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Posted Date: 19 June 2023

doi: 10.20944/preprints202306.1349.v1

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Compound Drought-Heat Weather Extremes Induce a More Severe Summer Fire Season in the Three Gorges Reservoir Area, Subtropical China

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Abstract: Global warming is increasing the frequency and intensity of compound drought-heat events (CDHEs), potentially leading to larger and more extreme fire seasons in mesic forests. Wildfire activity in subtropical China, under the influence of monsoonal rainfall, was historically limited to dry winters and rare in rainy summers. Here we seek to test that this area is on the brink of a major change in its fire regime characterized by larger fire seasons, extending into the summer, leading to increases in burned area. We analyze fire activity in Chongqing Municipality (46,890 km2), an important area in subtropical China hosting the Three Gorges Reservoir Area. We observed significant increases in summer forest fires under anomalous dry-hot summer conditions, where total burned area was 3-6 higher than the historical annual mean (largely confined to the winter season). Vapor pressure deficit, an indicator of hot and dry conditions, was a strong predictor of fire activity, with major wildfires occurring on days where VPD was higher than 3.5kPa. Results indicate that major wildfire activity may occur in the area as a result of climate change, unless strong fire prevention policies are implemented.

Keywords: compound drought-heat extremes; summer/winter fire seasons; VPD; weather variables; Three Gorges Reservoir; China; climate change

1. Introduction

Climate change is increasing the frequency and intensity in fire weather and burned area in many forested areas worldwide [1]. Climate change directly acts on fire weather and it also affects biomass production, thus exerting a strong influence over the annual timing of fires and their interannual variability [1]. One of the consequences of climate change is the lengthening of the forest fire season [1,2], resulting from the increase in mean temperatures [3] (i.e., winter, summer and year-around average temperature). Another consequence is the increase in the frequency of extreme weather days, showing compound drought-heat events (CDHEs) [4].

The conjunction of these compound factors is becoming increasingly common in subtropical China [5,6], with important implications for forest management and forest fire prevention. The impact of CDHEs can be especially severe in summer, the traditional rainy season in areas under monsoonal rainfall, as it may reduce precipitation significantly. Summer CDHEs may increase fuel dryness very quickly, especially in dead fine fuels, which respond very rapidly to increases in vapor pressure deficit [7]. The historical fire season in subtropical China occurs during winter months [8], but CDHEs may lengthen it into the summer. An anomalous summer fire season could thus develop on the top of the historical winter fire season, with potentially dramatic consequences for wildfire activity.

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This hypothesis needs to be empirically tested in subtropical China. Current empirical research indicates that CDHEs are increasing their frequencies, duration and intensity and model projections indicate that this trend is expected to accentuate in the future, particularly in summer [9,10].

In this article, our aim is to evaluate the effects of extreme weather CDHEs on forest fire activity (i.e., burned area) and fire seasonality in the subtropical region of Chongqing, China for the last 22 years (2001-2022). This area is important as it is home to the Three Gorges Reservoir Area, and where remnant patches of the native biodiverse forests are still present [11]. We assess fire trends over the 21st century and focus on the effects of the different summer CDHEs that have occurred within this region (2006, 2011, 2013, and 2022) [12].

More specifically, we seek to test the general hypothesis that increases in summer CDHEs are leading to a bimodal fire season pattern, with burned area peaking in winter and in summer, which contrasts with the historical fire season, with a single peak in the winter. We will focus on vapor pressure deficit (VPD) because this is a proxy for hot and dry weather, which strongly affects live (LFMC) and dead (DFMC) fuel moisture content [7,13]. VPD will be used as a benchmark to calculate the intensity and duration of extreme weather CDHEs. Winter season is here broadly defined as the period extending between October and March, whereas the summer season is defined between April and September.

To this end, we first identify the summers with CDHEs, and assess their effects on forest burned area by comparing summer burned areas with those recorded during the winter seasons for the period 2001-2022. Second, we compare fire weather variables between the regular-humid summer seasons (i.e., rainy and without fire), and the anomalous-dry (CDHE) summer seasons (i.e., extremely dry and hot conditions), to identify critical weather thresholds, and analyze their relationship with forest burned area. Finally, we discuss the implications of increasing extreme CDHEs for forest burned area, fire seasonality, and local ecosystem management in the context of climate change.

2. Study Region, Materials and Methods

2.1. Study region

The demarcation of the reservoir area of the Three Gorges Hydropower Station, mainly in Chongqing administrative region of central China (Figure 1), presents a subtropical vegetation typical of three ecoregions with a historical subtropical summer monsoon humid climate:

(a) Sichuan Basin evergreen broadleaf forest ecoregion;
(b) Daba Mountains evergreen forest ecoregion; and
(c) Guizhou Plateau broadleaf and evergreen forest ecoregion [11].

Most areas in Chongqing show 1000-1300 mm of annual rainfall, 70% of which falls between May and September (i.e., during the summer season). Evergreen-broadleaf formations, highly representative of the vegetation in subtropical China, mainly include the Cyclobalanopsis spp. and Lithocarpus spp. (Fagaceae), Machilus spp. (Lauraceae), Schima spp. and Gordonia spp. (Theaceae) in the semi-natural forests of Chongqing [14]. Meanwhile, secondary forests have been expanding for the last decades, for both timber production and environmental purposes. According to recent local studies, forest vegetation in Chongqing has been recovering fast, with an average NDVI 4.4% increment per decade during the whole study period 2000-2019 [15].

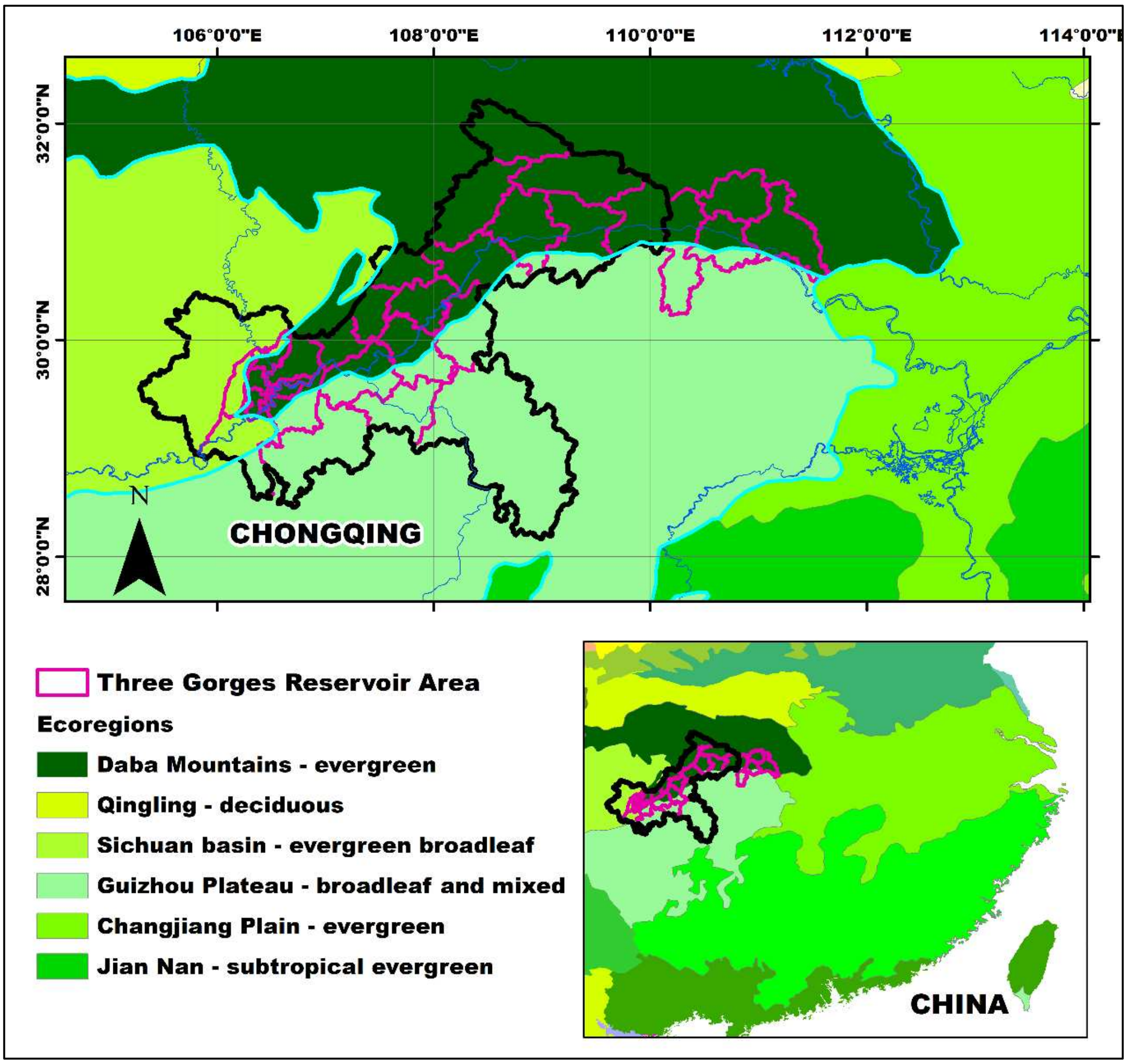

Figure 1. Forest ecoregions in the study area of the Three Gorges Reservoir, located inside Chongqing Municipality and Hubei Province.

2.2. Burned area (2001-2022) data

Fire data for Chongqing region were retrieved from MODIS product MCD64A1, and the forest fire statistics contained in the GLOBFIRE database [16]. Forest fire records in GLOBFIRE are also calculated from MCD64A1 – the same data source – allowing for direct data comparability. We used GLOBFIRE data for the period 2001-2020 – the section of data focused on China and spatially filtering for Chongqing Municipality – while we directly downloaded MCD64A1 raw satellite images for the most recent period 2021-2022. We first analyzed annual (January – December) historical burned area trends between 2001-2022.

Within the summer season, we focus on the contrast between the high CDHEs years with anomalous summer fire weather seasons on the one hand (2006, 2011, 2013 and 2022; see Results section), and the summer normal rainy season (without fires) on the other. We also compare between the historical winter and the summer fire seasons for the period 2001-2022. Fire statistics were mainly burned area (ha). The length of the fire season was calculated by accumulating the number of days between the first and the last fire of the (summer/winter) season; the cumulative burned area was then calculated by summing up the total burned area within the season.

2.3. Weather variables and VPD (2001-2022)

We obtained the 2001-2022 meteorological data series from 35 local weather stations in Chongqing (between July 1st and September 30th), for the following variables: daily precipitation, daily maximum temperature, and daily mean relative humidity. We carried out kriging spatial interpolation, with data from the 35 weather stations, using the krige function of the gstat package [17] and other R libraries (sf, sp, raster, rgdal, rasterVis) within the RStudio programming environment (RStudio 2023.03.0 Build 386). The spatial pixel resolution is longitude 0.201° (WGS84 geographic coordinates), i.e., equivalent to longitude 19.5 km and latitude 22.4 km (UTM Zone 48N).

Daily meteorological data were also collected for the brunt of the summer period (July- August, 2001-2022) from the Copernicus ERA5 satellite collections (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview), consisting of precipitation, maximum temperature (2 meters above terrain surface), and relative humidity at 3pm (2 meters above surface) (Supplementary Information). The spatial resolution of these data was 0.1°, which in the study area are equivalent to 9.84 km longitude x 11.25 km latitude (UTM Zone 48N).

In our analyses, we used raw variables such as precipitation, temperature and relative humidity and we calculated vapor pressure deficit (VPD). VPD provides robust estimations of environmental drought-heat stress and environmental fire risk [18,19], as it is highly correlated with DFMC.

We calculated central-estimation statistics (mean and median) over the whole territory of Chongqing: cumulative mean daily precipitation, median daily max temperature, median relative humidity, median VPD.

2.4. Spatiotemporal analyses

We first represented the summer fire centroids of 2006, 2011, 2013 and 2022 (the most salient summer fire seasons in Chongqing; shown later). For each year (period 2001-2022) we also calculated the daily VPD 85th percentile across the whole territory of Chongqing Municipality, which we used to reveal the most extreme weather phenomena. We then calculated, at each pixel of Chongqing Municipality, the total number of days under VPD > 3.5 kPa – a threshold which is highly correlated with the biggest fires in our study region – within the summer period (July-August-Sept, for 2006, 2011, 2013 and 2022, and also for each year of the rest of the normal humid summers between 2001 and 2021); using the statistical base function density in RStudio, we calculated the Probability Density Function of the total number of days under VPD > 3.5 kPa, to understand the probability and extent in ha affected by environmental heat-drought stress (% of the territory affected by varying ranges of number of days under VPD > 3.5 kPa). Finally, we calculated the regression between summer total burned area (dependent variable) and summer mean VPD > 3.5 kPa (independent variable, i.e., the mean across the whole territory of Chongqing Municipality).

3. Results

3.1. Cumulative burned area

We first analyzed the seasonal pattern of forest fires for the 2001-2022 historical period in the Chongqing Administrative Region (Figure 2), and we observed that: (1) there were two salient fire seasons that could be clearly identified, i.e., a winter fire season (February-March, with 5,360 ha burned) and a summer fire season (July-September, with 17,915 ha burned); (2) the summer fire season was only apparent in a few years (2006, 2011, 2013 and 2022), but fire activity led to a larger proportion of cumulative burned area. The summers of 2006 and 2022 were the seasons with highest fire activity (with 8,535 ha and 6,480 ha burned respectively), which affected more than 3 times the burned area of the year with highest winter fire activity, which was 2015 (2,360 ha burned). Meanwhile, in the summer of 2011 2,595 ha were burned. Annual burned area ranged from 0% to 0.17% of the forested area in Chongqing Municipality (46,890 km2).

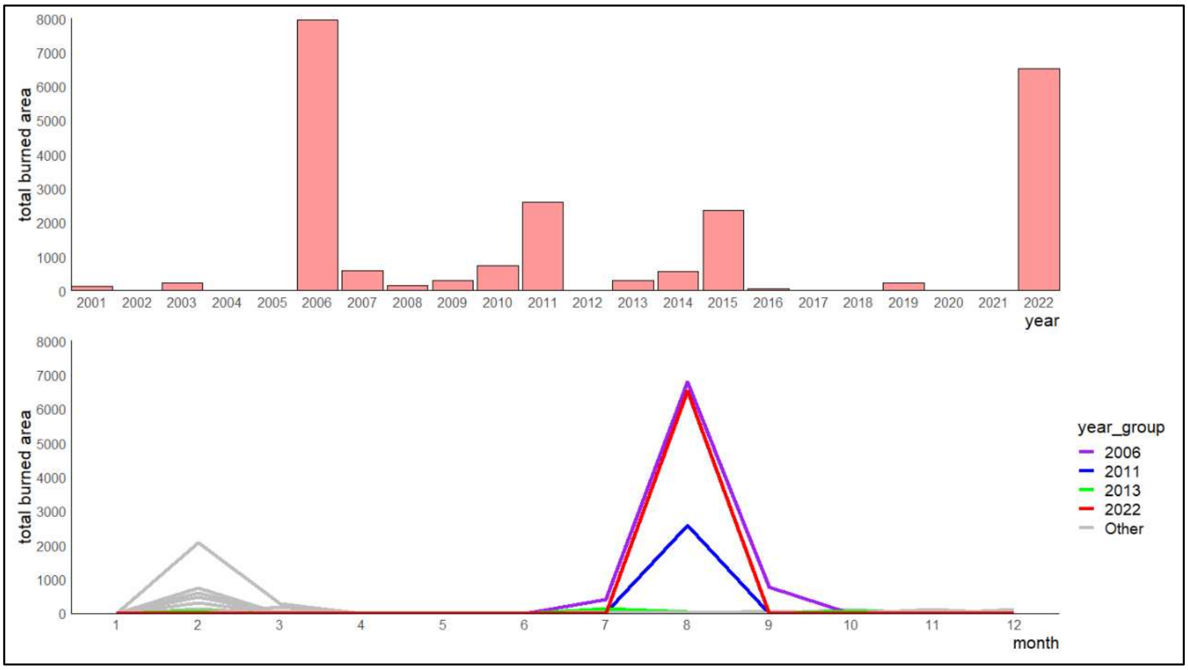

Figure 2. 2006, 2011 and 2022 summer fire seasons had the highest burned area. Total burned forest area (a) per year, and (b) per month for the period 2001-2022.

3.2. Weather variables

The data collected from the 35 weather stations in Chongqing indicated that the hot-dry summers (July-August-September) of 2006, 2011, 2013 and 2022 were the most extreme, especially in the case of 2022 with highest temperatures, lowest precipitation and highest VPD (Figure 3). This pattern was also observed when analyzing the Copernicus ERA5 satellite image analysis of the same weather variables (See Supplementary Material, Figures S1, S2, S3, S4).

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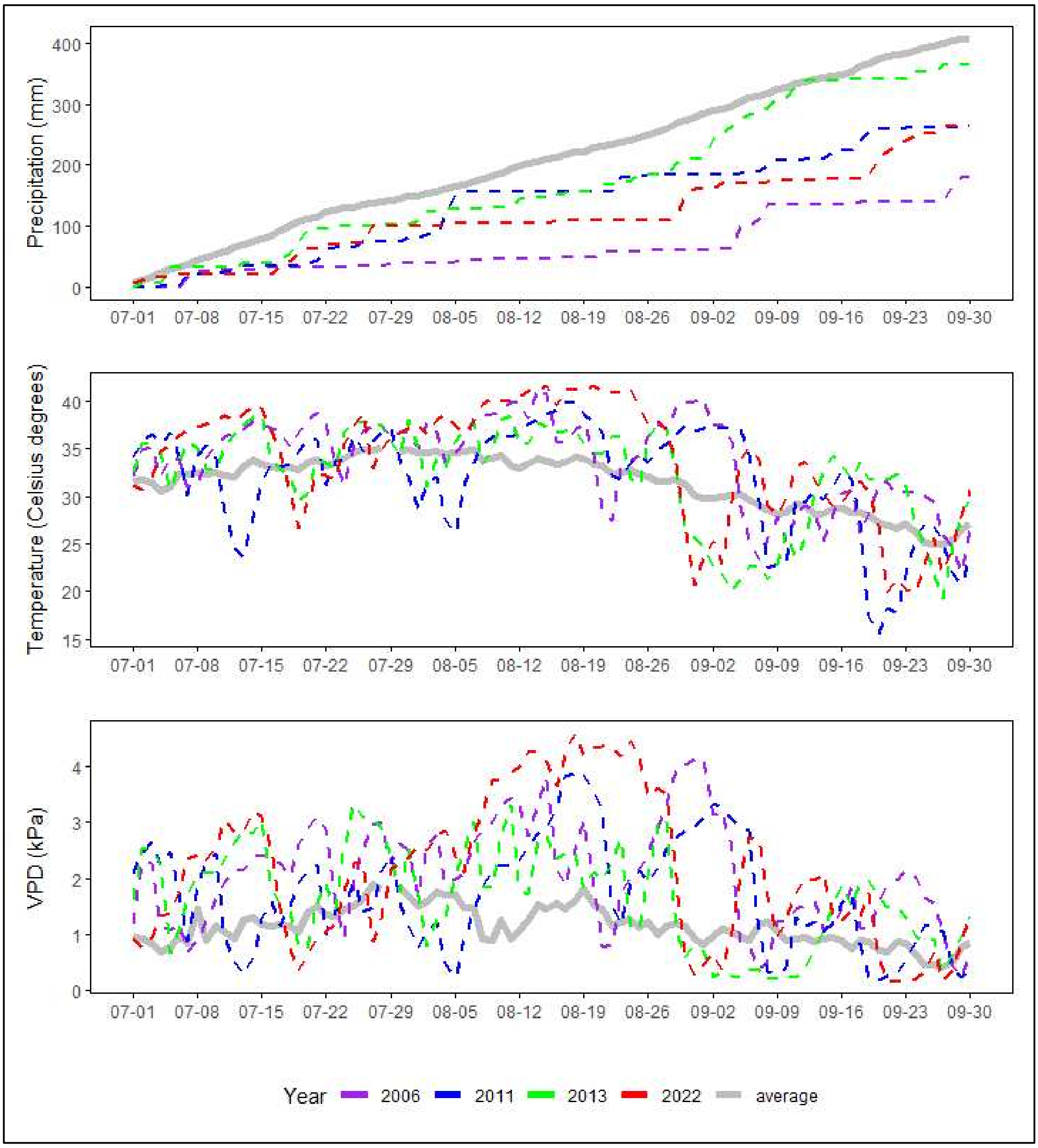

Figure 3. 2006 (in purple), 2011 (blue), 2013 (green) and 2022 (red) had the summer seasons with lowest mean precipitation (a), highest median temperature (b), and highest VPD (c). Daily weather variables during the summer season (July-August-September) for the period 2001-2022. The statistics (medians and mean) are calculated across the whole territory contained within Chongqing Municipality.

The month of August in 2022 was the driest in the last 22 years in our study region: between the 28th of July and the 28th of August, precipitation levels were the lowest in Chongqing according to the weather data, stored either by satellite products (Figure S1) or in Chongqing's 35 weather stations (Figure 3); this pattern highly converges with the fact that 2022 was the driest in China for the last 61 years [12]. Even at places of Chongqing with the highest rainfall during July and August of 2022, it rained less than a total amount of 300 mm during the period, cumulative precipitation only reaching between 160-200 mm at most areas. In an average year, precipitation levels is around 300mm in these two months (Figure 3).

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The highest temperature and lowest relative humidity values occurred in the summers of 2022 and 2006 (Figure 3; Figures S2, S3), when the highest VPD occurred, followed by the summers of 2011 and 2013 (Figure 4), using both, weather station and ERA5 data (Figure S4).

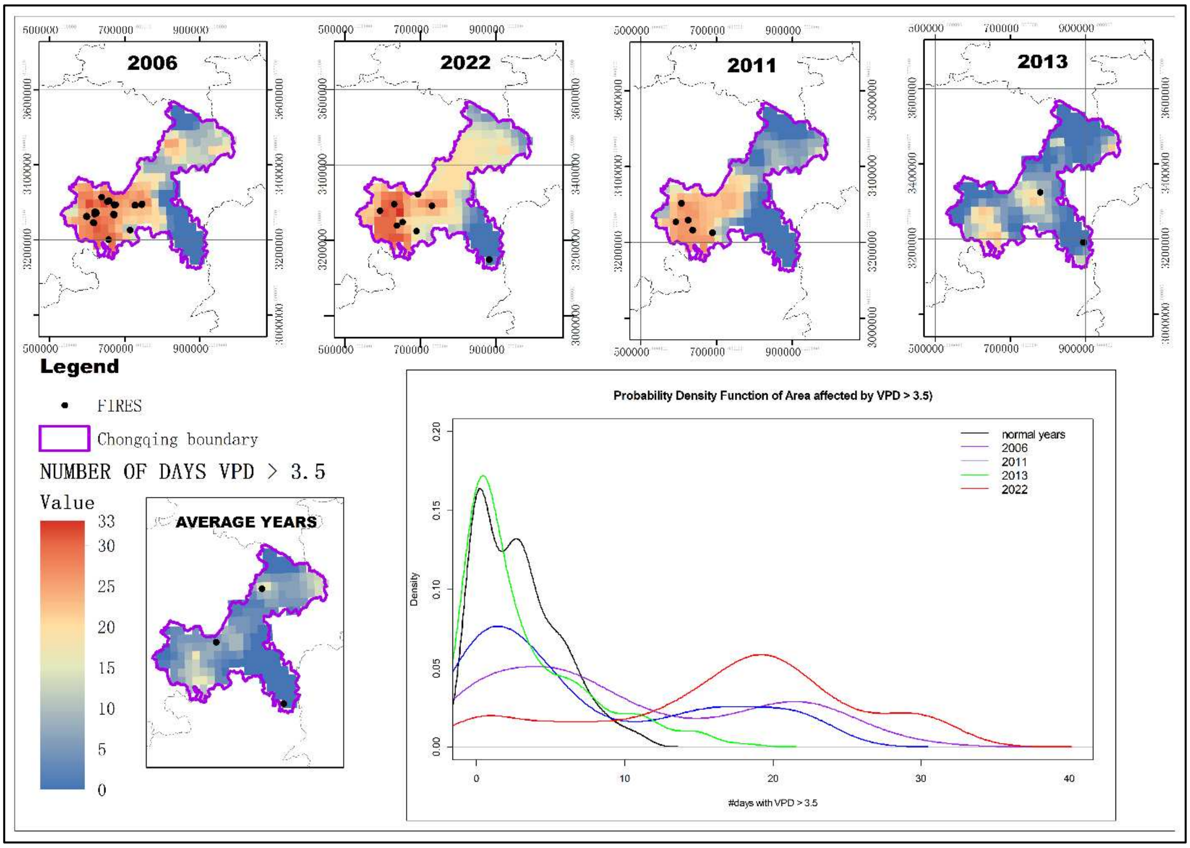

Figure 4. 2006, 2011, 2013 and 2022 summer fire seasons show a significant association between fire frequency, burned area and VPD. Daily dynamics of VPD 85th percentile plotted against each forest fire (black points), whose position in the figure is determined by its *specific VPD and specific day* when each fire occurred; the size of each fire point is determined by each forest fire's burned area.

We defined extreme fire weather days as those when VPD was higher than 3.5 kPa because in our research region this is the threshold above which most big fires (>100 ha) tended to occur (Figure S5). The number of extreme fire weather days within the summers (July-August-September) of 2006, 2011, 2013 and 2022) ranged from five days to 30 days, while the number of days in the normally humid summers ranged from zero to ten days (Figure 4).

We observed strong relationships between VPD and burned area (Figure 5), where fires tend to occur at locations with highest VPD. The summer of 2006 shows a fire progression that escalates between the 3rd week of July and the 1st of September. In contrast, the summer of 2022 concentrates fires during 9 days, between the 18th and 26th of August. The summers of 2011 and 2013 had less burned area relative to the most extreme years of 2006 and 2022 (Figure 5).

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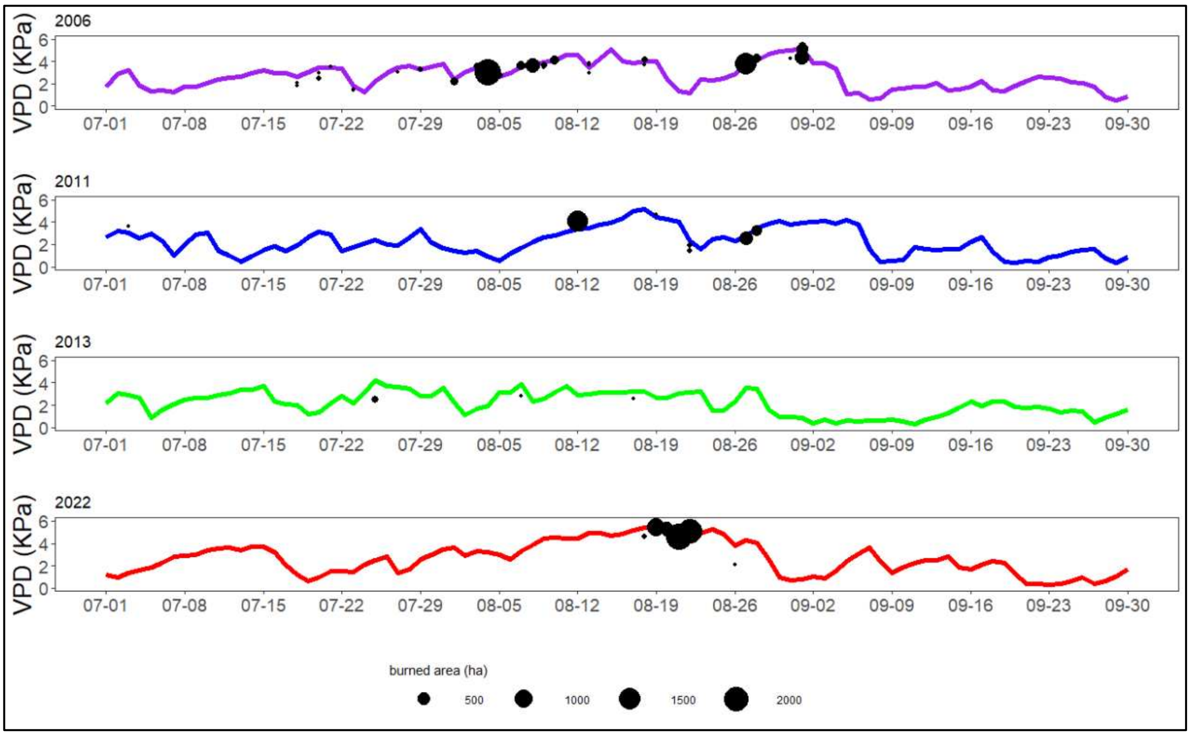

Figure 5. 2006 and 2022 had the largest area affected by longest time under high vapor pressure deficit, as shown in: (a) spatial representation of the number of days with VPD above 3.5 kPa, and (b) probability density function of the area affected by VPD > 3.5 kPa.

A clear spatial-temporal pattern emerges (Figure 4): in the average humid summers, less than 10 days with VPD > 3.5 kPa occurred in 98% of the territory (i.e., only 2% of the total area [% of forested pixels] was affected by more than 10 days with VPD > 3.5 kPa). However, in the summers of 2006, 2011 and 2022, we observed that 38%, 31% and 77% of the total area were respectively affected by more than 10 days with VPD > 3.5 kPa (Figure 4). In the summer of 2013, 8% of the total territory of Chongqing was affected by more than 10 days with VPD > 3.5 kPa.

There was also a strong, linear relationship ($R^2 = 0.82$) between the number of days with VPD above 3.5 kPa (daily 3pm VPD value) and burned area (Figure 6). The years 2006 and 2022 both showed the summers with the largest area and the highest number of days with VPD above 3.5 kPa. Therefore, there is a clear separation between three groups of years: drought-heat summers (2006 and 2022) with more than 10 days (across 100% of the forested region) with VPD > 3.5 kPa and more than 6,000 ha burned; an intermediate group with between five and 10 days (VPD > 3.5 kPa) and around 2,500 ha burned; and a final group of summers with less than five days (VPD > 3.5 kPa) with very little burned area, including also the summer of 2013. Furthermore, the difference in VPD between dry summer and winter fire seasons (See Supplementary Material, Figure S5) is a key factor that explains why the largest burned area occurs in these recent anomalous summers with CDHEs (most fire VPD values > 3 kPa), and why winter burned area is much smaller (most fire VPD values well below 1 kPa).

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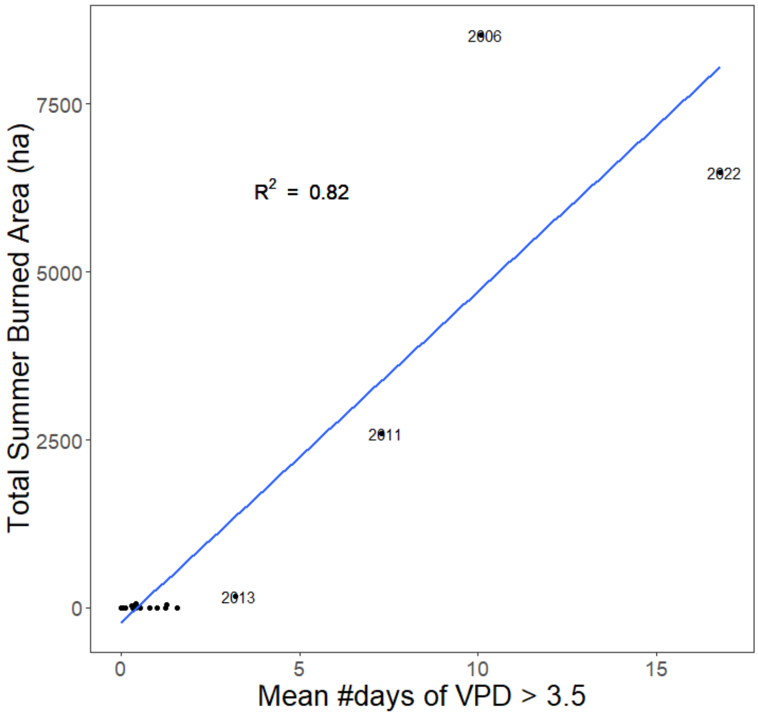

Figure 6. Significant correlation between mean number of days with VPD > 3.5 kPa and total summer burned area.

4. Discussion

4.1. Summer compound drought and heat events (CDHEs) effects on burned area

In our study area, summer CDHEs were directly associated with larger forest fires, especially in 2006 and 2022 (Figure 6). The 2022 summer season has been the most extreme in terms of the burned area, fire weather and the number of extreme fire days (number of days with VPD > 3.5 kPa) (Figures 2, 3, 4, 5, and 6). Forest fires were only paralleled by the 2006 summer season (8,535 ha burned) in Chongqing Municipality.

The difference in burned area between the dry summer seasons and the other seasons (i.e., dry winter season and humid summer season) is particularly marked in Chongqing (Figure 2): burned area in most winter seasons were featured by burned area below 1,000 ha (except for the case of 2015, when it reached 2,000 ha); meanwhile, summer seasons with CDHEs (especially the case of 2006 and 2022) were about more than 6 times above the historical winter fire seasons (Figure 2). Meanwhile, normal rainy summers had practically no fires.

According to our analyses (Figure 2, Figure S5), we have strong evidence in support of our hypothesis that increases in summer VPD summer, as result of increasing CDHEs, cause a sharp increase in burned area, relative to both humid summers (without fires) and to the dry winter season (relatively with much less burned area than in dry-hot summers).

Even though 6,480 ha (2022 summer) and 8,535 ha (2006 summer) are relatively small areas when compared with the extent of forest fires in other biomes [20], this is important as it could indicate that fires in tropical forests, where fire activity was putatively limited by high moisture, may be increasing as a result of climate change.

4.2. Compound drought and heat events (CDHEs) effects fire seasonality

With regard to the effect of CDHEs on fire season length, forest fires in the summer seasons of 2006, 2011 and 2022 nearly spanned through a minimum of two weeks (2022) and a maximum of 1.5 months (2006) (Figure 5). A potential direct consequence of the higher frequency and intensity of CDHEs in subtropical China – where summers have been historically rainy (i.e., burned area near 0 ha) – is that, a newly emerging, more frequent and intense summer fire season be added on top of the historical winter fire season. On the other hand, a shifting temporal pattern between summer and winter fire seasons has been detected in Chongqing (Figure S6), i.e., one historical dry winter season and another newly emerging CDHE summer season. In fact, a possible explanation of this temporal differentiation is that the respective fires of these two seasons in Chongqing are also essentially driven by different factors.

Firstly, historical dry winter season fires are generally featured by presenting both lowest forest cover and VPD values: they are mostly agricultural fires related to human land management activities in the countryside. On the other hand, the newly emerging fire summer season (CDHE) is instead featured by a higher forest cover and highest VPD values, what points to forest fires driven by accidental human behavior and the propensity of weather to fires.

Secondly, forest fire prevention measures are promptly implemented at the county-level in China – strong fire-suppression policy factors, being related to the fact that China still has an important population living in the countryside and the high security priorities prevalent in Chinese society. The strong fire-suppression policy might also act as a cautionary warning preventing fires from occurring on successive seasons.

Thirdly, ecological-landscape factors may also play a role whereby forest landscapes tending to be sparse, young (biomass-limited) and fragmented stands in subtropical China – still undergoing a steady recovery process via forest community succession – hindering the occurrence of extensive and continuous-area fires. In fact, this two latter ecological-landscape and strong fire-suppression factors may explain why subtropical forest fires in Chongqing Municipality are relatively small when compared with other world biomes.

Notwithstanding fire seasons thus tend to appear quite time-spaced, we cannot rule out the possibility that in the near future fires spread all the year around (both in winter and summer), as fire season lengthening has been widely observed across different biomes of the world. This is consistent with the projections provided by climate change and ecological modeling, although that possibility is also co-dependent on biomass-fuel availability.

4.3. Ecological considerations in the era of anthropogenic global warming

The pervasive influence of regional climate change in subtropical China (here understood as mean temperature increases plus CDHEs) can be tracked through the four-switches model [21] of forest fire activity. The extent of forest burned area essentially depends on the following four factors: (1) fire weather; (2) fuel moisture content; (3) fuel-stock spatial continuity; and (4) ignition [22]. According to several studies conducted in Chongqing forests, 80% of fires in Chongqing Municipality are originated due to human factors [23,24]. In fact, this number is very similar to the national average in China, nearly 90% due to human factors (China Forest Statistics Yearbook, 2004-2016).

Climate change generally affects (1) and (2), and promotes (3) – via growing season extension, rising-CO2 fertilization – resulting in higher biomass production (provided that minimum water requirements are met); finally, climate change might even affect ignition via intensifying lighting frequencies [1]. Moreover, not only does forest burned area depend on biophysical factors but, given the concurrent impacts of human demography and socioeconomic dynamics, forest fires can be best understood under the interaction of both bioclimatic (i.e., the interplay between climate and forest primary production) and human factors; the latter human behavioral factors in fact exert a key influence on the local division between winter (agricultural) / summer (forest) fires. These fires may imply certain soil erosion impacts that need to be considered and thoroughly quantified to avoid potential siltation in the reservoir.

Another key message to be taken from the 2022 extreme fire season is the importance of incorporating extreme weather events and their return period into forest fire early-detection systems, also in regional planning for ecological restoration programs. Attribution methods provide robust evidence linking climate change with an increasing frequency in extreme weather events [25], and new-generation climatic models predict this trend is going to accentuate under near-future higher emission scenarios [1]. More intense and longer heat waves, especially when combined with low precipitation, facilitate the spread of forest fires, such as the devastating 2022 summer fire season in Southwestern Europe [18]. The extension and severity of forest fires in Australia [20,26–29], the Western USA [2,30,31], and the Mediterranean Region [13,32] have attracted the attention of both scientists and broader society.

4.4. Limitations and future work

In this study we have based our analysis on two types of data: (a) China Meteorological Network's weather stations and Copernicus ERA5 for meteorological variables (precipitation, temperature, relative humidity, calculated VPD), and (b) MODIS product MCD64A1 for fire burned area (either from direct satellite images or extracting the data contained in the GLOBFIRE database). We have used VPD as a proxy of dead fuel moisture content (DFMC), as abundant research evidence confirms the tight correlation between the two variables. Ideally, we would have also conducted field work to collect data on both DFMC and LFMC (live fuel moisture content); however, due to time limitations to conduct field work in Chongqing, we would rather use VPD as a proxy of DFMC.

As climate change unfolds, scenarios predict that more frequent and intense heat waves will follow, posing direct implications for fire weather in subtropical China and other locations of the country. It is important to continue research in the field of forest fire prediction, ecological modeling, and fire detection, which minimize the impacts of forest fires on human lives, wealth assets and ecosystems.

With regard to the biomass-limitation factor, the undergoing process of forest biomass recovery due to China's forest conservation policy needs to be considered in fire prevention and prediction modeling: what kinds of forest community-succession trajectories and ecosystem carbon balance dynamics are going to emerge in the context of global warming? what forest species will perform better under new warmer and likely drier conditions in terms of ecosystem functionality (e.g., soil erosion control, water provision, carbon storage, biodiversity protection)? These are relevant research questions, which need to be simultaneous and iteratively addressed in connection with forest fire dynamics. As mean temperature rises, and weather extremes become the new normal, regional planning for ecological restoration programs needs to factor in these newly emergent conditions in the future community succession trajectories.

5. Conclusions

Compound drought and heat events (CDHEs) are becoming more exacerbated and persistent in Southern Australia and Western North America [33], and also in China [5], threatening natural ecosystems and agriculture sustainability, having important socioeconomic impacts and facilitating the spread of forest fires. Firstly, in this study we have a strong indication that summer CDHEs are triggering an abrupt increase in burned area in Chongqing, subtropical China, via increases in summer VPD (as it is highly correlated with dead fuel moisture content, DFMC). Moreover, summer CDHE-driven VPD (most fires above 3.5 kPa) is much higher than the historical winter fire season VPD baselines (most winter fires below 1 kPa), resulting in larger burned areas in dry-hot summers than in the historical dry winters. Still, fire area numbers in our study region are relatively very low in comparison with other biomes such as the Mediterranean forests. In fact, we have evidence that in Chongqing for the last 15 years a shifting temporal pattern between mutually exclusive winter and summer fire seasons has emerged, what may be explained by human agricultural activities, strong fire-suppression policy, and ecological-landscape (biomass-limitation) factors. We have to be cautious since forest community succession are likely undergoing novel trajectories of change as a result of global warming.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org. Figure S1: Precipitation between July 1st and August 31st (period 2001-2022), Figure S2: Maximum temperature between July 1st and August 31st (period 2001-2022), Figure S3: Relative humidity between July 1st and August 31st (period 2001-2022), Figure S4: Vapor pressure deficit (VPD) between July 1st and August 31st (period 2001-2022), Figure S5: Winter fires tend to occur on lower forest cover (smaller circles in blue), whereas summer CDHE fires are occurring on landscapes (bigger circles in red). Burned area and VPD, controlled for each season (i.e. summer and winter). The radius of circles represents the forest cover (%), Figure S6: Alternating fire seasons between the historical mild winter and the newly emerging virulent summer season, with higher VPD and burned area records. Scatter plot between VPD and year (of each individual fire), controlling for summer/winter season and burned area (individual fires' point size).

Author Contributions: Conceptualization, Y.Y., and V.R.D.; data curation, L.G.R., Y.H., M.S., and V.R.D; formal analysis, L.G.R.; funding acquisition, V.R.D and Y.Y; methodology, L.G.R. and V.R.D.; writing—original draft, L.G.R.; writing—review and editing, V.R.D., and Y.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (U20A20179, 31850410483), the Talent Proposals in Sichuan Province (2020JDRC0065) and by Southwest University of Science and Technology (18ZX7131).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest and the funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

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