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Different historical fire–climate patterns in California

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Abstract. The relationship between annual variation in area burned and seasonal temperatures and precipitation was investigated for the major climate divisions in California. Historical analyses showed marked differences in fires on montane and foothill landscapes. Based on roughly a century of data, there are five important lessons on fire–climate relationships in California: (1) seasonal variations in temperature appear to have had minimal influence on area burned in the lower elevation, mostly non-forested, landscapes; (2) temperature has been a significant factor in controlling fire activity in higher elevation montane forests, but this varied greatly with season – winter and autumn temperatures showed no significant effect, whereas spring and summer temperatures were important determinants of area burned; (3) current season precipitation has been a strong controller of fire activity in forests, with drier years resulting in greater area burned on most United States Forest Service (USFS) lands in the state, but the effect of current-year precipitation was decidedly less on lower elevation California Department of Forestry and Fire Protection lands; (4) in largely grass-dominated foothills and valleys the magnitude of prior-year rainfall was positively tied to area burned in the following year, and we hypothesise that this is tied to greater fuel volume in the year following high rainfall. In the southern part of the state this effect has become stronger in recent decades and this likely is due to accelerated type conversion from shrubland to grassland in the latter part of the 20th century; (5) the strongest fire–climate models were on USFS lands in the Sierra Nevada Mountains, and these explained 42–52% of the variation in area burned; however, the models changed over time, with winter and spring precipitation being the primary drivers in the first half of the 20th century, but replaced by spring and summer temperatures after 1960.

Additional keywords: area burned, chaparral, climate change, forests, grasslands, ignitions, seasonal temperatures.

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Introduction

Wildfires have increased in western USA forests over the past several decades, and these changes are often attributed to a combination of climate change and past fire suppression (Westerling *et al.* 2006; Littell *et al.* 2009; Miller *et al.* 2009). However, a pattern of increasing fires is not universally applicable because some non-forested landscapes have not experienced increases in fire activity (Baker 2013) and appear to be less sensitive to annual climate variation (Keeley and Syphard 2015). Some of the variation in response is potentially due to different fire activity metrics: for example, Keeley and Syphard (2015) reported area burned per unit area protected, Westerling *et al.* (2014) used number of fires >200 ha or >400 ha (Westerling *et al.* 2006), and Barbero *et al.* (2015) used number of fires >5000 ha. Usually, number of large fires is interpreted as a surrogate for area burned; however, in California, number of fires >400 ha is only moderately correlated with annual area burned ($r^2 = 0.49$, $P < 0.001$ for the years 1963–2013) (Keeley and Syphard 2016). Regardless of the metric, research supports the conclusion that wildfire activity in the western USA is not uniform and different regions respond to different environmental drivers (Parisien *et al.* 2012).

It is of particular interest how these patterns of fire activity may play out in future fire regimes during an era of global change, and it is unlikely there will be universal rules governing this response across diverse landscapes (Parisien *et al.* 2012). Forecasting how global warming may influence future fire regimes has been addressed through modelling efforts that validate results based on limited historical data of fire–climate relationships (e.g. Krawchuk *et al.* 2009) and simplifying assumptions such as no ignition limitations (Moritz and Knowles 2016). The validity of such modelling approaches hinges on an understanding of the historical relationships between fire and climate in different ecosystems. It is widely recognised that more detailed study of historical patterns of how climate variation has affected fire activity is needed if we are to make adequate predictions about future climate change effects on fire regimes (McKenzie *et al.* 2004; Safford *et al.* 2012).

Indeed, Doerr and Santin (2016) maintain that many of the reports on western USA trends in fire activity are based on insufficient time to be reliable indicators of future fire patterns.

Complicating this issue is the fact that western USA landscapes vary geographically in their fire–climate relationships (McKenzie *et al.* 2004; Gedalof *et al.* 2005; Collins *et al.* 2006; Littell *et al.* 2009). Generalisations that temperature anomalies across the western USA are correlated with increased number of large fires (Westerling *et al.* 2014) are often interpreted as indicative of changing fire patterns. However, when considering all of the western USA, or similar large regions spanning a significant latitudinal range (e.g. Abatzoglou and Williams 2016), such analyses potentially confound spatial and temporal patterns (Keeley and Syphard 2016). Thus, it is our contention that to parse out climate from other factors affecting fire regimes we need to focus on historical fire–climate relationships within more climatically homogeneous subregions. California provides a unique landscape for addressing questions of how fire–climate patterns vary geographically and ecologically across different climate divisions. It has a substantially larger latitudinal and elevational range and greater diversity of fire-prone plant communities than other western USA states. Also, a long record of fire history data (over a century for some agencies) is available for both montane coniferous forests and lower elevation, mostly non-forested, landscapes (Keeley and Syphard 2015).

The National Oceanic and Atmospheric Administration (NOAA) has divided California into regions of climatically homogeneous divisions that provide a useful basis for both geographical and ecological fire patterns within the state. These records also illustrate that year-to-year variation in seasonal temperatures over the past century has been at least as large as the expected changes under future global warming scenarios. For example, Deser *et al.* (2012) predict that by 2060, global temperatures in summer will increase 2–3°C and winter temperatures by 2–6°C, with the greatest changes in winter at the highest northern latitudes and in summer mostly at temperate and subtropical latitudes. Over the past century this degree of change has been observed in the year-to-year variation in seasonal temperatures in California; see for example the seasonal temperatures observed over an 84-year period in a California site (see Table S1 available as online supplementary material). Thus, tying annual fire activity to seasonal patterns of temperature and precipitation may provide insights into future potential fire regimes. This paper compares the annual variation in seasonal temperatures and precipitation with the annual changes in area burned for the five most fire-prone climate divisions on forested and non-forested landscapes.

Methods

Annual summaries of area burned and number of fires by cause were analysed separately for lands protected by the higher elevation federal US Forest Service (USFS) and lower elevation state-protected California Department of Forestry and Fire Protection (Cal Fire) lands. This comprises a substantial sampling of the state but some significant landscapes such as the National Park Service and Bureau of Land Management lands are not included due to their more limited fire record. It is important to recognise that the USFS manages national forests for multiple use. Cal Fire, on the other hand, is responsible for providing fire protection for mostly private lands and state parks. USFS fire data covered 17 national forests and included the years 1910–2013, spatially explicit at the level of the national forest. Cal Fire data covered direct protection areas, which are mostly state responsibility lands with smaller amounts of federal lands, and included the years 1919–2013, spatially explicit at the county level. Only 30 counties had data sets we deemed sufficient to analyse temporal trends, arbitrarily designated as having data for 95% of the years between 1919 and 2013 (all counties were missing 1927). An additional 21 counties had significant gaps in the data set so they were not used to examine temporal patterns but were used for the analysis of fire–climate relationships (years of data for each county by climate division are in Table S2). Data for USFS lands were available from the University of California, Berkeley Biosciences Library. Cal Fire data from 1931 to 2013 were available in the annually published *Redbook* series available from research libraries or directly from the agency, but data from 1919 to 1930 are unpublished and were obtained from the California State Archives in Sacramento.

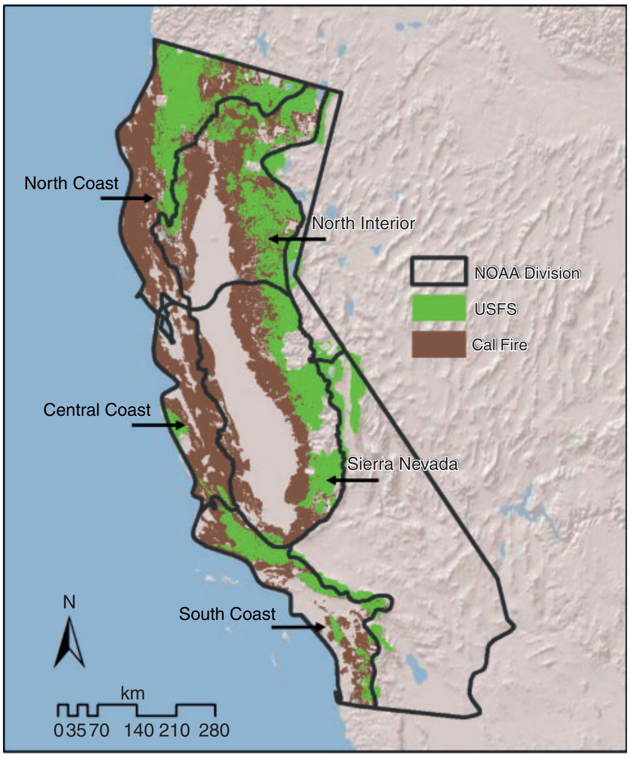

Fig. 1. California's five most fire-prone National Oceanic and Atmospheric Administration (NOAA) climate divisions with United States Forest Service (USFS) forest lands (green) and Cal Fire protected lands (brown) highlighted. (For colour figure, see online version available at http://www.publish.csiro.au/nid/17.htm.)

The USFS and Cal Fire lands used in this study are illustrated in Fig. 1. In 1910, this landscape comprised 9.8 million ha of USFS lands (decreased to 9.5 in 2013) and a somewhat greater

Table 1. Mean latitude, distance from coast, elevation and vegetation for United States Forest Service (USFS) and Cal Fire protected lands within the five climate divisions

Only vegetation burned during the period of study (1919–2013) was available for Cal Fire lands

	Latitude (°)		Coast (km)		Elevation (m)		Vegetation (%)[A]								Area burned by type (%)		
	USFS	Cal Fire	USFS	Cal Fire	USFS	Cal Fire	USFS				Cal Fire				Cal Fire		
							Conifer	Hdwd	Shrub	Grass	Conifer	Hdwd	Shrub	Grass	Forest	Shrub	Grass
North Coast	40	39	75	50	1320	540	72	6	15	3	52	20	7	16	33	42	25
North Interior	41	40	220	170	1800	740	69	7	17	3	35	27	12	18	24	40	36
Sierra Nevada	38	37	255	165	2190	500	57	12	17	4	8	29	7	49	10	33	57
Central Coast	35	37	35	28	1345	430	4	24	69	4	6	29	17	43	12	51	37
South Coast	34	34	85	55	1550	660	12	10	73	2	2	14	49	19	2	81	17

[A]Other categories (e.g. barren, agricultural) not listed.

area of Cal Fire protected lands (11.7 million ha in 1919, increased to 12.5 in 2013). Area protected sometimes changed from year to year and these changes were utilised in our analysis. One exception was the area protected by Cal Fire during most of the 1940s, which was not recorded in the annual reports and we were unable to find these data in Cal Fire records or the state archives; thus, for those years we utilised the last known values for area protected in 1939. Comparisons of mean latitude, distance from coast and elevation for USFS and Cal Fire lands are presented by climate division in Table 1. In all divisions, USFS lands were more interior and at a higher elevation than Cal Fire protected lands.

The GIS map of areas protected by USFS and Cal Fire were overlaid on a vegetation map for the state (http://frap.fire.ca.gov/data/statewide/FGDC_metadata/fveg15_1.xml, accessed 13 February 2017) and the proportion of major vegetation types presented in Table 1. In the Sierra Nevada and further north, the USFS lands comprised mostly coniferous forests, whereas in central and southern California the bulk of the USFS lands were dominated by chaparral, grasslands and oak woodlands. Cal Fire lands in the northern part of the state had a third to half of the landscape covered by conifer forests but conifer forests were a minor part of Cal Fire lands in the rest of the state. Area burned by vegetation type was available in the Cal Fire annual reports, but not in the USFS reports, and is presented in *Annual fire–climate relationships* below.

Fire histories were investigated in climatically homogenous areas as defined by NOAA's National Climatic Data Center (Guttman and Quayle 1996). Homogeneity is a relative term and within any division, some parameters (e.g. temperature) may exhibit greater or lesser homogeneity than others (e.g. precipitation). Despite some limitations to these climate divisions (Vose *et al.* 2014), this analysis provides a finer climate division than used in prior studies (e.g. Westerling *et al.* 2006; Littell *et al.* 2009; Abatzoglou and Williams 2016). The five California climate divisions that comprised the fire-prone landscapes in the state were, from north to south, Division 1 (North Coast), 2 (North Interior), 5 (Sierra Nevada), 4 (Central Coast) and 6 (South Coast). For analysis, all USFS forests and Cal Fire counties were assigned to one of the five NOAA climate divisions (Fig. 1). Where these forests or counties overlapped with more than one division they were assigned to the division in which the majority of their land area occurred. To capture the long-term pattern of burning in the state we made decadal summaries of area burned and number of fires, and evaluated the trends using least squares regression. These decadal averages did not require log transformation. We also calculated the temporal patterns of area burned by year and these data required log transformation to meet assumptions of least squares regression.

To evaluate climate effects on fire activity we utilised PRISM climate for the USFS lands and the Cal Fire lands separately (Fig. 1). For every year in the analysis, we extracted 2.5 arc-minute PRISM data (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, accessed 15 January 2014) for areas within the boundaries of the Cal Fire and USFS regions. For each region and year, we computed area-weighted averages of monthly mean precipitation and temperature within each forest and county.

Least squares regression was used to model the response of annual area burned to climate variables of mean temperature and precipitation. These were analysed separately by season: winter = December (previous year), January, February; spring = March, April, May; summer = June, July, August; autumn = September, October, November. The substantial annual variation in area burned required this response variable be log-transformed to meet linear regression assumptions. We also examined maximum seasonal temperatures but these were only presented for those few cases where they demonstrated a marked difference from mean temperature. Regressions of area burned with monthly mean and maximum temperatures were also performed and where significant they are reported as well. The Durbin–Watson D statistics were all between 1 and 2, indicating no first order autocorrelation of residuals. These analyses were conducted with Systat 11.0 software (http://www.systat.com/, accessed 7 March 2017).

We recognised that area burned was likely controlled by multiple variables and developed multivariate models that included mean temperature for each season, total annual precipitation and prior-year (winter and spring) precipitation variables. We considered all possible combinations of the predictor variables and used AICc to rank and select the best supported models for each region using package MuMIn in R (Burnham and Anderson 2002; R Development Core Team 2012). To ensure multicollinearity would not be an issue, we calculated correlation coefficients among all potential explanatory

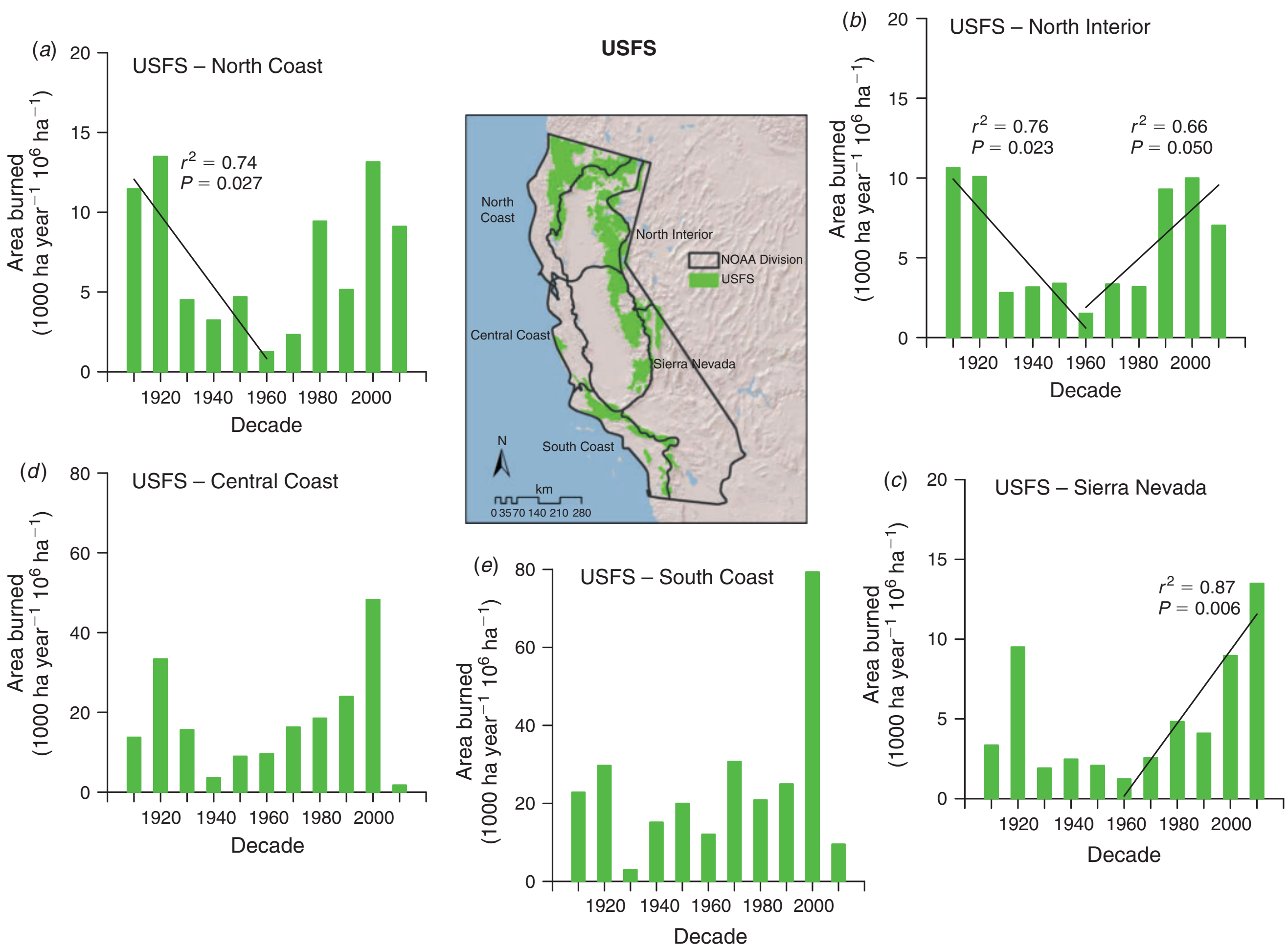

Fig. 2. Decadal burning on USFS lands in California climate divisions. Note *y*-axis scale change in (*d*) and (*e*).

variables and none were strongly correlated (r < 0.5). In addition, we calculated the variance inflation factor, which ranged from 1.0 to 1.7, indicating very little of the variance in adjusted R^2 was due to collinearity (Montgomery *et al.* 2001). The predicted residual error sum of squares (PRESS) statistic was calculated to provide a cross-validation of model fit and this is discussed along with the models.

Results

Historical trends

On USFS lands throughout the state there were high levels of area burned in the 1920s and then again in the early 21st century (Fig. 2). Area burned in the most recent decade was generally lower than in the previous two decades, but it represented only the first four years of the decade, thus biasing the data by a smaller sample size; because of this, to avoid further bias, all the decadal data were presented as area burned per year. All five of the divisions exhibited a trend towards decreased area burned during the first 50 years of the record but increased area burned in the last half of the record. However, these data were not always statistically significant; for example, the two northern California divisions (Fig. 2*a*,*b*) showed a significant decline during the first half of the century and a significant increase during the second half of the record in the two interior divisions (Fig. 2*b*, *c*). These data were also analysed by year and exhibited the same patterns, but for most divisions the trends of decreased burning in the first half of the record and increased burning in the second half were statistically significant (Table S3).

Cal Fire protected lands also showed substantial burning in the 1920s (Fig. 3) and a significant decline through the rest of the historical record, with a notable exception being the South Coast. The South Coast (Fig. 3*e*) differed from the rest of the state in having substantial peaks in the 1940s and the first decade of the 21st century. These patterns are further supported by the annual analysis (Table S3) that showed that only within the South Coast division was there any evidence of an increase in area burned in recent years. Throughout the state, the majority of burning on Cal Fire lands occurred in non-forested vegetation, primarily shrublands and grasslands (Table 1).

Very little of the variation in annual area burned is obviously correlated with patterns of ignitions (Fig. 4). All regions exhibited very similar temporal patterns of ignition frequency and so these are presented as state-wide totals by decade. Both USFS and Cal Fire protected lands had the lowest number of fires in the early record but ignitions began to increase in the

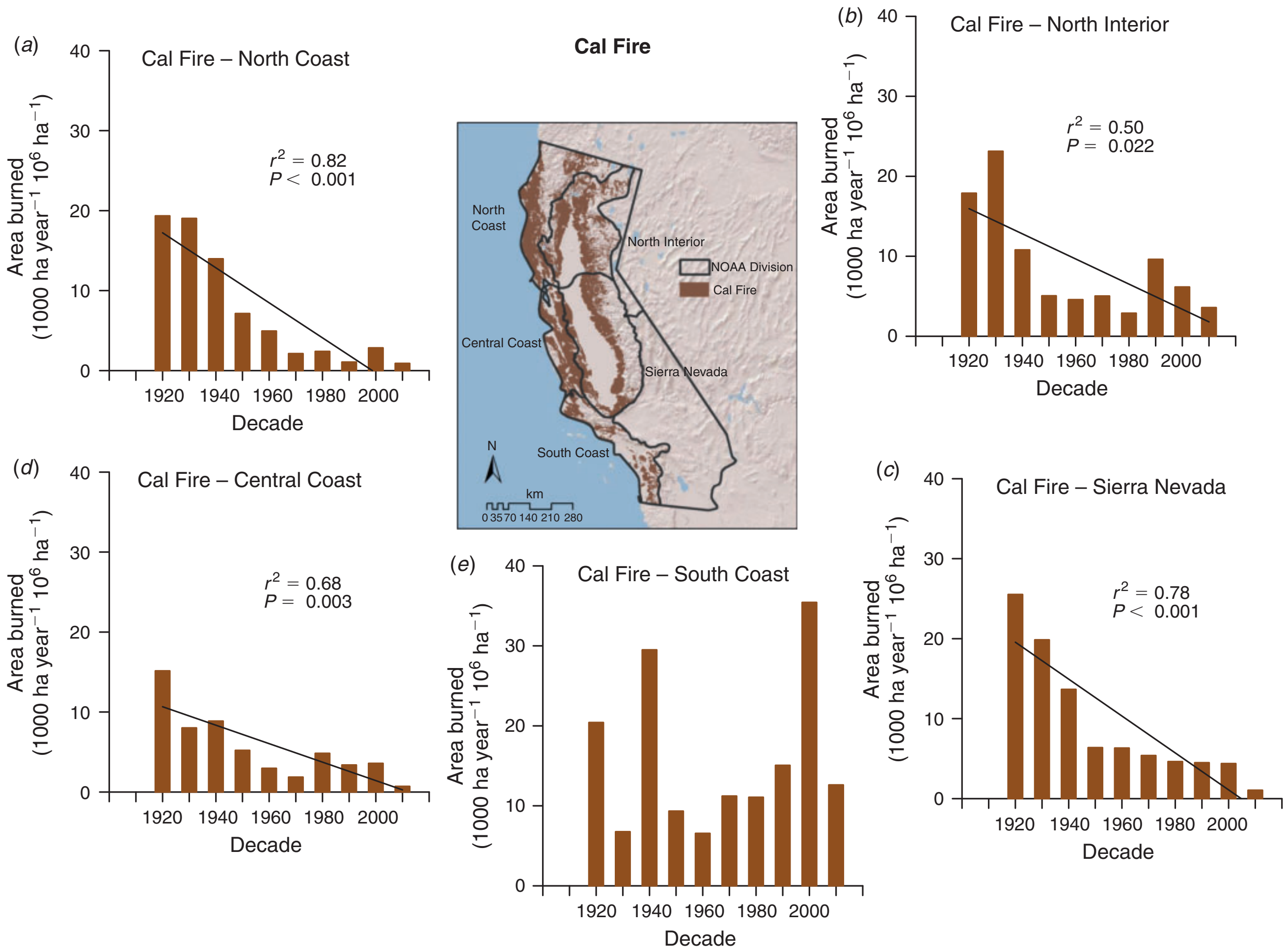

Fig. 3. Decadal burning on Cal Fire protected lands in California climate divisions.

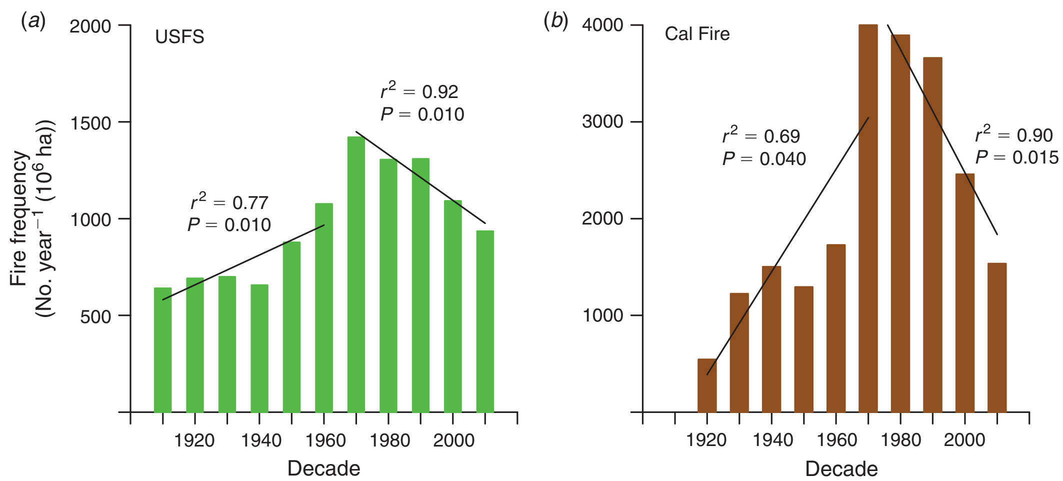

Fig. 4. Decadal patterns of ignitions on (*a*) USFS and (*b*) Cal Fire lands.

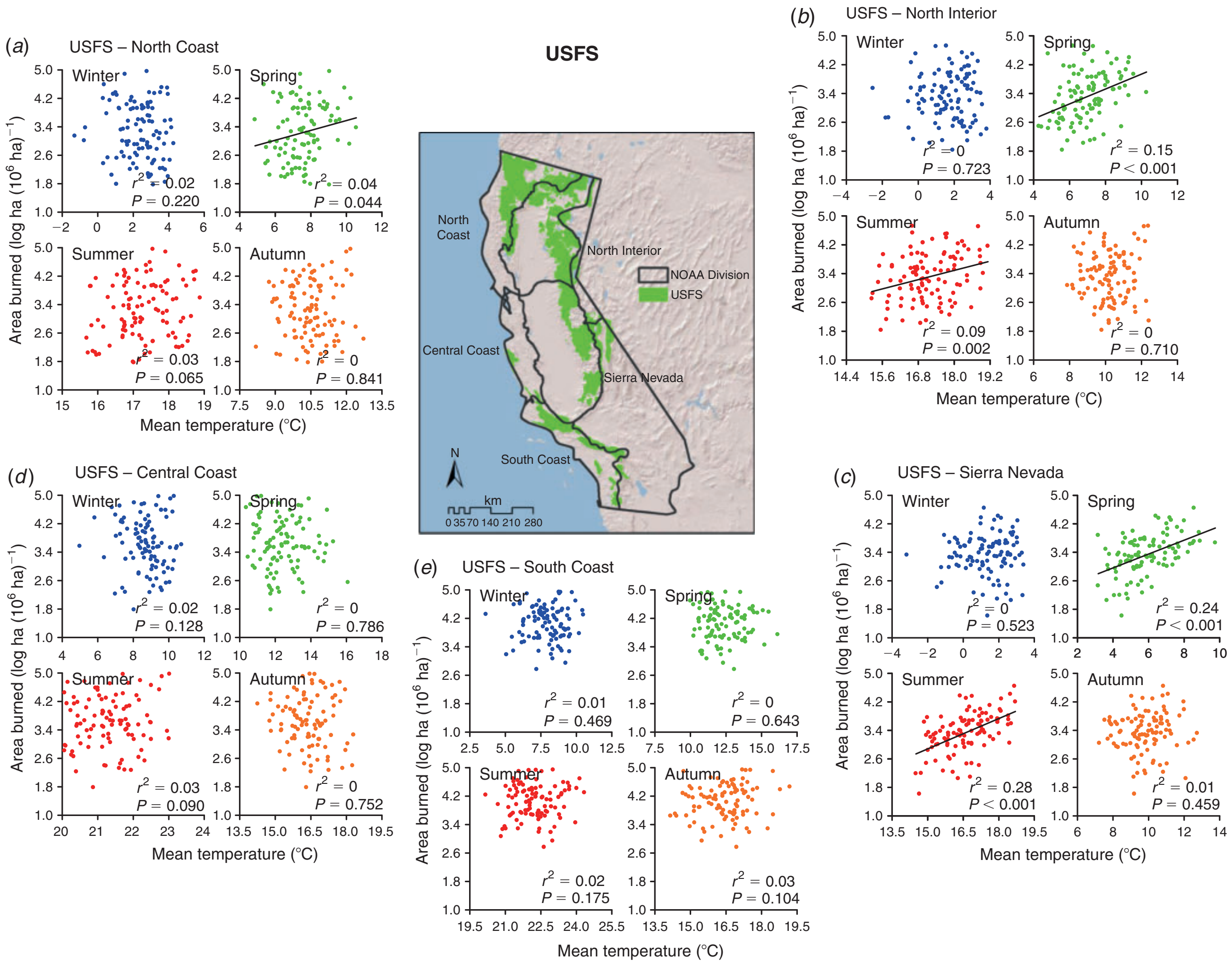

Fig. 5. Relationship of area burned and mean seasonal temperature for USFS lands (1910–2013) by climate division: winter = December–February; spring = March–May; summer = June–August; autumn = September–November.

1960s and peaked between 1970 and 1990, subsequently declining on both USFS and Cal Fire lands.

Annual fire–climate relationships

For all of these analyses, we compared annual fire activity with both seasonal and monthly climate parameters. The monthly analysis provided results comparable with seasonal data, although r^2 values for the three months within each season were in most cases lower than seasonal values. Thus, the presentation here focused on fire response to seasonal patterns of temperature and precipitation.

When seasonal mean temperature and precipitation were analysed for the entire state, winter, spring, summer and autumn all showed significant relationships with log area burned for both USFS and Cal Fire lands (not shown). However, as illustrated in the following presentation, when analysed within each of the five climatically homogenous divisions, these state-wide patterns did not hold up, illustrating the need for finer-scale analysis.

For example, at the scale of climate divisions, mean winter temperature and area burned were not significantly related for any division on either USFS (Fig. 5) or Cal Fire (Fig. 6) lands, and the same was true for maximum winter temperature (not shown). On USFS lands spring temperature was only slightly significantly correlated with area burned in the North Coast ($r^2 = 0.04$, Fig. 5*a*), but more strongly correlated in the North Interior and Sierra Nevada ($r^2 = 0.15$, 0.24, Figs 5*b*, *c*, respectively), and in all three of these divisions mean April temperature contributed most to this relationship (not shown). Mean summer temperature was also only slightly significantly related to area burned in the North Interior ($r^2 = 0.09$, Fig. 5*b*), but more strongly a factor in the Sierra Nevada ($r^2 = 0.28$, Fig. 5*b*, *c*). Although the North Coast had no significant relationship between mean summer temperature and area burned (Fig. 5*a*), there was a significant positive relationship with maximum summer temperature ($r^2 = 0.11$, $P < 0.001$; not shown). Maximum summer temperature was significantly related to area burned in all three northern divisions; June was highest, followed by July and then August (not shown).

In the two USFS divisions in the south, mean seasonal temperatures had no significant relationship with area burned

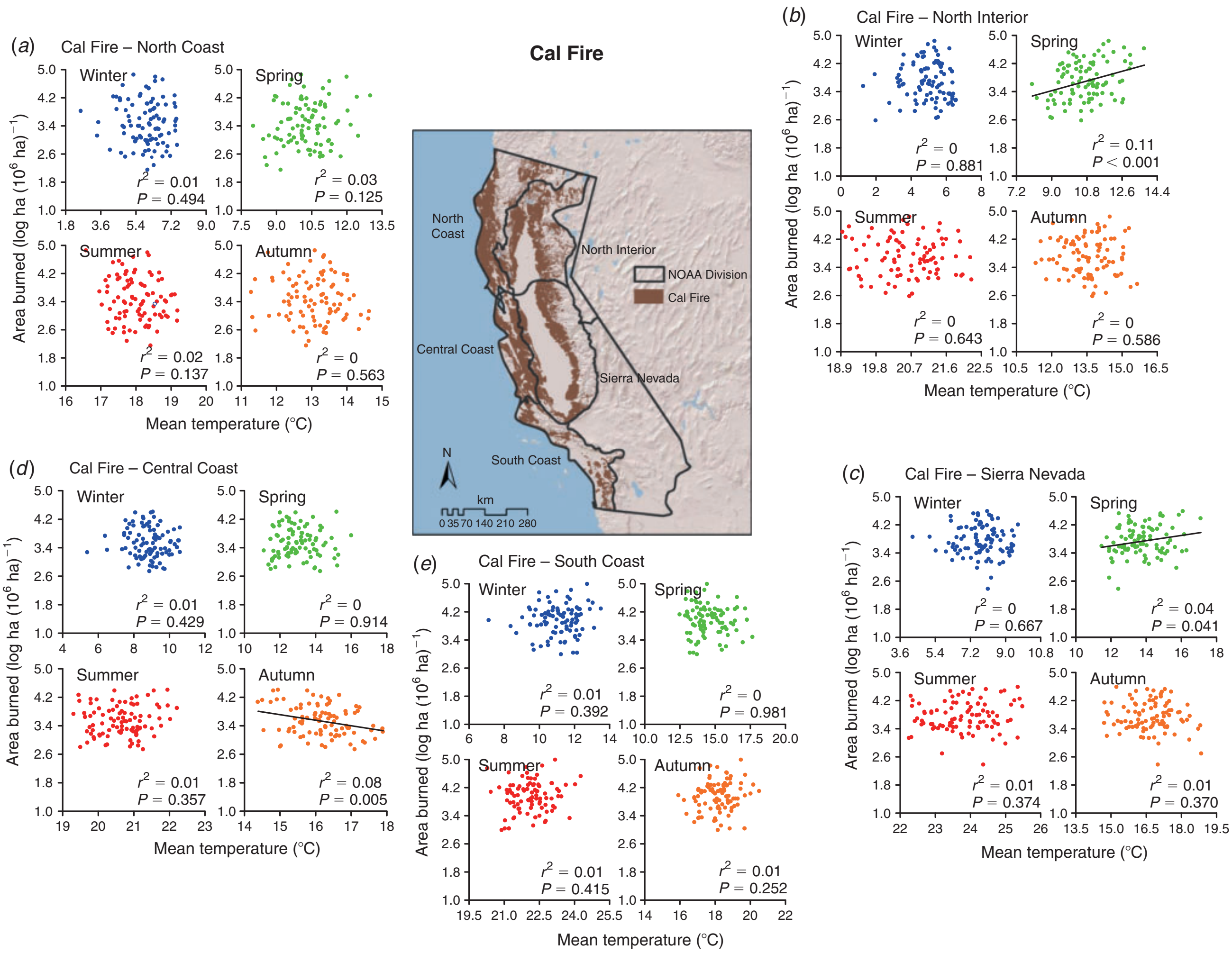

Fig. 6. Relationship of area burned and mean seasonal temperature for Cal Fire protected lands (1919–2013) by climate division: winter = December–February; spring = March–May; summer = June–August; autumn = September–November.

(Fig. 5*d*, *e*). Maximum temperatures were slightly correlated but explained very little of the annual variation in area burned in a couple of cases: maximum temperature in June in the Central Coast ($r^2 = 0.05$, $P = 0.028$) and September in the South Coast ($r^2 = 0.06$, $P = 0.012$).

On the lower elevation Cal Fire protected landscapes, mean seasonal temperature was not strongly tied to area burned in any of the divisions (Fig. 6). In the North Interior and Sierra Nevada there was a slightly significant relationship with mean spring temperature ($r^2 = 0.11$ and 0.04, Fig. 6*b*, *c*) and this was due entirely to May temperature, both mean and maximum (not shown). These relationships were much stronger in these two divisions when area burned on only 'forested' Cal Fire lands was compared with mean spring temperature (North Interior $r^2 = 0.21$, $P < 0.001$; Sierra Nevada $r^2 = 0.11$, $P < 0.001$).

Summer temperatures on Cal Fire protected lands were not significantly related to area burned (including when forested lands were analysed separately) (Fig. 6). However, in the Sierra Nevada foothills, maximum July temperature was significantly related to area burned ($r^2 = 0.16$, $P < 0.001$). In the Central Coast, mean summer temperature was not significant (Fig. 6*d*) although there was a slight correlation with mean June temperature ($r^2 = 0.06$, $P = 0.029$) and with maximum July temperature ($r^2 = 0.14$, $P < 0.001$), and a slightly negative relationship with autumn temperature ($r^2 = 0.08$, Fig. 6*d*), driven by mean October temperature (not shown). Cal Fire lands in the South Coast showed no relationship between area burned and mean or maximum temperatures in any season (Fig. 6*e*) or any month (not shown).

Patterns of seasonal precipitation varied markedly from temperature patterns, in that winter conditions were significant in determining fire activity on most USFS lands ($r^2 = 0.08$, 0.08, 0.06, 0.06; Fig. 7*a*, *b*, *c*, *d*). This negative relationship was also observed with spring precipitation in the Sierra Nevada and northward ($r^2 = 0.07$, 0.12, 9.21; Fig. 7*a*, *b*, *c*), and summer precipitation in the Sierra Nevada and northward ($r^2 = 0.11$, 0.13, 0.04; Fig. 7*a*, *b*, *c*). The only exception to these patterns was the South Coast where winter, spring and summer precipitation were not related to fire activity, and autumn precipitation was only slightly significant ($r^2 = 0.04$, Fig. 7*e*). For the four

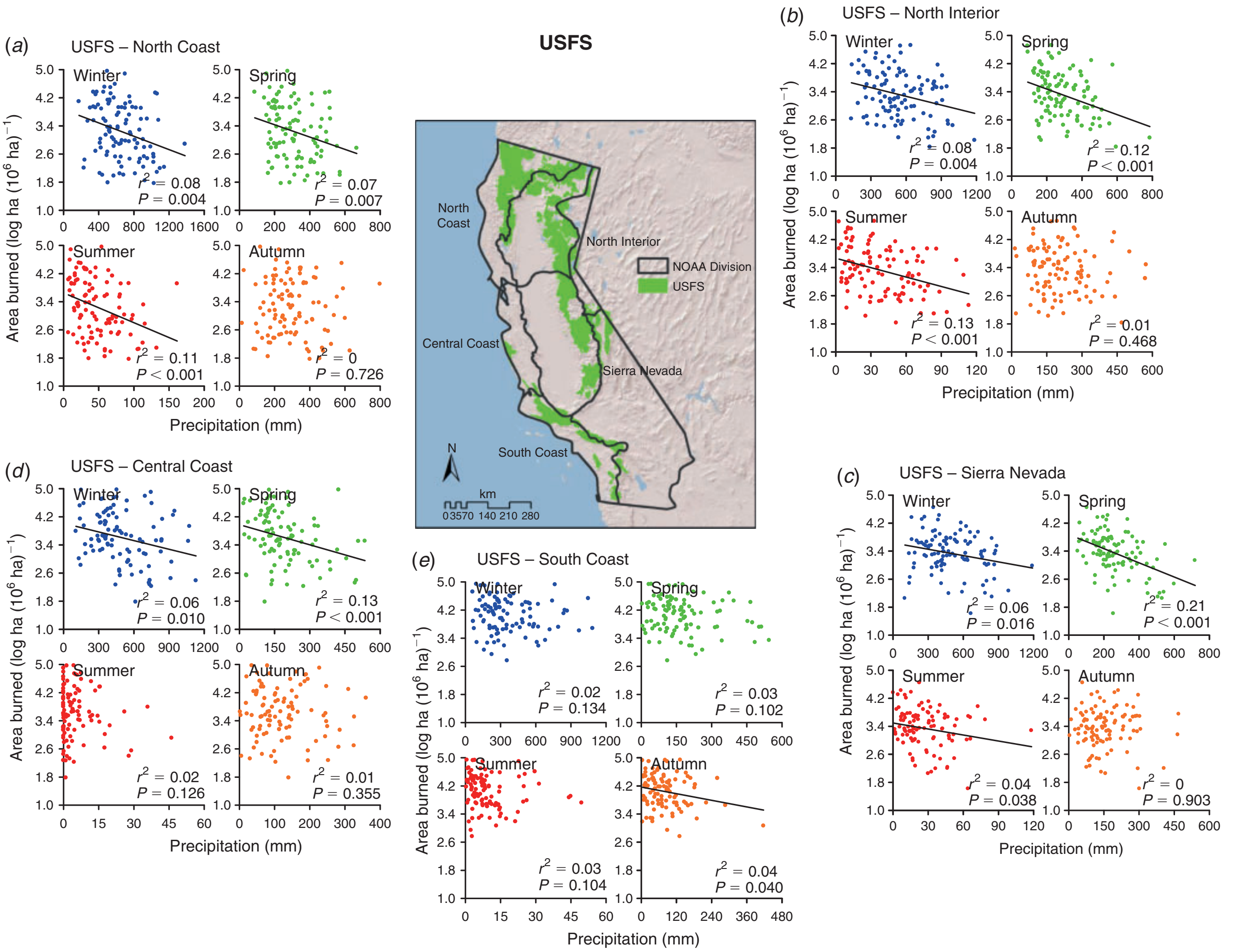

Fig. 7. Relationship of area burned and seasonal precipitation for USFS lands (1910–2013) by climate division: winter = December– February; spring = March–May; summer = June–August; autumn = September–November.

divisions where spring precipitation was significant, individual months that were significant varied between the coast and the interior: for the North Coast and Central Coast, April and May were significant, whereas in the North Interior and Sierra Nevada, March and April were significant (not shown). During the summer, June precipitation was important in the two northern divisions but in the Sierra Nevada, August precipitation alone had an r^2 twice that of the summer value (not shown).

On Cal Fire lands, winter precipitation showed a slightly significant effect in the northern California divisions ($r^2 = 0.05$, 0.12; Fig. 8*a*, *b*) and spring precipitation ($r^2 = 0.12$, 0.17; Fig. 8*a*, *b*), but not in the Sierra Nevada (Fig. 8*c*). This effect was substantially larger when only forested Cal Fire lands were examined (for spring precipitation, North Coast $r^2 = 0.24$, $P < 0.001$; North Interior $r^2 = 0.23$, $P < 0.001$; Sierra Nevada $r^2 = 0.14$, $P < 0.001$).

In addition to current-year climates, we investigated the potential for lag effects by prior-year precipitation. This analysis revealed that on USFS lands, the only significant result was a weak positive relationship between area burned and prior-year precipitation in the South Coast ($r^2 = 0.05$, $P = 0.027$). On Cal Fire lands, this relationship was weakly significant in both the Sierra Nevada ($r^2 = 0.08$, $P = 0.006$) and South Coast ($r^2 = 0.07$, $P = 0.011$).

These bivariate regressions with temperature and precipitation provide a first cut analysis of where climate may play the biggest role in determining area burned; however, even in divisions where they are significant they seldom explained more than a quarter of the variation in area burned. Where climate does limit fire activity we would expect it to be controlled by the interaction of multiple climate parameters. As the interaction between temperature and precipitation is likely more important than these parameters alone, we investigated multivariate models using all the potentially relevant climate parameters in AIC model development.

Considering the full 104-year record, USFS lands in the northern part of the state exhibited the strongest models, with spring temperature being the most informative parameter (Table 2). For the two southern divisions the models were weaker and the strongest parameter was prior-year precipitation.

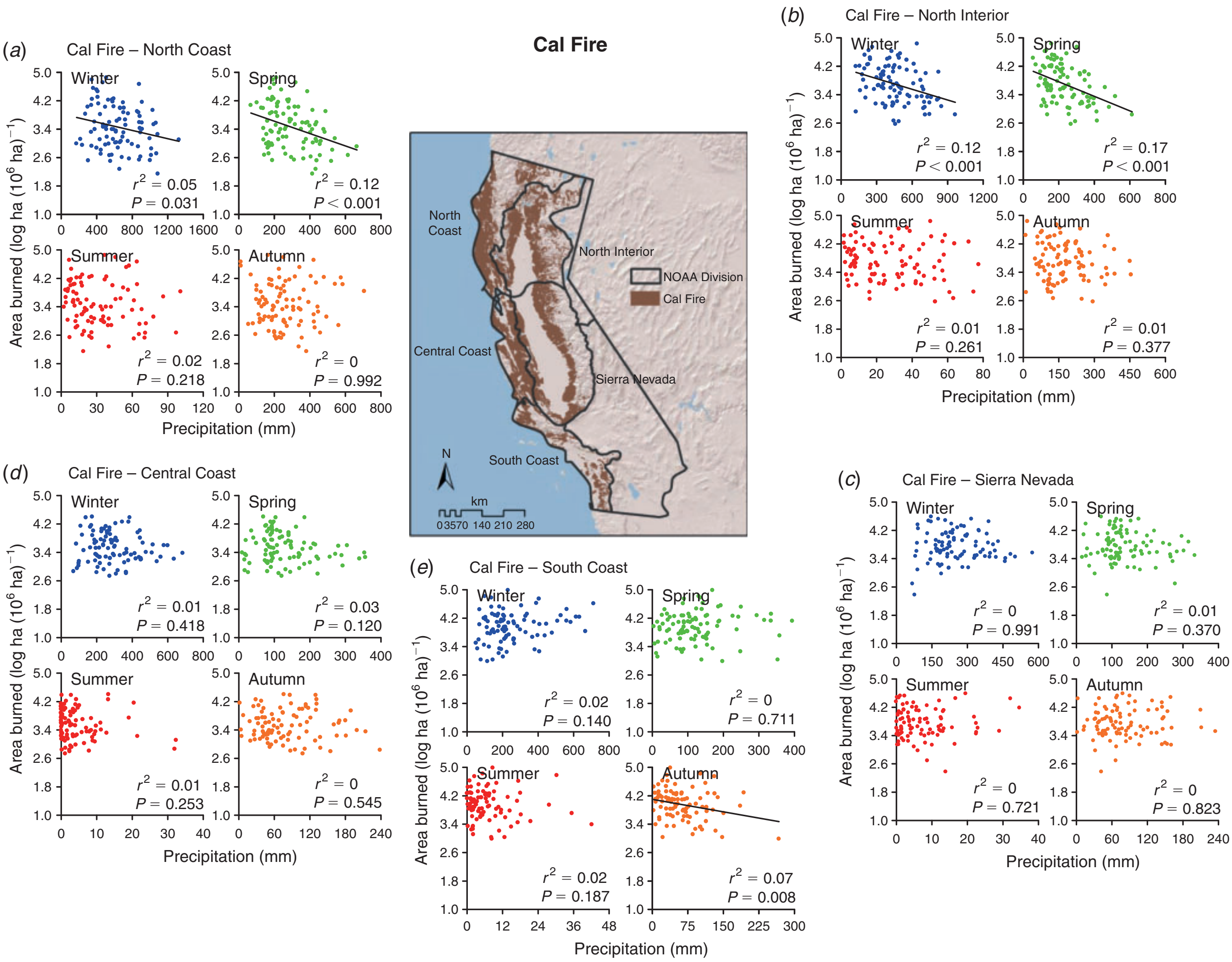

Fig. 8. Relationship of area burned and seasonal precipitation for Cal Fire protected lands (1919–2013) by climate division: winter = December–February; spring = March–May; summer = June–August; autumn = September–November.

When USFS data were broken down into the first part of the 20th century *v.* the last half of the record, models all produced higher R^2 values and often very different models between the first and second half of the record. For example, in the Sierra Nevada during the years 1910–1959 the R^2 value was 0.42 and the model was driven entirely by winter and spring precipitation. However, from 1960 to 2013, precipitation was replaced by spring and summer temperatures as the drivers of area burned, with $R^2 = 0.52$. Another obvious change over time in climate models was the emergence of prior-year precipitation in the Central Coast and South Coast as the most important determinant of area burned in the second half of the record (Table 2). The change in fire–climate relationships over time is reflected in the PRESS statistic. Over the entire period 1910–2013 this statistic was very high, indicative of relatively limited predictability of the model. However, it was substantially lower for models developed separately for early *v.* late parts of the 20th century, indicating greater predictability of these models.

Across the entire period of record, Cal Fire lands exhibited the weakest R^2 values but these increased when sorted by early *v.* late; however, the models changed between the first and second half of the record (Table 2).One striking pattern was the common response of area burned in the last half century on Cal Fire lands in the Sierra Nevada, Central Coast and South Coast being most strongly controlled by prior-year precipitation. This was also observed on USFS lands in the Central Coast and South Coast.

Discussion

20th–21st century trends in fires

Over the past century there was a 1920s peak in area burned on most USFS and Cal Fire protected lands in California (Figs 2 and 3), and this is mirrored on USFS lands throughout the western USA (Littell *et al.* 2009). On both USFS and Cal Fire lands in California, area burned declined to its lowest levels between 1950 and 1970. This decline in area burned is often attributed to fire suppression, which was presumably less effective in the 1920s but became increasingly more effective in subsequent decades (Clar 1969; Skinner and Chang 1996; Cermak 2005; North *et al.* 2015), although it was much more effective on forested than on shrubland-dominated landscapes (Keeley *et al.* 1999;

Table 2. Akaike information criterion regression models of climate variables on area burned (temperatures are the seasonal mean and precipitation the seasonal total)

PRESS, predicted residual error sum of squares; RMSE, root mean square error; Prior ppt, prior-year winter–spring precipitation

USFS 104 years	Adjusted R^2	Best model	PRESS RMSE (log ha per million ha)
(1910–2013)			
North coast	0.20	Temp spr – Ppt win – Ppt sum	54.5
North interior	0.31	Temp spr – Ppt aut – Ppt sum – Ppt win	53.4
Sierra Nevada	0.39	Temp spr + Temp sum – Ppt spr	21.3
Central coast	0.18	Prior ppt – Ppt spr – Ppt win – Temp spr	54.4
South coast	0.09	Prior ppt – Ppt aut – Ppt sum – Ppt win	27.6
USFS Early period (1910–1959)			
North coast	0.40	–Prior ppt – Ppt spr – Ppt sum – Ppt win	14.0
North interior	0.34	Prior ppt – Ppt spr – Ppt win – Temp aut + Temp sum	12.6
Sierra Nevada	0.42	–Ppt spr – Ppt win	8.2
Central coast	0.25	–Ppt spr – Ppt sum – Temp spr	21.4
South coast	0.08	–Ppt win – Temp sum	12.7
USFS Late period (1960–2013)			
North coast	0.26	Prior ppt + Temp aut + Temp sum	30.7
North interior	0.36	Prior ppt – Ppt aut – Ppt sum – Ppt win + Temp spr	20.8
Sierra Nevada	0.52	Temp spr + Temp sum	10.3
Central coast	0.25	Prior ppt – Ppt spr – Temp spr + Temp sum	31.0
South coast	0.26	Prior ppt – Ppt aut – Ppt sum + Temp sum	12.8
Cal Fire 95 years (1919–2013)			
North coast	0.15	–Ppt spr – Ppt win – Temp sum	32.6
North interior	0.25	Temp spr – Ppt spr – Ppt win	20.9
Sierra Nevada	0.09	Prior ppt + Temp spr	15.9
Central coast	0.09	Prior ppt – Ppt aut – Temp aut	15.3
South coast	0.00		
Cal Fire Early period (1919–1959)			
North coast	0.30	Temp win + Temp spr – Ppt spr – Ppt win	7.5
North interior	0.35	Temp win + Temp spr – Ppt aut – Ppt win	7.5
Sierra Nevada	0.25	Ppt aut + Ppt sum + Temp spr	4.0
Central coast	0.08	–Ppt spr	4.6
South coast	0.00		
Cal Fire Late period (1960–2013)			
North coast	0.15	–Prior ppt – Ppt spr	10.5
North interior	0.32	–Ppt spr – Ppt win	8.7
Sierra Nevada	0.27	Prior ppt + Temp aut + Temp sum	6.1
Central coast	0.23	Prior ppt + Ppt win + Temp sum	5.9

Safford and Van de Water 2014). However, the fact that area burned in USFS forests was equally controlled by climate during the first and second halves of the 20th century (Table 2) suggests that the mid-20th century decline in burning is not due entirely to management effects.

In the last four decades there has been an increase in burning on all USFS lands in California (Fig. 2; Table S3) and in other western USA forests (Littell *et al.* 2009). In contrast, this has not generally been observed on the largely non-forested lower elevation Cal Fire lands (Fig. 3; Table S3), and this is true of some other non-forested landscapes in the western USA (Baker 2013; Dennison *et al.* 2014; J. Littell pers. comm., 19 April 2016). Thus, the claim commonly made in research papers and the media that fire activity is increasing throughout the western USA is certainly an over-statement (see Doerr and Santin 2016 for further examples of misconceptions about global patterns of burning).

One obvious explanation for different patterns of burning would be historical changes in number of ignitions. However, this does not seem to have much explanatory ability because on both USFS and Cal Fire lands the lowest number of ignitions (Fig. 4*a*, *b*) was associated with decades that had the highest area burned (Figs 2 and 3). We have considered the possibility that patterns of ignitions could be the result of artefacts due to deficiencies in reporting. For example, it was suggested that early USFS records were deficient; Stephens (2005) maintained that USFS data prior to 1940 were inaccurate, and in support of that he cited a note by Mitchell (1947). However, that report presents an opinion and no evidence of such weaknesses in early data. Our study of state and federal archive records leaves us with the impression that during the early decades of the 1900s, state and federal fire agencies in California were vigilant in reporting ignitions and we see no obvious deficiencies in reporting. For example, by 1920 there were several hundred fire wardens strategically placed throughout the state to respond to fires on state responsibility lands (unpubl. data California State Archives). These wardens, listed by name in the records, were apparently held to a strict standard of reporting all fires in their jurisdiction. However, in these early decades it stands to reason that lightning-ignited fires in remote areas may have been overlooked. If we assume the frequency of lightning-ignited fires has not changed over time, then comparison of the proportion of lightning fires over the last century should provide a crude estimate of fires missed during the early 1900s; this comparison suggests that perhaps 0–11% of the lightning fires might have been missed on USFS lands and 0–2% on Cal Fire lands (Keeley and Safford 2016). This is not of a magnitude to explain the low ignitions early in the 20th century; as most fires in California are ignited by people, the lower ignitions during the first half of the 20th century were likely due to lower population density.

Particularly remarkable is how similar USFS and Cal Fire lands were in the increase in ignitions through 1970 and then a significant decrease in the last couple of decades; this pattern was consistent when examined at the scale of individual climate divisions (data not shown). The pattern has not been reported previously and we have no definitive explanation. We suspect it is not climatically driven but is due to changes in types of ignitions or management activities that have focused on improving fire prevention measures. Alternatively it could be that the increase in area burned in recent years on USFS lands (Fig. 2) has decreased fuel availability, which in turn has decreased ignition opportunities (Fig. 4*a*). This seems unlikely because only a relatively small percentage of available USFS lands burn each decade, and a similar decline in ignitions is observed on Cal Fire protected lands (Fig. 4*b*), which generally have not had an increase in area burned (Fig. 3). In summary, the recent decline in ignitions remains an enigma in need of further research.

Climate and fires

Based on our historical analyses, there are five important lessons on fire–climate relationships in California. These are related to temperature and precipitation patterns and both show interactions in their spatial and temporal distribution:

1) Annual variations in temperature appear to have had minimal influence over area burned in the lower elevation, mostly non-forested landscapes (e.g. Figs 5*d*, *e* and 6*d*, *e*).
2) Temperature has been a significant factor driving area burned in higher elevation montane forests, but this varies with season; winter and autumn temperatures seem to play little role in dictating fire activity, but spring and summer temperatures are significantly tied to area burned (e.g. Fig. 5*a*, *b*, *c*).
3) Current-year precipitation has been a strong controller of area burned on higher elevation USFS lands throughout the state (Fig. 7), but on the lower elevation Cal Fire lands it has been important largely in the northern part of the state (Fig. 8), where a third or more of the protected lands are forested (Table 1).
4) Precipitation plays a very different role in the largely grass-dominated Cal Fire foothills of the Sierra Nevada (Keeley and Syphard 2015), and in recent years on grass and shrub-dominated southern California landscapes (Table 2). Rather than current-year precipitation controlling fires, it is the prior-year rainfall that is important, and we assume this reflects higher grass production that increases the fuel volume in the following year.
5) Fire–climate relationships have changed over time. On USFS lands in the Sierra Nevada, precipitation was a primary driver of area burned in the first half of the 20th century but temperature has become more important in recent decades (Table 2). In the southern part of the state there was little or no significant relationship between climate and fire in the first part of the 20th century, but over the past five decades the prior-year precipitation has become significant.

Global climate models predict increasing annual temperatures, but translating this into changes in future fire regimes requires an understanding of which season's temperature increases are most likely. Deser *et al.* (2012) found that global climate models predict the greatest temperature rise to occur in winter. In California, area burned is insensitive to winter temperature (Figs 5 and 6), suggesting some caution in interpreting global warming projections of increased winter temperatures in terms of future fire activity.

In the southern part of the state, and in lower elevations (Cal Fire protected lands), higher temperatures in any season are not reflected in substantially greater fire activity. This insensitivity to annual changes in seasonal temperatures suggests several possibilities. It could be that on these landscapes in most years, climate reaches a threshold conducive to large fire events, and higher temperatures in some years do not change the likelihood of large fire events. This is suggested by the observation that where temperature is correlated with greater area burned (e.g. Sierra Nevada USFS lands, Fig. 5*c*) the most extreme fire years occur when mean summer temperatures approach 19°C, whereas in the southern part of the state, where area burned is not correlated with temperature (e.g. Figs 5*e*, 6*e*), all summers have temperatures in excess of that threshold (Fig. 5*d*, *e*). This is consistent with the conclusion that climate change may play a larger role in dictating fire regimes in cooler mesic over hotter arid environments (Pausas and Paula 2012; Steel *et al.* 2015). On these more arid landscapes primed for a major fire event most years, timing of ignitions may play a far greater role in determining fire outcomes.

It is important to recognise that warmer and drier conditions leading to an increase in fire activity are not a recent phenomenon as we found models relating area burned to these parameters for the first half of the 20th century (Table 2), as has Higuera *et al.* (2015). Although it is possible that some extreme heat waves have an anthropogenic component as far back as the 1930s (King *et al.* 2016), it seems unlikely that the fire–climate models for the first half of the 20th century were driven by anthropogenic global warming.

Two interesting historical changes in fire–climate relationships are illustrated by the Sierra Nevada and the South Coast. In Sierra Nevada USFS forests, there was a very strong relationship between area burned and precipitation during the first part of the 20th century, but this switched in the last 50 years to a model controlled by spring and summer temperature (Table 2). This increase in the role of temperature in controlling area burned is consistent with an expectation that global warming will increase fire activity in forested landscapes (Abatzoglou and Williams 2016). These models also illustrate these forested landscapes vary from year to year in their flammability; in years where temperatures are high and precipitation low, their flammability increases. These forests have a climate-limited fire regime.

In southern California on Cal Fire lands, there was no significant relationship with climate parameters during the first half of the record but this changed in the second period, 1960–2013 (Table 2). However, the primary drivers of area burned were not current-year temperatures and drought, but rather prior-year precipitation. This latter variable is generally thought to affect fire activity by high rainfall increasing herbaceous fuels that enhance fire activity in subsequent years, and is primarily observed in grasslands and savannas (Crimmin and Comrie 2004; Littell *et al.* 2009; Gray *et al.* 2014; Keeley and Syphard 2015). This suggests that fires in these grass-dominated ecosystems are fuel limited. We suggest that the reason this effect was not observed in the first half of the 20th century but was very pronounced in the last five decades in the South Coast (Table 2) is tied to increased type conversion from shrublands to alien-dominated grasslands during the 20th century (Keeley 1990; Hamilton 1997; Halsey and Syphard 2016). Despite the fact that the South Coast division is dominated by chaparral, this model still applies because shrubland fires generally ignite in adjacent herbaceous vegetation, which acts as a wick spreading fire into dense shrublands (Syphard and Keeley 2015).

Annual drought variation plays a major role in determining fire activity throughout the western USA (Taylor and Beaty 2005; Collins *et al.* 2006; Swetnam and Anderson 2008; Littell *et al.* 2016). In California, we found that generally winter, spring and summer drought is associated with greater area burned (e.g. Fig. 7*a*, *b*, *c*, *d*); however, it commonly works in association with temperature (Table 2). Droughts affect fires by reducing soil moisture, which in turn reduces live fuel moisture, thus extending the length of the fire season – contributing to greater area burned (Dennison *et al.* 2008). The effect of drought on dead surface fuels is unclear. Droughts reduce relative humidity, which affects dead fuel moisture, but more research is needed to parse out the effects of drought *v.* temperature in determining dead fuel moisture.

California varies more dramatically from year to year in precipitation than anywhere else in the conterminous US (Dettinger 2016) and thus periodic droughts are a feature of this landscape. Global climate models do not predict substantial changes in future precipitation but the distribution is likely to change to a greater proportion of precipitation in larger storms and less rainfall between such events. This could intensify droughts in some landscapes but not necessarily all. Regardless of precipitation patterns, expected global warming will potentially make the effect of droughts more severe for vegetation (Williams *et al.* 2015), and increase fuel aridity (Abatzoglou and Williams 2016).

Long-term drought

Seasonal drought as measured in this study may not be nearly as critical as long-term drought effects. For example, in southern California shrublands it was found that megafires were associated with droughts of a year or longer and this did not appear to be due to effects on live fuel moisture (Keeley and Zedler 2009). These authors hypothesised that such extreme antecedent drought caused dieback of woody vegetation and this greatly increased dead canopy fuels, which contributed to an increased rate of fire spread, particularly from spot fires. Extended droughts resulting in dieback can leave a dead fuel legacy on the landscape and contribute to large fires in subsequent years, even in years when precipitation returns to normal. For example, in the last decade there has been an extraordinary number of large fire events (Keeley and Zedler 2009) and it has been the driest decade in modern history (Keeley and Syphard 2016). This dead fuel legacy effect could account for why we found little relationship between annual precipitation and area burned in that year for the South Coast (Figs 7*e*, 8*e*).

This shrubland model is less applicable to forested environments. For example, the 2012–2015 extreme drought in the Sierra Nevada (Asner *et al.* 2016) resulted in extensive tree mortality (see fig. 4 in Keeley and Syphard 2016). In the long run this will increase surface fuels but potentially reduce ladder fuels for some period of time, and the net effect on fires is unclear.

Further illustration of how fuel structure influences the fire–drought relationship is seen in grasslands where fires are driven by herbaceous fuels. Fires are typically limited in drought years due to reduced fuel production, but increase in years following high rainfall (Littell *et al.* 2009; Gray *et al.* 2014; Keeley and Syphard 2015).

Weather

Much of the annual variability in area burned not explained by climate in the present study is likely related to weather. Fire weather often plays a key role in determining fire behaviour and is not captured by studies of fire–climate relationships. Some of the worst fire events are heavily influenced by brief heat waves that rapidly dry both live and dead fuels. Such heat waves may not greatly influence average seasonal temperatures and thus may be missed in the sort of analysis done here.

Anomalous wind events likewise play a substantial role in large fires, and this is generally true throughout the western USA. The extreme fires of 1910 known as the Big Burn were the result of numerous factors, but fire weather involving high temperatures and extreme winds were prominent (Diaz and Swetnam 2013).

In all likelihood, extreme winds are a significant reason why the South Coast shows almost no effect of seasonal temperature and precipitation on area burned (Figs 5*e*, 6*e*, 7*e*, 8*e*); one exception is the inhibitory effect of autumn precipitation (Figs 7*e*, 8*e*) as reported in other studies (Keeley 2004; Jin *et al.* 2014), which presumably reflects high fuel moisture at the time of the worst wind events. On an annual basis, the region experiences 10–30 Santa Ana wind events, which persist for days with gusts exceeding 100 k h^{-1} and relative humidity (RH) <5% (Jones *et al.* 2010). Roughly 50% of the area burned occurs under these conditions (Jin *et al.* 2014) and nearly all loss of lives and property occurs from fires driven by these winds (Keeley *et al.* 2009*b*).

The effect of Santa Ana winds on fire events varies both spatially (Moritz *et al.* 2010) and temporally. There are two peaks of Santa Ana winds, in autumn and spring, but the worst fires occur during autumn Santa Ana winds, due to the lower fuel moisture following summer drought (Rolinski *et al.* 2016). Typically there are 10–20 days of these winds every autumn in the region, but this is only a limited proportion of events that result in uncontrollable fires. For example, over the past century there have been only around a dozen very large Santa Ana wind-driven fires (Keeley *et al.* 2009*b*), yet over this period there have been one to two orders of magnitude more Santa Ana wind events. We found that the number of Santa Ana wind events over the period 1979–2007 (based on data from Jones *et al.* 2010) bore no relationship with area burned in the South Coast region ($r^2 = 0.00$, $P = 0.98$). The primary reason is that Santa Ana wind-driven fires are ignition limited and require precisely timed human ignitions during these wind events; relative to the frequency of Santa Ana winds, such ignitions are rather uncommon. However, once an ignition does occur, the severity of the winds and aridity of fuels will affect the ultimate size of the fire event (Rolinksi *et al.* 2016).

Modelling studies suggest future changes in Santa Ana winds but they produce conflicting results, which complicate forecasts. Models by Hughes *et al.* (2011) predicted around 20% fewer Santa Ana wind days in the mid-21st century, whereas Miller and Schlegel (2006) models showed these events would be more frequent. Regardless, both studies concluded that fire conditions in Santa Ana-prone landscapes would be worse in the future. Hughes *et al.* (2011) noted that although their models predicted fewer such events, conditions would be hotter and drier than at present. Considering the extreme humidity and temperature conditions under contemporary Santa Ana wind events, it is questionable whether or not the changes they predict will have any measurable effect on future fire events, particularly as the timing of human ignitions is the major determinant of these catastrophic fires. Miller and Schlegel (2006) predicted more Santa Ana events in December and warned that future fire regimes would become more dangerous. However, winter Santa Ana wind events are less likely to be a threat because there is a greater chance of autumn precipitation events prior to these winds and this would reduce the likelihood of dangerous fire events (Keeley 2004; present study Figs 6*e*, 8*e*).

Other anthropogenic effects

Some of the variation in annual area burned not accounted for by the climate models presented here is likely tied to direct anthropogenic effects related to land management. It has already been suggested that the decline in area burned observed on both USFS (Fig. 2) and Cal Fire (Fig. 3) lands during the first half of the 20th century may be tied to fire suppression. In addition, increased burning in the last four decades on USFS lands has long been thought to be tied to anomalous fuel accumulation resulting from highly effective fire suppression in western forests (North *et al.* 2015).

Other land management decisions also alter fuel structure in ways that affect fires. Silvicultural practices that involve clear cuts and replanting of dense even-aged monocultures produce hazardous fuels. Past harvesting practices have compromised USFS capacity for allowing natural fires to burn in Sierra Nevada plantations (McKelvey and Johnston 1996). To reduce the fire hazard, such plantations require a regular schedule of stand thinning, which is not always economically feasible. Where thinning does occur, it has the potential for greatly increasing dead surface fuels depending on how thinned material is handled.

Direct anthropogenic effects have also involved increasing ignitions and the timing of ignitions during extreme fire weather conditions. It has been suggested that the 1920s peak in area burned (Figs 2 and 3) may have been in part due to greatly increased human access to wildland areas resulting from large increases in automobile registrations and road construction (Keeley and Fotheringham 2003). Similarly, the sharp 1940s spike in the South Coast (Fig. 3*e*) has been attributed to the influx of fire-naïve migrants from the eastern half of the US during World War II to work in aircraft factories.

Throughout the state, humans are a major source of fire ignitions, and at lower elevations and lower latitudes they are responsible for the vast majority of area burned. These landscapes also have the weakest fire–climate relationship, and we suggest they may represent more ignition-limited than climate-limited fire regimes.

Fire management practices have changed over time and may account for some of the variation we observed in this study. For example, during the first half of the 20th century both the USFS and Cal Fire maintained what was known as the '10 am policy,' which meant that with the outbreak of a fire all available resources were devoted to the attack with the goal of extinguishing it by 1000 hours the next day. However, in the 1960s, with growing recognition of the natural role of fire in western forests, there was a change in USFS policy to be less aggressive on fires that fit certain conditions. Rather than extinguish all fires, many were constrained within watersheds or larger management units, with the ultimate effect of increasing fire size. Thus, some of the increase in area burned after 1960 (Fig. 2) is potentially tied to changes in management decisions. Cal Fire, which protects lands closely associated with more resources at risk, has to this day maintained the 10 am policy and on most of their lands there has not been an increase in area burned (Fig. 3).

Explanations for any given fire event may invoke many of these anthropogenic factors as well as climate and weather. For example, the massive 2013 Rim Fire that occurred on the west side of the Sierra Nevada Range in California burned over 100 000 ha, mostly in the Stanislaus National Forest, and comprised mostly high-intensity crown fire (Potter 2014). Climate, drought, fire weather, human ignition and past land management practices all contributed to this event. It followed a severe drought and burned during a hot spell with erratic winds;

a significant portion was fuelled by young pine plantations of dense contiguous fuels (Potter 2014; Kane *et al.* 2015). This event provides a useful lesson for how to examine future fire regimes. Climate and weather events, which are largely outside our immediate control, are only part of the fire problem. There are many direct anthropogenic factors that can be addressed to reduce future fire risk.

Conclusions

The results of this study raise questions about broad-brush approaches to fire–climate relationships. When analysed collectively, the picture for California is very different than that for homogenous climatic divisions. When lumping all of the state's climate divisions together, temperatures in all four seasons showed highly significant effects on annual variation in area burned. However, within climate divisions, winter and autumn temperatures were never significant, and in some divisions, no season showed a significant fire–climate relationship. The reason for such differences between the broad-brush approach and more localised climate divisions is that fire–climate relationships are quite different from one climate division to another. In addition, broad-brush approaches are less able to separate changes from year to year with latitudinal changes in fire activity. For example, in California more area burns in the southern part of the state and temperatures in all seasons are warmer; thus, state wide it is to be expected that higher temperatures will correlate with more area burned. It is apparent that studies across all of California or the entire western USA (Westerling *et al.* 2014; Abatzoglou and Williams 2016) are mixing both temporal and spatial variation; thus it is difficult to parse out the factors most responsible for future fire regimes.

The best fire climate models presented here (Table 2) predict only around 50% of the variation in historical annual area burned, and for most of California's fire-prone landscape they explain much less. Variation in year-to-year burning is a multivariate phenomenon; factors not accounted for in this study include long-term drought, fire weather and human disruptions in natural fire regimes, both through adding ignitions and suppressing fires that lead to anomalous accumulation of fuels. With respect to how climate influences fires, we recognise three types of ecosystems: (1) flammability-limited, (2) fuel-limited and (3) ignition-limited systems. These are modal patterns and describe what we perceive as the most important determinant of fire activity.

Flammability-limited ecosystems are best represented by higher elevation montane coniferous forests where the annual window of opportunity for significant fires varies markedly from year to year in response to seasonal climates (e.g. Figs 5*c*, 7*c*). These are the most climate-limited fire regimes and expected global warming will likely increase area burned by increasing the length of the fire season and the severity of drought effects on fuel moisture. Forecasting future climate effects is complicated by anthropogenic effects on fuel structure in these forests; in particular, the patterns of dead surface fuels and density of in-growth of young trees. Temperature and precipitation (snow) have different effects on these two fuel types: for example, soil moisture greatly affects live fuels but has a more limited effect on dead surface fuels.

Fuel-limited ecosystems such as grasslands and savannas have fire regimes that are markedly controlled by annual patterns of herbaceous fuels (e.g. Figs 6*c*, 8*c*). They respond primarily to annual variations in precipitation but exhibit a markedly different response from flammability-limited systems. Drought years greatly limit fuel production and thus these ecosystems do not respond to drought with increased burning. The strongest climatic controller is the level of precipitation in the prior year, as high rainfall increases fuel production, and fuel is most flammable after a year or more of drying (Table 2). Global warming may ultimately reduce burning in these fuel-limited ecosystems through higher temperatures that may limit the growing season even during years of high precipitation – though we have no direct evidence for this.

Ignition-limited ecosystems such as southern California shrublands (e.g. Figs 5*e*, 6*e*, 7*e*, 8*e*) exist on a landscape where in most years the summer and autumn climates are conducive to significant fire events. Global warming is not likely to shift these systems towards greater fire-prone conditions, although the potential exists for increasing the length of the fire season. One of the major controllers is fire weather conditions; in particular, short-term heat waves and high winds. One could think of these as weather-limited systems except that extreme conditions such as Santa Ana wind events occur on an annual basis, but do not regularly result in large fire events. Major fires are dependent on the juxtaposition of such weather events with anthropogenic ignitions. Future fire regimes will be less affected by global warming than by other global changes, in particular population growth, because over 95% of ignitions are due to humans. As populations increase we expect a greater chance of ignitions during severe fire weather conditions.

Altering future fire activity in these different ecosystems will require very different approaches. Flammability-limited systems might be better controlled by altering fuel structures both through fire management activities and altering silvicultural practices (North *et al.* 2015). In fuel-limited ecosystems, we may be able to control fire activity by altering rangeland practices where livestock have the capacity to alter fire outcomes through fuel consumption (e.g. Bond and Keeley 2005). Perhaps the greatest opportunity for altering future fire regimes is in ignition-limited ecosystems where better control of human activity is a potentially more tractable option than controlling climate, weather or fuels (Keeley *et al.* 2009*a*).

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Supplementary material

Different historical fire–climate patterns in California

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Table S1. An example of seasonal temperature variation over an 84-year period for a foothill site in the southern Sierra Nevada illustrating the large year-to-year variation

Winter = Dec, Jan, Feb; Spring = March, April, May; Summer = June, July, August; Autumn = September, October, November (data from http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca0343). Note: although many montane sites exhibit a significant increase in temperature over this time period, it is commonly not observed in lower elevation sites such as this one, however interpreting these data presents many complications (e.g. Vose *et al*. 2014)

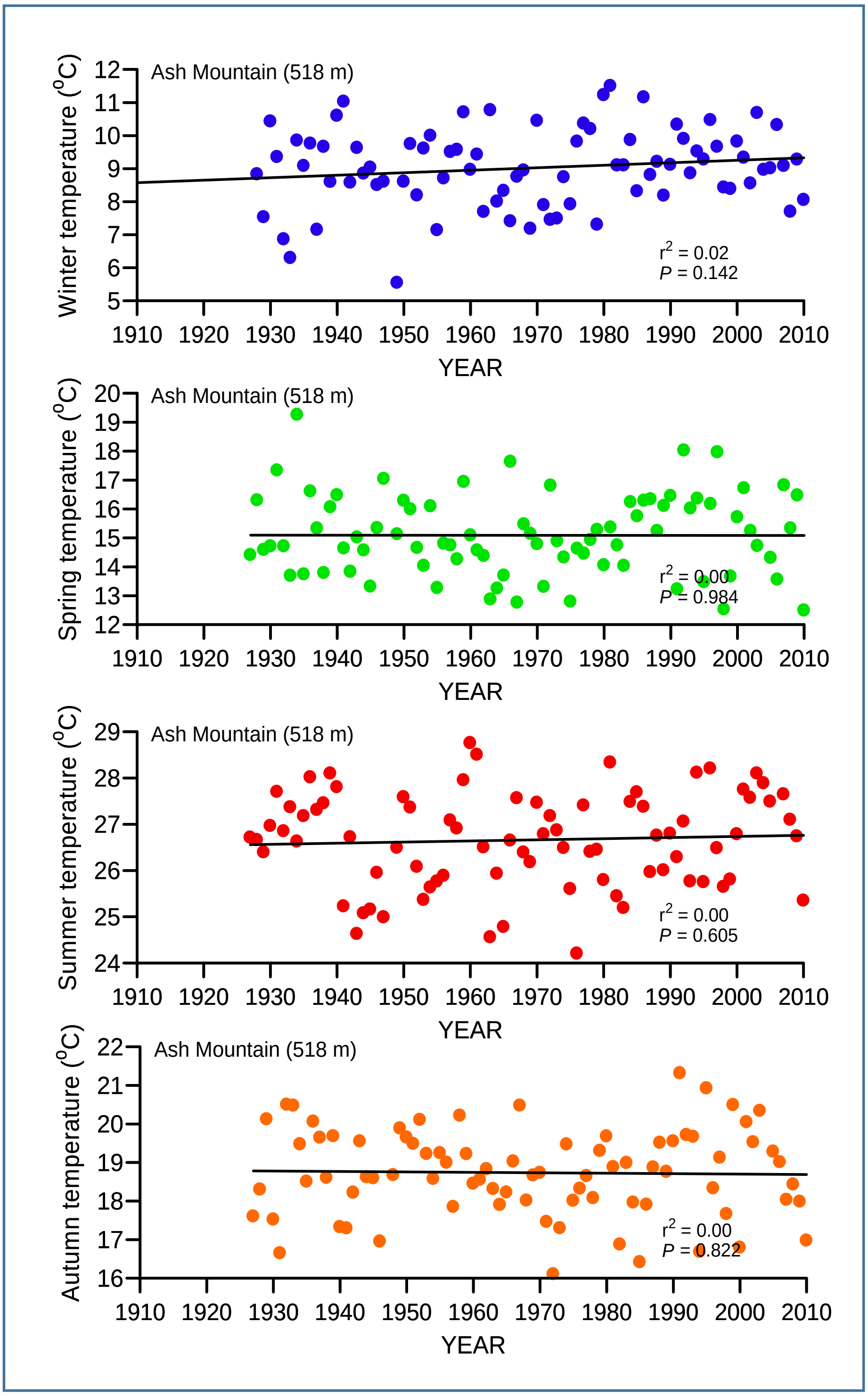

Table S2. Number of years of Cal Fire data for California counties

Division	County	Years
1	Del Norte	80
1	Humboldt	92
1	Lake	93
1	Marin	79
1	Mendocino	94
1	Napa	94
1	Siskiyou	94
1	Sonoma	93
1	Trinity	89
2	Butte	94
2	Colusa	80
2	Glenn	76
2	Lassen	91
2	Modoc	65
2	Nevada	94
2	Placer	94
2	Plumas	37
2	Shasta	94
2	Solano	79
2	Tehama	94
2	Yolo	76
2	Yuba	94
4	Alameda	77
4	Contra Costa	74
4	Monterey	91
4	San Benito	90
4	San Luis Obi	89
4	San Mateo	79
4	Santa Clara	94
4	Santa Cruz	94
5	Amador	94
5	Calaveras	94
5	El Dorado	94
5	Fresno	93
5	Inyo-Mono	53
5	Kern	75
5	Kings	51
5	Madera	93
5	Mariposa	91
5	Merced	75
5	San Joaquin	72
5	Stanislaus	75
5	Tulare	92

5	Tuolumne	94
6	Los Angeles	78
6	Orange	87
6	Riverside	94
6	San Bernardi	91
6	San Diego	90
6	Santa Barbar	75
6	Ventura	77

Table S3. Decadal data from Fig 2 and 3 (log hectares) analysed by year

Note: *r* is presented to indicate direction of change.

USFS	1910–2013			1910–1959			1960–2013		
	r	*P*	*n*	*r*	*P*	*n*	*r*	*P*	*n*
North Coast	–.22	0.027	(104)	–.33	0.021	(50)	.42	0.001	(54)
North Interior	–.13	0.187	(104)	–.35	0.014	(50)	.41	0.002	(54)
Sierra Nevada	.08	0.442	(104)	–.41	0.003	(50)	.51	<0.001	(54)
Central Coast	–.00	0.971	(104)	–.34	0.014	(50)	.24	0.087	(54)
South Coast	.21	0.036	(104)	.01	0.958	(50)	.30	0.028	(54)
Cal Fire									
North Coast	–.67	<0.001	(94)	–.21	0.201	(40)	–.36	0.009	(54)
North Interior	–.49	<0.001	(94)	–.47	0.002	(40)	–.08	0.585	(54)
Sierra Nevada	–.63	<0.001	(94)	–.47	0.002	(40)	–.26	0.074	(54)
Central Coast	–.54	<0.001	(94)	–.46	0.003	(40)	–.04	0.781	(54)
South Coast	.14	0.166	(94)	.16	0.311	(40)	–.44	0.001	(54)

References for supplementary material

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