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CLIMATOLOGY

Ignitions explain more than temperature or precipitation in driving Santa Ana wind fires

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Autumn and winter Santa Ana wind (SAW)–driven wildfires play a substantial role in area burned and societal losses in southern California. Temperature during the event and antecedent precipitation in the week or month prior play a minor role in determining area burned. Burning is dependent on wind intensity and number of human-ignited fires. Over 75% of all SAW events generate no fires; rather, fires during a SAW event are dependent on a fire being ignited. Models explained 40 to 50% of area burned, with number of ignitions being the strongest variable. One hundred percent of SAW fires were human caused, and in the past decade, powerline failures have been the dominant cause. Future fire losses can be reduced by greater emphasis on maintenance of utility lines and attention to planning urban growth in ways that reduce the potential for powerline ignitions.

INTRODUCTION

California has captured international attention in recent years because of frequent catastrophic wildfires. These fires often differ in their causal factors, and a useful generalization is that fire behavior is sometimes dominated by high fuel loads and other times by high winds resulting from synoptic weather conditions (*1*, *2*). These two extremes typically differ in seasonality, geographical distribution, ignition source, and impacts on people and management needs (*3*, *4*). As a general rule, fuel-dominated fires are summer forest fires, often ignited by lightning and occur in wildlands where few lives or properties are at risk. These fires are also the ones most sensitive to climate change impacts (*5*–*7*). In contrast, wind-dominated fires driven by synoptic weather conditions are autumn events in coastal California, which often result in substantial loss of lives and property (*4*). The focus of the present study is on the latter type of fires.

Wind-dominated fires

Although wind can be a factor in many fires, here we are concerned with those fires dominated by extreme winds generated by synoptic weather patterns of high and low pressure (*1*–*3*). These are typically autumn and winter winds with gusts over 100 kph, known in California as Santa Ana winds (SAWs) in the south and as North winds, Diablo winds, or Mono winds in the north (*4*, *8*, *9*). These foehn-type winds are autumn and winter episodic pulses of offshore flow and are associated with wildfires that have been most destructive to lives, property, and health (*3*, *10*, *11*). Similar catastrophic foehn wind-driven fires, sometimes associated with localized katabatic winds, also occur in the Mediterranean Basin and southeastern Australia among other regions (*12*, *13*).

A recent study (*14*) examined meteorological characteristics of autumn months (September, October, and November) and found that across California there has been an ~1°C increase in temperature and ~30% decrease in precipitation over the past 4 decades. They (*14*) surmised that these climatic changes enabled extreme SAW fires resulting in increased area burned over this period. Using the Canadian Fire Weather Index (CFWI) (*15*), which predicts fuel moisture and fire behavior, they used global climate model output to predict an increase in autumn fire weather conditions in the future and inferred that there would be an increase in area burned by southern California SAW fires in the 21st century.

However, the study in (*14*) assumed that SAW fire size and area burned was controlled by temperature and precipitation before or during a SAW event, and that CFWI was a reliable predictor of area burned during SAW fires. Also, as acknowledged by (*14*), their conclusions of increased SAW fire activity in the future did not include other potential factors such as changes in human ignitions. The role of ignitions in controlling wildfire patterns has been demonstrated to be an important determinant of area burned nationwide (*16*–*19*), although in modeling studies it is often explicitly assumed to not be a limiting factor (*10*), or it is an implicit assumption (*20*).

The focus of our study was to delineate the factors that determine area burned by SAW fires. We used a 71-year history of SAW days in southern California and the SAW Regional Index (SAWRI) of daily windspeed, along with daily temperature and precipitation (*21*–*23*), plus PRISM data of monthly temperature and precipitation in southern California. These weather and climate data were overlaid on the CAL FIRE Fire and Resource Assessment Program (FRAP) fire history database for southern California (see Materials and Methods) to determine those weather, climate, and ignition factors most strongly associated with area burned. We also examined the extent to which CFWI could reliably predict area burned during SAW fires and modeled the most important determinants of area burned.

RESULTS

Seventy-one-year history of SAWs and fire

From 1948 to 2018, there were 3258 days with SAWs, and contiguous days of these winds were considered a SAW event. There were 643 SAW events that lasted from 1 to 36 days each (90% between 1 and 10 days) averaging 5.2 days per event. SAW days were concentrated between October and January, with shifts in the past 35 years

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in peak month, average wind speed per event, and duration of events (Fig. 1). Some of the most notable changes were a substantial drop in SAW events in September during the past 35 years and increased wind speeds in October through January.

During the 71 years (1948–2018), a total of 3,269,611 ha burned in the region with 45.3% from fires ignited during SAW events. Although there were many more summer fires than autumn and winter SAW fires, the largest fires were during SAW events; 42 events had very large areas burned, ranging from 5000 ha to several over 100,000 ha (Fig. 2A). There was marked temporal variation. In recent years (1984–2018), October had the peak of SAW-associated wildfire numbers and hectares burned, and September and November had a drop in both numbers and hectares burned (Fig. 2, B and C) over the first 36 years of our record. In brief, over the past 35 years,

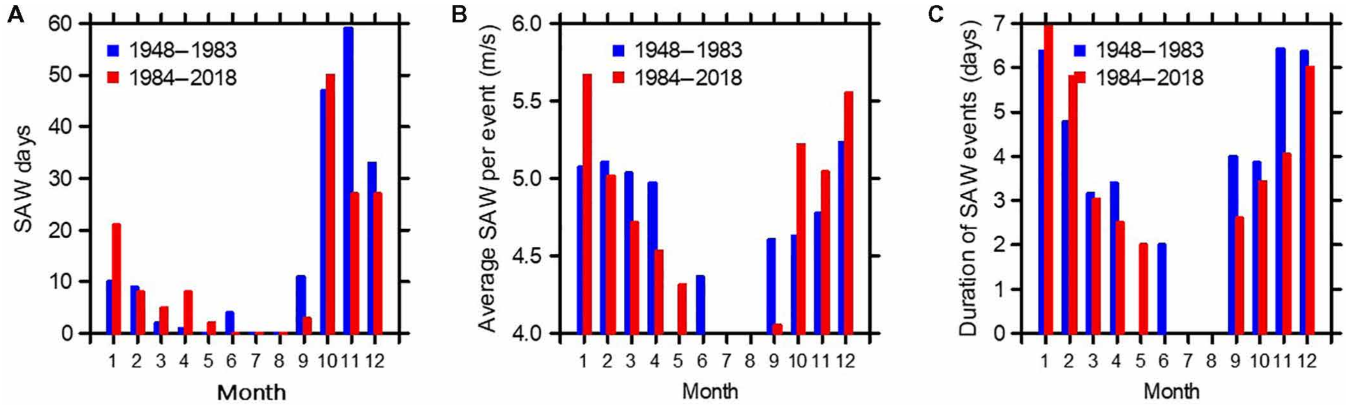

Fig. 1. SAW monthly distribution over 71 years. (**A**) Days with SAW winds, (**B**) average SAW wind speed per SAW event, and (**C**) duration of SAW events, for the first half (1948–1983) and second half (1984–2018).

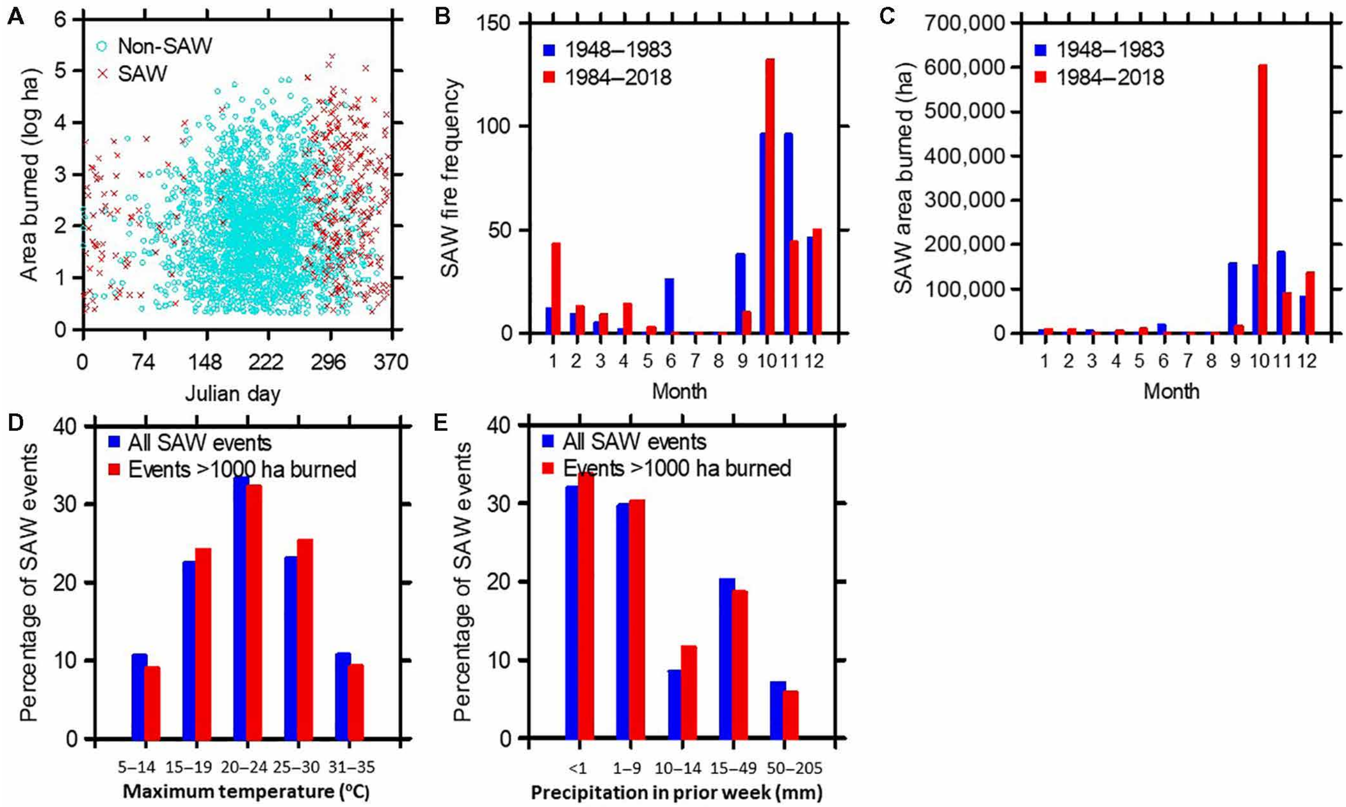

Fig. 2. SAW events and fire. (**A**) Area burned by SAW and non-SAW fires in southern California for all years, and monthly distribution for the first half and second half of our 71-year record for (**B**) SAW fire frequency and (**C**) SAW area burned. (**D**) Percentage distribution for all SAW events and just those with fires over 1000 ha for Tmax during a SAW event and (**E**) precipitation in the week before the SAW event.

the SAW fire season no longer includes September as an important month, and of greater importance are winter months December and January.

Climate and weather

Two weather parameters inferred to be important in determining area burned by SAW fire events are temperature and precipitation (*14*). Our data provide a good basis for testing those hypotheses, as temperature and precipitation associated with SAW events varied markedly between events.

Maximum temperature during SAW events varied from 5.9° to 35.2°C across the southern California region. Monthly averages for Tmax (maximum temperature) during SAW events ranged from October (15.6° to 35.2°C), November (9.5° to 32.0°C), December (5.9° to 29.4°C), and January (6.7° to 27.3°C). However, fires >1000 ha burned were not associated with higher temperatures (Fig. 2D). Even for very large SAW fires (>5000 ha), the Tmax during these SAW events was not significantly higher than the average for a SAW event that month ($P = 0.705$ to 0.853 for October, December, and January with one-sample t test); in fact, Tmax in November during events with >5000 ha burned was significantly lower than the long-term November mean ($P = 0.004$, $n = 11$).

In addition to temperature during the SAW events, we examined temperature in the months before SAW fires (see Table 1 for a complete list of variables included in multiple regression models). Area burned during SAW events was only affected by temperature for December and was not significant enough to be included in the strongest models. Instead, the models were largely driven by number of ignitions and SAW speed (Table 2).

Precipitation in the week before SAWs event likewise did not appear to play a substantial role (Fig. 2E). Approximately two-thirds of all SAW events with fires >1000 ha had <10-mm precipitation, but this matched closely the distribution of precipitation during all SAW events. Comparison with monthly means during all events showed no significant difference for events with >1000 ha burned (October: $P = 0.901$, $n = 27$; November: $P = 0.764$, $n = 23$; December: $P = 0.065$, $n = 17$). For large fires >5000 ha, there was no significant evidence that prior precipitation played a role in contributing to autumn fires (October to November) ($P > 0.054$), but in winter, December SAW events with large fires had 3.7 mm, versus 14.6 mm for all December SAW events ($P = 0.002$, $n = 6$), indicating that droughts that extended into December contributed to more area burned by the occasional SAW fire.

Precipitation in antecedent months had a significant effect on area burned in some autumn and winter months, although in all cases its importance was outweighed by number of ignitions and SAW speed (Table 2). Of particular interest is the observation that antecedent precipitation in the month or months before SAW events showed some significant effect in the first 36 years of record but not in the most recent 35 years (Table 2). In the past 35 years, the importance of precipitation varied by month; in October (the month with the highest area burned), the most significant variable after ignitions and maximum SAW speed was the prior 5-year drought [as measured by Palmer Drought Severity Index (PDSI)], but in December, it was November and December ppt, although ppt was not significant in models that included ignitions and SAW speed (Table 2).

CFWI, inferred to model future SAW fire risk (*14*), was evaluated in terms of area burned during SAW events. This index uses the daily weather conditions of noon (local standard time), relative humidity, 24-hour precipitation, and 10-m wind speed to estimate two sets of parameters: fine fuel moisture content (FFMC) and the fire weather index (FWI), which is a rating of potential fire intensity and considered an index of fire danger. These were calculated for every day over the 71-year period and summarized by average values for SAW events for each month (Table 3). FFMC was not a significant factor affecting area burned for any of the months October, November, December, and January. FWI showed a slightly significant effect only for December. In short, using CFWI to predict future SAW fire events is not reliable for autumn months and weakly significant for December.

Table 1. Independent variables of weather, ignitions, and climate included in multiple regression models presented in Table 2.
Winter (Win) = December (from prior year), January, February;
Spring (Spr) = March, April, May;
Summer (Sum) = June, July, August;
Autumn (Aut) = September, October, November.

Variable (symbol)	Definition
Weather variables associated with SAW event	
Maximum temperature (TMAX)	Mean for days of event
Minimum temperature (TMIN)	Mean for days of event
Precipitation (PPT)	Total for days of event
Precipitation (PPT5days)	Total for 5 days before event
Precipitation (PPT6days)	Total for first day and prior 5 days
Precipitation (PPT7days)	Total for first day and prior 6 days
Precipitation (PPT8days)	Total for first day and prior 7 days
Minimum relative humidity (RHMIN)	Mean for the days of event
Mean wind speed (SAWmean)	Mean for days of the event
Maximum wind speed (SAWmax)	Maximum during the event
Duration of Santa Ana winds (SAWdays)	Days of event
Cumulative wind speed for event (CumulativeSAW)	Sum of wind speeds for all days of event
Days since end of prior event (LastSAW)	Days between end of last event and beginning of next event
Ignitions	
Number of ignitions during event (Ignitions)	Recorded wildfires during the days of the SAW event
Climate: Monthly or seasonal	
Mean monthly temperature (Tmean)	For months and for seasons
Maximum monthly temperature (Tmax)	For months and for seasons
Monthly precipitation (Ppt)	Total for month or season
Palmer Drought Severity Index (PDSI)	Mean for all months of year
(Prior yr PDSI)	Mean for all months of prior year
(Prior 2yr drought)	Mean for current and prior year
(Prior 3yr drought)	Mean for current and prior 2 years
(Prior 4yr drought)	Mean for current and prior 3 years
(Prior 5yr drought)	Mean for current and prior 4 years

Table 2. Significant multiple regression models for area burned during SAW events. All significant models are presented, except where there was a lack of independence between independent variables. Variables presented in order of *P* value. See Table 1 for description of independent variables.

	Adjusted r^2	*P*
October 1948–1983 (*n* = 34)		
Log ha = SAWmean	0.143	0.016
Log ha = Cumulative	0.205	0.004
Log ha = SAWmax	0.227	0.003
Log ha = SAWmean + SAWdays	0.276	0.003
Log ha = Ignitions	0.222	0.003
Log ha = Ignitions + Cumulative	0.343	0.001
Log ha = SAWmean + Ignitions + SAWdays	0.390	<0.001
Log ha = SAWmax − PptSep	0.320	0.001
Log ha = SAWmax + Ignitions	0.337	0.001
Log ha = SAWmax + Ignitions − PptSep	0.409	<0.001
Log ha = SAWmean + Ignitions + SAWdays	0.390	<0.001
Log ha = SAWmean + Ignitions + SAWdays − PptSep	0.440	<0.001
October 1984–2018 (*n* = 33)		
Log ha = SAWmax	0.156	0.011
Log ha = Ignitions	0.214	0.003
Log ha = Ignitions + SAWmax	0.296	0.001
Log ha = Ignitions + SAWmax + Prior 5yr drought	0.359	0.001
Log ha = Ignitions + SAWmax + Prior 5yr drought − PPT	0.420	<0.001
November 1948–1983 (*n* = 50)		
Log ha = −TMAX	0.084	0.023
Log ha = −TMIN	0.074	0.031
Log ha = SAWmean	0.116	0.009
Log ha = SAWmax	0.175	0.001
Log ha = Ignitions	0.256	<0.001
Log ha = SAWmean + SAWdays	0.135	0.012
Log ha = Ignitions + SAWmean	0.350	<0.001
Log ha = Ignitions + SAWmax	0.392	<0.001
Log ha = SAWmean − TMAX	0.209	0.002
Log ha = SAWmean − TMIN	0.195	0.002
Log ha = SAWmax − TMAX	0.232	0.001
Log ha = SAWmax − TMIN	0.220	0.001
Log ha = SAWmax − PptSep	0.213	0.001
Log ha = SAWmax − PptAut	0.295	<0.001
Log ha = SAWmax − PptAut − TMAX	0.395	<0.001
Log ha = SAWmax − PptSum − PptAut	0.339	<0.001
Log ha = SAWmax + Ignitions − PptAut	0.404	<0.001
November 1984–2018 (*n* = 62)		
Log ha = SAWdays	0.074	0.019
Log ha = CumulativeSAW	0.069	0.022
Log ha = −RHMIN	0.131	0.002
Log ha = SAWdays − PptOct	0.121	0.008
Log ha = Ignitions	0.248	<0.001

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	Adjusted r^2	P
Log ha = Ignitions + SAWdays	0.298	<0.001
December 1948–1983 ($n = 64$)		
Log ha = SAWmax	0.090	0.009
Log ha = SAWdays	0.137	0.002
Log ha = Cumulative SAW	0.151	0.001
Log ha = Ignitions	0.425	<0.001
Log ha = −PptNov	0.132	0.002
Log ha = −PptDec	0.105	0.005
Log ha = TmeanDec	0.101	0.006
Log ha = TmaxSep	0.094	0.008
Log ha = TmaxNov	0.097	0.007
Log ha = TmaxDec	0.172	<0.001
Log ha = TmaxDec + TmaxNov	0.190	<0.001
Log ha = −PptNov − PptDec	0.189	0.001
Log ha = SAWdays − PptNov − PptDec	0.261	<0.001
Log ha = Ignitions + SAWmax	0.462	<0.001
Log ha = Ignitions + SAWdays	0.490	<0.001
Log ha = Ignitions + Cumulative SAW	0.492	<0.001
December 1984–2018 ($n = 77$)		
Log ha = −RHMIN	0.186	<0.001
Log ha = SAWmax	0.211	<0.001
Log ha = SAWdays	0.199	<0.001
Log ha = Cumulative SAW	0.256	<0.001
Log ha = Ignitions	0.353	<0.001
Log ha = Ignitions − RHMIN	0.384	<0.001
Log ha = TmeanDec	0.150	<0.001
Log ha = TmaxDec	0.195	<0.001
Log ha = −PptDec	0.136	0.001
Log ha = SAWmax − RHMIN	0.250	<0.001
Log ha = SAWdays + SAWmean	0.221	<0.001
Log ha = SAWdays − RHMIN	0.264	<0.001
Log ha = SAWdays − PptNov	0.262	<0.001
Log ha = SAWdays − PptDec	0.254	<0.001
Log ha = Cumulative SAW − PptNov	0.321	<0.001
Log ha = Cumulative SAW − PptDec	0.305	<0.001
Log ha = Cumulative SAW − PptNov − PptDec	0.340	<0.001
Log ha = Ignitions + SAWdays	0.436	<0.001
Log ha = Ignitions + SAWmax	0.463	<0.001
Log ha = Ignitions + SAWmax + SAWdays	0.480	<0.001
January 1948–1983 ($n = 60$)		
Log ha = SAWdays	0.346	<0.001
Log ha = TmeanJan	0.050	0.008
Log ha = TmaxJan	0.098	0.047
Log ha = Cumulative SAW	0.226	<0.001
Log ha = Ignitions	0.559	<0.001

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	Adjusted r^2	P
Log ha = Ignitions + Cumulative SAW	0.619	<0.001
Log ha = Ignitions + SAWdays	0.668	<0.001
January 1984–2018 (n = 67)		
Log ha = −RHMIN	0.047	0.041
Log ha = SAWmean	0.116	0.002
Log ha = SAWmax	0.083	0.009
Log ha = Ignitions	0.230	<0.001
Log ha = Ignitions + SAWmean	0.280	<0.001
Log ha = Ignitions + SAWmax	0.285	<0.001

Table 3. Area burned during SAW events predicted by CFWI. Models based on mean weather values during SAW events that had fires for years 1979–2018; FFMC is the fine fuel moisture content, and FWI is the fire weather index, which is a numeric rating of fire intensity and is used as a general index of fire danger.

	Adjusted r^2	P
October (n = 28)		
Log ha = FFMC	0.035	0.170
Log ha = FWI	0.098	0.058
November (n = 19)		
Log ha = FFMC	0.000	0.939
Log ha = FWI	0.000	0.335
December (n = 12)		
Log ha = FFMC	0.000	0.828
Log ha = FWI	0.274	0.046
January (n = 11)		
Log ha = FFMC	0.090	0.193
Log ha = FWI	0.000	0.442

Area burned during SAW events was affected by wind intensity. SAW wind speeds defined in (*21*) (see also Materials and Methods) were almost equally divided [50% versus 48% between weak (<5 m/s; n = 1587) and moderate (5 to 9.99 m/s; n = 1594), with 77 days in the top 2% of average wind speeds as extreme (≥10 m/s)]. Average wind speed was not markedly different between events with no fires versus events with high area burned (Fig. 3A). However, maximum wind speed was tied to greater area burned by fires in the 1000 to 5000 ha class (Fig. 3B). The cumulative SAW index per event (i.e., sum of wind speeds for all days during a SAW event) showed that higher values were also associated with large fires 1000 to 5000 ha, but not tied to the largest fires.

The majority of fires and area burned occurred during moderate winds (Fig. 4, A and B). Although frequency of fires during extreme winds was low (Fig. 4A), the area burned was substantial in the past 35 years (Fig. 4B). The largest fire was associated with four extreme wind days during that SAW event (Fig. 4C). This was the Thomas Fire that occurred in December 2017. Not only it had the highest number of extreme wind days over the 71-year period of our record, but also the SAW event lasted 16 days; although not record breaking, it was three times longer than the average SAW event. However, the presence of multiple extreme wind days during a SAW event did not dictate a large fire, as there were SAW events with 2 and 3 days of extreme winds and no fire activity (Fig. 4C).

Ignitions

The number and type of ignitions played a substantial role in determining area burned in Southern California wildfires. Of the 643 SAW events, >75% had no fires (Fig. 5A), showing that ignitions were a limiting factor in SAW area burned. Even during extreme winds (Fig. 5B), there was >50% chance of no burning. During SAW events, 100% of the fires were caused by humans, either intentionally or accidentally. From 1948 to 1983, campfires were the leading cause, whereas from 1984 to 2018 arson and powerline failures dominated (Fig. 5C), and in the past decade, arson fires played a minor role compared to powerline failures (fig. S1).

DISCUSSION

This study shows that (i) SAW wind speed plays a key role in area burned, (ii) variation in SAW windspeed outweighs fuel characteristics in explaining area burned, (iii) winds alone are insufficient to explain burning without consideration of human ignitions, (iv) ignition sources have changed markedly in recent decades, and (v) autumn and winter temperature and precipitation are less critical than winds and ignitions, and have substantially different effects on autumn versus winter SAW events.

Warmer temperatures do not play a significant role in area burned during autumn SAW events. October, which has been the peak of fire activity in the past 35 years, shows no relationship between area burned and temperature during the SAW event or in months before the SAW event. In November, the only significant relationship is that for the first 35 years of our dataset, more area burned during cool SAW events, as measured by maximum and minimum temperatures during the event (Table 2). Winter, however, is a different story. Temperatures during the event and in months before the event were significant; however, they explained only 5 to 20% of the variation and were not significant predictors in the best models that explained up to 50% of the variation, based on ignitions and SAW days and wind speed.

Precipitation is more complicated. Rain in the week before a SAW event showed little relationship with area burned for most months

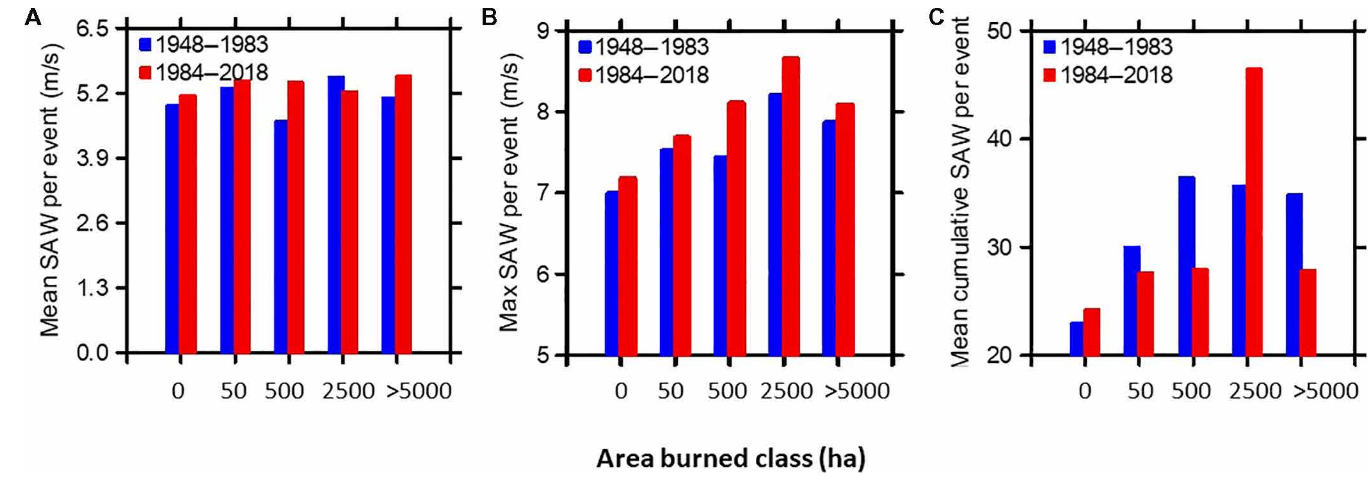

Fig. 3. Burn classes. Percentage of SAW events that fall into one of five area burned classes: 0 = no area burned, 50 = 1 to 99 ha, 500 = 100 to 999 ha, 2500 = 1000 to 4999 ha, >5000 = >5000 ha for (**A**) all SAW events and (**B**) SAW events with at least one extreme wind day. (**C**) Cumulative SAW index per event.

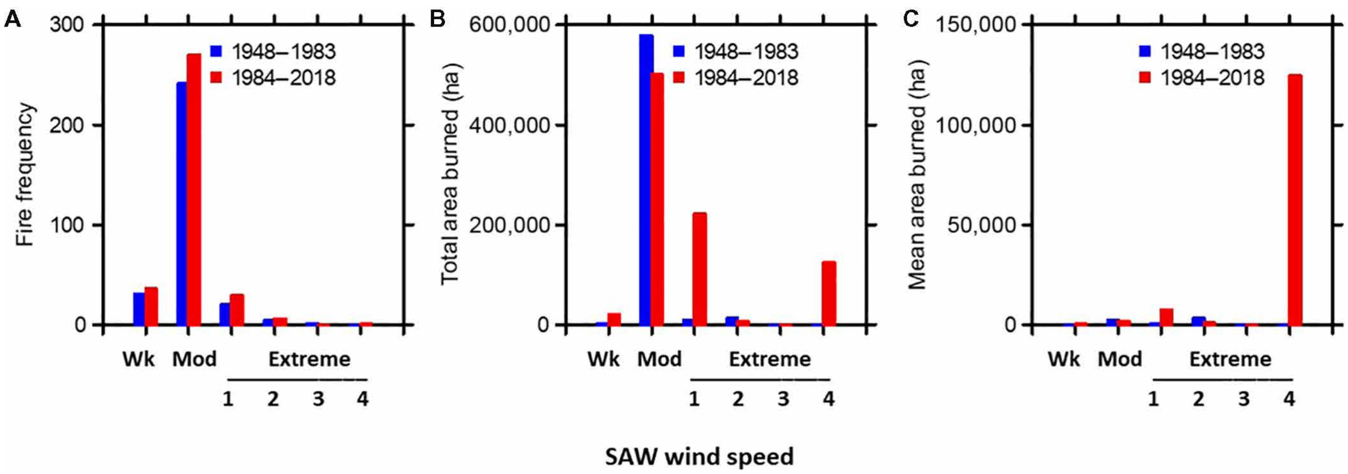

Fig. 4. Weak, moderate, and extreme winds. (**A**) Fire frequency, (**B**) total area burned, and (**C**) mean area burned per fire for each of the three SAW wind speed categories: Weak (Wk) = <5 m/s, Moderated (Mod) = 5 to 9.99 m/s, and Extreme = ≥10 m/s [extreme winds are presented separately for the number of extreme days per event; for the first half (1948–1983) and second half (1984–2018)]. The single large fire event in (C) was the 2017 Thomas Fire with 4 days of extreme winds.

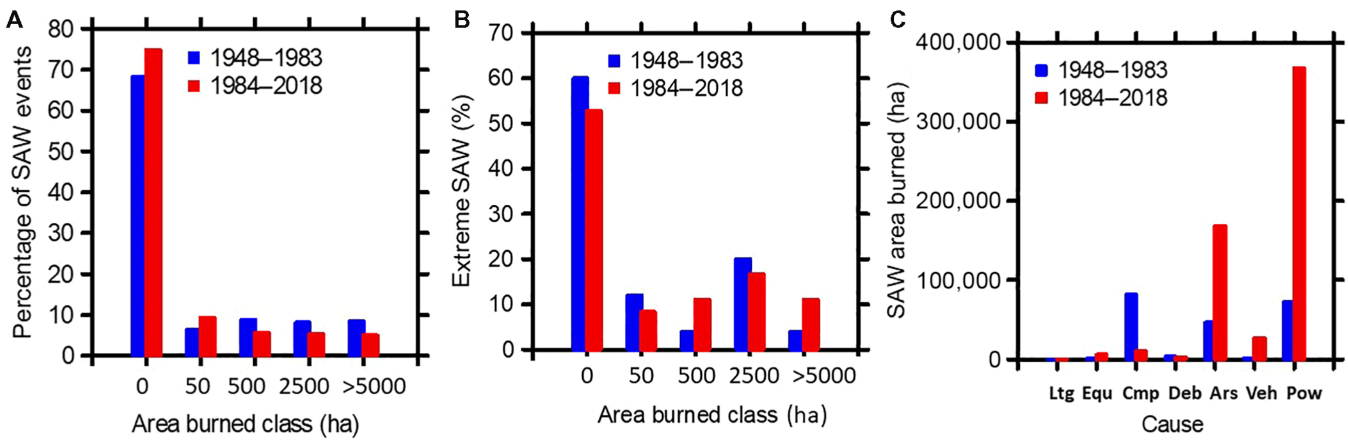

Fig. 5. Percentage of SAW events with and without fire. Area burned classes: 0 = no area burned, 50 = 1 to 99 ha, 500 = 100 to 999 ha, 2500 = 1000 to 4999 ha, >5000 = >5000 ha for (**A**) all SAW events and (**B**) events with at least 1 day of extreme winds. (**C**) Area burned by ignition source for all SAW events. Ltg, lightning; Equ, equipment; Cmp, camping; Deb, debris burning; Ars, arson; Veh, vehicle; Pow, powerline related, for years 1948–1983 versus 1984–2018.

(Fig. 2E and Table 2). However, the role of monthly antecedent precipitation varied with the month and between early (1948–1983) and late (1984–2018) years. SAW area burned in October during the early years showed a significant relationship with September precipitation when coupled with maximum SAW speed and ignitions (Table 2). In the past 35 years, October precipitation in the week before a SAW event was significant, but outweighed in importance by number of ignitions, maximum SAW speed, and prior 5-year drought. In November, antecedent precipitation in summer and autumn months was significant in the earlier years, but outweighed in importance by maximum SAW speed, duration of SAW events, and ignitions; however, over the past 35 years, precipitation has played a minor role in fire activity. In December, antecedent rainfall was significant during all 71 years of record, and when coupled with the cumulative SAW index, it accounted for 34% of the variation; however, antecedent rainfall was no longer significant in the best model that included ignitions, maximum SAW speed, and SAW days, which explained 48% of the variation.

Fuels are the primary means by which climate variation translates into fire activity. Climate and weather affect fuels through changes in either fuel moisture or fuel load. CFWI (Table 3) shows that variation in fuel moisture, is not a significant factor in determining area burned during any SAW month. In southern California, variation in fuel moisture is a determining factor of large fires in the summer, but is a less deterministic factor in autumn SAW fires (*24*). This does not mean that fuel moisture is not important, but just that it is already at a very low level at the beginning of autumn and during droughts stays at that level until significant precipitation (*25*). For example, the massive 2017 Thomas Fire (Fig. 4C) began in early December near the end of a severe drought; live fuel moisture at the time was 53 to 59% for chaparral shrubs in adjacent LA County; however, that was not substantially lower than what was recorded at the same sites for mid-September at 57% (*26*). Although late autumn and winter droughts may not further reduce fuel moisture, they have the potential to alter fuel structure; because live fuel moisture is at a critical threshold in early autumn, further drying could increase the level of dead fuels. The potential role of extended droughts causing vegetative dieback is also suggested by the inclusion of 5-year droughts in the October model (Table 2).

In summary, SAW speed is an important factor determining area burned, but SAW events by themselves do not predict large fire events; over 75% of all wind events result in no fires. Even extreme winds do not always result in large fires, e.g., events with two and three extreme SAW days had little or no area burned. Thus, a major limiting factor to large fires is whether or not there is an ignition that escapes initial attack during the wind event, and the probability of this increases with the number of fires ignited. The importance of this factor cannot be underestimated, as in all months the effect of number of ignitions during a wind event is a major factor determining area burned. In the southern California region, 100% of all SAW fires are the result of human ignitions, either intentionally or accidentally. Over the past 71 years, the sources have changed markedly, with arson, and especially powerline failures, becoming more frequent in the latter part of the 20th century (*27*, *28*). This pattern is evident in other regions subjected to autumn wind-driven fires such as the North Bay counties in the state, where powerlines have become a major source of fires. Two factors account for this: a history of inadequate maintenance of powerlines and increased expansion of the power grid (*4*). The former potential cause is being addressed by utility companies; however, the role of how to manage population growth in ways that would minimize expansion of distribution/transmission lines vulnerable to SAW winds has received little or no attention.

MATERIALS AND METHODS

Santa Ana winds

SAW conditions are identified using SAWRI, initially developed by (*21*) and subsequently computed from the daily hybrid downscaling of National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Global Reanalysis 1 winds (SAWRI) in (*22*). These were available from 1948 to 2018 at a daily resolution. In brief, SAWRI is the regional mean wind speed during periods of consistent northeasterly winds over the southern California domain, as described in (*21*). On the basis of RD1-SAWRI, we constrained SAW days to those with a minimum spatial extent of local SAW condition in at least ~60% of the SAW domain. SAW events were defined as contiguous days with a SAWRI greater than 0. One exception was when SAW days were separated by a day with zero winds, we considered that day and the prior and subsequent SAW days as constituting a single SAW event.

Fire history for southern California included ignitions that began south of Santa Barbara County for the years 1948–2018 from the CAL FIRE FRAP fire history database (http://frap.fire.ca.gov/data/frapgisdata). This is a spatially explicit database that is relatively complete for the time period being considered (*29*). Some additions were made to this database from agency records of CAL FIRE and the U.S. Forest Service (USFS); a total of 85 fires were added, ranging from 10 to 11,600 ha each. Also, using these data sources, internet searches and published literature 289 fires were updated with start and end dates and causes (i.e., ignition sources). Reported start dates were considered dates of ignition and correlated with SAW days/events. Fires that lacked a start date could not be included and this accounted for 22.9% of all area burned during the period 1948–2018, and this proportion was roughly the same for both the first half of the record (1948–1983; $n = 36$ years) and the second half (1984–2018; $n = 35$ years). FRAP records showed 65% of the fires from National Oceanic and Atmospheric Administration (NOAA) Division 6 as of unknown cause (largely because many fires are added to the FRAP database soon after the event when cause had not yet been determined), so we considered data from (*27*, *28*), based on annual reports, a more reliable representation of ignition sources. However, the vast majority of fires listed in the FRAP fire history database as undetermined origin were relatively small and area burned by cause was substantially better, with only 30% of area burned of undetermined origin in our modified FRAP fire history database. For fires burning during SAW events, all those over 1000 ha had a recorded cause. The number of ignitions during a SAW event was based on the number of reported fires for the days during that event.

Climate and weather

To evaluate climate effects on fire activity, we used monthly PRISM temperature and precipitation data. For every year in the analysis, we extracted 2.5 arc min PRISM data (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, accessed 15 January 2019) for areas within the boundaries of the study region. PDSIs were taken from NOAA (https:// ncdc.noaa.gov/temp-and-precip/drought/historical-palmers/, accessed 20 January 2021).

Weather parameters of Tmax, Tmin, RH, and Precipitation were obtained from downscaled databases, as described in (*22*, *23*).

Analyses

Statistical analyses and graphical presentation were conducted with Systat software (version 13.0, Systat Software Inc., San Jose, CA; http:// systat.com/). For the climate analysis, we developed multiple regression models that predicted area burned on monthly temperature, monthly precipitation, and PDSI for the current year and prior years up to 5 years. Residual plots were visually examined to see if they were normally distributed. To ensure that multicollinearity would not be an issue, we calculated correlation coefficients among all potential explanatory variables and eliminated those that were correlated ($P < 0.05$) with other variables in the model.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/7/30/eabh2262/DC1

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