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ASSESSMENT OF FIRE RISK IN THE VALE DO PARAÍBA REGION, SOUTHEAST ATLANTIC RAINFOREST, BRAZIL

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Abstract

In recent times, the area burned by wildfires in the Atlantic Rainforest, a biodiversity hotspot, has increased and its occurrence may threaten this biome. The objective of this study was to evaluate the performance of three fire risk indices for a historical time series in Vale do Paraíba Paulista, southeast Atlantic Rainforest, Brazil. Daily meteorological data from automatic weather stations and hotspots records from INPE fire monitoring program were used to validate the formulas. Three fire risk indices were calculated: Angstron, Monte Alegre Formula (MAF) and Telecyn. We expected that we would find an increase in fire risk in recent years in the region, which we found for some municipalities, and that burning risk would be higher in dry months, which we showed. Moreover, we argued that protected areas surrounding higher fire risk sites are being threatened, especially near São Luiz do Paraitinga and Taubaté. Lastly, considering the higher probability in detecting fire risk in higher classes, Angstron was the most adequate for Campos do Jordão and MAF for Sao Luiz do Paraitinga, Taubaté and Cachoeira Paulista.

Keywords: Atlantic rainforest. Burning. Monitoring.

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1 Introduction

The Atlantic Rainforest is considered one of the most important forested biomes of Brazil, located mainly along the east coast (MORELLATO and HADDAD, 2000). Recognized as a biodiversity hotspot (MYERS et al., 2000), it supports a high diversity of ecosystems, including lowland and montane forest, cloud forest, deciduous and semideciduous forest and high-elevation grasslands (BEHLING et al., 2020). Although a net gain in native forest cover has occurred in recent decades in some portions (SAPUCCI et al., 2021), only 13% of its native vegetation cover remains in Brazil (FUNDAÇÃO SOS MATA ATLÂNTICA/INPE, 2018).

Tropical rainforests, like the Atlantic Rainforest have not evolved under fire as an ecological factor, and thus species do not have adaptations that favor their resistance and resilience after fire events (PIVELLO et al., 2021). Human activities are the main sources of fire foci in forests (KRASOVISKII et al., 2018) and, in recent times, the area burned by wildfires in the Atlantic Rainforest has increased (INPE, 2020), disrupting ecological processes, killing individual trees, and threatening species that are not adapted to this disturbance (HARDESTY et al., 2005). In the light of global warming and the predicted increase in extreme climatic events, there is also an expected increase in the frequency of forest fires (COLLINS et al., 2014).

The occurrence and spread of forest fires are strongly associated with weather conditions, i.e., fire regime (frequency, duration, season, intensity) is directly linked to relative humidity, temperature and wind speed (SORIANO et al., 2015). As a fire prevention and management strategy, different burning risk indices were developed using climatic variables (CASAVECCHIA et al., 2019), which show the likelihood of a fire occurrence and whose interpretation of these indices helps to design a prevention plan (SANT'ANNA et al., 2007; WHITE et al., 2015).

The objective of this study was to evaluate the performance of three fire risk indices for a historical time series in Vale do Paraíba Paulista, southeast Atlantic Rainforest, Brazil. We expected that the Southeast Atlantic Rainforest would have an increase in fire risk in recent years and that burning risk would be higher in dry months.

2 Material and Methods

Study Area

This study was carried out in Vale do Paraíba Paulista, São Paulo state, southeast Brazil, in the municipalities of Cachoeira Paulista, Campos do Jordão, São Luiz do Paraitinga and Taubaté (Figure 1).

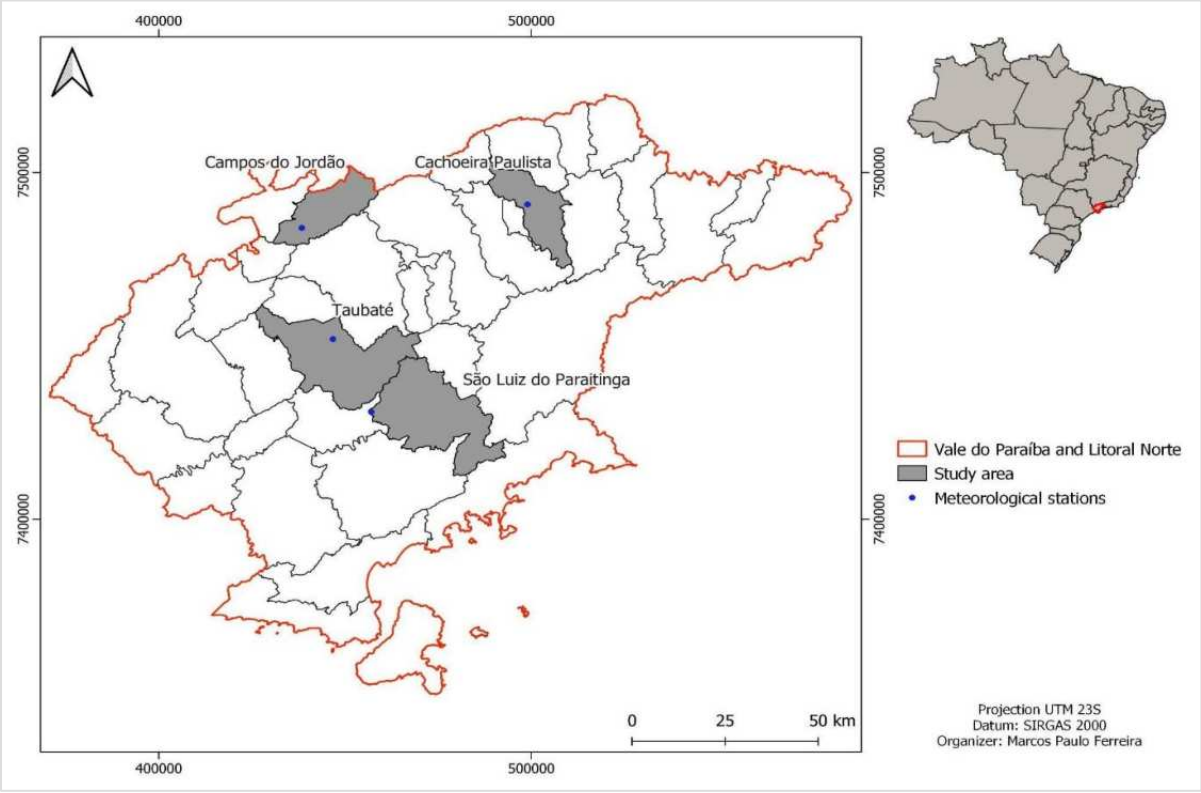

Figure 1. Locations of meteorological stations in the municipalities studied (grey) in Vale do Paraíba Paulista (red), southeast Brazil.

Cachoeira Paulista has an area of 287,990 km², with a predominant humid subtropical climate (CWA), characterized by dry winters and hot summers and montane rainforests (FERREIRA, 2012). Campos do Jordão is located in the Serra da Mantiqueira with a total area of 289,981 km², with cold winters and mild summers, semideciduous forests and high-altitude grasslands (MARO, 2014). São Luiz do Paraitinga covers an area of 617,315 km² with a predominance of montane rainforests and a temperate subtropical climate (CFB), with cold and dry winters and mild summers (TABARELLI and MANTOVANI, 2000). Taubaté comprises an area of 625,003 km² and has a humid subtropical climate (CFA), with humid winters and hot/mild summers (PISANI, 2018).

Vale do Paraíba Paulista, is located in Paraiba do Sul river basin, between São Paulo and Rio de Janeiro, both Brazilian biggest cities, and with a current population estimated at more than 2,5 million inhabitants along the basin (IBGE, 2021). The landscape is dominated by pasture, small fragments of secondary forest and *Eucalyptus* species silviculture (Sapucci et al., 2021).

Historically, sugar cane in the 17h century, coffee in the 19th and urban-industrial expansion along the road-railway axis (1950) gave rise to an anthropogenic landscape (Devide, 2004). Years later, industrial production, especially linked to pulp and paper, and low intensity pasture took over the region. Since then, the region has become a focus of natural regeneration of the Atlantic Forest, having its vegetation cover increased to more than 35% by 2015 (NUMATA et al., 2017; SILVA et al., 2017). In the region, there are several protected areas.

Data Collection

The data used in this analysis was obtained free of charge from two sources, the National Institute of Meteorology and the Queimadas Program database.

The meteorological data (daily precipitation, relative humidity, dry bulb temperature, dewpoint temperature) was extracted from the network of automatic weather stations of the National Institute of Meteorology (INMET, 2022), which collects and provides meteorological information through monitoring, in order to calculate the fire risk through the indices. In Vale do Paraíba Paulista, municipalities that had stations were Cachoeira Paulista, Campos do Jordão, São Luiz do Paraitinga and Taubaté (Table 1).

The calculation of the time series comprises the period from 2010 – 2018 for Campos do Jordão, São Luiz do Paraitinga and Taubaté, and from 20/10/2017 to 20/10/2020 for Cachoeira Paulista, due to the lack of continuous data.

Table 1. Location and start of the operation period of the automatic weather stations in Vale do Paraíba Paulista.

Municipality	INMET code	Latitude	Longitude	Altitude (m)	Start of operations
Cachoeira Paulista	A - 769	22.688889	45.05556	586	10/19/2017
Campos do Jordão	A - 706	22.750278	45.603889	1,662	03/12/2002
São Luiz do Paraitinga	A - 740	23.228333	45.416944	862	10/31/2007
Taubaté	A - 728	23.141667	45.520833	582	12/19/2006

Hotspots were extracted from the Queimadas Program database (INPE, 2019), which is a monitoring system from the National Institute for Space Research that detects its occurrence in Brazil.

This directory uses images from the AVHRR/3 optical sensors on board the NOAA-18 and 19 and METOP-B and C, MODIS aboard NASA TERRA and AQUA and VIIRS from NPP-Suomi and NOAA-20, with two images per day, as well as images from the geostationary satellites GOES-16 and MSG-3 with six images per hour (INPE, 2020). Although all satellites were used, only one record per day was computed in order to avoid data overestimation.

The data was downloaded for all the municipalities and between the same period of meteorological data, being loaded and spatialized in Quantum Gis. 3.16.11 (QGIS Development Team, 2011). Then, it was loaded the urban perimeter through Sistema Ambiental Paulista (DATAGEO, 2022) in order to overlap the hotspot with urban area and exclude the hotspot that might be associated to heat islands, according to Alvares et al. (2014).

The hotspots were used to evaluate the performance of the indices. Following the methodology of Alvares et al. (2014), its monthly and annual frequency distribution was verified and, then, within each risk class for each day of the study period was classified as fire day if at least one heat focus was recorded on that day, and non-fire day, if there was no heat focus. The analysis of days with and without fire was carried out in Quantum Gis 3.16.11 (QGIS Development Team, 2011), by joining fire foci layers with fire risk layers (Angstron, MAF and Telecyn).

The formulas performance was assessed by two methods of comparison, between the index classes and the number of hotspots in each hazard class. The first method was to verify the proportion of fire days and non-fire days for each index by overlapping the occurrence or not of fire foci with its fire risk per day by using Microsoft Excel 2013, in order to assess its occurrence or not. The second one verified, on a monthly scale, the Pearson correlation coefficient between hotspots obtained by the Queimadas Program database and the number of days of each fire risk class in the time series, using Python programming language (version 3.6), through of scripts implemented in Jupyter Notebook (ANACONDA, 2021) (See code on the

link: https://data.mendeley.com/drafts/wbdkr6wcb3). In the Pearson correlation, the coefficient is between 1 and -1, where 1 indicates a positive relationship and -1 a negative relationship.

Fire Indices

Three fire indices were determined and calculated based on meteorological data: Angstron, Monte Alegre Formula and Telecyn. Those indices are widely used for many years and whose calculation is not complex.

The Angstron index (ANGSTRON, 1942) (Equation 1) was developed in Sweden and is a noncumulative index that determines the fire risk based on two variables (relative humidity (%) at 1 p.m.; air temperature (°C) at 1 p.m.). This index determines two risk classes in its classification (Table S1).

$A = 0.05 * RH - 0.1 * (T - 27)$ (equation 1)

where: A= Angstron index, RH = relative humidity (%) at 1 p.m. and T = air temperature (°C) at 1 p.m.

The Monte Alegre formula (MAF) (SOARES, 1972) (equation 2) is a cumulative index developed for the region of Telêmaco Borba, Paraná, Brazil and consists of two variables for its calculation (relative humidity (%); number of days without rain greater than or equal to 13.0 mm).

$MAF = \sum_{i=1}^{n} \left(\frac{100}{hi}\right)$ (equation 2)

where: MAF = Monte Alegre formula, Hi = relative humidity (%) at 13 hours, n = number of days without precipitation higher or equal to 13mm.

The formula has some restrictions according to the daily precipitation, in order to obtain the cumulative values (Table S2) to be translated into a risk scale (Table S3).

The Telecyn index (TELECYN, 1970) (equation 3) was developed in the former Union of Soviet Socialist Republics and includes two variables (air temperature (°C); dew point temperature (°C) at 1 p.m.) calculated cumulatively until a precipitation event, when a new calculation begins. The risk scale of this index is described in table S4.

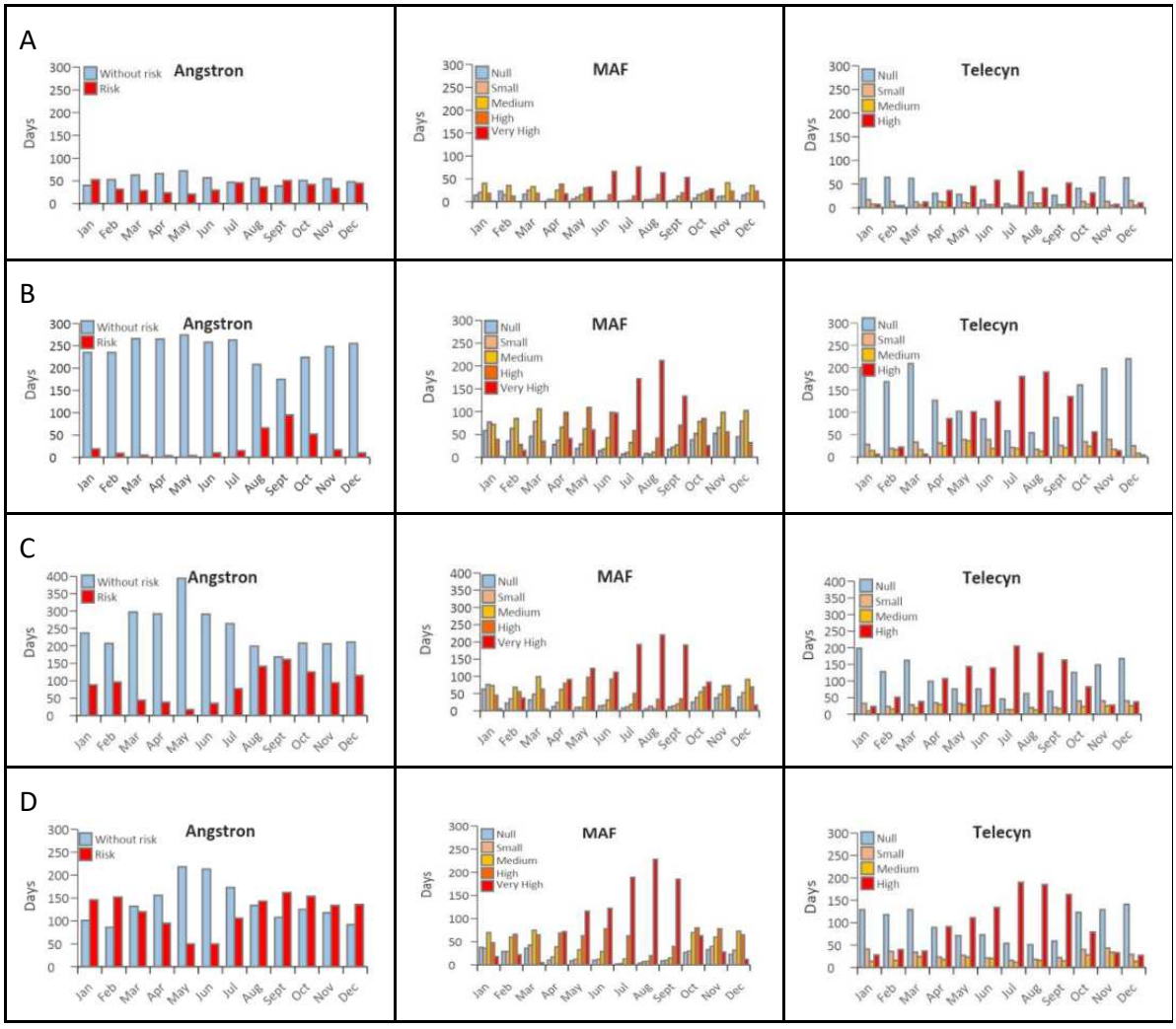

Figure 2. Fire risk days estimated by Angstron, Monte Alegre Formula and Telecyn per month for the period 2017-2020 in Cachoeira Paulista (A) and 2010-2018 for Campos do Jordão (B), São Luiz do Paraitinga (C) and Taubaté (D).

$T = \sum_{i=1}^{n} \log(T - r)$ (equation 3)

where: T = Telecyn index, T = air temperature (°C), r = dew point temperature (°C).

3 Results

The number of days per month in which fire risk was observed varied between the different indices and months between 2010 and 2020 (Figure 2). In general, for all indices and municipalities, the highest fire risk was concentrated between May and September, being reduced between November and April. Angstron indicated more days with no risk, than with risk along the year, except for Taubaté. MAF and Telecyn overlapped in the verification of high fire risk. We found that Campos do Jordão and Taubaté had more days with high and very high fire risk.

When we looked into the distribution throughout the years, we verified a variation between the indices (Figure 3).

In all study areas, Angstron index had more days/year classified as without fire risk than with fire risk. Meanwhile, MAF and Telecyn showed similarities in terms of higher fire risk but differences regarding no risk, with Telecyn having more days/year classified as without fire risk. São Luiz do Paraitinga and Taubaté had more days with high and very high fire risk per year and 2014 peaked with very high fire risk.

From 2010 to 2018, a total of 175, 422 and 716 hotspots were recorded for Campos do Jordão, São Luiz do Paraitinga and Taubaté, respectively, and from 2017 to 2020, 470 hotspots, in the rural area of Cachoeira Paulista (Figure 4).

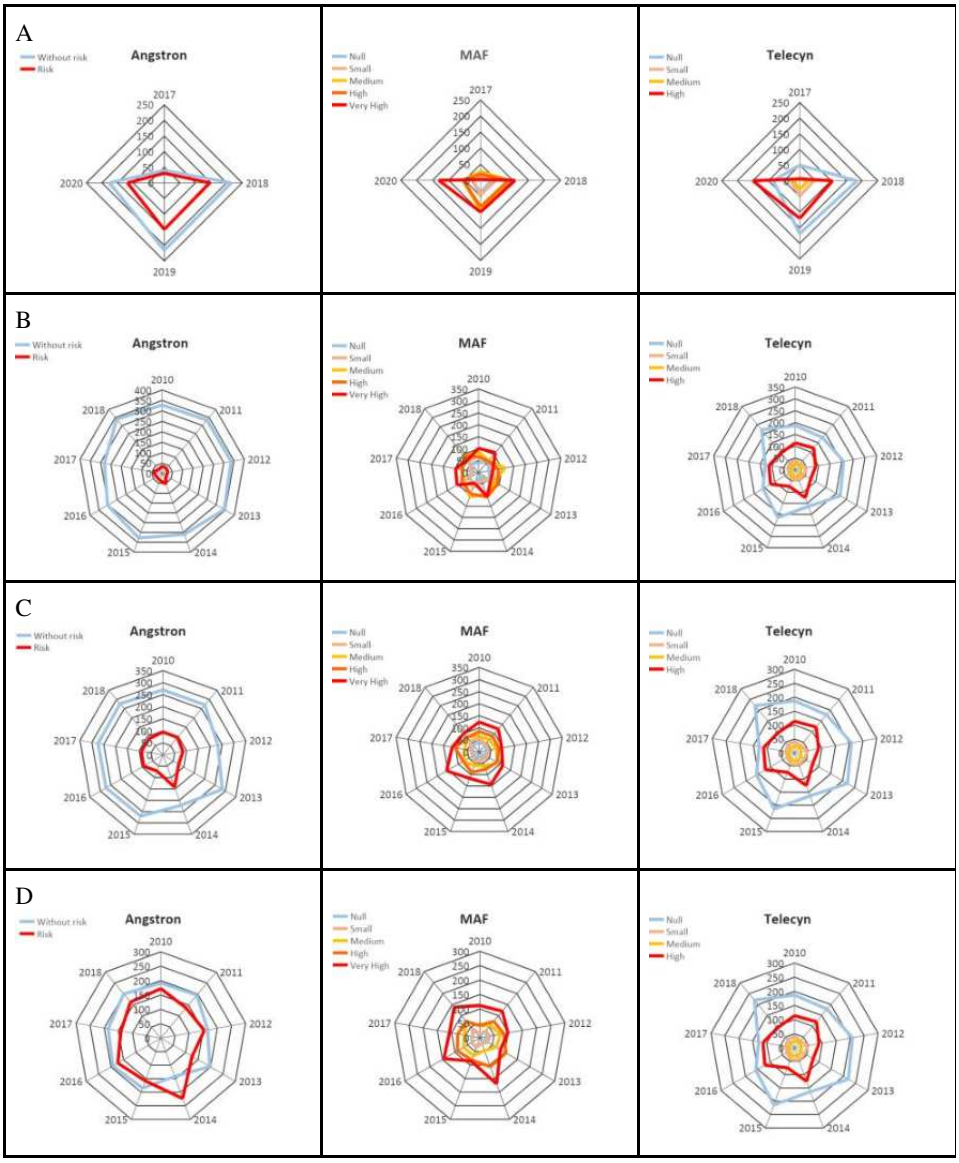

Figure 3. Fire risk days estimated by Angstron, Monte Alegre Formula and Telecyn per year for the period 2017–2020 in Cachoeira Paulista (A) and 2010–2018 for Campos do Jordão (B), São Luiz do Paraitinga (C) and Taubaté (D).

The hotspots distribution was seasonal, with a higher concentration in winter and spring months, with 89% in Campos do Jordão, 81% in São Luiz do Paraitinga and 75% in Taubaté of these hotspots being recorded in August, September and October alone, and 92% in July, August, September and October for Cachoeira Paulista.

Regarding the annual variability, from 2010 to 2018, the highest fire outbreaks concentrations were present in 2012, 2014, 2016 and 2017 in Campos do Jordão and São Luiz do Paraitinga and in 2014, 2016 and 2017 in Taubaté, with a peak in 2014 for these three municipalities. Moreover, from 2017 to 2020, Cachoeira Paulista had a growing trend of fire outbreaks.

Hotspots mostly overlapped with higher fire risk for Angstron, MAF and Telecyn, respectively (Figure S1). The correlation was mainly related to very high and high fire risk in all studied municipalities again for MAF and Telecyn, whereas for Angstron the fire risk correlation was for Campos do Jordão and São Luís do Paraitinga (Table 2).

4 Discussion

We observed that in the four studied municipalities higher fire risk was concentrated between winter and early spring (the drier season).

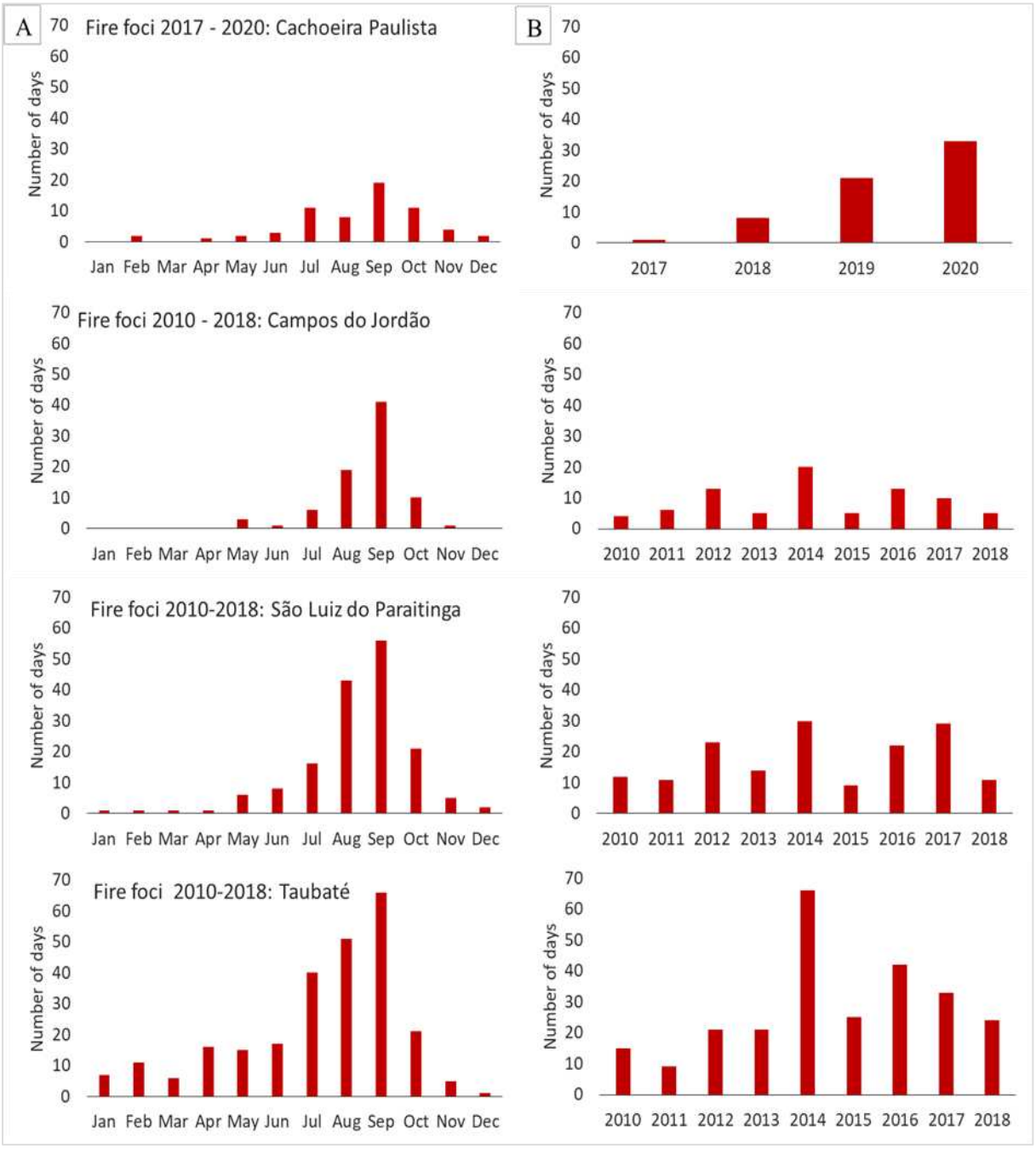

Figure 4. Number of days with hotspots per month (A) and per year (B) recorded in Cachoeira Paulista (2017–2020), Campos do Jordão, São Luiz do Paraitinga and Taubaté (2010–2018) by INPE's Programa Queimadas. Source: INPE (2020).

Table 2. Pearson correlation coefficient between number of days in fire risk classes, on a monthly scale, and number of hotspots (in grey - ρ<0.05) for Angstron, MAF and Telecyn.

	Angstron		MAF					Telecyn			
	No Risk	Risk	Null	Small	Medium	High	Very High	Null	Small	Medium	High
Cachoeira Paulista	-0.10	0.57	-0.17	-	0.13	0.16	0.74	-0.30	0.09	-0.16	0.65
Campos do Jordão	-0.75	0.92	-	-	-0.26	0.17	0.64	0.25	-0.22	0.41	0.68
São Luiz do Paraitinga	-0.27	0.75	0.03	0.56	-0.31	-0.55	0.78	-0.24	0.26	0.01	0.65
Taubaté	0.77	0.41	-	-0.24	0.60	0.15	0.91	-0.20	-0.26	0.02	0.86

Alvares et al. (2014), evaluating Monte Alegre formula for Piracicaba between 1943 and 2012, observed a marked distribution of fire risk classes over the months, with greater frequency between the months of June and September. In addition, Santana et al. (2011) and Santos et al. (2006) stated that the period of occurrence of fires in protected areas in dry forests happened between June and October.

We also verified that a higher fire risk was concentrated in three months in Campos do Jordão, while in other municipalities very high fire risk occurred in six (Cachoeira Paulista and Taubaté) to seven months (São Luiz do Paraitinga). Campos do Jordão is located in Serra da Mantiqueira and it is under cold winters and mild summers, what can make the region less vulnerable to a long fire season; contrary to the valley, that is predominantly under humid subtropical climate (CWA), characterized by dry winters and hot summers.

In recent years, Cachoeira Paulista and Campos do Jordão are having higher fire risk days, while in São Luiz do Paraitinga and Taubaté, very high fire risk was observed in the last six years. The higher fire risk indicated for the years analyzed can be justified by several factors.

In 2010, an abnormal warming of the sea surface temperature was recorded in the Tropical and North Atlantic (MARENGO et al., 2011; BARBOSA et al., 2019; OLIVEIRA-JUNIOR et al., 2020), as well as occurrence of El Niño - Southern Oscillation phenomenon in 2015 and 2016, causing atmospheric instability (MACHADO et al., 2020), such as changing the distribution and frequency of precipitation, which directly impacts fire risk (MIRANDA et al., 2022). Furthermore, human actions must be considered, which contribute to the occurrence of fires, through burning practices without proper planning and knowledge of ecosystem fire regime (RIBEIRO et al., 2011).

We found significant and positive correlations at higher fire risk classes for MAF and Telecyn, respectively, for all municipalities. On the other hand, the fire risk for Angstron was only significant for Campos do Jordão and São Luiz do Paraitinga. Soriano et al. (2015) in a study carried out in the southern Pantanal (Mato Grosso do Sul), found similar results for Angstron, MAF and Telecyn. According to the authors, MAF had the capacity to detect the highest number of fire foci in the high and very high classes (22% and 64%, respectively); Telecyn also had the same tendency (69%), but with a very low probability of occurrence in the small and medium classes and Angstron showed the highest probability of detection on days when there was no fire foci.

As we verified São Luiz do Paraitinga and Taubaté are more threatened by fires, attention should be given to protected areas located on those municipalities (such as Environmental Protection Area (APA) Silveiras, APA Serra da Mantiqueira, APA Bacia do Rio Paraíba do Sul, Area of Relevant Ecological Interest (ARIE) Pedra Branca, National Forest (FLONA) de Lorena, State Park (PE) Serra do Mar – Santa Virginia), due to the longer period of higher fire risk and to fire incidents in the region, especially in buffer zones of those sites. According to Guedes et al. (2020), fire in Vale do Paraíba is less likely to occur where forest cover is higher, however these protected areas are being threatened by fire occurrences in pasture areas around those sites. Furthermore, Jesus et al. (2020), when analyzing fire occurrences in protected areas in Brazil from 2003 to 2017, observed that sustainable use ones (such as APA) were more likely to burn, because private rural land composes those sites, what makes fire prevention and fighting more difficult.

5 Conclusions

This research aimed to apply three fire risk indices for Southeast Atlantic Rainforest (Vale do Paraíba Paulista region), evaluating the period between 2010 and 2020. We expected that the Southeast Atlantic Rainforest would have an increase in fire risk in recent years, which we found for some municipalities, and that burning risk would be higher in dry months, which we showed.

Considering the higher probability in detecting fire risk in higher classes, Angstron was the most adequate to detect fire risk in Campos do Jordão and MAF in São Luiz do Paraitinga, Taubaté and Cachoeira Paulista.

Supplementary material: Table S1, Table S2, Table S3, Table S4, Figure S1. Access on: https://environmentalsmoke.com.br/index.php/EnvSmoke/article/view/223/209

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Author1: Conceptualization (Equal), Project administration (Lead), Data curation (Equal), Formal analysis (Equal), Investigation (Equal), Methodology

(Equal), Visualization (Equal), Writing – original draft (Equal), Writing – review & editing (Equal), CRediT Taxonomy.
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DECLARATION OF INTEREST

The authors disclose that they have no known competing financial interests or personal relationships that could have appeared to influence the study reported in this manuscript.

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