UFSM

Ciência Florestal

ISSN 1980-5098
OPEN ACCESS

Ci. Fl., Santa Maria, v. 36, e92101, p. 1-26, 2026 • https://doi.org/10.5902/1980509892101
Submitted: 20th/05/2025 • Approved: 21st/10/2025 • Published: 30th/06/2026

Articles

Forest fire risk assessment in Botucatu, São Paulo (2015-2024) using the Monte Alegre Method

Análise do risco de incêndio florestal utilizando o Método de Monte Alegre entre 2015 e 2024 no município de Botucatu - São Paulo

Jose Rafael Franco[I], Sonia Maria Fernandes Ustulin[I], Maria José Brito Zakia[I], Victor Crespo de Oliveira[II], Matheus Rodrigues Raniero[I], Valdemiro Simão João Pitoro[I], Marcus Vinícius Contes Calça[I], Enzo Dal Pai[I]

[I]São Paulo State University, Botucatu, SP, Brazil
[II]Federal University of São Carlos, Buri, SP, Brazil

ABSTRACT

Wildfires are a major threat to ecosystems and environmental security, and their occurrence is strongly influenced by regional climatic patterns. This study aimed to assess wildfire risk in the municipality of Botucatu, São Paulo, Brazil, from 2015 to 2024, using the Monte Alegre Formula (FMA, from the Portuguese *Fórmula de Monte Alegre*). Daily precipitation and relative humidity data from the Lageado Farm Meteorological Station (UNESP) recorded at 1:00 p.m. local time were analyzed. The results revealed a marked seasonal pattern of wildfire risk, with elevated FMA values between May and September, especially in July and August, corresponding to the regional winter. The year 2021 presented the highest annual average FMA value (37.00), associated with an extreme drought event of 92 consecutive days without rainfall. Years with annual precipitation below the historical mean (1,500 mm) exhibited a higher frequency of days with "very high" or "maximum" wildfire risk. The findings indicate that the intra-annual distribution of rainfall plays a more critical role in wildfire risk dynamics than total annual precipitation. The results underscore the need for continuous monitoring and suggest that threshold adjustments are necessary to enhance the applicability of the index to different regional contexts. This study offers valuable technical support for the management of fire-prone areas and the development of effective prevention and mitigation strategies.

Keywords: Precipitation; Relative humidity; Drought; Monitoring

RESUMO

Os incêndios florestais representam uma das principais ameaças aos ecossistemas e à segurança ambiental, sendo influenciados pelas condições climáticas regionais. O objetivo desta pesquisa foi avaliar o risco de incêndio florestal no município de Botucatu, São Paulo, Brasil, entre os anos de 2015 e 2024, utilizando a Fórmula de Monte Alegre (FMA). Foram analisados dados diários de precipitação e umidade relativa do ar registrados às 13h, provenientes da Estação Meteorológica da Fazenda Lageado (UNESP). Os resultados demonstraram uma clara sazonalidade do risco de incêndio florestal, com maiores valores de FMA observados nos meses de maio a setembro, especialmente em julho e agosto, período que coincide com o inverno climático da região. O ano de 2021 apresentou o maior valor médio anual de FMA (37,00), refletindo um evento extremo de 92 dias consecutivos sem chuva. Observou-se que anos com precipitação total inferior à média histórica (1.500 mm) concentraram maior número de dias com risco de incêndio florestal “muito alto” e “máximo”. A análise integrada mostrou que a distribuição intra-anual das chuvas é mais determinante que o volume total anual na dinâmica do risco de incêndio florestal. Os resultados reforçam a importância do monitoramento contínuo e apontam a necessidade de ajustes nos limiares do índice para aumentar sua eficiência em diferentes contextos regionais. Este estudo fornece subsídios técnicos relevantes para a gestão de áreas suscetíveis a incêndios florestais e para a formulação de estratégias de prevenção e mitigação.

Palavras-chave: Precipitação; Umidade relativa do ar; Seca; Monitoramento

1 INTRODUCTION

Wildfires cause extensive environmental, economic, and social damage worldwide (Tetto *et al*., 2010; Li *et al*., 2023; Maccarthy *et al*., 2024). Although natural fires are part of the ecological dynamics of many ecosystems, human activity has substantially increased wildfire occurrence in recent years (Lorenzo *et al*., 2015; Jones *et al*., 2024; Sayedi *et al*., 2024).

The growing frequency and intensity of wildfires have resulted in biodiversity loss, degradation of ecosystem services, adverse effects on human health, increased extinction risk for species, and the aggravation of climate change. Wildfires also elevate atmospheric pollutant emissions and contribute significantly to global pollution, underscoring the need for studies focused on wildfire risk assessment and monitoring (Beu, 2022; Singh, 2022; Marfella *et al*., 2024).

Brazil accounts for approximately 46.3% of wildfire hotspots in South America, making it the country with the highest number of occurrences on the continent. In

2024, 46 municipalities in São Paulo state were under maximum alert, demonstrating heightened vulnerability even in highly urbanized regions. These events directly affect multiple sectors of society and pose a challenge to the implementation of sustainable development policies (Marques, 2024). Between 2015 and 2020, wildfires generated an estimated R$ 11 billion in losses to public funds (Janone, 2021). Beyond economic costs, wildfires produce severe ecological impacts and public health consequences, including fatalities and increased respiratory diseases (Costa *et al*., 2023).

Climatic conditions are key determinants of wildfire occurrence. Among them, precipitation plays a central role and is directly linked to fire risk in native vegetation, whereby the higher the number of days without precipitation in a region, the greater the likelihood of fire outbreaks. Extended dry periods combined with low relative humidity lead to reduced cloud formation, which in turn allows greater solar radiation to reach the Earth's surface, raising air temperature and increasing wildfire risk (Torres, 2006; Molina, González-Cabán, ilva, 2019; Wasserman, Mueller, 2023).

Meteorological-based fire danger indices are widely used to support decision-making for prevention strategies (Alves *et al*., 2014). In Brazil, the most applied indicator for wildfire risk monitoring is the Monte Alegre Formula (FMA from the Portuguese *Fórmula de Monte Alegre*), developed using meteorological data and fire records from Monte Alegre Farm in Telêmaco Borba, Paraná state (Santos *et al*., 2021).

The FMA is used by forestry companies across Brazil and in other South American countries (Nunes *et al*., 2010; Silva *et al*., 2020; Cavalcante *et al*., 2021). It estimates the probability of ignition based on meteorological variables and indicates the likelihood of wildfire occurrence given the presence of an ignition source (Nunes, Soares, Batista, 2005). Since its development in 1972, the method has been evaluated in several regions, including Irati (Paraná) (Tetto *et al*., 2010), São Mateus and Conceição da Barra (Espírito Santo) (Borges *et al*., 2011), Piracicaba (São Paulo) (Alves *et al*., 2014), and Niassa Province, Mozambique (Máquina *et al*., 2024).

Botucatu, located in the interior of São Paulo state, has an economy based on agriculture and livestock, with sugarcane and eucalyptus plantations playing a major role (Rossi *et al*., 2018). The dominance of these crops highlights the importance of understanding wildfire risk to help local producers and forestry companies identify periods of elevated risk and potential ignition hotspots, supporting mitigation and prevention strategies.

Accordingly, this study aimed to evaluate wildfire risk in Botucatu (São Paulo, Brazil) from 2015 to 2024 using the Monte Alegre Formula (FMA), identifying periods of highest risk and analyzing temporal patterns to provide guidance and technical support for local producers and forestry stakeholders.

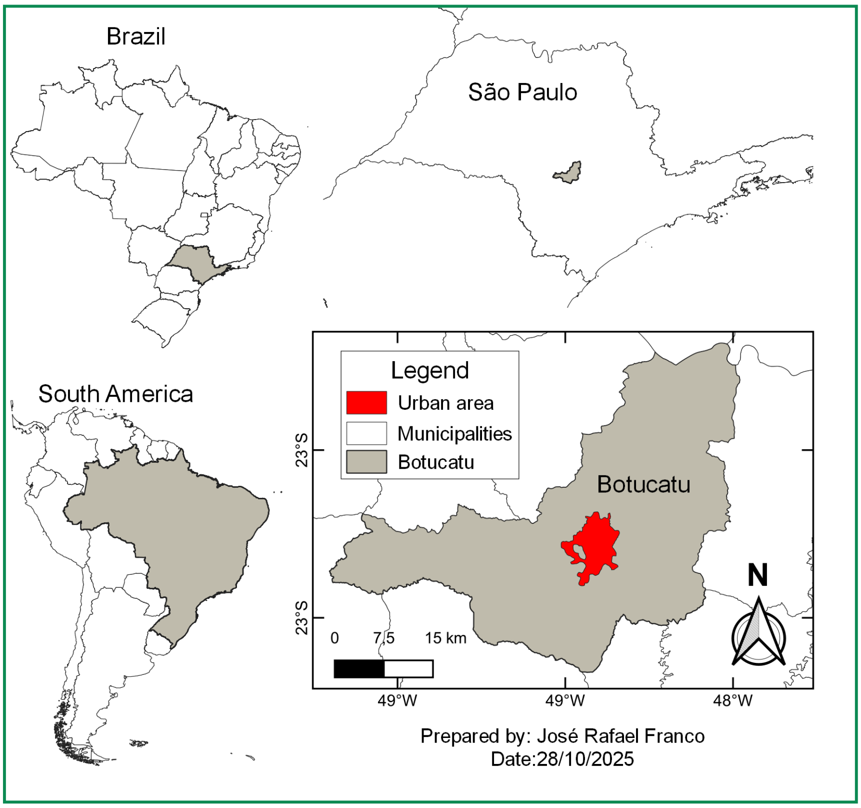
2 MATERIALS AND METHODS

2.1 Location and climate

This study used a climatic data series from the Meteorological Station of the Department of Rural Engineering and Socioeconomics at the Faculty of Agricultural Sciences, São Paulo State University "Júlio de Mesquita Filho" (UNESP), located in Botucatu, São Paulo, Brazil (22º54'S, 48º27'W, and 786 m elevation). Botucatu (Figure 1) lies between two major hydrographic basins (Barra Bonita and Jurumirim) in a region characterized by the Cuesta landform and drained by the Tietê and Paranapanema river systems (Rossi *et al*., 2018).

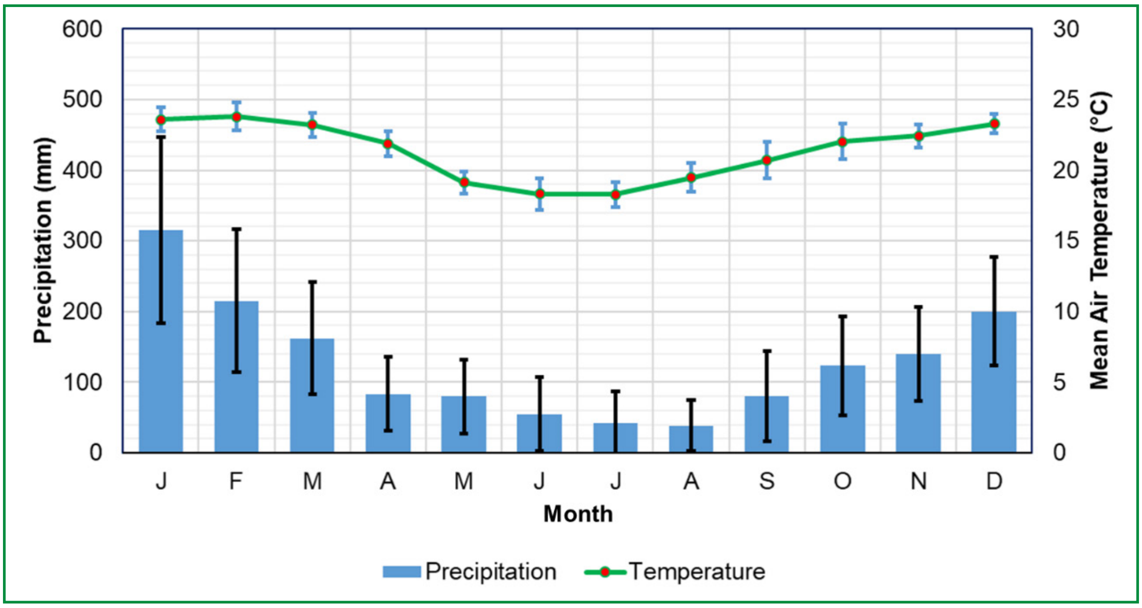
Botucatu experiences hot, rainy summers and cold, dry winters, characteristic of a humid tropical climate with a pronounced dry season. Figure 2 presents the climatological normals for the municipality, illustrating the seasonal pattern of mean air temperature and monthly precipitation from 1991 to 2020, together with their respective standard deviations (Franco *et al*., 2023).

Figure 1 – Geographic location of the municipality of Botucatu, São Paulo, Brazil



Source: Authors (2025)

Figure 2 – Climatological normals for 1991–2020, based on records from the Lageado Meteorological Station, Faculty of Agricultural Sciences, UNESP, Botucatu, São Paulo, Brazil



Source: Franco *et al*. (2023)

According to the Köppen climate classification, the climate of Botucatu is Aw, characterized by hot and rainy summers and dry winters. Climatological normals for 1991–2020 indicate an average annual temperature of 21.34 °C, with mean minimum and maximum values of 17.24 °C and 26.51 °C, respectively. Mean annual relative humidity is approximately 70%, and average annual precipitation totals about 1,500 mm, distributed across roughly 107 rainy days per year (Franco *et al*., 2023). February is the warmest month, with a mean maximum temperature of 28.65 °C, and January the wettest, averaging 315.14 mm of precipitation and 75.79% relative humidity. The lowest temperatures occur in June and July (mean 18.28 °C), whereas August is the driest month, with 41.85 mm of precipitation and 60.79% relative humidity (Franco *et al*., 2023).

2.2 Instruments and measurements

Meteorological data on relative humidity and precipitation were collected at hourly and daily intervals from January 2015 to December 2024, totaling 3,495 days. Relative humidity was measured using an HC2S3 sensor (Rotronic HygroMer IN1) with ±0.8% accuracy at 23 °C. Precipitation was recorded with a TB4 Rain Gauge (Vaisala) with accuracy of 0.3 mb at 20 °C, 0.6 mb at 40 °C, and ±1 mb from −20 °C to 45 °C, within a measurement range of 500–1100 mb. Data acquisition and storage were carried out using a CR1000 Datalogger (Campbell Scientific).

Measurements were initially logged at 5-minute intervals, with one reading collected every 5 seconds. Each stored value represents the mean of 60 internal readings. From these 5-minute records, hourly and daily averages of the agrometeorological variables were obtained. For the present analysis, daily precipitation totals and hourly relative humidity values recorded at 1:00 p.m. local time were used.

2.3 Monte Alegre Formula

Wildfire risk was assessed using the FMA (Equation 1), based on daily precipitation and relative humidity measured at 1:00 p.m. local time.

$$\mathrm{FMA} = \sum_{i=1}^{n} \left(\frac{100}{\mathrm{UR}_{13H}} \right) \tag{1}$$

where: FMA represents the wildfire risk index (the higher the value, the greater the risk of outbreaks); $UR_{13}H$ the relative humidity at 1:00 p.m. (%); n the number of days in the analysis period (daily $UR_{13}H$ values are typically summed over a given interval, such as a week or month); and 100 / $UR_{13}H$ the daily wildfire risk component. Lower relative humidity results in higher index values, indicating greater wildfire likelihood.

When precipitation exceeds 13 mm, the FMA value is set to zero (no wildfire risk). If precipitation is below 13 mm, a multiplier is applied to the FMA value based on the rainfall volume recorded the previous day (Table 1).

Table 1 – Adjustment of the Monte Alegre Formula (FMA) based on daily precipitation

Daily Precipitation (mm)	FMA Adjustment Rule
< 2.5	FMA = (FMA_previous × 1.0) + FMA_current
2.5 a 4.9	FMA = (FMA_previous × 0.7) + FMA_current
5.0 a 9.9	FMA = (FMA_previous × 0.4) + FMA_current
10.0 a 12.9	FMA = (FMA_previous × 0.2) + FMA_current
> 12.9	FMA = 0

Source: Soares (1972)

The wildfire risk index is classified into five categories, from Low to Maximum Risk, according to the daily FMA value (Table 2).

Table 2 – Wildfire risk classification and color scale of the Monte Alegre Formula (FMA)

FMA	Risk Category	Legend
< 1	Low	
1 – 3	Moderate	
3.1 – 8.0	High	
8.1 – 20.0	Very High	
> 20	Maximum Risk	

Source: Soares (1972)

2.4 Data organization and analysis

Meteorological measurements were initially recorded at high frequency (one reading every 5 seconds, aggregated into 5 minute-intervals) and subsequently processed to obtain hourly and daily averages of the variables of interest. Organization of the data on daily and annual scales enabled the assessment of temporal dynamics relevant to wildfire risk. Preliminary data and database structuring were carried out in Microsoft Excel.

Statistical and graphical analyses were performed in R Studio using the R programming language and associated packages. The ggplot2 package (Wickham *et al*., 2023) was used to produce descriptive visualizations, while the heatmap.2 function from the gplots package (Warnes *et al*., 2024) was employed to generate heatmaps and identify seasonal and interannual patterns in wildfire risk.

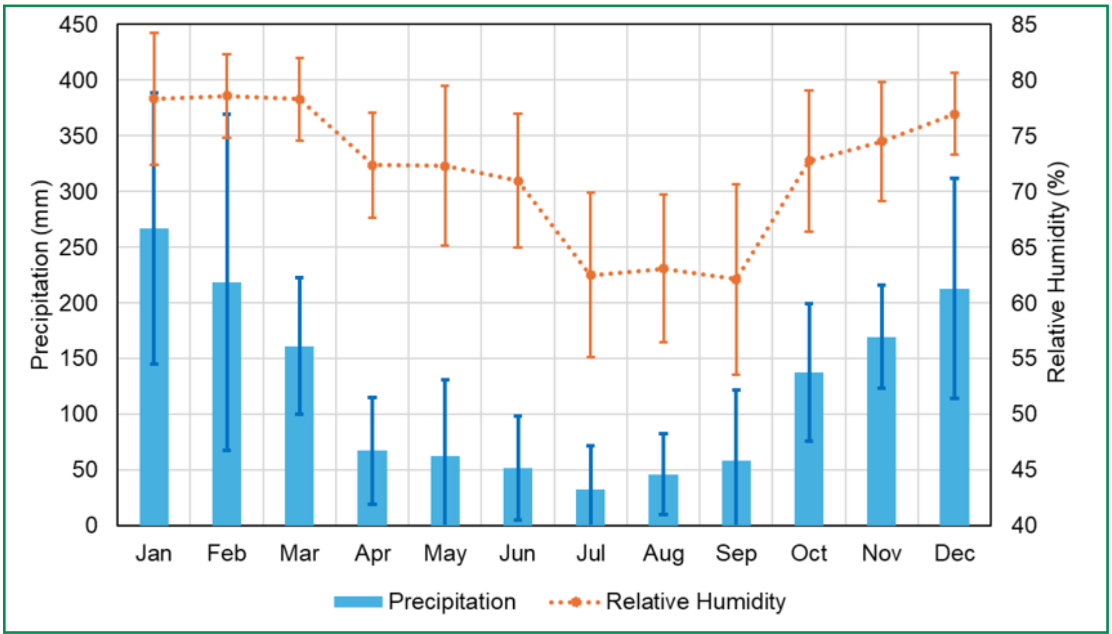
3 RESULTS AND DISCUSSION

3.1 Relative Humidity and Precipitation

Between 2015 and 2024, marked variability was detected in mean precipitation and relative humidity in Botucatu, reflecting seasonal patterns and considerable amplitude in the data, as shown by the associated standard deviations (Figure 3).

The combined analysis of precipitation and relative humidity highlights a pronounced seasonal pattern. January (268.00 mm) and February (228.77 mm) recorded the highest precipitation totals, followed by a sharp decline beginning in April (67.16 mm), which represents approximately one-third of the March total. From May to July, precipitation remains low, with June (32.51 mm) being the driest month in the period. Beginning in August, precipitation gradually increases until December, when a new peak is reached. October, for example, records 137.85 mm, indicating the transition to the wet season.

Figure 3 – Mean relative humidity and precipitation in Botucatu, São Paulo, Brazil, from 2015 to 2024



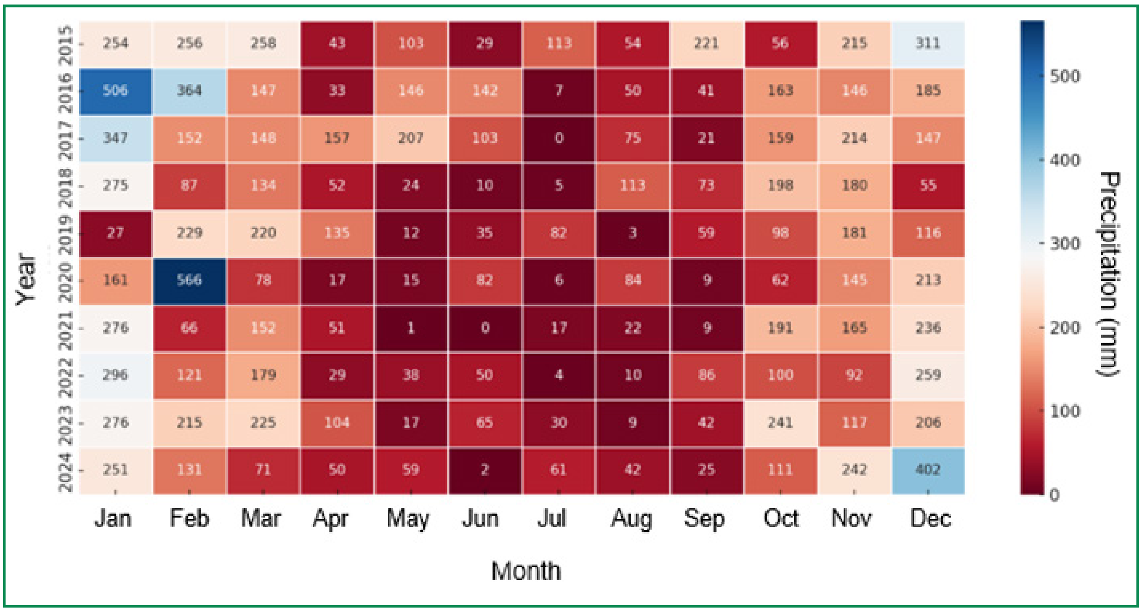
Source: Authors (2025)

Relative humidity varies in a similar manner, closely tracking precipitation behavior. During months with precipitation above 150 mm (January, February, March, November, and December), average relative humidity remains high, between 75.40% and 79.51%. As precipitation decreases from April to June, relative humidity also declines, ranging from 72.38% to 70.96%. The most critical period occurs between July and September, when relative humidity reaches its lowest values (62.52% to 63.07%), and, in combination with low precipitation, heightens wildfire risk. With the return of rainfall in October, relative humidity increases again, reaching 74.49% in November.

Monthly precipitation data from 2015 to 2024 clearly demonstrate seasonal rainfall dynamics in Botucatu, with peak precipitation in the summer months and a significant reduction during winter (Figure 4).

The heatmap of monthly precipitation reveals key relationships between water availability and wildfire risk. From June to September, precipitation is consistently low across the study period, frequently falling below 50 mm, as observed in July 2016 (7 mm), June 2017 (0 mm), July 2019 (8 mm), and August 2021 (17 mm). This marked reduction in soil and native vegetation moisture during the dry season increases fuel flammability and substantially elevates wildfire risk.

Figure 4 – Heatmap of monthly precipitation from 2015 to 2024 in Botucatu, São Paulo, Brazil



Source: Authors (2025)

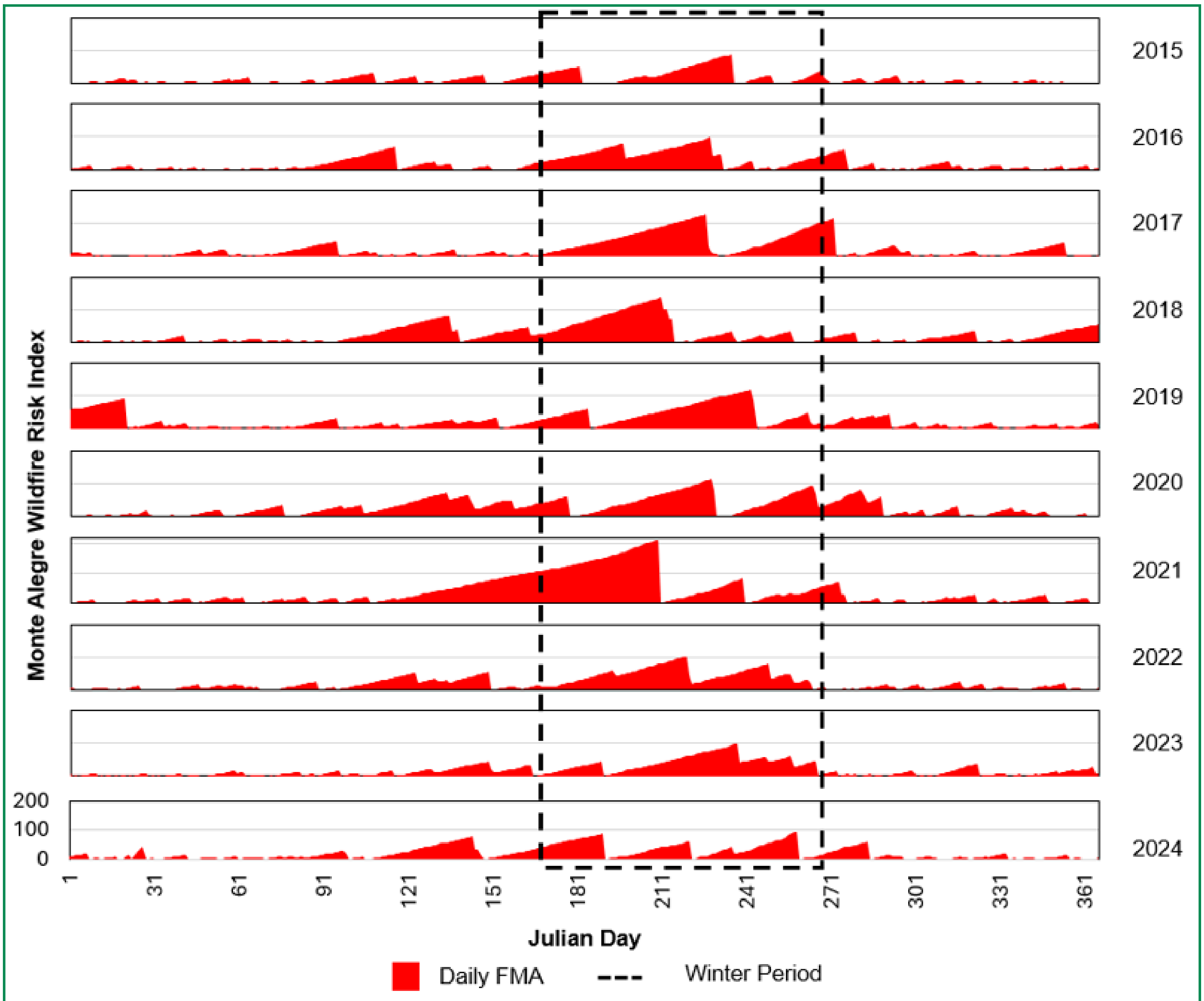
By contrast, the wettest months, such as February 2021 (566 mm) and December 2024 (402 mm), correspond to peaks of lower wildfire risk due to high relative humidity, which inhibits ignition and fire spread. However, biomass accumulation during the wet season can become fuel for wildfires during the subsequent dry months, underscoring the need for vegetation management and strategic prevention strategies by environmental authorities.

Interannual precipitation variability (Figure 4) between 2015 and 2024 is particularly evident in drier years such as 2017 and 2021, when prolonged deficits likely favored conditions for large-scale wildfires. These findings reinforce the importance of continuous climatic monitoring and proactive mitigation strategies based on seasonal forecasts and climate-risk alerts.

3.2 Wildfire risk analysis

Figure 5 shows daily values of the wildfire risk index calculated using the Monte Alegre Formula (FMA, 1972) for each year from 2015 to 2024. The winter period stands out, with consistently elevated FMA values, reflecting the driest conditions of the year and the highest probability of wildfire occurrence in native vegetation.

Figure 5 – Daily Monte Alegre Formula (FMA) values from 2015 to 2024 in Botucatu, São Paulo, Brazil



Source: Authors (2025)

The wildfire risk index from 2015 to 2024 shows substantial variability in both the intensity and duration of dry periods. In 2015, a peak FMA value of 90.12 occurred after 43 consecutive rain-free days between June and August; however, rainfall was otherwise well-distributed throughout the year, resulting in the lowest overall wildfire risk of the series.

In 2016, four drought events exceeded 25 consecutive rain-free days, producing elevated wildfire risk index values, particularly in August (FMA of 98.50). Intermittent low-intensity rainfall events were insufficient to reset the index, allowing wildfire risk to accumulate in native vegetation.

The highest pre-2021 peaks were observed in July 2017 (FMA = 126.24) and July 2018 (FMA = 134.59), associated with dry spells of 62 and 46 consecutive days, respectively. Scattered rainfall events below the 13 mm reset threshold did not meaningfully reduce the FMA values, resulting in persistent high risk.

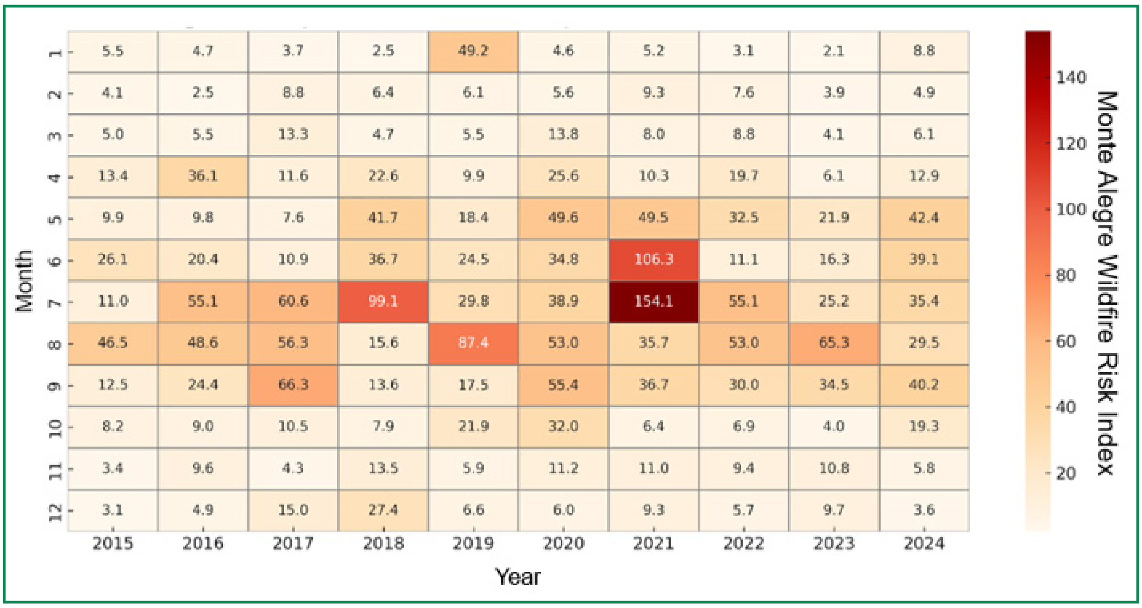
In 2019, two distinct events occurred: an unusual January dry spell lasting 49 days (FMA = 89.28) and another in August lasting 56 days (FMA = 118.85). In 2020, multiple moderate droughts occurred, the most significant in August (45 days, FMA = 113.53) and September (30 days, FMA = 95.09). However, sporadic rainfall during these periods helped mitigate the increase of the index.

The most extreme event in the record occurred in 2021, when 92 consecutive days without rainfall, beginning in June, produced the highest wildfire risk index of the series (FMA = 211.47). This episode represents the most severe wildfire-favorable condition identified during the study period (2015–2024).

After 2021, wildfire risk returned to moderate levels. In 2022, the most notable events were a 25-day dry period in August (FMA = 100.70) and a 27-day dry spell in September (FMA = 78.90). In 2023, a single critical event was observed: 47 consecutive dry days in August (FMA = 97.58). In 2024, five dry spells ranging from 20 to 42 days resulted in distributed wildfire risk throughout the dry season.

Overall, the wildfire risk displays a consistent seasonal pattern from 2015 to 2024 (Figure 6), with peak values between July and September, aligning with the dry season in most tropical and subtropical regions of Brazil. This period is marked by low midday humidity and an absence of precipitation, creating favorable conditions for wildfire ignition and spread.

Figure 6 – Monthly Monte Alegre Formula (FMA) values from 2015 to 2024 in Botucatu, São Paulo, Brazil

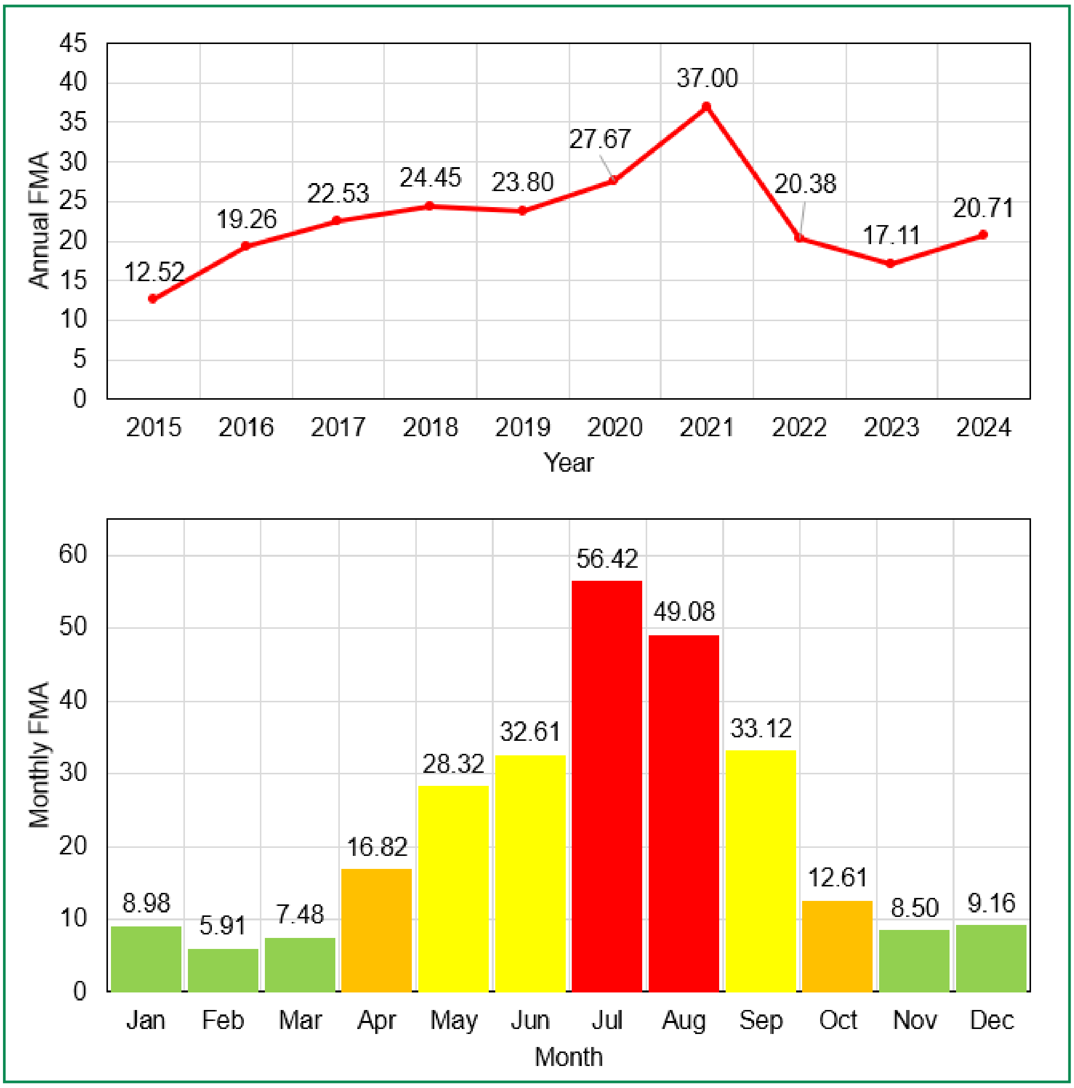


Source: Authors (2025)

The peak wildfire risk value in August 2020 (FMA = 154.1) reflects a period of markedly low relative humidity. The years 2018 and 2020 were notable for prolonged intervals of elevated wildfire risk, with multiple consecutive months registering high index values. Additional critical periods occurred in June 2020, August 2018, and September 2017, when high evaporative demand likely imposed stress on vegetation. Conversely, the lowest values were recorded from January to March, consistent with the humid summer season.

The highest annual mean wildfire risk index occurred in 2021 (FMA = 37.00), which differed statistically from the other years and represented the most critical widlfire-prone period in the time series (Figure 7a). A pronounced seasonal pattern was also evident, with July (FMA = 56.42) and August (FMA = 49.08) exhibiting the highest mean values (Figure 7b), corresponding to the peak of the dry season and the period of greatest wildfire potential.

Figure 7 – Annual and monthly Monte Alegre Formula (FMA) values from 2015 to 2024 in Botucatu, São Paulo, Brazil



Source: Authors (2025)

In 2021, an extreme drought event lasting 92 consecutive days without significant precipitation was observed in the daily dataset. This led to severe vegetation drying and produced the highest wildfire risk index value in the time series. By contrast, 2015 (FMA = 12.52) and 2022 (FMA = 20.38) registered the lowest mean values, driven by more regular rainfall throughout the year and frequent precipitation events exceeding 13 mm, which reset the Monte Alegre Formula (FMA) to zero.

Figure 6b illustrates a pronounced seasonal pattern, with peak mean values in July (FMA = 56.42). This period coincides with the regional winter, when precipitation and relative humidity levels reach their lowest levels. These conditions accelerate the drying of surface fuels, increasing vegetation flammability and wildfire potential.

Intermediate wildfire risk values were observed in May, June, and September (FMA ranging from 28.32 to 33.12), indicating that elevated risk extends beyond the core winter months into late autumn and early spring. Conversely, the lowest values occurred from December to March, reflecting wetter conditions and higher relative humidity, which reduce ignition probability and spread.

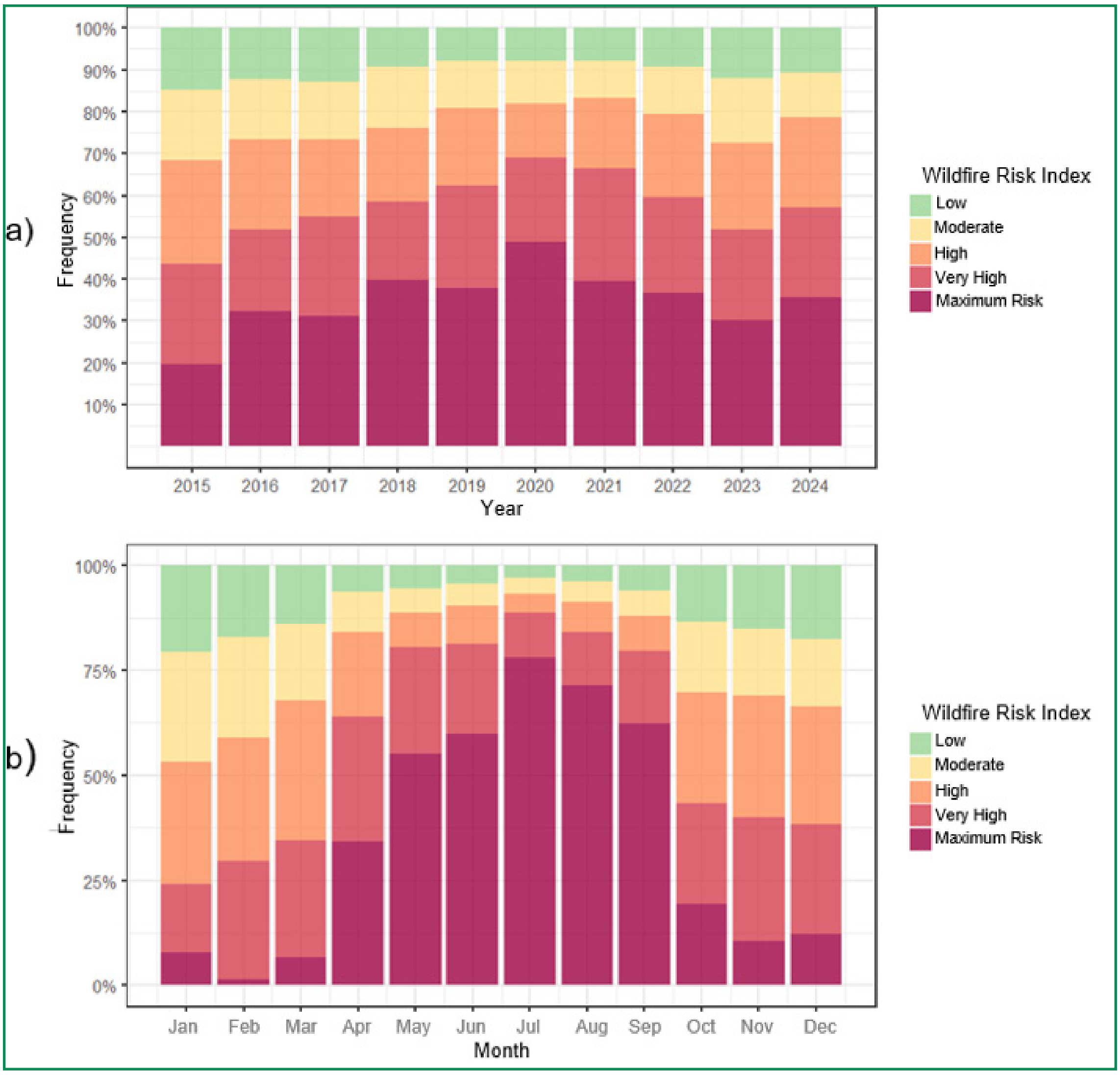
Figure 8 presents the percentage distribution of wildfire risk classes for Botucatu from 2015 to 2024. Winter months (June to September) show the highest proportion of days classified as “very high” and “maximum risk,” consistent with the combination of low relative humidity and scarce precipitation characteristic of this season.

By contrast, summer months (December to March) are dominated by low to moderate risk categories, reflecting humid conditions and reduced vegetation flammability. These results align with previous studies in southeastern Brazil, which emphasize the strong influence of seasonal climate patterns on wildfire occurrence and severity (Alves *et al*., 2014; Santos *et al*., 2021).

Overall, the findings highlight that intra-annual precipitation distribution plays a more critical role in wildfire risk dynamics than total annual rainfall, underscoring the need for continuous monitoring and targeted prevention strategies focused on the dry season.

Across the study period, days classified as “very high” and “maximum risk” accounted for a substantial share of the annual total, ranging from 35% to 55%. This trend was especially pronounced in 2019, 2020, and 2021 — years characterized by prolonged droughts and irregular rainfall distribution, which heightened fuel dryness and increased wildfire risk. Conversely, 2015 and 2022 exhibited a greater proportion of low- to moderate-risk days due to more regular precipitation throughout the year, which helped limit wildfire risk. These patterns underscore the strong influence of seasonal climate variability on wildfire risk dynamics (Figure 8a).

Figure 8 – Relative frequency of Monte Alegre Formula (FMA) wildfire risk categories on an annual and monthly basis for Botucatu, São Paulo, Brazil



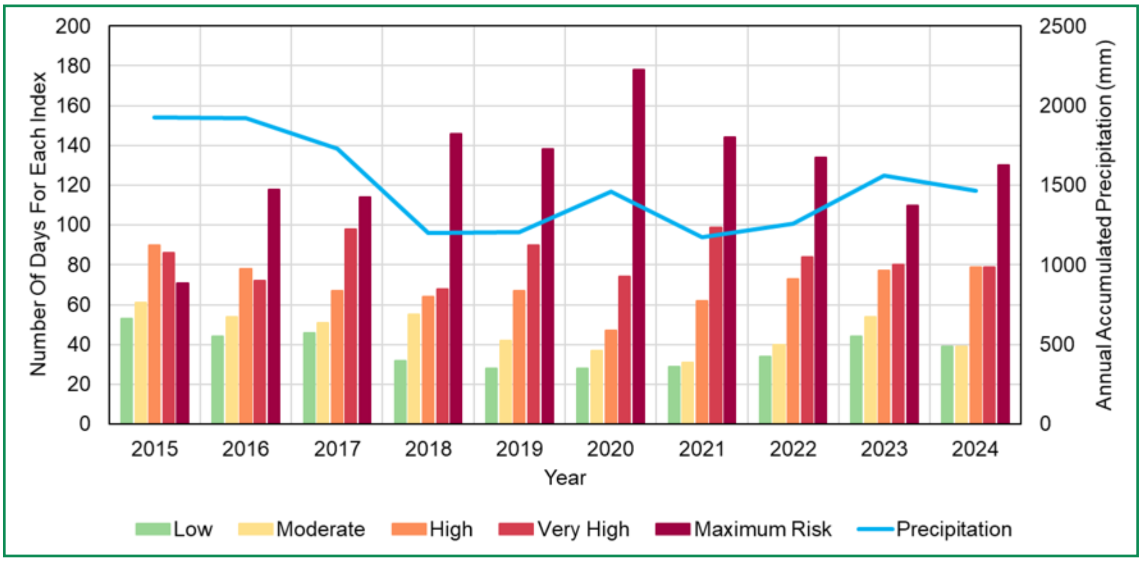
Source: Authors (2025)

A distinct seasonal cycle is evident, with June, July, and August exhibiting the highest percentages of days in the “very high” and “maximum risk” categories, exceeding 80% in some months. This peak aligns with the winter dry season, when reduced precipitation and lower relative humidity accelerate the drying of surface fuels, increasing vegetation flammability and promoting fire ignition and spread (Figure 8b).

By contrast, the rainy season months of December, January, and February show predominantly low and moderate wildfire risk values. This seasonal reversal highlights the effectiveness of the FMA in capturing regional climatic seasonality and its direct influence on wildfire risk.

Figure 9 illustrates the annual number of days in each FMA wildfire risk category, along with annual accumulated precipitation for period 2015–2024 in Botucatu. The combined analysis reveals a clear inverse relationship between precipitation and wildfire severity.

Figure 9 – Annual number of days in each Monte Alegre Formula (FMA) wildfire risk category and annual precipitation totals from 2015 to 2024 in Botucatu, São Paulo, Brazil



Source: Authors (2025)

Years with higher total precipitation, such as 2015, 2016, and 2023 (approximately1,500 to 1,700 mm), exhibited fewer days classified as “very high” and “maximum risk” and a higher frequency of days in the “low,” “moderate,” and “high” categories. This suggests that greater and more evenly distributed precipitation reduces fuel flammability and, consequently, helps mitigate wildfire risk.

Importantly, in all years analyzed, the combined proportion of days classified as “very high” and “maximum risk” exceeded 50% of the annual total. This finding demonstrates the persistent recurrence of critical fire-favorable conditions, even in comparatively wetter years, emphasizing the need for continuous monitoring and sustained prevention strategies, regardless of interannual precipitation variability.

3.3 Preventive measures and priority months for implementation

Considering the seasonal dynamics of wildfire risk in Botucatu (SP), a set of preventive actions is proposed for agroforestry companies, rural properties, and other high-risk areas. Table 3 outlines these measures and the recommended months for their execution, based on observed climatic patterns and fluctuations in the wildfire risk index derived from the FMA. This guidance aims to support strategic planning, resource allocation, staff preparation, and the timely implementation of prevention and rapid-response actions for wildfire management.

Table 3 – Recommended wildfire prevention measures and priority months for implementation in Botucatu, São Paulo, Brazil

Preventive Measures	**Period**	**Remarks**
Construction and maintenance of firebreaks and fuel-break trenches	May to September	Reinforce firebreaks prior to winter and inspect them after heavy rainfall.
Availability of a water truck (*caminhão-pipa*) on standby	May to September	Keep the unit filled and positioned near high-risk areas.
Installation and upkeep of water reservoirs	April to May	Ensure adequate emergency water supply before the dry season.
Training and organization of rural fire brigades	April to May	Train personnel for wildfire suppression before winter.
Maintenance of internal access roads	April to May	Maintain open access routes for firefighting crews and water trucks.
Removal of dry vegetation and residue clearing	April to September	Eliminate accumulated flammable material.
Preventive maintenance of agricultural equipment	April to September	Prevent ignition caused by sparks or equipment overheating.
Inspection of rural electrical systems	April to September	Reduce ignition risk associated with electrical failures.
Daily monitoring of weather and FMA wildfire risk index	May to September	Use FMA values to guide alert levels.
Planning of authorized controlled burns	April to May	Conduct only with authorization from environmental authorities.

Source: Authors (2025)

3.4 Comparative evaluation of the Monte Alegre Formula

Since its development by Soares (1972), the FMA has been extensively applied in Brazil as a meteorology-based tool for assessing wildfire risk, primarily using precipitation and relative humidity. Research conducted across different Brazilian biomes and land-use contexts demonstrates the formula's effectiveness, while also underscoring the need for regional calibration to local climatic regimes and landscape characteristics.

To support a comparative understanding of FMA applications nationwide, Table 4 synthesizes key findings from previous studies, including geographic location, periods of highest wildfire risk, and the main conclusions drawn by the authors.

Table 4 indicates a consistent pattern across the Southeast region, where winter months, particularly August, concentrate the highest wildfire risks, as documented in Piracicaba (SP) by Alves *et al*. (2014) and Cegatta (2018). The present results for Botucatu (SP) align with this trend, reinforcing the importance of the dry season in shaping wildfire conditions in São Paulo state. In southern Brazil, the FMA has also shown strong performance (Tetto *et al*., 2010), although seasonal risk dynamics may vary depending on local climatic regions.

A recurring theme in prior research is the need for regional calibration of FMA. Studies by Nunes *et al*. (2010), Santos *et al*. (2021), Soriano *et al*. (2015), and Kovalsyki *et al*. (2014) emphasize the need to adjust FMA risk thresholds or adopt modified forms such as FMA+ to enhance performance under different bioclimatic settings, including eucalyptus plantation areas, the Pantanal, and the Cerrado.

Consistent with these findings, our results show that July and August represent the most critical months for wildfire occurrence in Botucatu, with a predominance of days classified as "very high" or "maximum risk" during winter, reinforcing the pattern observed in southeastern Brazil. The comparison with long-term precipitation patterns further demonstrates that rainfall timing and distribution are as influential as the total annual rainfall in determining and controlling wildfire risk.

Table 4 – Summary of findings from studies applying the Monte Alegre Formula (FMA) in Brazil

Location	Authors (Year)	Peak-Risk Months	Key Findings
Piracicaba (SP)	Alves *et al*. (2014) e Cegatta (2018)	August	High frequency of maximum-risk days in the dry season; ~75% of August days classified as maximum risk.
Irati (PR)	Tetto *et al*. (2010)	June and August	FMA effective; authors suggested new risk classes to avoid overestimating “high” and “very high” risk days.
São Mateus e Conceição da Barra (ES)	Borges *et al*. (2011)	Most of the year	FMA outperformed other wildfire risk indices and was considered the most suitable for the region.
Região Central de São Paulo (SP)	Santos *et al*. (2021)	Not specified	Recommended modifying FMA risk classes to improve accuracy in productive forest areas.
Telêmaco Borba (PR)	Nunes *et al*. (2010)	Not specified	Original FMA showed inconsistencies; the modified FMA+ version produced superior results for the region.
Nhecolândia (MS)	Soriano *et al*. (2015)	August and September	Regional adjustments recommended for Pantanal conditions to improve wildfire risk estimation (MS/MT).
Ponta Grossa (PR)	Kovalsyki *et al*. (2014)	July and August	Reinforced the need for local calibration of the FMA for improved accuracy.

Source: Authors (2025)

4 CONCLUSIONS

Applying the Monte Alegre Formula (FMA) to the 2015-2024 period in Botucatu (SP), Brazil, enabled the identification of clear seasonal and interannual wildfire risk patterns. The winter months (June-September) emerged as the period of highest vulnerability, especially July and August, underscoring the need for rural producers, agroforestry companies, and environmental protection agencies in the region to adopt targeted preparedness actions. During this season, coordinated prevention efforts are essential, including trained response teams, available wildfire suppression equipment, and robust contingency plans to reduce losses, protect ecosystems, and safeguard rural operations.

Overall, the FMA proved to be an effective tool for operational wildfire risk monitoring. However, its performance can be enhanced through regional calibration of risk class thresholds, in line with previous research. The insights generated in this study can inform proactive management and assist landowners, agroforestry companies, and environmental agencies in planning preventive strategies, and contribute to sustainable territorial management and the mitigation of environmental disasters in Botucatu.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Coordination for the Improvement of Higher Education Personnel (CAPES) for the financial support provided through scholarships (Financial Code 001; Programa de Redução de Assimetrias da Pós-Graduação - PRAPG - 88887.217205/2025-00), which made this work possible. We also thank the São Paulo State University (UNESP) for the institutional support and research infrastructure essential to the development of this study.

REFERENCES

ALBES, C. A.; CEGATTA, I. R.; VIEIRA, L. A. A.; PAVANI, R. F.; MATTOS, E. M.; SENTELHAS, P. C.; STEPA, J. L.; SOARES, R. V. Perigo de incêndio florestal: aplicação da Fórmula de Monte Alegre e avaliação do histórico para Piracicaba, SP. **Scientia Forestal**, v. 42, n. 104, p. 521-532, 2014.

BEU, C. M. L.; Avaliação da fórmula de monte alegre modificada aplicada aos dados da Flona de Ipanema, Merra-2 e produtos de sensoriamento remoto, **Revista Brasileira de Climatologia**, Dourados, MS, v.31, jul./dez.2022.

BORGES, T. S.; FIEDLER, N. C.; SANTOS, A. R.; LOUREIRO, E. B.; MAFIA, R. G. Desempenho de Alguns Índices de Risco de Incêndios em Plantios de Eucalipto no Norte do Espírito Santo. **Floresta e Ambiente**, n.18 v.2, p.153-159. 2011.

CAVALCANTE, R. B. L.; SOUZA, B. M.; RAMOS, S. J.; GASTAUER, M.; NASCIMENTO, W. R.; CALDEIRA, C. F.; SOUZA-FILHO, P. W. M. Assessment of fire hazard weather indices in the eastern Amazon: a case study for different land uses. **Acta Amazonica**, v. 51, n.4, p. 352 – 362, 2021. DOI: http://dx.doi.org/10.1590/1809-4392202101172

CEGATTA, I. **Risco de incêndio pela Fórmula de Monte Alegre**. Available at: https://italocegatta.github.io/risco-de-incendio-pela-formula-de-monte-alegre/. Accessed on: 22 de set. de 2024.

COSTA, A. DAS G.; LIMA, G. S.; TORRES, F. T. P.; RODRIGUES, V. B.; SILVA JÚNIOR, M. R. DA; ALMEIDA, M. P. DE. Causas e período de ocorrência de incêndios florestais em unidades de conservação federais brasileiras de 2006 a 2012. **Ciência Florestal**, v. 33, n. 2, 2023. DOI: https://doi.org/10.5902/1980509869028

COLONICO, M.; TOMAO, A.; ASCOLI, D.; CORONA, P.; GIONNINO, F.; MORIS, J. V.; ROMANO, R., SALVATI, L., BARBATI, A. Rural development funding and wildfire prevention: Evidences of spatial mismatches with fire activity. **Land Use Policy**. v. 117. 2022. DOI: https://doi.org/10.1016/j.landusepol.2022.106079

Defesa Civil de SP atua na prevenção de queimadas e alerta para riscos de incêndio. São Paulo: Portal do Governo do Estado de São Paulo, 7 maio 2024. Available at: https://www.saopaulo.sp.gov.br. Accessed on: 4 Aug. 2024.

FRANCO. J. R.; DAL PAI, E.; CALÇA, M. V. C.; RANIERO, M. R.; DAL PAI, A; SARNIGHAUSEN, V. C. R. SÁNCHEZ ROMÁN. R. M., Atualização da normal climatológica e classificação climática de Köppen para o município de Botucatu-SP, **Irriga**, v. 28, n. 1, p. 77-92, 2023. DOI: http://dx.doi.org/10.15809/irriga.2023v28n1p77-92

JANOME, L. **Incêndios florestais no Brasil causaram prejuízo de R$1,1 bilhão em seis anos**. 2021. Available at: https://www.cnnbrasil.com.br/economia/macroeconomia/incendios-florestais-no-brasil-causaram-prejuizo-de-r-11-bilhao-em-seis-anos/#:~:text=Al%C3%A9m%20de%20perdas%20humanas%20e,aos%20cofres%20p%C3%BAblicos%20do%20pa%C3%ADs. Accessed on: 20 Apr. 2025.

JONES, M. W., *et al.,* **State of Wildfires 2023–2024, Earth Syst. Sci. Data, 16, 3601–3685**, DOI: https://doi.org/10.5194/essd-16-3601-2024

KOVALSYKI, B.; TETTO, A. F.; BATISTA, A. C.; SOUSA, N. J.; TAKASHINA, I. K. Avaliação da eficiência da fórmula de monte alegre para o Município de ponta grossa – pr. A, **Centro Científico Conhecer - Goiânia**, v.10, n.19, 2014.

LI, T.; CUI, L.; LIU, L; CHEN, Y.; LIU, H.; SONG, X., XU, Z. Advances in the study of global forest wildfires. **J Soils Sediments**, n. 23, p. 2654–2668, 2023. DOI: https://doi.org/10.1007/s11368-023-03533-8

LORENZO, J. M.; TERAMOTO, E. T.; SÁNCHEZ-ROMAN, R. M.; ORELLANA GONZÁLEZ, A. M. G.; ESCOBEDO, J. F. Influência das queimadas no comportamento das chuvas nos municípios de Botucatu e Piracicaba, Estado de São Paulo. **Irriga**, Botucatu, Edição Especial, IRRIGA & INOVAGRI, p.168-178, 2015. DOI: https://doi.org/10.15809/irriga.2015v1n2p168

MACCAETHY, J.; RICHTER, J.; TYUKAVINA, S.; WEISSE, M.; HARRIS, N. **The Latest Data Confirms: Forest Fires Are Getting Worse**. 2024. Available at: https://www.wri.org/insights/global-trends-forest-fires. Accessed on: 20 Apr. 2025.

MÁQUINA, D. A.; SILVA, A. J. V.; COSTA, A. A.; VINTUAR, P. A.; BASÍLIO, G. A.; DESCANSO, L. L. INÁCIO, J. P.; MALEI, B. A.; MARQUES, G. C. A. Mapeamento da susceptibilidade a ocorrência de incêndios florestais na província de Niassa, Moçambique. **LUMEN ET VIRTUS**, p.4973-4988, 2024. DOI: https://doi.org/10.56238/levv15n41-007

MARFELLA, L., MAIROTA, P., MARZAIOLI, R.; GLANVILE, H. C.; PAZIENZA, G.; RUTIGLIANO, F. A. Long-term impact of wildfire on soil physical, chemical and biological properties within a pine forest. **Eur J Forest Res**, 2024. DOI: https://doi.org/10.1007/s10342-024-01696-8

MARQUES, G. **Brasil registra 46% das queimadas na América do Sul em 2024**. UOL. Available at: https://noticias.uol.com.br/cotidiano/ultimas-noticias/2024/08/29/focos-incendios-queimadas-brasil-amazonia-america-do-sul-paises.htm. Accessed on: 20 Apr. 2025.

MOLINA, J. R.; GONZÁLEZ-CABÁN, A.; SILVA, F. R. Potential Effects of Climate Change on Fire Behavior, Economic Susceptibility and Suppression Costs in Mediterranean Ecosystems: Córdoba Province, **Forests**. V. 10 n. 8, 2019. DOI: https://doi.org/10.3390/f10080679

NUNES, J. R. S.; FIER, I. S. N.; SOARES, R. V.; BATISTA, A. C. Desempenho da Fórmula de Monte Alegre (FMA) e da Fórmula de Monte Alegre Alterada (FMA+) no Distrito Florestal de Monte Alegre, **Floresta**, v. 40, n. 2, p. 319-326, abr./jun. 2010.

PIVELLOA, V. R.; VIEIRAB, I.; CHRISTIANINIC, A. V.; RIBEIROD, D. B.; MENEZESE, L. S.; BERLINCKF, C. N.; MELOG, F. P. L.; MARENGOH, J. A.; TORNQUISTI, C. G.; TOMASJ, W. M.; OVERBECKE, G. E. Understanding Brazil's catastrophic fires: Causes, consequences and policy needed to prevent future tragedies. **Perspectives in ecology and conservation**. V. 19. n 3. pp 233-255, 2021. DOI: 10.1016/j.pecon.2021.06.005.

SANTOS, J. F. L.; KOVALSYKI, B. FERREIRA, T. S.; PAJEWSHI, F. BATISTA, A. C.; TETTO, A. F.; SOARES, R. V.; Adaptation of the Fórmula de Monte Alegre for the danger prediction of forest fires in the central region of São Paulo state. **Ciência Florestal**, v. 31, n. 4, p. 1867-1884, 2021. DOI: https://doi.org/10.5902/1980509852851

SAYEDI, S.S., ABBOTT, B.W., VANNIÈRE, B. *et al*. Assessing changes in global fire regimes. **fire ecol,** n. 20, v. 18, 2024. https://doi.org/10.1186/s42408-023-00237-9

SILVA, I. D. B.; VALLE, M. E.; BARROS, L. C.; MEYER, J. F. C. A. A wildfire warning system applied to the state of Acre in the Brazilian Amazon. **Applied Soft Computing**. V. 98, 2020. DOI: doi.org/10.1016/j.asoc.2020.106075

SINGH, S. Forest fire emissions: A contribution to global climate change. **Frontiers**, v. 5, 2022. https://doi.org/10.3389/ffgc.2022.925480

SORIANO, B. M.; DANIEL, O.; SANTOS, S. A. Eficiência de índices de risco de incêndios para o Pantanal Sul-Mato-Grossense. **Ciência Florestal**, v. 25, n. 4, p. 809-816, 2015. DOI: http://dx.doi.org/10.5902/1980509820231

SOARES, R. V. **Determinação de um índice de perigo de incêndio para a região centro paranaense, Brasil**. 72 p. Dissertação (Mestrado) - Instituto Interamericano de Ciências Agrícolas da OEA, Turrialba, Costa Rica, 1972

ROSSI, T. J.; ESCOBEDO, J. F.; SANTOS, C. M.; ROSSI, L. R.; SILVA, M. B. P.; DAL PAI, E. Global, diffuse and direct solar radiation of the infrared spectrum in Botucatu/SP/Brazil. **Renewable and Sustainable Energy Reviews**, v. 82, p. 448-459, 2018.

TETTO, A. F.; BATISTA, A. C.; SOARES, R. V.; NUNES, J. R. S. Comportamento e ajuste da fórmula de Monte Alegre na Floresta Nacional de Irati, Estado do Paraná. **Scientia Forestalis**, Piracicaba, v. 38, n.87, p. 409-417, set. 2010.

VIEIRA, H.J.; MISZINSKI, J.; BLAINSKI, É. **Risco de incêndio florestal**: Fórmula de Monte Alegre (FMA). Florianópolis – SC: Epagri, 2020. 6p. (Relatório do sistema AGROCONNECT). Available at: https://ciram.epagri.sc.gov.br/ciram_arquivos/agroconnect/boletins/Metodologia_Risco_Incendio.pdf. Accessed on: 20 Apr. 2025.

VIEGAS, D. X.; REIS, R. M.; CRUZ, H. G.; VIEGAS, M. T. V. Calibração do sistema canadiano de perigo de incêndio para aplicação em Portugal. **Silva Lusitana**, v. 12, n. 1, p. 77-93, 2004.

WASSERMAN, T. N., MUELLER, S. E. Climate influences on future fire severity: a synthesis of climate-fire interactions and impacts on fire regimes, high-severity fire, and forests in the western United States. **fire ecol,** v. 19, n. 43, 2023. DOI: https://doi.org/10.1186/s42408-023-00200-8

WARNES, G.; BOLKER, B; BONEBAKKER, L.; GENTLEMAN, R.; HUBER, W.; LIAW, A.; LUMLEY, T.; MAECHLER, M.; MAGNUSSON, A.; MOELLER, S.; SCHWARTZ, M.; VENABLES, B.; GALILI, T. **gplots**: Various R Programming Tools for Plotting Data. R package version 3.2.0. 2024. Available at: https://CRAN.R-project.org/package=gplots. Accessed on: 20 Apr. 2025.

WICKHAM H.; CHANG W; HENRY L.; PEDERSEN T. L.; THOMAS TAKAHASHI, K. **ggplot2**: Create Elegant Data Visualisations Using the Grammar of Graphics. 2023. Available at: https://cran.r-project.org/web/packages/ggplot2/index.html. Accessed on: 20 Apr. 2025.

Authorship Contribution

1 José Rafael Franco

Systems Analysis and Development Technologist, PhD in Agricultural Engineering, Professor at FATEC Botucatu

https://orcid.org/0000-0002-7129-4304 • jose_rafael.franco@hotmail.com

Contribution: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Writing – original draft; Writing – review & editing

2 Sonia Maria Fernandes Ustulin

Forestry Engineer, PhD Candidate in Forest Science at São Paulo State University (UNESP)

https://orcid.org/0000-0003-1425-5875 • sonia.ustulin@unesp.br

Contribution: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Supervision; Validation

3 Maria José Brito Zakia

Forestry Engineer, PhD in Environmental Engineering Sciences, Professor of the Professional Master's Program at ESCAS-IPE and Accredited Professor of the Graduate Program in Forest Resources at FCA/UNESP

https://orcid.org/0000-0002-9920-6230 • zeze.zakia@gmail.com

Contribution: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Supervision; Validation

4 Victor Crespo de Oliveira

Agricultural Engineer, PhD in Agricultural Engineering, Assistant Professor at the Federal University of São Carlos (UFSCar), Center for Nature Sciences (CCN)

https://orcid.org/0000-0003-2719-9972 • oliveiracrespovictor@gmail.com

Contribution: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Writing – original draft; Writing – review & editing

5 Matheus Rodrigues Raniero

Systems Analysis and Development Technologist, PhD in Agronomy (Energy in Agriculture)

https://orcid.org/0000-0001-8338-4887 • matheus.raniero@hotmail.com

Contribution: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Writing – original draft; Writing – review & editing

6 Valdemiro Simão João Pitoro

Agricultural Engineer, PhD Candidate in Agricultural Engineering, Professor at UniLúrio (Mozambique)

https://orcid.org/0000-0002-3871-3124 • valdemiro.pitoro@unesp.br

Contribution: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Writing – original draft; Writing – review & editing

7 Marcus Vinícius Contes Calça

Systems Analysis and Development Technologist, PhD in Agronomy (Energy in Agriculture), Professor at SENAI Botucatu

https://orcid.org/0000-0002-5685-3980 • mcontes@outlook.com

Contribution: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Writing – original draft; Writing – review & editing

8 Enzo Dal Pai

Agronomist, PhD in Agronomy (Energy in Agriculture), Professor at São Paulo State University (UNESP)

https://orcid.org/0000-0002-0570-8644 • enzo-dal.pai@unesp.br

Contribution: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Supervision; Validation

How to quote this article

FRANCO, J. R.; USTULIN, S. M. F.; ZAKIA, M. J. B.; OLIVEIRA, V. C.; RANIERO, M. R.; PITORO, V. S. J.; CALÇA, M. V. C.; DAL PAI, E. D. Forest fire risk assessment in Botucatu, São Paulo (2015-2024) using the Monte Alegre Method. **Ciência Florestal**, Santa Maria, v. 36, e 92101, p. 1-26, 2026. DOI 10.5902/1980509892101. Available from: https://doi.org/10.5902/1980509892101. Accessed in: day month abbr. year.

Data Availability Statement:

Datasets related to this article will be available upon request to the corresponding author.