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Original article

Local calibration of meteorological indices of forest fire danger in Jipijapa, Manabí, Ecuador

Calibración local de índices meteorológicos de peligro de incendios forestales en Jipijapa, Manabí, Ecuador

Calibração local de índices meteorológicos de perigo de incêndios florestais em Jipijapa, Manabí, Equador

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ABSTRACT

The monitoring of forest fire danger through meteorological indices constitutes a key tool for preventive fire management. However, their effectiveness depends on their adaptation to local conditions. This study aimed to locally calibrate the Nesterov Index and the Monte Alegre Formula (FMA), two meteorological fire danger indices, in Jipijapa, Manabí, Ecuador. Historical weather data and fire occurrence records were used to develop locally adjusted danger scales, evaluating the distribution of the number of days per danger class and their correspondence with fire occurrence. The original scales exhibited distributions inconsistent with expected fire behavior, while the adjusted scales showed a decreasing trend in the number of days from lower to higher danger classes, and an increasing trend in fire occurrence. The values of skill score (SS) and percentage of success (PS) improved substantially after calibration: the Nesterov Index reached an SS of 0.0815 and a PS of 59.56%, while the FMA achieved an SS of 0.0806 and a PS of 53.54%. These results show that both indices, once calibrated, are applicable to the local context of Jipijapa. Nevertheless, the operational use of the FMA is recommended due to its computational simplicity. This study reinforces the need to adapt meteorological indices at the regional level to improve the accuracy of forest fire danger assessment and enhance preventive fire management strategies.

Keywords: fire management, percentage of success, forest fire prevention, skill score, meteorological variables.

RESUMEN

El monitoreo del peligro de incendios forestales mediante índices meteorológicos constituye una herramienta clave para la gestión preventiva del fuego. Sin embargo, su efectividad depende de la adecuación a las condiciones locales. Este estudio tuvo como objetivo ajustar localmente los índices meteorológicos de peligro de incendios forestales Nesterov y Fórmula de Monte Alegre (FMA) en Jipijapa, Manabí, Ecuador. Se utilizaron datos meteorológicos históricos y registros de incendios para desarrollar escalas ajustadas de peligro, evaluando la distribución del número de días por clase de peligro y la correspondencia con la ocurrencia de incendios. Las escalas originales presentaron distribuciones no deseadas para el comportamiento esperado, mientras que las escalas ajustadas mostraron una tendencia decreciente en el número de días desde las clases de menor a mayor peligro, y una tendencia creciente en la ocurrencia de incendios. Los valores de skill score (SS) y porcentaje de éxito (PE) mejoraron sustancialmente tras el ajuste: el índice de Nesterov alcanzó un SS de 0,0815 y un PE de 59,56 %, mientras que el FMA obtuvo un SS de 0,0806 y un PE de 53,54 %. Estos resultados demuestran que ambos índices, una vez calibrados, son aplicables en el contexto local de Jipijapa. No obstante, se sugiere el uso operativo del índice FMA por su simplicidad de cálculo. Este estudio refuerza la necesidad de adaptar los índices meteorológicos a nivel regional para una evaluación más precisa del peligro de incendios forestales y una gestión preventiva más eficaz.

Palabras clave: manejo del fuego, porcentaje de éxito, prevención de incendios forestales, skill score, variables meteorológicas.

RESUMO

O monitoramento do perigo de incêndios florestais por meio de índices meteorológicos constitui uma ferramenta fundamental para a gestão preventiva do fogo. No entanto, sua eficácia depende da adequação às condições locais. Este estudo teve como objetivo calibrar localmente os índices meteorológicos de perigo de incêndios florestais Nesterov e Fórmula de Monte Alegre (FMA) em Jipijapa, Manabí, Equador. Foram utilizados dados meteorológicos históricos e registros de ocorrências de incêndios para desenvolver escalas ajustadas de perigo, avaliando a distribuição do número de dias por classe de perigo e a correspondência com a ocorrência de incêndios. As escalas originais apresentaram distribuições incompatíveis com o comportamento esperado do fogo, enquanto as escalas calibradas mostraram uma tendência decrescente no número de dias das classes de menor para maior perigo e uma tendência crescente na ocorrência de incêndios. Os valores do skill score (SS) e do percentual de acerto (PA) melhoraram substancialmente após a calibração: o índice de Nesterov atingiu um SS de 0,0815 e um PA de 59,56 %, enquanto a FMA obteve um SS de 0,0806 e um PA de 53,54 %. Esses resultados demonstram que ambos os índices, uma vez calibrados, são aplicáveis ao contexto local de Jipijapa. No entanto, recomenda-se o uso operacional da FMA devido à sua simplicidade de cálculo. Este estudo reforça a necessidade de adaptar os índices meteorológicos em nível regional para uma avaliação mais precisa do perigo de incêndios florestais e uma gestão preventiva mais eficaz.

Palavras chave: manejo do fogo, percentual de acerto, prevenção de incêndios florestais, skill score, variáveis meteorológicas.

INTRODUCTION

In a forested area, two types of factors can be distinguished as determining the degree of fire hazard: permanent factors (fuel material, topography, and forest type) and variable factors (weather conditions). Permanent factors are not appropriate for determining the degree of fire hazard because they do not change in the short term. However, variable factors provide a solid basis for determining the degree of fire hazard due to their rapid variation (Soares *et al*., 2017). Assigning a fire hazard index based on weather conditions is a way to provide tools to the agencies responsible for preventing and fighting forest fires (Kossoski *et al*., 2024).

Several researchers have established the relationship between the emergence and spread of forest fires and meteorological variables. Ramos Rodríguez *et al*. (2017) verified that the annual distribution of meteorological variables has a direct or inverse relationship with the distribution of fire occurrence and burned areas in the province of Pinar del Río, Cuba, during the period 2010-2014. Torres *et al*. (2019) also found high correlations between some fire behavior variables and environmental variables.

The influence of weather conditions on the behavior and spread of forest fires has been recognized through the development of a variety of fire weather indices, which combine information on air temperature, atmospheric humidity, and wind, among other factors (Sharples, 2022). The main fire hazard indices used in Brazil are the Angstron, Nesterov, Monte Alegre Formula (FMA), and Altered Monte Alegre Formula (FMA+) indices (Soares *et al*., 2017). The FMA + indices, by including wind speed, have been shown to improve the prediction of fire behavior (Almeida *et al*., 2022).

Mbanze) is also frequently used. *et al* ., 2017). Its effectiveness has been confirmed in studies in different biomes, although it generally requires adaptation to local conditions (Pérez-Sánchez *et al*., 2017). In Europe, especially in countries such as Austria, Germany, and Switzerland, it has been shown that the performance of an index varies significantly according to the ecological region and the season, which reinforces the importance of making local adjustments (Steinfeld *et al*., 2022).

Despite the existence of several fire hazard indices, the use of an inefficient index can lead to flawed decision-making regarding forest fire prevention and suppression procedures, while a reliable predictive index can facilitate better quantification and allocation of prevention resources (Torres *et al*., 2017). In this regard, recent studies have shown that local adjustments to the Nesterov and FMA indices significantly improve their predictive performance. For example, in eucalyptus plantations in the state of São Paulo, calibrating the FMA allowed for a more accurate classification of fire hazard (Santos *et al*., 2021). Similarly, in Chapada dos Guimarães National Park, the FMA demonstrated good predictive performance after adjusting the hazard class thresholds (Machado Neto *et al*., 2018).

In Ecuador, both the National Secretariat for Risk Management, through its Directorate for Monitoring Adverse Events, and the National Institute of Meteorology and Hydrology provide graphical information on the Haines index for the entire country. However, according to Potter (2018), this index, published in 1988 as the lower atmospheric severity index, was widely adopted in the United States, but its scientific validity has been questioned. Studies have suggested that it lacks a solid empirical foundation and its relationship with fire growth events is inconsistent. On the other hand, Pazmiño (2019), in analyzing the forest fire hazard associated with climatic factors, determined that the McArthur fire hazard index is a useful metric in the Andean region of the country.

Taking into account the above, and considering that there are several meteorological indices of forest fire danger that have been used for more than 100 years in different regions of the world, this study aimed to locally adjust the Nesterov and Monte Alegre formula meteorological indices of forest fire danger in Jipijapa, Manabí, Ecuador , based on the hypothesis that the Nesterov and FMA indices, once their respective hazard interpretation scales are adjusted, can be used in the Jipijapa canton, which would constitute the beginning of the introduction of the use of these indices in different regions of the country and a significant contribution to the *National Strategy for Integrated Fire Management in Ecuador*.

MATERIALS AND METHODS

Characterization of the study area

The canton of Jipijapa, comprised of three urban and seven rural parishes, is located in the southernmost part of the province of Manabí, Ecuador. The predominant climate is hot and dry in the western area and hot and humid with dry seasons in the eastern area, with an average temperature of 24 °C. This climate is influenced by two seasons: the dry season (between May and October) and the rainy season (between November and April). The highest humidity and temperature values are recorded in March, when the average air temperature reaches 28 °C. The average annual rainfall is 670 mm, with the majority occurring between February and March (Jipijapa Municipal Decentralized Autonomous Government, 2024).

Data collection and analysis

The meteorological database consisted of daily values measured at 1:00 PM for dry-bulb temperature, dew point temperature, and relative humidity, as well as accumulated precipitation over 24 hours up to the time of measurement. This information was obtained from NASA *Prediction. Of Worldwide Energy Resources* (https://power.larc.nasa.gov/) at UTM coordinates Longitude -80.5799 and Latitude -1.3488, the location of the Jipijapa Fire Department, while the fire occurrence data were provided by that institution. All data corresponds to the period between January 1, 2018, and December 31, 2023, which is equivalent to six years of observations.

The calculation of the daily hazard level according to the Nesterov and Monte Alegre Formula indices was performed using equations 1 and 2. The calculation restrictions due to precipitation and the scales for interpreting the hazard level proposed by Soares *et al.* (2017) were applied (Tables 1, 2, and 3). The number of days predicted for each hazard class was also quantified and analyzed, as well as the percentages they represent within each category.

$$\mathrm{I} = \sum_{n=1}^{n} Ts_{\mathrm{i}}\,(Ts_i - Tpr_i) \qquad (1)$$

Where: I - Nesterov Index; n - number of days with rainfall greater than 10 m; Ts - dry air temperature in °C; Tpr - dew point temperature in °C.

$$FMA = \sum_{i=1}^{n} \left(\frac{100}{H_i} \right) \quad (2)$$

Where: FMA - Monte Alegre formula index; n - number of days with rainfall greater than 12.9 mm; H - relative humidity in %.

Table 1. - *Restrictions on the sum of the Nesterov index*

Daily rainfall (mm)	Change in calculations
≤ 2	None
2.1 to 5.0	Decrease by 25% the value of I calculated on the previous day and add Ts (Ts-Tpr) of the day.
5.1 to 8.0	Decrease by 50% the value of I calculated on the previous day and add Ts (Ts-Tpr) of the day.
8.1 to 10.0	Disregard the previous sum and start a new calculation, i.e., I = Ts (Ts-Tpr) of the day.
> 10.0	Interrupt the calculation (I = 0), restarting the summation the next day or when the rain stops.

Table 2. - *Restrictions on the summation of the Monte Alegre formula index*

Daily rainfall (mm)	Change in calculations
≤ 2.4	None
2.5 to 4.9	Decrease by 30% in the FMA calculated on the previous day and add (100/H) of the day.
5.0 to 9.9	Decrease by 60% in the FMA calculated on the previous day and add (100/H) of the day.
10.0 to 12.9	Decrease by 80% the FMA calculated the day before and add (100/H) of the day
> 12.9	Stop the summation (FMA = 0) and restart the calculation the next day or when the rain stops.

Table 3. - *Original scale for interpreting the degree of danger*

Index Value		Degrees of danger
Nesterov	FMA	
≤ 300	≤ 1	I (Null)
301 to 500	1.1 to 3	II (Small)
501 to 1000	3.1 to 8	III (Middle)
1001 to 4000	8.1 to 20	IV (High)
> 4000	> 20	V (Very high)

To verify the fit of the index scales, the trend in the concentration of fire occurrence distribution within hazard classes during the study period was considered, taking into account two distributions that indicate the fit of the indices. According to Nunes *et a* . (2010), ideally, the number of days predicted for each hazard class should have an inverse relationship with the hazard class; that is, the higher the hazard class, the lower the number of days predicted for it. For the variable of fire occurrence in each hazard class, a direct relationship was sought, such that the higher the hazard class, the higher the observed values for this variable.

Based on the criteria above, and using the original hazard classes of the indices (Table 3), it was necessary to define new classes that were more appropriate for the location under study. Numerical and graphical analyses were performed on the variables of the number of days predicted in each hazard class and the occurrence of fires, with the aim of defining the boundaries of the new hazard classes for the indices under study.

The performance of the studied indices was obtained using the *skill score method,* which is based on a contingency table containing observed and predicted values for an event in a population over a specific period. The points indicating fire occurrence and non-occurrence were defined following Nunes *et al*. (2010), who consider the hazard classes Zero and Small as indicative of the probability of fire non-occurrence, and the hazard classes Medium, High, and Very High as indicative of the probability of fire occurrence. Based on this definition, the *skill score* and the percentage of successes for the indices were calculated for the original and adjusted hazard class scales. Tables 4 and 5 illustrate how the calculations were performed to obtain the *skill score* (SS), defined as the ratio of the difference between the number of correct predictions (G) and the expected number of correct predictions (H), and the difference between the number of observed days (N) and the number of days with predicted correct predictions.

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Table 4. - *Contingency Table*

Events		Observed		Total expected
		Occurrence	**Non-occurrence**	
Provided	Occurrence	TO	B	N2 = a+b
	Non-occurrence	C	D	N4 = c+d
Total observed		N1 = a+c	N3 = b+d	N = a+b+c+d

Table 5. - *Contingency table calculations*

Events		Observed		Total expected
		Occurrence	**Non-occurrence**	
Provided	Occurrence	a/(a+c)	b/(b+d)	-
	Non-occurrence	c/(a+c)	d/(b+d)	-
Total observed		1	1	2

The variables needed to perform the calculations are:

N – Total number of observations

$N = a + b + c + d$

a – Days on which fires were predicted and occurred

d – Days on which fires were not expected to occur and they did not occur

b – Days on which fires were predicted but did not occur

c – Days on which fires were not expected to occur but they did

G – Number of correct predictions

$G = a + d$

H – Expected number of hits

$H = N * (1 - p) * (1 - q) + N * p * q$

$p = N1 / N$ and $q = N2 / N$

SS – *Skill score*

SS = (G – H) / (N – H)

PE – Success Rate

PE = (G / N) *100

RESULTS

Number of days expected in each hazard class

The original scales of the indices under study (Table 3) generated undesirable distributions of the number of days expected in each hazard class (Figure 1), as they do not follow a decreasing trend from the Null to Very High class, which should be the expected behavior of that variable, which is an indicator that the indices are misaligned, so it was necessary to adjust them so that they can be used in Jipijapa.

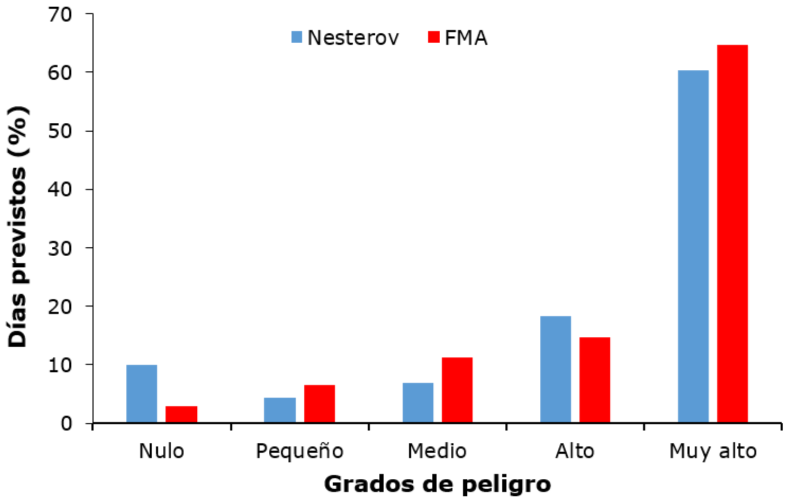

Figure 1. - *Distribution of the percentages of the number of days expected in each hazard class according to the original scales of the Nesterov and FMA indices in Jipijapa*

Taking into account the previous results, through numerical and graphical analyses of the variables number of days predicted in each hazard class and fire occurrence, the limits of the new hazard classes for the indices under study were defined (Table 6). The distribution of the percentages of days predicted in the period with the adjusted scales of the indices (Figure 2) is a desirable condition for the behavior of the number of predicted days, since it follows a decreasing trend from the zero class to very high, which represents the expected behavior for this variable and confirms that the indices are adjusted for the Jipijapa canton.

Table 6. - *Adjusted scale to interpret the degree of danger of the Nesterov and FMA indices in Jipijapa*

Index Value		Degrees of danger
Nesterov	**FMA**	
≤ 3000	≤ 12	I (Null)
3001 to 16000	12.1 to 55	II (Small)
16001 to 34000	55.1 to 150	III (Middle)
34001 to 56000	150.1 to 320	IV (High)
> 56000	> 320	V (Very high)

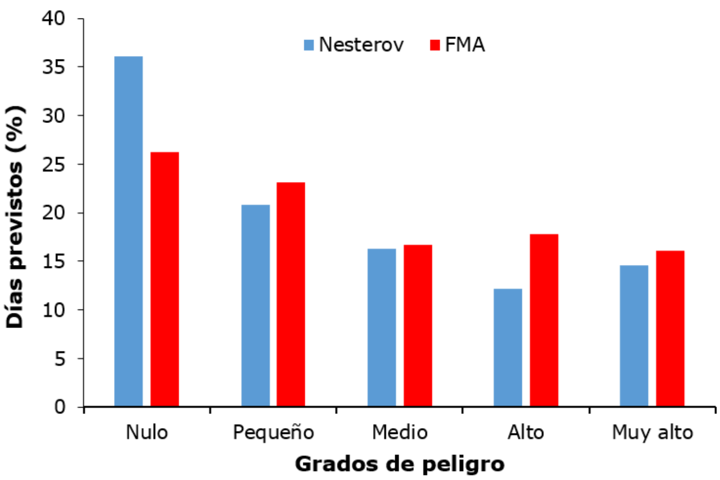

Figure 2. - *Distribution of the percentages of the number of days expected in each hazard class according to the adjusted scales of the Nesterov and FMA indices in Jipijapa*

Distribution of forest fire occurrence

In the case of the forest fire occurrence variable, the Nesterov and FMA indices, using the adjusted scale, showed an increasing distribution from class I (none) to class V (very high) (Table 7). This behavior is desirable for this variable across the hazard classes of the indices, thus demonstrating that the scales of both indices are well-suited for the Jipijapa canton.

Table 7. - *Distribution of the occurrence of forest fires according to the hazard classes of the adjusted scales of the Nesterov and FMA indices*

Degrees of danger	Nesterov		FMA	
	No.	**%**	**No.**	**%**
Null	17	11.89	10	6.99
Little	25	17.48	16	11.19
Half	31	21.68	33	23.08
High	35	24.48	45	31.47
Very high	35	24.48	39	27.27
Total	**143**	**100.00**	**143**	**100.00**

Performance of the Nseterov and FMA indices

Based on the original and adjusted scales of the Nesterov and FMA indices, Table 8 was compiled with the predicted and observed fire values. From this data, the values in Table 9 were calculated, showing the predicted events that did or did not occur on the original and adjusted scales.

Table 8. - *Number of days in which the Nesterov and FMA indices predicted occurrence and non-occurrence of fires and days with and without occurrence of fires for the original and adjusted scales in the Jipijapa canton*

Scales	Condition	Number of days - Nesterov		Number of days - FMA	
		Observed	**Expected**	**Observed**	**Expected**
Original	Occurrence	139	1876	142	1986
	Non-occurrence	4	315	1	205
	Total	**143**	**2191**	**143**	**2191**
Adjusted	Occurrence	101	945	117	1109
	Non-occurrence	42	1246	26	1082
	Total	**143**	**2191**	**143**	**2191**

Table 9. - *Contingency table and corresponding calculations for the Nesterov and FMA indices with the original and adjusted scales in the Jipijapa canton*

Scales	Indexes	Event		Observed		Total expected
				Occurrence	**Non-occurrence**	
Original	Nesterov	Provided	Occurrence	0.9720	0.8481	1,8202
			Non-occurrence	0.0280	0.1519	0.1798
		Total observed		**1**	**1**	**2**
	FMA	Provided	Occurrence	0.9930	0.9004	1,8934
			Non-occurrence	0.0070	0.0996	0.1066
		Total observed		**1**	**1**	**2**
Adjusted	Nesterov	Provided	Occurrence	0.7063	0.4121	1,1184
			Non-occurrence	0.2937	0.5879	0.8816
		Total observed		**1**	**1**	**2**
	FMA	Provided	Occurrence	0.8182	0.4844	1.3026
			Non-occurrence	0.1818	0.5156	0.6974
		Total observed		**1**	**1**	**2**

skill score and success percentage values obtained for the Nesterov and FMA indices, both on the original and adjusted scales (Table 10), show better performance for both indices on the adjusted scale, with the values obtained for both indicators being very similar, although it is possible to suggest the use of the FMA index due to its ease of use, since the calculation only considers two meteorological variables.

Table 10. - *Skill score (SS) and success percentage (PE) values for the Nesterov and FMA indices with the original and adjusted scales in the Jipijapa canton*

Indexes	**Original scale**		**adjusted scale**	
	H.H	**PE (%)**	**H.H**	**PE (%)**
Nesterov	0.0187	20.54	0.0815	59.56
FMA	0.0132	15.79	0.0806	53,54

DISCUSSION

Number of days expected in each hazard class

The results obtained in Jipijapa demonstrate that the original scales of the Nesterov and Monte Alegre Formula (FMA) meteorological indices do not adequately represent the local dynamics of fire hazard. The non-decreasing distribution of the number of predicted days per hazard class contradicts the expected pattern described in the scientific literature specializing in the performance evaluation of risk indices (Nunes *et al* ., 2010).

The results obtained in this research reveal that the Monte Alegre Fire Index (FMA), with local adjustments, showed significantly superior performance compared to the behavior observed under the meteorological conditions of Jipijapa, particularly during the months with the greatest water deficit and high temperatures. This observation partially agrees with studies such as that of Machado Neto *et al* . (2018), who reported that, although the FMA requires adjustments in its categorization, it effectively identified high-risk days in Chapada dos Guimarães National Park, Brazil. In the present study, the local adjustment not only corrected the overrepresentation of low-hazard classes but also increased the index's sensitivity to ignition events.

In contrast, the study by Borges *et al.* (2011) in eucalyptus plantations in Espírito Santo showed that the FMA $^{+}$ index, a modified version of the FMA, achieved better results in terms of success rate and *skill score* than the original FMA. In Jipijapa, however, the modified indices (such as FMA $^{+}$) did not significantly outperform the adjusted FMA, suggesting that the model's accuracy is strongly influenced by the local climate. This finding highlights the need for regional validations before adopting modified versions of the classic indices.

The Cuban experience reported by Ramos Rodríguez *et al.* (2012) also reinforces this finding, showing that both the Nesterov and FMA indices increase their sensitivity and accuracy when adjusted to specific site conditions. In the case of this study, the redesign of the hazard classes for both indices in Jipijapa yielded a desirable distribution curve, indicative of an operational improvement in the early warning system. In contrast, the study by Mbanze *et al.* (2017) in Lichinga showed better performance of the Nesterov index compared to the unadjusted FMA. However, the authors emphasize that the effectiveness of each index depends on its regional calibration. In their original state, both indices proved inadequate for Jipijapa, but with adjustments, they exhibited an expected and functional distribution.

Furthermore, Torres *et al.* (2017) emphasize the importance of considering not only meteorological conditions but also fire behavior and fuel moisture when selecting the most appropriate index for each region. Although this study did not include direct analyses of fire behavior in Jipijapa, the need to integrate biophysical and anthropogenic variables in future research remains relevant.

The study by Eugenio *et al.* (2020) is also key, as it demonstrates that the success of fire prediction using FMA^{+} depends on methodological adjustment to local conditions. Although FMA^{+} was not applied in this work , the methodological principles used for class recalibration align with their recommendations.

By adjusting the scales for both methodologies, a decreasing distribution of days was achieved, from the "None" class to "Very High," indicating a good adaptation to the climatic context of Jipijapa. This improvement is consistent with studies such as that of

Santos *et al*. (2021), who demonstrated that local calibration of FMA thresholds substantially improves their predictive performance.

Similarly, Almeida *et al*. (2022), when evaluating the performance of the FMA $^{+}$ in the Serra do Tombador Reserve (Goiás), identified its effectiveness especially in Cerrado vegetation areas, where surface fuel accumulation and climatic seasonality are predominant factors. However, the semi-arid conditions of Jipijapa impose different constraints, with a longer seasonality and less vegetation cover, which necessitates reconsidering the index's classification thresholds to maintain sensitivity without compromising specificity.

Furthermore, the research developed at the Taim Ecological Station by Marchesan *et al*. (2020), who integrated static and dynamic variables using GIS, highlight a methodological limitation of this study: the absence of topographic and land-use factors in the risk modeling. While the meteorological approach is operational and replicable, its predictive capacity could be significantly improved with a multivariate spatial approach.

A key issue is the scarcity of specific studies on the performance of these indices in dry ecosystems of the equatorial tropics. A critical gap has been identified in the literature, as most studies focus on temperate or humid tropical forests, with little evidence from transitional environments or dry savannas such as those in southern Manabí. In this regard, the present study provides novel and contextualized evidence on the local adjustment of meteorological fire hazard indices, highlighting the need for regional recalibrations to improve the effectiveness of early warning systems.

Distribution of forest fire occurrence

The results obtained for the variable “forest fire occurrence” empirically validate the suitability of the adjusted scales of the Nesterov and FMA indices to the climatic and operational context of the Jipijapa canton. The increasing distribution of fire occurrence from the “no” to “very high” hazard class demonstrates a positive correlation between the hazard level estimated by the indices and the actual occurrence of ignition events, which is an essential condition for the operational utility of any risk index.

This expected behavior has also been documented in studies such as that of Ramos Rodríguez *et al*. (2012), who recalibrated the FMA index classes under tropical conditions, obtaining significant improvements in the prediction of actual occurrences. In Jipijapa, although the original FMA index was used, adjustments to the scale resulted in an almost identical distribution in classes IV (High) and V (Very High), with more than 50% of the observed fires occurring in these classes.

Similarly, the results coincide with those of Mbanze *et al* . (2017), who also observed a progressive association between hazard classes and fire frequency when evaluating indices in Lichinga , Mozambique. However, their results showed greater effectiveness of the Nesterov index, while in Jipijapa, the adjusted FMA showed a slight superiority, capturing 58.74% of fires between classes IV and V, compared to 48.96% for the Nesterov index. This reinforces the need for local adaptations and the impossibility of extrapolating performance between ecosystems without prior recalibration.

For their part, Almeida *et al*. (2022), when analyzing the FMA $^{+}$ in Goiás, reported a consistent distribution of events with the increase in hazard classes, but warned about the underestimation of fires in the "Medium" class, which is also observable in the case of Jipijapa, where significant fires still occur in intermediate classes. This dispersion indicates that, although the model improves with adjustment, it remains sensitive to conditions not fully considered by meteorological indices.

Similarly, White *et al*. (2013) propose developing new indices from historical regional databases, precisely to improve the correspondence between hazard classes and actual events. Although this approach may be more accurate, it also requires robust time series, which, in the case of Jipijapa, are still under development.

Finally, it is important to highlight that other studies, such as Marchesan 's, *et al*. (2020), who incorporated static and dynamic variables into a multivariate model to map risk in southern Brazil, suggest that complementing meteorological indices with land use and topography information could improve the predictive accuracy of real-world events. In Jipijapa, this integration has not yet been implemented, representing a clear avenue for future research.

The comparison between the original and adjusted scales of the Nesterov and FMA indices, based on their respective contingency matrices, shows a clear and substantial improvement in predictive performance after local recalibration. The *skill score* (SS) and success rate (PR) values increased significantly: for the Nesterov index, the SS rose from 0.0187 to 0.0815, while the PR increased from 20.54% to 59.56%. The FMA also showed a comparable improvement (SS from 0.0132 to 0.0806 and PR from 15.79% to 53.54%). These results reflect an effective transition from near-random predictive ability to a moderately high level of accuracy, confirming the validity of the applied class adjustment.

This pattern aligns with the findings of Ramos Rodríguez *et al. (2012), who, after locally adjusting the Nesterov, FMA, and* FMA$^+$ hazard thresholds, reported significant improvements in the FMA$^+$ success rate (up to 57.1%). Similarly, Mbanze *Santos et al*. (2017) highlighted that the performance of these indices in Mozambique depended more on their adaptation to regional dynamics than on the formula itself. Santos *et al* . (2021) also reported that establishing new thresholds for hazard class definitions improved the efficiency of the Monte Alegre Formula in predicting fire occurrence in five eucalyptus-growing areas in the state of São Paulo, Brazil. Values with the original scales for PE ranged from 27.3% (Avaí) to 33.2% (Iaras), while those for SS ranged from 0.0159 (Lençóis Paulista) to 0.0215 (Iaras). After adjusting the scales to each area, the PE ranged from 61.2% (Lençóis Paulista) to 67.4% (Pratânia) and the SS was from 0.03 (Pratânia and Lençóis Paulista) to 0.04 (Avai , Iaras and Paulistânia).

The results obtained in Jipijapa also confirm the findings of Almeida *et al* . (2022), who validated the FMA$^+$ index as effective in areas of the Brazilian Cerrado after recalibrations based on empirical data. However, as in the present study, the authors cautioned that, even after adjustment, classification errors persist and must be mitigated by including complementary variables.

Additionally, White *et al*. (2013) proposed developing a specific meteorological index for the closed biome, considering that existing models did not adequately capture the local variability of risk. While the present research did not develop a new index, the results reinforce the recommendation that the scales of existing indices should be viewed as adaptable tools, not fixed standards.

On the other hand, Borges *et al*. (2011) pointed out that the operational simplicity of the FMA and FMA⁺ — requiring only two meteorological variables — represents a significant advantage in regions with limited meteorological infrastructure. This argument is particularly relevant in Jipijapa, where, although both indices showed similar improvements after adjustment, the FMA is suggested as the preferred option due to its greater ease of application and lower data requirements.

Furthermore, the works of Marchesan *et al*. (2020) and Eugenio *et al*. (2020) highlight the importance of integrating variables such as land use, altitude, and slope into predictive models. The present study, being limited to the meteorological component, could benefit from future methodological improvements in this area. Consideration could also be given to evaluating the performance of other indices such as the FMA⁺ and the *Fire Weather Index* (FWI), as well as the impact of interannual variability of phenomena such as El Niño on the predictability of the indices; validating the proposed adjustments using multivariate predictive models and ROC analysis; extending the temporal analysis to more years to strengthen correlations; and developing an index adapted to tropical drylands based on local data and machine learning techniques.

CONCLUSIONS

The local adjustment of the Nesterov and FMA indices has proven essential to improving their predictive and operational utility in the Jipijapa canton. The applied adjustment methodology was effective in achieving a class distribution consistent with theoretical expectations and validated by comparable studies.

The good correlation between the adjusted classes of the Nesterov and FMA indices and the observed occurrence of forest fires in Jipijapa demonstrates their validity as early warning tools. However, the need for future studies with indices that integrate ecological, anthropogenic, and topographic variables to increase the spatial and temporal sensitivity of the prediction is acknowledged.

A comparative evaluation of the Nesterov and FMA indices, using both their original and adjusted scales, demonstrates that the local adjustment substantially improves their operational effectiveness in Jipijapa. Although the Nesterov index performed slightly better, the simplicity of the FMA gives it a practical advantage, and its adoption with periodic validation is recommended.

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