire ; ε_{ij} = random error term

The spatial term, $s(xloc_j, yloc_j)$, in the regression equation was included to account for potential spatial correlation between adjacent cell locations and our regression was calculated for a single fire. The MTBS data on percent change in canopy cover (RdNBR) was used as the dependent variable. The independent/explanatory variables were a mixture of GIS layers (e.g., topography, weather, etc) and categorical variables (e.g., vegetation type, etc.) (Table 1). We conducted a correlation analysis to identify relationships among variables. This analysis was then used to select a set of variables with low correlation for inclusion in the final model. In order to evaluate the strength of the spatial model we predicted fire severity for the CCRNA landscape and calculated a confusion matrix. Because the model output was a continuous value of RdNBR we reclassified values into the five canopy cover change categories for comparison of observed and predicted values in the confusion matrix.

Table 3. Variables considered for models explaining patterns of fire severity in the CCRNA.

Variable	Resolution	Source	Type	Description
Dependent variables				
Percent canopy cover change	30 m	Monitoring Trends in Burn Severity (MTBS)	Continuous	0 - 100%
Percent change canopy cover	30 m	Monitoring Trends in Burn Severity (MTBS)	Categorical	Five category percent change in canopy cover classification subset to perim. 0 = outside perimeter, 1 = 0% canopy cover mortality, 2 = 0% < CC mort < 25%, 3 = 25% <= CC mort < 50%, 4 = 50% <= CC mort < 75%, 5 = CC mort >= 75%
Physical Explanatory Variables				
Elevation	30 m	Raw elevation from DEM	Continuous	1127 – 2074 meters
Slope position	30 m	Slope position derived from DEM using ArcGIS Spatial Analyst processing to classify canyons and ridges. 1 - Lower slopes, 2 - Middle slopes, 3 - Upper slopes	Categorical	Slope Position: 1- Lower 1/3, 2- Middle 1/3, 3- Upper 1/3
Aspect (2 classes - North and South)	30 m	CCRNA_Aspect ASP	Categorical	Aspect derived from 30 meter DEM in ArcGIS Spatial Analyst. Aspect was separated into two classes: SW (136-315) and NE (316-135).

Slope percent	30 m	Derived from DEM using ArcGIS Spatial Analyst	Continuous	0 – 108 %
Temperature, relative humidity, average wind speed		Weather variables and National Fire Danger Rating indices were calculated in Fire Family Plus using Carpenter Ridge RAWS weather station. Mean, minimum mean and maximum mean were calculated.	Continuous	24 – 34°C 15 - 32 % 3-6 km/h
Biological Explanatory Variables				
Vegetation cover		CalVeg Cover (2004)	Categorical	Coding: 1 - shrub, 2- Riparian, 3 - Early seral, 4 - Grassland, 5 - Barren, 6 - Hardwood, 7 - Mid seral, 8, Late seral open, 9 Late seral closed
1940s Vegetation Classification		Aerial photographs	Categorical	Classification of 1940s vegetation (1 - TR- tree, 2 - SH - shrub, 3 - BA- barren, and 4 - TS- Tree/Shrub
2010 Surface Fuel Layers		2010 California FRAP	Categorical	2010 California FRAP Surface fuel models 1 - Annual/pernnial grassland, 2 - Annual grass understory, 4 - Tall chaparral, 5 - Low shrub, 8-Hardwood forest litter, 9- Mixed conifer light litter, 10 - Mixed conifer medium litter, 99 - Barren

We also explored the relationships between each of the independent variables and the RdNBR using a classification and regression tree model (CART). CART models are advantageous because they can accommodate nonlinear and discontinuous relationships between variables and high order relationships (De'ath and Fabricus 2000). For some uses CART models also produce robust results despite spatial autocorrelation. Moreover, classification trees provide clear easy to interpret results.

SUMMARY OF RESULTS

Stand level fire effects

There was spatial variability in the severity of fire effects in the CCRNA based on slope aspect and slope position. The average and maximum height of bark char, and percentage of tree mortality was higher on north-facing than on other slope aspects (Table 4). The pattern of basal area mortality was similar and basal area mortality was higher on north and southwest facing slopes than other aspects (P<0.05) (Table 4).

Table 4. Average fire severity effects on trees from the 2008 Cub Fire in plots on different slope aspects in the CCRNA. Superscripts show the results of Kruskal-Wallis multiple comparison tests. Categories followed by the same letter were not different (P>0.05).

Bark Char (m)	Min.	Mean	Max.
NF[a]	0.7	10.5	26.9
NHW[b]	0.8	3.0	10.7
SF[b]	0.5	1.3	4.3
SHW[b]	0.3	5.1	19.7

Max. Bark Char (m)	Min.	Mean	Max.
NF[a]	3.6	25.8	49.8
NHW[b]	2.6	11.2	49.0
SF[b]	2.0	6.3	18.4
SHW[b]	1.0	14.5	33.8

Tree Mortality (%)	Min.	Mean	Max.
NF[a]	36	94	100
NHW[b]	18	65	100
SF[b]	30	58	92
SHW[ab]	33	80	100

Basal Area Mortality (%)	Min.	Mean	Max.
NF[a]	6	84	100
NHW[b]	5	42	100
SF[b]	0	29	100
SHW[ab]	1	59	100

Severity of fire effects also varied by slope position (Table 5). Height of bark char, tree mortality, and basal area mortality was higher ($P<0.05$) on upper slope positions than lower slope positions and middle slope positions had intermediate values for these variables. There was no difference in maximum char height in plots on different slope positions.

Table 5. Average fire severity effects on trees from the 2008 Cub Fire in plots on different slope positions in the CCRNA. Superscripts show the results of Kruskal-Wallis multiple comparison tests. Categories followed by the same letter were not different ($P>0.05$).

Bark Char (m)	Min.	Mean	Max.
Lower[a]	0.70	3.30	10.70
Middle[ab]	0.50	6.90	26.90
Upper[b]	0.30	8.70	22.40

Tree Mortality (%)	Min.	Mean	Max.
Lower[a]	18	72	100
Middle[ab]	28	77	100
Upper[b]	57	94	100

Basal Area Mortality (%)	Min.	Mean	Max.
Lower[a]	1	44	100
Middle[ab]	0	60	100
Upper[b]	5	84	100

Stand level potential fire behavior

There was spatial variability in stand level potential fire behavior on different slope aspects. Rate of spread, and flame lengths were higher ($P<0.05$) on the north and south west-facing slope than on the other slopes (Table 6). On the other hand, crowning index was higher on the south-facing slope (P<0.05) indicating that wind speeds needed to propagate crown fire were higher on south facing slopes. There was no difference in the torching index on the different slope aspects.

Table 6. Average potential fire behavior in plots on different slope aspects under day of burning weather conditions in the CCRNA. Superscripts show the results of Kruskal-Wallis multiple comparison tests. Categories followed by the same letter were not different (P>0.05).

Rate of spread (m hr^{-1})	Min.	Mean	Max.
NF[a]	18	80	410
NHW[b]	10	48	235
SF[b]	16	35	101
SHW[ab]	14	74	340

Flame length (m)	Min	Average	Max
NF[a]	0.3	1.0	6.6
NHW[b]	0.2	0.4	1.2
SF[ab]	0.2	0.4	0.9
SHW[ab]	0.2	1.3	8.8

Crowning index (km hr^{-1})	Min	Average	Max
NF[a]	5.6	27.3	54.2
NHW[a]	18.3	30.7	47.0
SF[b]	37.0	52.4	85.6
SHW[a]	9.0	28.4	60.7

Torching Index (km hr^{-1})	Min	Average	Max
NF[a]	0	42.8	337.8
NHW[a]	0	84.4	216.1
SF[a]	0	19.7	66.3
SHW[a]	0	53	237.4

There was little spatial variation in potential fire behavior by slope position. Only, crowning index varied with slope position and it was lower on upper slopes than on mid or lower slopes (Table 7). Rate of spread, flame length, and torching index were similar on the different slope positions under simulated weather conditions.

Table 7. Average potential fire behavior in plots on different slope positions under day of burning weather conditions in the CCRNA. Superscripts show the results of Kruskal-Wallis multiple comparison tests. Categories followed by the same letter were not different (P>0.05).

Rate of spread (m hr^{-1})	Min.	Average	Max
Lower[a]	10.1	60.4	235.4
Middle[a]	16.1	59.8	410.4
Upper[a]	9.0	19.1	340

Flame length (m)	Min	Average	Max
Lower[a]	0.2	0.5	1.5
Middle[a]	0.2	0.7	6.6
Upper[a]	0.2	1.6	8.8

Crowning index (km hr^{-1})	Min	Average	Max
Lower[a]	18.4	33.5	54.2
Middle[a]	5.6	36.5	85.6
Upper[b]	9.0	19.0	36.2

Torching Index (km hr^{-1})	Min	Average	Max
Lower[a]	0	50.4	216.1
Middle[a]	0	57.7	337.8
Upper[a]	0	41.8	141.9

Landscape scale fire effects

There was spatial variation in fire severity at the landscape scale as inferred from RdNBR estimates of pre and post fire vegetation cover change (Figure 4). Areas of high fire severity were proportionally higher on upper slopes (> 60%), lowest on lower slopes, and intermediate on mid-slope positions.

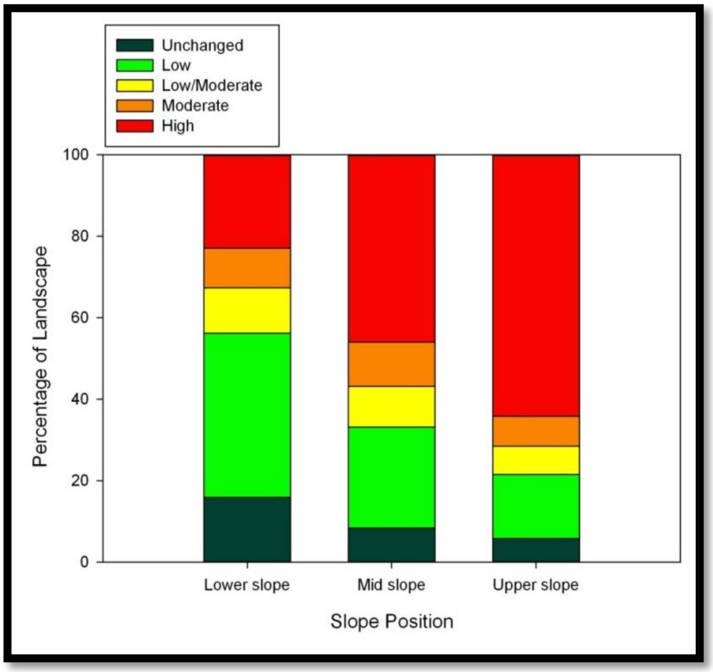

Figure 4. Proportion of area burned at different fire severity on low, middle, and upper slopes in the CCRNA. Fire severity is represented by percent change in pre and post fire canopy cover (unchanged = 0% canopy mortality, Low = 1-25% canopy mortality, Low-Moderate 25-50% canopy cover mortality, Moderate 50-75% canopy mortality, High > 75% canopy mortality.

There was also spatial variation in fire severity at the landscape scale by slope aspect (Figure 5). Overall, the proportion of area affected by higher severity fire was greater on the southwest facing slope than on the northeast facing slope. This slope aspect relationship, however, masks the stronger effect of slope position on fire severity.

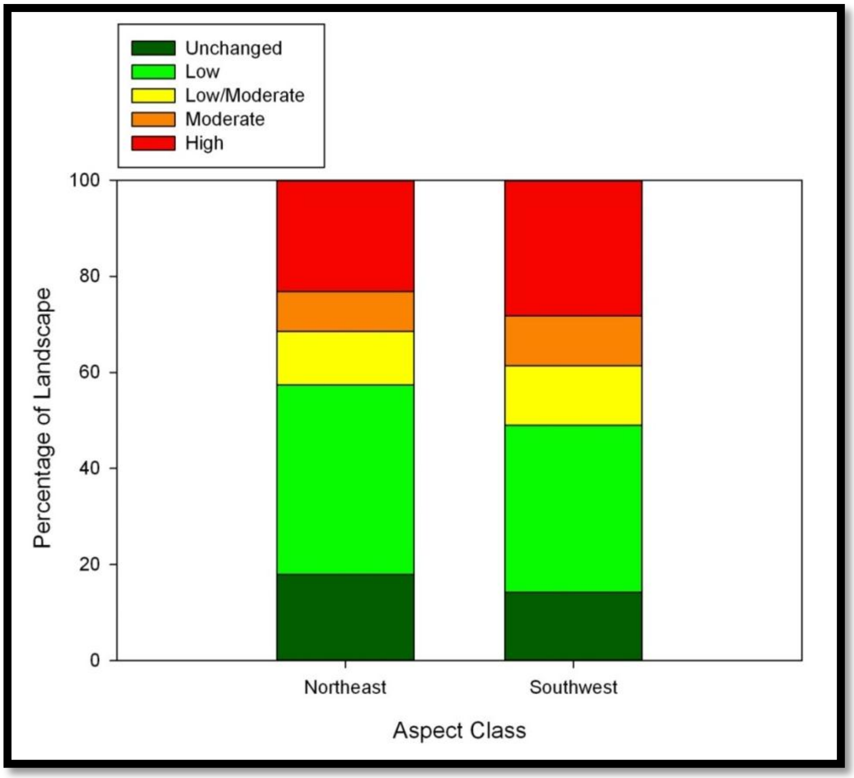

Figure 5. Proportion of area burned at different fire severity by slope aspect in the CCRNA. Fire severity is represented by percent change in pre and post fire canopy cover (unchanged = 0% canopy mortality, Low = 1-25% canopy mortality, Low-Moderate 25-50% canopy cover mortality, Moderate 50-75% canopy mortality, High > 75% canopy mortality.

Landscape scale potential fire behavior

There was little spatial variability in potential fire type as modeled by FlamMap (Figure 6). According to the FlamMap simulations most parts of the CCRNA had potential for passive crown fire. There were few areas with no fire, and the area of potential surface fire was also small and concentrated on the south facing ridge top. Observed fire severity, based on the magnitude of post-fire vegetation change evident in the MTBS data, in contrast, exhibits considerable spatial variability in fire severity (Figure 7). Moreover, the MTBS data show that upper slope areas were dominated by high severity in contrast to the modeled fire type for the south facing slope.

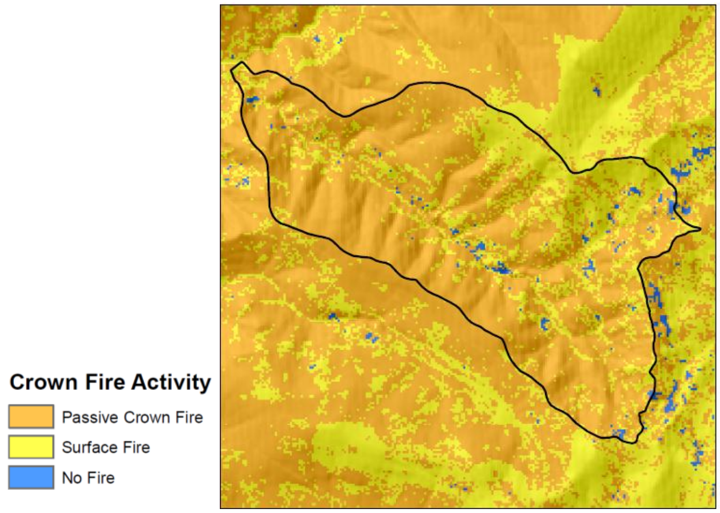

Figure 6. Fire type under day of burn weather conditions with LANDFIRE fuels in the CCRNA, Lassen National Forest, California

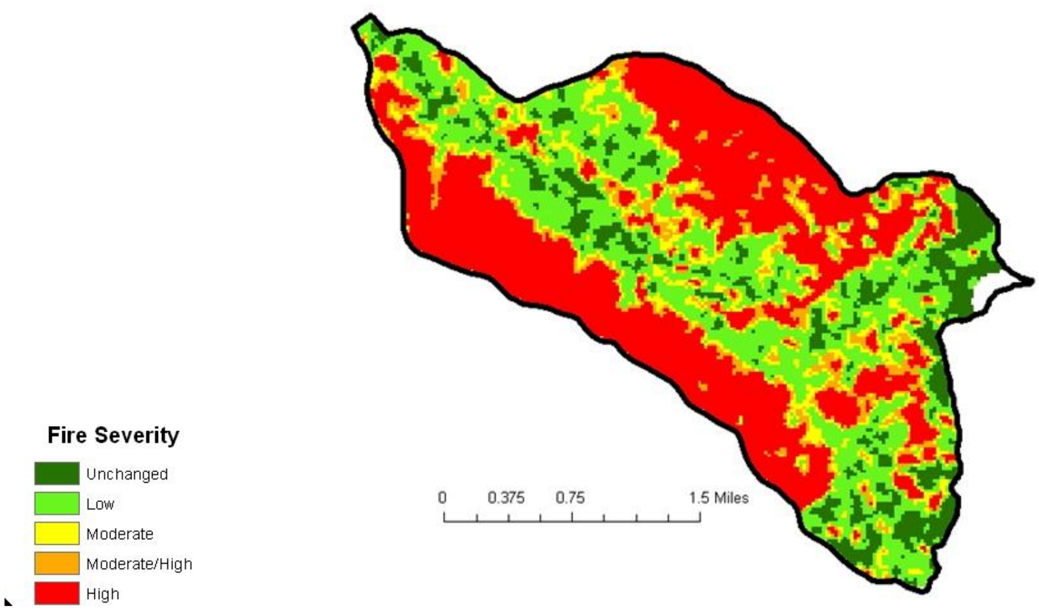

Figure 7. Observed pattern of fire severity as represented by RdNBR from the MTBS data.

Spatial analysis of drivers of fire severity

A range of variables were considered for the analysis of the fire severity patterns in the CCRNA (Table 3). Percent change in canopy cover was used as the dependent variable and approximates fire severity. It is highly correlated with the raw RdNBR data (>90%). Elevations in the CCRNA ranged from 1127 – 2074 meters, slope (%) ranged from 0 – 108% and slope position was equally distributed between the two slope aspects. CalVeg cover types within the fire perimeter were mainly late seral closed and shrub (Figure 8). The pre-fire surface fuel map indicates that surface fuels on the landscape were mainly mixed conifer with medium slash and low shrub (Figure 9). In 1941, the vegetation was classified as mostly shrub, and forest (Figure 3b). Mean daily temperature during the fire ranged from a low of 24°C to a high of 34°C and mean relative humidity during the fire ranged from a low of 15% to a high of 32%. The average daily wind speed during the fire was low and ranged from 3 – 6 km/h (Figure 2a-d).

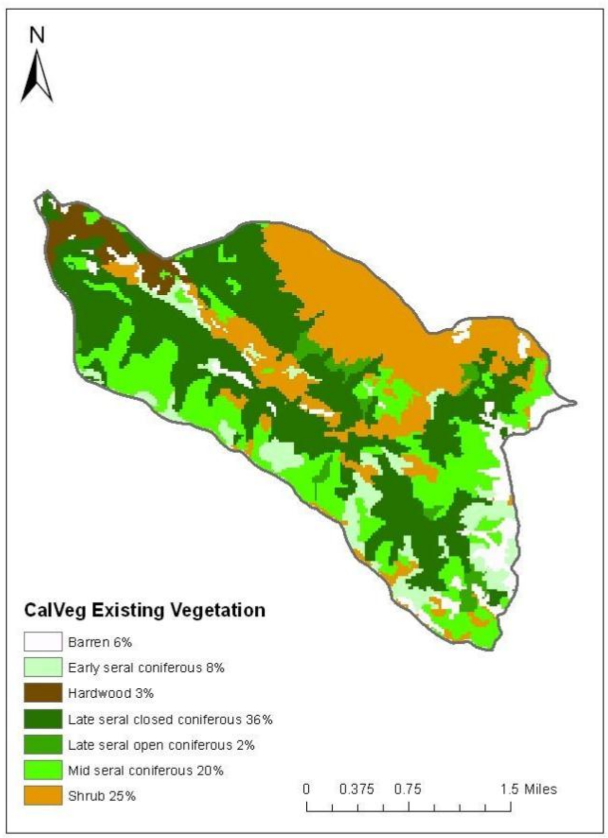

Figure 8. CalVeg classification of vegetation in the CCRNA, Lassen National Forest, California.

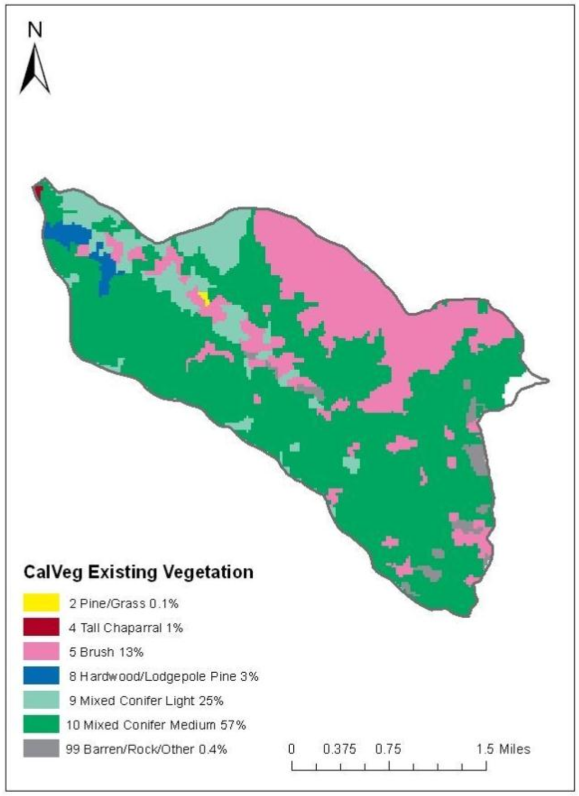

Figure 9. Surface fuel types in the CCRNA, Lassen National Forest California.

Correlation among variables and variable selection

The correlation analysis indicated that elevation was moderately correlated with slope position (Table 8). As expected, there were also moderate correlations between vegetation types and topographic variables.

Table 8. Pearson correlation coefficients between topographic and vegetation/fuels variables in the CCRNA.

	Slope position	Elevation	Aspect Class	Slope percent	1941 Vegetation	2010 Surface Fuel Type	CalVeg Type
Slope position	-	0.41	-0.03	0.02	0.23	-0.15	-0.40
Elevation	0.41	-	0.16	-0.19	n/a	n/a	n/a
Aspect Class	-0.03	0.16	-	-0.22			-0.38
Slope percent	0.02	-0.19	-0.22	-	n/a	n/a	n/a
1941 Vegetation Type	0.23	n/a	0.54	n/a	-	-0.55	-0.63
2010 Surface Fuel Type	-0.15	n/a	-0.50	n/a	-0.55	-	0.58
CalVeg Type	-0.4	n/a	-0.38	n/a	-0.63	0.58	-

Based on the correlation analysis elevation was removed as a variable in the spatial modeling because slope position and aspect class were both derived from a DEM and therefore explain the variability in elevation in similar ways.

Spatial autocorrelation

There was positive spatial autocorrelation in the fire severity data meaning that values up to a distance of approximately 1500 m tended to be similar (Figure 10a). This spatial autocorrelation was explained by the spatially explicit covariates, (e.g., elevation, aspect) in the model including the spatial term.

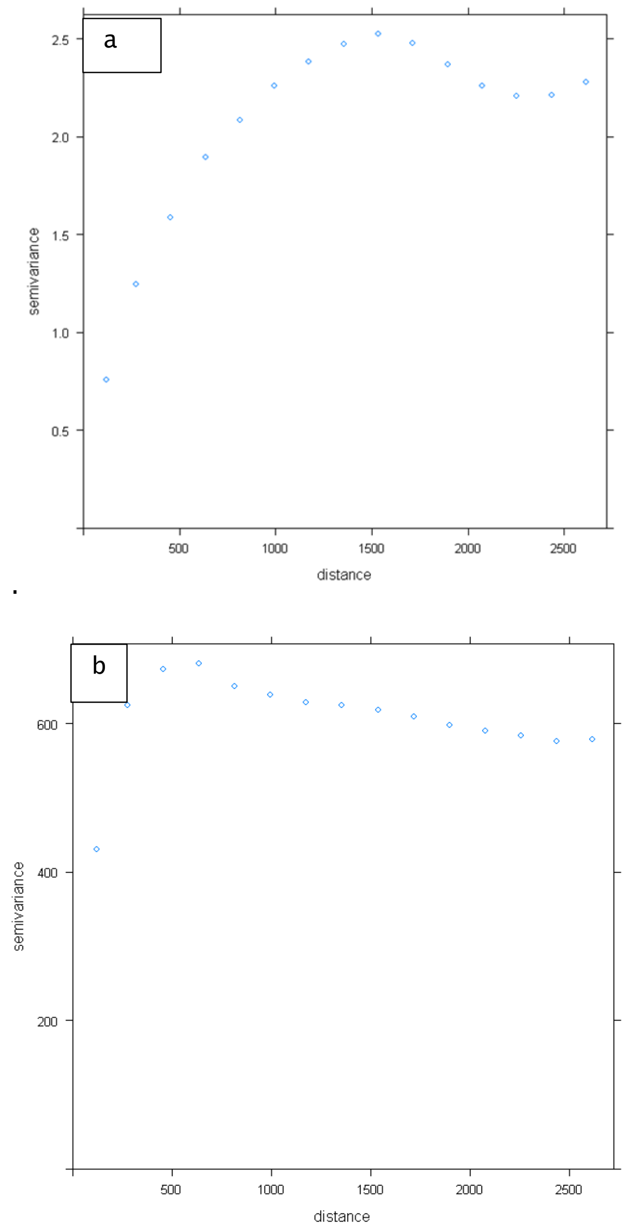

Figure 10. Spatial autocorrelation as represented by semivariance (a) raw data and (b) model residuals for fire severity in the CCRNA

Once the effects of these variables were removed the remaining residuals were no longer spatially correlated (Figure 10b). The spatial term was still significant in the model (p = <0.001) (Table 9), implying that some spatial variability still remained 'unexplained'.

Table 9. Parameter estimates for variables in the final general additive model to predict spatial patterns of fire severity in 2008 in the CCRNA as represented by RdNBR from MTBS data.

	Estimate	**Std. Error**	**t-value**	**Pr(>|t|)**	
(Intercept)	32.8898	0.4986	65.962	< 2e-16	***
Aspect Class (ASPCL[T.SW])	6.6931	0.6371	10.505	< 2e-16	***
Slope Position (SP[T.Mid])	10.3165	0.5148	20.041	< 2e-16	***
Slope Position (SP[T.Upper])	12.8587	0.5350	24.033	< 2e-16	***
1940s Vegetation (VEG40 [T.Shrub])	10.7037	0.4875	21.957	< 2e-16	***
1940s Vegetation VEG40[T.Barren]	-4.5613	1.0555	-4.321	1.56e-05	***
1940s Vegetation VEG40[T.Tree/Shrub]	2.7297	1.2019	2.271	0.0232	*
Approximate significance of smooth terms:					
Average Temperature (CUB_AT)	8.916	8.998	88.35	<2e-16	***
Slope percent (SPER)	8.455	8.856	88.35	<2e-16	***
Spatial term coordinates (UTMN, UTME)	28.881	28.999	440.34	<2e-16	***

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

General additive mixed model

Based on AIC model selection criteria (low AIC) the most appropriate model for predicting fire severity included slope position, aspect class, slope percent, existing vegetation and average temperature (Table 9 and 10).

Table 10. AIC (Akaike Information Criteria) for different models predicting fire severity (RdNDR) in the CCRNA.

Model Variables	AIC
Slope position, Aspect, Slope percent, Existing Vegetation, Average Temperature, Lat/Long	161524.9
Slope position, Aspect, Slope percent, Existing Vegetation, Average Wind speed, Lat/Long	161596.7
Slope position, Aspect, Slope percent, Existing Vegetation, Average Relative Humidity, Lat/Long	161732.7
Slope position, Aspect, Slope percent, 1940s Vegetation, Average Temperature, Lat/Long	162258.5
Slope position, Aspect, Slope percent, 1940s Vegetation, Average Wind speed, Lat/Long	162368.3

Slope position, Aspect, Slope percent, 1940s Vegetation, Average Relative Humidity, Lat/Long	162612.7
Slope position, Aspect, Slope percent, Surface Fuel Models, Average Temperature, Lat/Long	162385.7
Slope position, Aspect, Slope percent, Surface Fuel Models, Average Wind speed, Lat/Long	162484.7
Slope position, Aspect, Slope percent, Surface Fuel Models, Average Relative Humidity, Lat/Long	162707.3

In order to represent vegetation structure generated by late 19th century fire severity patterns inferred from our tree ring and plot data we chose the model with the 1941 vegetation type rather than existing vegetation. The moderately strong correlation between vegetation types in 1941 and 2004 and small difference in AIC (<1%) between the two models indicate these variables are providing similar prediction skill to the model.

Topographic variables (aspect class, slope position, and percent slope) were significant predictors of severity in the Cub Creek RNA fire (Table 9 and 11). Fire severity was highest on SW facing slopes regardless of dominant vegetation class (Table 9 and 11, Figure 11a). Slope position was significant in the model with both the mid- and upper slopes having higher fire severity than the lower slopes (Table 9 and 11; Figure 11b). In addition, the highest severity occurred in shrub cover type followed by portions of the landscape that were dominated by trees (Table 9 and 11, Figure 11c). Percent slope had little effect on fire severity (Table 11). Average temperature was also significant in the model with severity being highest at moderate temperatures (Table 11). The adjusted R^2 for the full model (all significant variables) was 64%.

Table 11. ANOVA for the final spatial model predicting the location of fire severity classes from RdNBR data in the CCRNA.

	df	**F**	**p-value**
Aspect Class	1	110.3	<0.0001
Coordinates (X, Y)	28.881	440.34	<0.0001
Average Temperature	8.998	88.35	<0.0001
Slope Position	2	332.7	<0.0001
1940s Vegetation	3	203.7	<0.0001
Slope percent	8.455	45.55	<0.0001

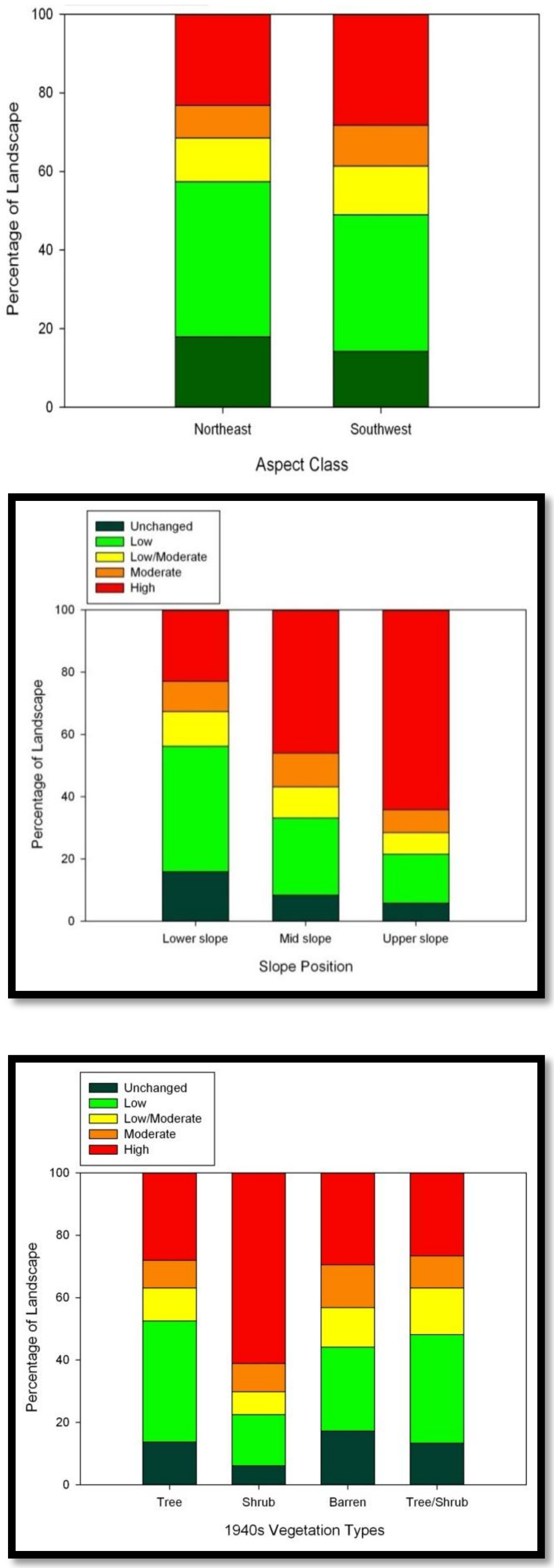

Figure 11. Percentage area burned at different fire severity on different slope aspects, different slope positions and in different 1941 vegetation types in the CCRNA. Fire severity is represented in fire severity classes by RdNBR data from the MTBS program.

Predictive spatial model

We used the general additive model to generate a map of predicted fire severity in the CCRNA (Figure 12). The model was successful at predicting the location of the low and high severity classes but poor at predicting moderate or unchanged severity classes. The overall producers accuracy for the model was 47% (Table 12).

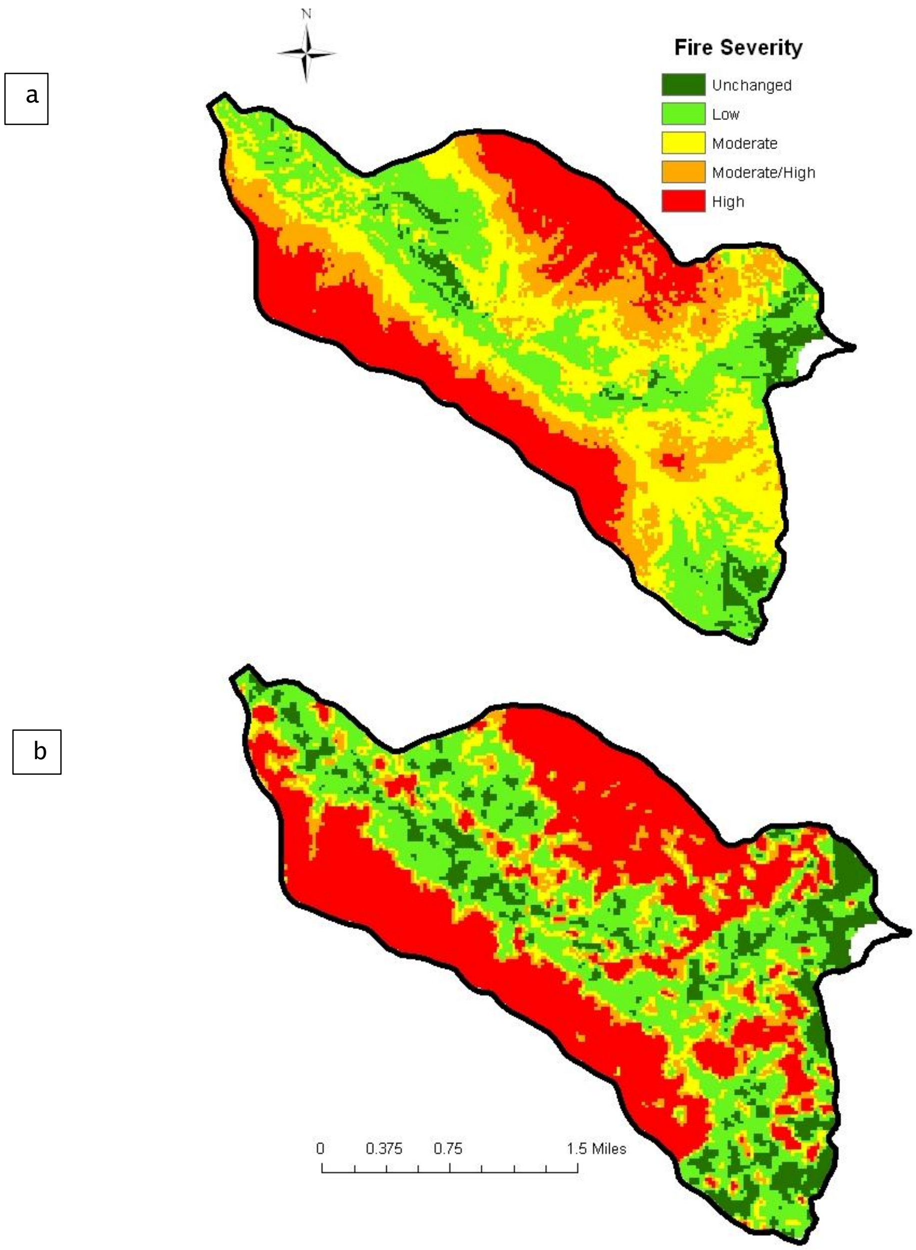

Figure 12. Predicted (a) and observed (b) values of fire severity for the CCRNA.

Table 12. Confusion matrix and prediction statistics for the final general additive model of fire severity for the CCRNA. The producers accuracy was 0.47, Kappa was 0.32, the no information rate was 0.40, Mcmears't test (P<0.001).

	Unchanged	Low	Moderate	Moderate/High	High
Unchanged	399	303	32	12	7
Low	1161	2441	488	265	214
Moderate	454	1919	829	699	838
Moderate/High	37	347	358	533	1959
High	0	5	30	147	4026

Classification tree

The classification tree analysis indicates there are differences in the relative importance of weather, topography, and vegetation type on fire severity patterns in the CCRNA (Figure 13). Slope position explained the greatest sums of squares followed by average temperature. On low slope positions under moderate temperatures fire severity was low but at higher temperatures fire severity was high. However, if temperatures were less than moderate and the vegetation was dominated by trees fire severity was low, but if the vegetation was shrubs fire severity was high. When the tree split to moderate and upper slopes and temperatures were high then fire severity was high. When temperatures were less than extreme and the vegetation was dominated by trees, fire severity was low. Similar to lower slope positions, middle and upper slopes dominated by shrubs burned at high severity.

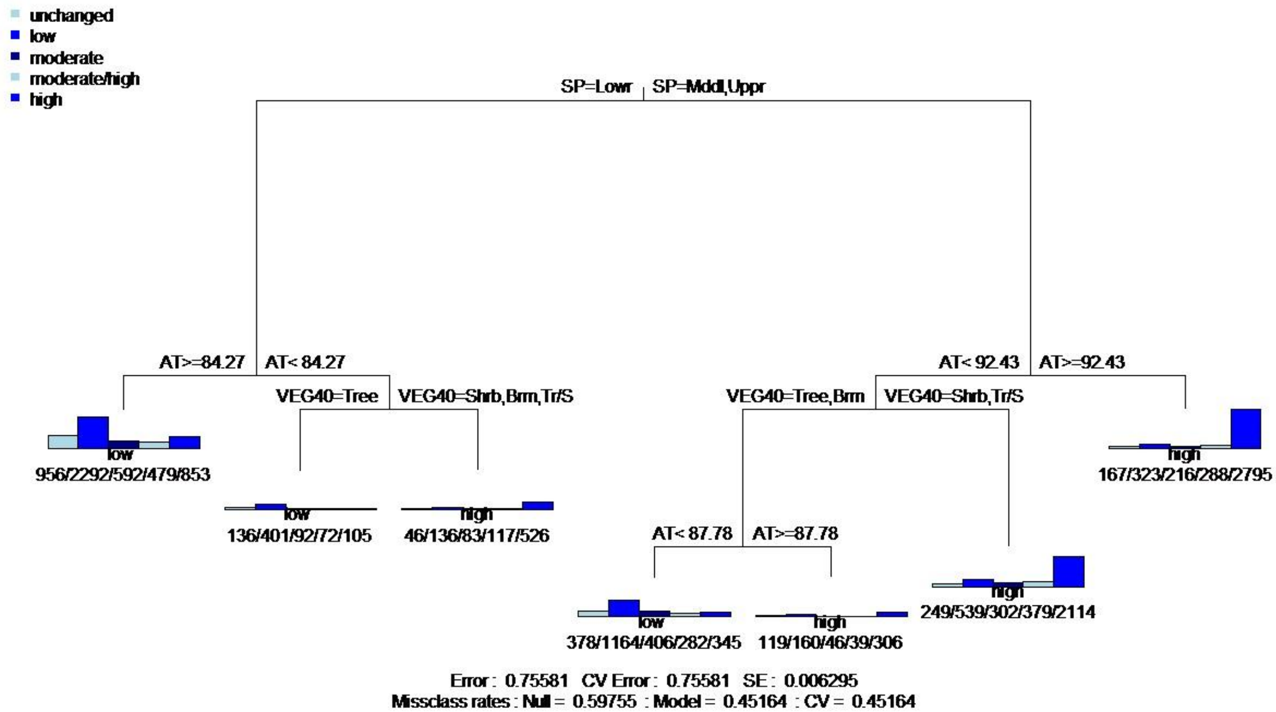

Figure 13. Classification tree of the relationships between topographic and weather variables and fire severity as measured by RdNBR in the CCRNA, Lassen National Forest California.

DISCUSSION

Mixed conifer forest composition in the CCRNA is strongly influenced by topographic variables such as slope aspect and elevation that influence spatial patterns of soil moisture and temperatures. Elevation, slope aspect and soil moisture, are all recognized as key environmental factors that influence species abundance patterns in mountainous western landscapes, including the southern Cascades and Sierra Nevada (Skinner and Taylor 2006; van Wagtendonk and Fites-Kaufman 2006).

Earlier work in the CCRNA demonstrated that topographic variables a strong association of topographic variables with the spatial pattern of pre fire suppression period fire regime parameters (Beaty and Taylor 2001). For example, fire return intervals were longest on higher, cooler, more mesic, north-facing slopes with white fir, Douglas-fir/white fir, or red fir/white fir forests and shortest on dry south-facing slopes with ponderosa pine/white fir forests and intermediate on west facing slopes with mixed pine-white fir-incense cedar forests. Several factors related to flammability of fuels contribute to the spatial variation in fire return intervals. Cooler temperatures, deeper snow packs, and later spring snowmelt shorten the period that fuels would be dry enough to burn at higher elevations or on north facing slopes compared to warmer, drier sites at low elevation or on south facing slopes. Moreover, in the Sierra Nevada, fine fuel is produced more rapidly in lower than upper elevation montane forests (Keifer et al. 2006), so fire could re-burn a patch sooner in lower elevation pine dominated forests. High elevation forests are also dominated by short-needled fir, pine, and hemlock (Parker 1989) species such as the red fir-white forests found at the highest elevation in the CCRNA. Fuel beds of short-needled species readily compact and have a higher bulk density with lower fire spread and intensity compared to the fuel beds of long needled pines (Agee 1993). The distinct spatial patterns of pre-fire suppression fire return intervals in the CCRNA, however, are not characteristic of all dry mixed pine-fir landscapes in California or in the western USA. For example, in a less topographically complex mixed conifer forest landscape in Yosemite National Park (Scholl and Taylor 2010), there was no spatial variation in pre fire suppression fire frequency related to topography or forest composition. In dry pine forests in Oregon and Washington, Heyerdahl et al. 2001 identified strong topographic control on pre fire suppression fire frequency in steep terrain with breaks in fuel continuity but not in other types of terrain. Apparently, topographic control on spatial patterns of fire regime characteristics may emerge primarily in more highly complex terrain (Taylor and Skinner 2003, Kellogg et al. 2008; McKenzie and Kennedy 2012).

Pre fire suppression fires in California mixed conifer forests have been described as being mainly low and moderate in severity (van Wagtendonk and Fites-Kaufman 2006), and whileour earlier work agrees, it also indicates that high severity burns were an intrinsic part of the fire regime in the CCRNA. The pre fire suppression burn severity patterns in CCRNA varied strongly with topographic position and slope aspect and the area that burned at high severity was most extensive on upper slope positions. Similar fire severity/slope position/slope aspect relationships for the pre fire suppression period have been identified in Douglas-fir mixed conifer forests on steep, complex terrain in the Klamath Mountains (Taylor and Skinner 1998). The concentration of high severity fire effects on mid- and upper-slope positions may be related to the probability of fire moving upslope as a head fire (more likely in upper slope positions) or downslope as a backing fire (more likely on lower slope positions), pre-heating of fuels on steep slopes, or higher afternoon upslope wind speeds (especially on south- and west-facing slopes) that tend to increase fire line intensity on upper slopes (Rothermel 1983, Weatherspoon and Skinner 1995, Taylor and Skinner 1998). A spatial pattern of vegetation/fuel types on mid and upper slope positions that characteristically burn at high severity could also become self-reinforcing and contribute to a strong slope position/fire severity association. Stands of montane chaparral on upper slope positions that establish after severe fire have been noted in mixed conifer forest landscapes in the Sierra Nevada and southern Cascade Range (Nagel and Taylor 2005; Skinner and Taylor 2006; Beaty and Taylor 2008).

Our working hypothesis for this research was that fire severity patterns in the 2008 fire would be related to spatially similar to pre fire suppression fire severity patterns. In other words, fire severity patterns in the CCRNA landscape would tend to repeated and self-reinforcing because of strong terrain/vegetation feedbacks that influence fire behavior and fire severity. The last 19th century fires in the CCRNA created, or maintained, a spatial association between area burned at high severity and slope position. In the late 19th century the area burned at high severity was more extensive on upper slopes, least, on lower slopes, and intermediate on mid slopes (Beaty and Taylor 2001). Our statistical comparison of plot level fire effects' for the 2008 fire exhibit a similar spatial pattern. Tree mortality, height of bark char, and percent of the basal area killed by the fire were highest on upper slopes, lowest, on lower slopes, and intermediate on mid slopes. The strong relationship between severity of stand level fire effects and slope position supports our hypothesis of a strong association between burn severity patterns in the late19th century and in 2008. The extent of severe fire in the 19th century was greater on the north-facing slopes than on other slopes similar to the 2008 reburn.

Modeled variation in pre-fire stand level fire behavior on different slope aspects was generally consistent with observed variation in the severity of stand level fire effects from the 2008 fire.

Modeled rate of spread and flame length were higher on the north and southwest facing slopes than on other slopes. The crowning index was also higher on south-facing slopes suggesting that a higher wind velocity is needed on the south-facing slope to carry a crown fire. In contrast to slope aspect, there was only one modeled stand level fire behavior parameter, crowing index, that varied with slope position and it was lower on upper slope positions. The lower crowning index at upper slope positions is consistent with the observed more severe fire effects in upper slope position plots. The values for flame length and the torching index on upper slope positions also tended to be higher but not significantly so. The lack of significance for these variables on upper slope positions is probably related to differences in day of burning weather conditions and/or fuels among plots.

The generally consistent association between modeled stand level fire behavior and the observed severity of fire effects in our plots was not evident in landscape fire behavior simulations. There was little spatial variability in fire type (i.e. surface, passive crown, active crown) under day of burn weather conditions across the CCRNA. The FlamMap simulations projected potential for passive crown fire for most locations in the CCRNA watershed. The lack of correspondence between modeled fire type, observed severity of plot level fire effects, and remotely sensed measurements of fire severity (MTBS data) is probably related to several factors. First, the surface and canopy fuel parameters that were used in the simulations (i.e. LandFire) were of coarse scale. Actual variability in surface and canopy fuels in the watershed was probably greater as evidenced by the variability in our plot level fuel parameters and this was not captured in the fuel parameter layers. Higher resolution surface and canopy fuel maps have been developed elsewhere using ground and remote sensing measurements (e.g. Pierce et al. 2012). However, fuel parameter maps that we generated using the Pierce et al (2012) approach did not increase spatial variability in fuel parameters sufficiently to produce FlamMap simulations of fire type similar to the 2008 fire severity patterns.

The lack of spatial variability in the FlamMap simulations of fire type could also be related to differences in site-level fire weather in the CCRNA compared to the use of data from the single Carpenter Ridge RAWS station used to drive simulations. Site-level weather conditions (i.e. temperature, humidity, wind speed) may have varied sufficiently to generate actual fire intensity that was not captured in the simulations. Moreover, temporal variability in other weather conditions that influence fire weather and fire intensity and hence fire severity may not be represented in RAWS data. For example, the CCRNA has deeply incised terrain that can facilitate development of persistent temperature inversions under the stable atmospheric conditions that are common in the region. Inversions trap smoke in canyons and valleys which can reduce temperatures, increase humidity, and reduce fire intensity leading to more surface fire, and less crowning (Robok 1988, 1991). The reduced fire intensity can reduce the severity of fire effects, particularly in lower slope positions. When temperature inversions lift and increase the altitude of the mixing layer, large areas of high-intensity fire can occur due to higher temperatures, lower humidity, and frequently higher wind speeds often leading to increased severity of fire effects. Inversion influenced fire behavior appears to be a particularly important control influencing spatial patterns of fire severity in the nearby Klamath Mountains and inversion influenced fire effects were characteristic of fires that burned for extended periods in 2008 in that region (Miller et al. 2012). The temperature and humidity data from Carpenter Ridge (Figure 2a,b), the daily fire spread map (Figure 2d) and a proxy of regional spread and intensity (Figure 14) suggest that an inversion that had been in place lifted during the period July 8-10. The RAWS station in the ridge was above the inversion and did not capture the site-level changes in conditions that took place in the canyon. Wind speed did not increase on the ridge during this period (Figure 2c).

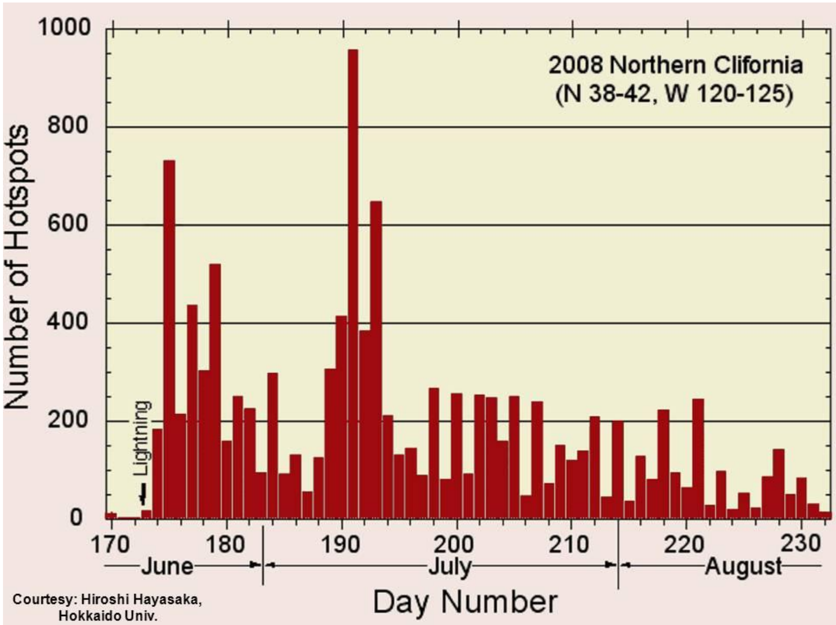

Figure 14. Time series of hotspots identified on Modis imagery from lightning fires ignited on across northern California June 20 and 21, 2008. The fire that burned through the CCRNA was ignited by this widespread lightning event. The graphic is modified from Hayasaka and Skinner (2009).

During the July 8-10 period fire spread rapidly across the north-facing slope in the CCRNA and burned much of it at high severity. This suggests that the duration and intensity of temperature inversions may also contribute to associations between topographic variables (i.e. slope position, aspect) and spatial patterns of fire severity in mountainous landscapes.

Spatial variability in fire effects across a landscape are driven by interactions between, vegetation/fuels, topography, and weather conditions for both individual fires and composites of sequential burns across a landscape (Agee 1993; Rollins et al. 2002; Collins et al. 2010). In the CCRNA, all three variable types contributed to a model explaining spatial variability in fire severity as measured by RdNBR. Slope position was the most important variable followed by 1941 vegetation type, and day of burn air temperature. In the CCRNA, the proportionof montane chaparral on mid and upper slope positions in 1941 amplified the importance of slope position. This strong slope position, fire- severity gradient has also been identified in other landscapes dominated by mixed conifer forest in California in the Klamath Mountains (Taylor and Skinner 1998) and northern Sierra Nevada (Beaty and Taylor 2008). Interestingly, in both of these landscapes there is evidence of high proportions of montane chaparral on mid and upper slopes in early aerial photographs (1939-1944). This suggests that pre-fire suppression patterns of fire severity in these landscapes were controlled by a combination of slope position and vegetation/fuel type before the onset of fire suppression. A recent synthesis on controls of fire severity in western forests and woodlands in different regions using RdNBR data (1984-2006) also identified a strong influence of topography on fire severity (Dillion et al. 2011). Overall, recent severity patterns, in large wildfires were found to be more strongly controlled by topographic variables (i.e. elevation, slope aspect, slope position, complexity) than by climate or weather variables. Fuel type, however, was not explicitly considered in Dillion et al. 2011). In a particular location, the importance of fuel conditions or extreme fire weather, of course, may generate fire severity patterns that deviate from the general trend related to topography. For example, in Yosemite National Park, high severity fire was associated with periods of extreme fire weather, and vegetation/fuel types characteristic of mid-slope and low/flat topographic positions (Collins et al. 2010).

The landscape analysis of fire severity in the CCRNA as measured by RdNBR supports our hypothesis that there is a tendency for patterns of severity to be repeated across a landscape. The last widespread fires in the CCRNA burned in the late 19th century and there was a strong spatial association between topographic position and apparent severity of these fires. Burn severity was mainly high on upper slopes, low on lower slopes, and intermediate on mid slope positions. Fire severity patterns in 2008 were similar and strongly associated with late 19th century severity patterns. In the CCRNA, areas on upper slopes that were montane chaparral in the late 19th century and were young even-sized and even-aged forest in 2008 burned at high severity. In contrast, older mixed sized and mixed aged forests on lower slopes burned at low severity. This suggests that patterns of fire severity may be related to self-reinforcing feedbacks between vegetation and fire that may have been initially generated by topographic effects on fire behavior. In the Klamath Mountains, areas dominated by sclerophyllous trees and shrubs burned more severely than areas dominated by closed evergreen need leaved forest. The feedback pattern between vegetation type and fire severity was also stronger with a short period between reburns after a long hiatus of fire before the first burn (Odion et al. 2009). Similarly, montane chaparral patches generated by high severity fire in Yosemite National Park reburned at high severity more often than other types of vegetation (Collins and Stephens 2010). The repeated fire severity pattern in the CCRNA suggests that self-reinforcing feedbacks between vegetation type and fire severity can persist for a century or more and be an important driver of contemporary patterns of fire severity.

Although self-reinforcing vegetation/fire interactions generated strong spatial associations between fire severity in the late 19th century and in 2008 other processes also contributed to the extent of high severity fire effects in 2008. Our original field measurements of forest size and forest age structure (Beaty and Taylor 2001) and the early aerial photographs indicate that the area of high severity fire in 2008 was more extensive than from burns in the late 19th century. Twenty percent of the area that was multi-sized and multi-aged forest in 1941 burned at high severity in 2008 rather than at moderate or low severity. This expansion in area of high fire severity is probably related to the increase in forest density and surface and canopy fuels in the CCRNA caused by fire suppression (Beaty and Taylor 2001). These vegetation changes likely made stands in the CCRNA more susceptible to high severity fire and increased the area that burned at high severity compared to the 19th century reference. This is part of an overall trend of increasing fire severity in the last several decades due to increased fuels and warming temperatures in the southern Cascades and Sierra Nevada California (Westerling et al. 2006; Miller et al. 2009a). The self-reinforcing feedbacks between fire and vegetation we identified in the CCRNA landscape suggests that expanded areas of high severity fire will have a tendency to burn at high severity fire again which may increase the future proportion of the landscape prone to burning at high severity.

Fires in mixed conifer forests are generally described as being frequent and low and moderate in severity. Under a regime of frequent low and moderate severity fire, burns consume surface fuel and kill mainly seedlings and sapling and occasionally small groups of main canopy trees (Kilgore and Taylor 1979; Scholl and Taylor 2010). Series of burns can create self-limiting conditions which impede the spread of fire until sufficient fuels are produced to carry the next fire (Collins et al. 2008; Scholl and Taylor 2010). Mixed conifer forests that develop under this fire regime tend to be multi-aged and have a fire grained (<0.2 ha) structure of open and closed canopy conditions and heterogeneous fuels which impedes development of high severity fire. The mixed conifer forest in the CCRNA included forests with this type of structure but mainly at lower slope positions. Upper slope positions in the CCRNA, in contrast, experienced higher severity fire. On these upper slopes forests were young and even-aged. The cumulative effect of the spatial variability in fire severity in the CCRNA had a strong influence on forest landscape characteristics. Forests with more old-growth characteristics (e.g. multi-layered, high density or large old trees, large diameter snags and coarse woody debris) tend to be found on lower slopes. Upper and mid slope positions tend to have a coarser-grained pattern of mainly younger stands with scattered patches of older trees. Similar spatial variation in forest structural characteristics across mixed conifer forest landscapes has been observed in the deeply dissected terrain of the Klamath Mountains (Taylor and Skinner 1998; Skinner et al. 2006). In landscapes with this type of fire driven forest structural variability, it may be advantageous for fire managers who want to reduce the likelihood of large severe fires to pattern the type and severity of treatments (prescribed fire, thinning, fuelbreaks) to historical patterns of fire severity.

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Deliverables

Project	Description	Delivery Dates
Workshop	Forest Management and Watershed Science Symposium: Paper presentation Management implications of altered fire regimes and changes in forest structure on east side ponderosa pine forests. Attended by federal, state, private fire and land managers and NGO staff	3/30/11
Conference	Participated in symposium on mixed severity fire regimes in the Pacific Northwest and northern California. Paper presented: Mixed severity fire regimes in the Klamath Mountains, northern California and southwestern Oregon. Meeting of the U.S. International Association of Landscape Ecology, Portland Oregon.	4/4/11
Conference	Fifth International Fire Ecology and Management Congress. Portland, Oregon, Papers presented: Self-reinforcing patterns of fire severity in a mixed conifer forest landscape in the southern Cascades, USA.	12/4/2012
Conference	United States Regional Meeting of the International Association of Landscape Ecology; Paper presented: Self-reinforcing patterns of fire severity in a mixed conifer forest landscape in the southern Cascades, USA	4/17/13
Workshop	Spatial Patterns and Controls on Severity of Recent Wildfires in Northern California. Susanville, CA. Presentations and discussion by Alan Taylor-PSU, Becky Estes-PSW, Carl Skinner-PSW, Hugh Safford –FS Regional Ecologist-PSW. Attended by 60 federal fire and land managers	1/8/2013
Data set	Geospatial data set on fire behavior and severity delivered to LNF.	1/8/2013
Data set	Geospatial data set on fire behavior and fire severity provided to attendees of workshop	1/8/2013
Invited Research Presentation	Self-reinforcing patterns of fire severity in a mixed conifer forest landscape, southern Cascades, USA. Penn State University	1/18/13
Final Report	Final report provided to the Lassen National Forest and Joint Fire Science Program	6/17/13
Draft manuscript	Self-reinforcing patterns of fire severity in a mixed conifer forest landscape, southern Cascades, USA	9/30/13
Draft Manuscript	Controls on spatial patterns of fire severity in a mixed conifer forest landscape in the southern Cascades USA	9/30/13

Workshop Agenda and List of Participants

Workshop: Spatial Patterns and Controls on Severity of Recent Wildfires in Northern California

Presented by Alan Taylor
Penn State University
And
Hugh Safford, Becky Estes and Carl Skinner
US Forest Service

Time: Tuesday January 8th, 2013
Location: USFS Lassen National Forest Supervisor's Office

Workshop Agenda

10:00 – 10:15 AM	Welcome – Hugh Safford
10:15 – 10:25 AM	Introduction of Projects and Objectives – Alan Taylor
10:25 – 11:10 AM	Fire Severity Patterns and Controls of the Storrie fire-Becky Estes
11:10 – 11:55 AM	Fire Severity Patterns and Controls in the Cub Fire-Alan Taylor
12:00-1:00	Lunch Provided
1:00 – 1:45 PM	Fire Severity Patterns and Controls in the Klamath Mountains and Applying Severity Information to Fire and Fuels Management-Carl Skinner
1:45-2:00	Open Question and Answer Period to Presenters
2:00-2:15	Evaluation

Detailed Topics

1. Introduction
   i) Challenges of the fire severity problem

2. Goals and Objectives
   a. Implications of fire severity patterns for fuels and fire management
3. How We Did It – Data sources
   a. MTBS
   b. Vegetation, fuels, weather, fire data layers
   c. Aerial imagery
   d. Plot and fire history data
4. How We Did It-Analysis Tools

   a. CART

    b. Random Forest
    c. GAM
5. Results
    a. Topographic patterns of fire severity
    b. Contributions of fuels, weather, and topography on fire severity patterns
6. Applications in Fuels and Fire Management
    a. Landscape fuels treatment
    b. Using expected patterns of fire severity to plan broader strategies of fuel treatments across landscapes (e.g. where are fires likely to be most severe, where are they likely to be least severe).
7. Products
    a. Publications and Presentations
8. Workshop Evaluation
    a. What do you think? - We want to know!
    b. Acknowledgements
    c. Questionnaire

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24	Kellison, Timothy -FS <tkellison@fs.fed.us>	X	LNF	SO
25	Kinateder, David J -FS <djkinateder@fs.fed.us>	X	PNF	SO
26	Kinnard, Cassie J -FS <cjkinnard@fs.fed.us>	X	LNF	ALRD
27	Kronner, Eric -FS <ekronner@fs.fed.us>	X	LNF	ALRD
28	Lent, Mervin D -FS <mlent@fs.fed.us>	X	LNF	ELRD
29	Lepley, Donald E -FS <dlepley@fs.fed.us>	X	LNF	SO
30	Lewis, Chuck A -FS <calewis@fs.fed.us>	X	LNF	ELRD
31	Mark Williams (markw52@frontier.com)	X	Ret	
32	Mayer, Deborah -FS <dmayer@fs.fed.us>	X	LNF	HCRD
33	McCartney, Wendy -FS <wendymccartney@fs.fed.us>	X	LNF	ELRD
34	McFarland, Melanie -FS <mmcfarland02@fs.fed.us>	X	LNF	SO
35	McRae, Heather -FS <hmcrae@fs.fed.us>	X	STNF	
36	Michael Klimek <mike_klimek@nps.gov>	X	LVNP	
37	Miranda-Cole, Esther R -FS <emirandacole@fs.fed.us>	X	LNF	SO
38	Mowery, Rick -FS <rmowery@fs.fed.us>	X	MNF	SO
39	Newburn, Benjamin T -FS <bnewburn@fs.fed.us>	X	ENT	
40	Payne, Lauren J -FS <ljpayne@fs.fed.us>	X	ENT	
41	PearsonRamirez, Terre E -FS <tramirez@fs.fed.us>	X	LNF	ELRD
42	Peters, Douglas W -FS <dwpeters@fs.fed.us>	X	LNF	SO
43	Peterson, Priscilla M -FS <pmpeterson@fs.fed.us>	X	LNF	SO
44	Ramirez David A -FS <daramirez@fs.fed.us>	X	Ret	
45	Rickman, Tom -FS <trickman@fs.fed.us>	X	LNF	ELRD
46	Robin Wills (Robin_Wills@nps.gov)	X	NPS	
47	Safford, Hugh D -FS <hughsafford@fs.fed.us>	X	RO	
48	Sanger, Allison L -FS <asanger@fs.fed.us>	X	LNF	SO
49	Skinner, Carl -FS <cskinner@fs.fed.us>	X	PSW	
50	Stawiarski, Scott -FS <sstawiarski@fs.fed.us>	X	LNF	SO
51	Stewart, Beth A -FS <bethstewart@fs.fed.us>	X	PNF	
52	Tom McCubbins (tom@tehamacountyrcd.org)	X	TRCD	
53	Tripp, Jamie L -FS <jltripp@fs.fed.us>	X	RO	
54	Vazquez, Alfred G -FS <avazquez@fs.fed.us>	X	Ret	
55	Villalovos, Anita -FS <avillalovos02@fs.fed.us>	X	LNF	ELRD
56	Weldon, Matthew L -FS <mweldon@fs.fed.us>	X	STNF	
57	Woodruff, William -FS <wwoodruff@fs.fed.us>	X	LNF	SO
58	Rogers, Brian J -FS <bjrogers@fs.fed.us>	v	LNF	SO