Factors affecting fuel break effectiveness in the control of large fires on the Los Padres National Forest, California

Article *in* International Journal of Wildland Fire · January 2011

DOI: 10.1071/WF10065

3 authors:

Alexandra Syphard
Conservation Biology Institute

Jon E Keeley
UCLA & USGS

Teresa J Brennan
United States Geological Survey

CSIRO PUBLISHING

www.publish.csiro.au/journals/ijwf *International Journal of Wildland Fire* **yyyy**, ••, •••–•••

Factors affecting fuel break effectiveness in the control of large fires on the Los Padres National Forest, California

Alexandra D. Syphard[A,D], *Jon E. Keeley*[B,C] *and Teresa J. Brennan*[B]

[A]Conservation Biology Institute, 10423 Sierra Vista Avenue, La Mesa, CA 91941, USA.
[B]US Geological Survey, Western Ecological Research Center, Sequoia–Kings Canyon Field Station, Three Rivers, CA 93271, USA.
[C]Department of Ecology and Evolutionary Biology, University of California, Los Angeles, CA 90095-1606, USA.
[D]Corresponding author. Email: asyphard@consbio.org

Abstract. As wildfires have increased in frequency and extent, so have the number of homes developed in the wildland–urban interface. In California, the predominant approach to mitigating fire risk is construction of fuel breaks, but there has been little empirical study of their role in controlling large fires. We constructed a spatial database of fuel breaks on the Los Padres National Forest in southern California to better understand characteristics of fuel breaks that affect the behaviour of large fires and to map where fires and fuel breaks most commonly intersect. We evaluated whether fires stopped or crossed over fuel breaks over a 28-year period and compared the outcomes with physical characteristics of the sites, weather and firefighting activities during the fire event. Many fuel breaks never intersected fires, but others intersected several, primarily in historically fire-prone areas. Fires stopped at fuel breaks 46% of the time, almost invariably owing to fire suppression activities. Firefighter access to treatments, smaller fires and longer fuel breaks were significant direct influences, and younger vegetation and fuel break maintenance indirectly improved the outcome by facilitating firefighter access. This study illustrates the importance of strategic location of fuel breaks because they have been most effective where they provided access for firefighting activities.

Additional keywords: chaparral, firefighter, mapping, pre-fire fuel treatment, southern California, strategic location, structural equation model, suppression, wildland–urban interface.

Manuscript received 30 June 2010, accepted 4 January 2011
Published online 1 September 2011

Introduction

In recent decades, wildfire frequency, extent or severity have increased across much of the western United States (Stephens 2005; Westerling *et al*. 2006; Miller *et al*. 2009), as well as other regions around the world (e.g. Pausas and Vallejo 1999; Montenegro *et al*. 2004). Concurrently, the number of homes built in the wildland–urban interface (WUI, where development meets or intermixes with wildland vegetation), and the areal extent of the WUI have grown dramatically – and are expected to continue growing for decades to come (Radeloff *et al*. 2005; Theobald and Romme 2007). The social and financial cost of so many homes located in fire-prone areas has been high. From 2002 to 2006 in the western US, US$6.3 billion was spent fighting fires, 92 lives were lost and more than 10 000 homes were destroyed (Gude *et al*. 2008). Considering the enormity of these effects, there is tremendous pressure to develop wildland fire-management practices to reduce urban losses.

Although reducing wildfire losses ultimately will require a combination of urban and wildland changes, historically the main focus has largely centred on wildland fuel reduction, often in the form of mechanical fuel treatments (Dellasala *et al*. 2004). Between 2001 and 2006, federal land management agencies in the western United States spent US$2.7 billion for fuel treatments (Schoennagel *et al*. 2009). Although the objective for constructing fuel treatments is generally to reduce the severity and spread of wildfires, specific expectations regarding how fuel treatments are supposed to function tend to vary among different stakeholders (e.g. public, special-interest groups, policy-makers or management agencies (Reinhardt *et al*. 2008). The typical objective of fuel treatments in many western US forests is to change fire behaviour, reduce the severity of fire effects and restore forest structure to conditions that would safely support a natural fire regime of frequent, low-intensity fires (Reinhardt *et al*. 2008). In urbanised areas, treatments are instead intended to prevent fire from spreading into development (Raab and Martin 2001; Radeloff *et al*. 2005), but there may be unrealistic expectations that these treatments can 'fire-proof' those areas (Reinhardt *et al*. 2008; Keeley *et al*. 2009*a*).

Along with differing expectations, the effectiveness or appropriateness of treatments are also likely to vary according to regional differences in vegetation type and structure, natural fire regime, weather conditions and local topography

 10.1071/WF10065

(Stratton 2004). The ecological implications of fuel treatments, and ecological effects of altered fire regimes, are also likely to vary from region to region, but ecological considerations are rarely incorporated into current forest laws and policies (Noss *et al*. 2006). Although fuel treatments and resource benefits are likely to be compatible in many forest types (Schwilk *et al*. 2009), treatments potentially create negative ecological effects in non-forested communities such as chaparral shrublands in southern California (Keeley *et al*. 2009*b*). Unlike forests, in which mechanical fuel treatments typically remove only surface fuel (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). The range of ecological effects includes exotic species expansion, erosion and watershed issues, and fragmentation of important habitat for threatened and endangered species.

Despite the potential ecological effects of fuel treatments in southern California shrublands, the pressure to mitigate fire risk is enormous. In this region, almost 1 million ha of land has burned since 2000, much of which was consumed in fires larger than 50 000 ha. In the fires of 2003 and 2007, ~5000 homes were destroyed. The population of the region is growing rapidly, and much of the housing development is distributed in scattered patterns that create thousands of miles of edge between houses and fire-prone vegetation (Pincetl *et al*. 2008). There are consequently complex trade-offs among the costs and benefits related to fuel management in southern California, as well as other fire-prone regions dominated by extensive development: creating fuel breaks is costly financially and may result in substantial ecological effects, but fuel breaks may play an important role in protecting communities from catastrophic losses.

Adding to the dilemma over costs and benefits in implementing fuel treatments is the uncertainty over the conditions under which fuel treatments are effective at mitigating fire risks. For example, the behaviour of chaparral fires under moderate weather conditions is very different than the behaviour during Santa Ana conditions, and the role of fuel breaks may vary accordingly (Keeley 2005; Keeley *et al*. 2009*a*). Although many managers recognise that the primary role of fuel breaks in developed areas and the WUI is to provide an anchor point and a safe place for firefighters to control and extinguish fires (Conard and Weise 1998; Witter and Taylor 2005), sometimes too much faith is placed in the ability of treatments to passively stop the spread of fire, which may be unlikely under severe weather conditions. A quantitative analysis of the role of fuel breaks may therefore provide critical insights that can inform peoples' expectations and can help to construct fuel breaks more efficiently.

Most research on fuel-treatment effectiveness has been conducted with simulation models at relatively small scales (e.g. Miller and Urban 2000; Finney *et al*. 2007; Schmidt *et al*. 2008), and there is some empirical research documenting how fires have responded to individual fuel treatments (e.g. Schoennagel *et al*. 2004; Raymond and Peterson 2005; Safford *et al*. 2009). However, there are insufficient examples to form general conclusions, particularly at a landscape scale.

Another consideration is that, if fuel breaks are constructed in locations where fires rarely or never encounter them, then those treatments will have no opportunity to play any role. In other words, two conditions need to be satisfied before a fuel treatment can function effectively: (1) the fire needs to actually intercept the treatment, and (2) the treatment must perform according to its expected role.

Considering these two conditions, and to better understand what role fuel treatments have played in reducing the effects of large fires, we analysed the relationships among fires and fuel breaks in the Los Padres National Forest in southern California over a period of 28 years to answer these research questions:

1. What proportion of treatments intersected fires, and can we explain and predict why some treatments encounter more fires than others?
2. What is the role of fuel breaks in controlling large fires, and what factors influence this role?

We expected this study to provide deeper understanding of the relative importance of factors influencing fuel-treatment success in southern California and to provide guidance on how to develop more efficient treatment strategies.

Methods

Study area

Our study area included all lands (~590 000 ha) within the Main Division (central ranger districts) of the Los Padres National Forest in southern California. The climate is Mediterranean, with cool wet winters and hot dry summers. The landscape is dominated by chaparral shrublands, which are highly flammable owing to dense community structure and the annual 6 months of drought every summer and autumn (Radtke *et al*. 1982; Conard and Regelbrugge 1994). Broad swaths of chaparral are often broken up by patches of coastal sage scrub, riparian woodlands, oak woodlands, grassland and coniferous forest. The region is topographically complex and rugged, with slopes often exceeding 35°, and much of the interior of the Los Padres National Forest study area is relatively inaccessible.

Adjacent to this rugged terrain are several urban areas, such as Santa Barbara and Ojai, and housing developments border much of the forest boundary, increasing the potential for wildfire to threaten lives and property. Slightly more than 10% of the land inside the forest boundary is occupied by privately owned inholdings (V. Radeloff, unpubl. data), and low-density housing exists within much of the forest, particularly near the boundary. Thus, the primary objective of firefighting and constructing fuel breaks is to stop fires and to prevent them from threatening structures. Humans also cause the majority of fire ignitions in the region (Moritz 1997).

Fuel treatment and fire data

The Los Padres National Forest provided written, pictorial and oral data on historic fuel treatments. Many recent fuel-treatment locations were provided digitally, but we also digitised older fuel breaks from hard-copy maps. To identify case studies for follow-up interviews and subsequent analysis, and to analyse the intersections among fuel treatments and fires, we used a Geographic Information System (GIS) to overlay the fuel treatment data with fire perimeter polygons, compiled by the California Department of Forestry-Fire and Resource Assessment Program (CALFIRE). The fire perimeter data only

represent the largest fires (with a minimum mapping unit of 4.04 ha (10 acres)), but they serve as the most comprehensive source of fire data in the state. The largest fires also account for the majority of area burned.

Quantifying number of intersections

Through GIS overlay analysis, we counted the number of times fires crossed fuel breaks from 1980 to 2007. We restricted our analysis to fires that occurred after 1980 owing to greater uncertainty in accuracy of GIS data before 1980 and because of the limited availability of firefighters and managers familiar with fires before 1980, which was critical for personal interviews. Some sections of fuel breaks intersected fires more frequently than other sections, so we stratified each fuel break spatially and classified it according to the number of intersections (ranging from 0 to 4). From this spatially stratified data layer, we randomly selected point samples (244 points; see below) to extract environmental data to relate to the number of intersections that occurred at those points. To ensure that all fuel breaks had an equal chance of intersecting fire, for this part of the analysis, we only evaluated those fuel breaks that had been constructed before 1980 and were intersected by fire that occurred in the period 1980–2007.

Based on a previous analysis of fire frequency (Syphard *et al*. 2008), we suspected that fire intersections and our predictor variables were likely to be spatially autocorrelated, which would violate the assumption of independence in regression models and potentially inflate model significance (Fortin *et al*. 1989; Haining 1990). The influence of spatial autocorrelation can be avoided by using a minimum distance to separate observations that is larger than the range of spatial autocorrelation (Miller *et al*. 2007). Therefore, after we estimated initial regressions models (see below), we plotted semivariograms of the models' deviance residuals. We determined that spatial autocorrelation was present when samples were within 1 km of each other, so we subsampled our data to avoid observations within that lag distance, which resulted in a sample size of 244 observations.

Selecting fuel break case studies

Through GIS overlay analysis, we identified all events in which a fire occurred within 100 m of a fuel break, to account for any spatial uncertainty in the boundaries of either the fires or the fuel breaks. For this analysis, we considered fuel breaks constructed at any date, but only fires later than the date of fuel break construction were included. After identifying all potential intersections between fires and fuel breaks, we conducted preliminary analyses to identify whether the fire appeared to have stopped at the fuel break or whether it spread across it. We then arranged personal interviews with fire personnel having first-hand knowledge of the incident.

Explanatory variables

To understand and to predict why fires intersect some sections of fuel breaks more than others, we explored the potential influence of several human and biophysical variables known to be associated with the spatial distribution of fire at a landscape scale (Syphard *et al*. 2008). We also considered the potential for historic fire regime (fire frequency and ignition density) to explain the number of intersections because we expected the fire history to reflect how some areas in a landscape are more fire-prone than others. Because the data for the number of fuel break intersections were collected from across the entire time period in the study (1980–2007), we did not consider variables related to specific points in time for that analysis. However, to identify the primary factors that affect the role of fuel breaks, we additionally considered variables related to fire events, including characteristics of the fires, fuel breaks, suppression activities and vegetation age, although we did not consider historic fire regime.

For the environmental and fire regime variables, we used a GIS to extract data values to relate to the dependent variables. For the analysis of number of intersections, we extracted data from the locations of the random sample points. For the case studies where fires intersected fuel breaks, we extracted data from the portion of the fuel break where the fire intersected and averaged the values for that area. By constraining the area of analysis, we ensured that we were only considering the potential local influence of those variables because some fuel breaks are quite long and may span large areas.

Human and biophysical environmental variables

Because the majority of fires in California are started by humans, the spatial distribution of fire tends to be strongly related to the distribution of human infrastructure (Syphard *et al*. 2007, 2008). Therefore, our explanatory human variables included distance to development, roads and trails (as in Syphard *et al*. 2008). We expected a larger number of intersections to occur in close proximity to human infrastructure, and we expected fires to stop more frequently near human infrastructure because firefighters would be able to access those areas more quickly. We used the Development Footprint data layer from CALFIRE (http://frap.cdf.ca.gov/data/frapgisdata/select.asp, accessed 13 July 2011) that delineates developed lands from 2000 Census block data, 2000 land ownership data, 1990s US Geological Survey National Land Cover Data (NLCD), and 2000 Census Urbanised Area data at 30-m resolution. The road data came from the 2000 US Topologically Integrated Geographic Encoding and Referencing system TIGER/Line files. The trail data came from the US Forest Service online GIS clearinghouse (http://www.fs.fed.us/r5/rsl/clearinghouse/gis-download.shtml, accessed 13 July 2011).

Independently of human influence, a region's fire regime and the distribution of fire patterns are influenced by biophysical factors, or the fire environment (Pyne *et al*. 1996). Based on the biophysical variables that significantly influenced fire patterns in another southern California landscape (Syphard *et al*. 2008), we explored the potential influence of elevation, slope gradient, solar radiation, fuel model and vegetation age. We also considered several climate variables, but they were strongly correlated with elevation, so we removed them from the analysis. Because these biophysical variables may affect fire spread rate, fuel moisture, flammability of fuels and fire intensity both directly and indirectly (Whelan 1995), we expected that their distribution and spatial variability would influence where fires would most frequently intersect fuel breaks. We expected them to also potentially influence the role of fuel breaks in constraining fire because of their influence on fire spread rates, which could inhibit firefighting efforts.

We acquired elevation data from the 30-m US Geological Survey Digital Elevation Model, and used it to derive slope gradients and to develop grids of terrain-distributed solar radiation, which mediates temperature and available fuel moisture (Dubayah and Rich 1995). Solar radiation tools in the Spatial Analyst extension of *ArcGIS 9.x* were used to calculate daily insolation for winter solstice with site latitude of 33°N, sky size of 200 cells per side and 0.2 clear sky irradiance, the fraction of global normal radiation flux that is diffuse. This has been shown to be a significant predictor of regional plant species distributions (Syphard and Franklin 2009).

Vegetation and fuel characteristics are often classified into fuel models that exemplify relatively uniform fire behaviour and rates of spread. We obtained spatial fuel model data from statewide maps developed by the US Forest Service (N. Amboy, pers. comm. January 2010) at 30-m resolution to evaluate whether number of intersections would vary according to fuel models. We were unable to evaluate fuel model in the statistical analysis of fuel break outcome because there were several fuel model types with only one observation in the data.

We also evaluated whether or not fuel break outcome would vary based on the age of surrounding vegetation at the time of fire. Because the majority of fires are stand-replacing in California shrublands, we used fire-history maps to determine the age of the vegetation by subtracting the time of last fire from the year of every fire event.

Fire history

Because some parts of a landscape are more fire-prone than others, we expected the number of intersections among fires and fuel breaks to be positively associated with those areas that have historically burned most frequently. To associate number of intersections with historic fire regime, we converted the fire perimeter polygon data layer into a continuous grid surface that reflected the number of fires that occurred in each cell throughout the fire history (1878–2007). We included the full history of fires for this variable because it provided a larger sample of fires to quantify which parts of the landscape tend to burn more frequently than others.

In addition to the fire perimeter database, we also used a database of ignitions (that occurred from 1970 to 2007) to evaluate whether number of intersections was positively related to areas of high ignition density. The ignition data were compiled from original fire reports on file at the Los Padres National Forest and included 1380 ignitions (71% caused by humans). To create the ignition-density grid, we used a point density function in a GIS that calculated, across the entire landscape, the relative magnitude of ignition occurrences per unit area based on the number ignition points that fell within a specified neighbourhood (3 km) around each cell.

Fire events

We calculated the size of every fire that intersected a fuel break using a GIS, and the month of the fire was listed in the fire perimeter database. To reduce the degrees of freedom in the analysis, we reclassified the fire months into spring–summer (April through July) *v.* fall (autumn)–winter (September–December). No fires occurred in the month of August in our dataset.

We explored two sets of weather data in relation to the fires that intersected fuel breaks. One was from the global surface summary of day product from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) (ftp://ftp.ncdc.noaa.gov/pub/data/gsod). There were seven NOAA weather stations within the proximity of the study area, and the available data included the mean, maximum and minimum daily temperature, mean and maximum wind speed, and daily precipitation. For some historic fires that burned over the course of many days, we had no way of knowing the date when the fire intersected the fuel break. Therefore, we downloaded and explored data for all dates in which the case-study fires occurred. We calculated the mean, maximum and minimum values, as well as the range and standard deviation, of weather data during the duration of the fire to relate them to fuel break outcome.

In addition to the NOAA data, we explored a data product developed by John Abatzoglou and colleagues at the Desert Research Institute Western Regional Climate Center in Reno, NV. The development of this product involved a hierarchical process in which 32-km North American Regional Reanalysis data, including relative humidity, temperature and wind speed parameters (http://www.emc.ncep.noaa.gov/mmb/rreanl/) were bias-corrected to fine-scale 4-km PRISM (Parameter-elevation Regressions on Independent Slopes Model) climate data, monthly temperature and precipitation (http://www.prism.oregonstate.edu/) and further corrected using Remote Automated Weather (RAWS) stations. From the 4-km continuous grids of weather data, we extracted minimum and maximum daily relative humidity, temperature, wind speed and direction from within the perimeters of case-study fires during the range of dates that they occurred. As with the NOAA data, we explored the potential influence of mean, maximum and minimum values, as well as the range and standard deviation, of weather data during the duration of the fire to relate them to fuel break outcome.

Characteristics of fuel breaks

We used GIS to calculate the length of the fuel breaks, and we included the entire fuel break length as our explanatory variable. The fuel break width was included in the attributes of the files that the forest service crews provided and ranged from 6 to 183 m (20–600 feet). A few of the fuel break widths were presented as ranges (e.g. 6–12 m or 91–180 m), so we used the mean of the range for the width value of those fuel breaks.

Because it was difficult to determine the condition of the fuel break (i.e. the amount of vegetation regrowth) at the moment of intersection through maintenance records or through GIS mapping, we asked fire personnel to indicate the condition of the fuel break on a scale from one to three (poor to excellent). All personnel based their ranking on the same criteria. A ranking of one meant that the fuel break was barely discernable from the surrounding vegetation; a ranking of two meant that the fuel break was apparent, but that vegetation was starting to regrow; and a ranking of three meant that the fuel break was in excellent condition with no vegetation regrowth or was primarily grass.

Suppression activities and other fire event information

Data on suppression activities were obtained during personal interviews based on a questionnaire to determine whether there

was access to the fuel break (yes or no) and the availability of firefighting resources (manpower and equipment) on a scale from one to three. For firefighting resources, a ranking of one meant that the firefighters did not have the equipment or manpower available to fight the fire; a ranking of two meant that equipment and manpower were available but not completely sufficient for properly fighting the fire; a ranking of three meant that the firefighters had all the equipment and manpower they needed to fight the fire. We also asked the firefighters to specify the vegetation type at the time of fire, but this variable was highly correlated with condition of fuel break, so we did not include that variable in the statistical analysis. In addition to asking specific interview questions, we documented any additional notes or insights about the fire events.

Statistical analysis

Number of intersections

To evaluate the influence of the explanatory variables on number of fuel break–fire intersections, we developed Poisson regression models because they are appropriate for count data (Agresti 1996). To explore the effects of the explanatory variables independently of their interactions with other variables, we first developed simple regression models. We evaluated linear and quadratic relationships for all the continuous variables, and then ranked variable importance based on the deviance explained in the simple models. In generalised linear models (which include Poisson and logistic regression), models are optimised through deviance reduction, and the deviance explained (D^2) is the equivalent to the R^2 in ordinary least-square models (Guisan and Zimmermann 2000). We used the rankings to establish the order to enter variables in a multiple regression, and we considered those variables that were significant at $P \leq 0.15$ and that were not correlated with other variables (bivariate correlation ≥ 0.3). Because distance to development was correlated with ignition density ($R = -0.4$) and distance to road ($R = 0.37$), we removed it from the multiple-regression analysis.

For the multiple-regression modelling, we were primarily interested in selecting the best model for predicting and mapping the number of intersections. Therefore, we identified several plausible multiple-regression models and selected the best-fit model as the one that explained the highest percentage deviance explained with the lowest Akaike information criterion (AIC) (Quinn and Keough 2002). We checked our Poisson model to ensure that overdispersion did not exist and that our residual deviance was equal to our residual degrees of freedom.

To evaluate the multiple-regression model, we predicted the number of intersections for the random sample points and calculated the Pearson's correlation coefficient between the actual number of intersections and the predicted number of intersections. We also calculated the root mean square error (RMSE) to quantify the discrepancy between observed and predicted values. All modelling was carried out in the R 2.7.0 statistical programming environment (R Development Core Team 2004).

We converted the multiple-regression model into a predictive map surface by applying the formula from model to the entire landscape using the regression coefficients and the GIS layers for the significant explanatory variables. For Poisson regression, the formula is:

$$n = \exp(B_0 + B_1 \times X_1 + B_2 \times X_2 + \ldots + B_k \times X_k)$$

where n is the number of fire–fuel break intersections, B_0 is a constant, and B_i are coefficients of the explanatory variables.

Fuel-treatment outcome

The response variable for fuel-treatment outcome was binary and indicated whether the fuel treatment constrained the fire or not. Therefore, instead of using Poisson regression, we estimated simple and multiple logistic regression models using the same approach as for number of intersections, although we did not create a predictive map. To evaluate the performance of the logistic multiple-regression model, we performed a leave-one-out cross-validation, which iteratively leaves one observation out of the model, fits the model and then calculates the predicted probability of the observation for every observation in the sample. Based on the cross-validated predictions, we calculated the area under the curve (AUC) for a receiver operating characteristic (ROC) plot (Hanley and McNeil 1982). The AUC ranges from 0.5 to 1, and, in this case, indicates the overall probability that, for a randomly selected set of binary observations (one in which fire stopped at a fuel break and the other in which fire did not stop), the model correctly identifies them.

After exploring the relationships among the explanatory variables through regression modelling and correlation analysis, we developed a structural equation model (SEM) to confirm hypotheses about the factors and interactions that were significant in explaining fuel-treatment outcome. We developed our hypotheses based on the regression analysis as well an exploration of correlations among all the variables. SEM has advantages over multiple-regression modelling because it can test whether our hypotheses are consistent with our data and can also test for indirect interactions (Grace and Pugesek 1998). Rather than a predictive modelling approach, SEM serves as a framework for interpreting relationships among a network of interrelated factors (Grace *et al*. 2010). We supplemented the multiple-regression analysis with SEM because our objective was to better understand the interactions among factors influencing the role of fuel breaks in controlling fires.

Because we were modelling categorical outcomes, we used the weighted least-squares with mean and variance adjustment (WLSMV) estimator, and evaluated model fit using chi-square and associated P values as well as other fit indices, including RMSE of approximation and weighted root mean square residual (Hooper *et al*. 2008). Owing to our limited dataset, we included paths that were significant at $P \leq 0.15$; however, we compared alternative models by removing 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) (J. B. Grace, pers. comm.). We performed the structural equation modelling with *Mplus version 5.1*.

Results

There were ~550 km of mapped fuel breaks in the study area (Fig. 1), including fuel break backbones along ridgelines as well

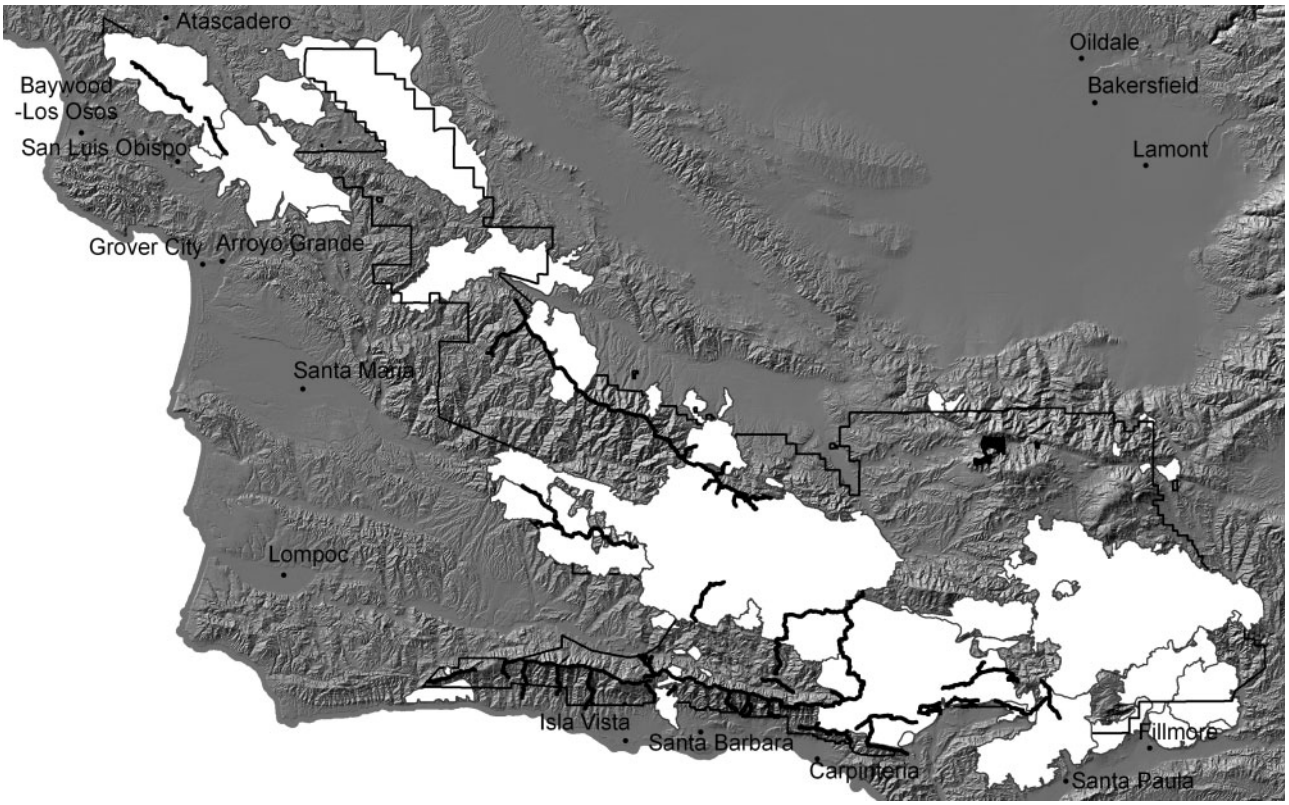

Fig. 1. Map showing location of fuel breaks (thick black lines) and fires (in white) that occurred between 1980 and 2007 in the Los Padres National Forest, CA. The thinner black line shows the study area.

as laterals. Most were constructed before 1980, but several were created within the last decade. Often, a combination of methods were used to create and maintain the fuel breaks, including dozers, discs, herbicide or spot herbicide, hand pile and burn, hand pile and chip, or mastication. These methods often varied along the length of individual fuel breaks, and maintenance methods changed over time. Although one fuel break (~28 km) was shaded, the rest of the fuel breaks were constructed similarly, as linear features on the landscape in which shrublands were converted primarily to grasslands.

From 1980 to 2007, 95 fires intersected the study area, with sizes ranging from 5 to almost 100 000 ha (the Zaca fire of 2007) (Fig. 1). Of these, 20 fires (21%) intersected at least one fuel break, and 8 of these 20 fires (40%) intersected more than one fuel break. Some portions of the fuel breaks never intersected any fires, but during the 28-year study period, some portions of fuel breaks intersected up to four fires (Fig. 2).

The GIS analysis identified 74 unique events in which fires intersected fuel breaks, but during personal interviews, 21 of those intersections were removed from the analysis owing to one of the following reasons: in one case, two fires were unnamed and nobody remembered them; in another, several fires did not spread into the fuel break, but rather spread away from it or parallel to it; and lastly, one of the fires in the database apparently never occurred. We did not consider fires spreading away from or parallel to the fuel break because the firefighters claimed in the interviews that the fuel break in those cases would have been irrelevant in the control of the fires. Therefore, the final number of fire and fuel break intersections was 53.

For 23 of the 53 events (46%), the fire was effectively constrained by the fuel breaks, and for 30 (54%) of the events, the fire spread across the fuel break. In all but one of the events in which fires stopped at the fuel breaks, firefighters had access to the treatment for suppression activities. For the events in which fires spread across fuel breaks, there were 11 occasions (37%) in which fire crews did not have access to the treatment and 19 events (63%) in which crews had access to the treatment, but the fire spread across it.

Results from the interviews with the firefighters revealed that the primary reasons that fires crossed fuel breaks were: (1) scarce resources were available if the fire was large or if other fires were burning simultaneously; (2) winds shifted during the event, making fire behaviour unpredictable; (3) the fuel break had not been maintained and was difficult to manoeuvre around; or (4) fire crews did not put suppression resources on the treatment.

During the interviews, the fire crews also described how they frequently ran dozers down the fuel breaks before the fires reached them. In wilderness areas, dozers are prohibited, so crews instead used hand-lines or hose-lay in preparation for the fire. If the fuel breaks were already type-converted to grass, the crews did not dozer them, but dropped retardant and water. If safe, firefighters waited for the fire with a hose-lay and hand-line to bare dirt. In many cases, substantial areas of the recorded fires

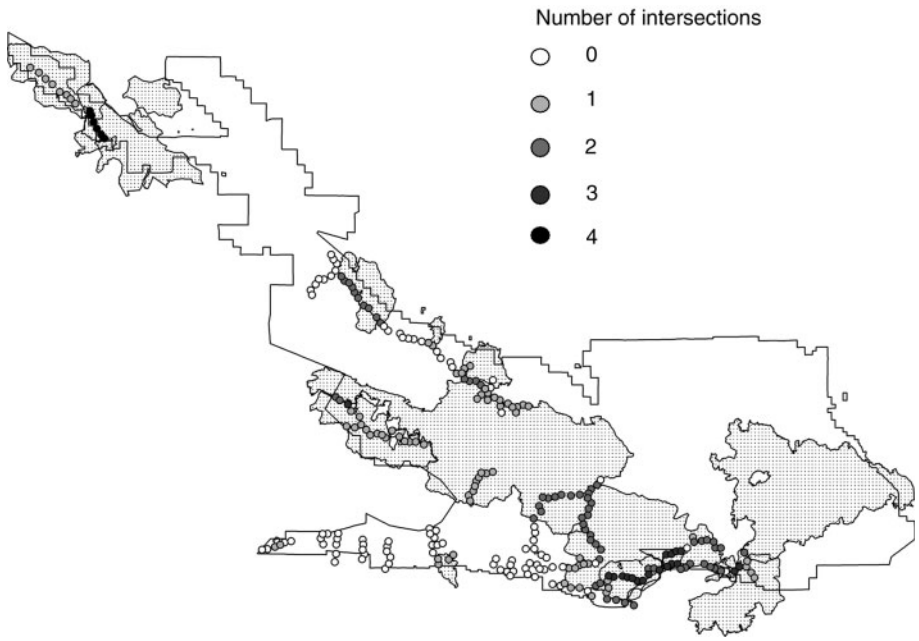

Fig. 2. Map of sample points on fuel breaks classified according to the number of times fires had intersected them from 1980 to 2007. Perimeters of fires that intersected fuel breaks are also shown.

had been burned through backfires to prevent the actively spreading fire from reaching the treatment. In one case (the ~100 000-ha Zaca fire), nearly 33 000 ha burned from backfire activity.

The crews described that they focussed most of their suppression efforts on the backbone fuel breaks, which are typically located along ridge lines. The lateral fuel breaks, running perpendicular to the backbone, were used to contain smaller fires that potentially were spreading within a drainage basin. The crews often put dozer lines down the laterals during the fire under those conditions.

For seven (13%) of the events cases, the fuel break changed the fire behaviour after the intersection such that crews could manoeuvre around the vicinity of the treatment and ultimately successfully suppress the fire.

Statistical analysis

Number of intersections

Almost 40% of the fuel treatments never intersected a fire, but ~30% of the treatments intersected two or more fires. Fires were most likely to intersect fuel breaks in areas where: historic fire frequency was high ($D^2 = 0.18$, $P < 0.001$); fuel breaks were in close proximity to trails ($D^2 = 0.07$, $P = 0.09$); distance to roads was intermediate ($D^2 = 0.04$, $P = 0.001$); historic ignition density was low ($D^2 = 0.02$, $P = 0.04$); and winter solar radiation was low ($D^2 = 0.02$, $P = 0.02$). None of the other variables explained significant variation in number of intersections.

All of these variables that were significant in the bivariate simple regressions were retained in the multiple-regression model explaining number of intersections; however, whereas the linear term and its quadratic were both significant for distance to roads in the simple model, only the linear term was retained in the multiple-regression model, which was highly significant ($D^2 = 0.28$, $P < 0.001$).

The map surface generated by applying the formula and coefficients of the multiple-regression model to the original GIS maps of the predictor variables showed the relative distribution of where fires are predicted to intersect fuel breaks most frequently (Fig. 3). The Pearson's correlation coefficient for the observed versus predicted observations was 0.57, and the RMSE was 0.74.

Fuel-treatment outcome

Five of the independent variables explained more than 5% of the residual deviance ($D^2 > 5$) in the bivariate simple regression analysis. Fires were most likely to stop at a fuel break when: there was firefighter access to treatment ($D^2 = 0.12$, $P = 0.01$); fire size was smaller ($D^2 = 0.11$, $P = 0.009$); vegetation age was younger ($D^2 = 0.10$, $P = 0.01$); fuel breaks were longer ($D^2 = 0.07$, $P = 0.03$); and there were adequate firefighting resources ($D^2 = 0.07$, $P = 0.12$). The fuel break outcome was not significantly explained by fire season, weather, any of the biophysical variables or distance to human infrastructure.

There was significant multicollinearity between access to treatment and vegetation age ($D^2 = 0.05$, $P = 0.09$). Access to treatment was also significantly related (again through simple bivariate regression) to the condition of the fuel break (better condition contributed to better access, $D^2 = 0.10$, $P = 0.05$) and fuel break width (wider fuel breaks contributed to better access, $D^2 = 0.06$, $P = 0.08$). These two variables were not considered in the multiple-regression model, but their effects were indirectly evaluated in the SEM.

After entering the significant variables in order of deviance explained and performing forward and backward stepwise regression, the final multiple-regression model for fuel-treatment outcome retained access, fire size and length of fuel break. The model was significant at $P = 0.006$, with a D^2

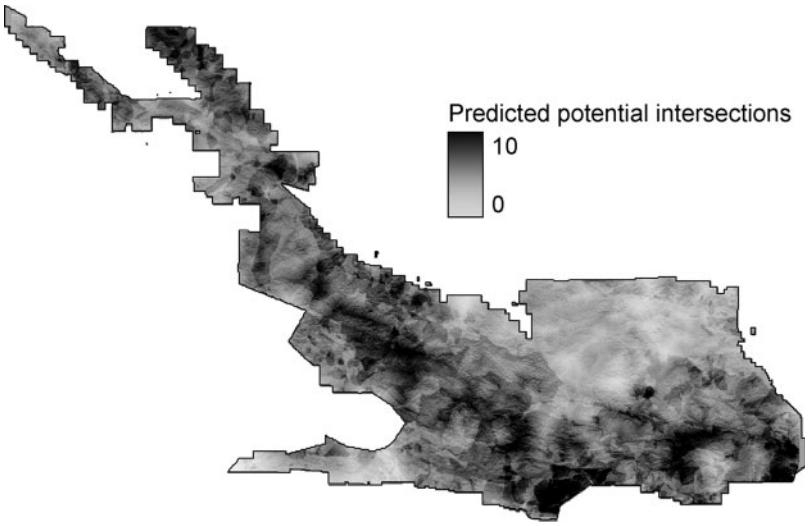

Fig. 3. Map showing predicted distribution of areas where fires and fuel breaks are most likely to intersect in the Los Padres National Forest, CA.

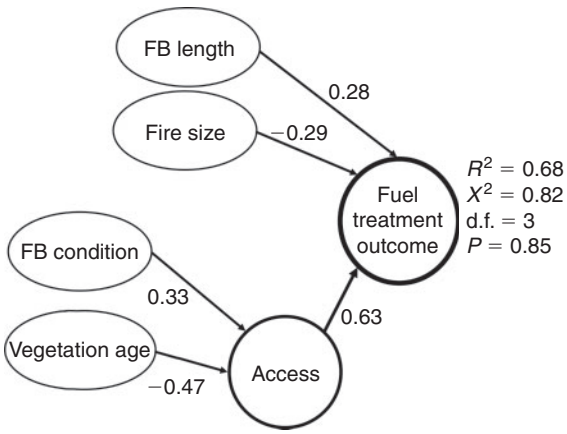

Fig. 4. Structural equation model of factors that directly and indirectly explain why fires stopped at fuel breaks (FBs) in the Los Padres National Forest. Coefficients shown along arrows are standardised values.

of 0.29. The leave-one-out cross-validation of the multiple-regression model resulted in an AUC of 0.84.

Based on exploration of the relationships among the variables, our structural equation model that explained why fires stopped at fuel breaks included the direct effects of the significant explanatory variables from the multiple regression (access, fire size and fuel break length) as well as indirect effects of vegetation age and fuel break condition based on their influence on treatment access (Fig. 4). The model chi-square was low (0.82), with a high P value (0.85) that indicated there was no significant difference between the data and our hypothesised model. The proportion of variance explained in fuel treatment outcome ($R^2 = 0.68$) was substantially higher than the generalised linear mode (GLM) multiple-regression model equivalent ($D^2 = 0.29$). Removal of any paths in the model resulted in an increase of chi-square that was greater than 3.84. The standardised coefficients in the SEM results indicated that fuel-treatment effectiveness was positively related to access to treatment and fuel break length and negatively related to fire size. There was a positive indirect effect of fuel break condition and a negative indirect effect of vegetation age on fuel-treatment outcome due to their direct effects on access to treatment.

Discussion

Because prefire fuel manipulation is one of the primary strategies used to manage wildfire, we evaluated the role that fuel breaks have played in controlling the extent of large fires in southern California. For a fuel break to function, it must: (1) encounter a fire, and (2) successfully function as expected, which in the WUI is to stop the spread of fire, either directly or by facilitating the alteration of fire behaviour. During the nearly three decades of our analysis, most of the fires that occurred (79%) burned without intersecting a fuel break, and many segments of fuel breaks never encountered a fire. However, certain fuel breaks intersected several fires, and our results showed that we can identify the factors that influence the likelihood of intersection and we can map where on the landscape treatments are likely to intersect fires. Our results also showed that the primary role of fuel breaks is to provide firefighters safe access to perform suppression activities. Only a few of the other variables that we considered as potentially influencing the role of fuel breaks were statistically significant.

A potential reason that some environmental variables did not significantly affect the fuel break–fire outcome is that they may have been relatively uniform across our study area relative to the sample size, which may have been too small to adequately explain substantial variation. In other words, there may be additional reasons that fires stop at fuel breaks, but there were not enough samples to adequately quantify these different effects. Regardless, the results strongly suggest that fires will

generally not stop at fuel breaks in our study area unless firefighters are present to suppress the fire. There was only one event in our analysis in which a fire stopped at a fuel break without active fire suppression. With firefighter control, however, fuel breaks had a decent success rate (46%), which is the exact same success rate found in old (and one of the only other) analyses of fuel break effectiveness in the region (Cecil 1941).

It is important to keep in mind that our statistical analysis was based on a response variable describing whether the fire stopped at the fuel break and did not reflect the role of fuel breaks in changing fire behaviour. In seven cases, the treatments did change the behaviour of the fire that ultimately allowed subsequent control, and if these are included, the success rate increases to 56%. The key variables that may be most important to consider in fire management and planning, therefore, may be related to those that affect firefighting activities.

Our results showed that access to the fuel break was critical in the success of fire control, and this was echoed by firefighters who generally viewed access as a function of the spread rate of the fire relative to location of fire origin, the location of the fuel break and the location of the crews at the time of the fire. Also, if the fire started at night, there were fewer people available, so they would have to travel from home to work to get to the engine. The speed of response is an important component in successful fire control (Halsey 2005), and this has been recognised for many decades, particularly in the Los Padres National Forest, which has extensive roadless and trailless areas (Show *et al*. 1941).

Once firefighters were in the vicinity of the fuel break, vegetation structure played an important role in determining whether they could access the fuel break in time to stop the fire, and this is reflected in our SEM (Fig. 4). In the high-elevation chaparral of the Los Padres National Forest, as well as chaparral elsewhere, stand age and fuel loads play a limited role in stopping the spread of fire, particularly during extreme weather conditions when fires will readily spread through all age classes of vegetation (Moritz 1997; Moritz *et al*. 2004; Keeley and Zedler 2009). Therefore, whereas young fuels may constrain fire in other vegetation types, the primary relationship in the present study is with firefighter access to fuel breaks. Chaparral is composed of dense, woody shrubs that form a continuous cover that makes it difficult to manoeuvre and contributes to dangerous flame lengths (Conard and Weise 1998), and therefore, younger vegetation makes it easier for crews to access the fuel break and establish an anchor point. In many cases, the crews will re-establish the fuel break (e.g. through dozers or handlines) once they arrive. However, if the fuel break is close to a fast-moving fire, there may not be time to re-establish the break and to fully prepare. Therefore, the condition of the fuel break was significant in explaining access to treatment owing to the time required to restore a fuel break in poor condition, especially when fires were fast and near. This suggests that maintaining current fuel breaks may be an important component of effective fire management.

Although maintaining current fuel breaks may increase their success rate, the length of the fuel break was also important, although fuel break width was insignificant. A possible reason that fuel break width was insignificant is that the widths provided in the data may have been approximations, and we also needed to average the range of widths for several of the fuel breaks. We considered that fuel break length may have facilitated firefighter access, but those two variables were not correlated. Therefore, longer fuel breaks may potentially provide greater number of opportunities for fires to intersect fuel breaks. Another consideration is that we did not explore the relative difference of main fuel breaks versus secondary or lateral fuel breaks (which tend to be shorter in length), and other research in the region has shown that laterals are not as effective and do not substantially improve firefighting (Omi 1977).

Although interviews confirmed that the rate of fire spread and fire weather conditions play an important role in the efficacy of fuel breaks (e.g. they determine whether fire crews can access the treatment on time or whether conditions are safe enough to anchor at the break), the only variable related to fire spread rate that was significant in our study was fire size. Although fire size can be a function of multiple interacting factors, larger fires are generally associated with faster spread rates (Anderson 1983; Finney 2003), and faster, or erratic, spread rates are likely to vary as a function of fire–atmosphere couplings as well as fire-induced wind (Sun *et al*. 2009). We made the basic assumption that fire size is correlated with rate of spread at least during some point during the duration of the fire, and consistent with our expectations, small fires were more likely to stop at fuel breaks than large fires. Although there is also the possibility fire size is smaller when fuel breaks are effective because the fuel break played a role in constraining the fire, conversations with firefighters during the interviews confirmed that larger fires are typically associated with severe weather conditions and are much more difficult and dangerous to control.

Although we explored two different sets of weather data, and multiple weather indicators, the likely reason that we found no statistically significant relationships is that many of our fires burned over several days, and we had no way of knowing the exact date and time that the intersection with the fuel break actually occurred. Because weather is highly variable over space and time, we were therefore unable to assign exact weather conditions to the location or moment of intersection. One example of the effect of weather on fuel break outcome that we were unable to capture was the Wheeler Fire number 2 of 1985, which burned for 2 weeks. The weather conditions during the first 4 days were erratic and extreme; the only fuel breaks that were effective were those that intersected the fire after these first 4 days (Salazar and González-Cabán 1987).

Even in other forest types, the influence of fuel breaks on fire spread and severity can be variable and are likely to vary according to weather conditions and other variables (Schoennagel *et al*. 2004). A 'one size fits all' approach to fire management has been cautioned against in several recent papers (Noss *et al*. 2006; Reinhardt *et al*. 2008; Keeley *et al*. 2009*b*) and we reiterate the warning for chaparral. There is high variability and complexity in the circumstances leading up to the intersection of fires and fuel breaks and the outcome of what happens (Keeley *et al*. 2009*a*), and the effectiveness of the fuel break in our study could not be predicted by variables such as fuel type, elevation, slope or average climate conditions. Furthermore, our study only accounted for the final realisation of the fire event and not for finer-scale factors that change fire behaviour during the course of the fire event or firebrand production during the spread of the fire.

Although many of the biophysical variables we considered did not significantly explain the role of fuel breaks in stopping fires, a suite of biophysical and human variables was important for developing a model that can predict which parts of the landscape are likely to experience the highest number of fire and fuel break intersections, at least on the landscape from which the model was developed. It was no surprise that historic fire frequency was the strongest predictor of number of fire–fuel break intersections because some areas are inherently more fire-prone than others. The negative relationship between ignition density and number of intersections was unexpected, but may be because the relationship between humans and fire tends to be non-linear (Syphard *et al*. 2007, 2009), and different factors control fire ignitions versus fire occurrence or spread (Syphard *et al*. 2007, 2008). Aside from solar radiation (which varies slowly over time), the other significant variables (distance to trails and roads) tend to be spatially dynamic (as more roads or trails are constructed), which means that predictive mapping models may have to be refitted as landscapes change.

The fact that a substantial proportion of the fuel breaks never intersected a fire during the course of the study suggests that fuel breaks have not historically been placed in areas where fires are most likely to intersect them. Although it is possible that a fire may cross these fuel breaks in the future, fire managers might want to consider focussing maintenance and new construction in areas where fires and fuel treatments are most likely to intersect and thus provide greater opportunities for controlling fires. Construction of fuel breaks can be costly (Agee *et al*. 2000) and may lead to negative resource effects in the chaparral (Witter and Taylor 2005; Merriam *et al*. 2006). Therefore, mapping where fires are most likely to intersect fuel treatments could be part of the planning process to increase efficiency of new construction.

Although fuel breaks surrounding communities clearly serve an important role in creating a safe space for firefighting activities, fuel breaks in remote areas and in areas that rarely or never intersect fires have a lower probability to serve a beneficial function. It is important to consider strategic placement in terms of values at risk, near communities and the WUI, in shrubland ecosystems or other areas where the resource benefits of fuel treatments have not been demonstrated as they have been in forests. Despite strong arguments for locating fuel breaks near communities where protection is most needed (Winter *et al*. 2002; Halsey 2005; Keeley *et al*. 2009*b*), most fuel break proposals continue to be located in more remote wildland areas (Ingalsbee 2005; Schoennagel *et al*. 2009). Other finer-scale factors may also be important for strategic placement (e.g. placing them on ridgelines or other landscape features that offer tactical advantages; Ingalsbee 2005). It is also important to consider that many homes are not ignited owing to direct fire spread, but from firebrands, and more research is needed on the location of fuel breaks relative to firebrand production and structure exposure (Mell *et al*. 2010).

Although this study focussed on the role of fuel breaks in southern California, the increasing threat of fire to human lives and structures, as well as to natural resources, is far-reaching within the United States as well as many other regions in the world. As more fuel breaks are being constructed to mitigate fire risk, there is ongoing need to better understand their role in controlling wildfires. Our methods of systematically exploring the historic role of fuel breaks could be adopted anywhere, and indeed, the specific factors affecting the role of fuel breaks are likely to vary even within the southern California region. Controls over fire regimes vary at multiple scales (Falk *et al*. 2007). Although there are substantial differences in fire regimes between conifer forests and shrublands, southern California is also spatially diverse, and the relative importance of variables predicting fuel break effectiveness, and where fires intersect fuel breaks, may vary according to the scale of the analysis or across the region.

Acknowledgements

Funding for this research was provided by the US Geological Survey Multi-Hazards Demonstration Project. We thank John Abatzoglou and Tim Brown for providing weather data, Jim Grace for providing guidance on structural equation modelling and Steve Davis for providing expert knowledge about firefighting on the Los Padres National Forest. Thanks also to Erik C. Berg, Richard Halsey, Brian Halstead and Hugh Safford for reviewing the manuscript and offering many valuable suggestions. Any use of trade, product or firm names in this publication is for descriptive purposes only and does not imply endorsement by the US government.

References

Agee JK, Bahro B, Finney MA, Omi PN, Sapsis DB, Skinner CN, van Wagtendonk JW, Weatherspoon CP (2000) The use of fuelbreaks in landscape fire management. *Forest Ecology and Management* **127**, 55–66. doi:10.1016/S0378-1127(99)00116-4

Agresti A (1996) 'An Introduction to Categorical Data Analysis.' (John Wiley and Sons: New York)

Anderson HE (1982) Aids to determining fuel models for estimating fire behavior. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-122. (Ogden, UT)

Anderson HE (1983) Predicting wind-driven wildland fire size and shape. USDA Forest Service, Intermountain Forest and Range Experiment Station, Research Paper, INT-305. (Ogden, UT)

Cecil GH (1941) Conclusions, firebreak study pages historical documents numbers 3024 to 3028 1936–1940. Pacific Southwest Region, Forest Fire Laboratory, National Archives and Records Administration (Washington, DC)

Conard SG, Regelbrugge JC (1994) On estimating fuel characteristics in California chaparral. In '12th Conference on Fire and Forest Meteorology', 26–28 October 1993, Jekyll Island, GA. pp. 120–129. (Society of American Foresters: Bethesda, MD)

Conard SG, Weise DR (1998) Management of fire regime, fuels, and fire effects in southern California chaparral: lessons from the past and thoughts for the future. *Tall Timbers Ecology Conference Proceedings* **20**, 342–350.

Dellasala DA, Williams JE, Williams CD, Franklin JF (2004) Beyond smoke and mirrors: a synthesis of fire policy and science. *Conservation Biology* **18**, 976–986. doi:10.1111/J.1523-1739.2004.00529.X

Dubayah R, Rich PM (1995) Topographic solar radiation for GIS. *International Journal of Geographic Information Systems* **9**, 405–419. doi:10.1080/02693799508902046

Falk DA, Miller C, McKenzie D, Black AE (2007) Cross-scale analysis of fire regimes. *Ecosystems* **10**, 809–823. doi:10.1007/S10021-007-9070-7

Finney MA (2003) Calculation of fire spread rates across random landscapes. *International Journal of Wildland Fire* **12**, 167–174. doi:10.1071/WF03010

Finney MA, Seli RC, McHugh CW, Ager AA, Bahro B, Agee JK (2007) Simulation of long-term landscape-level fuel treatment effects on large

wildfires. *International Journal of Wildland Fire* **16**, 712–727. doi:10.1071/WF06064

Fortin M, Drapeau P, Legendre P (1989) Spatial autocorrelation and sampling design in plant ecology. *Vegetatio* **83**, 209–222. doi:10.1007/BF00031693

Grace JB, Pugesek BH (1998) On the use of path analysis and related procedures for the investigation of ecological problems. *American Naturalist* **149**, 436–460. doi:10.1086/285999

Grace JB, Anderson TM, Olff H, Scheiner SM (2010) On the specification of structural equation models for ecological systems. *Ecological Monographs* **80**, 67–87. doi:10.1890/09-0464.1

Gude PH, Rasker R, van den Noort J (2008) Potential for future development on fire-prone lands. *Journal of Forestry* **106**, 198–205.

Guisan A, Zimmermann NE (2000) Predictive habitat distribution models in ecology. *Ecological Modelling* **135**, 147–186. doi:10.1016/S0304-3800(00)00354-9

Haining R (1990) 'Spatial Data Analysis in the Social and Environmental Sciences.' (Cambridge University Press: Cambridge, UK)

Halsey RW (2005) 'Fire, Chaparral, and Survival in Southern California.' (Sunbelt Publications: San Diego, CA)

Hanley JA, McNeil BJ (1982) The meaning and use of the area under a receiver operating characteristics curve. *Radiology* **143**, 29–36.

Hooper D, Coughlan J, Mullen MR (2008) Structural equation modeling: guidelines for determining model fit. *The Electronic Journal of Business Research Methods* **6**, 53–60.

Ingalsbee T (2005) Fuelbreaks for wildland fire management: a moat or a drawbridge for ecosystem fire restoration? *Fire Ecology* **1**, 85–99. doi:10.4996/FIREECOLOGY.0101085

Keeley JE (2005) Chaparral fuel modification: what do we know – and need to know? *Fire Management Today* **65**, 11–12.

Keeley JE, Zedler PA (2009) Large, high-intensity fire events in southern California shrublands: debunking the fine-grained age-patch model. *Ecological Applications* **19**, 69–94. doi:10.1890/08-0281.1

Keeley JE, Safford HD, Fotheringham CJ, Franklin J, Moritz MA (2009a). The 2007 southern California wildfires: lessons in complexity. *Journal of Forestry* **107**, 287–296.

Keeley JE, Aplet GH, Christensen NL, Conard SG, Johnson EA, Omi PN, Peterson DL, Swetnam TW (2009*b*) Ecological foundations for fire management in North American forest and shrubland ecosystems. USDA Forest Service, Pacific Northwest Research Station, General Technical Report PNW-GTR-779. (Portland OR)

Mell WE, Manzello SL, Maranghides A, Butry D, Rehm RG (2010) The wildland–urban interface problem – current approaches and research needs. *International Journal of Wildland Fire* **19**, 238–251. doi:10.1071/WF07131

Merriam KE, Keeley JE, Beyers JL (2006) Fuel breaks affect non-native species abundance in Californian plant communities. *Ecological Applications* **16**, 515–527. doi:10.1890/1051-0761(2006)016[0515:FBANSA]2.0.CO;2

Miller C, Urban DL (2000) Modeling the effects of fire management alterations on Sierra Nevada mixed-conifer forest. *Ecological Applications* **10**, 85–94. doi:10.1890/1051-0761(2000)010[0085:MTEOFM]2.0.CO;2

Miller J, Franklin J, Aspinall R (2007) Incorporating spatial dependence in predictive vegetation models. *Ecological Modelling* **202**, 225–242. doi:10.1016/J.ECOLMODEL.2006.12.012

Miller JD, Safford HD, Crimmins M, Thode AE (2009) Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade Mountains, California and Nevada, USA. *Ecosystems* **12**, 16–32. doi:10.1007/S10021-008-9201-9

Montenegro G, Ginocchio R, Segura A, Keeley JE, Gomez M (2004) Fire regimes and vegetation responses in two Mediterranean-climate regions. *Revista Chilena de Historia Natural* **77**, 455–464. doi:10.4067/S0716-078X2004000300005

Moritz MA (1997) Analyzing extreme disturbance events: fire in Los Padres National Forest. *Ecology* **7**, 1252–1262.

Moritz MA, Keeley JE, Johnson EA, Schaffner AA (2004) Testing a basic assumption of shrubland fire management: how important is fuel age? *Frontiers in Ecology and the Environment* **2**, 67–72. doi:10.1890/1540-9295(2004)002[0067:TABAOS]2.0.CO;2

Noss RF, Franklin JF, Baker WL, Schoennagel T, Moyle PB (2006) Managing fire-prone forests in the western United States. *Frontiers in Ecology and the Environment* **4**, 481–487. doi:10.1890/1540-9295(2006)4[481:MFFITW]2.0.CO;2

Omi PN (1977) A case study of fuel management performances, Angeles National Forest, 1960–1975. In 'Proceedings of the Symposium on Environmental Consequences of Fire and Fuel Management in Mediterranean Ecosystems', 7 August 1977, Palo Alto, CA. (Eds H A Mooney, C E Conrad) USDA Forest Service, Publication WO-3, pp. 404–411. (Washington, DC)

Pausas JG, Vallejo R (1999) The role of fire in European Mediterranean ecosystems. In 'Remote Sensing of Large Wildfires in the European Mediterranean Basin'. (Ed. E Chuvieco) pp. 3–16. (Springer-Verlag: New York)

Pincetl S, Rundel PW, Clark de Blasio J, Silver D, Scott T, Keeley JE, Halsey RW (2008) It's the land use, not the fuels: fires and land development in southern California. *Real Estate Review* **37**, 25–43.

Pyne SJ, Andrews PL, Laven RD (1996) 'Introduction to Wildland Fire.' (Wiley: New York)

Quinn GP, Keough MJ (2002) 'Experimental Design and Data Analysis for Biologists.' (Cambridge University Press: Cambridge, UK)

R Development Core Team (2004) R: a language and environment for statistical computing. (R Foundation for Statistical Computing: Vienna, Austria) Available at http://www.r-project.org/ [Verified 13 July 2011]

Raab TK, Martin MC (2001) Visualizing rhizosphere chemistry of legumes with mid-infrared synchrotron radiation. *Planta* **213**, 881–887. doi:10.1007/S004250100554

Radeloff VC, Hammer RB, Stewart SI, Fried JS, Holcomb SS, McKeefry JF (2005) The wildland–urban interface in the United States. *Ecological Applications* **15**, 799–805. doi:10.1890/04-1413

Radtke KWH, Arndt AM, Wakimoto RH (1982) Fire history of the Santa Monica Mountains. In 'Proceedings of the Symposium on Dynamics and Management of Mediterranean-type Ecosystems', 22–26 June 1981, San Diego, CA. (Eds CE Conrad, WC Oechel) USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, General Technical Report PSW-58, pp. 438–443. (Berkeley, CA)

Raymond CL, Peterson DL (2005) Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon, USA. *Canadian Journal of Forest Research* **35**, 2981–2995. doi:10.1139/X05-206

Reinhardt ED, Keane RE, Calkin DE, Cohen JD (2008) Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. *Forest Ecology and Management* **256**, 1997–2006. doi:10.1016/J.FORECO.2008.09.016

Rollins MG, Frame CK (2006) The LANDFIRE Prototype Project: nationally consistent and locally relevant geospatial data for wildland fire management. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-175. (Fort Collins, CO)

Safford HD, Schmidt DA, Carlson C (2009) Effects of fuel treatments on fire severity in an area of wildland–urban interface, Angora Fire, Lake Tahoe Basin, California. *Forest Ecology and Management* **258**, 773–787. doi:10.1016/J.FORECO.2009.05.024

Salazar LA, González-Cabán A (1987) Spatial relationship of a wildfire, fuelbreaks, and recently burned areas. *Western Journal of Applied Forestry* **2**, 55–58.

Schmidt DA, Taylor AH, Skinner CN (2008) The influence of fuels treatment and landscape arrangement on simulated fire behavior, Southern Cascade Range, California. *Forest Ecology and Management* **255**, 3170–3184. doi:10.1016/J.FORECO.2008.01.023

Schoennagel T, Veblen TT, Romme WH (2004) The interaction of fire, fuels, and climate across Rocky Mountain forests. *Bioscience* **54**, 661–676. doi:10.1641/0006-3568(2004)054[0661:TIOFFA]2.0.CO;2

Schoennagel T, Nelson CR, Theobald DM, Carnwath GC, Chapman TB (2009) Implementation of National Fire Plan treatments near the wildland–urban interface in the western United States. *Proceedings of the National Academy of Sciences of the United States of America* **106**, 10706–10711. doi:10.1073/PNAS.0900991106

Schwilk DW, Keeley JE, Knapp EE, McIver J, Bailey JD, Fettig CJ, Fiedler CE, Harrod RJ, Moghaddas JJ, Outcalt KW, Skinner CN, Stephens SL, Waldrop TA, Yaussy DA, Youngblood A (2009) The national fire and fire surrogate study: effects of fuel reduction methods on forest vegetation structure and fuels. *Ecological Applications* **19**, 285–304. doi:10.1890/07-1747.1

Show SB, Abell CA, Deering RL, Hanson PD (1941) A planning basis for adequate fire control on the southern California national forests. *Fire Control Notes* **5**, 1–59.

Stephens SL (2005) Forest fire causes and extent on United States Forest Service lands. *International Journal of Wildland Fire* **14**, 213–222. doi:10.1071/WF04006

Stratton RD (2004) Assessing the effectiveness of landscape fuel treatments on fire growth and behavior. *Journal of Forestry* **102**, 32–40.

Sun R, Krueger SK, Jenkins MA, Zulauf MA, Charney JJ (2009) The importance of fire–atmosphere coupling and boundary-layer turbulence to wildfire spread. *International Journal of Wildland Fire* **18**, 50–60. doi:10.1071/WF07072

Syphard AD, Franklin J (2009) Differences in spatial predictions among species distribution models vary with species traits and environmental predictors. *Ecography* **32**, 907–918. doi:10.1111/J.1600-0587.2009.05883.X

Syphard AD, Radeloff VC, Keeley JE, Hawbaker TJ, Clayton MK, Stewart SI, Hammer RB (2007) Human influence on California fire regimes. *Ecological Applications* **17**, 1388–1402. doi:10.1890/06-1128.1

Syphard AD, Radeloff VC, Keuler NS, Taylor RS, Hawbaker TJ, Stewart SI, Clayton MK (2008) Predicting spatial patterns of fire on a southern California landscape. *International Journal of Wildland Fire* **17**, 602–613. doi:10.1071/WF07087

Syphard AD, Radeloff VC, Hawbaker TJ, Stewart SI (2009) Conservation threats due to human-caused increases in fire frequency in Mediterranean-climate ecosystems. *Conservation Biology* **23**, 758–769. doi:10.1111/J.1523-1739.2009.01223.X

Theobald DM, Romme WH (2007) Expansion of the US wildland–urban interface. *Landscape and Urban Planning* **83**, 340–354. doi:10.1016/J.LANDURBPLAN.2007.06.002

Wakimoto RH (1977) Chaparral growth and fuel assessment in southern California. In 'Proceedings of the Symposium on Environmental Consequences of Fire and Fuel Management in Mediterranean Ecosystems', 1–5 August 1977, Palo Alto, CA. (Eds H A Mooney, CE Conrad) USDA Forest Service, General Technical Report WO-3, pp. 412–418. (Washington, DC)

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase western US forest wildfire activity. *Science* **313**, 940–943. doi:10.1126/SCIENCE.1128834

Whelan RJ (1995) 'The Ecology of Fire.' (Cambridge University Press: Cambridge, UK)

Winter GJ, Vogt C, Fried JS (2002) Fuel treatments at the wildland–urban interface: common concerns in diverse regions. *Journal of Forestry* **100**, 15–21.

Witter M, Taylor RS (2005) Preserving the future: a case study in fire management and conservation from the Santa Monica Mountains. In 'Fire, Chaparral, and Survival in Southern California'. (Ed. RW Halsey) pp. 109–115. (Sunbelt Publications: San Diego, CA)