Ambiente & Água - An Interdisciplinary Journal of Applied Science
ISSN 1980-993X – doi:10.4136/1980-993X
www.ambi-agua.net
E-mail: ambi.agua@gmail.com

The influence of climate parameters on fires in the Paraíba do Sul River valley, southeast Brazil

ARTICLES doi:10.4136/ambi-agua.2923

Received: 20 Mar. 2023; Accepted: 30 Jun. 2023

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ABSTRACT
Brazilian biomes have been experiencing an increase in fires during the whole year, but fires increase substantially during drier periods. Several indexes might be good indicators of the severity of the droughts, such as The Rainfall Anomaly Index (RAI), Standardized Precipitation Index (SPI) and the Vegetation Health Index (VHI). This study therefore aimed to understand the dynamics of climate, using some indexes and fires in Paraíba do Sul River Valley, Paulista portion, to verify whether fire is more likely to spread in hotter and drier years. We hypothesized that fire events are more frequent and burned areas are larger in hotter and drier years in the region. By conducting a cross-correlation analysis and separating the monthly data into dry and rainy seasons, it was possible to establish a correlation between climate parameters and fire. A significant correlation was found between RAI and fires in both seasons. Additionally, we observed that high occurrences of fire events and burning areas were more explained by RAI, VHI and SPI-3 in dry and wet seasons than by temperature and SPI-1, SPI-6 and SPI-12. We noticed a complex dynamic between fire events, burned area, the environment, and climatic variables. However, the studied indexes proved to be effective tools for detecting drought conditions in the region and their relationship to fire.

Keywords: burning, climatic indexes, Paraíba do Sul River Valley.

A influência das variáveis climáticas nas queimadas no Vale do Paraíba Paulista, sudeste do Brasil

RESUMO
Os biomas brasileiros têm experimentado um aumento nos eventos de queimadas (focos e área queimada) durante todo o ano, mas as queimadas aumentam substancialmente nos períodos mais secos. Vários índices podem ser bons indicadores para medir a severidade das secas como o Índice de Anomalia de Chuvas (RAI), Índice de Precipitação Padronizada (SPI) e o Índice de Saúde da Vegetação (VHI). Assim, este estudo teve como objetivo compreender a dinâmica entre clima, usando alguns índices, e incêndios no Vale do Rio Paraíba do Sul, porção paulista,

e verificar se há maior probabilidade de propagação do fogo em anos mais quentes e secos. Nossa hipótese é que os eventos de incêndio são mais frequentes e as áreas queimadas são maiores em anos mais quentes e secos na região. Ao realizar uma análise de correlação cruzada e separar os dados mensais em estação seca e chuvosa, foi possível estabelecer uma correlação entre os parâmetros climáticos e o fogo. Uma correlação significativa foi encontrada entre RAI e incêndios em ambas as estações. Adicionalmente, observamos que as altas ocorrências de eventos de incêndio e área queimada foram mais explicadas pelo RAI, VHI e SPI-3 nas estações seca e chuvosa do que pela temperatura e SPI-1, SPI-6 e SPI-12. Percebemos uma dinâmica complexa entre eventos de incêndio, área queimada, ambiente e variáveis climáticas. No entanto, os índices estudados se mostraram ferramentas eficazes para detectar as condições de seca na região e sua relação com o fogo.

Palavras-chave: índices climáticos, queimada, Vale do Paraíba Paulista.

1. INTRODUCTION

Every year, wildfires burn more than 400 million hectares worldwide (Andela *et al.*, 2017) and shape the structure and diversity of all biomes (Bond and Keeley, 2005). Since 2018, all Brazilian biomes have been experiencing an increase in fires (INPE, 2022). Humans are a major force driving many fire regimes around the globe (Archibald *et al.*, 2013), and, in Brazil, fire is often a key process when considering the drivers of forest loss and commodities agriculture (Barlow *et al.*, 2020).

Fire occurrence and propagation may be directly linked to climatic factors, such as precipitation, temperature and wind speed (Keeley *et al.*, 2011). In Brazil, fires have been registered during the whole year, but burnings increase substantially during drier periods (INPE, 2022). Lately, the increase in fires has been related to longer duration of dry seasons worldwide (Jolly *et al.*, 2015), explained by climate change (IPCC, 2021). According to Pivello *et al.* (2021), drier climates and land-use changes increase the risk of wildfires throughout Brazil.

The Paraíba do Sul River Valley is currently characterized by a landscape patchwork of tropical forest remnants and pastures (Sapucci *et al.*, 2021). Guedes *et al.* (2020) found a strong positive correlation between pasture area and burn probability in the region, while the opposite was verified for forest cover, reinforcing the role of pastures in fire ignition and transmission. Several conservation and restoration initiatives taking place in the region might be damaged by fires (WRI, 2022: FLR Hub, TNC: Programa Conservador da Mantiqueira), but also economic activities and population health. The region presents a seasonal precipitation variability, with a well defined rainy and dry season, associated with the South America Monsoon System (Reboita *et al.*, 2010). In winter (end of June to end of September), the accumulated precipitation does not exceed 200 mm and in summer the values reach 800 mm (Brasiliense *et al.*, 2020).

Ayres (2010) showed that floods and severe storms have a high frequency in the region. Zilli *et al.* (2016) analyzed extreme rainfall events in the rainy season across the southeastern coast of Brazil and, for the Paraiba do Sul River Valley Basin, they found an increase in the frequency and intensity of these events. Drought events are also recurrent in the region (Santana *et al.*, 2020) and have a major impact on water supply as registered on 2013/2015 (Coelho *et al.*, 2016; Marengo *et al.*, 2015; Nobre *et al.*, 2016).

Drought can be defined as a failure in hydrological balance. Such failure can include reduced rainfall over a period (more than average), inadequate timing of the precipitation, or a negative water balance due to increased atmospheric water demand related to high temperatures (UNDRR, 2021). Several indexes have been developed and are proven to be good indicators to measure the severity of the droughts around the world, such as the Rainfall Anomaly Index

(RAI: Rooy, 1965), the Standardized Precipitation Index (SPI: Hayes *et al.*, 2011), and the Vegetation Health Index (VHI: Tran *et al.*, 2017). RAI, SPI and VHI have been adopted to identify drought events in southeast Brazil (RAI: Noronha *et al.*, 2016; SPI: Blain and Kayano, 2011; Silva and Mello, 2021 and VHI: Gomes *et al.*, 2017). By using these indexes, we intend to have a broader analysis of drought, since SPI is based on a probability density function, with adjustable scales, RAI determines deviations referring to the normal condition of precipitation, with greater visible seasonality, and VHI is used as an indicator of the response of stressed vegetation.

In addition, in the last few years, studies have been applying drought indexes to verify the relation to wildfires occurrences in biomes and regions in Brazil: Alvarado *et al.* (2017), found increasing fire occurrence during the driest periods in Cerrado; Marengo *et al.* (2021) identified droughts by indexes such as VHI, concluding that water and heat stress increases flammability thresholds in Pantanal; and Teodoro *et al.* (2022) verified that the trend of fire occurrence in the Midwest, Southeast, and South regions of Brazil is related to precipitation, land surface temperature and SPI.

Fire risk assessment studies are extremely important to plan preventive measures, optimizing use of resources, compared to suppressive measures. This study therefore aimed to understand the dynamics between climate and fires in Paraíba do Sul River Valley, Paulista portion, and to verify whether fire is more likely to spread in hotter and drier years. We hypothesized that fire events are more frequent and burned areas are larger in hotter and drier years in the region.

2. MATERIAL AND METHODS

2.1. Study site

The Paraíba do Sul River Valley, Paulista portion (46.5° W – 43.5° W/ 22.5° S – 24° S, Figure 1), is located in southeast Brazil, São Paulo State. The valley population of over 2 million people (IBGE, 2021) in 39 municipalities sits on the fringe between the major metropolitan areas of São Paulo and Rio de Janeiro. Although populous, the mostly rural valley is currently characterized by a landscape patchwork of tropical forest remnants and pastures (Sapucci *et al.*, 2021). The region has a hilly relief, located between two mountain chains, “Serra da Mantiqueira” and “Serra do Mar” which altitude ranges from 800 m to 2,500 m above sea level, with its interior valley varying between 560 and 650 m altitude (Devide *et al.*, 2014).

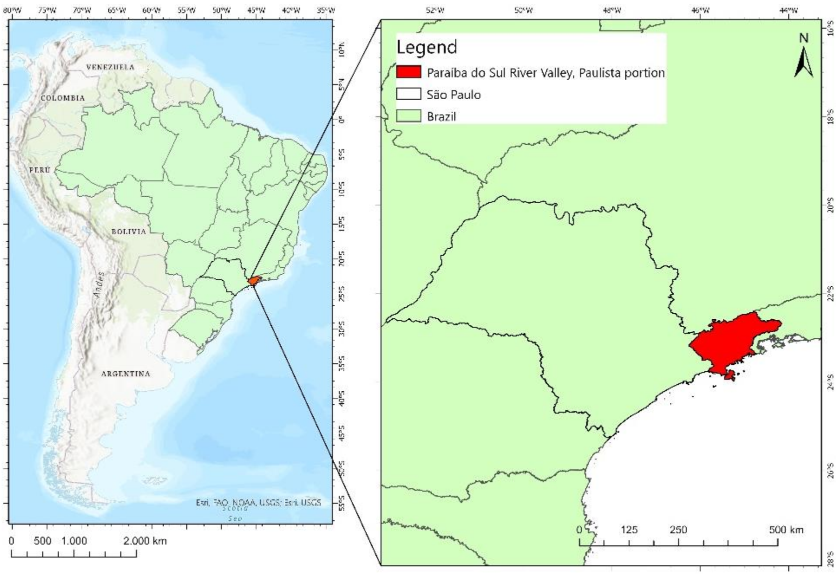

Figure 1. Study area indicating the Paraíba do Sul River Valley, Paulista portion, in Brazil, South America.

2.2. Datasets and index calculation

Monthly precipitation data was obtained for the studied region at Climate Hazards Group InfraRed Precipitation (CHIRPS, Funk *et al.*, 2015), with a spatial resolution of 0.05° × 0.05° from January 1981 to December 2021. For air temperature, monthly grid point data were used from the Climate Research Unit dataset (CRU, Harris *et al.*, 2020), with a spatial resolution of 0.5º × 0.5º, from 1981 to 2020 (Table 1). Fire data included monthly fire occurrences available at Programa Queimadas (INPE, 2022), from 1998 to 2021, with a spatial resolution of the sensors image AVHRR (NOAA satellites), MODIS (AQUA and TERRA satellites) and ABI (GOES satellite) about 1km x 1km, and burned area, with 300-meter resolution, available at Copernicus Global Land Service platform (CGLS, Hagolle *et al.*, 2005), through the 10 day composite burns detected. Although the used fire dataset is not homogeneous due to the different sensors and satellites, it is the most extended available dataset (from 1998), so it was selected for this study. Built-in NOAA, TERRA/AQUA, and GOES detection allow the monitoring of all focuses accumulated throughout the day by these three types of satellites. Thus, for precipitation and temperature data, a spatial average for the study area was considered for each year of the studied period. The fire data were also accounted for, as point data, in the area.

Table 1. Climatic and fire variables, and the respective data coverage periods, databases and references for each database.

Data	Period	Source	Reference
Precipitation	1981 – 2021	CHIRPS	Funk *et al.* (2015)
Temperature	1961 – 2020	CRU	Harris *et al.* (2020)
Fire events	1998 – 2021	Programa Queimadas	INPE (2022)
Burned Area	April 2014 – July 2021	CGLS	Hagolle *et al.* (2005)

The monthly burned area was calculated as the sum of three 10 days composite. It was necessary to cut the data file — which was obtained in Geotiff format and used in a GIS program — by using a shapefile of the study site. Burned pixels could be identified by the number one, so the Arcgis raster calculator was used to get the total number of burned pixels per month and, from the spatial resolution of 300 meters, the total burned area monthly was obtained. Data are derived from the daily synthesis of PROBA-V sensor data, which verifies the occurrence of burn scars at the study site, covering the period from April 2014 to July 2021. It was noticed that from July 2020 to March 2021 there was no register of burned areas, but as INPE registered fires, it may have been a period of lack of data, as not all burned pixels could be detected.

We calculated the 90th percentile for air temperature of each season of the year, so that a seasonal temperature threshold could be drawn, above which temperature was considered extreme. Seasonally accumulated rainfall values lower than the 10th percentile were considered extreme drought. These types of indexes were adapted from studies such as Carmello *et al.* (2013) and Geirinhas *et al.* (2018).

SPI was calculated fitting the Gamma two parameters Probability Density Function (PDF), demonstrated in Equation 1, where G(x) refers to cumulative probability; x to monthly precipitation; $\Gamma\ (\alpha)$ to gamma function; α and β, respectively, to parameters of shape and scale (Wu *et al.*, 2005). According to McKee *et al.* (1993), the SPI reference values are 0 to -0.99, for weak drought; -1 to -1.49, for moderate; -1.5 to -1.99, for severe; and ≤ -2, for extreme. SPI was calculated on different time scales (1, 3, 6 and 12 months), corresponding to the precipitation in the months of the referred scale. Thus, on a 6-month scale, for example, the precipitation associated with a given month corresponds to the sum of the 6 months preceding it, so that the analysis covers different types of droughts, from the fastest events to the most durable ones. To define a drought episode, we use the definition of Spinoni *et al.* (2014), which says that a drought episode can be noticed when there are at least two consecutive months with SPI values lower than -1.

$$G(x) = \frac{1}{\beta\,\Gamma\,(\alpha)} \int_0^x x^{\alpha-1} e^{-x/\beta}\, dx \qquad (1)$$

RAI verifies deviations referring to the normal condition of precipitation (Rooy, 1965), allowing comparison to a time series or spatiality evaluation of a drought. Therefore, measures are allocated in descending order and the average of the ten highest values is calculated, followed by the average of the ten lowest, which are represented by $\overline{\mathrm{M}}$ and $\overline{\mathrm{X}}$, respectively, as shown in Equations 2 and 3, since N is the monthly or annual precipitation (mm) and $\overline{\mathrm{N}}$ is the average monthly or annual precipitation of the series (mm).

$$RAI = 3\,\frac{N-\overline{\mathrm{N}}}{\overline{\mathrm{M}}-\overline{\mathrm{N}}} \qquad (2)$$

$$RAI = -3\,\frac{N-\overline{\mathrm{N}}}{\overline{\mathrm{X}}-\overline{\mathrm{N}}} \qquad (3)$$

Equation 2 expresses index value for positive anomalies, while Equation 3 refers to negative anomalies — below average. RAI was calculated with point data, on monthly and annual scales, and its reference values are > 4, for extremely rainy; 2 to 4, for very rainy; 0 to 2, for rainy; 0 to -2, for dry; -2 to -4, for very dry; < -4, for extremely dry (Araújo *et al.*, 2009).

VHI characterizes the health of the vegetation by assuming that stressed conditions are linked to lower than normal NDVI and higher than normal temperature (Kogan, 2001); it may be written as Equation 4. Where VCI refers to Vegetation Condition Index (Equation 5); TCI to Temperature Condition Index (Equation 6); T to the smoothed weekly temperature; Tmax and Tmin to its maximum and minimum, respectively; NDVI to the smoothed weekly index, NDVImax and NDVImin to its maximum and minimum. TCI is given by thermal channels of AVHRR (Kogan, 1995); thus, its temperatures depend mainly upon the surface temperature, but also on the total-column atmospheric water vapor, and on the surface-atmosphere temperature gradient (Gutman *et al.*, 1995). VHI reference values are 30 to 40, for abnormally dry; 20 to 30, for moderate drought; 12 to 20, for severe drought; 6 to 12, for extreme drought; < 6, for exceptional drought (Cunha *et al.*, 2019). According to CEMADEN (2021), if the VHI returns a value lower than 40 and this scenario persists for two consecutive months, a drought event is verified. This condition remains in effect until the index value reaches at least 45.

$$VHI = \frac{VCI+TCI}{2} \qquad (4)$$

$$VCI = 100\,\frac{NDVI-NDVI_{min}}{NDVI_{max}-NDVI_{min}} \qquad (5)$$

$$TCI = 100\,\frac{T_{max}-T}{T_{max}-T_{min}} \qquad (6)$$

We separate the climatic and fire data according to seasonality (wet, from October to March, and dry seasons, from April to September), and after that, to analyze whether SPI, RAI, VHI, 90th percentile for temperature and 10th percentile for rainfall (explanatory variables) were related to burning events and size area (response variables), we performed Pearson correlation tests. By using different indexes, it was possible to understand not only the drought event on a given time scale, but also the drying of vegetation and the deviations from the normal precipitation condition. The tests were considered statistically significant when p-value was lower than 0.05. Analyzes were performed in R Version 3.6.3 (R Core Team, 2019), by using the SPEI package for SPI calculation.

3. RESULTS AND DISCUSSION

The monthly variability of precipitation (1981 - 2021) and temperature (1981 - 2020) can be described in terms of seasonality, i.e., climatology is represented in blue in Figure 2. The higher accumulated rainfall occurred in summer months (234.23 mm were the average recorded in December; 269.60 mm in January; and 223.66 mm in February) and the lowest values in Winter (41.34 mm of rain in June; 33.30 mm in July; and 34.55 mm in August). Autumn (end of March to end of June) and Spring (end of September to end of December) were transition seasons with average precipitation between 64.47 mm (May) and 165.79 mm (November). The highest mean temperature occurred in February (22.8ºC) and the lowest in July (16.02ºC). The average annual precipitation was 1574.7 mm (standard deviation: 174.0 mm) and the average mean temperature was 19.9°C (standard deviation: 0.5°C).

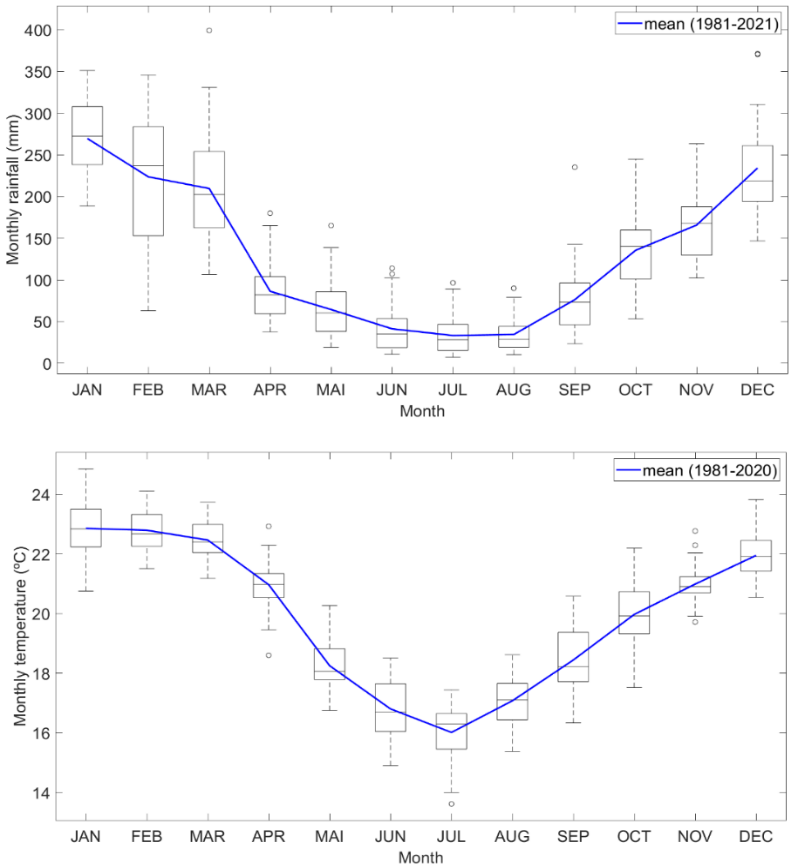

Figure 2. Boxplots of the monthly average rainfall distributions during 1981 - 2021 (upper) and monthly average temperature during 1981 - 2020 (lower) at Paraíba do Sul River Valley. Blue line represents climatology (1981-2021).

3.1. SPI, RAI and VHI temporal variability

We found a temporal variability in SPI indexes, ranging from dry to wet periods (Supplementary Material 1) in Paraíba do Sul River valley. We found 12 drought episodes (Figure 3) from 1998 to 2021 in Paraíba do Sul River Valley. October 2019 to December 2020 (14 months) was the longest drought event, when severe drought was registered for three months scale, and extreme, for six months scale. Further, 2003 was a dry year regarding duration and severity, and were also, 1999, 2000 and 2018; while the first two were extreme and the last, severe drought. Considering the entire series, the lowest SPI-3 values were in March 1984 (-2.82), June 2000 (-2.47) and November 1999 (-2.41). By calculating the ratio between drought severity (sum of SPI values, on its scale of 1, 3, 6 or 12 months, in the drought period, Fernandes *et al.*, 2009) and duration in months, we found the most intense drought years to be 2018, 2000 and 1999.

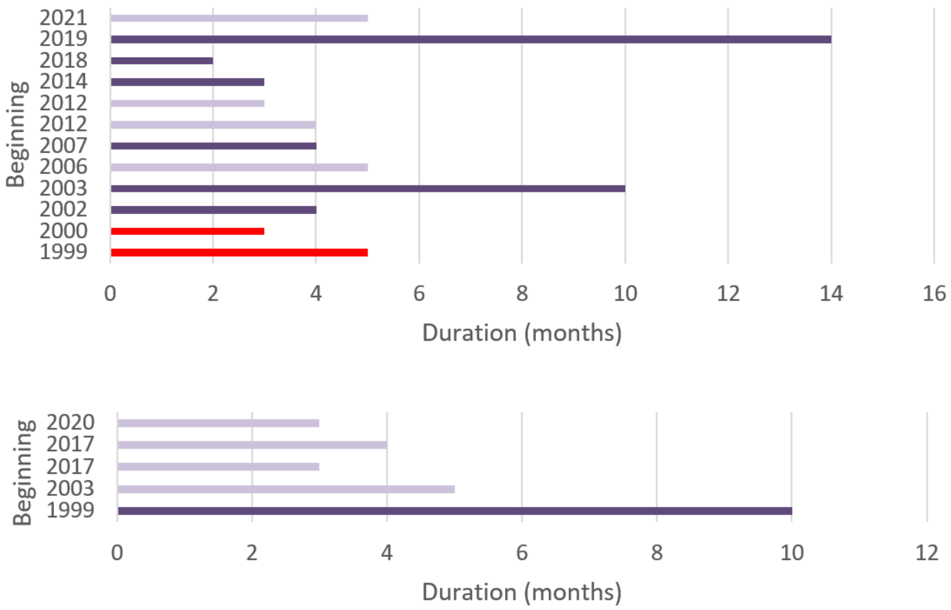

Figure 3. Identification and classification of drought episodes in Paraíba do Sul River Valley, from 1998 to 2021, according to the SPI-3 (upper) and to VHI (lower). In the top figure, light purple is moderate, dark purple is severe and red is extreme drought. In the bottom figure, light purple is abnormally dry and dark purple is in moderate drought. The years 2012 and 2017 are repeated due to the occurrence of two drought events in each of them.

RAI was also seasonal (Supplementary Material 2), with the driest months concentrated on June, July and August when very dry or dry categories were registered for the entire series. Noronha *et al.* (2016) observed the same results to the northwest of Rio de Janeiro state. The same authors stated that the seasonal behavior of the index and the great temporal variability of precipitation makes it difficult to calculate a possible anomaly in a small time interval. In general, between April and September, at least 85% of the years in the series had RAI $\leq$ -0,5 (dry). Only 1984 was classified as an extremely dry year and, after 1998, five years were classified as very dry, 2007, 2003, 1994, 1999 and 2014.

Regarding VHI, the longest drought since 1998 was from December 1999 to September 2000 (10 months), followed by June to October 2003, which overlapped SPI results and from August to November 2017, as shown in Figure 3 (and Supplementary Material 2). Thus, even though vegetation health is associated with precipitation conditions, not all SPI scales were linked to that. That might be explained by different vegetation types and how they respond to drought; i.e., denser vegetation may be more prone to burning when higher scales of SPI point to a long-term accumulated rainfall deficit, while pastures may have higher susceptibility due to a shorter period of water deficit.

3.2. Fire temporal variability

Highest proportions of burned areas (46.4%) occurred in July and August, and 37.4% occurred in Autumn. The same seasonality was observed for the number of fire occurrences, with 43.8% of burnings being recorded in Winter, followed by 27.8% in mid-spring. In addition, we noticed a maximum number of fires (157) in August 2003, and of burned areas (409.71 km²) in July 2021, as shown in Figure 4. August and September were also months with the highest susceptibility to fires in the remnants of the Atlantic Forest biome in Rio de Janeiro state (Clemente *et al.*, 2017). We found above average fire events in Summer and Winter and above average fire areas in Winter (Table 2).

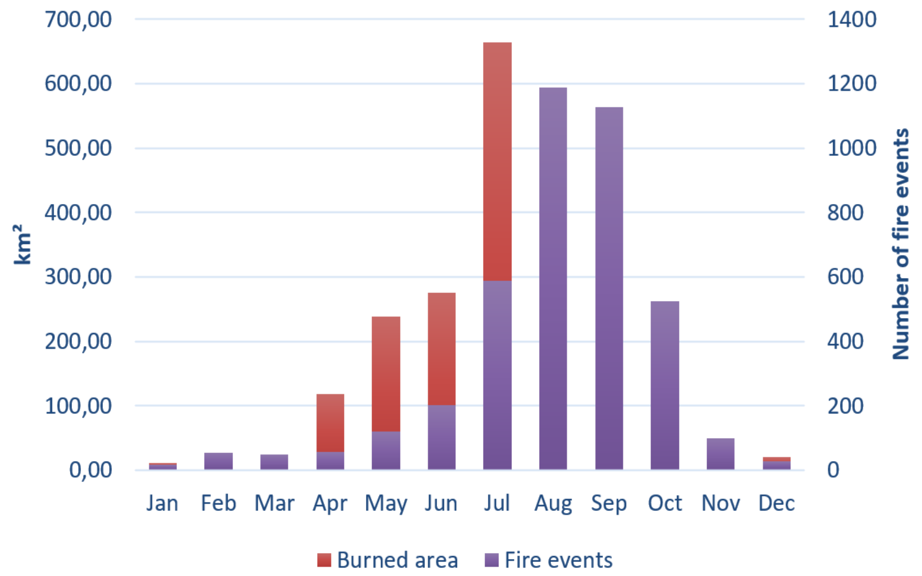

Figure 4. Annual distribution of occurrences of fires and burned areas over the years in Paraíba do Sul River Valley, since the burned area comprises the period from April 2014 to July 2021 and the number of fires from 1998 to 2021.

Table 2. Percentage of coincidence of months considered climatic extremes of temperature (hot extreme) or precipitation (dry extreme) for each season and above-average fire events.

Extreme conditions of temperature or precipitation at	Above average fires (months)	Above average burned area (months)
Summer (end of December to end of March)	35%	43%
Autumn (end of March to end of June)	22%	0%
Winter (end of June to end of September)	30%	100%
Spring (end of September to end of December)	25%	40%

3.3. Relation drought x fire

We found that precipitation, RAI, VHI and SPI-3 had more significant relations with burning events and area in dry and wet seasons (Table 3) than temperature and SPI-1, SPI-6 and SPI-12.

Lower precipitation explained more fire events and greater fire size in dry and wet seasons (Table 3), while temperature was not related to fire in the region (except for fire events in the wet season, as shown in Table 3). In Paraíba do Sul River valley, pasture is the main land use (Sapucci *et al.*, 2021) and cattle ranchers use fire (illegally) as a management tool to increase productivity of pastureland. Burnings that happen in dry months usually become large wildfires, due to climatic conditions, affecting large extensions and native forests in the region (Guedes *et al.*, 2020).

In general, SPI (except for SPI-3) was slightly related to fire in Paraíba do Sul River valley (Table 3). Similarly, other studies have found weak correlations between SPI and fire, such as Nunes *et al.* (2015); Alvarado *et al.* (2017), for annual rainfall data, and Teodoro *et al.* (2022), for abnormal weather conditions influenced by El Niño and La Niña events. SPI-3 was associated with fire events (dry and wet seasons) and fire size in the dry season.

Table 3. Correlation coefficient among climatic variables and fire events and burned area on dry and wet seasons. Bold represents P < 0.05 and significant correlations.

	Dry season		**Wet season**	
	Fire events	**Fire size**	**Fire events**	**Fire size**
Precipitation	**-0.307**	**-0.306**	**-0.351**	**-0.315**
Temperature	-0.141	-0.182	**-0.191**	-0.276
RAI	**-0.308**	**-0.306**	**-0.375**	**-0.327**
VHI	**-0.184**	0.056	**-0.251**	**-0.370**
SPI-1	**-0.193**	-0.206	-0.157	-0.105
SPI-3	**-0.290**	**-0.386**	**-0.213**	-0.128
SPI-6	**-0.339**	-0.074	**-0.173**	0.020
SPI-12	-0.071	-0.054	-0.147	0.010

RAI related to fire events and fire size in dry and wet seasons (Table 3). 2003, classified as a very dry year, according to RAI, had the highest number of fires in the period (489), while 2014 exceeded the average of burned area for subsequent years — disregarding years with possible absence of data — (143.2 km²), burned from April to December 2014. VHI is associated with fire events in both wet and dry seasons and fire size in the wet period (Table 3).

Fires in dry and wet seasons were explained by almost the same range of climatic variables, the only differences were: temperature and fire events in the wet season; SPI-1 and fire events in the dry season; VHI and fire size in the wet season and SPI-3 and fire size in the dry season (Table 3).

4. CONCLUSIONS

This study aimed to understand the dynamics between climate properties and fires in Paraíba do Sul River Valley, Paulista portion, and to verify whether fire was more likely to spread in hotter and drier years. Although we did find fire events being more frequent and burned areas being larger in hotter and drier periods in the region, we also noticed a complex dynamic between fire events, burned area and climatic variables. Nunes *et al.* (2015) had similar conclusions and pointed that higher linear correlation among the adopted parameters is found in more detailed analyses of local sites.

Specifically, we found that high occurrences of fire events and burning areas were more explained by RAI, VHI and SPI-3 in dry and wet seasons than by temperature and SPI-1, SPI-6 and SPI-12. In this context, the indexes proved to be good instruments for detecting drought conditions in the region. This study can contribute to preventive measures regarding fire susceptibility in the landscape.

5. ACKNOWLEDGMENTS

The authors thank FAPESP for the financial support granted (Process number 2020/12233-3). Klécia Massi is PQ-2 granted (309541/2022-0).

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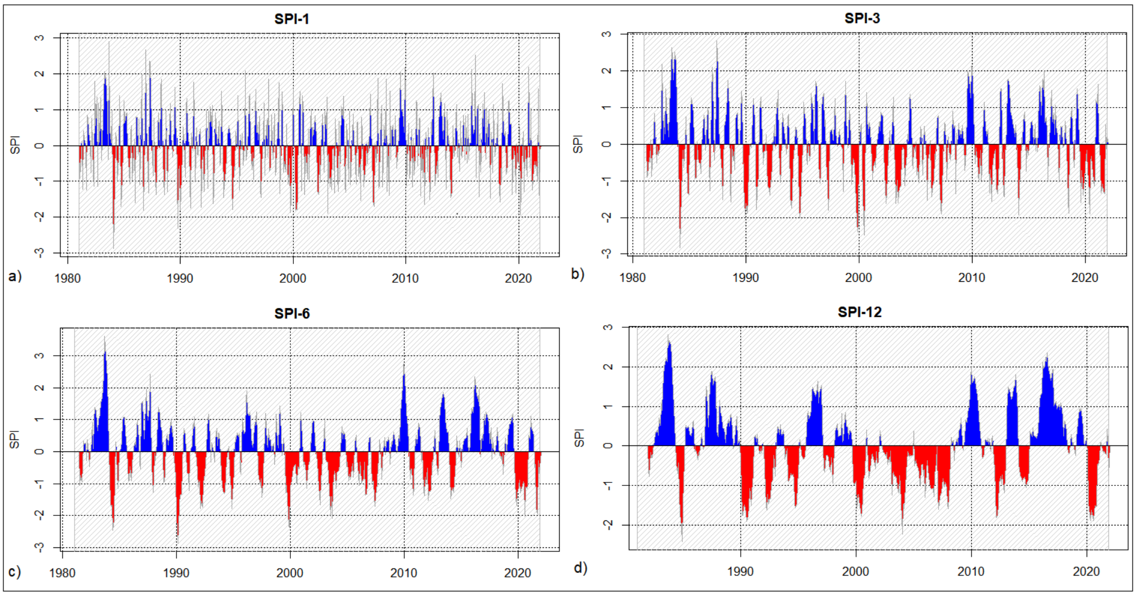
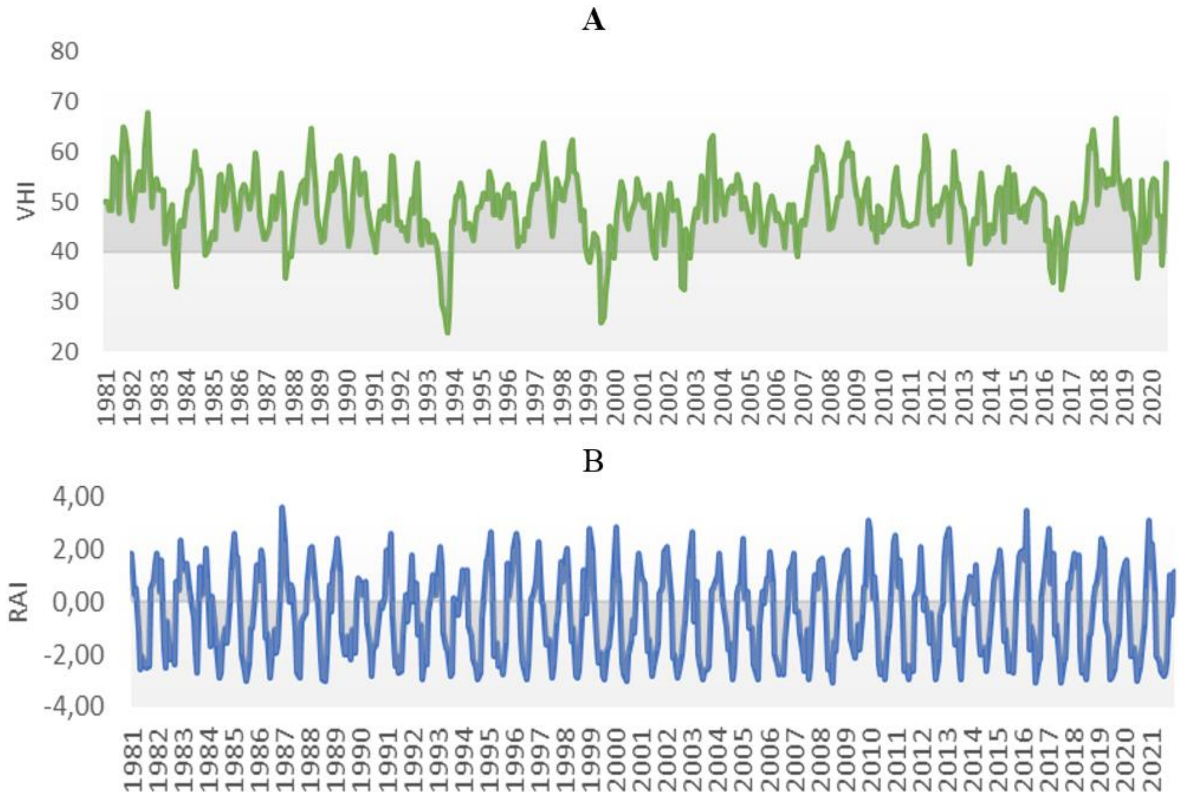
Supplementary Material



Supplementary Material 1. Time evolution of the SPI, from January 1981 to December 2021, for the scales: (a) 1 month, (b) 3 months, (c) 6 months and (d) 12 months.



Supplementary Material 2. Temporal evolution of drought indices, from 1981 to July 2021, for VHI (a), and to December 2021 for RAI (b).