Keeley and Syphard *Fire Ecology* (2019) 15:24
https://doi.org/10.1186/s42408-019-0041-0

Fire Ecology

Association for Fire Ecology

FORUM Open Access

Twenty-first century California, USA, wildfires: fuel-dominated vs. wind-dominated fires

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Abstract

Since the beginning of the twenty-first century California, USA, has experienced a substantial increase in the frequency of large wildfires, often with extreme impacts on people and property. Due to the size of the state, it is not surprising that the factors driving these changes differ across this region. Although there are always multiple factors driving wildfire behavior, we believe a helpful model for understanding fires in the state is to frame the discussion in terms of bottom-up vs. top-down controls on fire behavior; that is, fires that are clearly dominated by anomalously high fuel loads from those dominated by extreme wind events. Of course, this distinction is somewhat artificial in that all fires are controlled by multiple factors involving fuels, winds, and topography. However, we believe that fires clearly recognizable as fuel-dominated vs. wind-dominated provide interesting case studies of factors behind these two extremes. These two types of fires differ greatly in their (1) geographical distribution in the state, (2) past fire history, (3) prominent sources of ignition, (4) seasonal timing, (5) resources most at risk, and (6) requirement for different management responses.

Keywords: fire prevention, fire suppression, fuel loads, house protection, land planning, North Winds, population growth, Santa Ana Winds, silvicultural practices

Resumen

Desde comienzos del siglo veinte, California, EEUU, ha experimentado un incremento substancial en la frecuencia de grandes incendios, frecuentemente con grandes impactos en la gente y en las propiedades. Debido al tamaño del estado, no es sorprendente que los factores que conducen esos cambios difieran a través de esta región. Aunque siempre hay múltiples factores que gobiernan el comportamiento del fuego, creemos que un modelo útil para entender el fuego en el estado, es encuadrar la discusión en términos de control del comportamiento desde abajo hacia arriba (*bottom-up*) versus de arriba hacia abajo (*top-bottom*); es decir diferenciar los fuegos que son claramente dominados por anomalías en altas cargas de combustible de aquellos dominados por eventos de vientos extremos. Por supuesto, esta distinción es de alguna manera artificial, dado que todos los incendios son controlados por múltiples factores que implican combustibles, vientos, y topografía. Sin embargo, creemos que los fuegos reconocibles por ser dominados por los combustibles versus los dominados por el viento proveen de estudios de caso de los factores detrás de esos dos extremos. Estos dos tipos de fuegos difieren grandemente en (1) distribución geográfica en el estado, (2) historia de fuegos pasados, (3) fuentes de ignición preponderantes, (4) tiempo de ocurrencia estacional, (5) recursos en riesgo, y (6) requisitos para diferentes respuestas de manejo.

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Abbreviations

RAWS: remote automated weather station
WUI: wildland–urban interface

Introduction

California, USA, has a long history of massive wildfires such as the 1889 Santiago Canyon Fire in Orange County that exceeded 100 000 ha or the similarly large 1932 Matilija Fire or 1970 Laguna Fire (Keeley and Zedler 2009). Indeed, throughout the western US, large fires were not uncommon on pre-EuroAmerican landscapes (Keane et al. 2008). However, since 2000, the pace has greatly accelerated and factors behind this increase vary from one end of California to the other. While it is well known that fire behavior is a function of fuels, winds, drought, heat waves, and topography, fires often differ in the importance of one or more of these drivers. On the timber-rich interior US Forest Service (USFS) forests of the Sierra Nevada Mountain Range, anomalously large fuel loading due to a century of successful fire suppression and timber harvesting practices has been a dominant factor (Weatherspoon 1995; van Wagtendonk et al. 2018). However, west of these USFS lands, from Butte County in the north to San Diego County in the south, large fires have been driven by extreme winds, which are often an annual weather event (Nausler et al. 2018).

For this discussion, we make no pretense of having analyzed all major fires in the state but rather have selected those that we believe represent fires dominated by anomalous fuel loads (bottom-up controls) and compare characteristics with fires where extreme winds played a major role (top-down controls). Of course we recognize that, to some extent, the combination of fuels, winds, and topography are factors in most large fire events. However, we maintain that it is possible to recognize examples for which higher than normal fuel loads were a major factor from examples for which extreme weather events involving high winds played a dominant role. Examples of fires we interpret as fuel-dominated vs. wind-dominated are shown in Table 1. This is by no means an exhaustive list as there have been many other large fires since 2000, but we believe one could make a good case for either fuels or winds being the dominate factor driving the behavior of these particular events. These examples illustrate that fuel-dominated and wind-dominated fires tend to differ in their geographical distribution, fire history, source of ignition, seasonal timing, and resources most at risk, as well as management responses likely to reduce impacts of future fires.

Fuel-dominated fires

Particularly illustrative of fuel-dominated fires are the 2012 Rush Fire in steppe vegetation of northeastern California (Fig. 1a) and the 2015 Rough Fire (Fig. 1b) in the mixed conifer belt of the Sierra Nevada Range. Like a majority of fires in the northern part of the state, both were ignited by lightning (Keeley and Syphard 2018). Past fire history shows that much of the landscape within both fire perimeters had gone 75 or more years without fire due to highly successful fire suppression, on a landscape known to have historically experienced frequent fires (Taylor 2000; Stephens and Collins 2004). This period of fire exclusion has resulted in anomalous fuel loads, contributing to unusually severe fires that covered extraordinarily large areas. Similar massive

Table 1 Selected California, USA, wildfires, from 2003 to 2018, interpreted as fuel-dominated vs. wind-dominated (Data from California Department of Forestry and Fire Protection's Fire and Resource Assessment Program, http://www.frap.fire.ca.gov/)

Year	Fire name	County	Month	SA[a] (days)	Area (ha)	Cause	Lives lost (*n*)	Structures destroyed (*n*)
Fuel-dominated fires								
2007	Marble Cone	Monterey	Jul		72 000	Lightning	0	0
2012	Rush	Lassen	Aug		110 000	Lightning	0	1
2013	Rim	Stanislaus	Aug		104 200	Campfire	0	112
2015	Rough	Fresno	Jul		61 400	Lightning	0	4
Wind-dominated fires								
2003	Cedar	San Diego	Oct	3	109 00	Flares	15	2 720
2007	Witch	San Diego	Oct	2	80 200	Powerline[b]	2	1 265
2017	Tubbs	Sonoma	Oct	2	14 900	Powerline	22	5 643
2017	Thomas	Ventura	Dec	10	114 000	Powerline	2	1 063
2018	Woolsey	Ventura	Nov	2	39 000	Powerline	3	1 643
2018	Camp	Butte	Nov	2	62 000	Powerline	88	18 804

[a]Number of days of Santa Ana winds
[b]State and federal agencies use this designation for electric line failures from various causes

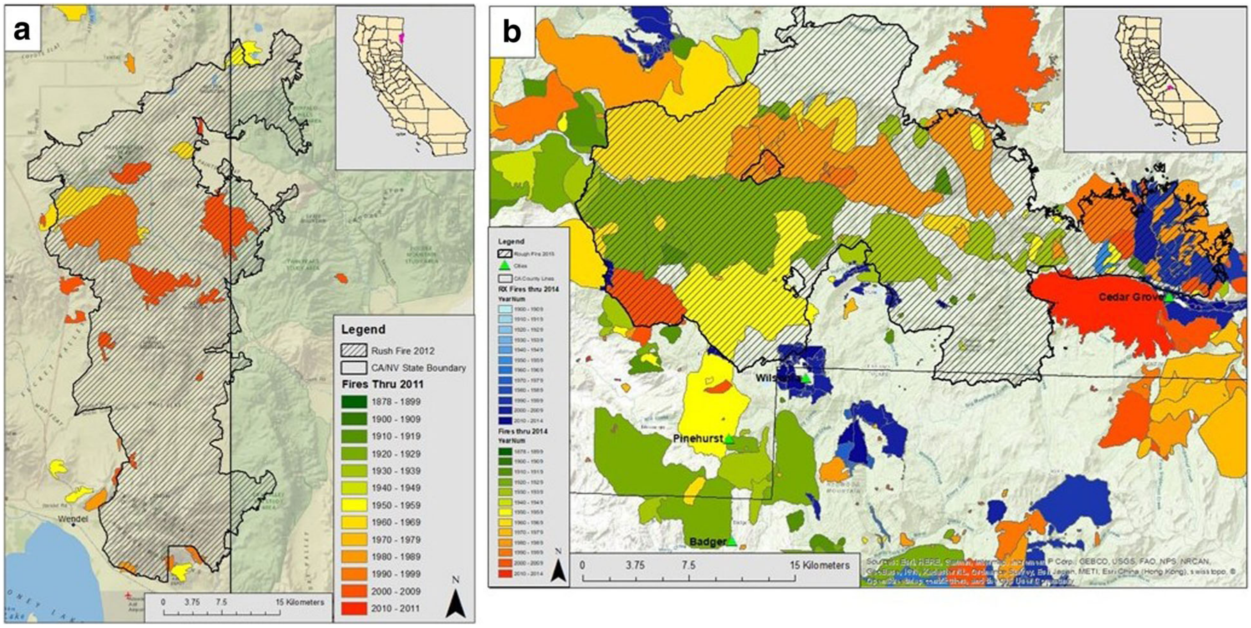


Fig. 1 (**a**) 2012 Rush Fire perimeter overlaid on prior fire history in northeastern California and adjacent Nevada, USA. Fire history shows that the vast majority of landscape had never had a recorded fire in over a century. Heavy fuel loads were likely a major factor in the ultimate size; however, recognition of this fire history, coupled with its remote location, could have influenced fire management decisions as to how aggressively to control the ultimate size of this fire. (**b**) 2015 Rough Fire in the southern Sierra Nevada mountains, perimeter overlaid on prior fire history. Insets illustrate location in California. CA = California, NV = Nevada, thru = through, RX = prescribed, and YearNum = calendar year. (Data from California Department of Forestry and Fire Protection's Fire and Resource Assessment Program, http://www.frap.fire.ca.gov/)

forest fires whose behavior was largely determined by high fuel loads due to unnatural fire exclusion include the 1997 Marble Cone Fire on the central coastal Los Padres Forest, and the 2013 Rim Fire on the Stanislaus Forest and adjacent Yosemite National Park (Table 1), as well as others. While a century of fire suppression has undoubtedly played a role in fuel accumulation (van Wagtendonk et al. 2018), the national forests have had a long history of timber harvesting (e.g., Fig. 2) that has led in some cases to dense even-aged plantations that have not always received appropriate thinning treatments in a timely manner and contributed to increased fire severity (Weatherspoon 1995). Although there is a wealth of papers focused on the role of fire suppression in generating heavy loads, few studies have tried to parse out the role of fire suppression vs. timber harvesting practices in creating hazardous fuels. Certainly, part of the reason is that young plantations often “require” fire suppression for decades to establish, and so, in these cases, anomalous fuel loads are due as much to silvicultural practices as to suppression of natural fires (Wuerthner 2006). Recent studies, however, show that, with intensive treatment, fire hazard can be reduced in these plantations (Knapp et al. 2017).

Fuel-driven fires are common in central and northern California conifer forests. On these landscapes, lightning is more frequently an ignition source than human ignitions (Keeley and Syphard 2018). Lightning peaks in June to July; thus, these fires tend to occur in the summer. In this mediterranean climate, summer predictably has low precipitation and high temperatures and these conditions contributes to drying of live and dead fuels. Particularly striking is that these fuel-dominated fires are not usually associated with significant loss of lives or loss of structures (Table 1). This is due to location in less populated regions and moderate rate of fire spread, allowing adequate time for evacuation.

One characteristic of fuel-dominated fires is that they sometimes generate their own winds. For example, the 2009 Station Fire in Los Angeles County burned through extensive stands of chaparral 50 to 100 years of age and this generated a plume, which subsequently collapsed, and these internally generated winds spread fire in multiple directions. Another example is the 2018 Carr Fire, where roughly half of the area within the perimeter had never experienced a fire in recorded history, and these fuels generated tornado-like winds. These winds represent bottom-up controls as they ultimately were the result of anomalously heavy fuel loads. It is important to recognize this origin because we potentially can alter the occurrence of these winds through fuel treatments, unlike top-down controls such as foehn winds discussed in the following section.

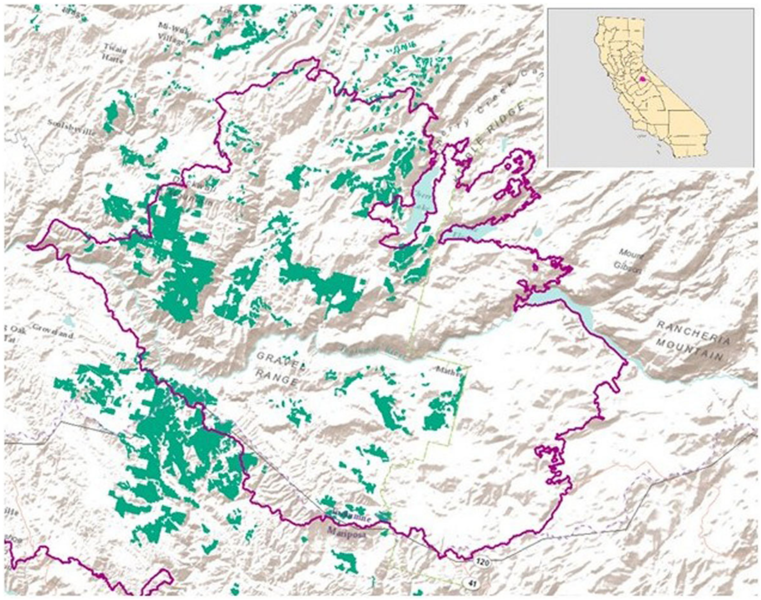
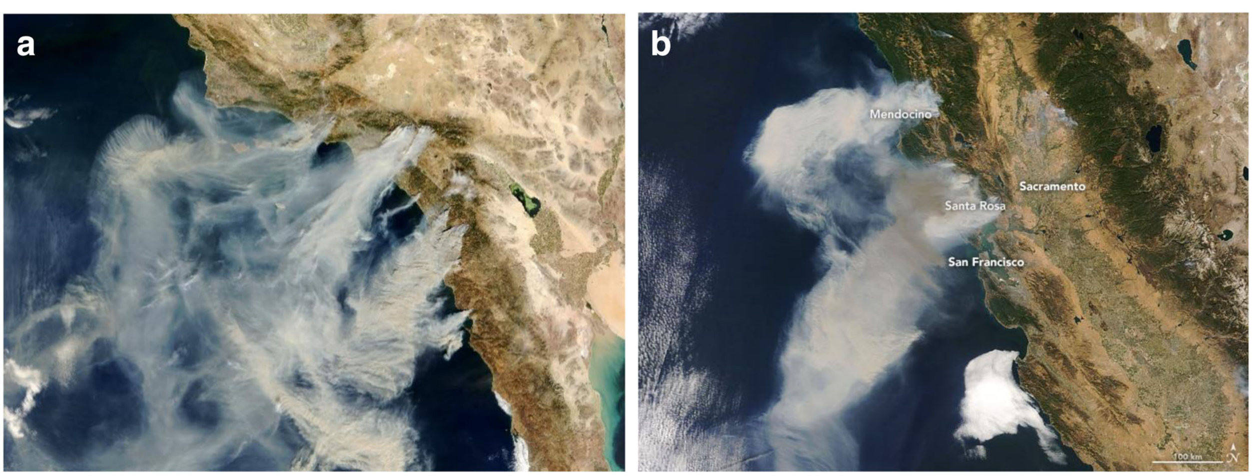


Fig. 2 2013 Rim Fire perimeter (purple line) overlaying recent (1988 to 2011) USFS silvicultural thinning and harvesting (green; https://data.fs.usda.gov/geodata/edw/datasets.php). Inset illustrates location in California, USA

Wind-dominated fires

The fires considered here are driven by synoptic weather conditions producing foehn winds in the western part of California, from north of San Francisco to San Diego in the south; known in the northern part of the state as North Winds, and as Santa Ana Winds in southern California (Box 1). Although these winds occur every autumn, the frequency of such wind events varies from year to year. However, long-term records show no relationship between the frequency of such winds and big fire events (Keeley and Syphard 2017). Why? Because humans are responsible for starting nearly all fires in this region (Keeley and Syphard 2018) and many times these winds do not coincide with a human ignition. Predicting when



Box 1 Extreme winds in California, USA, develop from a high pressure system in the interior Great Basin, coupled with a low pressure in the Pacific Ocean. (**a**) Smoke plumes blowing offshore from Santa Ana winds 26 October 2003 (MODIS image; https://www.nasa.gov/centers/goddard/news/topstory/2003/1027cafires.html). (**b**) Smoke plumes blowing offshore from North Winds during the Napa Sonoma fires of 9 October 2017 (MODIS image; https://earthobservatory.nasa.gov/images/91103/explosive-fires-in-northern-california). These are localized sub-regional events such that southern California Santa Ana wind events do not coincide with North Wind events. In northern California, other terms are sometimes used. For example, newspaper reporters coined the term Diablo Winds during the 1991 Tunnel Fire, apparently because these winds came from the direction of Mt. Diablo in Contra Costa County, to the east. Southern California journalists haven't been as creative and, for discussion, it is best to use North Winds and Santa Ana winds

humans will ignite a fire, either intentionally or through infrastructure such as powerline failures, is beyond current modeling capacity, making predictions of future fire regimes in this region rather speculative. Different sources of human ignitions do have distinct temporal signatures because certain activities tend to be most common at specific times of the year (Syphard and Keeley 2015). However, incorporating these temporal synchronicities into future forecasts will need to explicitly account for modeling of human behavior and infrastructure development (e.g., expansion of the power grid), which accounts for many recent disastrous fires.

Considering that these fire events are ignition limited and humans account for essentially all of these wind-dominated fires (not just in California but nationwide; see Abatzoglou et al. 2018), population growth must be viewed as an important causal agent. Indeed, one out of eight people in the US live in California, and the state has added six million more people since 2000. Some modest-sized counties such as Ventura, site of the massive 2018 Woolsey Fire (Table 1), has added over 100 000 inhabitants, and rapidly growing counties such as Riverside (interior southern California) have increased their population by >35% since 2000 (US Census Bureau 2000, 2017; https://www.census.gov/). Population growth has a definite hand in driving our surge in fires since it increases the probability that humans, or human infrastructures, provide an ignition source during one of these extreme wind events. In addition, increased population growth in crowded metropolitan areas forces more and more people into marginal landscapes of hazardous fuels, making more people vulnerable to fire, which accounts for why recent fires have been more destructive than earlier fires.

Perhaps the most revealing example is the 2017 Tubbs Fire in northern California, whose perimeter overlapped closely with the 1964 Hanly Fire, and although both were driven by extreme North Wind events, they had different outcomes (Keeley 2017). No one died in the Hanly Fire and only about 100 structures were lost, in contrast to 22 people and over 5500 structures lost in the Tubbs Fire. We hypothesize that the different outcomes were due in large part to population growth; for example, the city most heavily affected, Santa Rosa, grew from around 30 000 people in 1964 to 170 000 in 2017. This growth increased the chance of humans and human infrastructure igniting a fire during an extreme wind event, and, due to urban sprawl, it put more people at risk. Development patterns showed that a very small portion of the fire perimeter in 1964 had housing in it, but the vast majority of the area within the 2017 Tubbs Fire perimeter included either low- or high-density housing (Fig. 3). In other regions, increased development has been demonstrated to increase fire ignitions (Mobley 2019), potentially putting more people at risk.

Wildfires always depend on biomass fuels but, on these western California landscapes subject to extreme winds, vegetative fuels are rarely a limiting factor, primarily

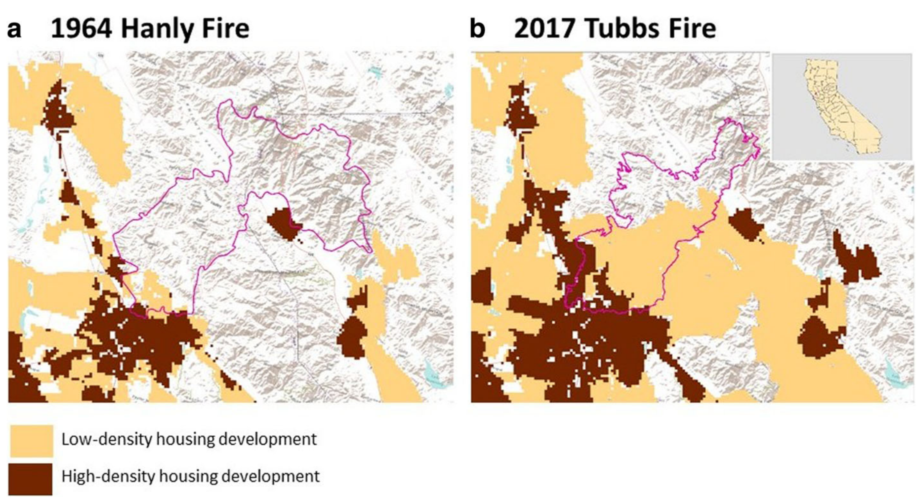


Fig. 3 (**a**) 1964 Hanly Fire perimeter (purple line) with low and high density housing distribution, and (**b**) 2017 Tubbs Fire perimeter (purple line) with housing distribution. Housing density data were spatially distributed and mapped using methods described in Hammer et al. 2004 and Syphard et al. 2009. Within the attributes of partial block groups, all areas designated as having housing density between 6.17 to 49 houses per square kilometer were mapped as low density, with 6.17 corresponding to the minimum housing density cutoff for low-density wildland–urban interface (WUI; Radeloff et al. 2005). The threshold of ≥50 houses per square kilometer corresponds to the same housing density as used for areas defined as medium or high density WUI. Some have downplayed the similarity of the Hanly and Tubbs fires because the former lasted three days and the Tubbs Fire much shorter. However, the Hanly Fire was nearly double the size of the Tubbs Fire and, in the last day of both fires, there was a rapid run from Calistoga to Santa Rosa, driven by North Winds, suggesting very similar fire behavior. Inset illustrates location in California

because coastal California, despite aggressive fire suppression, has burned repeatedly over the last century and thus fuels have not accumulated across most of this region (Safford and Van de Water 2014). Contrast, for example, the fire history on a fuel-dominated northern California fire such as the Rush Fire or Rough Fire (Fig. 1) with southern California wind-dominated fires such as the 2017 Thomas Fire or the 2018 Woolsey Fire (Fig. 4). Only about 1% of the Woolsey Fire landscape had escaped fire in the past and the vast majority has burned two to three times, far more frequently than the historical fire regime. Same with the Thomas Fire: vast stretches of that landscape had burned within the last few decades. Within the perimeters of both fires there were significant patches of relatively recent prescribed burns (Fig. 4a, b: blue). While the prescribed burns likely reduced fire severity on those sites, they did not halt the spread as high velocity winds blew across these stretches of reduced fuels.

The power of these winds is illustrated by the events in Coffey Park during the 2017 Tubbs Fire (Fig. 3b, southwest corner). Much of the community was destroyed with the loss of over 1000 homes and four deaths due to embers blown at over 110 kilometers per hour from a ridge nearly a kilometer to the east. Wildland fuels around the community were not an issue; indeed, there was a 4-lane freeway between that ridge and Coffey Park. While sources of urban ignition were tied to fire branding and ember cast from the nearby Tubbs Fire, evidence here suggests that, once ignited, fire behavior was driven within the community by high winds in conjunction with urban conflagration factors such as high housing density, building construction type and deficits, structural adjacency, ignitable landscaping, yard features, and internal fuel loading, rather than wildland fuels.

In short, extreme winds (Box 1) dominated the behavior of these fires (see Table 1), and there is little evidence that anomalous heavy wildland fuel loads were a determining factor in the ultimate size of these fires. This conclusion is not meant to suggest that fuel treatments play no role on these non-forested landscapes. Defensible space of 30 m around homes is clearly associated with home survival (Syphard et al. 2014), and strategically placed fuel breaks designed to protect communities can play an important role as anchor points for backfires (Syphard et al. 2011). When constructed adjacent to structures, fuel breaks also offer defensible space for access by firefighting resources due to reduced fuel density and thermal output. Beyond these specific conditions, it is doubtful that landscape-level fuel treatments will play much of a role in controlling the size of large wind-driven fires.

We acknowledge that vegetation treatments such as burning and mastication in chaparral may enhance more rapid control of fires under moderate summer weather conditions for which winds are not an issue. However, these fires are typically much smaller than Santa Ana Wind-driven fires (Jin et al. 2014) and seldom result in significant loss of lives and structures (Keeley et al. 2009). In other words, on these landscapes, fuel

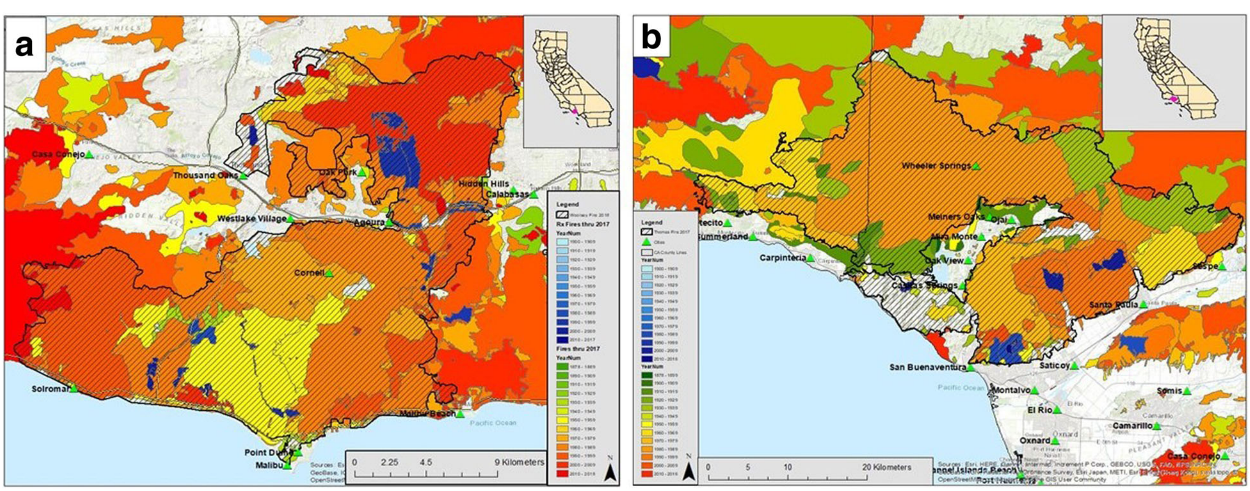


Fig. 4 (**a**) Perimeter of the 2018 Woolsey Fire in Los Angeles and Ventura counties overlaid on prior fire history, which shows that almost none of this landscape has escaped burning. Also, records indicate that over two thirds of this landscape has burned at least twice and some areas 10 or more times. (**b**) Perimeter of 2017 Thomas Fire in Ventura and Santa Barbara counties overlaid on prior fire history. Inset illustrates location in California, USA. CA = California, thru = through, RX = prescribed, and YearNum = calendar year. Based on the data from California Department of Forestry and Fire Protection's Fire and Resource Assessment Program and National Park Service records (https://www.nps.gov/samo/learn/management/loader.cfm?csModule=security/getfile&pageID=624273)

treatments far removed from the Wildland–Urban Interface (WUI) provide protection against the least threatening fires.

There is, however a cost to these fuel treatments. Unlike forests, where treatments may both reduce fire hazard and enhance resources, in California shrublands, frequent burning and mastication is associated with resource loss due to the sensitivity of native shrublands to frequent disturbance and threat of type conversion from native shrublands to alien-dominated grasslands (Brennan and Keeley 2017; Syphard et al. 2018). Thus, fuel treatments in chaparral shrublands may need to be evaluated on a cost-benefit basis. In some circumstances, fire hazard reduction may preempt resource needs, but this needs a clear justification of the benefits.

Extreme synoptic winds were a major factor in the recent Camp Fire (Remote Automated Weather Station [RAWS] data at Jarbo Gap, 8 Nov 2018, showed maximum wind speeds between 80 and 110 km h^{-1}; https://wrcc.dri.edu/cgi-bin/rawMAIN.pl?caCJAR) that was highly destructive to the town of Paradise, killing 88 people and destroying over 18 000 homes. In some ways, interpreting the Paradise fire as an extreme wind event may be the "exception that proves the rule," or, as Stephen J. Gould interpreted this axiom in his essay *Death before Birth,* "the exception that tests the rule." This was clearly a wind-dominated fire event, but fuels may have been an issue, however; this is currently under investigation. The fire began in the forests east of Paradise, which had burned about a decade ago, but then burned through previously unburned forests before reaching Paradise (Fig. 5). Whether or not the unburned forests surrounding Paradise played an important role in generating anomalous ember loads remains to be determined.

Preliminary observations showed that many homes that were destroyed had significant defensible space around them (Fig. 6a, d). Curiously, homes surrounded by trees were incinerated while often the surrounding tree canopies survived, showing the overwhelming influence of wind-driven ember loads and not home destruction by the radiant heat of the fire front (Fig. 6b, c; another example is the Safeway Market that was destroyed despite being surrounded by paved parking lots). Due to the lack of rain in the region for an extended period of time, relative humidities were low (around 10%, RAWS at Jarbo Gap), and homes essentially represented dead fuels that were likely at equilibrium with ambient atmospheric conditions. When homes were ignited by

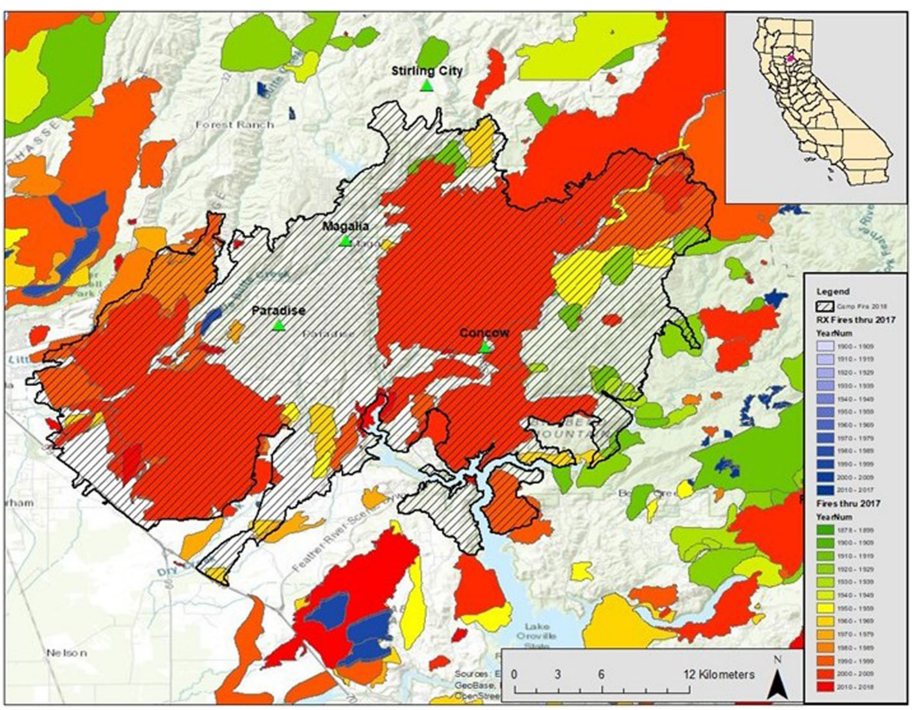


Fig. 5 Past fire history for the 2018 Camp Fire in Butte County in north central California, USA, and site of the worst catastrophic loss of lives and property in California (based on the California Department of Forestry and Fire Protection's Fire and Resource Assessment Program database; http://www.frap.fire.ca.gov/). The fire began east of the town of Paradise, and in a matter of hours burned through forests previously burned in 2008 and then forests with no recorded burning before reaching Paradise (https://inciweb.nwcg.gov/incident/map/6250/23/90834). Inset illustrates location in California. thru = through, RX = prescribed, and YearNum = calendar year

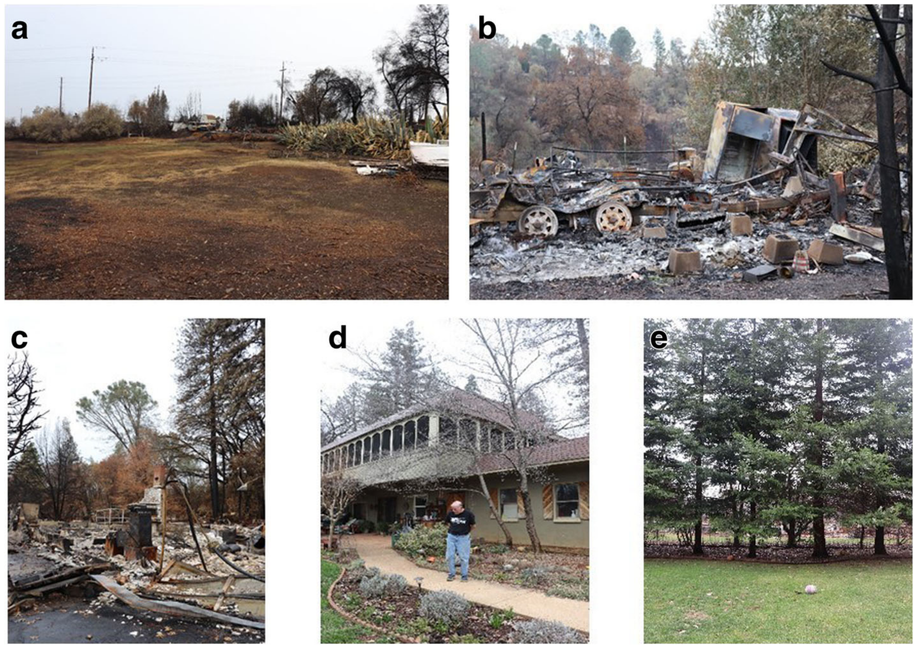


Fig. 6 (**a**) Home incinerated with very little vegetation surrounding the home, illustrating the role of embers, not radiant heat of the fire front (actually, lack of vegetation may have contributed to more rapid laminar flow of the ember load to the house. (**b**, **c**) Homes incinerated while adjacent green trees survived. (**d**) Home unburned while homes within 30 m were destroyed. (**e**) Home that survived had a border of green trees between it and adjacent destroyed homes, perhaps acting as a barrier to embers hitting the house. Photo credit: Jon Keeley, USGS, Nov 2018, in the town of Paradise

embers, they were rapidly incinerated whereas surrounding live trees that had access to water to elevate live fuel moisture remained green (Fig. 7). A hypothesis that has been brought up numerous times in discussions of these extreme wind-driven fires is the potential role of adequately watered trees around homes providing protection as "ember catchers."

Fig. 7 The Kilcrease Circle community in Paradise, California, USA, devastated by the Camp Fire, surrounded by green forest with canopies largely untouched by fire. (DigitalGlobe, a Maxar company satellite image from Nov 2018, used by permission; https://digitalglobe.app.box.com/s/um3og59f92yx0sit0c07p7gremd7r1vj)

Climate impacts

The dominant climatic influence for recent California fires is the extraordinary drought beginning in 2012 that continued through 2018 in southern California (Fig. 8). It has caused the death of forest trees (Fig. 9) at an unprecedented scale: well over 100 million since the drought began (Stephens et al. 2018). In southern California, the death of large patches of chaparral shrublands on slopes surrounding urban environments has not yet been quantified but is impressive (Fig. 10; Venturas et al. 2016). Such dieback is implicated as a factor in the recent southern California Woolsey Fire, because drought-induced vegetation mortality plays a major role in large fire events (Keeley and Zedler 2009). Indeed, all major fires in the region over the last 100 years have been preceded by an anomalously long drought (e.g., the 2003 Cedar Fire in San Diego, 52 months; 2017 Thomas Fire, 72 months; and 2018 Woolsey Fire, 83 months). It is hypothesized that the primary role of drought-caused vegetation dieback is that it greatly enhances the speed of fire spread due to the fact that embers blown ahead of the fire front require dead vegetation to ignite spot fires.

The role of global warming in these drought episodes is unknown, but it may have exacerbated the impact of these droughts on vegetation mortality (Williams et al. 2015). However, warming temperatures are just one of

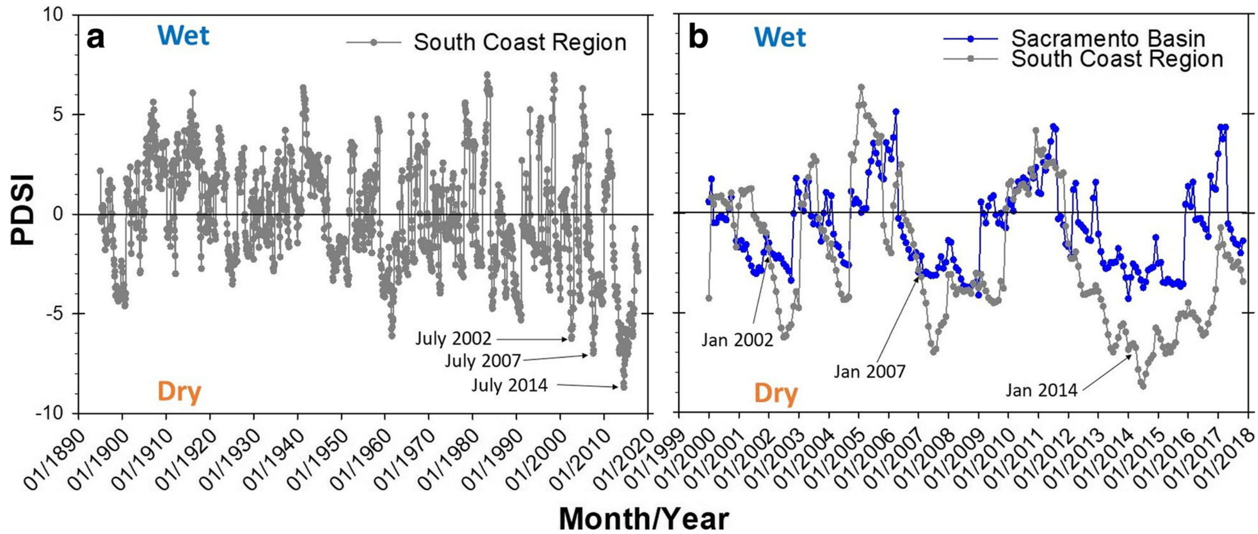


Fig. 8 Palmer Drought Severity Index (PDSI) values from (**a**) the last 121 yr and (**b**) since 2000 for the southern coast region of California. This region includes the cis-montane areas from about Pismo Beach to San Diego and is dominated by chaparral. For comparison, data are also shown from northern California, represented by the Sacramento Drainage Basin. PDSI values are based on precipitation inputs and temperature to measure drought conditions and this index is correlated with soil moisture. Negative PDSI values indicate drought, positive values indicate wet years and zero is the average. (**a**) In recent years, dry season (July) PDSI has reached a series of new record lows. (**b**) In the most recent extreme drought period, there was also intense drought during the normally moist winter (January 2014). From 2016 to the present, southern California has remained in drought, while northern California has had wet periods (**b**). Data are from the National Oceanographic and Atmospheric Administration (NOAA) National Centers for Environmental Information. Palmer Drought Severity Index (PDSI) in January for years 2000 to 2018 for northern and southern California, USA. (Reprinted with permission from Jacobsen and Pratt 2018.)

the extenuating factors; for example, the loss of the million trees in the Sierra Nevada and more northern forests during the recent drought was perhaps driven as much by a century of fire suppression that increased tree density, leading to more intense competition for water (Young et al. 2017; Stephens et al. 2018).

An important lesson about climate–fire relationships is recognition that California, which, north to south, comprises the largest latitudinal range of any Western state, has vastly different climates that dictate different fire behaviors. Western forests typically occur at higher elevations where annual climate variation plays a greater role in determining large fire events than in the foothills and coastal plains. Over 100 years of fire climate data for interior forests show that spring and summer temperatures have a positive relationship with area burned (Keeley and Syphard 2017) and predict that future global

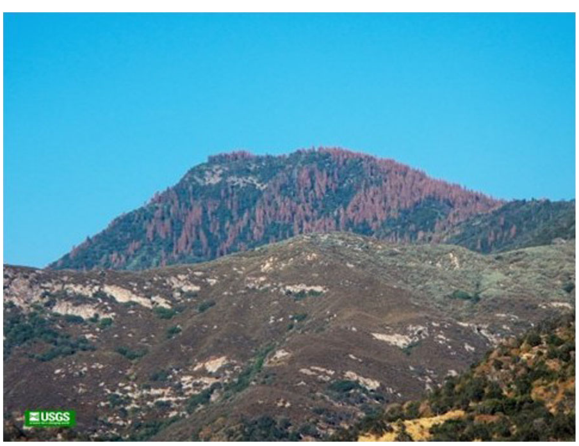


Fig. 9 Severe die-off of *Pinus ponderosa* Douglas ex C.Lawson in a mixed-conifer forest on the northwest-facing slope of Case Mountain in the southern Sierra Nevada Range, California, USA. Photo credit: Jon Keeley, USGS, July 2016

Fig. 10 Severe chaparral dieback in the Santa Monica Mountains of Los Angeles County, California, USA. Photo credit: Jon Keeley, USGS, April 2018

warming may increase fire hazard in these Western forests (Littell et al. 2009; Abatzoglou and Williams 2016).

Lower elevations west of the interior ranges are hot and dry enough every year to carry a large fire, and so it should be no surprise that annual temperature and precipitation variability shows no significant relationship with area burned over the past 100 years (Keeley and Syphard 2017). Briefly, in this region, other factors override most climate signals. The only climate signal we find is that, in recent decades, high winter rainfall has led to higher fire activity the following year, and this is likely due to the increased fuel load of exotic grasses, a relationship well documented in other grass-dominated parts of the Southwest (Crimmins and Comrie 2011). In short, high spring and summer temperatures and lower precipitation alter fuel conditions in montane forests, factors likely to be affected by global warming, but in coastal California the primary climate signal is precipitation with a positive effect on the volume of herbaceous fuels, not an expected global-warming impact (Keeley and Syphard 2016). Substantial increases in fire frequency in the last 50 years have increased loss of native shrublands and invasion of exotic grasses that have had a significant role in increasing fire frequency (Syphard et al. 2018).

One potential role for global warming affecting future fire regimes in these non-forested ecosystems is that it is likely that warmer spring temperatures will alter the competitive balance in post-fire environments such that alien annual grasses and forbs are favored over native shrub seedling recruitment, thus increasing the dominance of the more easily combustible fuels. This is supported by the observation that water-energy balance and soil moisture availability are strongly correlated with increasing dominance of alien herbaceous vegetation in southern California (Park et al. 2018; Syphard et al. 2018). Global warming will likely change the competitive balance and favor invasion of flammable grasses over native shrublands.

Managing fuel-dominated fire regimes

Where unnaturally high fuel loads are a dominant factor driving large fire events, pre-fire fuel treatments are a potential mitigating solution, particularly for montane forests in central and northern California. The Rim Fire is a good example since the bulk of burning occurred in the Stanislaus Forest as a high-intensity crown fire (Fig. 11a). However, when it reached those portions of Yosemite National Park with a long fire management history of prescription burning, the fire settled down into low-intensity surface fires, safe enough that investigators were then allowed into the active fire perimeter (Fig. 11b).

Prescription burning has been a regular part of fire management in national parks in the Sierra Nevada Range since the late 1960s (Schuft 1973), and the national forests have more recently incorporated this into their management practices (Fig. 12). Although national parks began this movement 50 years ago, it is clear that, over this period of time, they have not come close to returning historical fire frequencies (estimated at 10 to 30 years) to Sierra Nevada forests. For example, 50 years of prescription burning in national parks has only burned around 10% of the forested landscape, which, at this rate, would take 500 years to burn all of the forested landscape, assuming no reburning of previous burns. In the last decade, national forests in the Sierra Nevada

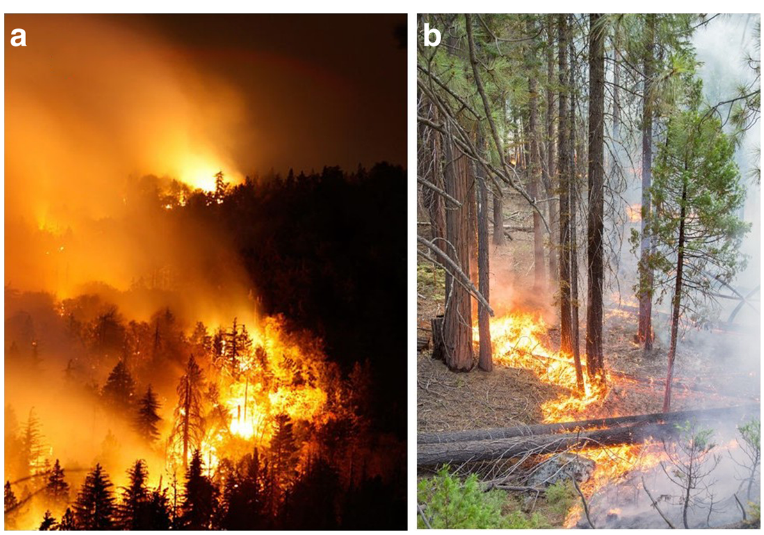


Fig. 11 2013 Rim Fire (**a**) crown fire on USFS lands, and (**b**) understory burning on national park land, California, USA. Photo credits: (**a**) USFS, and (**b**) Jon Keeley, USGS

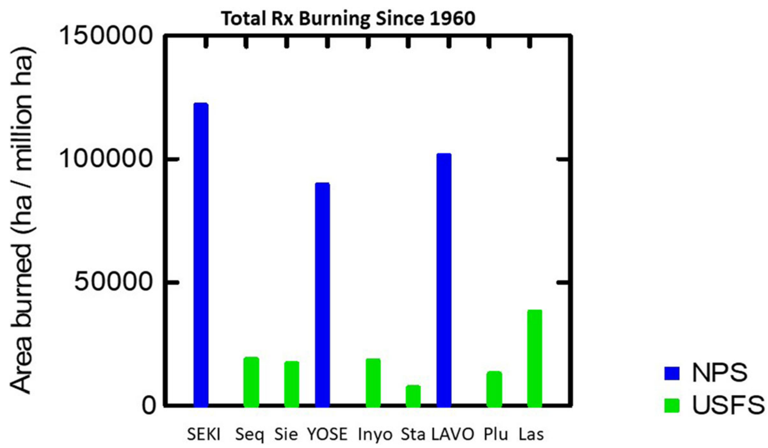


Fig. 12 Prescription burning in the three national parks in the Sierra Nevada and the two USFS forests adjacent to each park for the 50-year period 1968 to 2017. For comparative purposes, data are based on burnable land area within each unit. SEKI = Sequoia and Kings Canyon National Parks, Seq = Sequoia National Forest, Sie = Sierra National Forest, YOSE = Yosemite National Park, Inyo National Forest, Sta = Stanislaus National Forest, LAVO = Lassen Volcanic National Park, Plu = Plumas National Forest, Las = Lassen National Forest, NPS = National Park Service, and USFS = US Forest Service. Data from the California Department of Forestry and Fire Protection's Fire and Resource Assessment Program fire history database; http://www.frap.fire.ca.gov/

have accelerated prescription burning, but during this period have treated only a small percentage of the forested area. Factors limiting the extent of prescription burning include limited funding, tight air quality restrictions, and limited manpower due to diversion of resources to the increasing incidence of wildfires occurring at times suitable for prescription burning. The likelihood of restoring natural fire return intervals with prescription burning seems low.

In the late 1960s, Sequoia and Kings Canyon national parks initiated a "let-burn" program that permitted lightning fires to burn where they did not threaten resources (Kilgore and Briggs 1972). Today this program continues on National Park Service and US Forest Service lands throughout the western US as the Wildland Fire Use policy (Zimmerman and Lasko 2006). However, some of the same constraints as on prescription burning such as air quality restrictions apply to this program as well.

Mechanical treatments that remove understory fuels and thin the density of trees has two advantages over prescription burning: it can be done over a greater portion of the year and potentially can pay for itself through timber sales. Perhaps the major limitation is the ability to balance the harvesting so that trees of sufficient size attract commercial companies with the need to remove the smaller fuels and retain larger trees in order to reduce fire hazard (McIver et al. 2012). Balancing these two needs varies with forest types and location and is far from solved for much of the Sierra Nevada. Another problem is the environmental concerns over necessary ecosystem services provided by burning that cannot be emulated by mechanical treatments. By combining mechanical thinning with subsequent prescribed fire, however, and focusing treatments within areas of high crown-fire potential could minimize ecological impacts and restore adaptive capacity (Krofcheck et al. 2018). An added problem is that mechanical removal of trees is often not compatible with national park policy on management of their forests.

Managing wind-dominated fire regimes: the five "P"s

Fuels play a minor role in controlling the size of large wind-dominated fires. Thus, pre-fire fuel treatments may not be practical approaches to avoid future catastrophic wind-driven fires and their impacts. An important means for reducing the incidence of such fires is through fire prevention during extreme wind events. Indeed, in California on both state and federal lands, significant progress has been made over the last several decades in reducing fire starts (Keeley and Syphard 2018). However, some causes remain problematical, such as powerline-ignited fires (e.g., see Table 1).

Power companies are under increasing pressure to reduce the incidence of their equipment starting wildfires. This is particularly problematical because equipment failure usually occurs during extreme wind events. In addition, these winds are a predictable feature of many lower elevations west of the Sierra Nevada, and these are the landscapes most heavily populated, thus having the highest concentration of power distribution lines.

Given the seemingly inevitability of such extreme wind-dominated fire events, efforts that limit the impacts on people, both loss of lives and property, should be considered as an important management focus. This requires a multi-faceted approached, conveniently summarized as the five "P"s.

First, recognition that this is not so much a fuel problem as it is a *People* problem. The primary means of heading off these catastrophic fires is not with fuel treatments, but with the *Prevention* of human ignitions, particularly during severe wind events. Failing to do this, there is need for greater attention to *Planning* placement of developments with a strategic plan that puts fewer people at risk. For those homes at the WUI), *Protection* of homes from fires is critical. And lastly, agencies would benefit from increased capacity for *Prediction* of extreme wind patterns in real time and communicating that information to fire agencies and homeowners.

People

It should be recognized that the focus needs to be on communities and not on landscape scale fuel treatments.

Prevention

Recognizing the causes that are associated with the worst possible fires and the cultural factors governing their occurrence in different places and times can improve fire prevention. Humans account for 99% of all fires that occur in coastal California, north and south, and the ignition sources are potential points for reducing these disastrous fires. In the past several decades, there has been a dramatic decline in some human ignition sources (Keeley and Syphard 2018; e.g., arson, equipment, smoking), but other sources have not declined and even increased (e.g., powerlines), and the issue tends to be one of timing (i.e., synchronous with extreme fire weather) rather than total number.

Note that powerline failures are the cause of many of our most destructive fires (Table 1). With major power companies in the state—San Diego Gas & Electric, Southern California Edison, and Pacific Gas & Electric—all facing major lawsuits due to recent wildfires (https://www.edison.com/content/dam/eix/documents/investors/wildfires-document-library/2018-05-11-sce-butte-fires-amicus-ltr-re-pge-position.pdf), there is increasing attention being paid to how these companies can reduce their involvement in catastrophic fires. Previously, it was proposed that one solution would be underground powerlines (Keeley et al. 2009) and, although these are more costly, an effective solution might not require all rural distribution lines to be placed underground since the extreme winds follow predictable topographic features (Moritz et al. 2010); underground powerlines in these corridors could have value in minimizing powerline ignited fires. One solution in use by California power companies is to install weather stations on poles throughout their coverage area and continuously monitor weather conditions, shutting down those parts of the power grid experiencing severe winds (https://www.westernweathergroup.com/docs/Case%20Study%20Webpage_SDGE.pdf). Of course, shutting down the power grid could have immense negative impacts on homeowners, and time will tell how effective this solution is.

Planning

Community planning needs to give fire similar recognition as other hazards. It has long been recognized that people cannot control earthquakes and floods, so there are zoning restrictions for them. Fires, on the other hand, have been perceived as controllable, but history reveals that much of the recent increase in human fire impacts has resulted from communities being located in areas where fires are inevitable. There is thus a need for greater focus on fire-zoning (Kennedy and Troy 2009), and consideration of advantages by replacing community planning with regional planning.

A growing body of scientific research demonstrates that structures are most likely to be destroyed by wildfire in specific types of housing patterns and locations (e.g., low-to intermediate-density housing, close to the edge of a development, small to intermediate clusters of development interspersed within wildland vegetation, history of frequent fire, or located at the edge of a canyon or in a wind corridor). These characteristics are all associated with exposure to wildfire given the proximity to wildland vegetation or the overall propensity for fire to burn in that location (Syphard et al. 2012; Alexandre et al. 2016). Neighborhoods with high densities of flammable older homes have been among the most recent losses (Coffey Park and Paradise), particularly because these houses serve as dead fuel that facilitates house-to-house fire spread. Nevertheless, empirical studies in the US and in California show that, historically, the vast majority of structures are destroyed at low to intermediate densities in the WUI, where homes meet or intermingle with wildland vegetation (Kramer et al. 2018). Simulation studies projecting alternative scenarios of future development patterns suggest that both zoning and conservation decision-making can result in reduced probabilities of structure loss in the future (Syphard et al. 2012; Syphard and Keeley 2016). In-filling within community limits is perhaps the safest pattern as it reduces exposure to open space and puts fewer homes at risk. Gradual spread outward puts more people at risk, but so-called leapfrog developments that initiate new communities beyond the former WUI are likely to result in the greatest housing losses.

Protection

Beyond reducing the probability that fires reach urban neighborhoods, there are things that homeowners can do to protect their home in case a wildfire does reach the WUI. Of course, creating defensible space for fire fighters is number one (Syphard et al. 2013). However, recent work shows that maintaining green vegetation (i.e., via irrigation or landscaping with woody vegetation that has naturally high fuel moisture) can be as effective at reducing structure loss (Gibbons et al. 2018). In addition, home owners need to be vigilant about reducing plant litter accumulation on roofs, perhaps the major cause of home destruction from wildfires (Keeley et al. 2013). Also, building materials provide protective benefits.

Sprinklers on the roof could reduce the likelihood of embers igniting a house; however, there are many details to work out. It would need to be a stand-alone system, with independent power source (due to possible power shutdowns), and an independent water storage tank (since, during fires, water resources can be depleted). Assuming these problems are solved, there is still a potential problem of such a system working properly under extreme wind conditions when water spray is potentially blown off its intended target.

Prediction

Extreme wind events (with winds speeds over 70 km h^{-1}) move rapidly, and knowing the trajectory of the winds early in the event and related parameters could limit losses of lives and property. Progress is being made in prediction capacity (e.g., Rolinski et al. 2016; Cao and Fovell 2018), but for this to save lives, it requires effective communication systems, something that also needs further work.

Conclusions

One cannot understand recent California wildfires as fitting a single model. Fire suppression has been consistently brought up as the issue behind catastrophic fires, but that is misleading. For fuel-dominated fires, heavy fuel accumulation is not tied to just fire suppression but rather other land management practices that include past timber harvesting practices. The most disastrous fires in terms of loss of human lives and property are less tied to anomalous fuel loads than they are to extreme wind events. Management responses to these different fire types are radically different.

In interior conifer forests, past land management has produced dangerous fuel loads and pre-fire fuel treatments are the main approach to altering these fire outcomes. However, on lower elevation landscapes subjected to extreme wind events, fire suppression has never come close to excluding fires, and thus fuel accumulation is not the causal factor in these fires. Wind-driven fires are the result of annual foehn wind events coupled with occasional human ignitions, either directly or through infrastructure failures. The primary means of reducing impacts of these fires is through better fire prevention, improved land planning that puts fewer people at risk, enhanced homeowner protection, and improved agency prediction of fire spread trajectories and communicating those to fire-fighting agencies and homeowners.

Acknowledgements

Thanks to B. Keane for suggesting this project. We thank M. Rohde, Orange County Fire Department, retired; and D. Sapsis, T. Moody, and D. Passovoy from California Department of Forestry and Fire Protection for their comments on some of the ideas in this paper. Thanks to A. Pfaff in the US Geological Survey Sequoia and Kings Canyon National Parks office for creating all the fire history maps, to R. Halsey for bringing the post-fire Paradise image to our attention, and to K. Carringer at DigitalGlobe for assistance in obtaining permission to use this image. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the US government.

Authors' contributions

Both authors contributed to ideas, writing, and data presentation. Both authors read and approved the final manuscript.

Funding

Support from institutional funds.

Availability of data and materials

Links to data availability given in the references.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Received: 18 April 2019 Accepted: 21 May 2019
Published online: 18 July 2019

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