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Impact of antecedent climate on fire regimes in coastal California*

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Abstract. Severe fire weather is a major determinant of fire size in coastal California; however, it is unclear to what extent antecedent climate also controls fire activity. This study investigates the relationship between fire activity and climate in central coastal and southern California. Climate variables included the Palmer Drought Severity Index (PDSI), total monthly precipitation, mean monthly maximum temperature and the autumn and winter Southern Oscillation Indices (SOI). For both the central coast and the south coast regions there was no significant relationship between growing season PDSI, precipitation or temperature and number of fires. When examined by season, summer temperatures were positively correlated with number of fires in the central coast and autumn PDSI and precipitation were negatively correlated with fire occurrence in the south coast region. Area burned was not correlated with any current year climate variables in southern California although, in the central coast, drought during spring and autumn were correlated, but explained less than 10% of the variation in the area burned. Although there was a modest relationship between the Southern Oscillation Index (SOI) and local climate parameters, there was only a relatively weak relationship with fire activity. The importance of autumn foehn winds is illustrated by the observation that large fires occur most commonly during the autumn, regardless of PDSI. Antecedent climate, however, does appear to play some role in determining the length of the fire season on these landscape as PDSI is consistently related to the occurrence of large fires that occur before or after the autumn months.

Additional keywords: ENSO; drought; foehn winds.

Introduction

Natural crown fire regimes include diverse ecosystems from California shrublands to Rocky Mountain lodgepole forests and pose special problems for fire and resource managers (Johnson and Miyanishi 1995; Keeley 2002). California chaparral is of particular concern because it is the most extensive vegetation in California, covering over 3.5 million ha, or one-twentieth (Jones and Stokes Associates 1987) of the most populous state (33 million people) in the union.

Crown fire ecosystems stand in striking contrast to southwestern ponderosa pine forests where fire suppression policy has meant fire exclusion over much of that landscape throughout the 20th Century (Allen *et al.* 2002). In general, fire suppression activities have not greatly altered natural fire regimes in many crown fire ecosystems (Anderson *et al.* 1999; Keeley and Fotheringham 2001; Johnson *et al.* 2001). This is illustrated by burning patterns in the coastal ranges of central and southern California, where it is clear that fire suppression policy cannot be equated with fire exclusion (Moritz 1997, 1999, 2003; Conard and Weise 1998; Keeley *et al.* 1999), a pattern evident in other parts of the globe as well (Whelan 2002).

So why is fire suppression policy in much of the western USA so effective at excluding fires, but incapable of excluding fires on coastal chaparral landscapes? It certainly is not for lack of trying: in California expenditures on fire suppression have steadily increased during the 20th Century (Davis 1965; Clar 1969; Bonnicksen and Lee 1979; Kinney and Howitt 1984). Two obvious factors are fuels and weather. In western forests, fires typically burn surface fuels ignited during lightning storms, and weather conditions are, more often then not, conducive to rapid suppression (Keeley and Bond 2001). In contrast, chaparral fires always result in crown fires of some intensity. If these fires ignite during moderate weather conditions they are readily contained by suppression forces (Keeley 2002). However, it is a different story when they ignite during severe weather conditions and these conditions are possible year round (Countryman 1974; Keeley and Fotheringham 2003). More importantly autumn foehn winds, known as

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Santa Anas, occur at the end of 6 months or more of drought and produce the worst fire weather conditions in the country (Schroeder *et al.* 1964). While large wildfires throughout the western USA are nearly always associated with severe weather conditions (Schroeder *et al.* 1964), these conditions do not occur every year, whereas southern California Santa Ana winds are predictable annual events. The over-riding role of autumn Santa Ana winds is evident when one compares the seasonal distribution of fire in southern California with other regions. In the south-western USA both fire occurrence and area burned peak in the summer months (Swetnam and Betancourt 1998), whereas in southern California fire occurrence peaks in early summer, and area burned is offset by several months, peaking in mid-autumn (Keeley and Fotheringham 2003).

Although over the 20th Century there has not been a dramatic change in area burned in coastal California (Keeley *et al.* 1999), it is evident that historically there has always been substantial annual variation. In light of the fact that most burning occurs during extreme weather events, in particular autumn foehn winds, a question of immense practical importance is to what extent can fire managers predict future fire activity from the antecedent climate, months and years prior to a fire event? In particular to what extent does drought, as measured by the Palmer Drought Severity Index (PDSI), predict subsequent fire occurrence and annual area burned?

PDSI is a regional index based on the amount of soil moisture for a given period of time relative to the amount expected under ‘normal’ conditions (Palmer 1965). It is a combination of precipitation and evapotranspiration; being strongly influenced by antecedent precipitation anomalies and weakly influenced by temperature (Alley 1984). PDSI typically ranges from +6 to −6, where positive values indicate moist conditions and negative values indicate dry conditions. The index has provided valuable insights into the very different historical role of drought in the fire regimes of different forest types (Swetnam and Betancourt 1998; Swetnam and Baisan 2003).

More recently Westerling *et al.* (2002, 2003) have focused on a much narrower temporal range of fire data (last two decades of the 20th Century), but extended this analysis to include more of the fire-prone habitats of the western USA The conclusions from these papers are that PDSI is strongly correlated with area burned, there are lag effects such that PDSI may predict fire activity up to several years in the future, and there is much spatial variation in the form of the relationship between PDSI and fire activity throughout the West. Portions of coastal California were included in studies by Westerling *et al.* (2002, 2003) but, because the relationship between PDSI and fire activity in the interior regions of the West were much stronger, coastal California was not emphasized. The present investigation extends these studies by including fire data for all chaparral-dominated counties in coastal southern and central California, and includes a substantially longer fire dataset than previously considered.

Currently there is substantial effort being focused on detecting connections between local climates and global interactions between ocean temperature and atmospheric pressure, referred to as teleconnections (Diaz and Kiladis 1992). One of the more intensely studied patterns is that of El Niño events in which there is an intense warming of surface waters in the eastern Pacific and this is linked to changes in atmospheric patterns known as the Southern Oscillation. The linkage is sufficiently established that they are referred to as El Niño Southern Oscillation (ENSO) events and these ENSO events, measured by the Southern Oscillation Index (Stahle *et al.* 1998), are commonly tied to fire activity (Simard *et al.* 1985; Swetnam and Betancourt 1990; Brenner 1991; Harrison and Meindl 2001; Kitzberger *et al.* 2001; Heyerdahl *et al.* 2002; Kitzberger and Veblen 2003). There is a significant ENSO signal such that negative SOI events are correlated with greater precipitation, both in volume and duration, in the south-western USA (Cayan *et al.* 1999); however, the relationship between SOI and California climate is debatable (Schonher and Nicholson 1989; but cf. Gershunov *et al.* 2000) and appears to be modulated by other tropical intraseasonal oscillations (Mo and Higgins 1998). Here I explore the relationship of SOI to PDSI, precipitation and fire activity in these two regions.

Study area

This analysis dealt with the nine counties in coastal California from Monterey to San Diego. Central coastal counties included Monterey, San Luis Obispo, Santa Barbara and Ventura. Southern California counties were Los Angeles, San Bernardino, Riverside, Orange and San Diego (Fig. 1). Landscapes in this region are dominated by chaparral shrublands, often forming mosaics with sage scrub, grassland, woodland and coniferous forests. Historical patterns of burning are well documented (Moritz 1997, 2003; Conard and Weise 1998; Keeley *et al.* 1999) and there are sufficient differences between the central coast (Monterey–Ventura) and southern California (Los Angeles–San Diego) to warrant separate analysis (Keeley and Fotheringham 2003).

Methods

Data on numbers of fires and area burned came from the California Statewide Fire History Data Base (Keeley *et al.* 1999). For the counties studied here fire records were available for the 89 year period 1913–2001. Quality of records is an unknown, and conventional wisdom/urban legend contends that in earlier years many of the smaller-sized fires that are reported today were not recorded. Thus, it is possible that conclusions drawn about patterns of fire frequency may be unreliable; however, there is little reason to doubt the historical patterns of area burned since this is driven by large fire events. These data are for wildfires and do not include

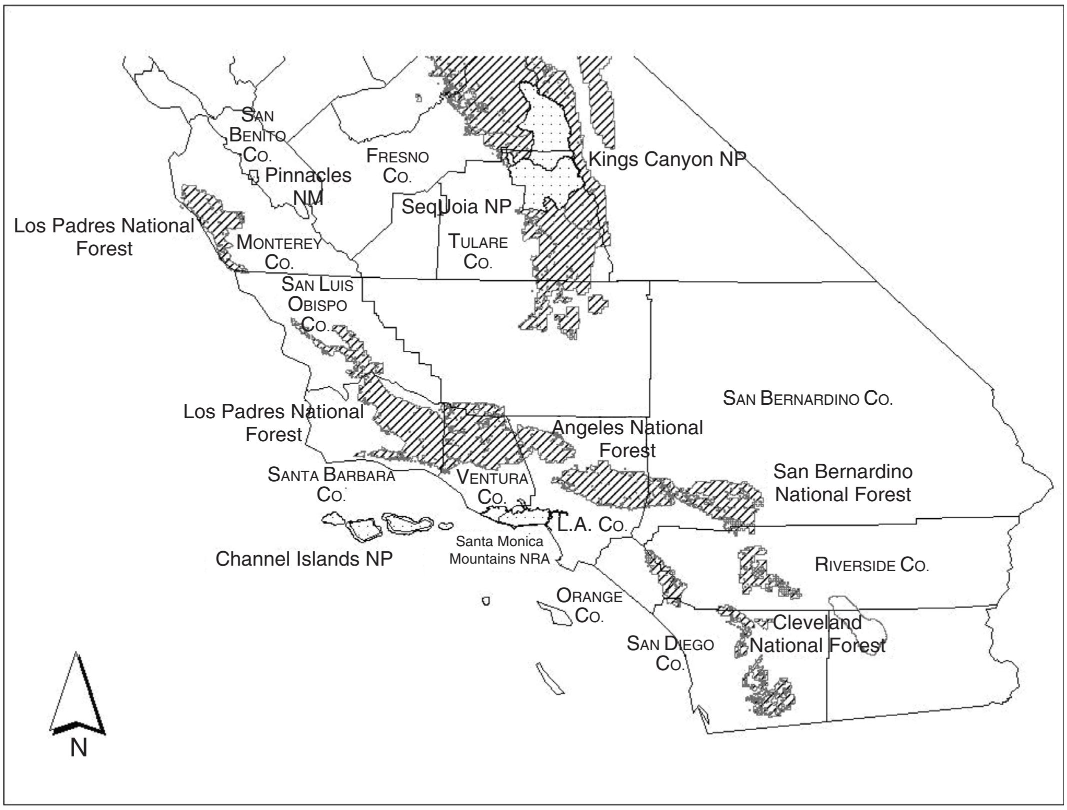

Fig. 1. California central coast counties include, from north to south, Monterey, San Luis Obispo, Santa Barbara, and Ventura and southern California counties are Los Angeles, San Bernardino, Riverside, Orange and San Diego.

prescription burning, but they do include backfires used in suppression activities.

Climatic data were downloaded from the National Oceanagraphic and Atmospheric Administration website (http://lwf.ncdc.noaa.gov/oa/climate/onlineprod/drought/xmgrg3.html, accessed November 2002). This NOAA website presents central coast and southern California indices based on combined values from all available stations in the region. Their circumscribed areas roughly parallel the counties I have designated for central coast and southern California (Fig. 1). Monthly PDSI, precipitation and average daily-maximum temperature were combined into seasonal values of average PDSI, total precipitation and average temperature. The Southern Oscillation Index was based on the autumn months (September–November) or winter months (December–February) (http://www.cdc.noaa.gov/Correlation/soi.data, accessed January 2003; Allen *et al.* 1996; Stahle *et al.* 1998) and indicates El Niño conditions when negative and La Niña when positive.

Ordinary least squares regression was used to investigate relationships between antecedent climate variables and area burned and number of fires for the chronological year January–December. Statistics calculated from these regressions used in these comparisons assume that the residuals from the regression are normally distributed. Residuals were regressed against the expected values for a normal probability plot. Residuals from regressions with number of fires gave reasonably tight fits in most of these normal probability plots. Those with area burned as the dependent variable did not exhibit as a tight a fit as those with number of fires, but they did fall approximately along the normal probability line. Since statistics calculated from ordinary least square regression are generally robust to departures from normality, this level of approximation was considered acceptable for these analyses. Residuals from log area and log fire frequency generally gave a tighter fit in these normal probability plots. However, following the differencing technique described below, log data commonly gave a similar fit to the normal probability plots. Since log transformed data generally gave a lower R^2, log values were not considered further.

One potential problem in ordinary least squares regression is that, for ordered sequences, autocorrelation of variables in the time series complicates interpretation of the bivariate model. The Durbin-Watson statistic indicates whether the residuals are correlated with their previous residuals and significant correlations indicate a lack of independence. In all regressions of number of fires *v.* climate variables there was a highly significant autocorrelation, $P < 0.01$. This was not the case with any of the regressions involving area burned *v.* climate. However, a few of these were significant at $P = 0.05$

and most were nearly significant at this level, so all data were treated the same. One means of handling such autocorrelations is with the time series technique of differencing where the value of the variable at time $t-1$ is subtracted from the variable at time t. These first-order difference values were then used in ordinary least squares regression and the Durbin-Watson statistic for these regressions indicated that autocorrelation had been removed. Differencing was used throughout these analyses except where indicated.

Multivariate techniques were used to combine climate parameters in various combinations in order to predict fire activity. Multiple regression was used with only those variables not exhibiting colinearity. An alternative approach that avoids the colinearity problem is principal components regression (Quinn and Keough 2002). Area burned or number of fires, as well as various combinations of independent variables, were converted to their principal components and these were used in regression analysis.

Results

Regional and seasonal climate comparisons

Fire occurrence was positively correlated between the central coast and south coast with ($R^2 = 0.109, P < 0.01, n = 89$), but there was no significant relationship between area burned in the central coast and south coast.

Climatic variables were mostly all highly correlated between these two regions. Average PDSI for the growing season (September–May) between the regions had an $R^2 = 0.263$, although spring and summer PDSI was much more strongly correlated, $R^2 = 0.506$ and 0.517, respectively. Precipitation patterns were more strongly correlated, with $R^2 = 0.601$ for the growing season; however, this was largely driven by similarity in winter and spring precipitation; for autumn $R^2 = 0.188$ and summer precipitation was not significantly correlated. Average temperatures for the growing season gave an $R^2 = 0.824$ but summer exhibited a weaker relationship with $R^2 = 0.466$.

Within both regions there was a highly significant ($P < 0.001$) correlation between winter PDSI and PDSI for spring, summer and autumn. Also, highly significant in both regions was the correlation between winter PDSI in year t and year $t+1$, but not for $t+2$. The same was true of autumn PDSI, but not for spring and summer.

For both regions autumn precipitation was highly significantly ($P < 0.001$) correlated with the subsequent winter precipitation and, in the south coast, winter was slightly ($P < 0.05$) correlated with spring precipitation. In the central coast region there was no significant relationship between winter precipitation and any of the subsequent seasons but, in the south, winter was slightly correlated with spring. Between years the only significant correlation was for winter precipitation in the central coast ($P < 0.05$). Temperatures were highly correlated between winter and spring and winter and summer in both regions. Between-year temperatures for winter, spring and autumn were not significant but in both regions summer temperatures between year t and year $t+1$ and $t+2$ were highly significant.

In both regions winter, spring and autumn PDSI had a highly significant ($P < 0.001$) positive correlation with precipitation during those seasons but not in summer. Also in both regions average spring temperature was negatively correlated with both PDSI and precipitation, but temperatures in other seasons showed no significant relationship.

PDSI, precipitation, temperature and fire activity

The relationship between annual fire occurrence and climate parameters of PDSI, precipitation, and temperature are shown in Table 1. For both the central coast and the south coast regions there was no significant relationship between growing season PDSI, precipitation or temperature and number of fires. When examined by season there were two slightly significant effects: in the central coast region summer temperatures were positively correlated with number of fires and in the south coast, autumn PDSI and precipitation were negatively correlated with fire occurrence.

Lag effects (Table 1) showed that for both regions the previous year's growing season PDSI and precipitation were positively correlated with fire occurrence. In the central coast fires were most strongly correlated with the previous winter's PDSI and in the south coast the previous year's spring PDSI was the strongest. For both regions summer PDSI in the previous year was positively correlated with fire occurrence and summer PDSI 2 years earlier was negatively correlated.

Table 2 presents the relationships between annual area burned and climate parameters. In the south coast region, area burned was not correlated with any current year climate variable. In the central coast region area burned was not correlated with growing season PDSI but there was a negative correlation with precipitation and temperature. In this region winter climate is not as relevant to area burned as is drought later in the year.

There was a slightly significant lag relationship between area burned and climate for both regions. Moist conditions in the winter (south) or spring (central) were correlated with increased area burned in the following year.

The generally low coefficient of determination or R^2 indicates relatively little of the variance in these data is explained by these regression models. In several instances R^2 values were greater when examined on a county by county basis. Also, when annual variation in this time series was smoothed by regressing decadal totals for fire activity *v.* climate variables, one county consistently exhibited very strong correlations. In Riverside County, 61% of the variation in area burned per decade could be explained by average autumn PDSI (Fig. 2). This pattern is very instructive because it illustrates one of the complications involved in relating climate parameters to burning in these human-dominated

Table 1. Number of fires *v.* seasonal averages of Palmer Drought Severity Index (PDSI), precipitation and temperature for central coast and southern California

Only significant regressions are reported. Because these are based on first-order differencing, sample size for this 89 year record is 88, or 87 for 1 year lag or 86 for 2 year lag. The growing season is from September to May. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$

	Central coast									South coast								
	PDSI			Precipitation			Temperature			PDSI			Precipitation			Temperature		
	r	R^2	P	r	R^2	P	r	R^2	P	r	R^2	P	r	R^2	P	r	R^2	P
Growing season																		
Winter																		
Spring																		
Summer							0.237	0.056	*									
Autumn										−0.219	0.048	*	−0.220	0.048	*			
1-year lag																		
Growing season	0.281	0.079	**	0.333	0.111	**				0.283	0.080	**	0.447	0.200	***			
Winter	0.355	0.126	***	0.317	0.101	**				0.293	0.086	*	0.487	0.237	***			
Spring	0.292	0.085	**							0.469	0.220	***	0.291	0.085	**			
Summer	0.244	0.060	*				−0.348	0.121	***	0.392	0.154	***						
Autumn										0.350	0.123	***						
2-year lag																		
Growing season													−0.219	0.046	*			
Winter							−0.211	0.044	*				−0.322	0.104	**			
Spring										−0.259	0.067	*				0.219	0.048	*
Summer	−0.284	0.070	**				0.219	0.048	*	−0.221	0.049	*	0.214	0.046	*			
Autumn																		

Table 2. Area burned *v.* seasonal averages of Palmer Drought Severity Index (PDSI), precipitation and temperature for central coast and southern California

Only significant regressions are reported. Because these are based on first-order differencing, sample size for this 89 year record is 88, or 87 for 1 year lag or 86 for 2 year lag. The growing season is from September to May. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$

	Central coast									South coast								
	PDSI			Precipitation			Temperature			PDSI			Precipitation			Temperature		
	r	R^2	P	r	R^2	P	r	R^2	P	r	R^2	P	r	R^2	P	r	R^2	P
Growing season				−0.226	0.051		−0.313	0.098	**									
Winter							−0.323	0.105	**									
Spring	−0.220	0.048	*	−0.248	0.062	*	−0.253	0.064	*									
Summer				−0.222	0.049	*												
Autumn	−0.303	0.092	**															
1-year lag																		
Growing season																		
Winter										0.245	0.061	*	0.298	0.089	**			
Spring				0.271	0.073	*	0.216	0.047	*									
Summer																		
Autumn																		
2–year lag																		
Growing season																		
Winter																		
Spring																		
Summer																		
Autumn																		

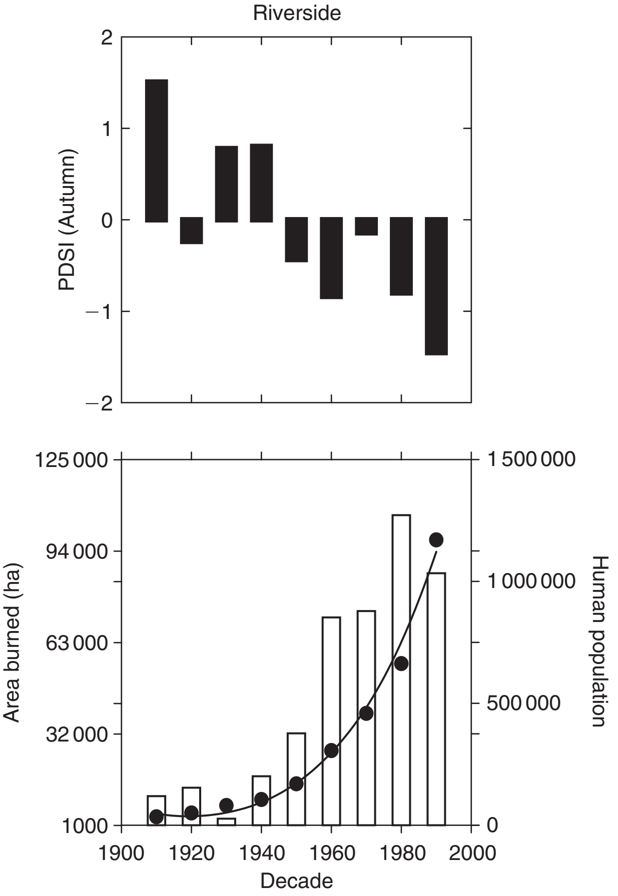

Fig. 2. Decadal variation in Palmer Drought Severity Index, area burned and human population for Riverside County. Population data USA Bureau of the Census, Washington, D.C., http://www.census.gov/population/cencounts/ca190090.txt, accessed Jan. 1999.

landscapes; namely, people play a critical role in controlling fire occurrence. If population growth for the county is overlaid (Fig. 2) it is apparent that area burned not only increases with more negative PDSI, but also with population growth. In this county population growth has grown at an exponential rate ($R^2 = 0.996$ for the semi-log model of log(population), and slightly more of the variance in area burned is explained by population size than by autumn PDSI ($R^2 = 0.68$, 0.61, respectively).

SOI, climate and fire

There was a strong teleconnection between the Southern Oscillation Index (SOI) and the drought index (PDSI) in the south coast region but a weaker connection in the central coast (Table 3). Despite this strong connection with the drought index in southern California, SOI exhibited no connection with fire occurrence and only a weak correlation with area burned, and no lag effects (Table 3). The connection between SOI and fire was somewhat stronger in the central coast region.

Antecedent climate and large fire events

The 89 year average PDSI for each month is shown along with 95% confidence limits and overlaid on top of this are all fires greater than or equal to 5000 ha (Figs 3 and 4). In both the central coast (Fig. 3) and south coast (Fig. 4), fires occurring during the autumn Santa Ana season were almost as likely to occur in mesic as well as xeric years. However, one pattern that emerges from both regions is that fires occurring early in the season and late in the season were invariably during years of drought.

This analysis suggested the hypothesis that climate–fire correlations may differ between fires in the summer and autumn. This hypothesis could not be tested across these regions because the Statewide Fire History Database does not consistently provide month of burning, typically being recorded for most large fires but, until recently, not for smaller fires. One exception is the Los Angeles County records, which are more detailed than other records in the CDF database. For this county the area burned by season, either summer (June–August) or autumn (September–November) were regressed against all climate parameters considered here. Regression analysis on these data indicated no evidence of autocorrelation so differencing was not utilized. Consistent with the pattern in Fig. 4, there was no significant relationship between climatic variables and area burned during the autumn fire season (September–November); however, during the summer fire season, area burned was negatively correlated with average summer PDSI ($R^2 = 0.045$, $P < 0.05$, $n = 88$).

Using climate variables to predict future fire activity

I explored the extent to which multiple regression, whcih includes more than one climate parameter, can be utilized to predict fire occurrence and area burned. One limitation in creating such models is that many of these climate variables are strongly correlated (see seasonal comparisons above) and create colinearity problems. Essentially all possible combinations of variables that did not exhibit colinearity were used in multiple regression analysis. The Durbin-Watson statistic indicated no significant autocorrelation in these data. For several of these models the correlation coefficients were markedly higher than for any of the simple linear regressions reported above; however in all cases the R^2, when adjusted for the number of parameters included, did not exceed any of the values given in Tables 1 and 2.

Alternatively, principal components regression allows use of more independent variables because colinearity is reduced or eliminated. Regressions involving both area or number of fires *v.* all reasonable combinations of antecedent weather parameters were tested. While these often generated very high correlation coefficients, the adjusted R^2 values were consistently equal to or lower than the highest R^2 values reported for simple linear regression in Tables 1 and 2.

Table 3. Teleconnections between the winter or autumn Southern Oscillation Index (SOI) and PDSI and fire activity for the central coast and southern California

Only significant regressions are reported. Because these are based on first-order differencing, sample size for this 89 year record is 88. SOI based on autumn + winter months showed weaker relationship to fire and is not presented. The growing season is from September to May. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$

	SOI autumn (beginning of growing season)			SOI winter			SOI autumn (1 year lag)			SOI autumn (2 year lag)			SOI winter (1 year lag)			SOI winter (2 year lag)		
	r	R^2	P	r	R^2	P	r	R^2	P	r	R^2	P	r	R^2	P	r	R^2	P
Central coast																		
PDSI																		
Winter							−0.310	0.096	**									
Spring	−0.265	0.070	*				−0.222	0.049	*									
Summer	−0.228	0.082	*				−0.272	0.074	**									
Autumn	−0.251	0.062	*															
No. of fires	−0.220	0.048	*													−0.311	0.097	**
Area burned																−0.384	0.148	***
South coast																		
PDSI																		
Growing season	−0.436	0.190	***	−0.325	0.106	**												
Winter	−0.387	0.149	***	−0.261	0.068	*												
Spring	−0.398	0.158	***	−0.314	0.099	**												
Summer	−0.346	0.120	***	−0.254	0.064	*												
No. of fires																		
Area burned	−0.215	0.046	*															

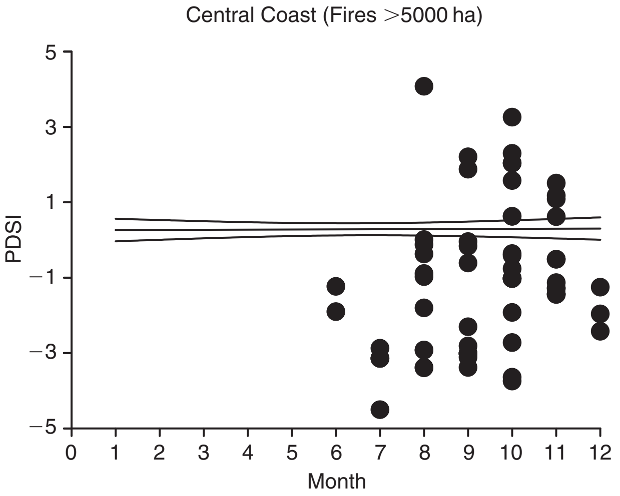

Fig. 3. Monthly Palmer Drought Severity Index Area (PDSI) averaged for 1895–2001 and 95% confidence limits (lines) and PDSI for the month of the largest (>5000 ha) fires (filled circles) recorded for the 20th Century from the central coast.

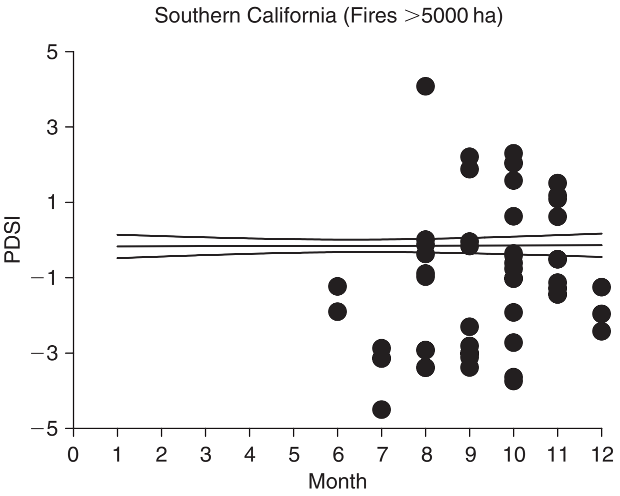

Fig. 4. Monthly Palmer Drought Severity Index Area (PDSI) averaged for 1895–2001 and 95% confidence limits (lines) and PDSI for the month of the largest (>5000 ha) fires (filled circles) recorded for the 20th Century from southern California.

A simpler approach to the problem of prediction is to ask whether or not climate variables can predict above-normal *v.* below-normal fire activity years. To do this, the 89 year mean and median for area burned and fire frequency were determined for each region. Results for the following analysis were very similar for the mean and median, so only the latter are reported here. Data were classified as a ‘high year’ if above and a ‘low year’ if below the median. Two-tailed *t*-tests were used to contrast climate variables for high and low fire years (Table 4). As with the regression analyses reported above, the central coast exhibited far more evidence of climate effects on fire activity, both during the current year as well as 1 and 2 year lag effects. Further illustrative of the lack of synchrony between these regions is the differences in how current year climate affects fire activity. In the central coast dry growing seasons are associated with fewer fires whereas in the south coast, dry conditions in autumn, long after the growing season, are associated with high fire occurrence and higher

Table 4. Average PDSI, precipitation and the SOI in years of high or low fire activity

Classified by whether the year fell above or below the median for number of fires or area burned. Growing season was September to May.
*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$

	Central coast						South coast					
	No. of fires			Area burned			No. of fires			Area burned		
	Low	High	P	Low	High	P	Low	High	P	Low	High	P
PDSI												
Autumn	–	–	–	–	–		0.504	−0.841	**	0.545	−0.820	**
Growing season	−0.122	0.816	*									
Growing season (1-year lag)	−0.413	1.118	***	−0.219	0.860	*						
Winter (1-year lag)	−0.603	1.329	***	−0.335	0.981	*						
Spring (1-year lag)	−0.554	1.394	***									
Summer (1-year lag)	−0.431	1.584	***									
Autumn (1-year lag)	−0.290	0.896	**									
Growing season (2-year lag)	−0.142	0.839	**									
Spring (2-year lag)				−0.217	1.032	*						
Summer (2-year lag)				−0.194	1.305	*	0.788	−0.415	*			
Precipitation (mm)												
Summer										11	6	*
Autumn										75	52	*
Growing season (1-year lag)	460	594	***									
Winter (1-year lag)	261	348	**									
Spring (1-year lag)				149	111	*						
Spring (2-year lag)				114	151	*				101	134	*
SOI												
Autumn	−0.828	0.418	*									
Winter				−2.876	0.811	*						
Winter (2-year lag)				0.934	−3.314	*						

acreage burned. One year lag effects are very prominent in the central coast but none were found for the south coast.

Discussion

Coastal California (Fig. 1) is an anomaly relative to much of the western USA in the lack of strong synchrony in fire–climate relationships between the south coast and central coast regions; fire occurrence is weakly correlated and area burned exhibits no significant correlation. One important driver is the difference in distribution of autumn foehn winds, which create what has been termed the 'worst fire conditions in the country' (Schroeder *et al.* 1964). In southern California large conflagrations are usually associated with these annual wind events that follow the long spring and summer drought. Increasing human presence in this region has undoubtedly increased the probability of ignitions during these severe fire weather events (Fig. 2). In southern California the main climatic determinant of area burned is autumn precipitation, which cuts short the annual drought and likely decreases the effectiveness of Santa Ana winds (Table 4).

In southern California the anomalous annual foehn wind conditions over-ride most climate signals. The extent of preceding drought is largely irrelevant to the size of these autumn fires because of the severity of weather during the fire event. Indeed the major fire years are not linked to years of drought (Fig. 4). For example, the largest fire year in southern California for the past 100 years was over 300 000 ha, which burned in the last week of October 2003, and precipitation for that year was above average (http://ols.nndc.noaa.gov/). This event, however, is dwarfed by a major event in the last week of September 1889, where it is estimated several times more area was burned in southern California (Barrett 1935), and precipitation was well above average that year as well. It has been widely cited that the magnitude of the recent 2003 fires was due in part to drought several years prior to the fires, and the creation of a greater volume of dead fuels. Indeed, the 2 years leading up to the fires of 2003 were far below normal and there was significant dieback in both shrublands and forests. However, it is an open question whether or not this had any impact on the size of these fires since they burned through substantial areas of young living fuels, which is consistent with the broader finding that fuel load appears to play a minor role in determining fire hazard on these landscapes (Moritz *et al.* 2004). Certainly these large fire events are not *dependent* upon prior droughts, as evident by the fact that the 3 years prior to the 1889 fires were years of average or above average rainfall.

Further north in the central coast, foehn autumn winds are less predictable (Moritz 1999, 2003; Keeley and Fotheringham 2003), and high summer temperatures are the best predictor of fire occurrence (Table 1) and low precipitation and high temperatures during winter, spring and summer are important determinants of area burned (Table 2). In this region Davis and Michaelson (1995) reported that fires generally ignite on days when the temperature is 3–5°C higher than the monthly average and large fires never originate on days when temperatures are <25°C at the Santa Barbara airport. Moritz (1999) found that large fires, defined as >4000 ha, were significantly correlated with days when the Santa Barbara airport temperature was >32°C.

One-year lag effects are much more strongly correlated with fire occurrence than the current year's climate, and in this respect these two regions exhibit some level of synchrony. In both regions high numbers of fires are predictable in years that are preceded by years with high rainfall and lack of drought (Table 1). As surmised from other studies (e.g. Swetnam and Baisan 2003; Westerling *et al.* 2003) it is very likely that this lag effect is the result of enhanced growing conditions increasing the level of herbaceous surface fuels, which in turn increase fire starts in the subsequent fire season. The lag effect in coastal California could be due to similar effects of precipitation on herbaceous growth. While much of the landscape that burns in fires is dominated by chaparral, ignitions most commonly occur in herbaceous vegetation along road corridors (Keeley and Fotheringham 2003). Herbaceous vegetation throughout these lower elevations in California is dominated by annuals that respond markedly to precipitation both in density and standing crop (Pitt and Heady 1978). These annuals cure rapidly in the mediterranean-climate summer droughts creating highly flammable fuel beds. Apparently in these wet years the annuals are not sufficiently cured by June, which is the peak month for fire occurrence (Keeley and Fotheringham 2003), and thus provide a substantial fuel bed for the following year.

Another potential lag effect could be that high fire activity in one year reduces fuels available for burning the next year. However, there is no evidence for this sort of effect since the moist conditions associated with the lag year are the opposite of the dry conditions conducive to burning during the fire year (Tables 1 and 4). In addition, area burned exhibited little or no autocorrelation between adjacent years and lag effects were weak for area burned (Tables 2 and 4).

Currently there is a great deal of interest in developing these fire–climate relationships into predictive tools useful to fire managers (Kitzberger 2002; Westerling *et al.* 2002). The extent to which this is possible in the southern and central coastal regions of California requires close examination. Despite statistically significant relationships between PDSI and fire activity, PDSI does not have high predictive power; typically it explains 5–10% of the variance and the highest observed was 22% for previous year's PDSI and fire occurrence.

However, while precise predictions of future fire activity may be poor, it might be useful if managers could at least predict whether or not the coming fire season would be abnormally high or low. This sort of analysis (Table 4) suggests that there may be a number of antecedent climate indicators available for predicting fire activity in the central coastal region but not for southern California. In the central coast region there are strong differences in lag year PDSI (and precipitation) preceding years of high and low fire occurrence, but fewer and weaker indicators for area burned. Knowledge about the expected magnitude of fire numbers at the beginning of the season may be valuable in planning efforts for local and regional fire managers. In contrast, the primary climatic indicators for fire activity in southern California are those immediately preceding fires.

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