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Forest-fire risk indices and zoning of hazardous areas in Sorocaba, São Paulo state, Brazil

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Abstract Forest-fire risk indices and fire-risk maps are important tools used in protected areas to guide strategies for preventing and fighting fires. This study compares the performance of three fire-risk indices for accuracy in predicting fires in semi-deciduous forest fragments, creates a fire-risk map by integrating historical fire occurrences in a probabilistic density surface using the Kernel density estimator (KDE) in the municipality (county) of Sorocaba, São Paulo state, Brazil. The logarithmic Telicyn index, Monte Alegre formula (MAF) and enhanced Monte Alegre formula (MAF+) were employed using data for the period from 1 January 2005 to 31 December 2016. Meteorological data and numbers of fire occurrences were obtained from the National Institute of Meteorology (INMET) and the Institute for Space Research (INPE), respectively. Two performance measures were calculated: Heidke skill score (SS) and success rate (SR). The MAF+ index proved to be the most accurate for the study area, with values of skill score and success rate of 0.611 and 62.8%, respectively. The fire-risk map revealed two most susceptible areas with high (63 km^2) and very high (47 km^2) risk of fires in the municipality of Sorocaba. Identification of the best risk index and the generation of fire-risk maps can contribute to better planning and cost reduction in preventing and fighting forest fires.

Keywords Monte Alegre formula · risk map · forest protection · monitoring

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1 Introduction

The forest fire regime is an important component in maintaining the function and structure of many terrestrial ecosystems, but it can also be considered a threat responsible for important economic and environmental impacts (e.g. economic losses in the forestry sector, degradation of land cover and changes in atmospheric composition) [13, 26]. If, on the one hand, forest fires can have a positive effect in terms of biodiversity and species richness [21, 29, 57], on the other hand can they impede hydrological processes and interfere both with the dynamic equilibrium of forests and with the carbon cycle [41, 15]. Considering the current scenario for global warming and expected increased frequency of occurrence of extreme events in the light of climate change, there is a tendency for future increase in the frequency of forest-fire outbreaks, mainly as a result of plant demographic processes that can change the growth of tree species and affect carbon sequestration by forests [9].

Monitoring meteorological parameters allows adoption of measures to reduce the potential damage of forest fires [17]. The main sources of ignition are human activities that are closely linked to the means of access to the forest, with increase in fire risk near roads in rural areas [12, 13]. Railways can also be sources of fire ignition, especially in the dry season. Sparks resulting from friction between the wheels of the train and the rails can start fires in dry vegetation, subsequently spreading to adjacent forests [27, 58].

An efficient plan to prevent and fight forest fires requires tools that include mapping areas that are most vulnerable to fire (i.e., fire-risk mapping) and the creation of forest-fire risk indices [30, 55]. A fire-risk map reveals the risk areas and facilitates the logistics for countermeasures by enabling rapid analysis of the situation for decision-making to prevent and combat forest fires [10]. Fire-risk indices show in advance the likelihood of forest-fire occurrence, and the interpretation of these values is linked to prevention plans and pre-suppression of fire [44, 55].

Several methods exist to interpolate historical ignition points and create a continuous wildfire risk map. The Kernel density estimation (KDE) is a nonparametric method that has been broadly used over the last two decades, especially after Koutsias et al. (2004), de la Riva et al. (2004) and Amatulli et al. (2007) explored how this technique is efficient to preserve a more realistic pattern of fire occurrence under broad pixel resolution [1, 22, 39], allowing appropriate forest fire-risk mapping [24].

Identifying areas of greatest fire risk makes it possible to adopt preventive measures in a timely fashion. These include construction of firebreaks, restriction of access to these locations in critical periods, reorganization of management and allocation of resources to strategic points [46, 50].

Fire-prevention plans in Brazil are mainly focused on protected areas. This is because these areas are fundamental to conserving biodiversity and maintaining ecological processes [16].

In addition to evaluating fire-risk indices, new models can be created to increase accuracy for the area under study. New tools can increase the efficiency of the resources allocated to protecting forests [55].

The objectives of the present study were to evaluate the accuracy of three fire-risk indices in semideciduous forest fragments, create a fire-risk map of the landscape in the municipality (county) of Sorocaba and determine the influence of roads and railways on the occurrence of fires.

2 Materials and Methods

2.1 Study site

This study was carried out in the rural portion of the municipality (county) of Sorocaba, São Paulo state, Brazil (47° 31′ 50″ W to 47° 31′ W and 23° 34′ 57″ S to 23° 35′ 25″ S)(Figure 1).

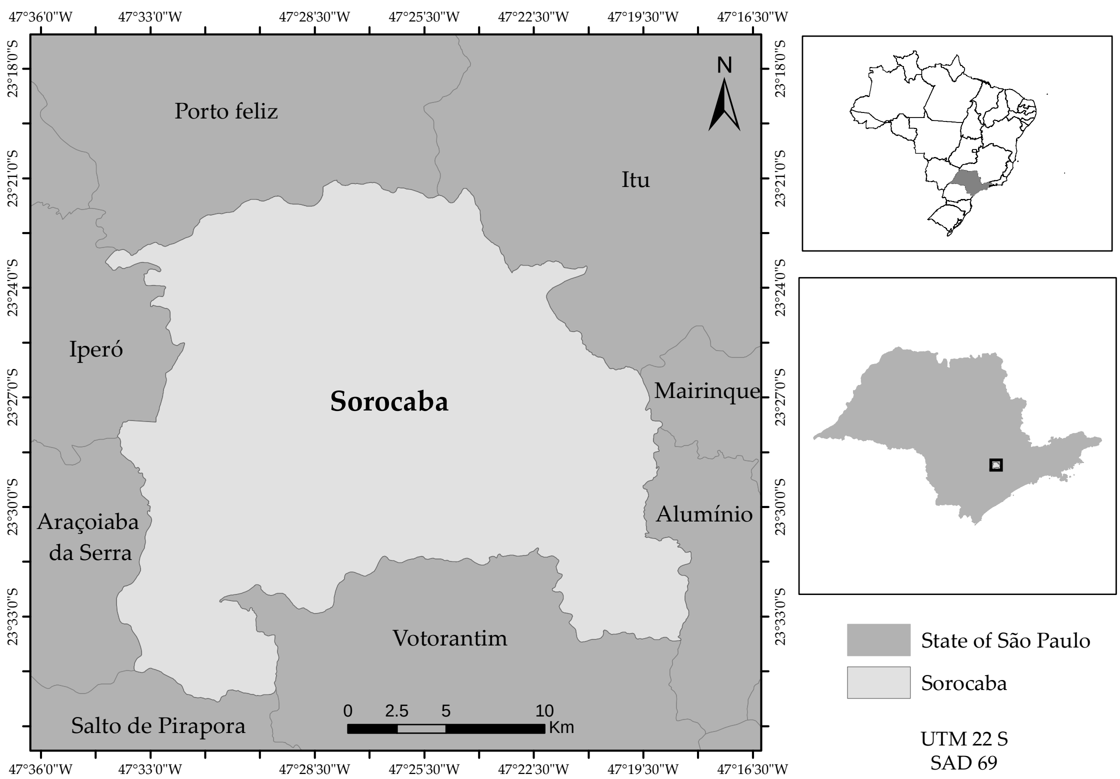

Fig. 1 Location of the municipality (county) of Sorocaba, São Paulo state, Brazil.

Sorocaba has 659,871 inhabitants and is one of the fastest growing cities in Brazil. Data released on July 1, 2017 as an estimate by the Brazilian Institute of Geography and Statistics (IBGE) show that, as compared to the estimate in 2016, the number of people living in Sorocaba increased by 1.13%, much more than the 0.77% growth in the country as a whole. In the last seven years, the city gained 73,246 new residents, and Sorocaba currently holds 13th place among Brazil's most populous municipalities (except for state capitals) [19].

The average elevation is 632 m with a maximum of 1028 m. The soil is classified as red latosol (Oxisol) and vegetation is that of a transition (ecotone) between Cerrado (central Brazilian savanna) and Atlantic forest, the former being very degraded and characterized by small fragments in secondary succession [14]. According to the Köppen classification, the climate is transitional Cwb (rainy and hot temperate with a moderately hot summer) to Cwa (seasonally dry with a warm to hot summer). Mean annual temperature is 22°C, and mean annual precipitation is 1310 mm [20].

2.2 Meteorological data and occurrence of fires

Daily records of average temperature (°C), relative humidity (%), wind speed (ms^{-1}) and precipitation (mm) used for the preparation of risk indices were obtained from the INMET (National Meteorology Institute) database for the period from 1 January 2005 to 31 December 2016 (Appendix A, Figure A1).

The hotspots that indicate fires, with their respective dates of occurrence and locations (latitude and longitude), were obtained from the INPE (National Institute of Space Research) database of MODIS satellite (AQUA_M-T) data with 1-km spatial resolution. Fire outbreaks were detected from the thermal signal composed of the wavelengths in the infrared range (Mid InfraRed-MIR) in a 500-m x 500-m pixel [40].

Occurrences were examined over the same period (1 January 2005 to 31 December 2016). Fire data were deleted in the case of duplicates, and 83 days were disregarded due to absence of weather data. The result was 4300 days of observation and 69 records of forest-fire occurrence in the study area.

2.3 Fire-risk map

As there are no uninhabited regions in the municipality, the risk map developed for the area was based on fire hazard associated with anthropogenic factors. This was done using a continuous density map of occurrences of outbreaks in a historical series of events [30, 31]. Annual outbreaks of fires were mapped based on their respective coordinates using ArcGIS software, UTM Zone 22 S projection and Datum SAD 69 (22s).

The Kernel density estimator (KDE) was used to determine critical areas for fire occurrence. This non-parametric density estimator produces a probabilistic density surface based on local information by superimposing a grid on the data for each observed event [37, 18]. This tool adjusts for inaccuracies in the locatures of hotspots and is appropriate for manipulating spatial data at the scale of a municipality [22, 39].

2.4 Evaluation of the performance of fire-risk indices

The fire-risk indices are related to daily meteorological elements (Figure A2). They are considered to be in cumulative form, providing reliable results for the climatic characteristics of a region [49].

To determine the performance of each index it was necessary to define the limit separating presence and absence of fire risk, for which the rating scales of the indices were categorized in binary form. The indices indicate absence of risk when the calculated value is less than the lower limit of the medium risk class, while the presence of risk is indicated when the values are above this limit [36].

The Monte Alegre formula (MAF) is a cumulative index that uses two climatic variables for which values are easy to obtain, these being the number of days without rain (an indirect measure of precipitation) and the relative humidity at 13:00 h (1:00 pm). This index was developed based on data from the central portion of the state of Paraná [47], which is adjacent to the state of São Paulo where the current study was carried out. Use of MAF for determining the daily risk of forest fires is notable for being relatively easy [48].

$$MAF = \sum_{i=1}^{n} (100/H_i) \quad (1)$$

Where:

MAF	Monte Alegre formula
n	Number of consecutive days with precipitation less than 13 mm
i	Day number in a sequence of rainless days
H	Percentage of relative humidity measured at 13:00 h

The index is subject to modifications in the calculation according to the daily precipitation, which is necessary for obtaining cumulative values (Table B1). Estimates of the degree of danger associated with the calculated value of MAF should be interpreted according to a scale of risk (Table B2).

The enhanced Monte Alegre formula (MAF+) was developed from the inclusion of wind speed (ms^{-1}) as a variable modifying the MAF (Equation 2). As was the case for MAF, this formula was developed for central Paraná [35].

$$MAF+ = \sum_{i=1}^{n} (100/H_i) * e^{0.04*v} \quad (2)$$

Where:

MAF+	Enhanced Monte Alegre formula
n	Number of consecutive days with precipitation less than 13 mm
i	Day number in a sequence of rainless days
H	Percentage of relative humidity measured at 13:00 h
e	Base of natural logarithms (2.718282)
v	Wind speed (ms^{-1})

Since MAF+ is also cumulative in character, this index is subject to modifications in the calculation in accord with daily precipitation (Table B3). As is the case with MAF, the estimate of the degree of danger that is associated with the calculated value of MAF+ must be interpreted according to a scale of risk (Table B4). The variable corresponding to the wind speed (such as that at 13:00 h) is considered to be non-cumulative in the equation.

The logarithmic Telicyn Index (I) was developed in the former Union of Soviet Socialist Republics [51]. The two variables included in this index are air temperature and the dew point at 13:00 h. Like other indices considered in this study, the logarithmic Telicyn Index is also calculated cumulatively up to the moment of each precipitation event, after which a new calculation cycle begins:

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

Where:

I	Telicyn index
T	Air temperature in °C
r	Dew point temperature in °C
log	Logarithm in base 10
n	Number of days without rain
i	Day number in a sequence of rainless days

The degree of danger related to the value calculated using Equation 3 must also be interpreted according to a scale of risk, and this index has only four classes of risk (Table B5). The logarithmic Telicyn index, the Monte Alegre formula (MAF) and the enhanced Monte Alegre formula (MAF+) were employed between 1 January 2005 and 31 December 2016. The predicted values for the occurrence of fires were obtained based on the scales for the three indices, the presence of risk being represented by the "medium," "high" and "very high" risk classes and the absence of risk by the "small" and "null" classes.

Comparison of the efficiency of the models was performed with two test parameters: the Heidke skill score (SS) and the success rate (SR). These parameters are based on a contingency table with observed and predicted values for occurrence of the events [34, 35, 36] (Table 1).

Table 1 Contingency table used to obtain the parameters that allow determination of ability to rate the skill score (SS) and success rate (SR). Adapted from [43].

Fires	**Observed**	**Not observed**	**Total**
Predicted	(a)	(b)	N_2=a+b
Not predicted	(c)	(d)	N_4=c+d
Total	N_1=a+c	N_3=b+d	N=a+b+c+d

Where:

N	Total number of observations (N = a + b + c + d)
a	Days on which occurrence of fires was predicted and they occurred (correct prediction)
b	Days on which occurrence of fires was predicted and they did not occur (incorrect prediction)
c	Days on which non-occurrence of fires was predicted and they occurred (incorrect prediction)
d	Days on which non-occurrence of fires was predicted and they did not occur (correct prediction)

The following parameters were obtained from Table 1:

C	Observed number of correct predictions (hits), where C = a + d
p	Probability of having at least one event per day, where $p = N_1/N$
q	Probability of exceeding the limit value of the index, in which $q = N_2/N$
E	Expected number of hits, where E = N * (1-p) * (1-q) + N * p* q
SS	Skill score, where SS = (C-E)/(N-E)
SR	Success rate, where SR = C/N

3 Results

3.1 Outbreaks of forest fires

Of the 4300 days analyzed, 69 (1.6%) had occurrence of forest fires in the study area. The largest number of forest-fire outbreaks (15) occurred in 2014, while 2008 and 2013 had the fewest outbreaks (1) (Figure 2).

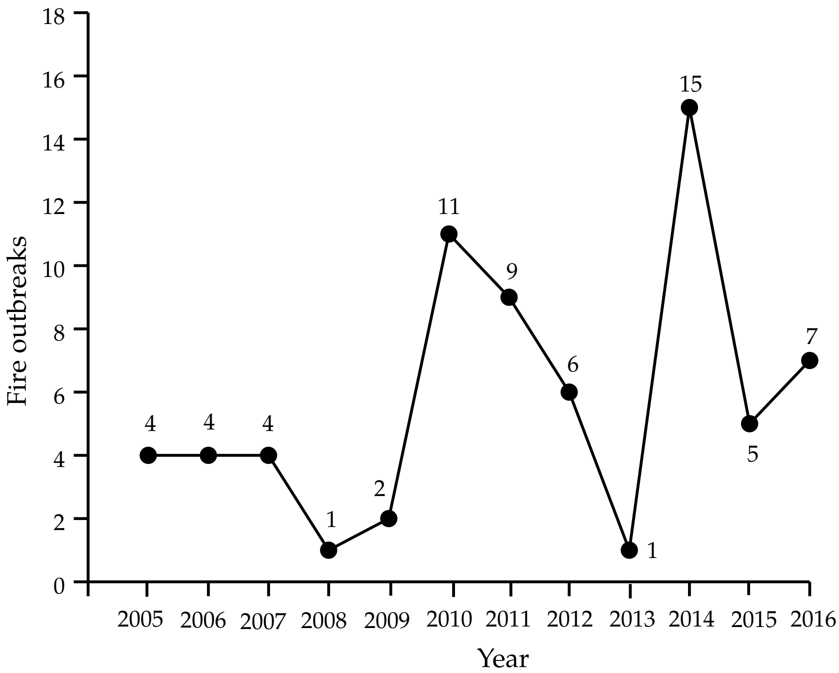

Fig. 2 Yearly distribution of outbreaks of forest fires from 2005 to 2016 in the municipality of Sorocaba, São Paulo state, Brazil.

Considering the monthly analysis of the cumulative total of outbreaks in the study period, August was the month with the highest number (23) of fire occurrences. The three-month period with the largest number of outbreaks was July, August and September (47) (Figure 3).

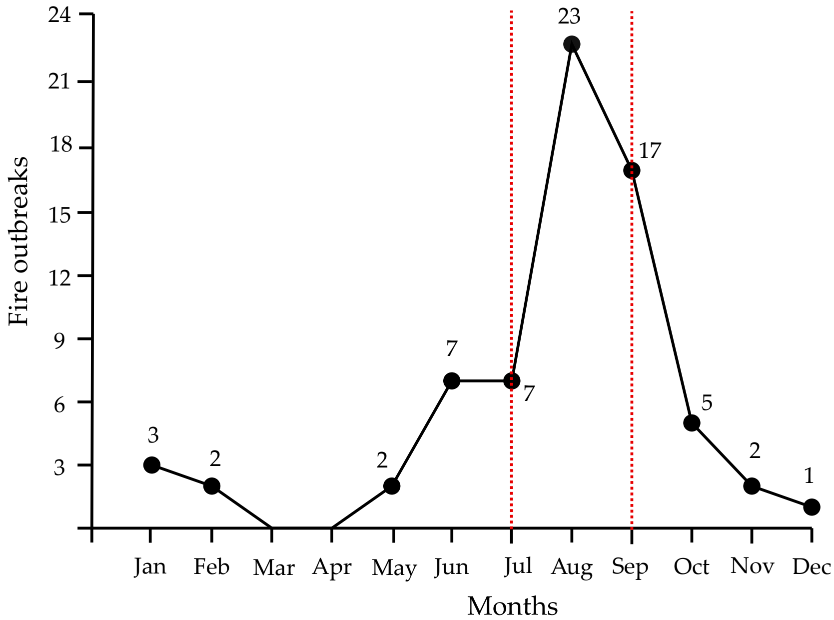

Fig. 3 Monthly distribution of outbreaks of forest fires from 2005 to 2016 in the municipality of Sorocaba, São Paulo state, Brazil. The red dashed lines represent the period with the greatest frequency of fires.

3.2 Performance of fire-risk indices

Performance of the indexes was quantified by the number of days from 2005 to 2016 for which fires were predicted and the number of days when fires were observed. Days in the study period were segregated into different classes in accord with each forest-fire risk index (Table 2).

Table 2 Distribution of days in fire-risk classes for each index from 2005 to 2016. Sorocaba, São Paulo, Brazil.

		Number of days per classes					
	Risk	**Absent**		**Present**			
Index		Null	Small	Medium	High	Very high	Total
MAF	Numbers of days	413	727	1124	1127	909	4300
	Percentage	9,60%	16,90%	26,10%	26,20%	21,10%	
	Total (%)	**26,50%**			**73,50%**		100%
MAF +	Numbers of days	1140	1124	718	585	733	4300
	Percentage	26,50%	26,10%	16,70%	13,60%	17,10%	
	Total (%)	**52,65%**			**47,35%**		100%
Telicyn	Numbers of days	1570	433	341	1956	x	4300
	Percentage	36,50%	10,10%	7,90%	45,50%	x	
	Total (%)	**46,60%**		**53,40%**		x	100%

The MAF showed the greatest numbers (3160 days or 73,50%) in the presence of fire-risk, considering the sum of "medium", "high" and "very high" classes. A tendency for a greater number of days in the classes for absence of risk was found for MAF+ (2264 days or 52.7%) as the sum of the "small" and "null" risk classes (Table 2).

The Telicyn risk index lacks the "very high" risk class and showed an intermediate number of observed days in classes that indicate the presence of risk, with 53.4%, considering the values of the "medium" and "high" risk classes. However, the percentage of days in low-risk classes was 46.6%, showing possible balance between classes (as was also the case for MAF+), probably depending on the climatic characteristics of the region.

Based on integration between the observed fire outbreaks and the adjusted scales of the risk indices, the values observed for fire occurrences were recorded in a contingency table. This was used to calculate skill score (SS) and success rate (SR) (Table 3).

Table 3 Number of days predicted by the indices for forest-fire occurrence and observed outbreaks in satellite data from 2005 to 2016 in the municipality of Sorocaba, São Paulo state, Brazil.

Risk index		Days observed	Days not observed	Total
MAF	Predicted	66	3063	3129
	Not predicted	3	1168	1171
	Total	69	4231	4300
MAF+	Predicted	53	1604	1657
	Not predicted	16	2627	2643
	Total	69	4231	4300
Telicyn	Predicted	64	2209	2273
	Not predicted	5	2022	2027
	Total	69	4231	4300

For calculation of SR, the days with hits or misses were quantified for each index. Hits were either days when occurrence of fire was predicted and one or more outbreaks occurred or days when fire occurrence as not predicted and no outbreak occurred.

The SR result obtained by MAF+ (62.8%) was higher when compared to the other indices, with a SR value of 48.5% for the logarithmic Telicyn index and 28.7% for MAF (Table 4). The SS values (Table 4) mirror the results for SR, with MAF+ achieving the highest value (0.611), followed by Telicyn (0.468) and MAF (0.264).

Table 4 . Skill score (SS) and success rate (SR) values from 2005 to 2016 for fire-risk indices in the municipality of Sorocaba, São Paulo state, Brazil.

Risk index	SS	SR
MAF	0.264	28.70%
MAF+	0.611	62.80%
Telicyn	0.468	48.50%

3.3 Fire-risk map

The risk map drawn from the smoothed density of fire outbreaks in the study period (2005 to 2016) identifies areas favorable for forest fires (Figure 4). The values generated by the algorithms for calculating Kernel density were categorized into five classes for classifying risk levels. Interpretation of risk levels (very low, low, moderate, high and very high) is a key step in delimitating areas that are most vulnerable to fire as part of a prevention plan [13].

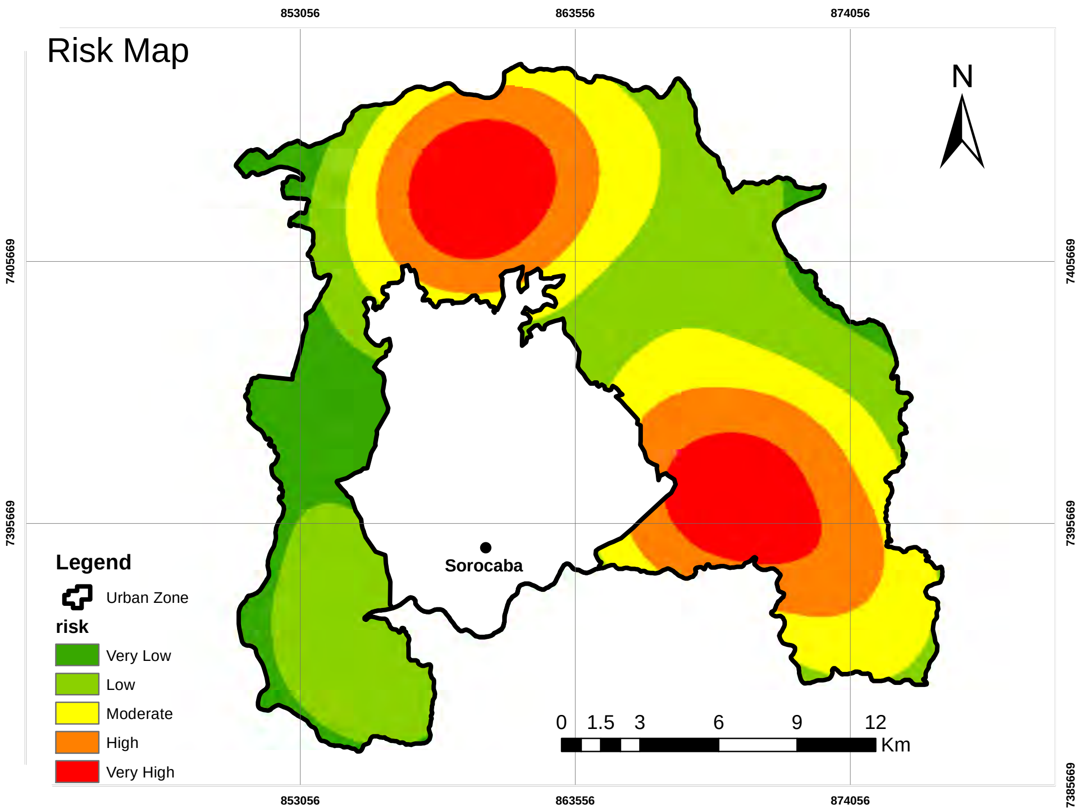

Fig. 4 Fire-risk map for the municipality of Sorocaba, São Paulo state, Brazil.

4 Discussion

Many forest-fire risk indices derived from daily meteorological variables have been created around the world based on the assumption that climate-related variables are the most important in determining fire risk [56]. The most frequently cited fire-risk indices in the literature are the Russian Nesterov Index [32], the Russian Logarithmic Index of Telicyn [51], the U.S. National Fire Danger Rating System [11], the Swedish Angstrom index [7], the Canadian Forest Fire Danger Rating System (CFFDRS) [52] and the Argentine index of Rodriguez and Moretti [42].

In Brazil, FMA [47] is the index that is most used by forestry and environment protection companies [54]. However, some studies have revealed that this is not the most suitable index for certain Brazilian regions, especially the north [45], northeast [54], mid-west [31] and even the southeast region [25], which is close to where the index was created. This is because most of the forest fire hazard indices based on empirical models are suitable only for local application because of the specific vegetation and climate from where they were developed [53].

The SS value obtained for MAF+ in the present study (0.611) was higher than the values found by Nunes [33] for the same index in Paraná for the period from 1998 to 2003 in the municipalities of Cambará, Telêmaco Borba, Guarapuava, Pinhais, Campo Mourão, Cascavel and Londrina (0.088, 0.117, 0.133, 0.283, 0.302, 0.334 and 0.338, respectively). The SR values we found for MAF (28.7%) and Telicyn (48.5%) in Sorocaba were below that for Guarapuava, which had the smallest value (49.3%) of the 13 municipalities evaluated by Nunes [33] in the state of Paraná.

Much of the rural area of Sorocaba is under eucalyptus plantations, and the area of these plantations rose from 233,406 ha in 2002 [23] to 323,478 ha in 2008 [5], an increase of 38.6% over this relatively short period. These areas have high risk of fires because, in addition to the availability of wood, a blanket of combustible material is offered by a continuous deposition of leaves and twigs on the soil surface [4]. Generally, the boundaries between zones of high and low risk of fires are consistent with the limits between continuous and fragmented forest [38].

Compared to the other indices, MAF+ showed the best performance in tests of SS and SR, as has also been reported for the period from 2003 to 2006 in predicting outbreaks of fire in areas with eucalyptus cultivation in the northern portion of the state of Espírito Santo, Brazil, with values of 0.18 for SR and 53.5%, for SS [4].

MAF+ includes wind speed as a variable, which differs from the original formula (MAF). With inclusion of this variable, MAF+ reflects, in addition to the probability of ignition, the potential for fires to spread [35].

The forest-fire risk map revealed two areas with the highest occurrences of outbreaks, the northwest and southeast portions of the study area. Of the entire area of the municipality of Sorocaba (343.1 km^2), 13.7% was classified as "very high risk" (47 km^2) and 18.5% was classified as "high risk" (63 km^2).

The northwestern portion of the municipality has eucalyptus plantations and lies next to the Ipanema National Forest; the northwest portion of the municipality also has a large number of roads. The high productivity of commercial plantations in these areas leads to a high concentration of biomass, which raises the risk of forest fires [6].

In the southeastern portion of the municipality, the large number of outbreaks recorded can be linked, in part, to the stretch of railway in association with a green area. Presence of the railway may therefore facilitate ignition and increase the risk of fires in adjacent vegetation in association with wind patterns [8].

The spatial statistical analysis of weights of evidence is able to capture the effect of distances of roads and railroads on fire outbreaks. It is a probabilistic method based on a Bayesian approach in log-linear form and is applicable when sufficient data are available to estimate the relative influence of different scenarios for the factors considered in the analysis [3]. However, the low spatial resolution of MODIS does not allow discussion of distances of less than 1 km, making this analysis unfeasible for this data set.

One suggestion for future studies aiming to use this analysis is to obtain the hotspots that indicate fire through the LANDSAT 8 thermal band. The spatial resolution of this reference satellite is 30 m (i.e., with much more spatial detail than MODIS), but the temporal resolution is 16 days, leading to the omission of many fire outbreaks.

The scenario for fire in a given location is linked to the socio-economic, political and environmental context of the region. There is a strong connection between the fire regime and territorial dynamics at different temporal scales [28]. Recent studies also point to the existence of a relationship between the type of vegetation and the frequency and intensity of forest fires in any given location [2].

Because fire-prevention planning requires monitoring of where and when a fire is likely to occur [24], the forest-fire risk map and fire-risk indices are two objective tools that should be used together for efficient pre-fire planning. While the fire-risk map helps managers in planning fire prevention strategies for showing the most fire-susceptible areas (based on historical fire occurrences), the indices indicate which days are most likely to the occurrence of forest fires (based on daily meteorological factors). Determining the best index for application in municipalities that do not have an index specific to their location is fundamental for planning forest-fire prevention.

MAF+ had the best result among the indices examined in this study. However, Brazil is a country with a wide diversity of climates, which is reflected in the different results of the various indices of forest-fire risk in different regions of the country.

5 Conclusions

Depending on climatic patterns in the region under study, one risk index may be more suitable than another for the prediction of fire events. The MAF+ index had the best performance in the municipality of Sorocaba, with a skill score (SS) value of 0.611 and a success rate (SR) of 62.3%. This indicates that wind speed is an important variable and should be considered for determining the degree of fire hazard in this region.

By developing a risk map, it was possible to identify the areas that are favorable for occurrence of forest fires. These areas are mainly in the northwestern and southeastern portions of the municipality. The risk of forest fires in Sorocaba is associated with local climatic conditions, with the network of roads and with the railway that crosses the municipality.

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A Appendix

A.1

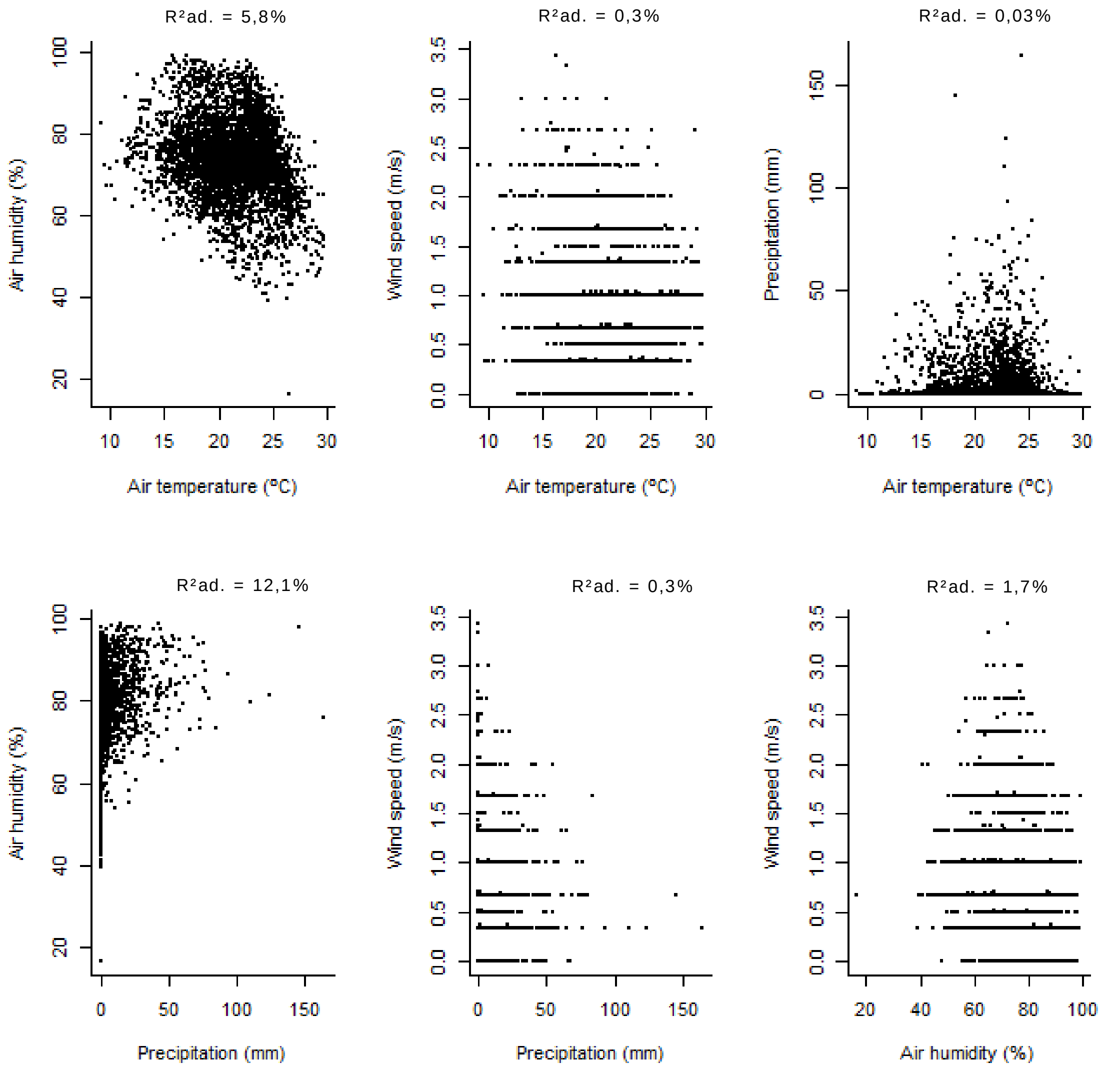

Fig. 5 Relationships between environmental variables, where R^2ad. is the adjusted R-squared. Data are from Brazil's National Institute of Meteorology (INMET).

548 A.2

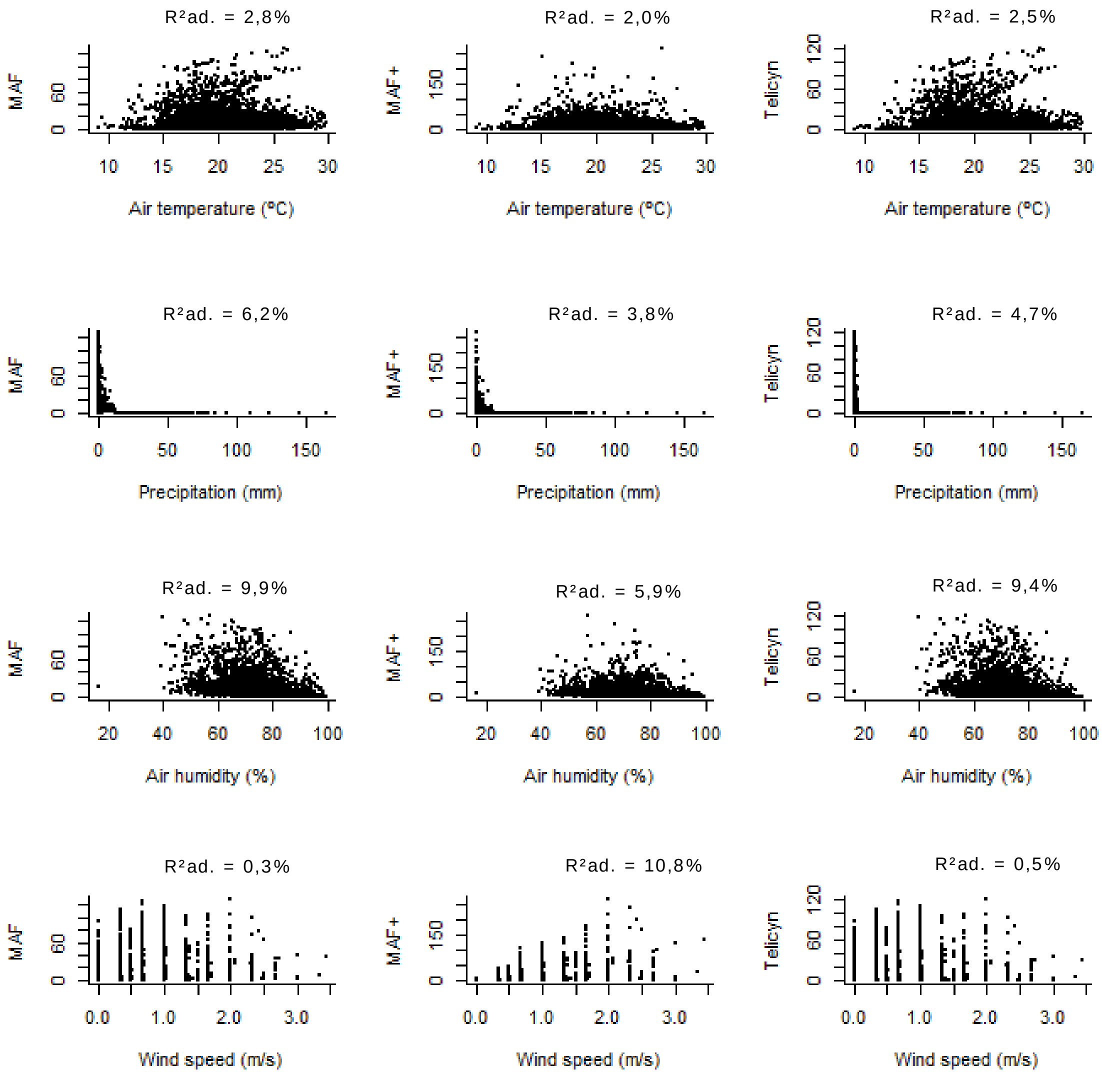

Fig. 6 Relationships between environmental variables and fire indices, where R^2ad. is the adjusted R-squared.

B Appendix

B.1

Table 5 Modification of calculation of the MAF on the basis of daily precipitation.

Daily precipitation (mm)	Change in calculation
≤ 2.4	None
2.5 to 4.9	30% reduction in the MAF calculated for the previous day and sum of (100/H) for the day
5.0 to 9.9	60% reduction of the MAF calculated for the previous day and sum of (100/H) for the day
10.0 to 12.9	80% reduction of the MAF calculated for the previous and sum of (100/H) for the day
> 12.9	Calculation interrupted (MAF = 0) and summing resumed the following day

B.2

Table 6 Scale of risk classes associated with the calculated values of MAF.

Calculated value of MAF	Forest-fire risk
≤ 1.0	Null
1.1 to 3.0	Small
3.1 to 8.0	Medium
8.1 to 20.0	High
> 20.0	Very high

B.3

Table 7 Modification of calculation of MAF+ as a function of daily precipitation.

Daily precipitation (mm)	Change in calculation
≤ 2.4	None
2.5 to 4.9	30% reduction in the MAF calculated for the previous day and sum of (100/H) for the day
5.0 to 9.9	60% reduction of the MAF calculated for the previous day and sum of (100/H) for the day
10.0 to 12.9	80% reduction of the MAF calculated for the previous and sum of (100/H) for the day
> 12.9	Calculation interrupted (MAF = 0) and summing resumed the following day

B.4

Table 8 Scale of risk classes associated with the calculated values of MAF+.

Calculated value of MAF	**Forest-fire risk**
≤ 3.0	Null
3.1 to 8.0	Small
8.1 to 14.0	Medium
14.1 tho 24.0	High
> 24.0	Very high

B.5

Table 9 Scale of risk classes associated with the calculated values of Telicyn.

Calculated value of Telicyn	**Forest-fire risk**
≤ 2.0	Null
2.1 to 3.5	Small
3.6 to 5.0	Medium
> 5.0	High