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The impact of antecedent fire area on burned area in southern California coastal ecosystems

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A B S T R A C T

Frequent wildfire disasters in southern California highlight the need for risk reduction strategies for the region, of which fuel reduction via prescribed burning is one option. However, there is no consensus about the effectiveness of prescribed fire in reducing the area of wildfire. Here, we use 29 years of historical fire mapping to quantify the relationship between annual wildfire area and antecedent fire area in predominantly shrub and grassland fuels in seven southern California counties, controlling for annual variation in weather patterns. This method has been used elsewhere to measure leverage: the reduction in wildfire area resulting from one unit of prescribed fire treatment. We found little evidence for a leverage effect (leverage = zero). Specifically our results showed no evidence that wildfire area was negatively influenced by previous fires, and only weak relationships with weather variables rainfall and Santa Ana wind occurrences, which were variables included to control for inter-annual variation. We conclude that this is because only 2% of the vegetation burns each year and so wildfires rarely encounter burned patches and chaparral shrublands can carry a fire within 1 or 2 years after previous fire. Prescribed burning is unlikely to have much influence on fire regimes in this area, though targeted treatment at the urban interface may be effective at providing defensible space for protecting assets. These results fit an emerging global model of fire leverage which position California at the bottom end of a continuum, with tropical savannas at the top (leverage = 1: direct replacement of wildfire by prescribed fire) and Australian eucalypt forests in the middle (leverage ~ 0.25).

1. Introduction

The destruction of property by wildfire is a major cost in southern coastal California USA, with property losses exceeding $1 billion occurring in 1993, 2003 and 2007 (http://lwf.ncdc.noaa.gov/oa/reports/billionz.html#chron, accessed 21/2/2012). Some individual fires have destroyed thousands of houses (e.g. the Cedar fire 2003 (Brillinger et al., 2009) and the Witch fire 2007 (Keeley et al., 2009)). Hence, strategies that reduce risk of loss are urgently needed. One of the principal strategies adopted in fire-prone environments around the world is fuel reduction, commonly achieved by prescribed burning. However, the role that fuel reduction and fuel accumulation has on fire occurrence and behavior in shrubland dominated landscapes in California is vigorously debated. Some argue that a build-up of fuel due to decades of effective suppression has led to larger and more destructive fires (Goforth and Minnich, 2007; Minnich and Chou, 1997), as postulated for many forest ecosystems in the other parts of the western USA (Donovan and Brown, 2007). Others have argued that suppression has not changed fire sizes in chaparral ecosystems (Keeley and Fotheringham, 2001) because the fuels involved can carry fire soon after a previous fire, and because most large fires in the region are driven by extreme weather conditions (Keeley and Zedler, 2009; Moritz, 2003; Zedler and Seiger, 2000).

A fundamental assumption in this debate is that areas of reduced fuel have an inhibitory effect on the behavior of subsequent wildfires. While it is well-established that wildfires spread more slowly and with lower intensity and spotting potential in reduced fuels (Fernandes and Botelho, 2003; Regelbrugge, 2000), the more general effect of reducing the incidence and/or area of wildfires at regional scales is not so certain. Thus, quantification of these effects is required. Recent research in Australia has explored this issue by relating the area burned in wildfire to the area

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recently treated over several decades at regional scales (Boer et al., 2009; Price et al., 2012; Price and Bradstock, 2011). This relationship has been called “leverage”: the unit area reduction in wildfire resulting from each unit of treatment. The findings are that although recent burning does reduce the area burned subsequently, the effect is modest and varies from region to region. For example, in the sclerophyll forests of south-eastern and south-western Australia, dominated by *Eucalyptus* spp., 3–4 ha of prescribed burning is required to reduce subsequent wildfire area by 1 ha (i.e. leverage = 0.25–0.33), whereas in the tropical savannas, this ratio is closer to 1 (i.e. exact replacement of wildfire by prescribed fire). Simulation studies for eucalypt forests corroborate these empirical studies (Bradstock et al., 2012; Price, in press), and in particular, highlight the likelihood that the leverage value of 1 is at the upper end of what is achievable anywhere in the world.

Given the ongoing threat that wildfires cause to communities in California and the uncertainty of the effects of prescribed burning, we apply the methods used in the Australian studies to estimate leverage in southern California. Area burned by wildfires in any given year, on average, should be negatively related to antecedent area burned by both prescribed and unplanned fires (this is the tested hypothesis). The strength of this relationship (i.e. the slope) will indicate leverage. The relationship may be masked to some extent by inter-annual variation in fire weather (e.g. temperature, humidity, wind speed) and longer term drought (Price and Bradstock, 2011), and these effects therefore need to be accounted for in analyses.

As well as providing empirical evidence for the effectiveness of prescribed fire in California, such a study contributes to an emerging understanding of global patterns of leverage which may help to predict leverage anywhere in the world (Price, in press). Such an understanding recognizes that prescribed fire effectiveness varies among biomes.

2. Materials and methods

2.1. Data

The study focused on the South Coast Ecoregion of California, comprising the counties of San Luis Obispo, Santa Barbara, Ventura, Los Angeles, Riverside, Orange and San Diego (4,175,000 ha, Fig. 1). Mapped wildfire perimeters from the region for the years 1979–2007 were obtained from the Fire Resource Assessment Program operated by the California Department of Forestry and Fire Protection (http://frap.cdf.ca.gov/projects/fire_data/fire_perimeters/methods.asp, accessed 6 March 2011). These comprise a total of 2380 wild fires with a combined area of 2,453,000 ha. These were supplemented with perimeters for 708 prescribed fires (USGS unpublished data), with a combined area of 100,200 ha. Fuel type data were obtained from the US Forest Service (N. Amboy) at 30 m resolution, classified into Scott and Burgan (2005) classes. The total area of burnable fuels (woodland/forest, grass or shrubland) was 31,300 km^2, which comprised 75.3% of the land area of the seven counties. Of this, 43.1% was classified as shrubland, 23.0% as grassland, 14.0% as shrub/grass mixture and 19.9% was woodland/forest. Considering the study area as a whole, the mean area of each fuel type burned per year over the 29 year period was 2.72% for woodland/forest fuels, 1.93% for shrub/grass, 1.74% for grass and 1.45% for shrub fuels. The study area was divided into the seven counties to increase the sample size, and hence the ability to detect a leverage effect rather than to explore geographic variation in leverage. For this purpose, large arbitrary spatial units such as counties are better than fuel types because a-priori we expect no systematic variation in burned area or leverage and because fuel types are arranged in small-scale mosaics and each fire will burn several patches. The analysis (see 2.2: Analysis) identifies a single leverage value for the entire study area rather than an individual value for each county. The area of burnable fuel types in each county was calculated, and the

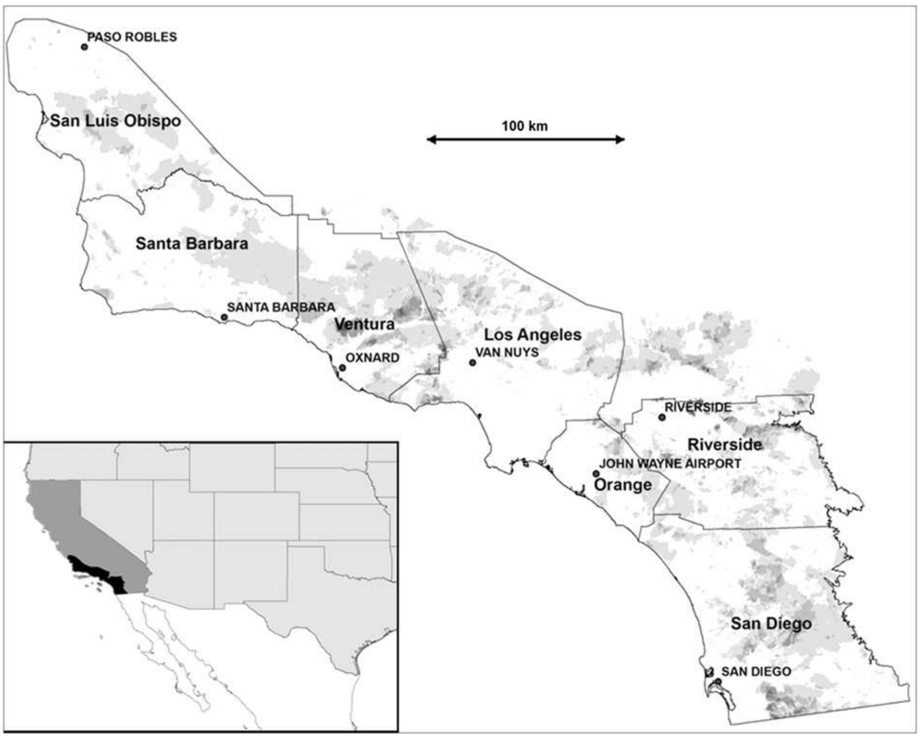

Fig. 1. The study area comprising seven Californian counties. The shading shows the number of fires experienced between 1979 and 2007 (white = 0, black = 8). Counties are labeled in bold, and weather stations in smaller, capitalized fonts. The inset map shows the seven counties in black and California in dark gray.

dependent variable for the analysis (wildfire area) was calculated as the percentage of the burnable area of each county that burned by wildfire in each year.

The primary predictor variable was the total area burned by wildfire or prescribed fire in the previous one or more years. The mean percentage burned in a moving window of the previous 2, 5 and 10 years was calculated as alternative predictors to the single past year. This was done because the nature of fuel accumulation may determine the temporal period over which antecedent area burned affects wildfire activity in given year (e.g. Boer et al., 2009). These variables were collectively referred to as 'past fire variables'.

Weather data was used to control for exogenous variation in annual area burned. In order to describe the general weather conditions for each year in each county, data from a single weather station was used for each county: Paso Robles (Air Force Catalog Station Number 723965) for San Luis Obispo; Santa Barbara Municipal (723925) for Santa Barbara; Oxnard (723927) for Ventura; Van Nuys Airport (722886) for Los Angeles; John Wayne Airport (722977) for Orange; Riverside (722860) for Riverside; and San Diego Lindbergh Field (722900) for San Diego. The weather stations were chosen using hierarchical criteria: 1) they must have an hourly record with few missing values for the duration of the study; 2) they should be as close as possible to the geographic centre of the county. Unfortunately three of the stations so chosen were less than 4 km from the coast (San Diego, Santa Barbara and Oxnard).

A range of hourly, daily and monthly data for these stations was sourced from the Desert Research Institute and the NOAA weather website (http://lwf.ncdc.noaa.gov/oa/climate/climatedata.html#hourly, accessed 10/12/2011). For years with missing or incomplete records, data from another station was substituted. For each of the stations, several annual summaries of the weather data were calculated. These were:

- Rainfall (annual sum, plus each calendar quarter, plus multi-year rainfall totals for up to 5 years).
- The number of days with Santa Ana winds, defined according to Sergius and Huntoon (1956) as one where the wind-speed exceeded 32 km h^{-1} on at least four separate hourly recordings at any time during the day, the wind direction was between North and East and the relative humidity at 1630 h was below 40%
- The number of hot days, where the temperature at 1630 h exceeded 25 °C
- The number of dry days where the relative humidity at 1630 h was below 20%
- The number of windy days where the maximum of the hourly values exceeded 32 km h^{-1}

2.2. Analysis

The leverage analysis was conducted using Generalized Linear Mixed Modeling (GLMM) where the sample consisted of values for each county in each year. Initially, each of the predictor variables was fitted against wildfire area, and the Akaike Information Criterion (AIC) and goodness-of-fit (Magee, 1990) were compared. The models were specified with a normal error distribution and county as a random variable to account for repeated measures. Explicit consideration in the analysis of spatial autocorrelation among counties was not necessary because the correlation in wildfire area among adjacent counties was low (mean = 0.18, see below) and because the mean fire size is only 0.22% of the mean county size so fires rarely affect multiple counties.

Then the past fire, rainfall and fire weather variable with the lowest AIC were combined in model selection approach (Burnham and Anderson, 2002) to derive the best model and supported alternatives (ΔAIC < 2). Leverage is the absolute value (without the minus sign) of the slope or estimate of the fire variable (if any is present in the preferred model) (Loehle, 2004). The total sample size was 203 (7 counties by 29 years), but only 24 years were used in the analysis ($n = 168$) because antecedent fire area for 5 years the fire area could not be calculated for an initial equivalent period. For analyses involving an antecedent period of 10 years, only 19 years of data were used. All analyses were repeated using log-transformed variables (both predictor and response variables), but these are not reported since this did not improve the results (authors' unpublished data). Separate analyses of the influence of either past wildfire or past prescribed fire only were also conducted, but these offered less insight than models containing the sum of these sources of fire and are therefore not reported (authors' unpublished data).

To further explore patterns and drivers of fire activity the correlation of wildfire area between each pair of counties was estimated. A strong correlation among counties would be consistent with broadscale inter-annual climate effects as drivers of fire activity, while a weak correlation would point to local factors, such as human ignition patterns as more likely drivers. If climate were responsible for broadscale fire patterns we would also expect there to be a strong correlation in annual rainfall, and number of Santa Ana days and dry days among counties, so this too was tested.

We also explored the tendency of fires to occur in recently burned fuels by calculating, for the six most active fire years across the entire ecoregion, the percentage of the wildfire area that burned in one-year-old fuel (i.e. fires that burned within the perimeter of areas burned in the previous year). We also calculated the percentage of one year old fuel, to estimate its availability. If the percentage of the fire that burned one-year-old fuel is similar to the availability of that fuel in the landscape, then it suggests that recent burning was not inhibiting fire. Since the sample size was small, no statistical test was conducted on these data.

3. Results

Over the 29 years studied, the mean wildfire area was 1.8% of the burnable area overall. However, there was high variability among years and counties, such that the standard deviation was 3.9%. Ventura had the highest mean (3.3% pa) and San Luis Obispo the lowest (0.96% pa) (Fig. 2). The correlation in annual wildfire area

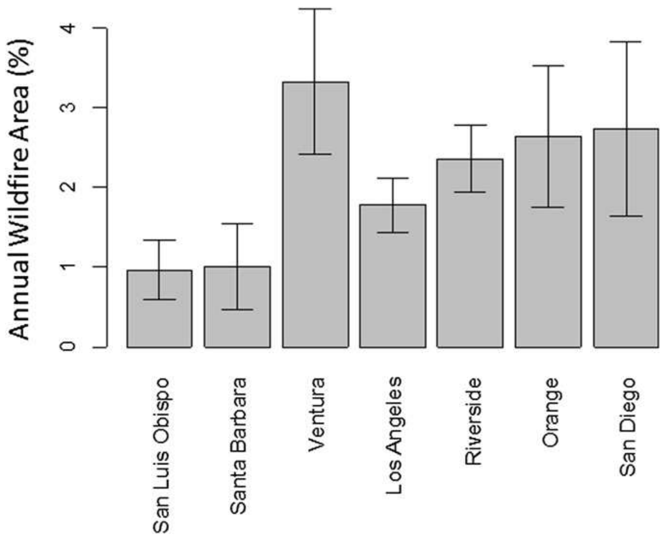

Fig. 2. The mean annual wildfire area of each county as a percentage of the burnable vegetation.

among counties was low (mean pair-wise $r = 0.211$, and highest between Santa Barbara and San Diego = 0.589), with several of the counties showing substantially different time trends in fire activity (Table 1a). In contrast, annual rainfall showed strong correlation among counties (mean $r = 0.825$, lowest between Santa Barbara and San Diego = 0.582, Table 1b), while the number of dry days was intermediate ($r = 0.559$, Table 1c). The number of Santa Ana days had low inter-county correlation, similar to that for wildfire area (mean $r = 0.242$, Table 1d).

None of the past fire variables had a significant relationship with wildfire area (Fig. 3, Table 2), but past fire 5 (mean area burned in the prior five years) had the lowest AIC value (lower than the null model) and a pseudo-r^2 of 0.19. The rainfall and fire weather variables were also poor predictors of wildfire area, though several were an improvement on the null model. The best rainfall variable was annual rainfall and the best fire weather variable was the number of dry days (Fig. 3). The best combined model for prediction of wildfire area contained only the number of dry days (Table 3). This model explained only 3.4% of variation and was only significant at the $p < 0.05$ level. There were several alternative, supported models consisting of: rainfall and the sum of dry days and rainfall; 5 years of antecedent fire plus rainfall, or 5 years of antecedent fire plus dry days. Of these, however, only rainfall had a significant (negative) effect on wildfire area.

In each of the major fire years, some portion of one year old fuels were burned (Table 4) and in several of them the amount burned was similar to the proportion of one year old fuels available in the landscape.

4. Discussion

This study provides no evidence of any inhibitory effect of past fire on subsequent fire (see Fig. 3) in southern California, with a very weak, positive relationship. We concluded that in effect, leverage is zero. This is in marked contrast to Australian studies that have found negative relationships in several biomes (Boer et al., 2009; Price et al., 2012; Price and Bradstock, 2011). Vilen and Fernandes (2011) have similarly found a negative relationship between antecedent fire and wildfire area in Portugal.

Why is leverage zero in California, but ~0.3 in Australian forests and 1 in Australian savannas? There are two probable reasons. Firstly, the average area burned each year is lower in southern California: i.e. circa. 2% of the burnable area of each county burns each year on average. Even accounting for small fires that may have been unrecorded in the database, this is less than half the rate in Australian forests and one tenth the amount in Australian savannas (Price et al., 2012; Price and Bradstock, 2011). Recently burned patches can only inhibit subsequent wildfires if they are encountered by them. When only 2% of the landscape burns each year, the

Table 1
Correlations among counties in the annual values for a) Wildfire area; b) Rainfall; c) Santa Ana days and d) Dry days.

	Orange	Ventura	San Luis Obispo	Riverside	Santa Barbara	San Diego
a) Wildfire area: Overall mean correlation $r = 0.211$.						
Ventura	0.192					
San Luis Obispo	−0.144	0.214				
Riverside	0.400	0.135	0.133			
Santa Barbara	0.537	0.171	−0.056	−0.109		
San Diego	0.228	0.454	−0.085	−0.106	0.589	
Los Angeles	0.479	0.173	0.022	0.161	0.518	0.518
b) Rainfall: Overall mean correlation $r = 0.825$.						
Ventura	0.938					
San Luis Obispo	0.881	0.785				
Riverside	0.915	0.925	0.800			
Santa Barbara	0.798	0.726	0.833	0.649		
San Diego	0.853	0.854	0.724	0.926	0.582	
Los Angeles	0.913	0.924	0.838	0.934	0.668	0.862
c) Dry days: Overall mean correlation $r = 0.559$.						
Ventura	0.797					
San Luis Obispo	0.546	0.594				
Riverside	0.252	0.455	0.439			
Santa Barbara	0.673	0.566	0.409	0.382		
San Diego	0.656	0.655	0.386	0.370	0.509	
Los Angeles	0.787	0.886	0.630	0.509	0.594	0.644
d) Santa Ana days: Overall mean correlation $r = 0.242$.						
Ventura	0.188					
San Luis Obispo	0.264	0.194				
Riverside	0.244	0.371	0.504			
Santa Barbara	0.216	0.201	0.480	0.366		
San Diego	0.388	0.215	−0.026	−0.050	0.040	
Los Angeles	0.294	0.518	0.045	0.236	0.312	0.092

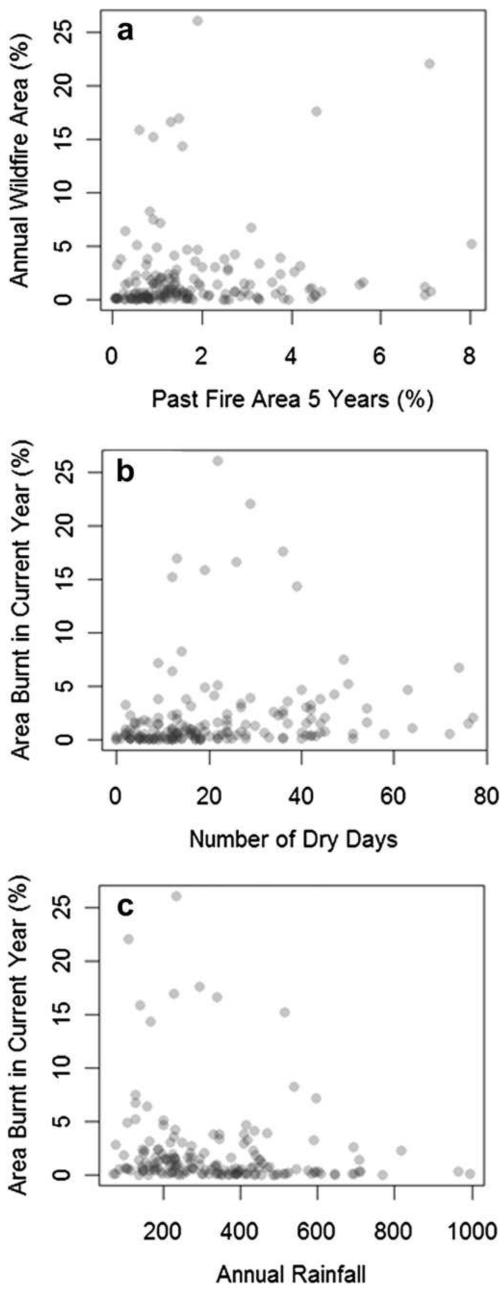

Fig. 3. The relationship between annual wildfire area and three predictor variables. a) Past fire 5 years; b) Number of dry days and c) Annual rainfall.

Table 2
Variables used and results of the analysis. ΔAIC represents the difference from a null model (−ve is an improvement).

Name	Description	ΔAIC	Pseudo-r^2
Wildfire area	The dependent variable: % of burnable vegetation burned in each county in each year		
Past fire			
Past fire 1	Total % of area burned in previous year	1.271	0.004
Past fire 2	Total % of area burned in previous 2 years	1.852	0.001
Past fire 5	Total % of area burned in previous 5 years	−1.256	0.019
Past fire 7	Total % of area burned in previous 7 years	0.475	0.009
Past fire 10	Total % of area burned in previous 10 years	−0.256	0.013
Fire weather			
Santa Ana days	Number of Santa Ana days	−0.994	0.018
Windy days	Number of days with wind speed > 20	0.825	0.007
Dry days	Number of days with 4.30 pm RH < 40	−3.819	0.034
Hot days	Number of days with 4.30 pm Temp. > 25 °C	1.815	0.001
Past rainfall			
Rainfall	Annual rainfall	−1.829	0.023
Rain quarter 1	Rainfall for Jan–March	0.585	0.008
Rain quarter 2	Rainfall for April–June	1.796	0.001
Rain quarter 3	Rainfall for July–Aug	−0.454	0.015
Rain quarter 4	Rainfall for Sept–Dec	−1.528	0.021
Past rain 2	Total rainfall for 2 years (including current)	−0.173	0.013
Past rain 3	Total rainfall for 3 years	1.677	0.002
Past rain 4	Total rainfall for 4 years	1.952	0
Past rain 5	Total rainfall for 5 years	0.893	0.007

chances that a wildfire will encounter a burned patch is low, even if the fuel load is reduced for several years. In a simulation experiment, Price (in press) found encounter rate to be the primary determinant of leverage. Encounter rates have been demonstrated to be lower than 10% during the assumed period of effectiveness of prescribed fires in the USA forests (Campbell et al., 2012; Rhodes and Baker, 2008) and lower than 20% in Australian eucalypt forests (Price and Bradstock, 2010).

Table 3
Final best model for wildfire area (and supported alternatives). ΔAIC refers to the difference in AIC between each supported alternative model and the best model. Estimate is the model coefficient for each variable. r^2 is the pseudo-r^2 for the model according to Magee's (1990) method. $n = 168$.

	Estimate	Std. error	*t*-Value	*p*-Value	ΔAIC	r^2
Best model						
(Intercept)	1.052	0.594	1.771	0.079	0	0.034
Dry days	0.047	0.021	2.291	0.023		
Supported alternatives						
(Intercept)	2.121	0.934	2.271	0.025	0.019	0.039
Rainfall	−0.002	0.002	−1.357	0.177		
Dry days	0.036	0.021	1.712	0.089		
(Intercept)	2.542	0.784	3.243	0.001	0.039	0.038
Past fire 5	0.311	0.200	1.551	0.123		
Rainfall	−0.003	0.002	−1.785	0.076		
(Intercept)	3.231	0.652	4.955	0.000	0.816	0.024
Rainfall	−0.003	0.002	−2.023	0.045		
(Intercept)	0.919	0.568	1.618	0.108	0.957	0.045
Past fire 5	0.264	0.207	1.272	0.205		
Dry days	0.032	0.019	1.655	0.100		

Table 4
Statistics for the percentage of areas recently burned for major fire seasons.

Year	Area burned (km^2)	% of fire burned last year	% of landscape burned last year
1980	1165	2.44	2.47
1985	1350	0.60	0.74
1993	1017	0.55	0.28
1996	1028	0.19	1.20
2003	3091	0.90	2.63
2007	3094	0.20	3.61

Secondly, Californian shrub and grass fuels accumulate rapidly and are sufficient to carry a repeat fire very soon after fire. While it takes many years for the structure and fuel loads of chaparral to return to pre-fire conditions, this is not necessary for fire propagation. Our data shows that fires burned through one-year-old fuels in all the major fire years and Keeley (2009) has documented several cases from the 2007 fires. Similarly, studies have found that chaparral fires do not depend on the availability of old fuels (Dunn, 1989; Keeley et al., 1999; Zedler et al., 1983) and are not stopped by a landscape mosaic of different fuel ages (Keeley and Fotheringham, 2001; Zedler and Seiger, 2000). Additionally, large areas of the chaparral are being type-converted to annual grasslands (mostly alien) as a result of repeat fires occurring in less than 5–10 years (Keeley et al., 2011). Grassland has lower fuel loads, but can carry a fire sooner than chaparral (Regelbrugge, 2000).

Moritz (2003) and Moritz et al. (2004) also found that fire in California is not fuel-age dependent and argued that this is because extreme fire (usually wind-driven) can burn through vegetation of any age. Although extreme fire weather is an important factor in Australian fires (Bradstock et al., 2009), in California the link between fires and the Santa Ana phenomenon of very dry and windy conditions is particularly strong (Moritz et al., 2010). On the other hand, Schoenberg et al. (2003) found an effect of fuel age for Los Angeles county, although Moritz *et al.* (Moritz et al., 2004) argue that a fuel effect may only occur in limited areas.

The result also casts further doubt on the argument that fuel accumulation due to past fire suppression has increased the chances of large, damaging fires occurring (Goforth and Minnich, 2007; Minnich and Chou, 1997). Several studies have interpreted a power-law distribution of fire sizes as evidence that fuel age drives fire patterns (Malamud et al., 2005; Minnich and Chou, 1997; Yoder et al., 2011). However, these patterns can be derived from exogenous drivers, including weather patterns (Boer et al., 2008) and topography (McKenzie and Kennedy, 2012). Our study suggests that low encounter rates and relatively rapid fuel recovery means that fire activity is relatively insensitive to the distribution of fuel ages and so the effect of suppression is likely to be minimal.

Even though fuel age may not determine fire area, we expected weather to have a strong influence on fire area. We had anticipated that broad climatic measures such as annual rainfall, temperature, Palmer Drought Index and the Burning Index would have low correlation with burned area based on previous studies (Keeley, 2004; Schoenberg et al., 2007). Rather, these studies and others (Moritz et al., 2010) argue that fire activity in southern California is driven by Santa Ana winds, so it is surprising that we found little effect of Santa Ana events. This is possibly because Santa Ana events are hard to quantify. A variety of methods have been used (Hughes and Hall, 2010; Raphael, 2003; Sergius and Huntoon, 1956) but none perfectly capture the ephemeral nature of the events. They are concentrated in particular areas, such as in the lee of mountain passes (Moritz et al., 2010), so their effects are diluted in this regional-scale analysis. Many events may be missed in the weather station chosen to represent each county because of the localized nature of the events or poor station selection. A second issue is that Santa Ana and related events are associated with particular intense fires that pose risk to human assets, but many fires occur outside of Santa Ana days, and many Santa Ana days pass without major fires, so the strong effect on particular fire events becomes diluted when annual and regional totals are considered. It is also possible that drought has a lingering effect by causing fuel availability to increase through vegetation dieback, and hence to remain high even in subsequent years with good rainfall (Keeley and Zedler, 2009). Such an effect would not have been identified in our analysis.

It is important to make a distinction between observed leverage and the potential effectiveness of fuel treatment at a local scale. Leverage measures the historical influence of fire on fire over the long term, at large scales according to natural spatial patterns. Leverage is low because fires seldom encounter burned patches and patches can re-burn soon after. However, individual patches do have an effect on the behavior of a subsequent wildfire should one occur, including reducing the fire intensity and spotting potential (Fernandes and Botelho, 2003; Regelbrugge, 2000), slowing or in some cases stopping the spread of the fire (Price and Bradstock, 2010). Since the main fire advantage in these effects will be near the interface with assets to be protected, treatment should primarily target those areas, rather than in the broader landscape. This is a similar conclusion to that found in some Australian studies (Gibbons et al., 2012; Price and Bradstock, 2010, 2011), but has also been stated before in California (Regelbrugge, 2000). Such an approach will also minimize the potential for adverse ecological effects stemming from too-frequent fires in the broader landscape (Keeley et al., 2005). Also, long linear treatments may be much more effective than patches because they reduce the chance that wildfire will burn around the burned patch (Price, in press; Price et al., 2007). In other words, the quality and context of the area treated is a better measure of treatment than overall acres treated. Note also that mechanical and chemical removal of plants are more common fuel treatments than prescribed fire in southern California, and in general these have been found to be effective at stopping wildfires only when they improve access to the fire for fire-fighters so that effects such as reduced intensity and spotting can be taken advantage of (Syphard et al., 2011).

5. Conclusions

Our study has found that regional-scale patterns of fire extent in southern coastal California are not influenced by fuel age, and hence prescribed fire treatment will not help to reduce wildfire area. However, this does not negate the inhibitory effect that individual burned patches have on subsequent fire, should one encounter a recently burned patch. Hence, fuel treatment should be focussed close to the assets that need protection.

The zero value for leverage in California is in contrast to other biomes where similar analyses have been conducted and contributes to a developing set of empirical tests of a global model of leverage variation. The model proposed by Price (in press) postulates that the primary proximate drivers are mean extent burned (positive) and fuel accumulation rate (negative), though ultimately these two drivers are determined by climatic, ignition and other factors. California has very low fire extent (<2%) and rapid fuel recovery, for which the model predicts very low leverage. The tropical savannas have high leverage (~1) because almost 30% of the landscape burns each year (Price et al., 2012). Australian forests have intermediate leverage because the fire extent is intermediate (~5%) and fuels accumulate relatively slowly (Boer et al., 2009). While there is a need for further empirical testing (for example in boreal forests), the model seems robust and may be used to predict leverage values in other fire prone biomes of the world. This is important because a prescribed burning program should not be implemented unless its effectiveness has been quantified.

Acknowledgments

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