Floresta e Ambiente 2019; 26(2): e20170304
https://doi.org/10.1590/2179-8087.030417
ISSN 2179-8087 (online)

Original Article

Conservation of Nature

Forest Fire Hazard in the Serra do Brigadeiro State Park (MG)

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ABSTRACT

The objective of this study was to analyze the effectiveness of forest fire hazard indices for the Serra do Brigadeiro State Park region (MG). Although no weather station is present in this territory, the use of data obtained in the municipality of Viçosa (38 km distance) was effective to calculate the hazard. According to the results, the use of high and very high hazard classes to predict occurrences proved to be more efficient. The Telicyn, Nesterov, FMA and FMA+ indices showed better results when daily mean data was used while FWI responded better with daily maximum temperature and relative humidity at 3:00 p.m. The P-EVAP and FWI indices were the most efficient to predict fires in the study region.

Keywords: fire, PESB, prediction.

1. INTRODUCTION

The characteristics of forest fires are affected by the complex interactions between vegetation, climate, topography and anthropogenic activities over time. At a regional level, the climate was determinant, affecting the moisture content of the fuel, as well as the amount of biomass, which is the main controller of the principal fire characteristics, in addition to the type of vegetation found (Chang et al., 2015).

Therefore, because of its ability to provide quantitative estimates of the possibility of forest fire occurrence, the hazard indices, based on meteorological data, have become important tools to evaluate the potential risk of regional fires over time (Holsten et al., 2013).

For Wastl et al. (2012), most studies assess temporal trends and potential meteorological hazard occurrences by calculating different hazard indices for forest fires from historical meteorological observations or outputs of numerical climate models. For the authors, the number of indices is significant, as is the variety of results, which justifies studies that determine the most suitable indices for each region.

On the other hand, according to Viegas et al. (2004), the application of a method to a particular region would lack prior calibration, without taking into account the specific properties of the climate, the fire regime and the prevention and combat structure of that region. However, despite the vast literature on the use of fire hazard indices, (Bedia et al., 2015; Borges et al., 2011; Holsten et al., 2013; Nunes et al., 2006, 2007, 2010; Padilla & Veja-Garcia, 2011; Rodríguez et al., 2012; Sampaio, 1991, 1999; Torres & Ribeiro, 2008; Viegas et al., 1999, 2004; Wastl et al., 2012; Zumbrunnen et al., 2011), there are few studies that investigate the adequacy of these indices given the conditions of their place of application.

For Pezzatti et al. (2013), all regions, even the smallest, present their own specific fire behavior conditions. Therefore, there is a need to study local fire data to better understand occurrences, leading to more effective damage reduction measures.

Given this, the objective of this study was to analyze the effectiveness of the Fire Weather Index (FWI), logarithmic Telicyn index, the Nesterov index, accumulated levels of precipitation minus evaporation (P-EVAP) and precipitation evaporation (EVAP/P), Monte Alegre formula (FMA) and altered Monte Alegre formula (FMA+), for the prediction of forest fires in the region of the Serra de Brigadeiro State Park (MG) and to assess which meteorological data is most appropriate to calculate these indices in the region.

2. MATERIALS AND METHODS

Serra do Brigadeiro State Park (PESB) is located in the Zona da Mata mineira. It covers part of the territory of the municipalities of Araponga, Fervedouro, Miradouro, Ervália, Sericita, Pedra Bonita, Muriaé and Divino. It has an area of 14,984 hectares, between the Meridian 42°20' and 42°40' W, and the parallels 20°20' and 21°00' S. Located in the Serra da Mantiqueira, its altitude ranges from 1,000 to 2,000 meters, with deep valleys and small plateaus that exert a significant influence on the climatic characteristics of the park. Its rainy period occurs between November and March, and its hottest, driest period is from April to September, with the quarter between June and August being the coldest (Paula et al., 2015). For this study, in addition to the park area, a buffer that extends one kilometer (15,134 hectares) from the limits of the UC was also included, totaling 30,118 hectares.

Thirty-four occurrences of fire were recorded, covering 67 days between 2007 and 2014. The records were acquired from the database of the Center for Forestry Studies and Development of the State Institute of Forests (CEDEF/IEF – MG), having as their source the field surveys for the records of occurrences of fires (ROIs) of PESB. Additionally, 30 days with fire outbreaks were identified using the detection system of the National Institute of Spatial Research/weather Forecasting Center and Climate Studies (INPE, 2015), totaling 97 days with records of occurrences (by ROI or by satellite) within the studied period.

The choice of the study area was based firstly on it being a Conservation Unit (UC), with the occurrences of forest fires being one of the ongoing threats to its aims; secondly, due to the area having, according to the classification adopted by the Canadian Forest Service (Ramsey & Higgins, 1981), most of its events (79.41%) in the classes III (between 4.1 and 40 ha) and IV (between 40.1 and 200 ha), which contradicts the results found by Santos et al. (2006). In studies of fires in protected areas throughout the national

territory, they observed most of the occurrences within class I (< 0.1 ha) by lowering the percentage linearly according to the size classes. Thirdly, it was chosen because, as with the national UCs, the PESB does not have a meteorological station within its territory. Therefore, we sought to analyze the efficiency of the use of meteorological data originated from stations near to the UCs to predict fire occurrences.

As such, to calculate the indices, the meteorological elements were measured at a station located on the campus of the Federal University of Viçosa (38 km from the park). The adequacy of the data for the study site was evaluated by the correlation between meteorological variables and the monthly fire occurrences.

Seven fire hazard levels were analyzed: Logarithmic index of Telicyn; Cumulative indices of Precipitation – Evaporation (P-EVAP); the division of evaporation by precipitation (EVAP/P); Nesterov index; Monte Alegre formula (FMA); altered Monte Alegre formula (FMA+); and the Canadian Fire Weather Index (FWI) (Van Wagner, 1987; Sampaio, 1999; Nunes et al., 2007). The choice of the indices used was due to their frequency in the literature and the ease of acquisition of the data and the necessary calculations.

2.1. Logarithmic index of Telicyn

Basic equation (Equation 1):

$$I = \sum_{i=1}^{n} \log(ti - ri) \quad (1)$$

being: I = index of Telicyn; t = air temperature in °C; r = dew point temperature in °C; log = logarithm in base 10.

The occurrence of precipitation equal to or greater than 2.5 mm, abandons the sum and resumes the calculation the next day, or when the rain ceases. On rainy days, the index is equal to zero (Table 1).

2.2. EVAP/P

The EVAP/P index is also cumulative and relates the division of evaporation by precipitation, with both measurements taken daily in mm. For its calculation, the restrictions of Table 1 were used.

2.3. P-EVAP

The cumulative index P-EVAP relates the difference between precipitation (p) and evaporation (EVAP), with both measurements being taken daily in mm, precipitation also presents some restrictions (Table 1).

2.4. Nesterov index

Basic equation (Equation 2):

$$G = \sum_{i=1}^{n} di \times ti \quad (2)$$

being: G = Nesterov index; d = air saturation deficit in millibars; t = air temperature in °C.

Table 1. Restrictions of the indexes according to the rain.

Index	Rain (mm)	Change in calculation
Telicyn	>2.5	Abandon the sum and start calculating the next day, or when the rains cease. On the day(s) of rain the index is equal to zero.
EVAP/P	< 1	Does not enter in the calculation.
	1 to 15	Divide the EVAP/P before the rain of the day.
	>15	When interrupting the calculation, start over the next day or when the rains cease. On the day of rain EVAP/P = 0.
Nesterov and P-EVAP	≤2.0	None.
	2.1 to 5.0	Shoot down 25% on the value of G calculated on the eve and Add (d.t) of the day.
	5.1 to 8.0	Shoot down 50% in value of G calculated on the eve and add (d.t) of the day.
	8.1 to 10.0	Leave the previous sum and start new calculation, i.e. G = (d.t) of the day.
	>10.0	Stop the calculation (G = 0), resuming the sum the next day or when the rains cease.
FMA and FMA$^+$	≤2.4	None.
	2.5 to 4.9	Shoot down 30% on FMA calculated on the eve and sum (100/H) of the day.
	5.0 to 9.9	Shoot down 60% on FMA calculated on the eve and add (100/H) of the day.
	10.0 to 12.9	Shoot down 80% on FMA calculated on the eve and add (100/H) of the day.
	>12.9	Stop the calculation (FMA = 0), resuming the sum the next day or when the rains cease.

Source: Torres & Ribeiro (2008).

The air saturation deficit, in turn, is equal to the difference between the maximum water vapor pressure and the actual water vapor pressure, and can be calculated by the following expression (Equation 3):

$$d = E \times (\frac{1 - H}{100}) \quad (3)$$

being: d = air saturation deficit in millibars; E = maximum water vapor pressure in millibars; H = relative humidity in %.

In the Nesterov index, the continuity of the sum is limited by the occurrence of precipitations according to the Table 1.

2.5. Monte Alegre Formula

Basic equation (Equation 4):

$$FMA = \sum_{i=1}^{n} (\frac{100}{Hi}) \quad (4)$$

being: FMA = Monte Alegre Formula; H = relative humidity (%); n = number of days without rain.

The Index describes restrictions on precipitation, as shown in Table 1.

2.6. Altered Monte Alegre formula

Basic equation (Equation 5):

$$FMA^{+} = \sum_{i=1}^{n} (\frac{100}{Hi}) \times e^{0,04v} \quad (5)$$

being: FMA^{+} = Altered Monte Alegre formula; H = relative humidity (%); n = number of days without rain; v = wind speed in m/s; e = base of natural logarithms (2,718282).

Being cumulative, this index is also subject to the precipitation restrictions, as shown in Table 1.

2.7. Fire Weather Index

The FWI index of the Canadian Forest Fire Danger Rating System (CFFDRS) presents 6 components: In the first level the FFMC – index of moisture content of fine fuels; DMC –moisture content of the organic layer; and DC – dry index, representative of the water deficit in the soil. All this is calculated from meteorological data (temperature in °C) and relative air humidity (%), and wind speed at a height of 10 m (m/s).

At an intermediate level, there are two indices related to aspects of fire behavior and propagation: ISI – Initial propagation index that incorporates the moisture content of the fine fuels and wind speed values to obtain a measurement of the fire spread speed over flat terrain, as would occur at the initial stage of a fire; and BUI – which integrates the two sub-indices DMC and DC to obtain an estimate of the proportion of available vegetation (medium and coarse particles) that will effectively participate in the fire propagation.

The final result of the system is a conjugation of the two groups, indicated by the hazard index (FWI), which constitutes the output data that most directly relates to the possibility of the fires occurrence and the respective danger (Viegas et al., 2004).

The 6 components of the FWI were calculated sequentially using a set of tables (Van Wagner, 1987). This study used the free software FWI CALCULATOR v.10.2.1.

The indices were compared using the method known as Skill Score (SS), which is based on a contingency table (Table 2) containing the observed values and the predicted values for an event in a population. The SSit is the reason for the difference between the corrections in the forecast (G) and the expected number of hits (H), and the difference between the number of days observed (N) and the number of days with prediction of hits (Torres & Ribeiro, 2008; Nunes et al., 2010).

In order to determine the performance of each index, it was necessary to define the limit that would break the predictions of occurrences or non-occurrences of fires. Two situations were considered: in the first (T1), the indices indicated a prediction of occurrences when they presented medium, high and very high danger degrees; in the second (T2), the indices indicated danger of occurrence when they showed high and very high hazard levels (Table 3). Another analysis was related to the time of use of the meteorological data (wind speed, temperature and relative humidity of the air) of the FMA indices, FMA+, FWI, Telicyn and Nesterov, the measured values were used at 1:00 p.m. and 3:00 p.m., with average data and daily maximum values.

Table 2. Contingency table and calculation of the Skill Score.

Predicted	Observed		Total predicted
	Fires	No fires	
Fires	a	b	N2 = a + b
No fires	c	d	N4 = c + d
Total observed	N1 = a + c	N3 = b + d	N = a + b + c + d
Calculations of the contingency table			
Predicted	**Observed**		**Total predicted**
	Fires	**No fires**	
Fires	a / (a + c)	b / (b + d)	
No fires	c / (a + c)	d / (b + d)	

The variables for the realization of the calculations are:
G – Number of hits in the forecast. G = a + d;
p – Likely to have at least one event per day. p = N1 / N;
q – Likely to exceed the limit value of the index. q = N2 / N;
H – Expected number of hits. H = N * (1 – p) * (1 – q) + N * p * q;
SS – *Skill Score*. SS = (G – H) / (N – H);
PS – Percentage of success. PS = G / N.

Source: Borges et al. (2011); Nunes et al. (2006, 2007, 2010); Rodríguez et al. (2012); Torres & Ribeiro (2008).

Table 3. Fire hazard class according to the value obtained for each index.

Index	Null	Low	Average	High	Very high
Telicyn	< 2	2.1 to 3.5	3.6 to 5	5 to 15	> 15
EVAP/P	< 5	5 to 20	20.1 to 50	50.1 to 100	> 100
P-EVAP	> - 5	-5 to -30	-30.1 to -55	-55.1 to -125	<-125
Nesterov	≤ 300	301 to 500	501 to 1000	1001 to 4000	> 4000
FWI	0 to 1.9	2 to 4.9	5 to 8.9	9 to 16.9	> 17
FMA$^+$	≤ 3	3.1 to 8	8.1 to 14	14.1 to 24	> 24
FMA	≤ 1	1.1 to 3	3.1 to 8	8.1 to 20	> 20

Source: Van Wagner (1987); Torres & Ribeiro (2008); Nunes et al. (2010).

3. RESULTS AND DISCUSSION

Despite the distance between the meteorological station and the study area (38 km), according to Table 4, the data showed a strong correlation between the number of occurrences and the burnt area and relative air humidity and evaporation and a moderate correlation between the burnt area and wind speed.

The low correlation between the number of occurrences and wind speed, and precipitation and temperature has already been reported in the literature. According to Torres et al. (2011), in terms of wind speed, this can be explained by the period of higher vertical and horizontal movement of air that is prevalent during summer, the season with the least number of fires. On the other hand, winter, characterized by lower wind speeds, presents a greater concentration of occurrences. The same happens with the lowest temperature coefficient, the seasonal variation of the same tends to mask their relationship with this phenomenon. Jacobi (2007) has also observed this situation, finding a low correlation between the number of occurrences and temperature and wind speed. Regarding precipitation, Santana et al. (2011) obtained field observations which showed that periods of increased fire did not begin as soon as the rainy period ended, since the soil and the combustible material, especially ground cover, remained damp for some time. Likewise, the beginning of the rainy season once again did not correspond to immediate reduction in the occurrence of fires, since soil and combustible material with low moisture content must absorb moisture to the point where it no longer ignites, which can take some time. Corroborating this, Sampaio (1999) reports that the period of greatest occurrence of fires begins two months after the beginning of the dry period and ends two months after the end of that same period.

Table 4. Pearson correlation coefficient (r) between monthly average meteorological elements and occurrences of monthly fires in the ESPB and environment between 2007 and 2015.

Month	Wind	Evaporation (mm)	Rain (mm)	T (°C)	UR (%)	(%) fires*	(%) Burned area*
Jan	1.21	72.26	232.05	22.69	79.28	5.88	0.90
Feb	1.41	79.04	90.18	22.99	76.67	5.88	2.25
Mar	0.81	66.83	190.26	22.33	82.03	0.00	0.00
Apr	0.85	57.76	65.84	20.74	82.70	0.00	0.00
May	0.88	58.15	32.60	17.88	82.44	0.00	0.00
Jun	0.88	53.35	16.04	16.71	83.00	0.00	0.00
Jul	0.92	67.46	6.84	16.56	80.04	0.00	0.00
Aug	1.02	90.74	5.74	17.63	73.06	41.18	11.68
Sep	1.48	107.33	47.41	19.51	68.13	32.35	71.45
Oct	1.40	99.91	92.36	21.10	72.68	8.82	12.97
Nov	1.37	74.06	209.04	21.47	78.47	5.88	0.75
Dec	1.23	71.98	322.95	22.62	80.38	0.00	0.00
r nº	0.35	0.75	-0.33	-0.22	-0.82	-	-
r area	0.51	0.75	-0.24	-0.10	-0.81	-	-

*We used only data from the ROIs.

Analyzing time of meteorological data use, the logarithmic index of Telicyn, Nesterov, FMA and FMA+ indices presented better results when using the average daily data, while the FWI responded better with the maximum daily temperature and relative humidity at 3:00 p.m. The results are different from other studies that use the data taken at 1:00 p.m. (Nunes et al., 2006, 2007, 2010; Viegas et al., 2004) and 3:00 p.m. (Torres & Ribeiro, 2008) as the most efficient, which highlights the differences arising from the climatic characteristics of each region. Thus, this was the data used to determine the most appropriate index for the study region (Tables 5 and 6).

According to Nunes et al. (2010), the number of days predicted by each danger class should have an inverse relationship with the danger class, such that the higher the danger class, the lower the number of days predicted by it. The only index that meets this condition is EVAP/P, all the other indices point to an imbalance between classes (Table 5).

Another desirable condition, according to Nunes et al. (2010), is that the number of occurrences increases depending on the danger class, with only the Telicyn and Nesterov indices not meeting this condition. In this item highlighted for the FWI, 97.48% of the occurrences were observed when the index indicated high or very high danger and only 1.26% of the occurrences when it indicated null or low danger.

In the literature, there is great variability in relation to these results. In Espírito Santo state, Borges et al. (2011) observed that the FMA index concentrates a percentage of 31.90% of the days in the high danger class and 24.72% in the very high class. In the same study, the FMA+ and Nesterov indices also showed a higher percentage of days in the higher danger classes.

In Paraná state, Nunes et al. (2010) observed that the FMA presented a higher percentage of days in the high, average and low classes in the low and null classes, while the FMA+ presented a higher percentage in the null class, decreasing to the smallest percentage at very high classes.

Rodríguez et al. (2012), in Cuba, observed that the distribution of the number of days predicted for each danger class, analyzing the Nesterov, FMA and FMA+ indices, presented an increasing tendency, from the null class to very high, not being ideal for the behavior of this variable. To improve the performance of the indices, the authors adjusted the descriptive classes.

Analyzing the number of days when fires were recorded in the north of Espírito Santo state, Borges et al. (2011) found 37.29% of FMA in the high danger class and 43.96% in the very high danger class, totaling 81.25%. They also observed a greater number of days with recorded fires in the high and very high danger classes for FMA+, obtaining average values of 25.08% and 42.11%, respectively (67.19% in total).

Table 5. Percentage of expected number of days and observed fires according to the classes of indices.

INDEX	Null		Low		Average		High		Very high	
	Days	Fires	Days	Fires	Days	Fires	Days	Fires	Days	Fires
EVAP/P	27.79%	0.63%	21.63%	3.14%	19.13%	17.61%	17.21%	38.36%	14.24%	40.25%
Telicyn*	45.35%	3.14%	10.13%	5.66%	5.92%	6.92%	22.25%	61.01%	16.36%	23.27%
P-EVAP	29.43%	1.26%	26.25%	5.66%	11.81%	8.18%	19.47%	35.85%	13.04%	49.06%
FWI**	26.18%	0.63%	12.39%	0.63%	14.85%	1.26%	25.56%	10.06%	21.01%	87.42%
FMA+*	20.94%	0.63%	16.87%	1.89%	11.29%	4.40%	10.44%	3.77%	40.45%	89.31%
FMA*	14.54%	0.63%	15.26%	1.26%	18.04%	4.40%	18.62%	16.98%	33.54%	76.73%
Nesterov*	32.92%	1.26%	8.49%	1.26%	14.20%	5.03%	35.35%	47.80%	9.03%	44.65%

* Using daily average data of wind speed, temperature and relative humidity. ** Using the maximum daily temperature, relative humidity at 3:00 p.m. and daily average wind speed.

Table 6. Skill Score and Success Percentage of each index.

Rank	Index	SS	PS
1º	P-EVAP T2*	0.554087	77.70%
2º	FWI T2**	0.538361	76.92%
3º	P-EVAP T1*	0.515689	75.78%
4º	Nesterov T2*	0.508314	75.42%
5º	EVAP/P T2*	0.498795	74.94%
6º	Telicyn T1*	0.493564	74.68%
7º	Telicyn T2*	0.483013	74.15%
8º	EVAP/P T1*	0.482713	74.14%
9º	FMA+ T2*	0.446199	72.31%
10º	FMA T2*	0.439459	71.97%
11º	Nesterov T1*	0.411325	70.57%
12º	FWI T1**	0.394588	69.73%
13º	FMA+ T1*	0.373323	68.67%
14º	FMA T1*	0.295283	64.76%

T1 – Considering the classes average, high and very high as prediction of occurrences; T2 – Considering the high and very high classes as instances forecast; * Using daily average data of wind speed, temperature and relative humidity; ** Using the maximum daily temperature, relative humidity at 3:00 p.m. and daily average wind speed.

For the Nesterov Index, they observed an unbalanced trend, with the values concentrated in the high and very high danger classes, with percentages equivalent to 45.81% and 43.10%, respectively, totaling 88.91%.

Comparing the FMA results to the state of Paraná, with occurrences of heat outbreaks detected by INPE, Deppe et al. (2004) verified that 52% of the outbreaks were present in the extreme danger class and 46.4% in the high danger class. Only 1.5% of the outbreaks occurred in areas of moderate danger, while the number of outbreaks detected in the low and null danger classes was zero.

Analyzing the descriptive classes that indicate or not the danger of occurrences, all studies analyzed (Borges et al., 2011; Deppe et al., 2004; Nunes et al., 2006, 2007, 2010; Rodríguez et al., 2012; Sampaio, 1999; Torres & Ribeiro, 2008) consider the average danger class as indicative of occurrence. However, it was observed in this study that all indices analyzed, with the exception of the Telicyn index, were more efficient when they considered this class as non-indicative of occurrences (Table 6). FWI, which jumps from the penultimate to the second most efficient index under this condition, stands out.

In a study conducted in Germany by Holsten et al. (2013), the Canadian index was also the most effective for that country, while the Nesterov index was the least efficient. On the other hand, in Switzerland, Zumbrunnen et al. (2011) found the Nesterov index to be the most efficient.

In Espírito Santo state, Borges et al. (2011) concluded that the results obtained by the FMA+ index were superior to the other indices, attaining the highest Skill Score at 0.2055 and 0.1503, respectively, obtained by the Nesterov equation. The lowest values were observed for the original FMA (0.0946).

In the forest district of Monte Alegre in Paraná state, the FMA and FMA+ values obtained were 0.0517 and 0.1165 for the SS and 34.32% and 55.64% for PS, respectively (Nunes et al., 2010).

Sampaio (1999), in the interior of the state of São Paulo, found the most efficient index to be the FWI (0.1838 SS and 71.38% PS), secondly the logarithmic Telicyn index (0.137 and 62.90%), Nesterov third (0.102 and 50.47%), and FMA fourth (0.061 and 36.92%).

In the municipality of Juiz de Fora, also in the Zona da Mata mineira, Torres & Ribeiro (2008) found better results for the EVAP/P index (0.534 and 78%), followed by Telicyn (0.511 and 76%), P-EVAP (0.473 and 75%), Nesterov (0.406 and 69%), and FMA (0.388 and 68%).

Of all the studies considered (Borges et al., 2011; Deppe et al., 2004; Nunes et al., 2006, 2007, 2010; Rodríguez et al., 2012; Sampaio, 1999; Torres & Ribeiro, 2008), the Skill Score for the P-EVAP and FWI indices observed in the PESB achieved the highest values, indicating the adequacy of data collected in the municipality of Viçosa to determine the fire hazard in the PESB. The changes promoted in the original methodologies, with relation to the values indicating fire hazard and time of measurement of the data used in the calculation, improved the efficiency of the indices for the study area.

4. CONCLUSION

The meteorological data obtained in the municipality of Viçosa was effective in predicting the danger of vegetation fires in the Serra de Brigadeiro State Park.

The efficiency of the fire hazard indices used increases when the middle danger class is not considered as indicative of danger.

The Telicyn, Nesterov, FMA and FMA+ indices presented better results when using the average daily data, while the FWI responded better with the maximum daily temperature and relative humidity at 3:00 p.m.

The P-EVAP and FWI indices are the most efficient to forecast fires in the study region.

SUBMISSION STATUS

Submitted: 15 mar., 2017
Accepted: 12 mar., 2018

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