Forest Ecology and Management 261 (2011) 2038–2048

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Comparing the role of fuel breaks across southern California national forests

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A R T I C L E I N F O

Article history:
Received 3 January 2011
Received in revised form 23 February 2011
Accepted 24 February 2011

Keywords:
Structural equation model
Fuel treatment
National forest
Wildland–urban interface
Firefighting
Fire management

A B S T R A C T

Fuel treatment of wildland vegetation is the primary approach advocated for mitigating fire risk at the wildland–urban interface (WUI), but little systematic research has been conducted to understand what role fuel treatments play in controlling large fires, which factors influence this role, or how the role of fuel treatments may vary over space and time. We assembled a spatial database of fuel breaks and fires from the last 30 years in four southern California national forests to better understand which factors are consistently important for fuel breaks in the control of large fires. We also explored which landscape features influence where fires and fuel breaks are most likely to intersect. The relative importance of significant factors explaining fuel break outcome and number of fire and fuel break intersections varied among the forests, which reflects high levels of regional landscape diversity. Nevertheless, several factors were consistently important across all the forests. In general, fuel breaks played an important role in controlling large fires only when they facilitated fire management, primarily by providing access for firefighting activities. Fire weather and fuel break maintenance were also consistently important. Models and maps predicting where fuel breaks and fires are most likely to intersect performed well in the regions where the models were developed, but these models did not extend well to other regions, reflecting how the environmental controls of fire regimes vary even within a single ecoregion. Nevertheless, similar mapping methods could be adopted in different landscapes to help with strategic location of fuel breaks. Strategic location of fuel breaks should also account for access points near communities, where fire protection is most important.

1. Introduction

Wildfire is a key natural process in many ecosystems, but fire frequency, extent, and/or severity have surged across the globe in recent decades (Bowman et al., 2009; Flannigan et al., 2009; Westerling et al., 2006). The social and economic consequences of these fires are immense, with dramatic increases in property destruction and firefighting expenditures (Butry et al., 2001; NIFC, 2009). Altered fire regimes also threaten ecosystem integrity and biodiversity (Pausas and Keeley, 2009; Pyne, 2004). In many parts of the world the fire problem has been exacerbated by the continued expansion of the wildland–urban interface, where homes and lives are most vulnerable to wildfires, and where human ignitions increase the likelihood of fire occurring (Radeloff et al., 2005; Syphard et al., 2007). Mitigating the risk of wildfire at the wildland–urban interface, therefore, is now described as a major objective in the National Fire Plan (2001), the Healthy Forests Restoration Act (2003), and other federal fire management documents. The primary approach advocated for mitigating fire risk is to reduce hazardous fuel loads through fuel treatments of vegetation in wildland areas. In the last decade, expenditures on fuel treatments and area treated has increased markedly (Mell et al., 2010), with U.S. federal land management agencies receiving billions of dollars and treating millions of hectares of land (Schoennagel et al., 2009).

Despite this recent surge in treatment area and expenditure, fuel treatments have been a cornerstone of fire management in the U.S.A. for the better part of the 20th century. Yet, little systematic research has been conducted to understand what role fuel treatments have played in controlling fire, which factors influence this role, or how the role of fuel treatments may vary over space and time. A number of simulation studies have improved our understanding of potential fuel treatment effectiveness in modifying forest fire behavior (e.g., Finney et al., 2007; Miller and Urban, 2000; Schmidt et al., 2008). However, most empirical studies have focused on relatively localized effects when fires have intersected fuel treatments on forests (e.g., Finney et al., 2005; Martinson and Omi, 2003; Raymond and Peterson, 2005; Schoennagel et al., 2004). Due to this relatively small temporal and spatial scale (but see

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doi:10.1016/j.foreco.2011.02.030

Syphard et al., in press-b), these studies have not contributed to an understanding of factors that influence sustainable fuel treatment performance over broad landscapes. This is important because many parts of the western U.S. that intersect with urban environments comprise heterogeneous landscapes that include forest and non-forested ecosystems and because strategic planning requires an understanding of how repeated fire events over time are affected by fuel treatments.

Due in part to the paucity of appropriate research, there is no comprehensive fire policy in the United States that provides forest mangers with science-based guidance on where, how, and when fuel treatments should be conducted (Agee et al., 2000; Franklin and Agee, 2003). Instead, within-agency policies are established and implemented according to the agencies' missions and objectives, and many policies are not publicly reviewed or debated (Franklin and Agee, 2003). Developing scientifically based general principles and guidelines for using fuel treatments to control fires could benefit managers if these guidelines were to facilitate decision-making with regards to strategic placement and tactical response. Given limits in time and money, managers need to prioritize where to place new fuel treatments and to determine the level of maintenance needed for current fuel treatments (Dellasala et al., 2004). Thus, a scientifically based methodology and set of principles could make the decision-making process not only easier but more defensible as well. Furthermore, a better understanding of the factors that influence the role of fuel treatments could lead to the identification of additional management considerations and the development of improved management practices.

The primary problem with development of general guidelines for fuel treatments is that fire-prone regions are highly variable with regards to their natural fire regimes and the factors that control them. Fire regimes vary as a function of forest type, fuels, terrain, climate, and ignition sources (Pyne et al., 1996; Keeley et al., 2009), and fuel treatment effectiveness may also vary according to these factors (Schoennagel et al., 2004). In addition, human development and other infrastructure strongly influence fire regimes and vulnerability to fire. Humans start and stop fires both directly (e.g., via suppression or accidental ignitions) and indirectly (e.g., via land use planning, land cover change, exotic species introduction, climate change), and their influence varies by scale and by locale (Cardille et al., 2001; Prestemon et al., 2002; Syphard et al., 2009). These variations in fire regime and human influence complicate the notion of general principles because management programs need to account for these differences (Noss et al., 2006).

Another reason that a "one size fits all" approach to fire management is problematic is that fuel treatment objectives are likely to vary from region to region, particularly for wildland areas versus the wildland–urban interface (Keeley et al., 2009). In wildland areas, particularly in western U.S. forests, fuel treatments are intended to change fire behavior and to reduce the severity of fire effects, whereas fuel treatments in the wildland–urban interface are intended to prevent fire from spreading into communities (Radeloff et al., 2005; Reinhardt et al., 2008). Therefore, the effectiveness of fuel treatments, and the factors that contribute to their effectiveness, may change as a function of fuel treatment objectives.

One way to determine how well certain guidelines may transfer from region to region is to identify which factors affecting fuel treatment outcome are most likely to vary. Identifying these could help to determine what aspects of plans need to be developed separately for each management area. Common decision-making tools could be developed that account for regional differences in those variables. If there are factors that are universally influential across different regions or landscapes, these could help in the development of general management considerations.

In California, where a substantial portion of the landscape comprises non-forested ecosystems such as chaparral and sage scrub, fuel breaks have been a major part of fire management activities since the 1930s (Davis, 1965). Unlike forests where mechanical fuel treatments remove only surface fuels (preserving larger, older trees), fuel break construction in chaparral typically involves complete removal of vegetation, chemical herbicides, and permanent conversion of native shrublands to weedy herbaceous associations (Wakimoto, 1977).

In southern California, differences in natural fire regimes and the way fire regimes have been altered by past land use complicate fire management in the region. In the shrubland-dominated foothills and coastal valleys, fire frequency has substantially increased along with population growth and urban expansion (Keeley et al., 1999; Syphard et al., 2007). This increased fire frequency not only threatens homes and lives, but many shrublands cannot tolerate repeated fires and under such conditions are often replaced with non-native grasslands (Keeley and Fotheringham, 2003; Syphard et al., 2006). In shrubland-dominated regions, fuel manipulation projects involve a trade-off. On one hand, fuel breaks are needed to protect homes and lives, which are at an elevated risk in these crown fire shrublands; on the other hand, construction of fuel breaks typically involves complete removal of vegetation and may result in a range of ecological impacts. Thus, fire management in the region is greatly complicated by the need to balance both fire and resource management.

In the less extensive montane coniferous forests in the region, fire frequency has been unnaturally low during the last century, and fire hazard has consequently increased due to accumulated fuels associated with fire suppression and logging (Keeley, 2006), problems similar to other forests in the western U.S. (Miller et al., 2009). Because thinning and fuel manipulation is intended to improve forest vigor and reduce risk of catastrophic loss to wildfire (often by restoring forests to more historic conditions), fuel treatments and resource benefits are likely to be compatible in these forested regions (Schwilk et al., 2009). However, this model of fuel accumulation and ecological compatibility with fuel treatments has often been inappropriately applied to chaparral (Keeley and Fotheringham, 2004, 2006).

To better understand the factors that influence the role of fuel treatments in controlling large fires in southern California, and how the role of fuel treatments varies across different landscapes, we assembled a spatial database of fuel breaks and fires from the last 30 years in four national forests. For this analysis, we only considered fuel manipulation projects that were clearly intended to serve as fuel breaks, which are defined as wide blocks, or strips, on which vegetation was manipulated to create lower fuel volume and reduced flammability (Green, 1977). Thus, prescribed fires and burn piles were excluded, as were any dozer lines created to aid suppression activities during the time that a fire was burning. We analyzed relationships among fires and fuel breaks to answer:

(1) What are the most important environmental and management variables affecting the role of fuel breaks in controlling large fires, and do these factors vary among national forests?
(2) What are the primary factors affecting the spatial pattern of fires and fuel break intersections, and do they vary among national forests?

Because we restricted our analysis to U.S. Forest Service national forests, we assumed these landscapes would be broadly similar in the tactical approaches used in the construction and maintenance of fuel breaks. Thus, this study could help determine how well management approaches for one national forest may transfer to other national forests. Also, on these largely non-forested landscapes we assumed that the primary management objective for fuel breaks in the region is to control the spread of fire and protect communities.

Table 1
Characteristics of fires and fuel breaks in the four southern California national forests. Fire rotation was calculated from 1980 to 2007.

	Angeles	Cleveland	Los Padres	San Bernardino
Area (ha)	26,375	21,117	61,464	30,408
Number of fires since 1980	175	118	96	253
Fire rotation period (years)	32	14	35	30
Fuel break length (km)	1834	482	550	1199

Table 2
Variables considered and retained in the multiple regression models explaining number of fire and fuel break intersections in three national forests. All variables retained in the models are designated through a significance symbol.

	Angeles	Los Padres	San Bernardino
Elevation	*		*
Slope			
Solar radiation		*	
USFS fuel model	*		*
Distance road		**	
Distance development			
Distance trails		**	
Historic fire frequency	***	**	***
Ignition density	*	*	
Deviance explained	37.27	27.55	54.7

* $p = 0.05$.
** $p = 0.01$.
*** $p = 0.001$.

2. Methods

2.1. The national forests of southern California

The area of study included the Los Padres, Angeles, San Bernardino, and Cleveland National Forests (Table 1), an area spanning the extent of the state's South Coast Ecoregion (Keeley, 2006), which encompasses approximately 3.4 million ha (8% of the state) and is home to more than 19 million people (US Census 2000) (Fig. 1). Although the region is the most threatened hotspot of biodiversity in the continental US (Hunter, 1999), the national forest lands together occupy more than 1.5 million ha and offer some measure of protection for the region's biodiversity.

The South Coast Ecoregion is characterized by a Mediterranean-type climate, with cool, wet winters and warm, dry summers. Chaparral shrublands are the most extensive vegetation type, but there is extraordinary ecosystem diversity in the region, owing largely to a relatively sharp elevational gradient from sea level to more than 3500 m. Therefore, chaparral forms a mosaic with other vegetation types, including coastal sage scrub shrublands, grasslands, oak woodlands, and montane coniferous forests, and natural fire regimes are correspondingly variable (Keeley, 2006; Wells et al., 2004).

Fire management on the national forests is the responsibility of the U.S. Forest Service. The two primary strategies for management are to (1) suppress all actively burning fires, and (2) reduce the extent of future fires through mechanical construction of fuel breaks and limited use of prescription burning. We focus exclusively on fuel breaks in this study.

2.2. Data for dependent variables: fuel break outcome and fire/fuel break intersections

We acquired information on historic fuel breaks and their location from U.S. forest service staff on each of the four forests. We developed a digital spatial database of fuel breaks for the four forests by combining existing GIS layers with files that we created ourselves by digitizing fuel breaks that had been drawn on paper maps. Due to the substantial number of fuel breaks that were hand drawn, we conducted follow-up interviews to validate the newly digitized data.

On all the forests, we overlaid the fuel break GIS layer with fire perimeter polygons compiled by the California Department of Forestry-Fire and Resource Assessment Program (CALFIRE). The fire perimeter data represent the largest fires, with a minimum mapping unit of 4.04 ha (10 acres).

To evaluate factors affecting fuel break outcome, we first used a GIS overlay to identify all events in which a fire intersected a fuel break (within a 100 m buffer distance to account for potential data uncertainty). These events were considered potential case studies to retain for subsequent analysis. To be included for consideration, the date of the fire had to be later than the date of fuel break construction. For the case studies, we conducted a preliminary assessment as to whether fires stopped or crossed over fuel breaks, and then confirmed the outcome during personal interviews with firefighters who had first-hand knowledge of the event.

Although data for some of the explanatory variables were acquired during personal interviews, we also used a GIS to extract information for other explanatory variables to relate to the fuel break outcome. See below for description of explanatory variables. For this analysis, we extracted data only from the portion of the fuel break that intersected the fire and averaged values across that area. In some cases, fires stopped at a portion of the fuel break, but ultimately crossed over the fuel break. For those cases, we classified the fuel break as not having stopped fire (for statistical analysis purposes only), and we only extracted explanatory variables for the section of the fuel break where the fire crossed over.

To analyze factors influencing the number of times fires intersected fuel breaks, we spatially stratified and classified all fuel breaks according to the number times they intersected fires during the study period. We only considered fires that had occurred since 1980, and to ensure that all fuel breaks had an equal chance of experiencing a fire, we only looked at fuel breaks that had been constructed before 1980. From this spatially stratified layer, we randomly selected point samples (greater than 1 km apart, to avoid spatial autocorrelation) to extract environmental data used as explanatory variables. The dependent variable was number of intersections at each sample location.

2.3. Explanatory variables for role of fuel breaks

The factors we considered as potentially influencing the role of fuel breaks on the forests included human and biophysical variables that have previously explained landscape-scale fire patterns in the region (Syphard et al., 2008), and that we used in a previous study of fuel breaks on a single national forest (Table 2, Syphard et al., in press-a). In addition to static landscape features, we also considered variables related to the actual event when a fire intersected a fuel break, including characteristics of fires, fuel breaks, vegetation age, and firefighting activities.

For the human variables, we considered distance to roads, trails, and development (Table 2) because fire ignitions in the region tend to occur near human activities (Syphard et al., 2008). We also hypothesized that these human variables may influence firefighting access and resources. For these three variables, we developed continuous grid surfaces reflecting the Euclidean distance to the nearest feature (road, trail, or development) and extrapolated values from those grids for the areas where fuel breaks intersected fires.

Biophysical variables (including climate, terrain, and fuels) influence fire spread rate, fuel moisture, flammability, and fire intensity (Pyne et al., 1996; Whelan, 1995). Therefore, we evaluated the potential influence of elevation, slope, solar radiation, vegetation age, and fuel model on fuel break outcome (Table 2). After

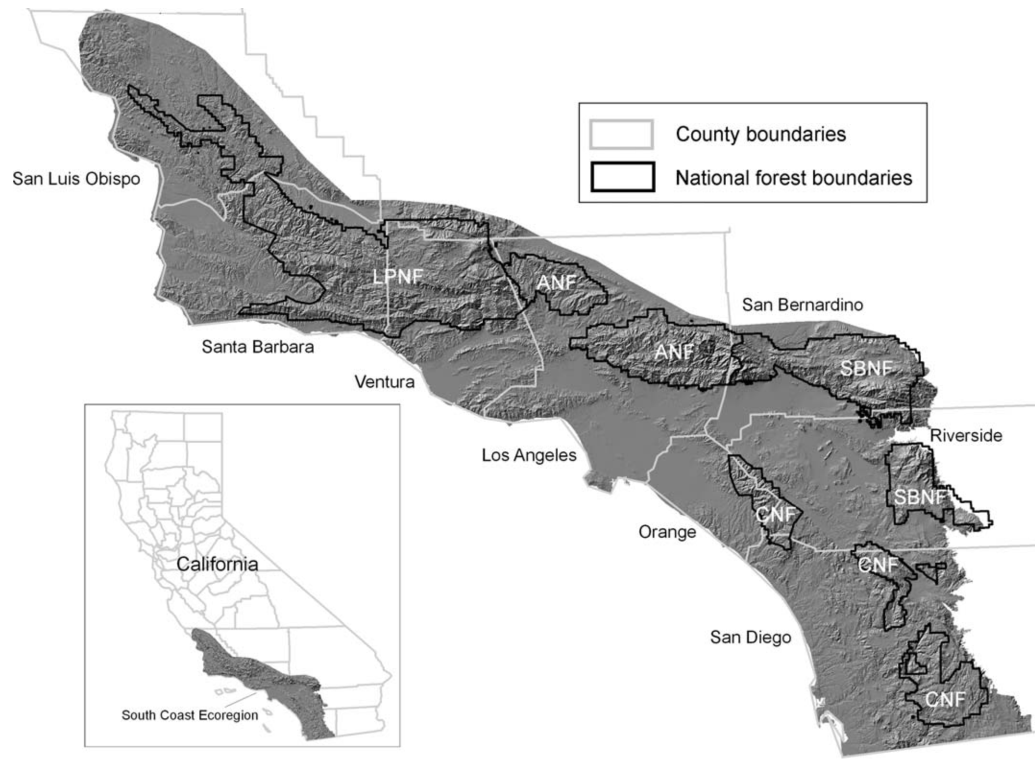

Fig. 1. Study area showing the four national forests of southern California. ANF is Angeles National Forest, CNF is Cleveland National Forest, LPNF is Los Padres National Forest, and SBNF is San Bernardino National Forest.

preliminary regression analysis, we found that climate variables were significantly correlated with terrain variables, so we did not include them. Because most fires are stand-replacing in southern California shrublands, we determined vegetation age by calculating the time since last fire in the area immediately adjacent to the fuel break before the fire intersected it.

Severe weather conditions are likely to strongly influence fire spread rates and intensity (Moritz et al., 2004; Keeley and Zedler, 2009), and lead to conditions that are dangerous for firefighters (Halsey, 2005). However, previous analysis indicated that, because weather is highly variable over space and time, it is difficult to attribute exact weather conditions to the moment of intersection (Syphard et al., in press-a). Instead, we considered fire size and season as potential explanatory variables because they indirectly reflect the severity of weather conditions (Finney, 2003; Westerling et al., 2004), particularly because of the importance of autumn Santa Ana winds in this region (Moritz et al., 2010). We calculated fire size from the fire perimeter data through GIS calculations, and we derived fire season from the attributes of the fire perimeter data. We reclassified the months of the fires into winter and spring (January through May), summer (June through August), and autumn (September through November) to reduce the degrees of freedom in the data.

We obtained information on fuel break condition and firefighting activities through personal interviews with firefighters and managers who were most familiar with the fire events. Fuel break length was calculated from the GIS files, but data on fuel break width were largely unavailable for all four forests. Because written fuel break maintenance records were often unavailable, we determined how well the fuel break had been maintained by asking fire personnel to indicate the condition of the fuel break at the time the fire intersected it on a scale from one to three. The ranking reflected poor to excellent conditions, with poor reflecting fuel breaks where the vegetation had almost entirely regrown, and excellent reflecting fuel breaks that were either entirely grass, or no vegetation had regrown. To evaluate the importance of management activities, we also asked personnel to indicate whether they were able to gain access to the fuel break for firefighting (yes or no) and whether they had sufficient resources available (including manpower and equipment) to fight the fire, again on a scale of one to three, from poor (no resources) to excellent (full resources).

2.4. Explanatory variables for mapping number of intersections

To explain and map areas where fires and fuel breaks are most likely to intersect, we evaluated the same human and biophysical variables as for the fuel break outcome (Table 2). However, we did not consider fire and management variables related to single events because we were interested in trends across the entire study period (1980–2007). In addition, we hypothesized that significantly more fire and fuel break intersections would occur in areas that were historically fire-prone. Therefore, we additionally explored historic fire frequency (derived through overlay of fire perimeters from 1878 to 2007) as well as spatially interpolated ignition density as explanatory variables.

2.5. Fuel treatment outcome: structural equation modeling

Structural equation modeling provides advantages over traditional multiple regression analysis because it uses existing information to examine potential causal pathways among intercorrelated variables and identify indirect relationships (Bollen, 1989; Grace and Pugesek, 1998). The model is statistically evaluated to determine the degree of consistency with empirical data and compare the outcomes of alternative models. Although structural equation modeling is a confirmatory approach that tests a priori hypotheses of about interrelationships among variables, it is often essential to use exploratory regression and correlation analysis to suggest which pathways to explore (Grace, 2006).

For the different national forests, we initially conducted correlation analyses and built simple and multiple logistic regression models to explore the relationships among the explanatory variables and fuel break outcome. We used logistic regression because the response variable for fuel treatment outcome was binary, indicating whether the fuel treatment stopped the fire or not. Based on the hypothesized interrelationships developed through correlation and regression analysis, we developed and tested structural equation models using Mplus version 5.1 software. Because we modeled categorical outcomes, we used the weighted least-squares with mean and variance adjustment (WLSMV) estimator. To ensure that we retained only the important pathways in the final models, we sequentially removed one path at a time to ensure that, if a path were removed, the chi-square did not increase more than 3.84 points (the single degree-of-freedom test) (James B. Grace, personal communication). We also examined the fit of alternative models through *p*-values, root mean square error of approximation, and weighted root mean square residual (Hooper et al., 2008).

2.6. Number of intersections: multiple regression and predictive mapping

To evaluate the relative influence of the explanatory variables on the number of times fires intersected fuel breaks on the forests, we developed simple and multiple Poisson regression models that were appropriate for count response variables (Agresti, 1996). Because the objective of this part of our study was to create predictive maps (rather than explore causal pathways), we only used multiple regression analysis, as opposed to structural equation modeling. We first conducted simple regression models with each variable (and quadratic terms for continuous variables) to establish rankings for entering the variables into a multiple regression.

For the multiple regression models, we entered variables according to the amount of deviance they explained [D^2, equivalent to the R^2 in ordinary least square models (Guisan and Zimmermann, 2000)] and only considered those variables that were significant at $p \leq 0.15$. We evaluated correlation coefficients in the models for all of the forests and avoided including two variables with a bivariate correlation ≥ 0.3. For each forest, we evaluated alternative plausible multiple regression models with different combinations of predictor variables and selected the best model as the one that explained the highest percentage deviance with the lowest Akaike information criterion (AIC) (Quinn and Keough, 2002). We also checked to ensure that overdispersion was not present in the models.

After selecting the best multiple regression models, we converted them into continuous map surfaces that reflected the predicted number of fires that would intersect fuel breaks across the entire forest. We created these maps by applying the Poisson regression formula and predicted coefficients onto the GIS layers of the significant explanatory variables (as in Syphard et al., 2008). We evaluated the correspondence of the predicted number of intersections to the actual intersections that occurred through Pearson correlation coefficients. We also quantified the magnitude of discrepancy among predicted and observed values by calculating the root mean square error (RMSE).

To test how well the models that explained the number of intersections on one national forest matched the models in the other forests, we applied the models developed on each forest to the entire South Coast Ecoregion and compared the maps. To quantify the spatial correspondence among the maps, we used a Pearson's correlation coefficient to calculate pairwise correlations (Termansen et al., 2006; Syphard and Franklin, 2009). High correlations among maps would indicate that the factors controlling the spatial pattern of fire and fuel break intersections were similar among the forests, and low correlations would suggest that those factors vary.

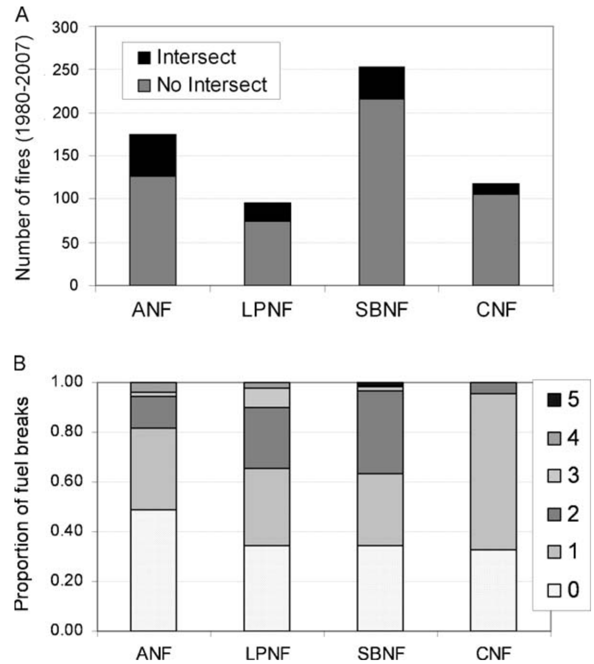

Fig. 2. Number of fires that occurred in four national forests divided into those that intersected a fuel break and those that did not intersect a fuel break (A); and proportion of fuel break area intersected by 0–5 fires from 1980 to 2007 (B). ANF is Angeles National Forest, CNF is Cleveland National Forest, LPNF is Los Padres National Forest, and SBNF is San Bernardino National Forest.

3. Results

3.1. Summary of fuel break and fire intersections and outcomes

During the 28 years of the analysis, 641 fires occurred within the boundaries of the four national forests. On average, 23% of those fires intersected a fuels treatment, but the proportion of intersections varied among the forests (Fig. 2A). In fact, the number of intersections among fires and fuel breaks on the Cleveland National Forest was only 13 (11% of the intersections), and this small number precluded us from including that forest in our statistical analyses.

For the fuel breaks that we considered in our spatial analysis of intersections (i.e., those constructed on or before 1980), approximately 25–50% of the fuel break area never intersected a fire. On the other hand, approximately 10–45% of the fuel break area intersected multiple (two or more) fires. The proportion of fuel break area that intersected fires varied among the four forests (Fig. 2B).

When fires intersected fuel breaks, the percentage that stopped at the fuel breaks ranged from 22 to 47%, and the percentage that crossed over the fuel breaks ranged from 29 to 65%, depending on the forest (Fig. 3). We distinguished another group of fuel break intersections where fires crossed over fuel breaks, but the fuel breaks did change fire behavior enough to facilitate firefighter access and eventually help with the suppression of the fire. When this group is considered along with the other cases in which the fuel break held a portion of the fire, the percentage ranged from 10 to 23% (Fig. 3).

3.2. Fuel treatment outcome: structural equation modeling

Among the three national forests that we analyzed, there were seven variables that significantly affected fuel break/fire outcomes. However, the structural equation models revealed differences in the number and combination of important variables as well as

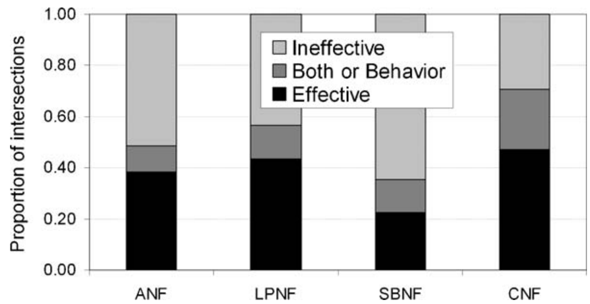

Fig. 3. Proportion of fire and fuel break intersections in four forests divided into those that effectively stopped a fire (Effective); those in which only a portion stopped a fire or that changed fire behavior (Both or Behavior); and those in which the fires crossed over the fuel break (Ineffective). ANF is Angeles National Forest, CNF is Cleveland National Forest, LPNF is Los Padres National Forest, and SBNF is San Bernardino National Forest.

differences in the interrelationships among them. We tested alternative models with different explanatory variables and different direct and indirect effects. The final model varied among the forests (Fig. 4). Despite these differences, most of the variables were common to at least two of the three forests; and three variables were common to all forests: firefighter access, fire size, and fuel break condition.

Firefighter access was the only variable to directly improve the outcome in all three forests, and it was the most influential variable for the Los Padres and Angeles National Forests. The proportion of events in which firefighters had access to fuel breaks was slightly lower in the Angeles than in the other two forests (Fig. 5C). On the Los Padres and San Bernardino forests, fire size was directly and negatively related to fuel break outcome; in the Angeles, fire size negatively affected firefighter access and thus indirectly influenced fuel break outcome. On average, the fires were smaller in the Angeles, but fire sizes were highly variable on all of the forests (Fig. 6). On the Los Padres and Angeles forests, fuel break condition facilitated firefighter access to fuel break and thus indirectly improved fuel break outcome; the relationship was direct in the San Bernardino, which reported the largest proportion of fuel breaks with low scores for fuel break condition (Fig. 5B).

The Los Padres was the only forest for which season was not important in explaining fuel break outcome, as later-season fires (i.e., September through November) had a direct negative influence on outcome for the Angeles; and for the San Bernardino, later-season fires contributed to increased fire size, so the effect was indirectly negative. Most of the fires on the Los Padres occurred in the summer months, whereas fires in the autumn were most common for the other two forests (Fig. 5E). The Los Padres was the only forest in which firefighting resources were not influential in explaining outcome. On both the Angeles and San Bernardino, resources indirectly improved fuel treatment outcome; but on the Angeles, the primary relationship was by improving access and on the San Bernardino, the primary relationship was through reduction in fire size. The overall distribution of firefighting resources, according to the interviews, was variable among the forests (Fig. 5A). Finally, the Los Padres was the only forest in which fuel break length had a significant direct and positive impact on fuel treatment outcome, and this forest had longer fuel breaks, on average, than the other two forests (Fig. 6).

The Angeles was the only forest in which vegetation age was not important. On the Los Padres, younger vegetation surrounding the fuel breaks improved firefighter access to the treatment, so the relationship was indirectly negative. On the San Bernardino, the relationship was direct and positive. Although the average vegetation age was lowest on the San

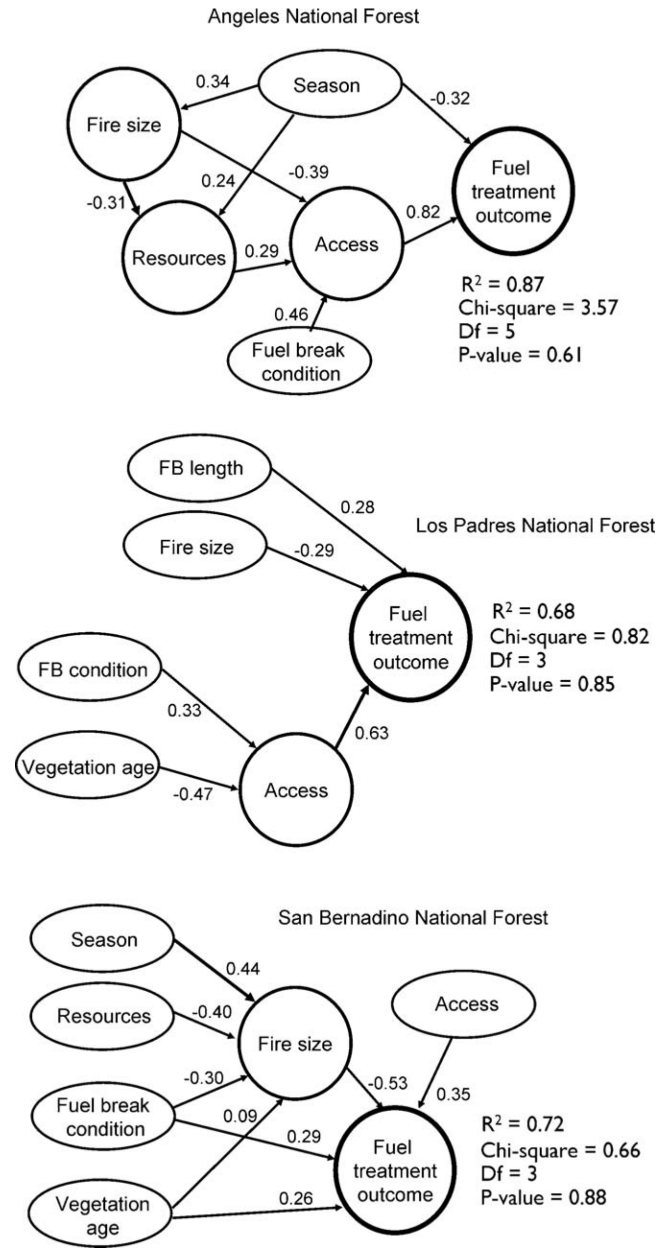

Fig. 4. Structural equation model of factors that directly and indirectly explain why fires stopped at fuel breaks in the Angeles, Los Padres, and San Bernardino National Forests. Solid arrows represent direction of effect, and coefficients shown along arrows are standardized values. Circles represent endogenous (or dependent) variables in the models. Due to insufficient number of fuel break/fire intersections the Cleveland National Forest was not included.

Bernardino, there was a lot of variability in age for all the forests (Fig. 6).

3.3. Number of intersections: multiple regression and predictive mapping

Of the variables we considered for explaining the number of fire and fuel break intersections in the forests, historic fire frequency was the only one that was retained in all three of the multiple regression models (Table 2). For all three forests, the number of intersections was strongly and positively related to the number of fires that had occurred since 1878 (date of the earliest fire in the database). Ignition density was also positively related to the number of intersections on the Angeles and Los Padres National

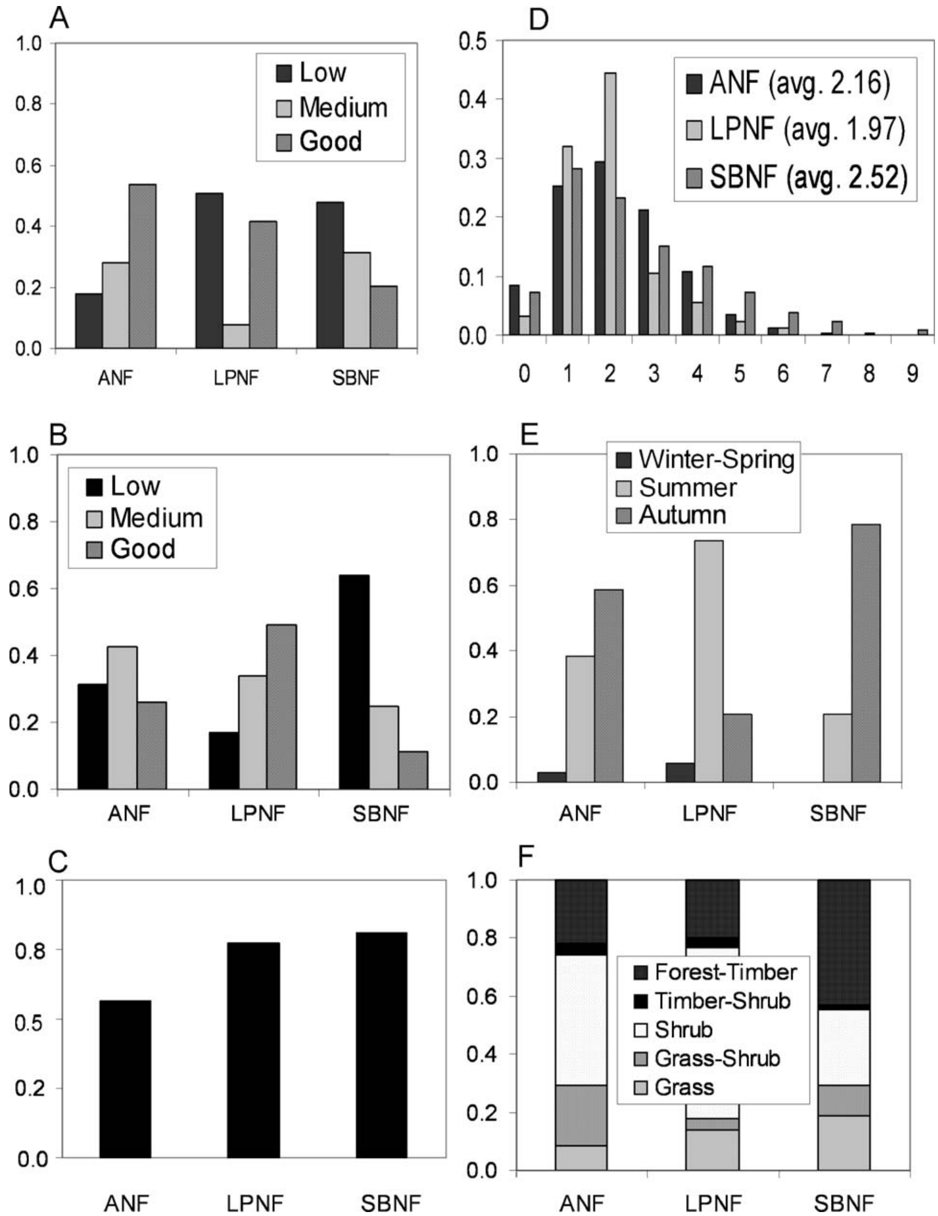

Fig. 5. Distribution of categorical variables for three national forests that were significant in any of the statistical models. The *y*-axis for all charts represents the proportion of observations within each forest. The charts represent (A) firefighting resources; (B) fuel break condition; C) Access to fuel break; (D) historic fire frequency (with the average for each forest indicated in the legend); (E) season when intersection occurred; (F) fuel type. ANF is Angeles National Forest, LPNF is Los Padres National Forest, and SBNF is San Bernardino National Forest.

Forests, but was not retained in the model for the San Bernardino National Forest. The Los Padres had the lowest average number of fires and lowest ignition density, whereas the San Bernardino had the highest fire frequency and ignition density (Figs. 5D and 6).

For both the Angeles and San Bernardino National Forests, the number of intersections was negatively related to elevation, which was slightly higher on average on the San Bernardino than the other forests (Fig. 6). The fuel model parameter was also significant in explaining model variation for only the Angeles and San Bernardino. A larger number of intersections occurred in forest and timber fuel models on the San Bernardino National Forest (“TU” or “TL”, Scott and Burgan (2005)), whereas the shrub models (“SH”, Scott and Burgan (2005)) were more influential in the Angeles (Fig. 5F). Three variables were retained in the multiple-regression model for the Los Padres that were not important in the other forests. On the Los Padres, fires were more likely to intersect fuel breaks when fuel breaks were in close proximity to trails, distance to roads was intermediate, and winter solar radiation was low. Both the average distance to trails and solar radiation were lower on the Los Padres than in the other two forests, but the average distance to roads was similar, with high variation in the three forests (Fig. 6).

The three map surfaces developed by applying the multiple-regression model formulas and coefficients to the GIS maps of the significant variables reflect a continuous probability distribution of where fires and fuel breaks are most likely to intersect (Fig. 6). The Pearson’s correlation coefficients between the observed number of intersections and the number of intersections predicted by the model ranged between 0.59 and 0.74 (Table 3), and the root mean squared error ranged from 0.28 to 1.31 intersections. The correlations among the three maps generated by the differ-

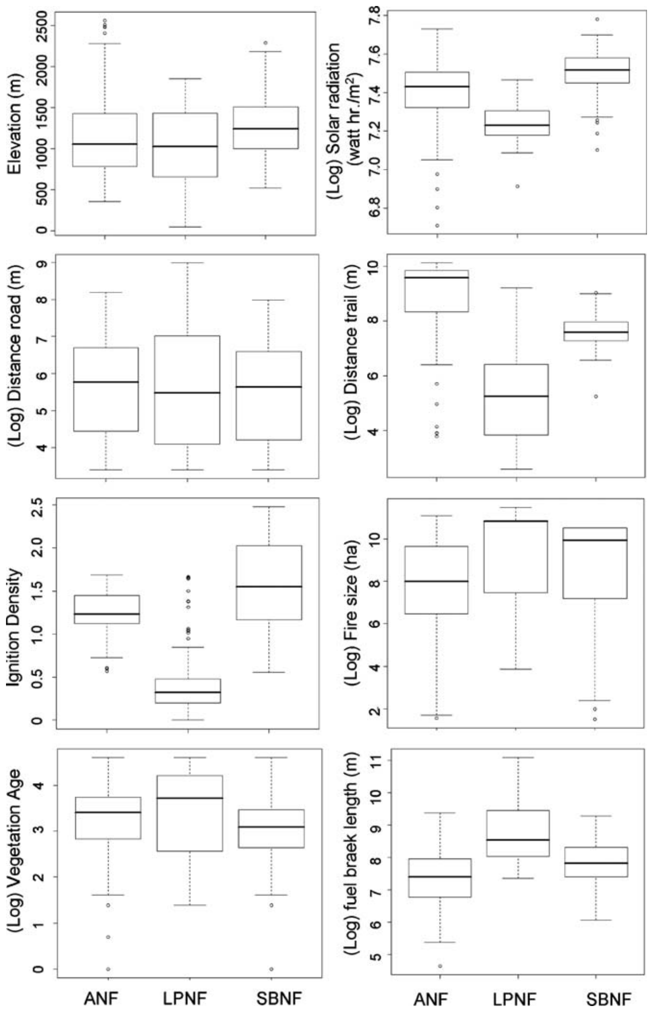

Fig. 6. Distribution of continuous variables for three national forests that were significant in any of the statistical models.

ent multiple-regression models were lower, particularly for the Los Padres model (correlation of 0.21 with the Angeles and 0.16 with the San Bernardino). The Angeles and San Bernardino maps, however, had a much stronger correlation (0.54) (Fig. 7).

4. Discussion

The four southern California national forests studied here all share several features in common; they are in rugged terrain, are dominated by non-forested ecosystems, and contain a substantial amount of wildland–urban interface. These national forests, however, differ in the proportions of vegetation types, biophysical characteristics, and the relative proportions of wildland–urban interface and intermix landscapes. These differences are part of the reason the significant factors explaining fuel break/fire outcomes and number of intersections were different among forests. Nevertheless, several factors were consistently important across all forests in explaining the number of intersections between fuel breaks and big fires and the role of fuel breaks in altering fire spread. These similarities support several general conclusions about the role of fuel breaks in controlling large fires in southern California.

Table 3
Pearson correlation coefficients among prediction maps for three national forests and among predicted and observed number of intersections within each forest. Root mean squared error (RMSE) is calculated between the observed and predicted number of intersections within each forest.

	Angeles	Los Padres	San Bernardino
Angeles map	1.00	0.21	0.54
Los Padres map	0.21	1.00	0.16
San Bernardino map	0.54	0.16	1.00
Observed *N* intersections	0.61	0.59	0.74
RMSE	1.31	0.76	0.28

One conclusion is that the primary role of fuel breaks in the region is to facilitate fire management activities. Two of the three fire management variables we considered (access and fuel break condition) were important in all three structural equation models (Fig. 4), and firefighter resources was important for two of the forests (Angeles and San Bernardino). Furthermore, while other important variables in the models (related to vegetation structure, fire size, and season) were not directly related to management, these variables often indirectly influence management, for example, by affecting access to treatment areas. Demonstrating the strength of these indirect effects is one of the benefits to structural equation modeling (Grace, 2006).

Firefighter access to fuel breaks was the most influential factor in fuel treatment outcome for the Los Padres and Angeles, and was also highly significant for the San Bernardino. The high level of significance for this variable supports the notion that, without firefighters present to control fires, fires will generally not stop at fuel breaks. Although three fires stopped on their own at the top of ridges on the San Bernardino, these fires constituted less than 1% of the cases. Only one fire stopped passively on the Los Padres, and none of the fires in our analysis stopped without firefighters on the Angeles. Despite this conclusion, it is important to point out that the fire perimeter database only includes fires greater than 10 ha; therefore, it is possible that some smaller fires do stop passively (i.e., without fire fighting actions) at fuel breaks. Many fire management personnel understand that fuel breaks are unlikely to passively stop most fires, particularly during extreme weather conditions, but the public, news media, and policy-makers may unrealistically expect otherwise. Our results show that such beliefs could lead to a false sense of security about the protective value of fuel breaks.

Most of the largest fire events in southern California occur during severe weather conditions in autumn, prior to winter rains, when dry, offshore Santa Ana winds can exceed 30 ms^{-1} (Miller and Shlegel, 2006; Moritz et al., 2010). Fighting fires during these weather conditions can be extremely dangerous, and during these wind events, multiple fires often break out simultaneously. These severe weather conditions likely explain why fire size was another variable that was highly significant in explaining fuel treatment outcome in all three forests. Discussions during the interviews confirmed that fires were more difficult to control, and likely to become large, under severe weather conditions. There are a number of reasons for this: the speed of such fires, which can cover 10,000 ha within a day or two, and thus the lack of time for accessing fuel breaks, the danger of aggressively attacking fires under such conditions, and firefighting resources spread too thin because of multiple fire fronts. Consistent with the effect of fire size, fire season was significant on the Angeles and San Bernardino because Santa Ana winds typically occur during the fall (and this was the season when fuel treatment/fire outcomes were poorest). The reason that season was not important for the Los Padres, but fire size was, is that Santa Ana winds are much less predictable there (Moritz et al., 2004, 2010). The Los Padres regularly experiences strong, hot wind downcanyon wind events known as "sundowners," typically in summer (Ryan, 1996), but these are not annual events as are Santa Ana winds. It is possible for severe-weather fire events to occur in any season, not just the fall, across the entire southern California region. This explains why fire size was important on all three forests.

In addition to fire management and fire weather (i.e., size and season), there was evidence that vegetation structure played an

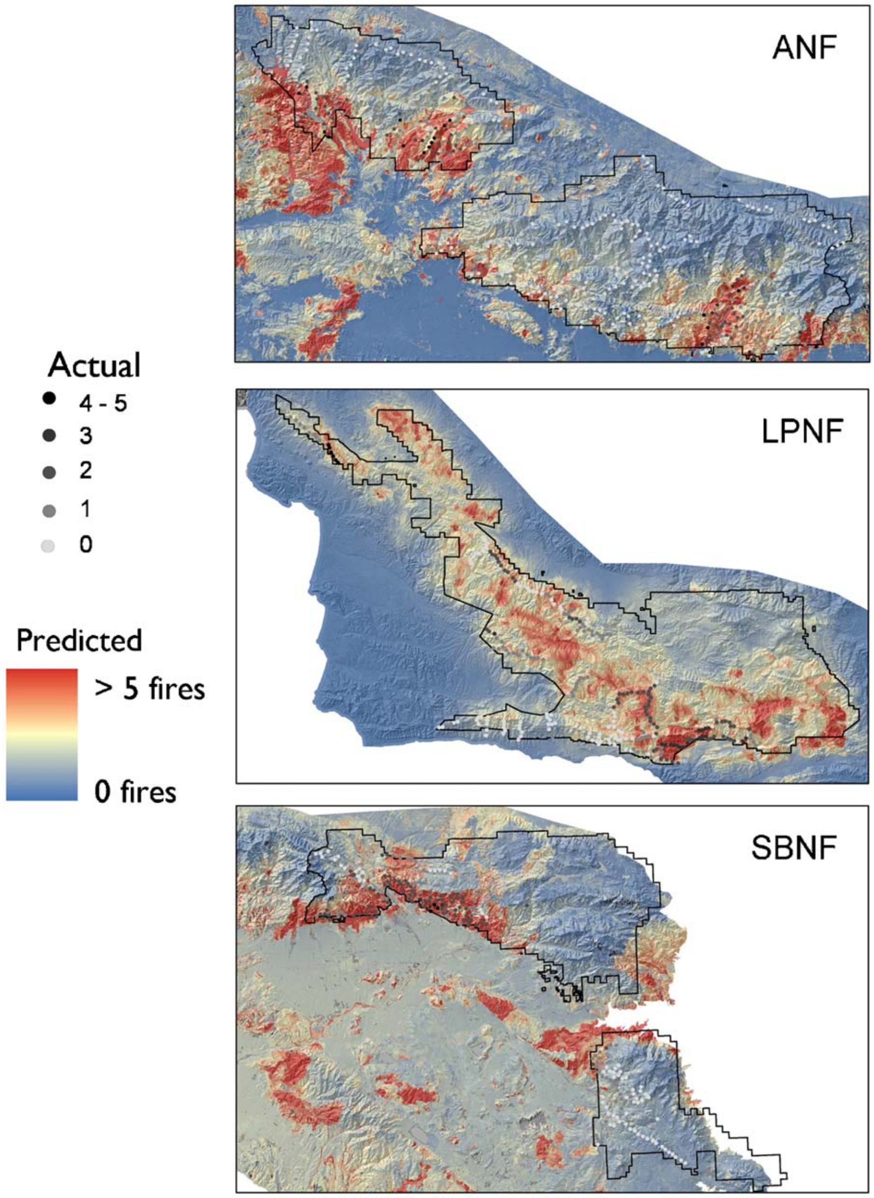

Fig. 7. Maps showing predicted distribution of areas most likely to intersect fuel breaks in the Angeles, Los Padres, and San Bernardino National Forests. The sample points along the fuel breaks also show the actual number of times fires intersected fuel breaks at those locations from 1980 to 2007.

important role in improving fuel break outcome in all three forests, and this was generally because well-maintained fuel breaks were much easier for firefighters to access in time to prepare the fuel break for suppression activities. Because young vegetation typically has a lower fuel load than old vegetation, one of the premises of conducting fuel manipulation is that young vegetation can directly slow or stop the spread of fire. However, in southern California shrublands, stand age and fuel loads play a limited role in stopping the spread of fire, particularly during extreme weather conditions, when fires often spread through or over very young age classes (Keeley and Zedler, 2009; Moritz, 1997; Moritz et al., 2004). Accordingly, while vegetation age was significant in the Los Padres, younger vegetation did not directly prevent fires from spreading, but helped facilitate firefighter access to fuel breaks. There are some parts of the Los Padres where, because of the lack of consistent Santa Ana influence, fuel age may play a role in controlling fire spread (Moritz, 1997). This particularly applies to the coastal area near the city of Santa Barbara. Regardless, the most significant relationship was between vegetation age and firefighter access.

Fuel break condition (i.e., how well it was maintained) played a similar role as vegetation age, and it was influential in all three forests. While the relationship was direct on the San Bernardino, better-maintained fuel breaks improved access to fuel breaks in the Los Padres and the Angeles, and thus, the relationship was indirect. Southern California chaparral forms a dense, continuous cover that is extremely difficult to maneuver in (Halsey, 2005), which likely explains why well-maintained fuel breaks improved the outcome.

As in the models for fuel break outcome, the models explaining the number of fire and fuel break intersections reflected regional landscape diversity and differences among the forests, while nevertheless suggesting several general conclusions. By far the most significant variable, and the only variable consistently significant for all forests, was historic fire frequency. This result is not surprising because areas that have burned most frequently in the past are likely to be most fire-prone in general. Ignition density patterns were also significant for two of the forests. Nevertheless, fire history was not the only factor explaining why fuel breaks intersect fires more in some places than in others. Fire and fuel break intersections were a function of a combination of biophysical and human variables for all the forests, but the biophysical variables were generally more important than the human ones. This is consistent with other regional studies that have shown biophysical factors to be strongly related to patterns of fire occurrence and area burned, whereas human variables are most significant for explaining ignition patterns and fire frequency (Parisien and Moritz, 2009; Syphard et al., 2007, 2008).

The maps of predicted distribution of areas where fuel breaks are most likely to intersect with large fires did not correlate well among the forests, yet there was good correlation among observed and predicted number of intersections within the forests. In other words, the combination of factors that best predicted the number of intersections in one forest did not match well with the combination of factors that best predicted the intersections in the other forests. These differences reflect how the environmental controls of fire regimes vary from region to region, even within a single ecoregion. Therefore, a "one size fits all" management approach would be inappropriate if the objective were to map likely areas for fires and fuel treatments to intersect. While developing a model for one region and applying it to a different region may be inappropriate, the modeling methodology adopted here could easily be applied anywhere. These types of maps could be part of a manager's toolset in helping to identify areas where new fuel breaks could be constructed or where current fuel breaks should be maintained.

We cannot directly attribute differences in the influential variables of our models to differences among the forests because we only statistically analyzed three national forests. Nevertheless, the differences among the national forests do provide a perspective on the variability of the region, despite the fact that it all falls within the same ecoregion. This is striking considering that southern California has a distinctive fire regime, owing to the defining characteristics of the region's Mediterranean-type climate. Because of the cool, wet winters and hot, dry summers, and the specific properties of chaparral, this vegetation is particularly flammable for a substantial portion of the year and burns in large, stand-replacing, high-intensity fires (Pyne et al., 1996). The region's fire regime and fire management issues are typically most starkly contrasted against those in forested regions (Keeley et al., 2009). While it has been recognized that many fire management practices in forested regions are inappropriate for southern California shrublands (Halsey, 2005; Keeley and Fotheringham, 2006), this study shows how certain aspects of fire management may need to be individually tailored at even finer scales, dependent on terrain, proximity to urban environments, regional weather patterns, and fuel type composition.

In southern California, fuel treatments can lead to ecological degradation because they often involve complete removal of vegetation, facilitate the spread of exotic species, and may thus indirectly contribute to increased fire frequency in a region where recurrent fire already threatens the native shrublands (Merriam et al., 2006, 2007). These resource costs should be considered relative to the benefits of protecting communities, and these trade-offs should be considered when constructing new fuel breaks in the region. This is in contrast to forested regions, where the objective of protecting communities is often coupled with the objective of reshaping the age structure and composition of forests to resemble historic conditions (Reinhardt et al., 2008). In these forests, fuel breaks and resource benefits generally are mutually beneficial. Regardless of the region, mitigating fire risk to communities is a priority for federal land managers, yet most fuel treatments are not placed within the wildland–urban interface where they may have the greatest potential for protecting homes. Across the western United States, only 3% of the area treated from 2004 to 2008 was located in this interface (Schoennagel et al., 2009).

Many new fuel breaks are currently being constructed in southern California. In fact, the most likely reason there were not enough fire and fuel break intersections to complete a statistical analysis in the Cleveland National Forest is because a large proportion of the fuel treatments have been recently constructed. Despite the large amount of new fuel break construction, the results of this study show that many fires never actually intersect fuel breaks, and large areas of fuel breaks never intersect fire. Also, the forests that had the highest density and area of fuel breaks did not have the highest overall effectiveness of fuel breaks, suggesting that treating more area alone does not necessarily increase the safety of a region. It may be more effective to have fewer fuel breaks in strategically placed locations than to have greater area of fuel breaks overall, at least in terms of protecting communities. The results from all three forests show that fuel breaks played an important role in controlling large fires primarily where they provided access for firefighting activities. Strategically locating fewer fuel breaks could also reduce the potential for resource costs.

Discussion in the interviews revealed that many strategic decisions do go into placing fuel breaks. While these decisions are often based on years of fire management experience, quantitative and spatially explicit analyses could potentially be helpful in refining these strategic decisions. For example, maps like the ones generated here, showing where fuel treatments are mostly likely to intersect fires, could be combined with further spatial analyses of where access is best and where communities need the most protection. In particular, this study strongly supports the notion of constructing fuel breaks along the wildland–urban interface where firefighters will have better access to the fuel breaks, and where the fuel breaks will provide an immediate line of defense adjacent to homes that are at risk. The case studies from all four national forests demonstrate that fuel breaks will not stop fires without firefighter presence. Therefore, constructing fuel breaks in remote, backcountry locations will do little to save homes during a wildfire because most firefighters will be needed to protect the wildland–urban interface, and fires will not be stopped by those fuel breaks that are located farther away. Finally, because access to fuel breaks was consistently improved when vegetation structure was favorable, this study suggests that maintaining fuel breaks in strategic locations may be just as important as constructing new fuel breaks.

Acknowledgments

Support for this paper was provided by the USGS Multi-Hazards Demonstration Project. Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. government.

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