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RESEARCH ARTICLE

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Extreme fire spread events and area burned under recent and future climate in the western USA

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Abstract

Aim: Wildfire activity in recent years is notable not only for an expansion of total area burned but also for large, single-day fire spread events that pose challenges to ecological systems and human communities. Our objectives were to gain new insight into the relationships between extreme single-day fire spread events, annual area burned, and fire season climate and to predict changes under future warming.

Location: Fire-prone regions of the western USA.

Time period: 2002–2020; a future +2°C scenario.

Methods: We used a satellite-derived dataset of daily fire spread events and gridded climate data to assess relationships between extreme single-day fire spread events, annual area burned, and fire season maximum temperature, climate moisture deficit, and vapour pressure deficit. We then developed models to predict fire activity under a 2°C warming scenario.

Results: Extreme single-day fire spread events >1,100 ha (the top 16%, >1 *SD*) accounted for 70% of the cumulative area burned over the period of analysis. The variation in annual area burned was closely tied to the number and mean size of spread events and distributional skewness towards more large events. For example, we identified 441 extreme events in 2020 that together burned 2.2 million ha across our study area, in contrast to an average of 168 per year that burned 0.5 million ha annually between 2002 and 2019. Fire season climate variables were correlated with the annual number of extreme events and area burned. Our models predicted that the annual number of extreme fire spread events more than double under a 2°C warming scenario, with an attendant doubling in the area burned.

Conclusions: Exceptional fire seasons like 2020 will become more likely, and wildfire activity under future extremes is predicted to exceed anything yet witnessed. Safeguarding human communities and supporting resilient ecosystems will require new lines of scientific inquiry, new land management approaches and accelerated climate mitigation efforts.

KEYWORDS
climate change, extreme wildfire event, fire behaviour, fire run, fire suppression, megafire

1 | INTRODUCTION

Expanding wildfire activity in the western USA poses profound challenges to both human communities and ecological systems (McWethy et al., 2019). Recent fire years have resulted in significant air quality impacts, billions of dollars of economic damage and unacceptable losses of human life. A rapidly growing body of work in the western USA reveals directional changes in both the drivers and the consequences of recent wildfire activity, including increases in fire season length (Westerling et al., 2006), extreme fire weather (Jolly et al., 2015), fuel aridity (Abatzoglou & Williams, 2016), total area burned (Dennison et al., 2014) and area burned severely (Parks & Abatzoglou, 2020). Similar increases in wildfire activity associated with climate are also occurring in other regions of the Earth, including Australia (Boer et al., 2017; Shi et al. 2021), Canada (Coogan et al., 2019) and Siberia (Kharuk et al., 2021), and are predicted to continue under future climate (Bedia et al., 2015; Krawchuk et al., 2009; Wang et al., 2017). Rapidly changing aspects of wildfires and fire regimes are leading to concerns about increasing vulnerability of biota, ecosystem function and human communities within these landscapes (Coop et al., 2020; Mietkiewicz et al., 2020; Pickrell & Pennisi, 2020; Xu et al., 2020).

Recent fire seasons in the western USA and elsewhere have been characterized not only by high total area burned, but also by periods of extremely rapid fire growth and very large single-day fire spread events. Throughout a fire season, short-duration but extreme events can have outsized effects, vastly expanding the area burned in individual fires (i.e., “megafires”; Adams, 2013) and contributing disproportionately to cumulative social and ecological impacts (Duane et al., 2021). Exemplifying such effects, 4 million ha burned in the USA in the 2020 fire season, mostly in western states (www.nifc.gov), with many states seeing record-setting fires. In Oregon and Washington, there were multiple days of individual fire growth >10,000 ha (including one report of 40,000 ha) and a record-setting wildfire in Colorado that burned *c*. 1,500 ha/h for >24 h in October (https://inciweb.nwcg.gov/). Likewise, California reported a record-setting individual fire (the 400,000-ha August Complex) that exhibited extreme fire growth under high winds and low fuel moisture over several days in early September, contributing to a record total annual area burned (1.7 million ha; www.fire.ca.gov) in the state.

Observations of very large single-day fire runs within the context of recent record-breaking fires and fire seasons raise a suite of research questions and hypotheses (Duane et al., 2021). New methods to calculate daily fire spread from satellite observations have catalysed the development of datasets of daily fire spread over expanded spatial and temporal scales (Parks, 2014) and are leading to analyses that provide new insights into wildfire activity (Hart & Preston, 2020; Wang et al., 2017). At a foundational level, aggregate fire effects, such as area burned, represent the accumulation of thousands of single-day fire spread events. Increasing annual area burned in the western USA (Dennison et al., 2014) might thus be attributable to (H1) an increasing number of fire spread events, (H2) increasing mean size of fire spread events, and/or (H3) an increase in the occurrence of exceptionally large fire spread events (Figure 1).

Understanding patterns in daily fire spread events could lead to expectations about how extreme wildfire activity might change, particularly under future warming. As with all types of fire behaviour, extreme fire events depend upon a complex set of interactions among wildland fuels, topography, weather and the fire itself (Werth et al., 2016). Yet, there is increasing recognition that climate change is altering many of these interactions. Warming can increase the fire season duration and the number of fire events (e.g., Westerling et al., 2006), and the mean or median fire season temperature is frequently a strong predictor of area burned (Kirchmeier-Young et al., 2019). Longer fire seasons and more fires also increase the odds that fires will coincide with extreme fire weather that promotes large fire growth (Abatzoglou et al., 2021; Jain et al., 2018). Fuel moisture is another key determinant of fuel ignition and spread that is strongly affected by climate change, and decreasing fuel moisture directly relates to increases in the annual area burned (Abatzoglou & Williams, 2016; Wotton et al., 2010). Under extreme droughts, large areas are characterized as having low fuel moistures, which can support rapid fire spread across large scales. Strengthening vapour pressure deficit can also shape the availability of live and dead wildland fuels (Duane et al., 2021; Stephens et al., 2018). Therefore, climate metrics directly related to changes in fire season length, fuel moisture and fuel availability (such as maximum temperature, climate moisture deficit and vapour pressure deficit) would be expected to be related strongly to the potential for extreme fire growth events (e.g., Wang et al., 2017).

Growing evidence suggests that climate change will continue to expand fire activity in the coming decades, but with interannual variability (e.g., El Niño Southern Oscillation, Pacific Decadal Oscillation; Crimmins, 2011; Trouet et al., 2009) likely to result in climatic conditions and patterns in fire spread events outside of those experienced within recent observations. What constitutes an extreme under contemporary climate might change as once rare conditions (such as occurred in 2020) become more common. Thus, we might ask whether climate and attendant fire activity in the western USA in 2020 could be representative of future norms and what type of wildfire activity could occur during future extremes.

Our study aimed to evaluate daily fire spread events and relate variation therein to annual area burned and climate in the western USA. To do so, we used a unique, satellite-derived dataset that

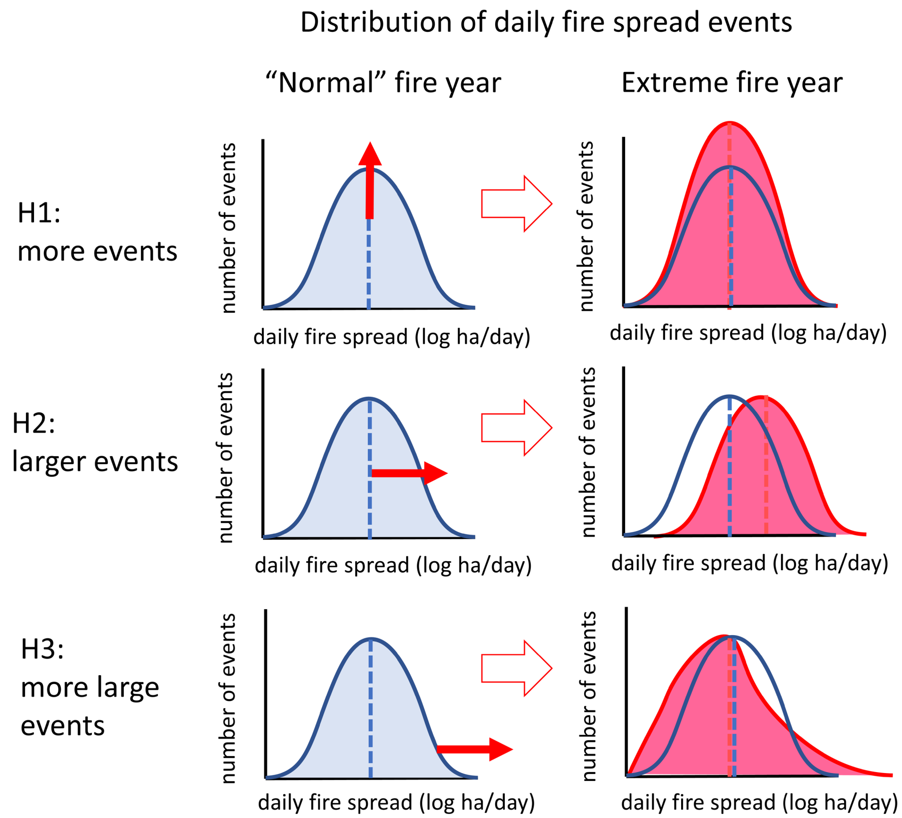


FIGURE 1 Hypothetical distribution of daily fire spread events during normal and extreme fire years. Increases in the annual area burned could potentially be accounted for by more fire spread events (number), larger event size (mean) and/or more large events (right skewness)

depicts daily area burned in every fire occurring between 2002 and 2020. We have three specific objectives, as follows: (1) to provide summary statistics on daily fire spread in relationship to cumulative area burned and quantify the degree to which patterns in fire spread events shape annual area burned; (2) to identify relationships between the annual number of extreme fire spread events (≥1,100 ha/day) and fire season climate across four large ecoregions and the western USA as a whole; and (3) to project the annual number of large spread events (≥1,100 ha/day) and total annual area burned under climate change. As a point of reference, we contrast fire spread events in 2020 with earlier observations and future projections. The use of statistical models (rather than process-based models or physical models) to predict the likelihood of extreme fire spread represents a novel approach with the potential to lead to new research directions and inform appropriate societal responses to challenges posed by future wildfires.

2 | METHODS

Our study was conducted within four large, fire-prone ecoregions of the western USA (the Southwest, Northern Mountains, Western Mountains and California Coast). The ecoregional delineation we adopt here broadly follows Olson & Dinerstein (2002) and parallels other regional analyses of wildfire patterns in the western USA (e.g., Dennison et al., 2014; Parks & Abatzoglou, 2020).

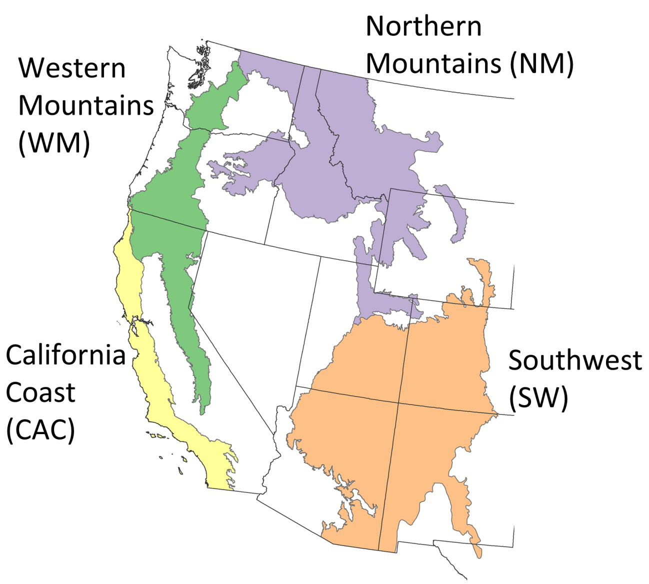


FIGURE 2 Study area in the western USA, comprising four fire-prone ecoregions

2.1 | Data

Our analyses are based on measurements of the daily fire spread (in hectares per day) for individual wildfires. Following the methods of Parks (2014), we developed spatially continuous maps depicting the day of burning for all fires whose centroid intersected our study area in the western USA from 2002 to 2020 (Figure 2). Briefly, this procedure interpolates VIIRS and MODIS fire detections (from https://firms.modaps.eosdis.nasa.gov/active_fire/) to map the day of burning within the entire area of the final fire perimeter at a resolution of 30 m. This day-of-burning interpolation technique has been used successfully in several previous fire studies (e.g., Downing et al., 2021; Hart & Preston, 2020; Holsinger et al., 2016; Meigs et al., 2020; Wang et al., 2017). All day-of-burning interpolations were constrained to the final fire perimeters as obtained from national repositories; we obtained 2002–2018 fire perimeters from the Monitoring Trends in Burn Severity (MTBS) programme (Picotte et al., 2020). Fire perimeters from 2019 and 2020 were downloaded from the National Interagency Fire Center (NIFC; interagency fire perimeter history – all years; available at https://data-nifc.opendata.arcgis.com/datasets/); fires <400 ha were removed to match the MTBS dataset. Given minor differences between the NIFC and MTBS databases, we performed a sensitivity analysis to examine whether a bias correction to 2019 and 2020 NIFC fire counts and area burned would influence our findings or interpretations. We found that such a correction led to negligible increases in future projections and thus elected to use the data from NIFC without adjustments, noting that as more and better data become available, more refined future projections will become feasible. Fires with <10 fire detections were excluded from the analysis because of uncertainty associated with interpolating small numbers of detections. Fire detections that occurred between midnight and 06.00 h were assigned to the previous day. In total, we interpolated day of burning for 2,391 fires and 20,991 unique fire spread events ranging in size from 25 to 74,509 ha. Example day-of-burning maps are shown in Figure 3.

Climate data used in our analyses include mean climatic water deficit (hereafter, Deficit), mean maximum temperature (Tmax) and mean vapour pressure deficit (VPD). Each of these variables has been shown to be correlated with various measures of fire activity, including annual area burned, annual area burned at high severity and mean fire severity (e.g., Abatzoglou et al., 2017; Parks & Abatzoglou, 2020; Williams et al., 2014), and would be expected to predict the occurrence of extreme fire spread events, as described previously. Climate data were acquired from TerraClimate (Abatzoglou et al., 2018; http://www.climatologylab.org/terraclimate.html). All climate variables were converted to *z*-scores based on the mean and *SD* of a 1986–2015 reference period. Given collinearity between these variables, and following Williams et al. (2014), we also developed a single synthetic variable incorporating Deficit, Tmax and VPD, which we refer to hereafter as fire season Aridity. Aridity is calculated as the average of the *z*-scores of Deficit, Tmax and VPD.

Using the methods of Parks and Abatzoglou (2020), we summarized monthly climate data across each ecoregion and the study area in the western USA over the 3-month period ending with the month identified as having the most area burned for each ecoregion, as defined by the number of monthly MODIS fire detections that intersected fire perimeters during the 2002–2020 period. Hereafter, we refer to this as "fire season climate", which corresponds to June–August for the western USA as a whole and for all ecoregions except the Southwest, in which fire season climate is April–June.

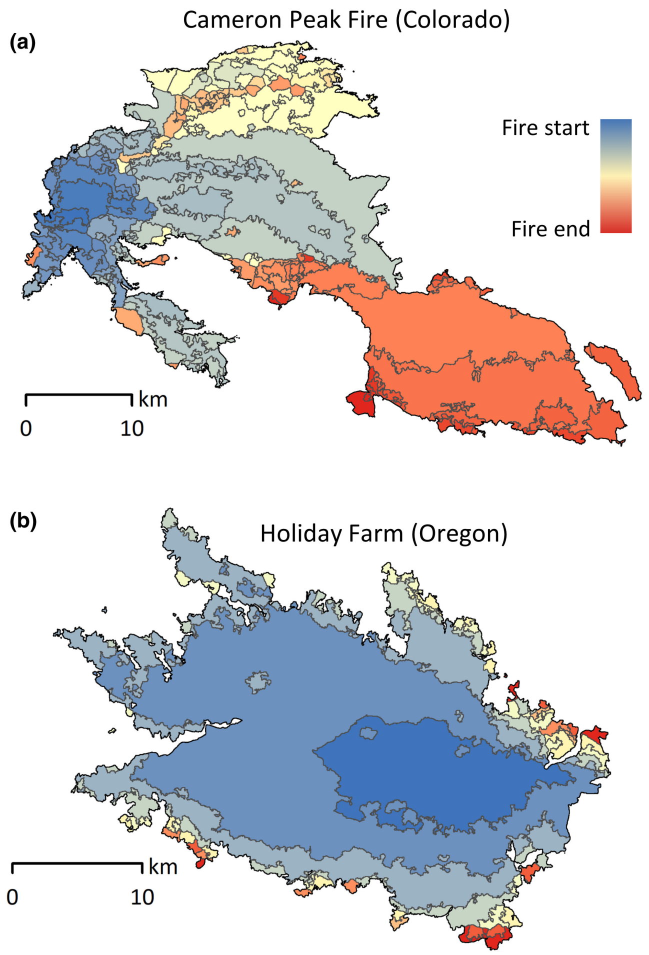


FIGURE 3 Representative day-of-burning maps for two fires that occurred in 2020, Cameron Peak and Holiday Farm

In addition to observed climate data, we also acquired data from TerraClimate for a future climate scenario that corresponds to a global mean temperature 2°C above pre-industrial. As developed by TerraClimate, this scenario superposes projected multi-model changes in both climate means and interannual variability to measured values from a 1986–2015 reference period (Qin et al., 2020). Thus, projections include monthly values for each year over a 30-year time frame; as before, we summarized the three +2°C climate metrics over the fire season representative of each ecoregion and converted them to *z*-scores based on the 1986–2015 reference period.

2.2 | Analyses

We examined the distribution of daily fire spread in relationship to the cumulative area burned (2002–2020) across the study area in the western USA, calculating values of the mean, median, first and second *SD*, top 10% and 1% of spread events, and proportions of total area burned above each. Calculations were based on log_{10}-transformed area burned; native values (in hectares) presented in the Results are back-transformed. We were also interested in understanding relationships between annual distributional parameters and annual area burned (Figure 1), including (H1) the number of fire spread events, (H2) mean event size, and (H3) skewness (i.e., a right skew would be indicative of disproportionate influences by large events). To calculate the relative contribution of these three factors (number of spread events, mean size of spread events, and skewness), we built a linear regression model with log_{10} annual area burned as the dependent variable and the three distributional parameters as the independent variables, and we evaluated models using different combinations of terms using the Akaike information criterion (AIC). To determine the relative contribution of each term in our final model, we calculated the difference between the full model and a model with that term removed (relativized/standardized to 100%). All analyses were conducted in R (R Core Team, 2021).

Next, we assessed relationships between fire season climate and the annual number of extreme fire spread events, which we define here as ≥1,100 ha/day (>1 *SD* from the logarithmic mean of daily fire spread). This value (number of extreme spread events) is essentially a single metric relating to the number, mean size and right skew of event size distributions described above. We first calculated the correlation (Pearson's *r*) between the annual number of extreme spread events and climate metrics (Deficit, Tmax, VPD and Aridity). This analysis was conducted for each ecoregion and for the western USA as a whole.

Lastly, we predicted the annual number of extreme spread events and area burned under a future climate scenario (2°C above pre-industrial) in contrast to the 1986–2015 reference climate period and the extreme year of 2020. To do so, we built a generalized linear model (GLM) for the relationship between number of extreme events and Aridity across the western USA over the 2002–2020 period of observation using a negative binomial distribution ("glm.nb" function in the MASS package in R; Ripley et al., 2013). Annual area burned (log_{10}) was modelled in a similar manner via a simple linear model. Using these models, we then predicted the number of extreme fire spread events and annual area burned for the western USA under a +2°C warming climate. We modelled responses for both the reference and future climate periods, thereby providing a means to compare changes in the number of extreme fire spread events and annual area burned under recent climate and 2°C warming relative to pre-industrial conditions. We also predict the number of extreme fire spread events and annual area burned for the year 2020 conditions. We contrast model predictions to the observed number of extreme fire spread events and area burned in 2020, in order to examine how the 2020 fire season might compare with expectations under climate change.

3 | RESULTS

Daily fire spread followed a slightly skewed log-normal distribution, with a median value of 260 ha/day and a mean of 295 ha/day (Figure 4). Single-day spread events >1,100 ha represented the top 16% of events (1 *SD* from the mean) and accounted for 70% of total area burned. Described another way, the top 10% of fire spread events burned 58% of the total area and the top 1% of events burned 20% of the total area. Parameters of annual distributions of daily fire spread were closely linked to the annual area burned. The number of events ($p < .001$), mean event size ($p < .001$) and skewness ($p = .03$) were all significant predictors of annual area burned in our best-fitting model ($r^2 = .90$, 15 d.f.). Relative contributions each term were as follows: number of events, 68%; mean event size, 29%; and skewness, 3%. Distributions of events (Figure 5) during an exceptional fire year (2020) in contrast to the mean from the previous 18 years (2002–2019) illustrate key differences in the number and average size of daily fire spread events.

The annual number of extreme fire spread events >1,100 ha/day was linked to fire season climate, with Pearson's *r* between .43 and .69 for three metrics of fire season climate (Deficit, Tmax and VPD) and between .52 and .69 for our synthetic Aridity metric ($p < .01$ for all models; Figure 6). A generalized linear (negative binomial) model predicting the total count of extreme fire spread events from Aridity provided robust predictions for the entire study area ($p < .001$, McFadden's $r^2 = .42$); this model was then used to predict of the annual number of extreme spread events for a warming scenario of 2°C above pre-industrial in contrast to a 1986–2015 reference period, and modelled and observed activity in 2020. This model predicted a mean of 343 extreme spread events per year under the +2°C scenario, ranging from a minimum of 81 to a maximum of 815 events in extreme future years (Figure 7). In contrast, the mean modelled number of extreme spread events in the reference period was 129, with a range of 32–302. Model predictions for the 2020 fire season climate were 324 extreme spread events; the observed number was 441.

The annual area burned across the western USA was also linked to Aridity ($p = .004$; $r^2 = .40$); this model was then used to project the annual area burned under the +2°C warming scenario as described above. The projected mean annual area burned under +2°C was 1.4×10^6 ha, ranging from 0.3×10^6 to 3.4×10^6 ha. The model mean for the reference period was 0.6×10^6 ha (0.1×10^6 to 1.3×10^6 ha). The prediction for the 2020 climate was 1.4×10^6 ha; the observed area burned in the study area in 2020 was 2.5×10^6 ha.

4 | DISCUSSION

Our findings shed new light on relationships between extreme single-day fire spread events, annual area burned and climate. Extreme fire spread events are disproportionately important in driving cumulative area, highlighted by the findings that 10% of events accounted for 58% of the total area burned and that the top 1% of events burned 20% of the total area. Thus, changes in the occurrence or size of relatively uncommon single-day events have probably played a role in recent trends of increasing annual area burned in western North America (Dennison et al., 2014; Littell et al., 2009) and in other areas of the globe (Coogan et al., 2019; Shi et al., 2021). Relationships

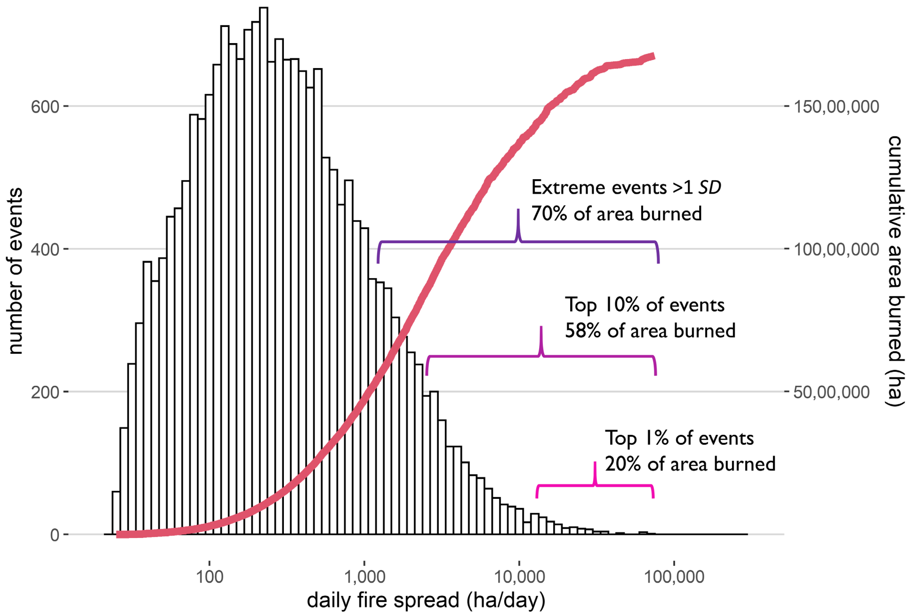


FIGURE 4 Distribution of daily fire spread events and the cumulative area burned during the 2002–2020 study period. Extreme events ≥1,100 ha (the top 16%, 1 *SD*) account for 70% of the area burned

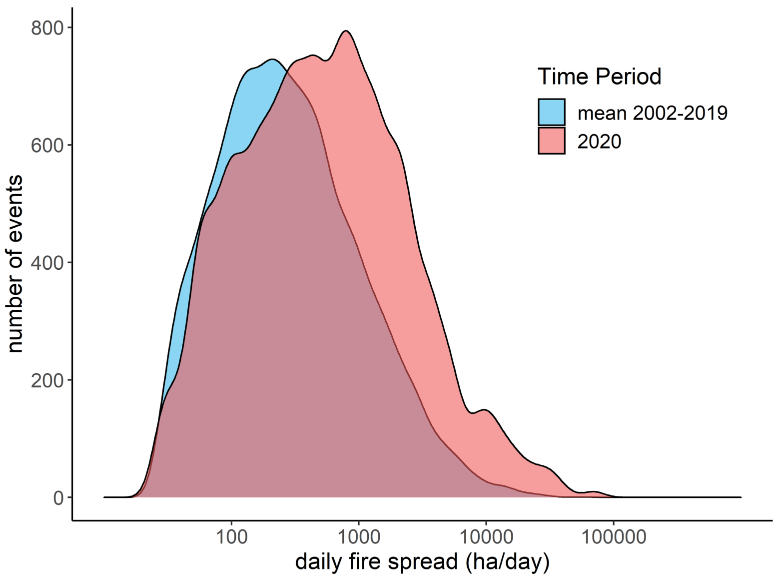
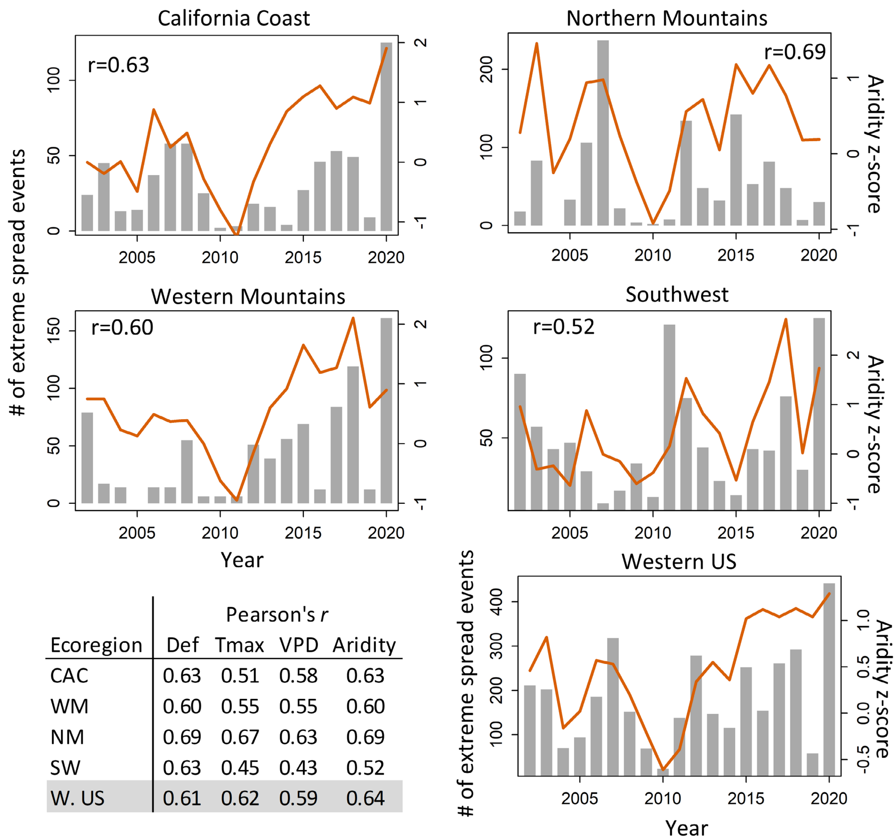


FIGURE 5 Distribution of daily fire spread events in a large fire year (2020) in contrast to means from the preceding 18 years (2002–2019) illustrates shifts in both the number and the mean size of daily spread events

between the annual area burned and the number, mean size and distributional skew of fire spread events, and between the occurrence of extreme events and fire season climate variables associated with increasing annual area burned (Abatzoglou & Williams, 2016), attest to the potential for more extreme fire spread events to drive increasing area burned during future warmer and drier fire seasons.

Our study is the first to relate individual, single-day fire spread events to fire season climate, identifying relationships between the annual occurrence of extreme fire spread events and Deficit, Tmax, VPD and our synthetic Aridity metric. It is not surprising that the warmer and drier conditions promote fuel beds that are both more receptive to ignition and can sustain rapid fire spread (Rego et al., 2021) and are therefore associated with increasing likelihood of extreme single-day spread events at the scale of fire seasons and ecoregions. These findings are consistent with other studies identifying strong relationships between measures of fire season warmth, aridity and annual area burned (Higuera & Abatzoglou, 2021; Mueller et al., 2020) and burn severity (Abatzoglou et al., 2017; Crockett & Westerling, 2018; Parks & Abatzoglou, 2020). Here, we show how annual area burned is a function of the number of daily fire spread events, mean fire spread event size and right skewness in the distribution of event sizes, each of which might be increased by warming and drying. Furthermore, expanded fire season length (Westerling et al., 2006) would be expected to lead directly to an increase in the number of fire spread events, thereby raising the odds that an event occurs within a narrower subset of spatial and temporal conditions



Ecoregion	Def	Tmax	VPD	Aridity
CAC	0.63	0.51	0.58	0.63
WM	0.60	0.55	0.55	0.60
NM	0.69	0.67	0.63	0.69
SW	0.63	0.45	0.43	0.52
W. US	0.61	0.62	0.59	0.64

FIGURE 6 Plots show the annual number of extreme spread events (≥1,100 ha/day) and fire season climate (our synthetic Aridity metric); Pearson's *r* is indicated. Table (bottom left) shows Pearson's *r* for the correlation between the number of extreme spread events and metrics of fire season climate [mean climatic water deficit (Deficit), mean maximum temperature (Tmax), mean vapour pressure deficit (VPD) and Aridity (defined in the main text as the average of the other three variables)]

(e.g., strong east winds coinciding with drought in the north-western USA in 2020; Abatzoglou et al., 2021) that promote and sustain rapid fire growth.

Improved quantification of the biophysical controls of daily fire spread beyond climate (e.g., fire weather, landscape fuel configuration, topography and management) represents a crucial research need, especially for better prediction of the likelihood and magnitude of extreme spread events and the implementation of strategies to reduce or mitigate them. We focused on fire season climate, a top-down factor driving extreme spread events, but others have identified the importance of a suite of variables, including daily weather and topography (Holsinger et al., 2016), not investigated here. Fire weather, including wind and atmospheric stability, is undoubtedly a key driver of extreme spread events, which are often linked to the formation of pyrocumulonimbus clouds (Duane et al., 2021). Pyrocumulonimbus formation can, in turn, create positive feedbacks of increased wind gusts, lightning ignitions and spotting conducive to rapid fire spread (Finney et al., 2015). Accordingly, the incorporation of appropriately scaled crucial weather variables into models of fire spread could lead to considerable gains in predictive power. The Haines index is one such metric of atmospheric stability that might also be rising in association with climate change (Tang et al., 2015), elevating the probability of extreme spread events. Satellite-derived maps of the day of burning, such as we use here, also present opportunities to gain a better understanding of how spatial factors (e.g., topography, fuel type and abundance, management treatments) might interact with temporally variable weather and climate (Downing et al., 2021; Hart & Preston, 2020).

With a projected 2°C warming, fire season climate will become more favourable to rapid fire spread, leading to projected increases in yearly numbers of extreme spread events and area burned. Expanding wildfire activity associated with climate change has been projected in various regions of the Earth (Flannigan et al., 2009). Here, we illustrate how expanding area burned might be affected disproportionately by increases in extreme daily fire spread events associated with warming and increasing aridity. The causes and consequences of such increases were exemplified by the 2020 fire year in western North America, which was anomalous in climatic conditions, the size of fire spread events, and the total area burned (Higuera & Abatzoglou, 2021). Unprecedented wildfire activity in 2020 was not limited to the western USA, but was also reported in at least four continents and across an exceptional latitudinal range. In Australia, 30–40 million ha burned in the 2019–2020 fire season in fires that were exceptionally large and severe (Boer et al., 2020; Bowman et al., 2020; Collins et al., 2021; Nolan et al., 2020); high levels of burning also occurred in arctic Siberia (McCarty et al., 2020; Witze, 2020) and tropical South

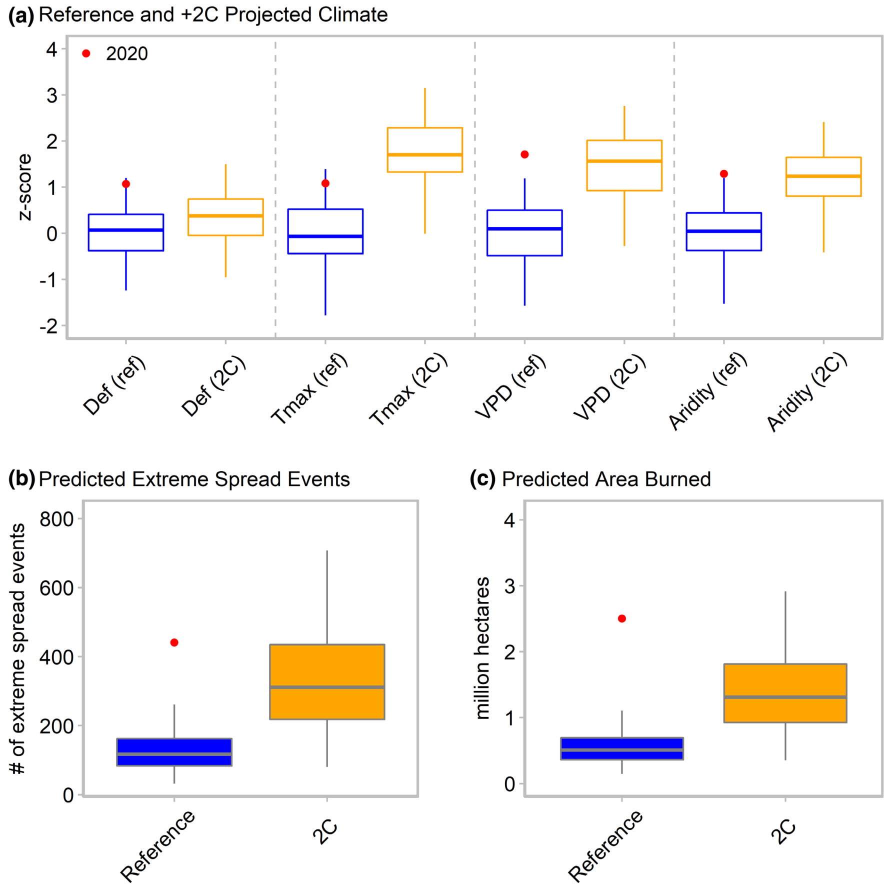


FIGURE 7 Reference period (1986–2015) versus future (+2°C) projections (a) for four climate variables [mean climatic water deficit (Def), mean maximum temperature (Tmax), mean vapour pressure deficit (VPD) and Aridity (defined in the main text as the average of the other three variables)]; (b) predicted number of extreme events >1,100 ha/day; and (c) annual area burned. Red dots represent observed climate and fire activity in 2020

America (Garcia et al., 2021). Our models suggest that under a 2°C warming scenario, the climatic conditions and wildfire activity that occurred in the western USA in 2020 will not represent a future outlier. Instead, the number of extreme fire events that occurred in 2020 will approximate the third quartile, with one in four years having at least as many events, and wildfire activity under future extremes far exceeding anything yet witnessed.

Robust relationships between the frequency of extreme fire spread events and climate aridity, along with the disproportionate contributions of extreme fire spread events to aggregate fire effects, clearly point towards a future characterized by more extreme fire impacts than have occurred yet. The predictions presented here can be considered in light of model limitations that highlight both opportunities for future research and considerations for management and policy. First, we note that fire season climate accounted for 42% of the observed variation in extreme fire spread events, implying that slightly more than half of the observed variation was associated with other factors, such as those discussed previously. Improving our understanding of the role of atmospheric conditions, topography and fuels in promoting or inhibiting extreme fire spread events provides rich topics for additional research. Technological advancements that foster spatial and temporal measurements of the fuels complex, weather and fire behaviour could play a significant role in furthering our ability to study extreme fire events, quantify mechanisms responsible for such events and improve predictive capabilities. Second, we acknowledge that our projections assume that current fire–climate relationships hold in the future, which might not be the case. As one example, fire–vegetation feedbacks have the potential to modulate climate-driven increases in wildfire activity. Wildfires consume fuels and might therefore reduce fire likelihood, fire spread and area burned (Parks et al., 2015; Hurteau et al., 2019). However, some fire-catalysed changes in vegetation can also increase landscape flammability (Tepley et al., 2017). We also note that our analysis focused on counts of events and hectares burned without investigation of other metrics of how they burned (i.e., heat release rate) or ecological consequences (i.e., severity). An improved understanding of each of these factors will be needed to decrease uncertainty around forecasts of future fire activity.

Better understanding the capacity for human activities to modulate the undesirable effects of extreme fire spread is also imperative. Contemporary fire management policies appear to be relatively ineffective in mitigating extreme fire spread events, which are occurring despite recent annual fire suppression expenditures of $1–3 billion in the USA (data available from the NIFC; www.nifc.gov). Explosive fire growth during extreme fire spread events can severely reduce the efficacy of fire suppression as currently practised. Extreme burning conditions that facilitate early fire growth allow fires to escape initial attack; as these fires continue to grow, their size and potential to impact communities and other values can subsequently overwhelm fire management resources. Given the likelihood of increasing societal and ecological exposure to extreme fire spread events, new approaches to fire management and policy may be needed (Cochrane & Bowman, 2021; Moritz et al., 2014; Smith et al., 2016). In some settings, management activities might be directed towards reducing undesirable effects of fire, such as by promotion of frequent but low- to moderate-severity fire to prevent anomalously severe fire and attendant ecological changes (Walker et al., 2018). In other settings, higher-severity prescribed fire and managed wildfire might be useful to change fuel types and reduce landscape flammability (e.g., shifts from conifer to broadleaf forest types). Enhancing community preparedness under extreme burning conditions will also be critical to safeguarding human lives and infrastructure.

Beyond fire and fuel management, the relationships we have identified here between fire season climate and extreme fire spread events emphasize the overriding importance of climate mitigation as a means of reducing future extremes of burning. The +2°C scenario we consider here (Qin et al., 2020) is well within the range of mid- to late-century projections. Rapid reductions in atmospheric greenhouse gas emissions coupled with maintenance or enhancement of global carbon sinks could play a key role in lessening future exposure of human and natural communities to undesirable and unmanageable wildfire activity.

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CONFLICT OF INTEREST

The authors declare they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data and code are available upon request.

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BIOSKETCH

The author team of **Jonathan D. Coop**, **Sean A. Parks**, **Camille S. Stevens-Rumann**, **Scott M. Ritter** and **Chad M. Hoffman** is broadly interested in gaining an understanding of the causes and consequences of changing climate and wildfire activity in western North American forest ecosystems.

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