CSIRO PUBLISHING

RESEARCH PAPER
https://doi.org/10.1071/WF25166

International Journal of WILDLAND FIRE
International Association of Wildland Fire

Causal analysis of fire regime drivers in California

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

For full list of author affiliations and declarations see end of paper

***Correspondence to:**
Jon E. Keeley
U.S. Geological Survey, Western Ecological Research Center, Sequoia-Kings Canyon Field Station, Three Rivers, CA 93271, USA
Email: jon_keeley@usgs.gov

Received: 27 June 2024
Accepted: 23 October 2025
Published: 8 December 2025

Cite this: Keeley JE and Syphard AD (2025) Causal analysis of fire regime drivers in California. *International Journal of Wildland Fire* **34**, WF25166. doi:10.1071/WF25166

ABSTRACT

Background. Understanding the relative contribution of climate and human factors to wildfires is critical for managing risk across California's diverse ecosystems, in the United States (US). **Aims.** We propose a model that distinguishes between proximate and ultimate drivers of fire regimes and apply it to a century of fire and climate data to assess regional variation in causal mechanisms. **Methods.** We analyzed fire statistics (1910–2021) alongside climate and weather data, stratifying the state by 10 ecoregions. **Key results.** Northern forests had the strongest correlation with the proximate factor fuel aridity, ultimately due to climate. Fire rotation intervals exceeded 100 years, implicating woody fuel accumulation as an additional factor. Lightning ignitions occurred in decadal bursts, with dense strike events potentially overwhelming fire-fighting resources. Lower elevation/latitude foothill ecoregions experienced highest fire activity following wet winters and springs, implicating control by herbaceous fuel loads and a negative effect of global warming on future fires. Human ignitions dominate in these ecoregions, and population growth contributes to expansion of powerlines, a major ignition source. **Conclusions.** While climate change may increase fire activity in forested ecoregions, its role is less pronounced in non-forested ecoregions, where human ignition sources are the dominant factor. **Implications.** Different areas within ecoregions may require different management actions that reflect the specific proximate and ultimate factors at play.

Keywords: climate, fire ignitions, fuel load, proximate and ultimate explanations, wind.

Introduction

Global change and other factors are altering fire regimes in many parts of the globe, and there is a need to understand where and why fire activity is changing. One of the key factors associated with changing fire regimes is global warming due to its effect on fuel aridity, considered to be an important driver of fire activity (Flannigan *et al.* 2009). There is widespread evidence that over broad regions atmospheric aridity in recent decades is associated with area burned, and a common metric of fuel aridity is vapor pressure deficit (VPD) (Diffenbaugh *et al.* 2021; Clarke *et al.* 2022).

Recent studies conducted across western North America have reported a significant relationship between VPD and area burned and predict that fire activity will increase in the future due to global warming's intensifying effect on atmospheric aridity (Seager *et al.* 2015; Williams *et al.* 2015; Abatzoglou and Williams 2016; He *et al.* 2025). One limitation of broad-scale studies, however, is that they potentially confound the effects of space and time, as climates and vegetation are variable across western North America. As a result, subregional differences in climate-fire relationships may be masked as noise in aggregated analyses, potentially obscuring areas that diverge meaningfully from the dominant regional pattern. In addition, a major limitation of broad scale studies focused solely on fuel moisture is that they do not account for other drivers of fire regimes such as fuel load, weather, ignitions and management, which vary across broad regions and may benefit from the application of more fine-scale spatial analysis to parse out the relative importance of different drivers (MacDonald *et al* 2023).

In addition to evaluating the relative influence of multiple factors across diverse regions, much of the literature implicating climate change as the causal agent behind increasing wildfires relies on correlations with factors presumed to influence fire behavior.

For example, correlations between climate variables and fire activity have been used to suggest that global warming will lead to greater annual extremes in fire behavior (Zhou *et al.* 2023). However, these studies often lack a causal mechanism (*sensu* Grace *et al.* 2025) connecting climate change to fire. For instance, in response to the unusually extreme winds that drove the recent Los Angeles (LA) wildfires in January of 2025, some media reports claimed that the extreme behavior of these winds was consistent with expectations from global warming, and thus attributed the disaster to anthropogenic climate change (Hossenfelder 2025; Qiu *et al.* 2025). However, establishing causality requires a plausible and testable mechanism. Santa Ana wind speed, widely considered to be the primary factor responsible for the damage from these LA fires (Murphy and Mass 2025), is influenced by the spatial proximity of high and low pressure systems. To date, no model has demonstrated that anthropogenic climate change is altering the distribution of high and low pressure cells in a way that would explain increased wind speed. Indeed, Meehl *et al.* (2025) reported on an example of foehn winds that suggested recent climate change had contributed to decreased wind speeds relative to historical patterns, and concluded that the mechanism behind this was in need of research. Guzman-Morales and Gershunov (2019) projected decreases in frequency and intensity of future Santa Ana Winds.

When mechanisms are proposed they need to be supported with known causal relationships. For example, Swain *et al.* (2025) reported correlations that implied high winter/spring rainfall followed by a dry year resulted in high fuel production and this contributed to the catastrophic impact of the January 2025 LA fires. They attributed this to the effect of high rainfall on herbaceous fuel production, a well known phenomenon and something we demonstrate below. However, in this Mediterranean climate herbaceous fuels are always dry and flammable in autumn regardless of whether or not there has been a long-term drought. In addition, as they acknowledge in their introduction, these fires started in chaparral, an evergreen shrubland with little herbaceous vegetation. A high rainfall year may increase primary growth in these shrubs, but these fine fuels comprise a minor part of the total fuel volume (Kummerow *et al.* 1981), and fire spread is largely a function of the long term accumulation of dead fuels (Keeley *et al.* 2022). Swain *et al.* (2025) coined the term 'whiplash effect' to describe the sequence of high rainfall followed by dry years (something not unique in the history of this region) and speculated that climate change was going to increase this so-called whiplash effect. However, it is unlikely such an effect can explain the catastrophic LA fires as fire spread was due to urban fuels, primarily the homes themselves, and wildland fuels played little if any role (Witze 2025).

One further example of how correlations may not contribute to causal knowledge is the study by Goss *et al.* (2020), who reported correlations between the Fire Weather Index (FWI) and increased temperature and precipitation in California, United States (US). They concluded that there was strong evidence for a human fingerprint on the observed increase in the FWI, which they claimed were meteorological preconditions necessary for extreme autumn wildfires in California. However, the FWI was designed for fires in Canadian forests (van Wagner 1987), and Goss *et al.* (2020) failed to demonstrate that the FWI was tied to greater area burned in California. This is a critical flaw because a long-term study by Keeley *et al.* (2024) reported that in southern California during October, the autumn month with the greatest area burned (Keeley *et al.* 2021), large fires were not associated with a higher FWI. Also, Goss *et al.* (2020) contended temperature was a major factor driving the FWI in California, but Keeley *et al.* (2021) reported that temperature during any autumn month in the South Coast was not significantly related to area burned. In short, climatic influences on the FWI do not mean they will translate into increased area burned.

These examples are not meant to discount the potential role of climate change, but they illustrate the need for an explicit causal analysis that provides mechanisms (e.g. Grace *et al.* 2025; Pausas *et al.* 2025), and without understanding the mechanisms, fire management strategies might inadvertently focus on the wrong factors. The purpose of our study is to introduce a conceptual model that may lead to a better causal analysis of mechanistic factors driving fire regimes.

We use a conceptual model that considers both proximate factors, which explain directly how fire responds, and ultimate factors, which explain why changes in proximate factors occur (Fig. 1), and apply this model to parse out the factors driving fire regimes in different ecoregions across California. Our causal analysis takes a mechanistic approach (Grace *et al.* 2025 refer to this as causal knowledge analysis – see also Grace 2024) and argues that proximate factors are dependent on ultimate factors. It's important to recognize that, as environments change, the ultimate drivers of fire regimes may change, and thus proximate factors change. For example, California mixed conifer forests, due to high productivity and lightning ignitions, historically experienced frequent low intensity surface fires, which kept the mass of surface fuels low, and fires were limited by the rate of surface fuel accumulation (Stephens *et al.* 2007). Under those conditions, the primary proximate factor was rate of understory fuel accumulation coupled with woody fuel moisture (Swetnam and Baisan 2003). However, after a century of fire suppression, fire exclusion has resulted in fuel loads that are always sufficient to propagate fire (Stephens *et al.* 2022), and thus, today fuel moisture is likely the most limiting proximate factor.

We contend that drivers of fire regimes are well captured by considering these proximate factors, (1) fuel condition, (2) fuel load, (3) wind and (4) ignitions, and their ultimate causes, which are outlined below and depicted in Fig. 1:

(1) Fuel condition: this is largely moisture content, which is ultimately dependent on climate, particularly annual variation in aridity throughout the year. It is most important in forests that are flammability limited in

many years, and less important where vegetation is fire-prone most years.

(2) Fuel load: fuel load mechanisms vary with fuel type.
   a. Herbaceous fuel loads are ultimately a function of annual variation in climate that alters growing conditions for grasses and forbs. They are also affected by longer term changes due to vegetation type conversion where woody vegetation has been replaced by non-native herbaceous plant invasions;
   b. Woody fuels are ultimately the result of fuel accumulation, both surface and canopy fuels, due to long fire-free intervals, arising from several sources. Some wetter forest types have a naturally low fire frequency (e.g. coast redwood forests, Keeley and Pausas 2025). Alternatively, semi-arid forests that have been subjected to effective fire suppression also exhibit fuel accumulation. Both have low fire frequency and a concomitant accumulation of woody fuels. Other ultimate sources of high fuel loads include forests and shrublands subjected to severe droughts or insect outbreaks, both of which result in biomass dieback that converts potential fuels to available fuels. The ratio of live and dead fuels must also be considered.

(3) Extreme winds: ultimately these are the result of annual synoptic weather conditions in particular regions, or result from internally generated tornadic winds in fires arising from heavy fuel loads; both contribute to high intensity fires.

(4) Ignitions
   a. Lightning ignitions are ultimately driven by storms that often produce massive numbers of ignitions and may last for several days over broad regions, potentially overwhelming fire-fighting resources;
   b. Human ignitions are ultimately due to direct effects such as arson, and indirect effects are from infrastructure such as powerline failures, which are most common during extreme wind events.

We use different ecosystems in California to demonstrate how these fire regime drivers play different causal roles in response to different ultimate drivers for different regions and illustrate the value of our conceptual model. Previous studies have shown that across the state, fire regimes are quite diverse in time and space (Littell *et al.* 2009; Keeley and Syphard 2017; Williams *et al.* 2019; Syphard and Keeley 2020), but beyond recognizing differences between forests and non-forests, few generalizations can be made. Although some studies describe fire activity according to dominant vegetation types, we focused on climatically similar areas since most California landscapes comprise a mosaic of grasslands, shrublands, woodlands and forests, and most large fires burn across several vegetation types (Fertel *et al.* 2022, 2023). In this study we examined more than a century of fire history and climate data in five California climate divisions, on both lower elevation foothills and higher elevation montane landscapes. In addition to understanding the extent to which different ecoregions have different drivers, a challenge is how to go about quantifying those drivers and their causal agents, which we suggest is best done with the conceptual model in Fig. 1. There is an important need for this research as described by Taylor *et al.* (2016), who made a strong case for the urgency to understand the role of human vs climate-driven fire activity in California.

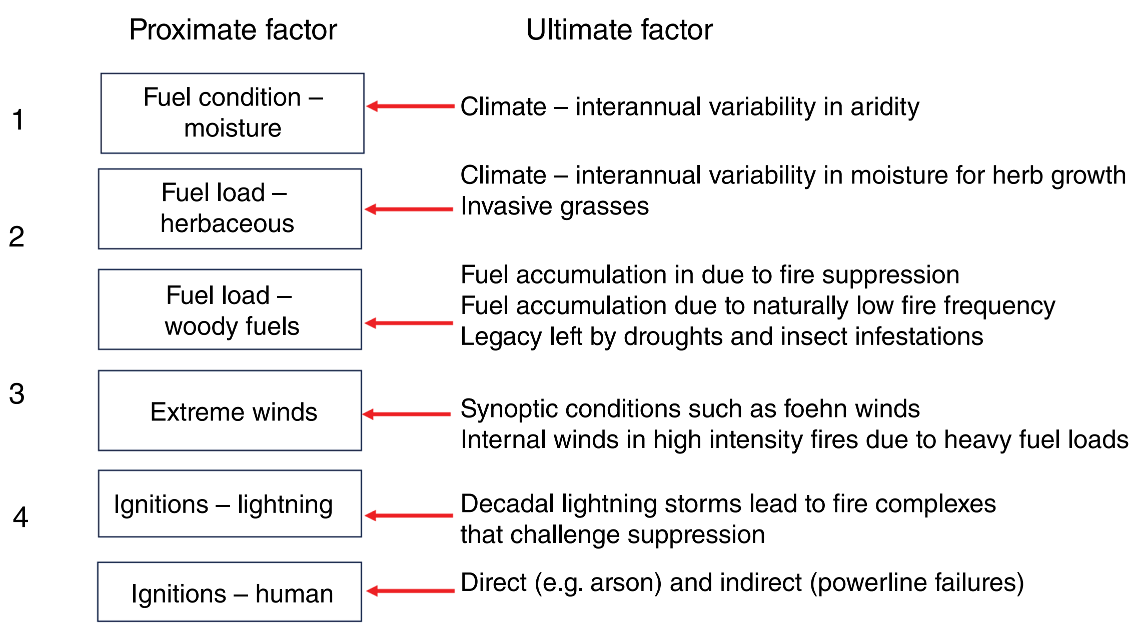


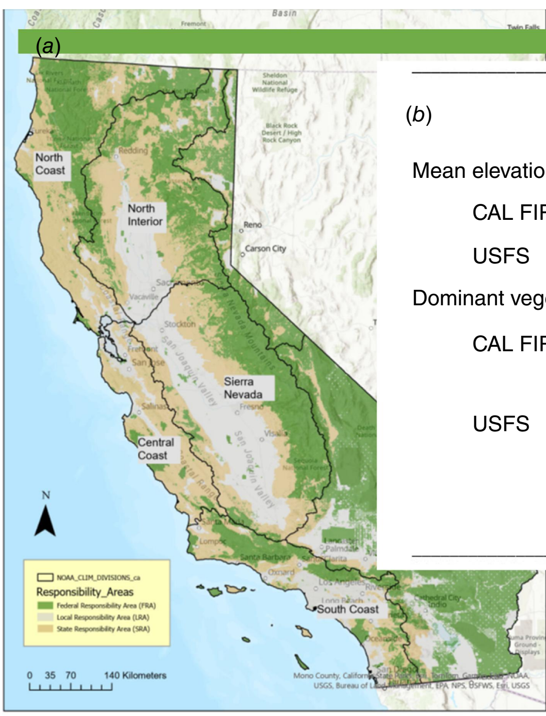
Fig. 1. Proximate and ultimate factors driving fire regimes. (1) fuel condition, (2) fuel load, (3) wind and (4) ignitions. Arrows indicate the ultimate factor that determines the proximate factor.

The foundational evidence for understanding proximate and ultimate controls on fire regimes in California is changes in fire regimes over much of the 20th and 21st centuries (1910–2021). We begin with a historical overview of fire frequency and area burned in the 10 California ecoregions that include 5 National Oceanic and Atmospheric Administration (NOAA) climate divisions, and within each division, lower-elevation California Department of Forestry and Fire Protection (CAL FIRE) and upper-elevation US Forest Service (USFS) lands (Fig. 2*a*). Next we evaluate ecoregional differences in ignition sources. Then we compare divisions for the largest wildfires and the fire history within the perimeters of these fires, as time since last fire has implications for fuel load (Steel *et al.* 2015). We broaden this analysis by considering the fire rotation interval for all climate divisions, defined as the time it would take to burn the equivalent area within the division based on the rate of burning in the 100 years prior to the largest fire. This estimate has, in some forests, been shown to be equivalent to the directly observable fire rotation interval (Beaty and Taylor 2001). We follow with climate comparisons and regression analyses of the relationships between climate predictors and annual fire frequency and area burned. We then consider divisional differences in wind characteristics and their relationship to area burned. In order to evaluate long term changes we distinguish Historical (1910 USFS/1919 CALFIRE – 1969) from Recent (1970–2021) eras. Comparing Historical vs Recent eras provides an average over five decades that can be more revealing than trend analysis that emphasizes spikes every few years over a shorter time period, and this is illustrated for VPD in the Results Section.

Methods

To characterize the different climatic conditions contributing to fire activity, we used five of the seven NOAA climate divisions in California (Vose *et al.* 2014), which capture the bulk of the historically burned area (Fig. 2*a*). These divisions are designated as climatically homogeneous areas (Guttman and Quayle 1996), although a better description is that climates within a division are more similar than they are to neighboring divisions. The five divisions were Division 1 (North Coast), Division 2 (North Interior), Division 4 (Central Coast), Division 5 (Sierra Nevada) and Division 6 (South Coast); names have been abbreviated or renamed to provide a more useful description. The five divisions reflect strong gradients in climate and vegetation, and we considered separately the lower elevation valleys and foothills protected by CAL FIRE (1919–2021) and the montane USFS (1910–2021) lands, resulting in 10 ecoregions.

Our analysis provides a finer division of climate regions than used in other studies; e.g. Williams *et al.* (2019) did not distinguish between North Coast and North Interior ranges



(*b*)	North Coast	North Interior	Sierra Nevada	Central Coast	South Coast
Mean elevation (m)					
CAL FIRE	540	740	500	430	660
USFS	1320	1800	2190	1345	1550
Dominant vegetation (%)					
CAL FIRE	Conifer(52)	Conifer(35)	Grass(49)	Grass(43)	Shrub(81)
	Hrdwd(20)	Hrdwd(27)	Hrdwd(29)	Hrdwd(29)	Grass(19)
USFS	Conifer(72)	Conifer(69)	Conifer(57)	Shrub(69)	Shrub(43)
	Shrub(15)	Shrub(17)	Shrub(17)	Hrdwd(24)	Conifer(12)

Fig. 2. (*a*) National Oceanic and Atmospheric Administration (NOAA) five climate divisions used in this study for California Department of Forestry and Fire Protection (CAL FIRE) (tan) and United States Forest Service (USFS) (green) protected lands plus (*b*) mean elevation and top two dominant vegetation types (%); conifer, grass, shrub, and hrdwd = hardwoods, for the 10 ecoregions investigated here.

and grouped all of the Sierra Nevada Range, that spans over 700 km north to south, which is almost double the NOAA division designated here, as Sierra Nevada. Also, they restricted their analysis to what they termed ‘summer fires’, defined as the 8 months March–October. Our study considered the total area burned annually, which included summer and autumn fires that are often driven by very different factors (e.g. Keeley *et al.* 2024).

Wildfire histories were assembled from annual summaries of all fires and included number of fires and area burned by ignition source for CAL FIRE counties in each climate division, obtained from written records (1919–1930 unpublished reports from the California State Archives, and 1931–2021 from annual Redbook publications; https://www.fire.ca.gov/our-impact/statistics). USFS data came from annual reports available at the University of California BioSciences Library (1910–1995, National Forest Fire Reports, US Department of Agriculture (USDA) Forest Service), and USFS FireStat (https://www.wildfire.gov/application/firestat) (1996–2020) and National Interagency Fire Center (https://www.nifc.gov/fire-information/statistics/wildfires) (2021). Due to large differences in division areas, fire activity was expressed as number of fires, or hectares burned, per million hectares protected.

Reporting of ignition sources has changed over time. In the first part of the 20th century powerline-ignited fires were of minor importance and not reported on USFS lands. Intentional ignitions were recorded as incendiary fires in the first part of the 20th century but beginning in 1981 reported as arson fires. This change was perhaps related to perceived intentions of people starting these fires, but this remains an interesting area for further research.

The perimeters of the largest fires for each climate division were obtained from the CAL FIRE Fire and Resource Assessment Program (FRAP) fire history database (http://frap.fire.ca.gov/data/frapgisdata). This is a spatially explicit database that provides day of ignition, final fire size and cause, and is relatively complete for this time period for fires >40 ha, though a number of additions and corrections were made, as described in Keeley *et al.* (2021). As illustrated in the comparison of fire history databases in California (Syphard and Keeley 2015) this is a spatially explicit database, and although smaller fires were not well captured prior to 1950, larger fires are represented throughout the 20th century. This database was also used to evaluate the role of winds in determining fire size as described below.

These CAL FIRE and USFS protected areas were overlaid on a vegetation map (https://www.fire.ca.gov/Home/What-We-Do/Fire-Resource-Assessment-Program/GIS-Mapping-and-Data-Analytics) to illustrate the dominant vegetation types in each ecoregion (Fig. 2*b*). We quantified the vegetation types within each ecoregion; as with most vegetation maps, this represents one point in time and does not portray historical changes in vegetation.

To evaluate climate and weather effects on fire activity we utilized Parameter-Elevation Regressions on Independent Slopes Model (PRISM) climate data (PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu/historical/ and https://prism.oregonstate.edu/recent/, accessed March 2025). For each year and month, within the boundaries of each of the five divisions, we extracted mean and maximum temperature, precipitation and maximum vapor pressure deficit. The Palmer Drought Severity Index (PDSI) was obtained from Dai and National Center for Atmospheric Research Staff (2023). Seasonal data were based on averages for: winter (prior-year-December, January, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November).

To evaluate the relative role of winds across these climate divisions, we extracted modeled hourly statistically downscaled wind speed and direction data, provided by Dan Cayan and David Pierce at Scripps Institution of Oceanography, University of California, San Diego (UCSD), for all fire perimeters from 1979 to 2019. The statistical downscaling was implemented using the Localized Constructed Analogs (LOCA) technique (Pierce and Cayan 2016; Pierce *et al.* 2018), trained from a 10-year (2004–2013) high resolution Weather Research and Forecast downscaled historical reanalysis https://cansac.dri.edu/cofframe.php?page=reanalysis.php supplied by T. Brown at the Desert Research Institute. The LOCA downscaled winds and humidity, and used the European Center’s ERA 0.25° (approximately 31 km) global reanalysis as the parent global model. The modeled LOCA downscaling produced gridded vector surface wind data at 3 km resolution.

Statistical analysis used parametric tests when appropriate. Many pairwise comparisons (see results) had normal distributions and equal variances (with high/low variance ratios less than two) and were tested with a Students *t*-test. When these assumptions were not met we used the Kruskal–Wallis non-parametric test; although designed for groups of three or more, with comparisons of two groups it produces results comparable to the commonly used Mann–Whitney test. Area burned was not normally distributed and so a Log10 transformation was used. We did not log transform fire frequency.

We used least squares regression to determine the best model (defined as the best linear unbiased estimator based on the highest R^2 value) for the two dependent variables, annual fire frequency (number of fires per year), and annual area burned for each climate division. Independent variables of seasonal climates included total precipitation, mean and maximum temperatures, maximum VPD, PDSI, and number of fires as an independent variable when area burned was the dependent variable. We started with all possible independent variables and iteratively removed them from the equation based on non-significance, or pairwise correlations with other independent variables. To avoid multicollinearity, we calculated correlation coefficients among all pairs of potential explanatory variables. Where correlations were significant ($P < 0.05$), we eliminated the one from the pair with the lowest significance (i.e. with higher P values) to produce the best model. We did not model variable interactions. We checked the Durbin–Watson D statistic, and there was no significant first-order autocorrelations; specifically all were between 1.5 and 2.5 Durbin Watson Test & Test Statistic - Statistics How. Independence of residuals was determined by visual inspection of residual plots. These analyses were conducted with Systat 13.0 software (Wilkinson 2010).

Results

Historical pattern of fires in the 10 California ecoregions

In all five climate divisions fires were much more abundant on CAL FIRE protected lands than on the higher elevation USFS lands (Fig. 3). Comparing Historical (1910 USFS/1919 CALFIRE – 1969) vs Recent (1970–2021) eras showed fire frequency increased significantly in the second half of the record, with the exception of the two northern USFS ecoregions. In the South Coast on both CAL FIRE and USFS lands, fire frequency was substantially higher than in other divisions. Over the 103 year record, the number of fires on CAL FIRE lands was not monotonic, but generally peaked in the 1970s–1980s.

Area burned (Fig. 4) exhibited substantial annual variation in all ecoregions, all had high area burned in recent years with the highest areas on USFS lands. In contrast to other divisions, the Central Coast and South Coast USFS ecoregions had high years of area burned throughout the 100+ year history.

Ignition sources

Of the 10 consistently reported ignition sources (Table 1), lightning was a dominant source on USFS lands in the Sierra Nevada and further north. In all but 2 of the 10 ecoregions, lightning-ignited fires increased in the Recent Era. The North Interior had the highest lightning ignitions on USFS lands and this did not change over time. On both CAL FIRE and USFS lands lightning ignitions occurred in most years, but were characterized by peaks at roughly 5–10 year intervals (Fig. 5).

Over 90% of all fires on CAL FIRE protected lands were due to human ignitions, with the Central Coast and South Coast having the highest proportion at 98% of all fires in the Recent Era (Table 2*a*). However, the pattern was different on USFS lands where human ignitions accounted for only about 50% or less of all fires in the North Coast, North Interior and Sierra Nevada. On the Central Coast and South Coast USFS lands human ignitions represented a much greater proportion of all ignitions (78–86%) than those divisions farther north, and in the latter division there was a highly significant increase in the Recent Era.

As with lightning ignitions, human ignitions have changed over time and the sources have changed as well (Table 1). The most consistent change was observed in smoking caused fires, where in all 10 ecoregions there was a highly significant decrease between the Historical and Recent eras. During the former era it was a leading cause of fires but in the latter it was a minor source. Another ignition source with consistent declines over time was railroad-ignited fires; on the lower elevation CAL FIRE lands it was an important ignition source

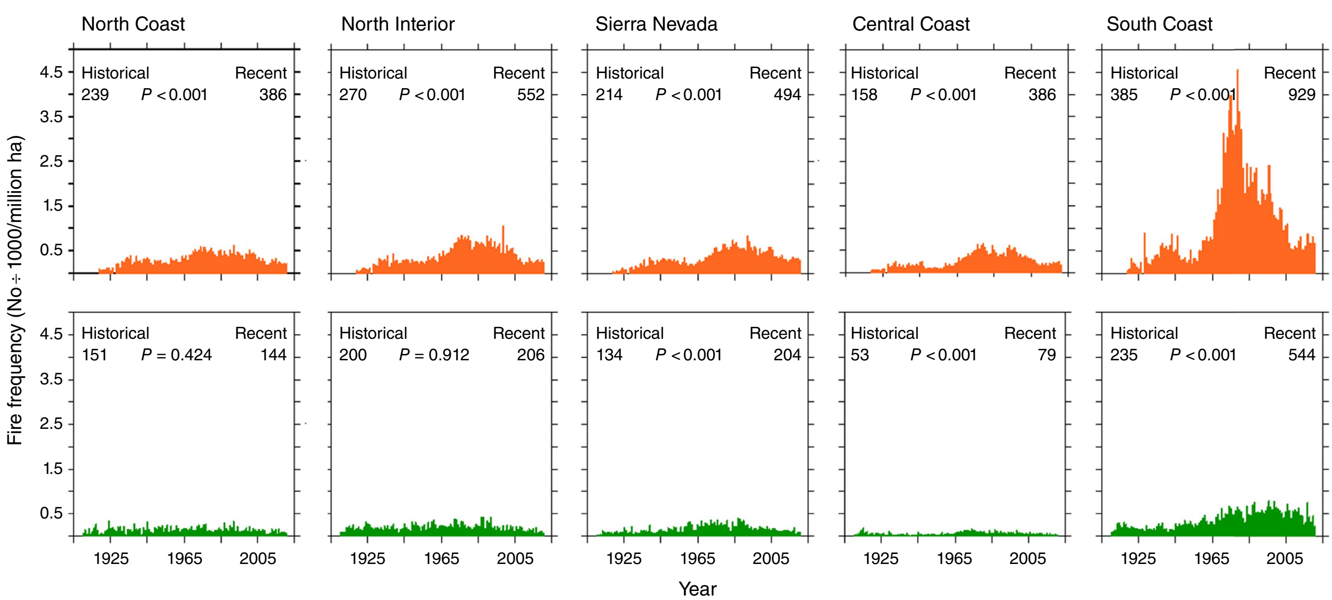


Fig. 3. Annual fire frequency for all fires in the ten ecoregions, California Department of Forestry and Fire Protection (CAL FIRE) upper panel in orange (1919–2021) and United States Forest Service (USFS) lower panel in green (1910–2021), with number of fires (÷1000) per million ha presented for the Historical (1910/1919–1969) and Recent (1970–2021) eras, and *P*-values for the Student's *t*-test.

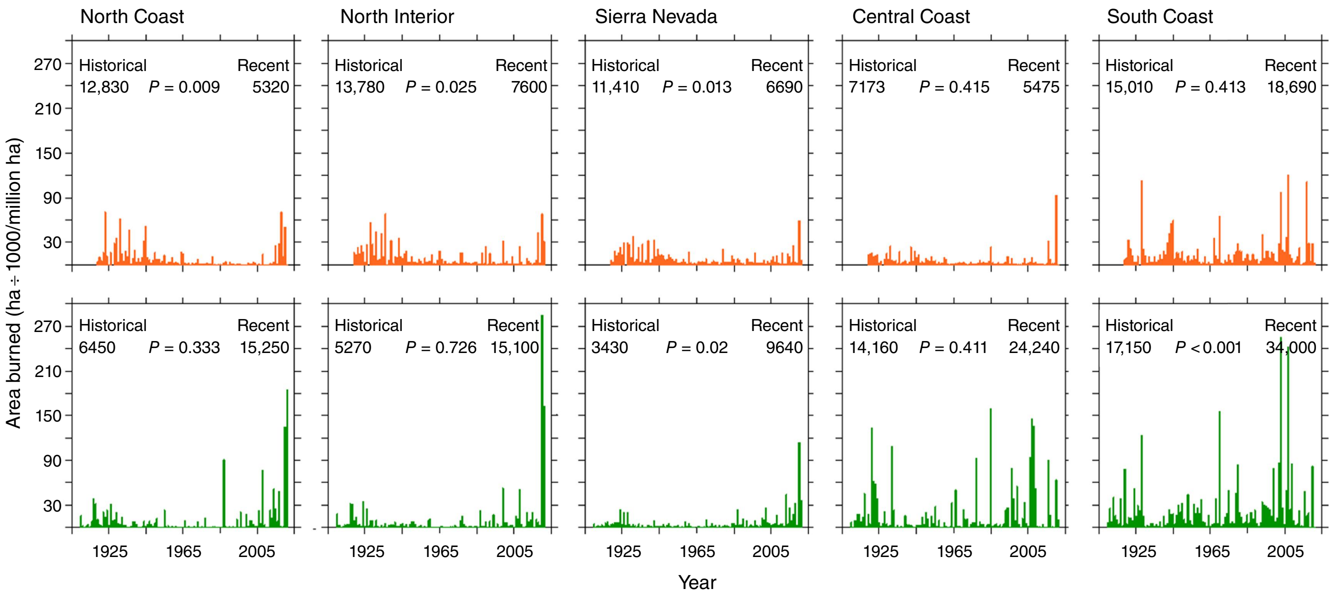


Fig. 4. Annual area burned for all fires in the ten ecoregions, California Department of Forestry and Fire Protection (CAL FIRE) upper panel in orange (1919–2021) and United States Forest Service (USFS) lower panel in green (1910–2021), with ha area burned (÷1000) per million ha presented for the Historical (1910/1919–1969) and Recent (1970–2021) eras, and *P*-values for the Student's *t*-test.

in the Historical Era, but declined significantly in the Recent Era. On USFS lands railroad-ignited fires were not as important of an ignition source. Camping ignitions on the other hand increased in the Recent Era in all but 1 of the 10 ecoregions. Arson has been an important source on CAL FIRE protected lands throughout the 103 years of record, and in the South Coast it increased five-fold between the Historical and Recent eras. Some ignition sources were most important on CAL FIRE lands; these were debris burning, equipment, powerlines, children playing and vehicles. Powerline fires were relatively unimportant in the Historical Era (i.e. low on CAL FIRE lands and not even reported on USFS lands), however they were high in the Recent Era on CAL FIRE lands, and many times more frequent than on USFS lands. Playing and vehicles were ignition sources that increased on CAL FIRE lands in the Recent Era in most divisions.

In terms of area burned, humans accounted for the majority of burned area in all ecoregions (Table 2*b*). On USFS lands in the North Interior and Sierra Nevada, lightning accounted for a significantly greater proportion of area burned in the Recent Era relative to the Historical Era, amounting to ~40% of area burned. In contrast, in the South Coast it accounted for only ~5% of area burned in the Recent Era.

Area burned by lightning-ignited fires has been important on both CAL FIRE and USFS lands (Table 3) but it wasn't tightly linked to number of ignitions; 8 of the 10 ecoregions exhibited increased number of lightning-ignited fires between Historical and Recent eras (Table 1) but only on Sierra Nevada USFS lands was there a highly significant increase in area burned (Table 3).

In contrast, smoking-ignited, as well as railroad-ignited fires, showed decreases in number (Table 1) and area burned (Table 3) on nearly all of the 10 ecoregions. Camping fires were never a major source of area burned. Arson was a very large source of area burned in all 10 ecoregions in the Historical Era, but dropped markedly in the Recent Era in 6 of the ecoregions. Debris burning was an important source during the Historical Era but declined in the Recent Era. In contrast, powerlines were only significant in the Recent Era and the highest annual average area burned was in the South Coast on both CAL FIRE and USFS lands.

Long term woody fuel accumulation

Fuel accumulation, which contributes to fire severity, is in part a function of time since fire (e.g. Steel *et al.* 2015). To illustrate potential differences between climate divisions we present the fire history within the perimeters of the largest fires in each climate division, all of which occurred in the last few years (Supplementary Fig. S1). For all but the South Coast, the largest fires burned landscapes in which two-thirds or more had no recorded fires since at least 1910 (see uncolored areas within the fire perimeters in Supplementary Fig. S1 and Table 4). The South Coast stood in stark contrast (Supplementary Fig. S1) in that within the perimeter of the largest fire only 8% of the landscape had escaped previous burning since 1910 (Table 4). Fire rotation intervals, which are based on the area burned in the 100 years prior to these recent large fires, represent the time required to burn an area equivalent to the entire division (Table 4). In the Sierra

Table 1. Fire frequency by ignition source for fires reported by the California Department of Forestry and Fire Protection (CAL FIRE) and the United States Forest Service (USFS) for each of the five climate divisions, separated into approximately the first half of records labeled Historical, and the second labeled Recent.

Ignition source/division	Fire frequency (number/year/million ha)					
	CAL FIRE			USFS		
	Historical (1919–1969)	Recent (1970–2021)	P	Historical (1910–1969)	Recent (1970–2021)	P
Lightning						
North Coast	18	30	0.002	88	87	0.986
North Interior	24	49	<0.001	104	125	0.143
Sierra Nevada	13	21	<0.001	72	106	0.002
Central Coast	3	5	0.006	8	15	0.005
South Coast	12	20	0.001	57	78	0.006
Smoking						
North Coast	56	18	<0.001	17	6	<0.001
North Interior	80	25	<0.001	33	11	<0.001
Sierra Nevada	67	25	<0.001	67	25	<0.001
Central Coast	44	15	<0.001	10	3	<0.001
South Coast	109	56	<0.001	45	25	<0.001
Railroad						
North Coast	7	3	<0.001	1	1	0.544
North Interior	18	8	<0.001	8	5	<0.001
Sierra Nevada	13	3	<0.001	13	3	<0.001
Central Coast	4	6	0.045	1	0	<0.001
South Coast	20	9	0.001	7	7	0.085
Camping						
North Coast	8	19	<0.001	8	10	0.044
North Interior	9	13	0.001	18	18	0.766
Sierra Nevada	7	11	0.001	8	11	<0.001
Central Coast	12	14	0.017	9	11	0.012
South Coast	19	49	<0.001	29	68	<0.001
Arson						
North Coast	49	45	0.542	17	11	0.357
North Interior	44	62	0.074	10	7	0.466
Sierra Nevada	34	53	0.001	34	53	<0.001
Central Coast	16	44	<0.001	6	11	0.080
South Coast	31	157	<0.001	18	74	<0.001
Debris						
North Coast	45	48	0.017	5	7	0.001
North Interior	45	76	<0.001	6	8	0.033
Sierra Nevada	57	57	0.999	5	8	<0.001
Central Coast	46	25	<0.001	6	3	0.004
South Coast	126	64	0.102	17	9	<0.001

(*Continued on next page*)

Table 1. *(Continued)*

Ignition source/division	Fire frequency (number/year/million ha)					
	CAL FIRE			USFS		
	Historical (1919–1969)	Recent (1970–2021)	*P*	Historical (1910–1969)	Recent (1970–2021)	*P*
Equipment						
North Coast	41	71	0.096	15	3	<0.001
North Interior	81	109	0.128	24	6	<0.001
Sierra Nevada	39	119	0.001	39	119	0.001
Central Coast	56	98	0.079	8	5	0.046
South Coast	79	179	0.026	41	45	0.969
Powerlines						
North Coast	0	15	<0.001	–	1	
North Interior	0	13	<0.001	–	1	
Sierra Nevada	0	20	<0.001	–	1	
Central Coast	0	20	<0.001	–	2	
South Coast	0	21	<0.001	–	8	
Playing						
North Coast	1	22	0.040	–	3	
North Interior	1	34	0.027	–	5	
Sierra Nevada	0	23	0.022	–	5	
Central Coast	0	23	0.045	–	4	
South Coast	0	96	0.017	–	40	
Vehicles						
North Coast	1	29	<0.001	–	3	
North Interior	22	55	0.451	–	5	
Sierra Nevada	9	48	0.050	–	7	
Central Coast	7	30	0.059	–	6	
South Coast	6	44	0.016	–	65	

Statistical comparisons were made with the Kruskal–Wallis test.

Nevada, North Interior and North Coast, rotation intervals were two to five times longer than in the South Coast.

Climate

Atmospheric aridity as measured by VPD has varied annually over the past 112 years in all climate divisions (Fig. 6). Regression analysis has found no significant change in VPD for any division over this time period (R^2 values varied from 0.000 to 0.023). Literature discussed in the introduction has shown trends in increased VPD in the last couple decades in the western US and have attributed this increase in aridity to anthropogenic climate change. There is support for this in some California climate divisions but not others. Regression analysis of California divisions since 2000 has found weakly significant increases in summer VPD in; North Coast $R^2 = 0.240$, $P = 0.012$, North Interior $R^2 = 0.170$, $P = 0.032$, Sierra Nevada $R^2 = 0.201$, $P = 0.021$, Central Coast $R^2 = 0.168$, $P = 0.033$, but not in the South Coast $R^2 = 0.000$, $P = 0.778$. Thus, recent increases in VPD are evident in the northern forested divisions but absent from the South Coast. However, in terms of attributing VPD changes to climate change, it is worth noting that the recent increases are not unprecedented; e.g. in the North Interior a similar two decade period beginning in 1920 also showed a significant increase in VPD, $R^2 = 0.167$, $P = 0.043$. In addition, in four of the five divisions the highest summer VPD was not in the last two decades (Fig. 6). The lack of trends over the last century led us to compare long term patterns in the Historical (1910–1969) vs Recent (1970–2021) eras (Table 5). Comparing these two time periods, winter VPD was higher in the Recent Era only in the South Coast. It was significantly lower in spring and summer in the North Coast, but lower in spring and summer in the North Coast, and lower in summer in the Sierra Nevada (Table 5).

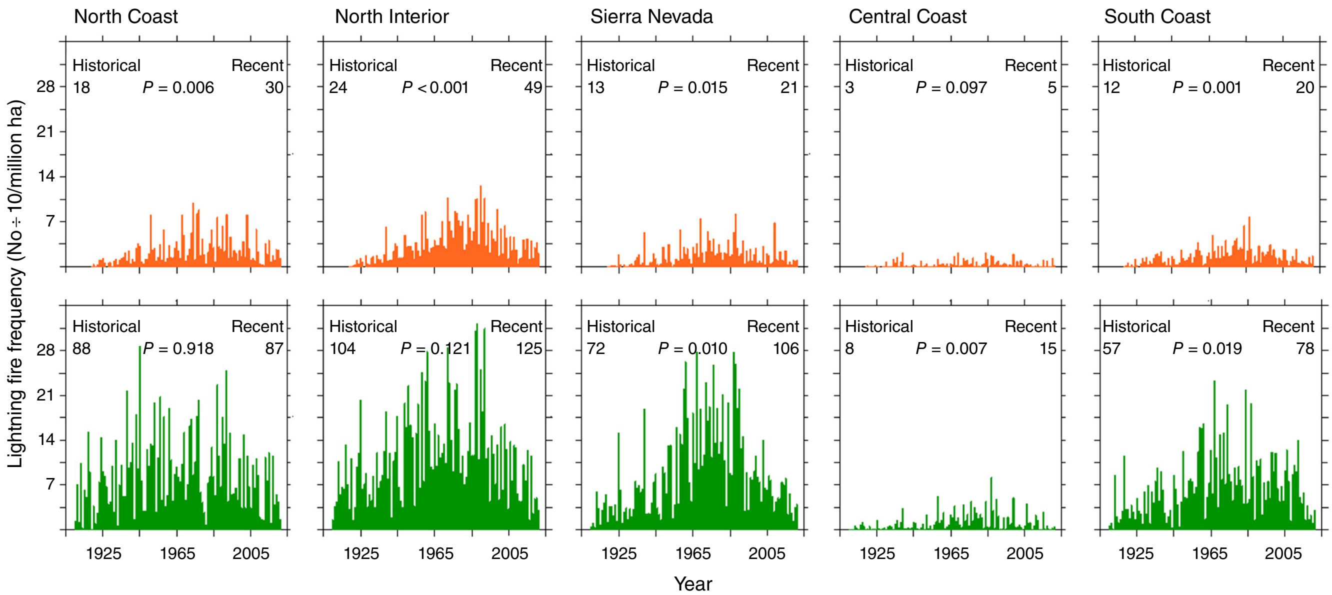


Fig. 5. Annual lightning fire frequency in the tenecoregions, California Department of Forestry and Fire Protection (CAL FIRE) upper panel in orange (1919–2021) and United Stattes Forest Service (USFS) lower panel in green (1910–2021), with fires (÷10) per million ha presented for the Historical (1910/1919–1969) and Recent (1970–2021) eras, and *P*-values for the Student's *t*-test.

Table 2. Proportion of fires due to human ignitions vs lightning ignitions: (*a*) Percentage of fires ignited by humans and (*b*) percentage of area burned ignited by humans, for fires reported by the California Department of Forestry and Fire Protection (CAL FIRE) and the United States Forest Service (USFS) for each of the five climate divisions, separated into approximately the first half of records labeled Historical, and the second labeled Recent.

(*a*)	Fire frequency (%)					
	CAL FIRE			USFS		
Division	**Historical (1919–1969)**	**Recent (1970–2021)**	***P***	**Historical (1910–1969)**	**Recent (1970–2021)**	***P***
North Coast	92.5	92.5	0.999	47.0	45.1	0.527
North Interior	92.1	91.2	0.934	51.1	43.4	0.011
Sierra Nevada	94.6	95.7	0.250	53.9	51.8	0.510
Central Coast	98.1	99.6	0.426	85.1	83.1	0.484
South Coast	96.7	97.7	0.019	77.9	86.0	<0.001

(*b*)	Area burned (%)					
	CAL FIRE			USFS		
Division	**Historical (1919–1969)**	**Recent (1970–2021)**	***P***	**Historical (1910–1969)**	**Recent (1970–2021)**	***P***
North Coast	95.8	88.5	0.045	74.7	63.9	0.126
North Interior	92.5	83.1	0.019	79.8	58.0	<0.001
Sierra Nevada	92.2	88.8	0.312	86.6	68.9	<0.001
Central Coast	91.1	91.8	0.916	92.8	88.6	0.342
South Coast	93.5	95.1	0.493	91.0	94.7	0.185

Statistical comparisons with the Student's *t*-test.

Over the 100+ year record there were significant increases in annual area burned with higher VPD in most ecoregions, although, the strength of that relationship varied with season and division (Fig. 7). With a few notable exceptions, it explained less than 10% of the variation in area burned (Fig. 7). Ecoregions where VPD explained more variance were in the North Coast, where spring, summer and autumn accounted for 15–17% and in the North Interior around 20%. In these two northern California ecoregions, CAL FIRE protected lands were unique in that there was a significant R^2 between annual area

Table 3. Area burned by ignition source for fires reported by the California Department of Forestry and Fire Protection (CAL FIRE) and the United States Forest Service (USFS) for each of the five climate divisions, separated into approximately the first half of records labeled Historical, and the second labeled Recent.

Ignition source/division	Area burned (ha/year/million ha)					
	CAL FIRE			USFS		
	Historical (1919–1969)	Recent (1970–2021)	*P*	Historical (1910–1969)	Recent (1970–2021)	*P*
Lightning						
North Coast	1600	6600	0.022	1100	9300	0.253
North Interior	1100	2300	0.906	1000	7600	0.042
Sierra Nevada	1400	2700	0.582	300	2900	<0.001
Central Coast	48	3999	0.005	300	5200	0.005
South Coast	300	800	0.880	1000	1300	0.391
Smoking						
North Coast	2000	420	<0.001	620	30	<0.001
North Interior	2900	130	<0.001	820	15	<0.001
Sierra Nevada	3500	120	<0.001	3500	125	0.001
Central Coast	3073	120	<0.001	1700	650	<0.001
South Coast	4200	270	<0.001	3140	1100	<0.001
Railroad						
North Coast	230	10	<0.001	10	3	0.141
North Interior	500	15	<0.001	570	170	<0.001
Sierra Nevada	340	40	<0.001	340	40	<0.001
Central Coast	164	12	<0.001	30	1	<0.001
South Coast	750	40	<0.001	280	50	0.036
Camping						
North Coast	320	35	<0.001	270	80	0.567
North Interior	730	120	<0.001	500	190	0.026
Sierra Nevada	220	110	0.003	220	110	0.236
Central Coast	367	429	<0.001	4070	2380	0.048
South Coast	930	300	0.952	1040	4810	0.054
Arson						
North Coast	5400	420	<0.001	2900	710	<0.001
North Interior	6500	840	<0.001	1100	300	<0.001
Sierra Nevada	3900	850	<0.001	3900	850	0.090
Central Coast	2693	608	<0.001	3110	2920	0.582
South Coast	4300	2700	0.893	3300	8190	0.142
Debris						
North Coast	1700	140	<0.001	150	80	0.834
North Interior	840	240	<0.001	150	80	0.015
Sierra Nevada	1340	200	<0.001	1340	200	0.004
Central Coast	896	317	<0.001	1500	1650	0.001
South Coast	1580	370	<0.001	910	610	<0.001

(*Continued on next page*)

Table 3. (*Continued*)

Ignition source/division	Area burned (ha/year/million ha)					
	CAL FIRE			USFS		
	Historical (1919–1969)	Recent (1970–2021)	*P*	Historical (1910–1969)	Recent (1970–2021)	*P*
Equipment						
North Coast	170	540	0.611	70	60	0.004
North Interior	600	1300	0.583	490	260	0.126
Sierra Nevada	800	1360	0.319	810	1360	0.893
Central Coast	566	1464	0.058	5200	3750	0.788
South Coast	620	3300	0.034	2550	2040	0.579
Powerlines						
North Coast	140	1020	0.852	–	3	–
North Interior	40	1550	0.621	–	120	–
Sierra Nevada	100	400	0.575	–	25	–
Central Coast	3	123	0.043	–	125	–
South Coast	–	2529	–	–	4470	–
Playing						
North Coast	1	40	0.191	–	6	–
North Interior	1	30	0.047	–	6	–
Sierra Nevada	40	75	0.641	–	60	–
Central Coast	1	37	0.080	–	230	–
South Coast	1	410	0.030	–	1460	–
Vehicles						
North Coast	20	60	0.597	–	65	–
North Interior	650	170	0.042	–	370	–
Sierra Nevada	900	470	0.097	–	240	–
Central Coast	650	776	0.880	–	1450	–
South Coast	140	310	0.821	–	560	–

Statistical comparisons with the Kruskal–Wallis test.

Table 4. Largest fires reported for each of the five climate divisions reported in FRAP, which iincludes California Department of Forestry and Fire Protection (CAL FIRE) and the United States Forest Service (USFS) fires, and the portion of area within the fire perimeter that had not burned since at least 1910. Also presented is the calculated fire rotation interval.

	Name	Year	ha	Area unburned since 1910 (%)	Fire rotation (years)	
					CAL FIRE	USFS
North Coast	August Cmplx	2020	417,933	66	131	128
North Interior	Dixie	2021	389,890	67	102	119
Sierra Nevada	Creek	2020	157,738	77	122	198
Central Coast	CZU	2020	160,422	86	110	53
South Coast	Thomas	2017	114,040	8	66	39

Fire rotation interval is thetime required to burn an area the size of the division, based on the 100 years of fires prior to the largest fire in the division.

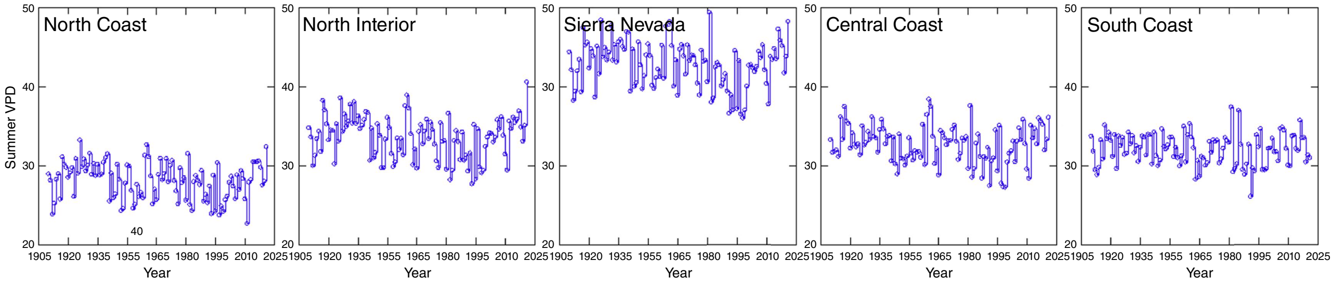


Fig. 6. Annual fluctuations in summer vapor pressure deficit (VPD) from 1910 to 2021 for the five climate divisions. Across the entire record Least Squares regression analysis showed no significant relationship between VPD and year, but in the last two decades there was a weakly significant increase in four of the divisions; North Coast R^2 = 0.240, P = 0.012, North Interior R^2 = 0.170, P = 0.032, Sierra Nevada R^2 = 0.201, P = 0.021, Central Coast R^2 = 0.168, P = 0.033 and South Coast R^2 = 0.000, P = 0.778.

Table 5. Seasonal distribution of vapor pressure deficit (VPD) and Palmer Drought Severity Index (PDSI) for the five climate divisions, separated into approximately the first half of records labeled Historical, and the second labeled Recent.

Season/division	VPD (hPa)			PDSI		
	Historical (1910–1969)	Recent (1970–2021)	*P*	Historical (1910–1969)	Recent (1970–2021)	*P*
Winter						
North Coast	6.0	6.1	0.727	−0.329	−0.321	0.979
North Interior	6.3	6.5	0.272	−0.314	−0.158	0.646
Sierra Nevada	8.5	8.5	0.786	−0.197	−0.630	0.298
Central Coast	9.3	9.5	0.588	−0.140	−0.445	0.466
South Coast	10.9	11.6	0.016	0.164	−1.048	0.007
Spring						
North Coast	13.4	12.7	0.035	−0.373	−0.185	0.615
North Interior	14.7	14.4	0.401	−0.305	0.002	0.420
Sierra Nevada	19.4	19.3	0.834	−0.138	−0.860	0.129
Central Coast	15.8	15.8	0.987	−0.061	−0.544	0.317
South Coast	16.4	16.5	0.850	0.387	−0.933	0.011
Summer						
North Coast	28.5	27.6	0.049	−0.152	−0.467	0.419
North Interior	34.0	33.1	0.060	−0.082	−0.225	0.735
Sierra Nevada	43.5	42.1	0.010	0.140	−0.943	0.041
Central Coast	33.0	32.3	0.084	0.336	−0.723	0.045
South Coast	32.1	32.0	0.767	0.697	−1.409	<0.001
Autumn						
North Coast	17.9	17.9	0.351	−0.357	−0.541	0.548
North Interior	19.8	19.5	0.426	−0.461	−0.266	0.540
Sierra Nevada	25.2	24.6	0.130	−0.185	−0.807	0.109
Central Coast	23.2	22.7	0.158	−0.069	−0.690	0.098
South Coast	23.3	23.4	0.947	0.314	−1.405	<0.001

Winter = Dec from prior year, Jan, Feb; Spring = March, April, May; Summer = June, July, August; Autumn = September, October; November, higher VPD indicates greater atmospheric aridity and higher PDSI indicates moister conditions. Statistical comparisons with the Student's *t*-test.

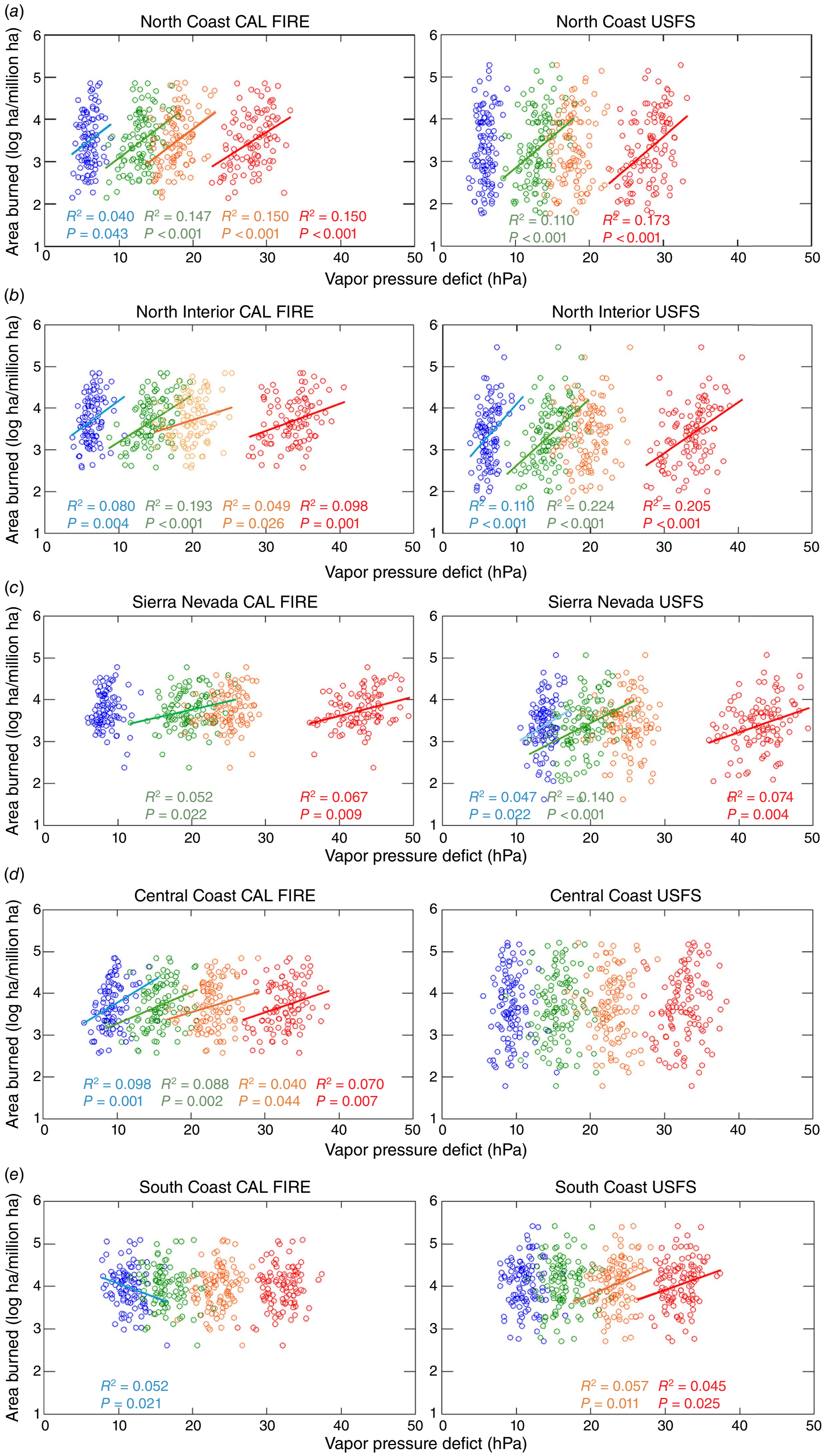


Fig. 7. Seasonal vapor pressure vs annual area burned for winter (blue), spring (green), red (summer) and autumn (orange) for the five California Department of Forestry and Fire Protection (CAL FIRE) (1919–2021) and United States Forest Service (USFS) (1910–2021) climate divisions (*a*–*e*) with R^2 and *P*-values for those with $P < 0.05$ based on Least Squares regression. Seasons are as described in Table 5 footnote.

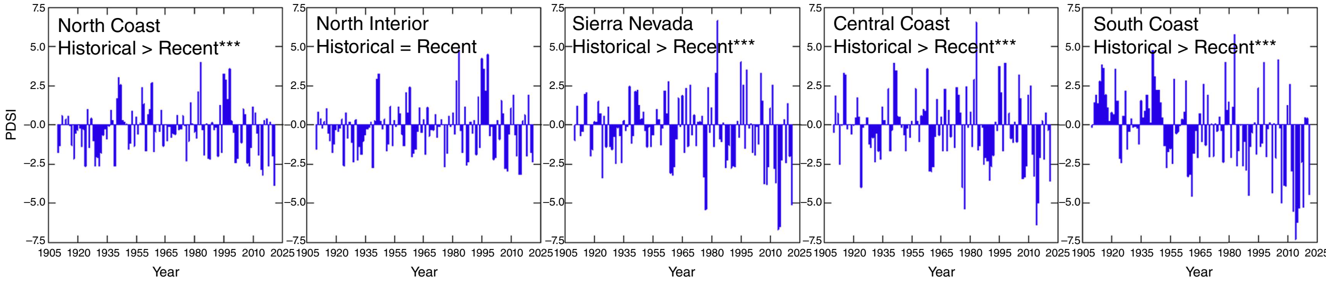


Fig. 8. Mean annual Palmer Drought Severity Index for the five climate divisions and Student's *t*-test comparison of Historical (1910–1969) vs Recent (1970–2021, *** = $P < 0.001$.

burned and VPD in all seasons. In the Sierra Nevada the strongest relationship between area burned and VPD was springtime VPD on USFS lands, but in the Central Coast there was no significant R^2 in any season on USFS lands. In the South Coast VPD explained only 0–5% of the annual variation in area burned.

Annual drought as measured by PDSI, which is a function of precipitation and temperature, showed substantial annual variation throughout the 112 year record in all climate divisions (Fig. 8). In the Recent Era all divisions except the North Interior had a significantly lower PDSI (i.e. greater drought) than the Historical Era. However, this pattern was not observed for individual seasons (Table 5). Summer droughts were significantly more severe in the Recent Era in the Sierra Nevada, Central Coast and South Coast; however, the South Coast stood out with significantly greater droughts in the Recent Era in all seasons. The North Coast and North Interior had no change in PDSI between Historical and Recent eras in all seasons.

Precipitation followed a Mediterranean climate, ramping up in the autumn, peaking in winter, and declining to very little in summer (Table 6). In all seasons the North Coast and North Interior had the highest precipitation. Over the 112 years of record there was no evidence of a change between the Historical and Recent eras in precipitation for any season in any climate division (Table 6).

Not surprisingly, mean temperatures were lowest in winter and highest in summer (Table 6). Temperatures were slightly, but significantly warmer in the Recent Era, with the exception of spring temperatures. In only the South Coast spring temperatures were significantly higher in the Recent Era.

Multivariate regression models were used to determine what combination of climate factors (seasonal mean temperature, precipitation, maximum VPD and PDSI) that were statistically significant in driving fire frequency (Table 7*a*) and area burned (Table 7*b*) for all fires in the 10 ecoregions. For each ecoregion and each era there was a different model determining number of fires and area burned. Climate models were also examined for just those fires ignited by lightning (Table 8).

North Coast

On CAL FIRE protected lands the number of fires (Table 7*a*) increased with increasing autumn temperatures in the Historical Era and this alone explained 25% of the annual variation. However, in the Recent Era number of fires increased with lower summer temperatures followed by lower spring precipitation. On USFS lands no climate variable explained number of fires in the Historical Era, however, in the Recent Era, in order of significance level, low spring precipitation, low winter temperature and high summer precipitation produced the highest R^2.

In terms of area burned (Table 7*b*), as much as one-third of the annual variation in area burned on both CAL FIRE and USFS lands was explained by aridity factors; was consistent with the patterns in Fig. 7*a*.

Number of lightning-ignited fires (Table 8*a*) during the Historical Era were tied to moist conditions in the prior 2 years, but to higher aridity in the Recent Era. The strongest model for area burned by this ignition source was 27% for USFS lands in the Recent Era, explained by a moist year coupled with moisture in the prior 3 years and high summer temperatures (Table 8*b*).

North interior

Historically the number of fires on both CAL FIRE and USFS lands were best predicted by higher summer and autumn temperatures, however, in the Recent Era seasonal temperatures and precipitation, indicating drier springs but cooler summer conditions, were the only significant factors (Table 7*a*).

Area burned (Table 7*b*) was strongly related to high VPD in most seasons in both the Historical and Recent eras. As shown with the bivariate analysis of VPD and annual area burned on USFS lands (Fig. 7*b*), this ecoregion had the strongest relationship between area burned and VPD, with spring and summer explaining approximately 20% of the variation in area burned, however, multiple regression showed that the combination of autumn, spring and summer VPD explained over 40% of the variation (Table 7*b*). One thing that changed between Historical and Recent eras was that in the latter era, number of fires was a significant independent variable in the model of CAL FIRE area burned.

This division has had the highest frequency of lightning-ignited fires (Table 1), and the strongest climate model showed 40% of the annual variation could be explained by moist conditions in the present and prior years coupled with

Table 6. Seasonal distribution of precipitation and mean temperature for the five climate divisions, separated into the first half labeled Historical, and the second labeled Recent.

Season/division	Precipitation (mm)			Mean temperature (°C)		
	Historical (1910–1969)	Recent (1970–2021)	*P*	Historical (1910–1969)	Recent (1970–2021)	*P*
Winter						
North Coast	579	582	0.940	5.0	5.6	0.007
North Interior	386	395	0.773	5.0	5.7	<0.001
Sierra Nevada	271	270	0.947	7.8	8.4	0.003
Central Coast	318	314	0.897	8.4	9.0	0.001
South Coast	281	273	0.799	8.0	9.0	<0.001
Spring						
North Coast	250	281	0.118	10.4	10.4	0.829
North Interior	183	208	0.136	10.7	11.0	0.193
Sierra Nevada	146	150	0.759	14.5	14.9	0.129
Central Coast	129	139	0.478	12.5	12.9	0.061
South Coast	140	136	0.842	12.2	12.7	0.006
Summer						
North Coast	34	36	0.762	18.9	19.3	0.001
North Interior	23	22	0.860	19.7	20.2	<0.001
Sierra Nevada	7	9	0.298	24.7	25.1	0.017
Central Coast	4	4	0.423	20.4	20.8	0.003
South Coast	7	9	0.164	20.4	21.1	<0.001
Autumn						
North Coast	235	243	0.726	13.0	13.3	0.065
North Interior	136	152	0.277	13.1	13.6	0.011
Sierra Nevada	81	93	0.227	16.9	17.4	0.005
Central Coast	74	89	0.132	15.9	16.3	0.010
South Coast	66	67	0.924	15.5	16.3	<0.001

Winter = Dec from prior year, Jan, Feb; Spring = March, April, May; Summer = June, July, August; Autumn = September, October., November. Statistical comparisons with Student's *t*-test.

higher summer and autumn temperatures (Table 8*a*). Over 35% of the area burned by lightning-ignited fires occurred when fires occurred in years and prior years with high moisture, coupled with drier conditions (Table 8*b*).

Sierra Nevada

Over 20% of the annual variation in number of fires (Table 7*a*) on CAL FIRE lands was explained by high PDSI (moist conditions) over the 4-year period (including the current year) in the Historical Era, and in the Recent Era, low summer temperatures and high moisture in the prior-year were the significant drivers behind fire frequency. On USFS lands, autumn temperatures were the only significant factor for number of fires in the Historical Era, but there were no significant climate drivers in the Recent Era.

Area burned (Table 7*b*) on CAL FIRE lands was best modeled with high spring temperature during the Historical Era and by high summer temperature and high winter precipitation in the Recent Era, though only about 10% of the annual variation in area burned was explained. However, on USFS lands over 40% was explained in both the Historical and Recent eras by a combination of lower aridity in the winter and prior years coupled with higher aridity in the spring and autumn. In the former era, number of fires was a significant factor but not in the latter era (Table 7*b*). In these multiple regression models temperature and drought were more significant than VPD.

On the lower elevation CAL FIRE lands number of lightning-ignited fires (Table 8*a*) and area burned (Table 8*b*), half to one-third of the variation was determined by moist years, or prior moist years coupled with warmer summer temperatures.

Table 7. Least squares regression models for each climate division for the California Department of Forestry and Fire Protection (CAL FIRE) and the United States Forest Service (USFS), separated into approximately the first half of records labeled Historical, and the second labeled Recent.

Division/jurisdiction	Historical (1910/1919–1969)			Recent (1970–2021)		
	R^2	P	Best model	R^2	P	Best model
(*a*) Fire frequency						
North Coast						
CAL FIRE	0.246	<0.001	Fires = Temp(aut)	0.186	0.002	Fires = -Temp(sum) - Ppt(spr)
USFS	–			0.175	0.007	Fires = -Ppt(spr) - Temp(win) + Ppt(sum)
North Interior						
CAL FIRE	0.259	<0.001	Fires = Temp(aut) + Temp(sum)	0.334	<0.001	Fires = -Temp(sum) - Ppt(spr)
USFS	0.176	0.001	Fires = Temp(sum)	0.170	0.032	Fires = -Ppt(spr) - Temp(sum)
Sierra Nevada						
CAL FIRE	0.205	0.002	Fires = PDSI(year0–3) + Temp(aut)	0.219	0.001	Fires = -Temp(sum) + PDSI(year-1)
USFS	0.128	0.003	Fires = Temp(aut)	–		
Central Coast						
CAL FIRE	0.123	0.007	Fires = Temp(aut)	0.281	<0.001	Fires = -Temp(sum) + PDSI(year-1)
USFS	–			0.275	<0.001	Fires = -PDSI(year-1) - Temp(sum) - Temp(aut)
South Coast						
CAL FIRE	0.175	0.004	Fires = PDSI(year-1) + Temp(aut)	0.260	0.001	Fires = -Temp(aut) - Temp(sum)
USFS	0.259	<0.001	Fires = -Temp(aut) - Temp(spr) + Temp(win) - Ppt(spr)	0.187	0.001	Fires = PDSI(year-1)
(*b*) Area burned						
North Coast						
CAL FIRE	0.358	<0.001	Log ha = -Ppt(win,spr) + VPD(aut) + Temp(win)	0.393	<0.001	Log ha = VPD(sum) + VPD(aut)
USFS	0.189	<0.001	Log ha = VPD(spr) + VPD(sum)	0.190	<0.001	Log ha = VPD(win,spr,sum)
North Interior						
CAL FIRE	0.282	<0.001	Log ha = VPD(spr) + VPD(win)	0.271	<0.001	Log ha = VPD(win,spr,sum) + Fires
USFS	0.302	<0.001	Log ha = VPD(sum) + VPD(spr)	0.416	<0.001	Log ha = VPD(aut) + VPD(spr) + VPD(sum)
Sierra Nevada						
CAL FIRE	0.105	0.012	Log ha = Temp(spr)	0.130	0.013	Log ha = Temp(sum) + Ppt(win)
USFS	0.411	<0.001	Log ha = -PDSI(spr) - Fires + PDSI(year0–2)	0.447	<0.001	Log ha = Temp(sum) - PDSI(aut) - VPD(win)
Central Coast						
CAL FIRE	0.243	0.001	Log ha = -PDSI(spr) + Temp(win)	0.231	<0.001	Log ha = -PDSI(year0) + PDSI(year-1)
USFS	0.184	0.002	Log ha = -Ppt(spr) - Ppt(win) - Ppt(aut)	0.129	0.013	Log ha = -Ppt(spr) - Temp(spr)
South Coast						
CAL FIRE	0.403	<0.004	Log ha = -Ppt(aut) + Fires + PDSI(year0)	0.120	0.016	Log ha = -VPD(win) + PDSI(year-1)
USFS	0.092	0.011	Log ha = -Ppt(aut)	0.240	<0.001	Log ha = Fires + VPD(sum)

Models with significant ($P < 0.05$) independent variables are presented in order, beginning with lowest P value for dependent variables: (*a*) fire frequency and (*b*) area burned using log 10 transformed data; to avoid collinearity we eliminated correlated independent variables (retaining the one with the lowest P value), and adjusted R^2 values are presented.

Ppt, total precipitation; Temp, mean temperature; VPD, maximum vapor pressure deficit; PDSI, Palmer Drought Severity Index; season and years in parentheses (win) = winter; (spr) = spring; (sum) = summer; (aut) = autumn; (win,spr) = mean of win and spr; (win,spr,sum) = mean of win, spr and sum; (year0) = current year; (year-1) = prior year; (year0–1) = mean of years 0 and -1; (year0–2) = mean of years 0, -1 and -2; (year0–3) = mean of years 0, -1, -2 and -3; (year0–4) = mean of years 0, -1, -2, -3 and -4; Fires, number of fires, in (*a*) used as a dependent variable or in (*b*) as an independent variable.

Table 8. Least squares regression models of lightning-ignoted fires for each climate division for the California Department of Forestry and Fire Protection (CAL FIRE) and the United States Forest Service (USFS), separated into approximately the first half of records labeled Historical, and the second labeled Recent.

Division/jurisdiction	Historical (1910/1919–1969)			Recent (1970–2021)		
	R^2	P	Best model	R^2	P	Best model
(*a*) Fire frequency						
North Coast						
CAL FIRE	0.313	<0.001	Fires = PDSI(year0–2) – VPD(win) + Temp(aut) + Ppt(sum)	0.164	0.009	Fires = -Ppt(spr) + VPD(aut) + Ppt(sum)
USFS	0.159	0.003	Fires = PDSI(year0–2) + PDSI(win)	0.125	0.006	Fires = VPD(spr)
North Interior						
CAL FIRE	0.402	<0.001	Fires = PDSI(year0–1) + Temp(sum) + Temp(aut)	0.130	0.012	Fires = -Ppt(spr) – Temp(sum)
USFS	0.175	0.006	Fires = Temp(sum) + Temp(aut)	0.096	0.015	Fires = -Ppt(spr)
Sierra Nevada						
CAL FIRE	0.099	0.015	Fires = Ppt(win)	0.082	0.022	Fires = PDSI(year0–3)
USFS	0.098	0.008	Fires = Temp(aut)	0.119	0.017	Fires = VPD(spr) +Temp(sum)
Central Coast						
CAL FIRE	0.089	0.020	Fires = Temp(aut)	–		
USFS	0.203	0.001	Fires = Temp(aut) + Temp(sum)	0.131	0.012	Fires = PDSI(year0–3) + PDSI(year-1)
South Coast						
CAL FIRE	0.273	<0.001	Fires = Temp(aut) + Temp(sum)	0.250	<0.001	Fires = PDSI(year0–4)
USFS	0.256	<0.001	Fires = Temp(sum) + Temp(aut) + Ppt(sum)	0.093	0.016	Fires = -Temp(aut)
(*b*) Area burned						
North Coast						
CAL FIRE	–			0.143	0.009	Log ha = VPD(aut) – Temp(sum) – Ppt(spr)
USFS	0.072	0.026	Log ha = -PDSI(sum)	0.271	<0.001	Log ha = Temp(sum) + PDSI(year0–3)
North Interior						
CAL FIRE	0.378	<0.001	Log ha = PDSI(year-1) + Temp(aut) + VPD(win)	0.369	<0.001	Log ha = VPD(aut) – Ppt(sum) + PDSI(year-1)
USFS	0.354	<0.001	Log ha = -Ppt(sum) + PDSI(year0–2) – PDSI(win)	0.448	<0.001	Log ha = VPD(year0) + PDSI(year-1)
Sierra Nevada						
CAL FIRE	0.215	0.001	Log ha = PDSI(year-1)	0.332	<0.001	Log ha = PDSI(year-1) + VPD(aut) – PDSI(win)
USFS	–			0.346	<0.001	Log ha = -PDSI(aut) – VPD(win) + Temp(sum)
Central Coast						
CAL FIRE	0.215	0.001	Log ha = PDSI(year-1)	0.332	<0.001	Log ha = PDSI(year-1) + VPD(aut) – PDSI(win)
USFS	0.205	0.002	Log ha = PDSI(year0–1) + Temp(sum) – Temp(win)	0.192	0.001	Log ha = -Temp(sum)
South Coast						
CAL FIRE	0.295	0.001	Log ha = Temp(sum) – PDSI(win,spr) + Ppt(spr)	0.249	0.001	Log ha = PDSI(sum) + PDSI(year-1)
USFS	–			0.181	0.001	Log ha = PDSI(year-1)

Models with significant (P < 0.05) independent variables are presented in order, beginning with lowest P value for dependent variables: (*a*) fire frequency and (*b*) area burned using log 10 transformed data; to avoid collinearity we eliminated correlated independent variables (retaining the one with the lowest P value), and adjusted R^2 values are presented. Ppt, total precipitation; Temp, mean temperature; VPD, maximum vapor pressure deficit; PDSI, Palmer Drought Severity Index; season and years in parentheses (win) = winter; (spr) = spring; (sum) = summer; (aut) = autumn; (win,spr) = mean of win and spr; (win,spr,sum) = mean of win, spr and sum; (year0) = current year; (year-1) = prior year; (year0–1) = mean of years 0 and -1; (year0–2) = mean of years 0, -1 and -2; (year0–3) = mean of years 0, -1, -2 and -3; (year0–4) = mean of years 0, -1, -2, -3 and -4; Fires, number of fires, in (*a*) used as a dependent variable or in (*b*) as an independent variable.

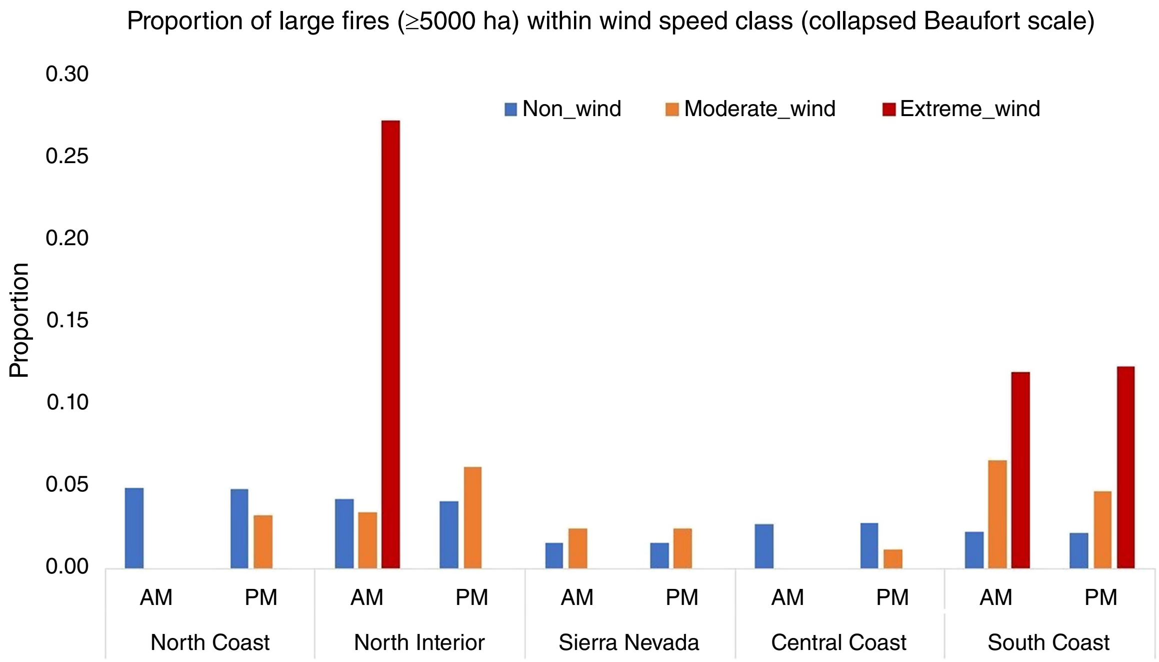


Fig. 9. Proportion of large fires (≥5000 ha) within Beaufort wind speed classes for the five divisions. Times are AM = midnight–noon, PM = noon–midnight, Pacific Standard Time (PST).

Central Coast

Number of fires in the Recent Era was dependent on low summer temperatures coupled with high moisture in the prior year (Table 7*a*). On USFS lands number of fires was a function of low moisture in the prior year PDSI(year − 1) and low summer and autumn temperatures.

Models for area burned (Table 7*b*) on CAL FIRE lands in the Recent Era showed 23% of the variation was explained by a dry year coupled with high moisture in the previous year. Much less was explained by climate variables on USFS lands where cooler dry spring conditions were significant factors.

Number of lightning-ignited fires and area burned by these ignitions were largely determined by a prior moist year coupled with current year aridity (Table 8*a*, *b*).

South Coast

Number of fires (Table 7*a*) on both CAL FIRE and USFS lands, during Historical and Recent eras, were associated with parameters reflecting lower temperatures and higher moisture in the prior year.

Area burned (Table 7*b*) in the Recent Era on CAL FIRE lands was likewise dependent on moist conditions the present and prior year; i.e. negative VPD in winter and high PDSI for the prior year. On the higher elevation USFS lands area burned was strongly related to ignitions and high summer VPD.

Lightning-ignited fires and area burned by these ignitions were largely determined by a prior moist year coupled with current year aridity (Table 8*a*, *b*).

Winds

Severe winds contribute to hazardous fire activity that ultimately arises from either synoptic weather conditions or extreme fire behavior related to high intensity fires. In terms of synoptic weather conditions, north-easterly winds are often associated with the most hazardous fire conditions in California. Large fires were associated with northeasterly winds in the AM (midnight–noon) and PM (noon–midnight) in the North Interior, Central Coast and South Coast (Fig. 9). However, extreme northeasterly winds associated with large fires were largely in the AM in the North Interior, in both AM and PM in the South Coast, and such extreme winds were not recorded for the Central Coast.

Discussion

Wildfire regimes are controlled by the nexus of vegetation, climate, land management and ignitions (Bradstock 2010; Pausas and Keeley 2021) and are multi-dimensional in time and space (Falk and Swetnam 2003). The complex interaction of these makes it no simple matter to parse out the role of different fire regime drivers for the diverse ecoregions in California. Regimes vary markedly between foothill and montane environments, and latitudinally from north to south. We use a conceptual model that considers proximate factors, which explain directly what fire is responding to, and ultimate factors, which explain the main driver affecting proximate factors (Fig. 1). Our causal analysis takes a mechanistic approach and argues that proximate factors are dependent on ultimate factors. However, as environments change, the ultimate drivers of fire regimes may change, and thus proximate factors may also change. Here we illustrate this conceptutal model through evaluation of the fire regime drivers for the 10 California ecoregions (Fig. 2).

North Coast

Both CAL FIRE protected and USFS lands are dominated by conifers, and secondarily with other woody vegetation including hardwoods and shrublands. On the lower elevation CAL FIRE lands humans accounted for roughly 90% of all fires and area burned; however, on higher elevation USFS lands, more than half of all fires were ignited by lightning, accounting for a third of the area burned in the Recent Era.

Summer and autumn temperatures in the North Coast are the lowest of all five climate divisions, and summer and autumn precipitation is the highest. Thus, these ecosystems are often flammability limited, and an important proximate factor driving fires is fuel condition. The ultimate factor is climatic aridity, and this is supported by the fact that this is the only division where annual area burned is a function of high VPD in all seasons (Fig. 7*a*). While VPD during any one season explained only 15–17% of the area burned, more complex models that included VPD in multiple seasons explained approximately 40% of the variation in annual area burned (Table 7*b*). Thus, climate is an important determinant of area burned, and fuel aridity appears to have been an important determinant in both Historical and Recent eras. The significant increase in summer VPD in the last couple decades (Fig. 6) suggests anthropogenic climate change may be contributing to an upward trend, and thus if this trend continues we might expect an increase in future fire activity.

This climate division holds the record for the largest fire in the state; two-thirds of the area burned within the August Complex fire perimeter had not recorded a fire since before 1910, conditions suggesting unusually high fuel accumulation. This is indicative of much of the North Coast as the rate of burning during the prior 100 years gives a fire rotation interval of ∼130 years. Thus, woody fuel accumulation is likely a major proximate factor in large fires, resulting from ultimate factors that include fire suppression (Stephens *et al.* 2018), and mesic summer conditions (Viers 1979; Keeley and Pausas 2025), an example of how a proximate driver may have more than one ultimate driver.

North Interior

This division shares much in common with the North Coast in terms of domination by conifers as well as the dominance of lightning ignitions. Also, in both divisions there has been a significant increase in number of lightning-ignited fires in the Recent Era on CAL FIRE lands. While this could be attributed to improved detection of fires, the absence of a similar pattern on the higher elevation, more remote USFS lands, suggests that detection alone does not explain the increase. Climate is potentially a factor as noted for the interior parts of the western US (Abatzoglou *et al.* 2016; Syphard *et al.* 2017). Another possible factor is that increased lightning fires on CAL FIRE lands may be more closely linked to landscape changes, such as increases in grass fuels (Song *et al.* 2024). The role of grass fuels is suggested by the high PDSI (i.e. high moisture) in the prior year for models of area burned in both Historical and Recent eras (Table 8*b*). Indeed, the best model for area burned by lightning-ignited fires is high moisture in the prior year, which would increase herbaceous fuels, coupled with dry conditions during the current fire season, which would convert these potential fuels into available fuels, and this model explains ∼45% of the variation in area burned by lightning-ignited fires (Table 8*b*).

Surges in lightning-ignited fires occur roughly every decade as previously reported by CAL FIRE (2008) for 1955, 1977, 1987, 1999 and 2008. These periodic clusters of lightning storms result in many simultaneous destructive fires that potentially overwhelm fire-fighting resources. The year 2020 is a good example, with more than 5000 lightning strikes during a short period resulting in simultaneous fires. Seven major fires ignited during a 3-day period from the North Coast to the North Interior, Central Coast, and Sierra Nevada, and eventually overlapped in time with other fires (Table 9). This outbreak of large fires close in time is a major factor accounting for their final fire size as it over-extended fire-fighting resources (Safford *et al.* 2022). However, travel restrictions during the peak of the Covid-19 pandemic likely also impacted fire-fighting capacity, potentially contributing to extreme fire sizes in 2020.

This division showed the strongest relationship between area burned and high VPD, indicating a drying climate is an ultimate driver of fires through its impact on fuel condition. On the lower elevation CAL FIRE lands, multiple regression analysis showed VPD accounted for about 27% of area burned (Table 7), and number of ignitions was a significant contributor to this model. On USFS lands, bivariate regression showed the summer VPD accounted for more than 20% of area burned (Fig. 7*b*), and multiple regression revealed the combined effect of spring, summer and autumn VPD, which explained roughly 40% of the annual variation in area burned (Table 7*b*).

VPD has been an important factor affecting area burned in both the Historical and Recent eras (Table 6). As with the North Coast, the significant increase in summer VPD in the last couple decades (Fig. 6) is consistent with anthropogenic climate change expectations, and if this trend continues as models predict (e.g. He *et al.* 2025), we might expect an increase in future fire activity due to climate drivers.

Although climate explained up to ∼40% of the annual variation in area burned, the other 60% remains unexplained by climate factors tested here. A contributor to large fires in this region is likely anomalously high fuel accumulation due to very effective fire suppression. Two-thirds of the area

Table 9. Cluster of lightning-ignited fires in the summer of 2020 in northern and central California.

Division	Fire	Dates	Size (ha)
North Coast	Caldwell	22 July–2 Sept	32,872
North Coast	July Cmplx	24 July–5 Aug	33,696
North Coast	Red Salmon	27 July–19 Nov	58,210
North Coast	LNU Cmplx	16 Aug–2 Oct	146,995
North Coast	August Cmplx	16 Aug–11 Sept	417,934
Central Coast	SCU Cmplx	16 Aug–11 Nov	160,423
Central Coast	CZU Cmplx	16 Aug–24 Sep	35,028
North Interior	North Cmplx	17 Aug–3 Dec	129,009
North Interior	Cold Spring	18 Aug–13 Sep	34,326
Sierra Nevada	Castle	19 Aug–4 Jan	69,061
Sierra Nevada	Creek	4 Sep–24 Dec	153,738

Based on Fire and Resource Assessment Program (FRAP) database.

burned within the Dixie Fire had never had a recorded fire (back to at least 1910), and the fire rotation interval for the division was more than 110 years, which is approximately an order of magnitude longer than the historical fire regime (Taylor 2000).

Another factor is extreme wind events, which can arise from internal conditions such as heavy fuel loads (Countryman 1971), as seen in the 2018 Carr Fire, but more commonly result from synoptic-scale events, labeled as foehn or downslope winds (Keeley and Syphard 2019). Such winds are an annual event in the South Coast, where they are known as Santa Ana Winds. In the northern part of the state, similar winds – known as the North, Mono or Diablo winds (Fig. 9) – are less predictable than Santa Ana Winds. Nonetheless, these autumn wind events are responsible for some of the most catastrophic fires in California, including the 2018 Camp Fire (Knapp *et al.* 2021; Mass and Ovens 2021).

In summary, today climate plays a major role in determining fire regimes in the North Interior, but long-term woody fuel accumulation cannot be ignored as a contributing factor. Predicting future fire regimes based solely on climate projections may be misleading, since with increasingly more area burned (from wildfires and prescribed burn treatments), reductions in fuel load may lead to less extreme fire sizes given fuel feedbacks (e.g. Abatzoglou *et al.* 2021; Hanan *et al.* 2022).

Sierra Nevada

This division is distinct from the more northern divisions in that the lower elevation CAL FIRE landscape is dominated by grasslands and savannas. This grass-dominated landscape helps explain why important drivers of fire frequency and area burned are moist conditions in the prior year and a moist winter (Table 7). Both contribute to the proximate driver of high herbaceous fuel loads (Fig. 1) as demonstrated by other investigators (Swetnam and Betancourt 1998; Crimmins and Comrie 2004; Littell *et al.* 2009; Albano *et al.* 2017). In other words, in the lower elevations of this division, climatic aridity (resulting from interannual variation, drought cycles or longer term changes in climate) does not increase fires via more arid fuel conditions; rather, years with less arid conditions increase area burned, presumably due to increased herbaceous fuel loads. If global warming was to increase, we might expect reductions in herbaceous fuel loads in grasslands and savannas, leading to a decrease in fire activity in this ecoregion (Kennedy *et al.* 2021).

In the higher-elevation forests of the Sierra Nevada, dominated by woody vegetation, area burned is dependent on high spring and summer temperatures that reduce woody fuel moisture – a pattern that held true in historical times as well (Taylor and Beaty 2005). It is noteworthy that in all of the forested ecoregions spring VPD was a significant factor driving annual area burned (Fig. 7), and this supports Westerling's (2016) contention about the importance of early spring snowmelt in determining annual area burned.

However, it seems inescapable that large fires are also driven by anomalous fuel accumulation. For example, three-fourths of the area burned in the largest fire (Creek Fire) had no recorded history of previous fire, and the division's fire rotation interval is estimated at between 112 and 198 years. In light of the known historical range of variation in fire return intervals of roughly 20 years (Stafford *et al.* 2022), effective fire suppression has contributed substantially to the fuel load. Thus, ultimate drivers of the fire regime appear to be a combination of both climate and fire suppression. Historically, prior to the advent of aggressively suppressing all fires, these forests experienced a frequent understory fire regime driven by lightning ignitions (Kilgore and Taylor 1979). Under such a regime, fire activity was likely regulated by the time required to accumulate sufficient woody fuels (Stephens *et al.* 2007), implying that fuel aridity played a secondary role. Looking ahead, increasing focus on fuel reduction treatments (Stephens *et al.* 2012) may reduce fire size, which over time may ultimately result in reduced available fuels and thus area burned (Kennedy *et al.* 2021).

Central Coast

On CAL FIRE lands dominated by grasslands, area burned is currently dependent on high moisture in the previous year coupled with dry conditions in the present year (Table 7), which is consistent with herbaceous fuel loads being a major driver of fire regimes. In the Historical Era, the significant drivers were factors that would affect woody plant fuel aridity, and the switch in drivers between Historical and Recent eras likely represents the substantial increase in grasslands due to vegetation type conversion over the past 70 years (Syphard *et al.* 2018, 2022; Fusco *et al.* 2021). Such land-cover changes may also impact future climate regimes

(Feddema *et al.* 2005), and thus possibly future fire regimes. On the higher elevation USFS lands dominated by woodlands, area burned was a function of low precipitation in winter, spring and autumn, contributing to drier woody fuels.

South Coast

On the lower elevation CAL FIRE landscapes in the Historical Era, burned area was primarily affected by low autumn precipitation, which has been shown to contribute to increased Santa Ana Wind driven fire size (Cayan *et al.* 2022). In the Recent Era, factors affecting herbaceous fuel loads are the only significant factors affecting area burned, consistent with and supporting the finding that vegetation type conversion from woody to herbaceous vegetation has been going on for many decades in this region (Syphard *et al.* 2018, 2022).

On USFS lands in the Recent Era, the number of ignitions is the best predictor of area burned among those tested, although the model explains roughly a quarter of the variance, indicating other factors are important. This pattern also holds for autumn Santa Ana wind-driven fires, where number of ignitions is a major determinant of area burned (Keeley *et al.* 2021). High summer VPD, which affects fuel moisture in summer fires, is the next most important factor (Table 7*b*).

The two very distinct fire seasons (autumn vs summer fires) in this climate division (Kolden and Abatzoglou 2018; Keeley *et al.* 2024) add further complications to parsing out the role of different ultimate drivers. In brief, it appears that summer fires are ultimately affected by climate (Turco *et al.* 2023), and there is very little evidence that fuel loads play a major role in either summer or autumn fires (Table 4). Autumn fires are largely a function of the unique Santa Ana Wind events when they coincide with human ignitions. Probability of an ignition is affected by prior year moisture, consistent with increasing herbaceous fuel growth, and this is consistent with the observation that most shrubland fires in this division ignite in grass vegetation (Syphard *et al.* 2018). However, powerline failures during Santa Ana Wind driven fires are the major ignition source for most large catastrophic fires (Keeley *et al.* 2021). The observation that this is a factor primarily in the Recent Era is most likely due to population growth that expands development, subsequently expanding electrical grid distribution lines into watersheds of hazardous fuels (Keeley and Syphard 2019). There is little evidence that global warming will play a direct role in driving future fires in this division, and even has the potential for distracting attention away from more immediate problems. For example, ascribing a catastrophic fire event as primarily due to climate change has the potential for reducing interest in more tractable solutions such as better land planning or home hardening. However, indirect effects of global warming will potentially impact shrubland and forest recovery by favoring alien grasses after fire, increasing the likelihood of vegetation type conversion (Davis *et al.* 2019).

The peak in fire frequency during the last quarter of the 20th century followed by a sharp decline in the 21st century was observed in all divisions, but was most striking in the South Coast (Fig. 3). This is somewhat surprising as the vast majority of fires in this division are human-ignited (Faivre *et al.* 2014; Syphard and Keeley 2015; Keeley and Syphard 2018; Keeley *et al.* 2021), and population density has continued to increase through the early decades of the 21st century, whereas area burned has increased (Fig. 4). Hypotheses for this pattern of declining ignitions coupled with increasing area burned in the 21st century reflect the complexity of the drivers of fire regimes in the region, and at least five hypotheses emerge. First, area burned is not dependent on ignitions. Second, the number of human-caused ignitions is not related to population size. Third, once a region reaches a certain threshold of population density, further population increases do not translate into more ignitions. Fourth, the rate of population growth during the 1970s and 1980s was rapid, resulting in firefighting resources lagging behind landscape development and population increases. Finally, agency programs targeting reduction in human ignitions have been overall very effective in recent decades, but have not fully targeted or decreased the most dangerous ignition sources.

The first hypothesis seems unlikely since human ignitions have greatly expanded the fire season and are dominant nationwide (Balch *et al.* 2017; Syphard *et al.* 2017); e.g. in California, population density has been shown to be an important factor determining ignitions in the foothills of the Sierra Nevada (Chen *et al.* 2021), and in the South Coast number of ignitions is significantly related to area burned (Keeley *et al.* 2021). In the South Coast, powerline-ignited fires were largely unknown in the Historical Era but a major source in the Recent times (Table 1), and this is tied to population growth that has expanded the electrical distribution lines into watersheds of dangerous fuels (Keeley and Syphard 2019).

The second hypothesis suggests other factors are involved, perhaps climate, but this is not strongly supported by the climate analysis presented for the South Coast (Table 7). Hypothesis 3 is consistent with a threshold of population growth that affects ignitions, and this would be supported by the nonlinear effects of human ignitions and distance from the wildland–urban interface (WUI) (Syphard *et al.* 2007). Hypothesis 4 seems likely, but we lack information on ignition thresholds and fire-fighting resource development. Hypothesis 5 has potential explanatory value. Human ignition sources have been the focus of fire reduction programs, and some fire ignition sources (e.g. smoking, railroads, debris burning, equipment, Table 1) have declined in the last couple of decades. However, not all reductions in ignition sources are necessarily due to such programs, for example, reduction in smoking caused fires is quite likely due to widely advertised health impacts (Smith 2008). Regardless, apparently fire reduction programs have not effectively addressed sources responsible for the greatest increases in area burned.

The ignition sources for some of California's largest fires have increased in frequency and area burned (Tables 1 and 3), and perhaps the most important of these is powerline ignitions e.g. Dixie and Thomas fires (Supplementary Fig. S1*b*, *e*). In the recent past powerline expansion into watersheds of hazardous fuels, in the South Coast, North Coast and North Interior have resulted in some of the largest and most devasting fires (Keeley and Syphard 2019; Rolinski *et al*. 2019; Troy *et al*. 2022). These types of fires are typically associated with extreme wind events such as Santa Ana Winds in the south or North Winds in the northern part of the state, which cause failures in electrical lines, and the powerful winds ensure such fires become large. It is critical to recognize that the winds *per se* are not the problem, as the vast majority of such extreme winds do not result in fires; rather fires are dependent on the coincidence of a human ignition source during a wind event (Keeley *et al.* 2021; Troy *et al.* 2022).

Conclusions

Studies of climatic effects on wildfire have focused on fuel conditions (specifically fuel aridity as measured by VPD) as a major potential factor resulting in increased fire activity, and have implicated climate change as a threat to forests of the western US (Abatzoglou and Williams 2016; He *et al.* 2025). Our study showed that high VPD was an important driver in some California ecoregions but not in others, suggesting global warming may impact fire regimes more in some ecoregions than others, and perhaps decrease fire activity in some.

The most extensive forested areas in California are in the North Coast and North Interior USFS lands, where aridity metrics can account for ~40% of the variation in annual area burned. Thus, in these forested landscapes it is clear that climate change has the potential to impact future fire regimes. Nevertheless, these ecoregions consist of different forest types with distinctive fire regimes (Beaty and Taylor 2001), and thus, there will likely be differences in the future role of climate on fire activity.

While fuel condition, which is ultimately tied to climate, is widely considered a major driver of area burned in the western US, it is only one of multiple proximate factors driving fire regimes (Fig. 1). Notably, 60% of the annual variation in area burned in these northern California forests cannot be explained by climate factors alone. The circumstantial evidence of massive woody fuel accumulation suggested by the long hiatus in burning for California forests (Table 4) likely accounts for a portion of this 60%. It has been well documented that fuel loads in these forests are exceedingly high, and they contribute to large, high severity fires, which are beyond the historical range of variability (Steel *et al*. 2015; Stevens *et al.* 2017; Miller 2020; Williams *et al.* 2023). The importance of reducing fuel loads as a strategy for dealing with increasing fire size and severity is widely recognized by fire managers and scientists (Graham *et al.* 2004; Safford *et al.* 2012; Stephens *et al.* 2012). Thus, there is increasing emphasis on funding understory prescription burning and mechanical biomass removal projects (Forest Management Task Force 2021). While the extent of area needing treatment is massive, research suggests that strategic application on a more limited scale may substantially reduce future area burned (Kim *et al.* 2009; Alcasena *et al.* 2022). In an attempt to parse out the role of climate and woody fuels in California wildfires, Brown *et al.* (2025) contend that fuel reduction projects have substantial potential for negating the effects of climatic warming. Future fire regimes in these forests will likely change as these fuel treatment programs progress.

In contrast to northern California forests, climatic aridity has a negative impact on area burned in some ecoregions, and those are mostly lower-elevation grassland-dominated landscapes such as CAL FIRE lands in the Sierra Nevada, Central Coast and South Coast. Herbaceous fuel loads are enhanced under cooler moist conditions during winter and spring, as well as in the prior year, and are a major driver of area burned in these ecosystems (Table 7*b*, see also Swetnam and Betancourt 1998; Crimmins and Comrie 2004; Littell *et al.* 2009; Albano *et al.* 2017; Gao *et al.* 2025). In these ecoregions, global warming would not be expected to increase fire activity and may even decrease it.

Several California climate divisions have fire regimes that are heavily impacted by factors other than fuel accumulation and climate. This is illustrated by the largest fire in the South Coast where only 8% of the area within the fire perimeter had escaped fire over the past century. This is a division with much shorter fire return intervals than in the rest of the state (Table 4), and a preponderance of fire has led to a landscape without heavy fuel accumulation (Keeley and Zedler 2009). As a consequence, management techniques designed for conifer forests such as prescription burning may not be appropriate. This is not only because of an absence of unnatural fuel accumulation in shrublands, but because prescription burning is a totally different treatment than in forests; specifically, in forests it is the understory that is treated and the overstory is left largely intact, whereas in shrublands the entire aboveground vegetation is killed. In forests burn prescriptions are compatible with both hazard reduction and resource conservation, however, in shrublands the prescription burn interval that reduces fire hazard is often not compatible with resource conservation (Keeley and Syphard 2019). This is primarily because over two-thirds of the shrub species in chaparral are entirely dependent on accumulating a seedbank between fires and when repeat fires occur too frequently (e.g. <15–25 year intervals) those species are often extirpated (Keeley *et al.* 2012), leading to type conversion to non-native grasslands (Syphard *et al.* 2018).

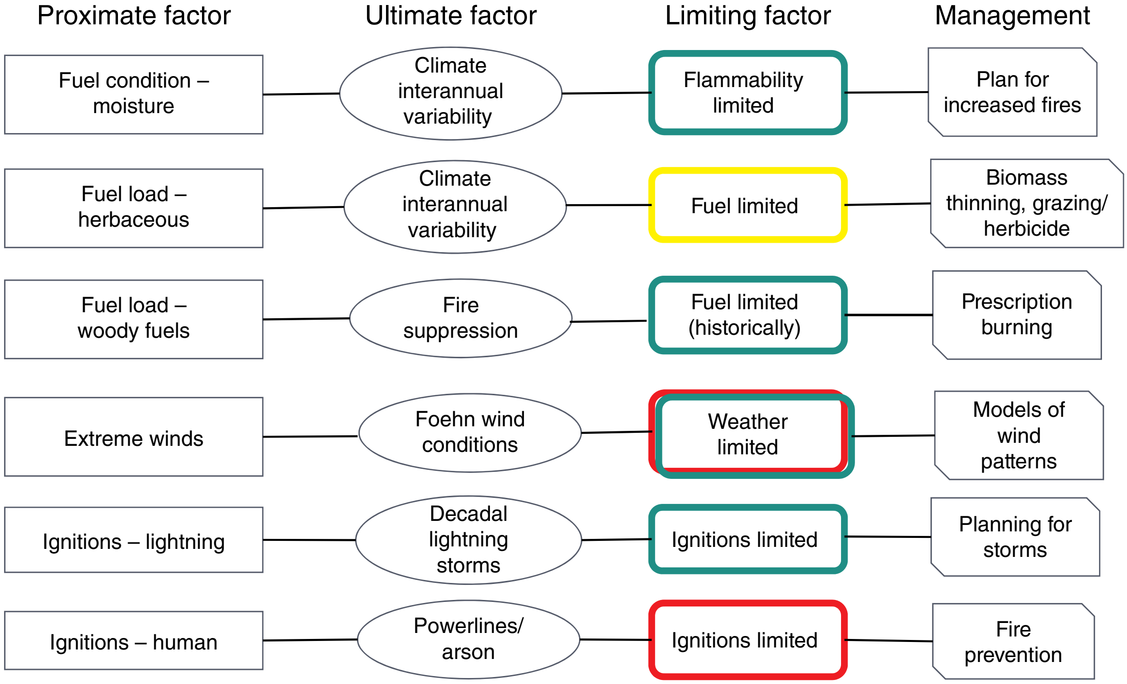


Fig. 10. Fire regime drivers with limiting factors and potential management responses (colors indicate vegetation types where the factor is most important, green = forests, yellow = grasslands, red = shrublands).

On South Coast USFS lands, the most important independent variable driving area burned has been number of fires (Table 7), supporting the finding that area burned is a function of human ignitions during extreme wind conditions (Keeley *et al.* 2021). On these landscapes, fire is a human-ignition problem and not so much a fuel or climate problem. The vast majority of fires are human-ignited, and both fire frequency and area burned due to human-ignitions are far more important here than in any other division. Planning for future fire regimes in these landscapes is not likely to benefit from a focus on climate change, but rather requires a serious attempt to eliminate human ignitions during the most dangerous red-flag weather conditions, as well as changes in land planning decisions that consider restricting development in fire prone landscapes.

Lastly, what we have learned from this analysis and the implications for fire management are summarized in a modified version of Fig. 1 (Fig. 10). Here we link the limiting factors to fire activity to likely ultimate and proximate factors and what they suggest in terms of future fire management responses in California and other fire-prone regions in the western US and worldwide. Effective fire management will require aligning interventions with the proximate and ultimate drivers in each region, rather than assuming a uniform role for climate across all landscapes.

Supplementary material

Supplementary material is available online.

References

Abatzoglou JT, Williams AP (2016) Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences of the United States of America* **113**, 11770–11775. doi:10.1073/pnas.1607171113

Abatzoglou JT, Kolden CA, Balch JK, Bradley BA (2016) Controls on interannual variability in lightning-caused fire activity in the western US. *Environmental Research Letters* **11**, 045005. doi:10.1088/1748-9326/11/4/045005

Abatzoglou JT, Battisti DS, Williams AP, Hansen WD, Harvey BJ, Kolden CA (2021) Projected increases in western US forest fire despite growing fuel constraints. *Communications Earth & Environment* **2**(1), 227. doi:10.1038/s43247-021-00299-0

Albano CM, Dettinger MD, Soulard CE (2017) Influence of atmospheric rivers on vegetation productivity and fire patterns in the southwestern U.S. *Journal of Geophysical Research: Biogeosciences* **122**, 308–323. doi:10.1002/2016JG003608

Alcasena F, Ager AA, Belavenutti P, Krawchuk M, Day MA (2022) Contrasting the efficiency of landscape versus community protection fuel treatment strategies to reduce wildfire exposure and risk. *Journal of Environmental Management* **309**, 114650. doi:10.1016/j.jenvman.2022.114650

Balch JK, Bradley BA, Abatzoglou JT, Nagy RC, Fusco EJ, Mahood AL (2017) Human-started wildfires expand the fire niche across the United States. *Proceedings of the National Academy of Sciences* **114**, 2946–2951. doi:10.1073/pnas.1617394114

Beaty RM, Taylor AH (2001) Spatial and temporal variation of fire regimes in a mixed conifer forest landscape, Southern Cascades, California, USA. *Journal of Biogeography* **28**, 955–966. doi:10.1046/j.1365-2699.2001.00591.x

Bradstock RA (2010) A biogeographic model of fire regimes in Australia: current and future implications. *Global Ecology and Biogeography* **19**, 145–158. doi:10.1111/j.1466-8238.2009.00512.x

Brown PT, Strenfel SJ, Bagley RB, Clements CB (2025) The potential for fuel reduction to reduce wildfire intensity in a warming California. *Environmental Research Letters* **20**, 024040. doi:10.1088/1748-9326/adab86

CAL FIRE (2008) 'June 2008 California Fire Siege Summary Report.' (Cal Fire FRAP: Sacramento, CA)

Cayan DR, DeHaan LL, Gershuvov A, Guzman-Morales J, Keeley JE, Mumford J, Syphard AD (2022) Autumn precipitation: the competition with Santa Winds in determining fire outcomes in southern California. *International Journal of Wildland Fire* **31**, 1056–1067. doi:10.1071/WF22065
Chen B, Jin Y, Scaduto E, Moritz MA, Goulden ML, Randerson JT (2021) Climate, fuel, and land use shaped the spatial pattern of wildfire in California's Sierra Nevada. *Journal of Geophysical Research: Biogeosciences* **126**, e2020JG005786. doi:10.1029/2020JG005786
Clarke H, Nolan RH, De Dios VR, Bradstock R, Griebel A, Khanal S, Boer MM (2022) Forest fire threatens global carbon sinks and population centres under rising atmospheric water demand. *Nature Communications* **13**(1), 7161. doi:10.1038/s41467-022-34966-3
Countryman CM (1971) 'Fire whirls…why, when, and where.' 14 p. (USDA Forest Service, Pacific Southwest Forest and Range Experiment Station)
Crimmins MA, Comrie AC (2004) Wildfire-climate interactions across southeast Arizona. *International Journal of Wildland Fire* **13**, 455–466. doi:10.1071/WF03064
Dai A, National Center for Atmospheric Research Staff (2023) The Climate Data Guide: Palmer Drought Severity Index (PDSI). Retrieved from https://climatedataguide.ucar.edu/climate-data/palmer-drought-severity-index-pdsi [3 March 2025, last modified 19 August 2023]
Davis KT, Dobrowski SZ, Higuera PE, Holden ZA, Veblen TT, Rother MT, Parks SA, Sala A, Maneta MP (2019) Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences* **116**(13), 6193–6198. doi:10.1073/pnas.1815107116
Diffenbaugh NS, Konings AG, Field CB (2021) Atmospheric variability contributes to increasing wildfire weather but not as much as global warming. *Proceedings of the National Academy of Sciences* **118**(46), e2117876118. doi:10.1073/pnas.2117876118
Faivre N, Jin Y, Goulden ML, Randerson JT (2014) Controls on the spatial pattern of wildfire ignitions in Southern California. *International Journal of Wildland Fire* **23**, 799–811. doi:10.1071/WF13136
Falk DA, Swetnam TW (2003) Scaling rules and probability models for surface fire regimes in ponderosa pine forests. In 'Proceedings RMRS-P-29.' pp. 301–317. (USDA Forest Service)
Feddema JJ, Oleson KW, Bonan GB, Mearns LO, Buja LE, Meehl GA, Washington WM (2005) The importance of land-cover change in simulating future climates. *Science* **310**, 1674–1678. doi:10.1126/science.1118160
Fertel HM, North MP, Latimer AM, Ng J (2022) Growth and spatial patterns of natural regeneration in Sierra Nevada mixed-conifer forests with a restored fire regime. *Forest Ecology and Management* **519**, 120270. doi:10.1016/j.foreco.2022.120270
Fertel HM, Bollins BM, Lydersen JM, Stephens SL (2023) Vegetation type change in California's northern Bay Area: a comparison of contemporary and historical aerial imagery. *Forest Ecology and Management* **542**, 121102. doi:10.1016/j.foreco.2023.121102
Flannigan MD, Krawchuk MA, de Groot WJ, Wotton BM, Gowman LM (2009) Implications of changing climate for global wildland fire. *International Journal of Wildland Fire* **18**, 483–507. doi:10.1071/WF08187
Forest Management Task Force (2021) 'California's wildfire and forest resilience action plan: recommendations of the governor's forest management task force.' (State of California: Sacramento, CA, USA)
Fusco EJ, Balch JK, Mahood AL, Nagy RC, Syphard AD, Bradley BA (2021) The human-grass-fire cycle: how people and invasives co-occur to drive fire regimes. *Frontiers in Ecology and Environment* **20**, 117–126. doi:10.1002/fee.2432
Gao X, Koven CD, Longo M, Robbins Z, Thornton P, Hall A, Levis S, Rahim S, Xu C, Kueppers LM (2025) California annual grass phenology and allometry influence ecosystem dynamics andfire regime in a vegetation demography model. *New Phytologist* **245**, 2480–2495. doi:10.1111/nph.20421
Goss M, Swain DL, Abatzoglou JT, Sarhadi A, Kolden CA, Williams AP, Diffenbaugh NS (2020) Climate change is increasing the likelihood of extreme autumn wildfire conditions across California. *Environmental Research Letters* **15**, 094016. doi:10.1088/1748-9326/ab83a7
Grace JB (2024) An integrative paradigm for building causal knowledge. *Ecological Monographs* **94**, e1628. doi:10.1002/ecm.1628
Grace JB, Huntington-Klein N, Schweiger EW, Martinez M, Osland MJ, Feher LC, Guntenspergen GR, Thorne KM (2025) Causal effects versus causal mechanisms: two traditions with different requirements and contributions towards causal understanding. *Ecology Letters* **28**, e70029. doi:10.1111/ele.70029
Graham RT, McCaffrey S, Jain TB (2004) 'Science basis for changing forest structure to modify wildfire behavior and severity.' (United States Department of Agriculture, Forest Service, Rocky Mountain Research Station)
Guttman NB, Quayle RG (1996) A historical perspective of U.S. climate regions. *Bulletin of the American Meteorological Society* **77**, 293–304. doi:10.1175/1520-0477(1996)077 < 0293:AHPOUC > 2.0.CO;2
Guzman-Morales J, Gershunov A (2019) Climate change suppresses Santa Ana winds of Southern California and sharpens their seasonality. *Geophysical Research Letters* **46**, 2772–2780. doi:10.1029/2018GL080261
Hanan EJ, Kennedy MC, Johnson MC, Smith AM (2022) Missing climate feedbacks in fire models: limitations and uncertainties in fuel loadings and the role of decomposition in fine fuel accumulation. *Journal of Advances in Modeling Earth Systems* **14**(3), e2021MS002818. doi:10.1029/2021MS002818
He Q, Williams AP, Johnston MR, Juang CS, Wang B (2025) Influence of time-averaging of climate data on estimates of atmospheric vapor pressure deficit and inferred relationships with wildfire area in the western United States. *Geophysical Research Letters* **52**, e2024GL113708. doi:10.1029/2024GL113708
Hossenfelder S (2025) Scientists misreport climate cause of LA wildfires. *Science News*. Available at https://www.youtube.com/watch?v=NZv5zBNIhvE
Keeley JE, Pausas JG (2025) *Sequoia* and *Sequoiadendron*: two paleoendemic megatrees with markedly different adaptive responses to recent high severity fires. *American Journal of Botany* **112**, e70089. doi:10.1002/ajb2.70089
Keeley JE, Syphard AD (2017) Different historical fire-climate relationships in California. *International Journal of Wildland Fire* **26**, 253–268. doi:10.1071/WF16102
Keeley JE, Syphard AD (2018) Historical patterns of wildfire ignition sources in California ecosystems. *International Journal of Wildland Fire* **27**, 781–799. doi:10.1071/WF18026
Keeley JE, Syphard AD (2019) Twenty-first century California, USA, wildfires: fuel-dominated vs. wind-dominated fires. *Fire Ecology* **15**, 24. doi:10.1186/s42408-019-0041-0
Keeley JE, Zedler PH (2009) Large, high-intensity fire events in southern California shrublands: debunking the fine-grain age patch model. *Ecological Applications* **19**, 69–94. doi:10.1890/08-0281.1
Keeley JE, Bond WJ, Bradstock RA, Pausas JG, Rundel PW (2012) 'Fire in Mediterranean climate ecosystems: ecology, evolution and management.' 528 p. (Cambridge University Press)
Keeley JE, Guzman-Morales J, Gershunov A, Syphard AD, Cayan D, Pierce DW, Flannigan M, Brown TJ (2021) Ignitions explain more than temperature or precipitation in driving Santa Ana wind fires. *Science Advances* **7**, eabh2262. doi:10.1126/sciadv.abh2262
Keeley JE, Brennan TJ, Syphard AD (2022) The effects of prolonged drought on vegetation dieback and megafires in southern California chaparral. *Ecosphere* **13**, e4203. doi:10.1002/ecs2.4203
Keeley JE, Flannigan M, Brown TJ, Rolinski T, Cayan D, Syphard AD, Guzman-Morales J, Gershunov A (2024) Climate and weather drivers in southern California Santa Ana wind and non-Santa Ana wind fires. *International Journal of Wildland Fire* **33**, WF23190. doi:10.1071/WF23190
Kennedy MC, Bart RR, Tague CL, Choate JS (2021) Does hot and dry equal more wildfire? Contrasting short- and long-term climate effects on fire in the Sierra Nevada. *Ecosphere* **12**(7), e03657. doi:10.1002/ecs2.3657
Kilgore BM, Taylor D (1979) Fire history of a sequoia-mixed conifer forest. *Ecology* **60**, 129–142. doi:10.2307/1936475
Kim Y-H, Bettinger P, Finney M (2009) Spatial optimization of the pattern of fuel management activities and subsequent effects on simulated wildfires. *European Journal of Operational Research* **197**, 253–265. doi:10.1016/j.ejor.2008.05.025
Knapp EE, Valachovic YS, Quarles SL, Johnson NG (2021) Housing arrangement and vegetation factors associated with single-family

home survival in the 2018 Camp Fire, California. *Fire Ecology* **17**, 25. doi:10.1186/s42408-021-00117-0

Kolden CA, Abatzoglou JT (2018) Spatial distribution of wildfires ignited under katabatic versus non-katabatic winds in Mediterranean southern California USA. *Fire* **1**, 19. doi:10.3390/fire1020019

Kummerow J, Montenegro G, Krause D (1981) Biomass, phenology, and growth. In 'Resource use by chaparral and matorral'. (Ed. PC Miller) pp. 69–96. (Springer New York: New York, NY, USA)

Littell JS, McKenzie D, Peterson DL, Westerling AL (2009) Climate and wildfire area burned in western US ecoprovinces, 1916–2003. *Ecological Applications* **19**, 1003–1021. doi:10.1890/07-1183.1

MacDonald GT, Wall T, Enquist CAF, LeRoy SR, *et al.* (2023) Drivers of California's changing wildfires: a state-of-the-knowledge synthesis. *International Journal of Wildland Fire* **32**, 1039–1058. doi:10.1071/WF22155

Mass CF, Ovens D (2021) The synoptic and mesoscale evolution accompanying the 2018 Camp Fire of northern California. *Bulletin of the American Meteorological Society* **102**(1), E168–E192. doi:10.1175/BAMS-D-20-0124.1

Meehl GA, Shields CA, Myers BM, *et al.* (2025) 'Earth, wind, and fire: are Boulder's extreme downslope winds changing?' (BAMS American Meterological Society E1370)

Miller R (2020) Prescribed burns in California: a historical case study of the integration of scientific research and policy. *Fire* **3**, 44. doi:10.3390/fire3030044

Murphy P, Mass C (2025) Weather associated with rapid-growth California wildfires. *Weather and Forecasting* **40**, 347–366. doi:10.1175/WAF-D-24-0025.1

Pausas JG, Keeley JE (2021) Wildfires and global change. *Frontiers in Ecology and the Environment* **19**, 387–395. doi:10.1002/fee.2359

Pausas JG, Keeley JE, Syphard AD (2025) Are fire regimes the result of top-down or bottom-up drivers? *Philosophical Transactions of the Royal Society B: Biological Sciences* **380**, 20230447. doi:10.1098/rstb.2023.0447

Pierce DW, Cayan DR (2016) Downscaling humidity with localized constructed analogs (LOCA) over the conterminous United States. *Climate Dynamics* **47**(1–2), 411–431. doi:10.1007/s00382-015-2845-1

Pierce DW, Kalansky JF, Cayan DR (2018) 'Climate, Drought, and Sea Level Rise Scenarios for California's Fourth Climate Change Assessment: A Report for California's Fourth Climate Change Assessment.' (California Energy Commission: Sacramento, CA)

Qiu M, Chen D, Kelp M, Li J, Huang G, Yazdi MD (2025) The rising threats of wildland–urban interface fires in the era of climate change: The Los Angeles 2025 fires. *The Innovation* **6**, 100835. doi:10.1016/j.xinn.2025.100835

Rolinski T, Capps SB, Zhuang W (2019) Santa Ana winds: a descriptive climatology. *Weather and Forecasting* **34**, 257–275. doi:10.1175/WAF-D-18-0160.1

Safford HD, Stevens JT, Merriam K, Meyer MD, Latimer AM (2012) Fuel treatment effectiveness in California yellow pine and mixed conifer forests. *Forest Ecology and Management* **274**, 17–28. doi:10.1016/j.foreco.2012.02.013

Safford HD, Paulson AK, Steel ZL, Young DJ, Wayman RB (2022) The 2020 California fire season: a year like no other, a return to the past or a harbinger of the future? *Global Ecology and Biogeography* **31**(10), 2005–2025. doi:10.1111/geb.13498

Seager R, Hooks A, Williams AP, Cook B, Nakamura J, Henderson H (2015) Climatology, variability, and trends in the U.S. vapor pressure deficit, an important fire-related meteorological quantity. *Journal of Applied Meterorology and Climatology* **54**, 1121–1141. doi:10.1175/JAMC-D-14-0321.1

Smith DR (2008) The historical decline of tobacco smoking among United States physicians: 1949–1984. *Tobacco Induced Diseases* **4**, **9**, doi:10.1186/1617-9625-4-9

Song Y, Xu C, Li X, Oppong F (2024) Lightning-induced wildfires: an overview. *Fire* **7**, 79. doi:10.3390/fire7030079

Steel ZL, Safford HD, Viers JH (2015) The fire frequency-severity relationship and the legacy of fire suppression in California forests. *Ecosphere* **6**(1), 8. doi:10.1890/ES14-00224.1

Stephens SL, Martin RE, Clinton NE (2007) Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands. *Forest Ecology and Management* **251**, 205–216. doi:10.1016/j.foreco.2007.06.005

Stephens SL, McIver JD, Boerner REJ, Fettig CJ, Fontaine JB, Hartsough BR, Kennedy PL, Schwilk DW (2012) The effects of forest fuel-reduction treatments in the United States. *Bioscience* **62**, 549–560. doi:10.1525/bio.2012.62.6.6

Stephens SL, Collins BM, Fettig CJ, Finney MA, Hoffman CM, Knapp EE, North MP, Safford H, Wayman RB (2018) Drought, tree mortality, wildfire in forests adapted to frequent fire. *BioScience* **68**, 77–88. doi:10.1093/biosci/bix146

Stephens SL, Bernal AA, Collins BM, Finney MA, Lautenberger C, Saah D (2022) Mass fire behavior created by extensive tree mortality and high tree density not predicted by operational fire behavior models in the southern Sierra Nevada. *Forest Ecology and Management* **528**, 120258. doi:10.1016/j.foreco.2022.120258

Stevens JT, Collins BM, Miller JD, North MP, Stephens SL (2017) Changing spatial patterns of stand-replacing fire in California conifer forests. *Forest Ecology and Management* **406**, 28–36. doi:10.1016/j.foreco.2017.08.051

Swain DL, Abatzoglou JT, Albano CM, Brunner MI, Diffenbaugh NS, Kolden C, Prein AF, Singh D, Skinner CB, Swetnam TW, Touma D (2025) Increasing hydroclimatic whiplash can amplify wildfire risk in a warming climate. *Global Change Biology* **31**, e70075. doi:10.1111/gcb.70075

Swetnam, TW, Baisan CH (2003) Tree-ring reconstructions of fire and climate history in the Sierra Nevada and southwestern United States. In 'Fire and climatic change in temperate ecosystems of the western Americas'. (Eds TT Veblen, WL Baker, G Montenegro, TW Swetnam) pp. 158–195. (Springer New York: New York, NY, USA)

Swetnam TW, Betancourt JL (1998) Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. *Journal of Climate* **11**, 3128–3147. doi:10.1175/1520-0442(1998)011 < 3128:MDAERT > 2.0.CO;2

Syphard AD, Keeley JE (2015) Location, timing and extent of wildfire vary by cause of ignition. *International Journal of Wildland Fire* **24**, 37–47. doi:10.1071/WF14024

Syphard AD, Keeley JE (2020) Mapping fire regime ecoregions in California. *International Journal of Wildland Fire* **29**, 591–601. doi:10.1071/WF19136

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

Syphard AD, Keeley JE, Pfaff AH, Ferschweiler K (2017) Human presence diminishes the importance of climate in driving fire activity across the United States. *Proceedings of the National Academy of Sciences* **114**, 13750–13755. doi:10.1073/pnas.1713885114

Syphard AD, Brennan TJ, Keeley JE (2018) Chaparral landscape conversion in southern California. In 'Valuing Chaparral. Ecological, Socio-Economic, and Management Perspectives'. (Eds EC Underwood, HD Safford, JE Keeley, N Molinari, JJ Hooper) pp. 311–334. (Springer: New York, USA)

Syphard AD, Brennan TJ, Rustigian-Romsos H, Keeley JE (2022) Fire-driven vegetation type conversion in southern California. *Ecological Applications* **32**(6), e2626. doi:10.1002/eap.2626

Taylor AH (2000) Fire regimes and forest changes in min and upper montane forests of the southern Cascades, Lassen Volcanic National Park, California, U.S.A. *Journal of Biogeography* **27**, 87–104. doi:10.1046/j.1365-2699.2000.00353.x

Taylor AH, Beaty RM (2005) Climatic influences on fire regimes in the northern Sierra Nevada mountains, Lake Tahoe Basin, Nevada, USA. *Journal of Biogeography* **32**, 425–438. doi:10.1111/j.1365-2699.2004.01208.x

Taylor AH, Trouet V, Skinner CN, Stephens S (2016) Socioecological transitions trigger fire regime shifts and modulate fire-climate interactions in the Sierra Nevada, USA, 1600-2015 CE. *Proceedings of the National Academy of Sciences* **113**, 13684–13689. doi:10.1073/pnas.1609775113

Troy A, Moghaddas J, Schmidt D, Romsos JS, Sapsis DB, Brewer W, Moody T (2022) An analysis of factors influencing structure loss resulting from the 2018 Camp Fire. *International Journal of Wildland Fire* **31**, 586–598. doi:10.107/WF21176

Turco M, Abatzoglou JT, Herrera S, Zhuang Y, Jerez S, Lucas DD, Aghakouchak A, Cvijanovic I (2023) Anthropogenic climate change impacts exacerbate summer forest fires in California. *Proceedings of the National Academy of Sciences* **120**, e22113815120. doi:10.1073/pnas.2213815120 van Wagner CE (1987) Development and structure of the Canadian forest fire weather index system. No. 35.

Viers Jr SD (1979) The role of fire in northern coast redwood forest dynamics. In 'Proceedings of the Second Conference on Scientific Research in the National Parks, Vol. 10'. (National Park Service)

Vose RS, Applequist S, Menne I, Williams CN, Fenimore C, Gleason K, Arndt D (2014) Improved historical temperature and precipitation time series for U.S. climate divisions. *Journal of Applied Meteorology and Climatology* **53**, 1232–1251. doi:10.1175/JAMC-D-13-0248

Westerling AL (2016) Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B: Biological Sciences* **371**, 20150178. doi:10.1098/rstb.2015.0178

Wilkinson L (2010) SYSTAT. *WIREs Computational Statistics* **2**, 256–257. doi:10.1002/wics.66

Williams AP, Seager R, Macalady AK, Berkelhammer M, Crimmins MA, Swetnam TW, Trugman AT, Buenning N, Noone D, McDowell NG, Hryniw N, Mora CI, Rahn T (2015) Correlations between components of the water balance and burned area reveal new insights for predicting forest fire area in the southwest United States. *International Journal of Wildland Fire* **24**, 14–26. doi:10.1071/WF14023

Williams AP, Abatzoglou JT, Gershunov A, Guzman-Morales J, Bishop DA, Balch JK, Lettenmaier DP (2019) Observed impacts of anthropogenic climate change on wildfire in California. *Earth's Future* **7**, 892–910. doi:10.1029/2019EF001210

Williams JN, Safford HD, Enstice N, Steel ZI, Paulson AK (2023) High-severity burned area and proportion exceed historic conditions in Sierra Nevada, California, and adjacent ranges. *Ecosphere* **14**(1), e4397. doi:10.1002/ecs2.4397

Witze A (2025) Why fires spread quickly in modern cities — and how to slow them down. *Nature* **637**, 1032–1033. doi:10.1038/d41586-025-00141-z

Zhou S, Yu B, Zhang Y (2023) Global concurrent climate extremes exacerbated by anthropogenic climate change. *Science Advances* **9**, eabo1638. doi:10.1126/sciadv.abo1638

Data availability. Data sources are available from publicly available sites cited in the Methods section.

Conflicts of interest. Alexandra Syphard is an Associate Editor of *International Journal of Wildland Fire* but was not involved in the peer review or decision-making process for this paper. The authors have no further conflicts of interest to declare.

Declaration of funding. This research was supported by the US Geological Survey, and the Conservation Biology Institute, 136 SW Washington Ave, Corvalis, OR, USA.

Acknowledgements. Thanks to Anne Pfaff for assistance with fire history data and maps, thanks to Jim Grace for discussions on causal analysis, and Mike Rohde, William Bond, Gavin Madakumbura, Jeffrey Heys, Tom Kimball, and Robin Stewart for reviews with helpful comments, and Dan Cayan and Tim Brown for wind data. We thank the anonymous associate editor who did an extensive and detailed critique, some of which was helpful. Any use of trade, product or firm names is for descriptive purposes only and does not imply endorsement by the US Government.

Author affiliations

[A]U.S. Geological Survey, Western Ecological Research Center, Sequoia-Kings Canyon Field Station, Three Rivers, CA 93271, USA.

[B]Department of Ecology and Evolutionary Biology, and La Kretz Center, University of California, Los Angeles, 90095, USA.

[C]Conservation Biology Institute, 136 SW Washington Avenue, Corvalis, OR 97333, USA.

[D]Department of Biology, San Diego State University, San Diego, CA, USA. Email: asyphard@yahoo.com