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Fire in the Earth System

Rapid Growth of Large Forest Fires Drives the Exponential Response of Annual Forest-Fire Area to Aridity in the Western United States

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Key Points:

- We developed a database of western United States wildfires and examined why annual forest area burned grows exponentially with aridity
- Individual fires grow at compounding rates, so fire enlargement driven by aridification is most rapid among large fires
- Approximately two-thirds of the increase in 1984–2019 forest burned area is shaped by each year's largest 10% of forest fires

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Annual forest area burned (AFAB) in the western United States (US) has increased as a positive exponential function of rising aridity in recent decades. This non-linear response has important implications for AFAB in a changing climate, yet the cause of the exponential AFAB-aridity relationship has not been given rigorous attention. We investigated the exponential AFAB-aridity relationship in western US forests using a new 1984–2019 database of fire events and 2001–2020 satellite-based records of daily fire growth. While forest-fire frequency and duration grow linearly with aridity, the exponential AFAB-aridity relationship results from the exponential growth rates of individual fires. Larger fires generally have more potential for growth due to more extensive firelines. Thus, forces that promote fire growth, such as aridification, have more potent effects on larger fires. As aridity increases linearly, the potential for growth of large fires accelerates, leading to exponential increases in AFAB.

Plain Language Summary

Though a natural phenomenon in the western United States (US), wildfires have burned over increasingly large forested areas as the climate has warmed and dried in recent decades, straining fire management and putting humans at risk. An important characteristic of the wildfire response to climate is that as fuels dry–mainly from low precipitation and heat–the amount of annual forest area burned increases exponentially. Although scientists frequently use this relationship to project wildfire responses to climate change, the cause of the exponential relationship has not been robustly investigated. We show here that the exponential response of annual burned area to fuel dryness is related to how individual wildfires spread. Fire growth is a dispersion phenomenon–similar to how the area of a circle increases exponentially as the radius grows incrementally, wildfires tend to grow at compounding rates; the larger a fire, the more potential it has for rapid growth. As western US forest fires have grown under climate change, larger fires have grown more rapidly than smaller fires and increases in annual forest-fire area have therefore accelerated. Annual western US forest area burned will likely continue to increase due to warming and drying until fuel availability becomes a limiting factor.

1. Introduction

Fire is a critical natural disturbance in western United States (US) forests, reducing biomass and shaping ecosystem structure and successional trajectories (Agee, 1998). Climate influences fire by modulating background fuel availability as well as flammability (Bradstock, 2010; Krawchuk & Moritz, 2011). Though climate varies among western US forests, there has been a strong positive trend in annual forest area burned (AFAB), largely attributed to an increasingly warm and dry climate (Dennison et al., 2014; Holden et al., 2018; Westerling, 2016). The recent trends toward aridification and more forest-fire activity are attributable to a combination of human-driven climate trends and natural climate variations (Abatzoglou & Williams, 2016; Zhuang et al., 2021). Climate trends are interacting with a century of fire exclusion, which has promoted both higher-severity forest fires due to fuel accumulation and also increased fire risk for humans due to population expansion into the wildland-urban interface (Calkin et al., 2015; Mietkiewicz et al., 2020; Radeloff et al., 2018).

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AFAB tends to increase exponentially in response to aridity in the western US and globally (Abatzoglou et al., 2018, 2021), usually depicted as a positive linear response of the logarithm of AFAB to linear increases in aridity (Abatzoglou & Williams, 2016; Littell et al., 2009; Swetnam & Betancourt, 1990). Thus, incremental increases in aridity drive ever-larger increases in AFAB, provided fuels are not limiting.

Though well-documented, the cause of the exponential response of AFAB to aridity has not been thoroughly studied, but the implications are profound in fuel-abundant regions such as western US forests where anthropogenic climate change is driving increased wildfire activity (Higuera & Abatzoglou, 2021; Williams et al., 2015). While fire sizes cannot increase indefinitely due to fuel limitation (Davis et al., 2019; Hurteau et al., 2019; Krawchuk & Moritz, 2011), the vast majority of western US forest area has not burned in recent decades (Abatzoglou et al., 2021). It follows that continued aridification should, in the near-term, lead to continued rapid increases in AFAB (Abatzoglou et al., 2021). However, there is uncertainty in these expectations without understanding what drives AFAB to respond exponentially to aridification. Here, we use a new database of large western US wildfire events and satellite measurements of daily fire spread to identify the cause of the positive exponential response of AFAB to increased aridity.

2. Materials and Methods

2.1. Study Period and Region

We investigated the continental US west of 103°W. We focused on forests, where fire activity is generally flammability-limited and less fuel-limited (Abatzoglou et al., 2018; Bradstock, 2010; Krawchuk & Moritz, 2011). We calculated fractional forest cover at 1-km resolution using 250-m resolution maps of US forest types based on the US Forest Service (USFS) Forest Inventory and Analysis (FIA) program (Ruefenacht et al., 2008; Text S1 in Supporting Information S1). This data set has been used previously in research on fire and drought in western US forests (e.g., Buotte et al., 2019). All forest types classified by Ruefenacht et al. (2008) were considered, including piñyon-juniper, which is often classified as woodland.

2.2. Wildfire Database

For this and future studies, we produced a new Western US MTBS-Interagency (WUMI) wildfire database of 18,368 wildfire events across the western US from 1984 to 2019 that are ≥1 km^2 (100 ha) in size (Figure S1 in Supporting Information S1). This database is composed of large wildfires (≥4.04 km^2) from the Monitoring Trends in Burn Severity (MTBS) program (Eidenshink et al., 2007) and wildfires ≥1 km^2 from the National Wildfire Coordinating Group (NWCG) and the California Department of Forestry and Fire Protection (CalFire; Figure S2 in Supporting Information S1). Although wildfires ≥4.04 km^2 account for >90% of area burned in the western US (Figure S3 in Supporting Information S1), they account for a small fraction of the total number of wildfires (Short, 2015). Smaller fires 1–4.04 km^2 account for nearly half of the wildfires in the WUMI database (Figure S4 in Supporting Information S1). For each fire, we estimated the forest area burned by overlaying the fire's burned area on the 1-km map of fractional forest coverage. See Text S1 in Supporting Information S1 for additional details about the WUMI wildfire database.

2.3. Fire Season

Calculations of AFAB were limited to fires that began during a 6-month fire season of May-October. This season accounts for the vast majority of western US's total forest area burned (97.8%) and number of forest fires (96.2%; Figure S5 in Supporting Information S1).

2.4. Extending AFAB Through 2020

We extended the time series of AFAB through 2020 using the Moderate Resolution Imaging Spectroradiometer (MODIS) v6 Burned Area Product (Giglio et al., 2016) following Abatzoglou et al. (2021). The MODIS v6 product maps daily burned area at a 500-m spatial resolution. We aggregated (summed) monthly 500-m MODIS burned areas to 1-km resolution, estimated forest area burned by multiplying these maps of MODIS burned area by the 1-km map of fractional forest coverage, and summed across May-October annually for 2001–2020. We adjusted the 2020 MODIS AFAB based on the linear relationship between MODIS- and WUMI-based AFAB during the 2001–2019 period of overlap ($r = 0.99$; Figure S6 in Supporting Information S1).

2.5. Climate Data

We used vapor-pressure deficit (VPD) as a proxy for aridity, as this variable correlates strongly with AFAB in the western US and regions within (Abatzoglou & Williams, 2016; Williams et al., 2015, 2019). VPD is the difference between saturation vapor pressure (e_s) and actual vapor pressure (e_a). Monthly e_a was calculated from monthly mean dew-point from the Parameter-elevation Regressions on Independent Slopes Model Group (Daly et al., 2004). Monthly e_s was calculated from mean daily maximum and minimum temperatures from the TopoWx data set through 2016 (Oyler et al., 2015) and extended through 2020 using a calibrated version of the National Oceanic and Atmospheric Administration (NOAA) Climgrid data set (Vose et al., 2014) following Williams et al. (2020). Forest-area-weighted VPD was averaged over March-October because AFAB is affected by aridity both during and in the months leading up to the forest-fire season (e.g., Abatzoglou & Williams, 2016; Williams et al., 2019).

2.6. Analyses of Trends and Statistical Relationships

We assessed trends in AFAB using the non-parametric Theil-Sen estimator (Theil, 1950; Sen, 1960). We assessed statistical relationships between pairs of variables using least squares linear regression. For each regression line, we tested whether the y-axis variable was better characterized as a linear or exponential function of the x-axis variable. We tested for an exponential fit by performing a log-transformation of the y-axis variable. We assessed goodness of fit for each regression line using the Pearson's correlation coefficient (r-value), but conservatively interpret that the linear fit is more appropriate unless the r-value for the exponential fit exceeds that of the linear fit by >0.05. Otherwise, little value is gained from the added complexity of a log-transformation.

2.7. Daily Fire Spread Data

For an analysis of daily spread of individual fires, we used the Fire Events Delineation (FIRED) database, covering 2001–2020 (Balch et al., 2020). The FIRED events product consists of 500-m maps of daily burned areas for individual fires in the continental US, derived from the MODIS burned-area product. We only considered fires that began in a western US forested area (1-km gridcell with fractional forest coverage ≥ 0.50) during May-October. We did not consider fires that spread over <3 days or were ≤ 1 km^2.

For each fire, we focused on the period of spread, excluding days at the end of many events when spread essentially stopped. We considered fire spread to have stopped when daily fire growth became very small relative to the prior-day total fire size ($<10^{-6}$ of prior-day size) and never returned above this rate.

3. Results and Discussion

3.1. Exponential Response of Burned Area to Aridity

Western US AFAB grew by 1574 km^2 per decade during 1984–2020 according to a linear trend (Figure 1a). We cannot measure the relative rate of linear change because the trend's starting value is negative; however, the log-fit of the trend—which would imply exponential growth of AFAB—indicates a 1000% increase in AFAB over 1984–2020. The log- and linear fits of the trend were similar ($r = 0.62$ vs 0.59, respectively, $p < 10^{-4}$), so we determined that the linear fit adequately described the 1984–2020 AFAB trend.

Western US AFAB correlated positively and strongly with March-October VPD during 1984–2020 (Figure 1b). This relationship is better characterized when AFAB is log-transformed ($r = 0.90$, $p < 10^{-4}$) than as a linear response ($r = 0.80$, $p < 10^{-4}$), indicating that the AFAB response to aridity is exponential. Consistent with

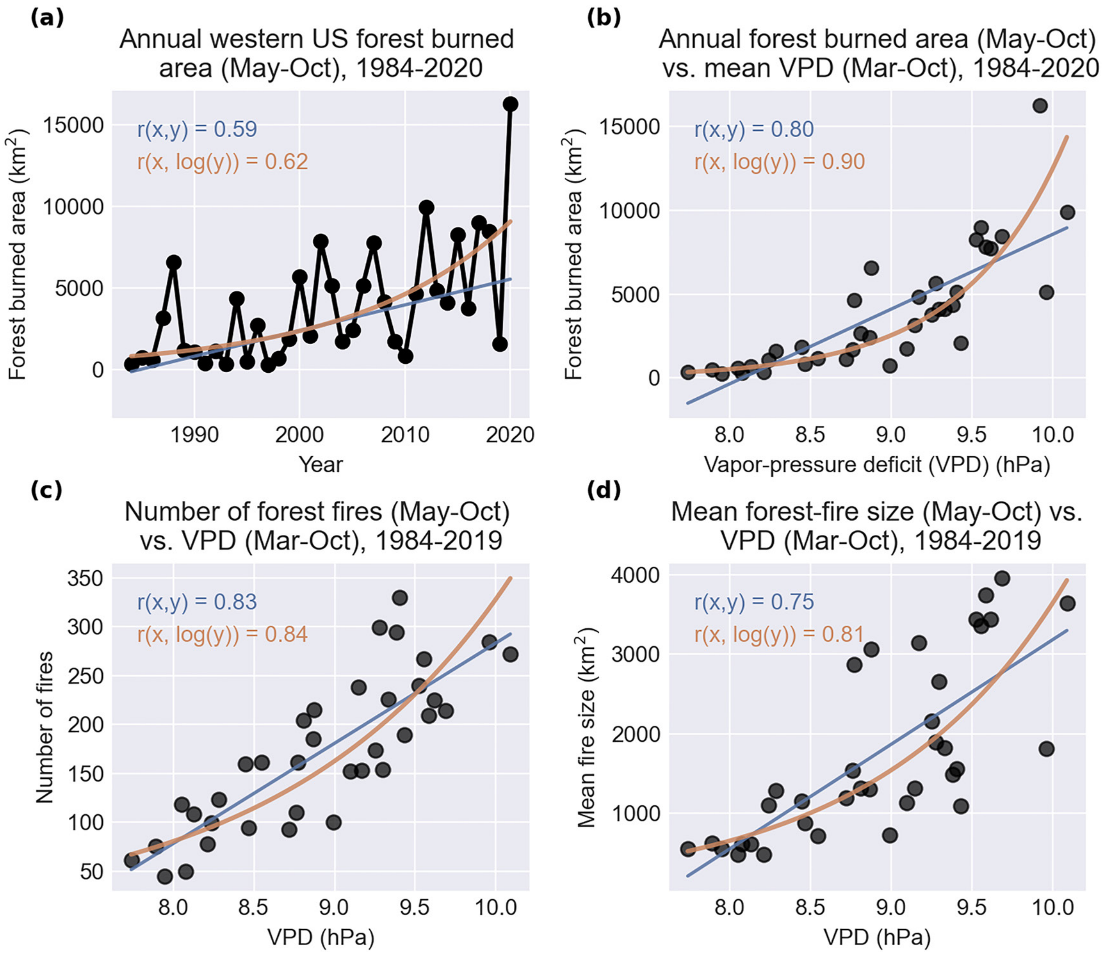

Figure 1. Western US forest fire and aridity. (a) Time series of annual forest area burned (AFAB). (b) AFAB versus vapor-pressure deficit (VPD). (c) Forest-fire frequency versus VPD. (d) Mean forest-fire size versus VPD. Orange/blue lines: Theil-Sen regression lines in (a), or least squares regression lines in (b)–(d), for y and $\log_{10}(y)$. In (c) and (d), the analyses end in 2019 because those analyses require annual fire frequency, which is calculated from our 1984–2019 WUMI database of individual fires.

Abatzoglou et al. (2021), the record-breaking AFAB in 2020 was well-aligned with the historical AFAB-aridity relationship.

While the above results indicate a strong response of forest-fire frequency to aridity, we note that our WUMI wildfire database only represents large ($\geq$1 km^2) fires. An analysis using the shorter (1992–2018) but more size-comprehensive wildfire database developed by Short (2021) reveals that the correlation between annual forest-fire frequency and aridity reduces as smaller fires—which are far more common than large fires—are considered (Figure S7 in Supporting Information S1). In contrast, the AFAB-aridity relationship is not sensitive to whether small fires are considered because small fires contribute minimally to interannual variability in AFAB.

In contrast to the exponential response of AFAB to aridity, we find that the response of the frequency of fire-season forest fires to aridity is linear. Figure 1c shows that the linear response of forest-fire frequency to March-October VPD is strong ($r = 0.83$, $p < 10^{-4}$), with no meaningful correlation improvement when forest-fire frequency is log-transformed ($r = 0.84$, $p < 10^{-4}$).

The AFAB and forest-fire frequency are not independent, as the forest area burned in a given fire season is equal to that season's forest-fire frequency multiplied by the season's mean forest-fire size. The fact that forest-fire frequency responds linearly to aridity implies that the exponential AFAB-aridity response must be due to an exponential response of forest-fire size. Indeed, mean forest-fire size is better characterized as an exponential rather than linear response to March-October VPD ($r = 0.81$ vs $r = 0.75$, respectively, $p < 10^{-4}$; Figure 1d).

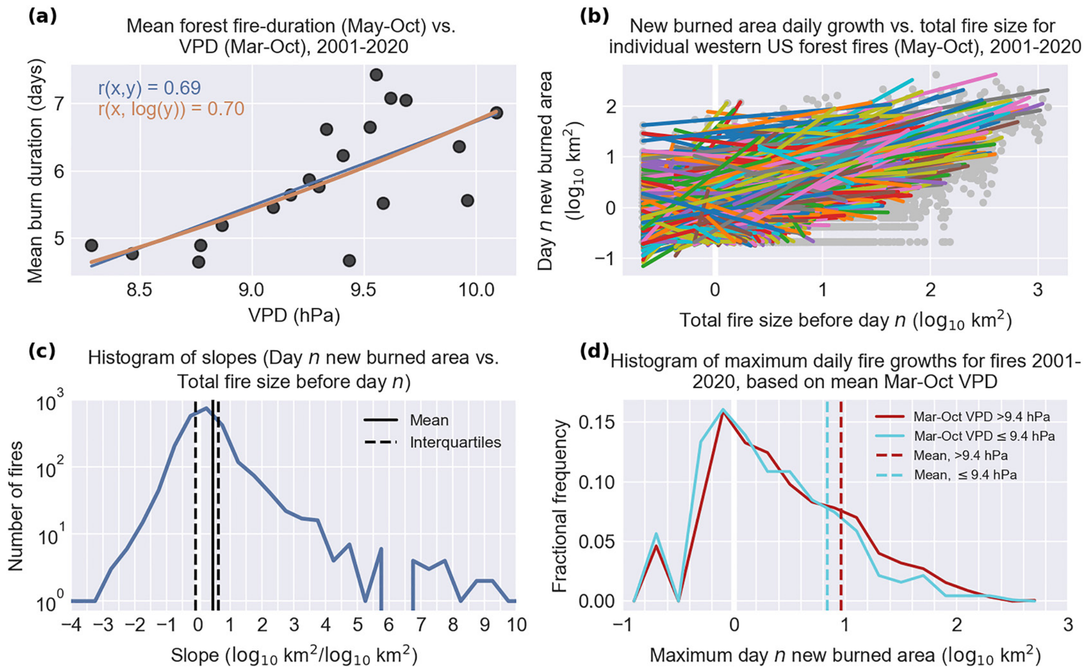

Figure 2. Forest fires grow exponentially. (a) Annual mean fire-duration of forest-fire events versus vapor-pressure deficit (VPD). (b) The logarithm of new burned area on day *n* for each of 2,352 fire events versus the logarithm of each fire's prior-day size. Gray dots: single-day values. Lines: event-specific regression lines. (c) Histogram of regression slopes in (b), with mean (solid black line) and interquartile (dashed lines) values, centered on 0.5 $\log_{10}$ km^2/$\log_{10}$ km^2 bins. (d) Histogram of maximum day *n* burned area growth for each fire event, separated by years in which March-Oct VPD was higher (red) versus lower (blue) than the 2001–2020 median value, centered on 0.2 $\log_{10}$ km^2 bins.

3.2. Exponential Growth Rates of Individual Fires

Because the exponential response of AFAB to aridity is specifically due to forest-fire size and not frequency, we next investigate the growth of individual forest fires (Balch et al., 2020). In Figure 2a, we test whether the exponential response of mean forest-fire size arises due to an exponential response of the mean duration of individual fires. This analysis indicates a positive correlation ($r = 0.68$, $p < 10^{-3}$) between the mean fire-duration and March-October VPD, where drier, warmer conditions lengthen forest-fire burn durations. There is not clear evidence that burn duration responds to VPD exponentially ($r = 0.70$, $p < 10^{-3}$) rather than linearly, suggesting the exponential AFAB-aridity relationship is not explained by an exponential response of burn duration.

We next used the FIRED database to investigate whether the exponential response of forest-fire size to aridity is related to the rate at which individual fires grow. The rationale for this investigation is that as a fire's active flame front grows, its potential to spawn additional burned area likely increases exponentially, similar to how the area of an elliptical fire—the shape of a fire from a single ignition point as represented in Rothermel's fire spread model (Andrews, 2018)—grows quadratically as its radius grows linearly. In Figure 2b, we plot the growth of 2,352 individual wildfires, where each day's spread in fire size (y-axis) is regressed against the total size of the fire as of the previous day (x-axis) during the fire's period of growth. Because there are too many regression lines to visualize in Figure 2b, Figure 2c provides a histogram of the slope values.

If fire growth was linear, we would expect each regression line to have a slope of zero, indicating a constant daily spread rate as the fire spreads. Instead, the slopes in Figure 2b are mostly (64%) positive, averaging a growth of 0.46 $\log_{10}$ km^2/$\log_{10}$ km^2 (Figure 2c). The predominance of positive relationships between daily spread rate and prior-day fire size indicates compounding daily growth rates. This tendency for exponential growth is notably more common among larger fires—81% of the 999 forest fires that reached >10 km^2 exhibited positive slopes, with an average growth slope of 0.57 $\log_{10}$ km^2/$\log_{10}$ km^2. For fires of sizes 10 km^2 (1,000 ha) and 1000 km^2 (100,000 ha), this translates to daily fire-size increases of approximately 5.7 and 566 km^2, respectively, highlighting the strong tendency for large fires to grow faster than small fires.

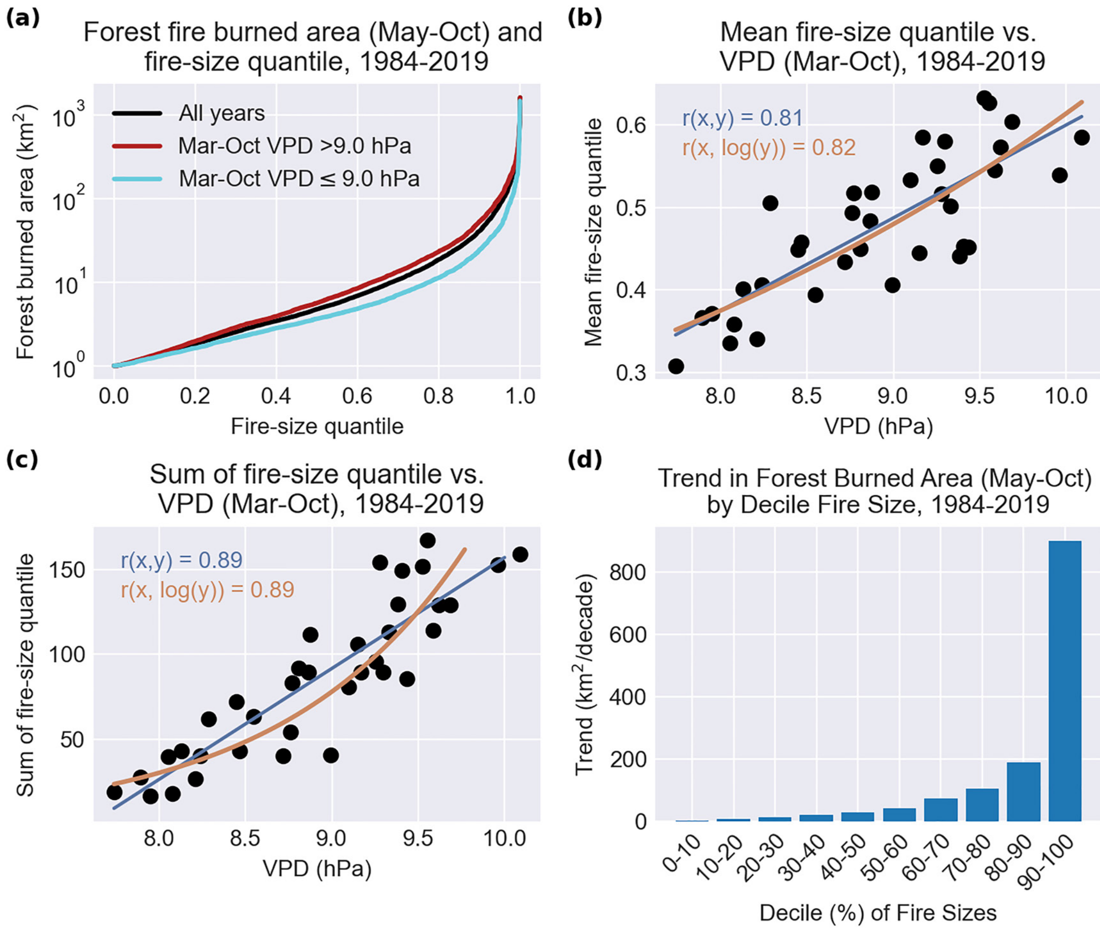

Figure 3. Aridity-driven increase in forest area burned is dominated by the largest fires. (a) Distribution of individual forest-fire sizes in (black) all years (1984–2019) and in years when vapor-pressure deficit (VPD) was above (red) versus below (blue) the 1984–2019 median. (b) Annual mean May-October fire-size quantile versus VPD. (c) Annual sum of fire-size quantiles versus mean VPD. (d) Trends in annual forest area burned by fire-size decile (each year's fires are ranked into deciles defined by that year's fires only).

The accelerated growth of larger forest fires is enhanced by aridity. Figure 2d demonstrates this with two histograms representing each forest fire's maximum daily growth during high-VPD years versus low-VPD years, when March-October VPD is above versus below the 2001–2020 median value. In high-VPD years, 20% of forest fires experienced at least one day when the new burned area exceeded 10 km^2, but just 13% of forest fires experienced a day with 10 km^2 of new growth in the low-VPD years. This results in a large difference in area burned on days with very high spread rates in high-VPD years versus low-VPD years given that high-VPD years also have more fire events (Figure 1c). In summary, larger fires have a greater tendency for rapid acceleration of their growth, and this effect is more dominant in high-aridity years because high-aridity years promote more large forest fires.

If aridity promotes larger fires, and if potential for rapid growth increases with fire size, then it follows that the effect of aridity on fire size should be much larger among large fires than among smaller fires. This is supported by a comparison of the distributions of individual forest-fire sizes from our 1984–2019 WUMI database among years when VPD was above versus below the 1984–2019 median (Figure 3a). Fire sizes in the high-VPD years are larger across the full spectrum of fire sizes in comparison to low-VPD years, but the difference is far greater among the larger fire-size quantiles (note the log-scale of the y-axis in Figure 3a).

The above interpretation that the exponential response of AFAB to aridity arises from the rapid growth of very large fires is further supported by Figures 3b and 3c. In these figures we re-plot the regressions of AFAB and annual mean fire size against VPD, which were originally shown in Figures 1b and 1d, but now AFAB and annual mean fire size have been recalculated from fire-size quantiles rather than from fire sizes in their native units of area. When individual fire sizes are expressed as quantiles, which have a uniform distribution by definition, the exponential responses of mean annual fire size and AFAB to aridity are eliminated and are instead best characterized as linear. Thus, the exponential responses of AFAB and mean annual fire size to aridity shown in Figures 1b and 1d arise mostly or entirely due to the exponential distribution of individual fire sizes, which arises from the compounding growth rates of individual fires as we demonstrated in Figure 2.

Collectively, the above results suggest that the observed increase in western US AFAB has occurred because of disproportionately large trends in the area burned by very large forest fires. This is confirmed in Figure 3d, where the 1984–2019 AFAB trend is dissected into contributions from fires in various size classes. In this trend graph, each year's forest fires are separated into decile fire-size classes and summed such that we can calculate how each fire-size decile contributed to the total AFAB trend in 1984–2019. We observe positive AFAB trends for all deciles, but the AFAB trends among the larger fires are far larger than those among smaller fires. Growth among just the largest 10% of fires each year accounts for 899 km^2/decade, or 67% of the 1984–2019 AFAB trend (the largest 30% of fires account for 89% of the trend).

3.3. Limitations and Future Work

The western US is highly heterogeneous in terms of climate, fuels, and human influence on fire. Future work should investigate the AFAB-aridity relationship on finer spatial scales to better understand the factors that modulate the strength and non-linearity of this relationship (Abatzoglou et al., 2018; Buotte et al., 2019; Littell et al., 2018). One avenue that warrants investigation is the relationship between aridity and the availability of large fuels (e.g., standing and lying dead trees) to burn. Another avenue is to investigate wind's effect on area burned, given the importance of winds on daily fire spread by pushing the active fireline. Disentangling the contributions of increasing fuel stocks, winds, and climate aridity could provide an improved mechanistic understanding of the nonlinear relationship between forest-fire area and aridity.

Wildfires are affected by many inter-related aridity variables besides VPD, and this study's conclusions are not specific to VPD. In this study, VPD is not assumed to be the only factor that affects fire activity, but is instead simply treated as a proxy for aridity because drier atmospheric conditions affect the fuel moisture content of live and dead trees, affecting fuel availability (Matthews, 2014; Konings et al., 2017). The general conclusions would hold if another climatological aridity metric strongly related to wildfire activity were used in place of VPD. Importantly, exercises that use historical fire-climate relationships to predict future fire activity are quite sensitive to the aridity metric(s) used as predictors because VPD is projected to change more dramatically in the future than other aridity metrics that also correlate well with AFAB (Alizadeh et al., 2021; Brey et al., 2021; Holden et al., 2018).

Finally, while MTBS provides accurate maps of burned area for large fires, it is a limitation that fire perimeters and the heterogeneous burn patterns within perimeters are not consistently available for many smaller fires in our database (Text S1 in Supporting Information S1). Assumptions about the distribution of area burned by these fires add uncertainty to our estimates of forest area burned, which could be improved by future work to provide high-resolution maps of burned area for fires smaller than those currently mapped by MTBS.

4. Conclusions

We examined the exponential nature of the response of annual forest area burned (AFAB) to aridity in the western US, which has been extensively observed in recent decades but not explicitly investigated to our knowledge. Using our new Western US MTBS-Interagency (WUMI) wildfire database and FIRED daily fire growth data, we showed that the exponential response of AFAB to aridity (using VPD as a proxy) is specific to fire sizes arising from the exponential spread rates of individual fires.

As aridity increases, the number and size of forest fires both increase. However, this increase is only exponential for fire size, leading us to conclude that the size of forest fires, and not the number of forest fires, is what drives the exponential response of AFAB to aridity.

Our exploration of daily fire growth shed light on the process responsible for the exponential response of forest area burned to aridity. As individual fires spread, their daily growth increments tend to increase at compounding, and therefore exponential, rates. Of course, many other processes, such as wind speed, slope, and fuel characteristics also critically modulate fire growth rates (Andrews, 2018; Rossa & Fernandes, 2018), but despite these effects we detected evidence for a strong positive effect of fire size on the potential for further growth.

The potential for large fires to accelerate in size more rapidly than small fires is likely an important mechanism underlying the exponential-like size distribution of individual fires, which is strongly and positively skewed and often characterized in fire studies as the generalized Pareto distribution (Moritz, 1997; Moritz et al., 2005; Hantson et al., 2015; Preisler et al., 2011; Ramesh, 2005; Schoenberg et al., 2003). Other natural hazards follow similar power-law distributions, including earthquakes, landslides, extreme precipitation, and floods (Malamud & Turcotte, 1999). The exponential-like distribution of wildfire sizes arises because, even if the compounding growth rates are normally distributed among fires and all fires burn for the same amount of time, the fires with the higher compounding rates will spread across disproportionately more area. In reality, fires with lower growth rates are much easier to suppress while still small, which enhances the positive skew of the fire-size distribution.

The connection between exponential growth of individual fires and the exponential response of AFAB to increasing aridity arises because large fires have more potential for growth than small fires. Increased aridity promotes larger forest fires across the full range of size classes. Because the effect is most potent among large fires, each incremental increase in aridity leads to a much larger increase in AFAB than the previous. Thus, the exponential response of AFAB to increasing aridity is driven by rapid growth of the largest forest fires. Over the past nearly four decades the largest 10% of each year's fires drove 67% of the observed increase in AFAB.

While modeling efforts already capture the exponential response of AFAB to aridity, our study provides a mechanistic explanation backed up by empirical detection. Fire scientists have long-capitalized on the exponential AFAB-aridity relationship in statistical models. For example, models aimed at estimating AFAB across a region often explicitly prescribe the observed slope of the regression of log(AFAB) versus aridity (Littell et al., 2009; Holden et al., 2018; Williams & Abatzoglou, 2016). Even statistical models that simulate individual fires implicitly prescribe an exponential response of fire sizes to aridity because simulated individual fires are forced to adhere to an observed fire-size distribution, which is exponential in nature (Preisler et al., 2011; Westerling et al., 2011). More process-driven models of individual fire spread, such as the Rothermel model, implicitly simulate the compounding fire growth because fires in those models grow in two dimensions as a function of a one-dimensional growth rate (Andrews, 2018). Our results are nonetheless important because we provide an explicit explanation for the exponential response of burned area to aridity that will guide future interpretations of observed and modeled changes in forest-fire activity.

Knowing that individual fire spread is the cause for the strong, stable AFAB-aridity relationship leads to new questions. Since an individual fire can only grow where fuels are available, increasingly large fires may reduce the potency of the effect of aridity on AFAB by reducing fuel continuity, although in some cases, severe fire and a drying climate may actually enhance future fire activity if forests convert to more flammable fuel types (Hurteau et al., 2019; Parks et al., 2015). However, the AFAB-aridity relationship has remained remarkably consistent over the past four decades as the AFAB has grown ever larger (Abatzoglou et al., 2021). At the large scale of the western US, AFAB is still generally well below prehistoric levels (Marlon et al., 2012; Swetnam & Betancourt, 1998; Stephens et al., 2007) and the majority of western US forest area has likely not burned in over a century. With an empirical understanding of what has driven the strong exponential response of western US AFAB to aridity in recent decades, we expect that abundant forest fuels will continue to support a strong, exponential AFAB-aridity relationship over the next few decades at least, implying an urgency for rapid adaptation to cope with increasingly intense fire seasons. Further research is also necessary to understand when and where the observed AFAB-aridity relationship will break down due to fuel limitation and what measures can be taken to pro-actively reduce risk of unwanted fire through pro-active fuel treatment.

Data Availability Statement

The WUMI wildfire database can be obtained at DRYAD (https://doi.org/10.5061/dryad.sf7m0cg72). The MTBS database can be obtained at https://www.mtbs.gov/direct-download (accessed 29 September 2021). The NWCG database can be obtained at https://famit.nwcg.gov/applications/FireAndWeatherData/ZipFiles (accessed 20 October 2021). The CalFire database can be obtained at https://frap.fire.ca.gov/frap-projects/fire-perimeters/ (accessed 20 October 2021). The FIRED data set can be obtained at https://scholar.colorado.edu/concern/datasets/d504rm74m (accessed 5 January 2022).

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