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Spatiotemporal analysis of fire occurrence along the Carajás Railway corridor, Eastern Amazon (2012–2021)

Análise espaço-temporal da ocorrência de incêndios ao longo da Estrada de Ferro Carajás, Amazônia Oriental (2012–2021)

Aécio Marcos Cunha [*], **Emily Ane Dionízio** [*], **Paulo Rógenes Monteiro Pontes** [*], **Rosane Barbosa Lopes Cavalcante** [**]

[*] Instituto Tecnológico Vale
[**] Instituto Tecnológico Vale, rosanecavalcante@gmail.com

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Abstract

Fire is commonly used in the Amazon for land clearing and management, resulting in significant environmental and climatic impacts, including greenhouse gas emissions, biodiversity loss, and air pollution. Understanding the spatiotemporal dynamics of fire occurrences is essential for improving prevention strategies and prioritizing areas for monitoring and control. This study aims to analyze the spatial and temporal distribution of fire hot spots along the Carajás Railway (CR), which connects mining areas in southeastern Pará to the port in Maranhão. We examined detected satellite-based hot spots from 2012 to 2021 across 28 municipalities intersected by the railway. We combined intra-annual and interannual analyses with land use and land cover classifications from the MapBiomas Project and applied Kernel Density Estimation to identify high-risk zones over time. The results indicate that fire activity peaks occurred in 2015 and 2017, largely influenced by El Niño events, with fire-prone zones shifting spatially throughout the fire season. Pastures accounted for over 98,000 fire records, followed by forest formations with over 62,000, reflecting the vulnerability of both anthropogenic and native landscapes. The findings highlight the importance of integrating fire forecasts with climatic and land-use monitoring to inform adaptive management strategies along key infrastructure corridors in the Eastern Amazon.

Keywords:
Forest fires, Land use, Kernel density estimation, Railway corridor.

Resumo

O fogo é comumente utilizado na Amazônia para limpeza e manejo da terra, resultando em impactos ambientais e climáticos significativos, incluindo emissões de gases de efeito estufa, perda de biodiversidade e poluição do ar. Compreender a dinâmica espaço-temporal da ocorrência de incêndios é essencial para melhorar as estratégias de prevenção e priorizar áreas para monitoramento e controle. Este estudo tem como objetivo analisar a distribuição espacial e temporal dos focos de calor ao longo da Estrada de Ferro Carajás (EFC), que conecta áreas de

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mineração no sudeste do Pará ao porto no Maranhão. Foram examinados focos de calor detectados por satélite entre 2012 e 2021 em 28 municípios cortados pela ferrovia. Combinamos análises intra e interanuais com classificações de uso e cobertura da terra do Projeto MapBiomas e aplicamos a Estimativa de Densidade por Kernel para identificar zonas de alto risco ao longo do tempo. Os resultados indicam picos de atividade de fogo em 2015 e 2017, influenciados por eventos de El Niño, com zonas propensas a incêndios se deslocando espacialmente ao longo da estação de queimadas. As pastagens responderam por mais de 98 mil registros de fogo, seguidas por formações florestais com mais de 62 mil, refletindo a vulnerabilidade tanto de paisagens antrópicas quanto nativas. Os achados destacam a importância de integrar previsões de incêndios com o monitoramento climático e do uso da terra para orientar estratégias adaptativas de manejo na Amazônia Oriental.

Palavras-chave:
Incêndios florestais, Uso da terra, Estimativa de densidade por kernel, Corredor ferroviário.

I. INTRODUCTION

The Amazon is recognized as one of the most biodiverse regions on the planet (Jenkins et al., 2013; Raven et al., 2020; IUCN, 2024), playing a critical role in global climate regulation and carbon cycling (Jung et al., 2021). However, the region continues to experience mounting pressures from land use change, particularly deforestation for the expansion of cattle ranching and monocultures (MapBiomas, 2024). While the probability of fire occurring naturally in the Amazon rainforest is low (Cochrane, 2009), fire is extensively employed as a method for clearing and maintaining pastures and agricultural areas (Alencar et al., 2020; Miranda et al., 2018; Pinto et al., 2017). However, it has been observed that such fires can become uncontrollable (Aragão; Shimabukuro, 2010). Forest fires contribute to forest degradation (Xaud et al., 2013; Lapola et al., 2023), greenhouse gas (GHG) emissions (Cochrane, 2009; Van der Werf et al., 2010) and air pollution (Rocha; Sant'Anna, 2022; Oliveira et al., 2023), with impacts on human health and risk to life (Human Rights Watch et al., 2020).

In addition to this relation with land use, especially deforestation (Martinez et al., 2017), fire events in the Amazon are also influenced by the climate intra-annual variability, with almost all events occurring during the dry season, and interannual variability, which oscillates between drier or wetter years depending on the influence of meteorological phenomena such as the El Niño–Southern Oscillation (ENOS). In the Amazon, El Niño events have been shown to be associated with prolonged droughts and an elevated risk of uncontrolled fires (Masullo, 2018; Sodré et al., 2018). During drier years, fires have been observed to enter forest areas (Latorre et al., 2016), particularly in areas that have previously experienced degradation, resulting in damage to both primary and secondary forests (Nepstad et al., 1999; 2004; Aragão et al., 2008; Cochrane; Barber, 2009). The

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current fire season in the Amazon is already increasing (Jolly et al., 2015), and with climate change, an increase in the frequency of fires and the duration of the fire season in the region is expected (Sun et al., 2019). This increase in fires has a synergistic and feedback effect related to that caused by land use (Castelanos et al., 2022).

The year 2024 saw the second-largest annual burned area in Brazil since 1985, and for the first time, forest formation was the land use class most affected by fire in the Amazon, surpassing pasture (MapBiomas Queimadas, 2025). In 2023, the state of Pará had the highest GHG emissions due to land use changes and fires (SEEG, 2024). One region of particular concern is the area surrounding the Carajás Railway (CR), which traverses 28 municipalities across the states of Pará and Maranhão. The CR is a major logistics corridor for iron ore exportation, and its route intersects a variety of ecological zones, including preserved forests, pasturelands, and areas of ongoing land conversion. The mosaic of land use, in conjunction with the region's seasonal climatic conditions, renders the area susceptible to recurrent fire outbreaks. These conflagrations pose risks not only to areas of natural vegetation but also to the populations residing in proximity to the railway network.

The utilization of satellite imagery in the monitoring of fire occurrences has proven to be of paramount importance. This approach has facilitated the tracking of spatiotemporal patterns and the analysis of changes in fire regimes. Moreover, the insights derived from this monitoring have contributed to the formulation of public policies related to environmental conservation and fire management (Anderson et al., 2017; Fragal; Gasparetto, 2017). Satellites employ thermal sensors to detect and record data on fire occurrences. These sensors are capable of identifying hot spots on the ground surface, which are commonly associated with fires. The efficacy of the model in identifying fire-prone zones has been demonstrated, and it can support the development of fire prevention strategies, particularly in areas experiencing increasing anthropogenic pressure, such as the eastern Amazon.

In this context, the objective of this study is to analyze the spatial and temporal patterns of fire occurrences along the CR corridor from 2012 to 2021. The study utilizes satellite fire detection data and land use and land cover (LULC) information to identify fire risk areas and support improved fire management practices in the eastern Amazon. The occurrence of fires in the vicinity of the CR can result in its shutdown, which can have significant ramifications for freight and passenger transport, as well as for the surrounding communities and the ecosystem. The expansion of the study area to the municipal boundaries was due to the effect of political factors on the occurrence of fires, including municipal actions and legislation pertaining to this subject. This analysis enabled us to understand the spatial distribution of fire in the region not only as a result

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of natural variations, such as climate, but also as a socially produced process that is reflected in land use and local management practices, which shape territories at environmental risk.

A multitude of studies have examined the distribution of hotspots according to LULC types in the Amazon region. However, these studies have typically focused on a specific municipality or protected area (see Pereira et al., 2018; Gama et al., 2019; Santos et al., 2021). By evaluating a larger region of great economic importance, this study enables the identification of areas with higher fire occurrences that extend beyond municipal boundaries. Consequently, this study optimizes fire management while maintaining the level of detail necessary to define actions at the municipal and regional scales. This, in turn, supports public-private risk management initiatives.

II. Materials and Methods

Study area

The present study focuses on the municipalities intersected by the CR, an 892-kilometer corridor extending from the municipality of Canaã dos Carajás in southeastern Pará to the Port of Ponta da Madeira in São Luís, Maranhão (Figure 1). The CR traverses a region of significant ecological and economic importance, characterized by a diverse mosaic of land use types, including preserved forests, secondary vegetation, pastures, urban areas, and zones of mineral extraction. The railway traverses a total of 27 municipalities, with five located in Pará and 22 in Maranhão, encompassing an area of approximately 176,000 km².

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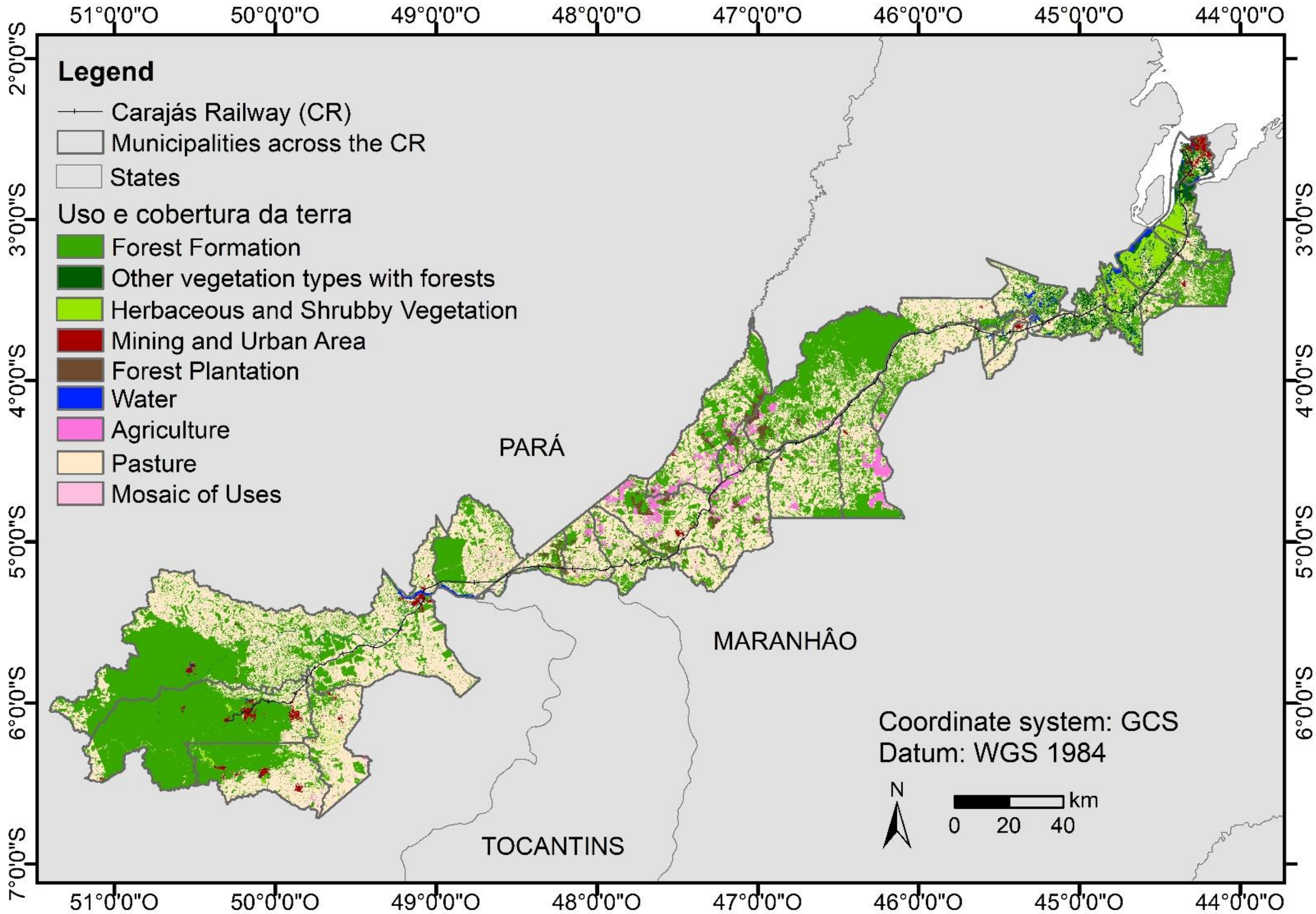

Figure 1 – Land use and land cover for the municipalities along the Carajás Railway in 2021 (Source: Mapbiomas Project).

The area falls within the Amazon biome, and forests and pasture currently dominate land use and land cover throughout the municipalities analyzed (Figure 1). The original vegetation in Pará was predominantly dense ombrophilous forests, with open ombrophilous forests and montane vegetation refuges in the municipalities south of the RC, corresponding to ferruginous rocky fields. In Maranhão, the vegetation included dense lowland ombrophilous forests, alluvial semi-deciduous seasonal forests, and pioneer fluvial and lacustrine formations and fluviometric influences (IBGE, 2022).

The prevailing climatic classification in this region is designated as Aw (tropical with summer rain) with a dry winter according to the Köppen (1948) classification system. This climate is characterized by a rainy season that extends from November to April during the summer months, and a distinct dry season that occurs from

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May to October, with July being the month with the least precipitation. The mean annual temperature is 27.4 °C, and the mean annual rainfall is 1,900 mm.

Fire hotspot data

The data regarding fire occurrences were obtained from the Burned Area Database of the Brazilian National Institute for Space Research (INPE). The database provides daily satellite detections of active fire hotspots based on thermal anomalies captured by multiple sensors. The Visible Infrared Imaging SpectroRadiometer Suite (VIIRS) sensor aboard the Suomi National Polar-orbiting Partnership (NPP-Suomi) was selected as the reference satellite. The spatial resolution of this sensor is 375 meters, and it undergoes daily revisit (NASA, 2020). Theoretically, the minimum detectable night fire area is 5 m^2, and fires with temperatures reaching 1000 K have an average commission error of 1.2% (Schroeder et al., 2014). The product provides the centroid of all pixels with fire detection. Utilizing a solitary reference satellite enables the comparison of spatial and temporal data without the confounding effects of the number of satellites and passes. This approach facilitates the composition of time series over extended periods, thereby enabling the analysis of trends in the number of outbreaks within specific regions and between regions during designated periods of interest.

NPP-Suomi was launched in 2011, and data are collected with the VIIRS sensor at 375 m resolution. For the present study, fire hot spot data were extracted for the period from January 2012 to December 2021. Each hotspot is accompanied by specific details, including the date of detection, geographical coordinates, and the time at which the signal was first detected. Monthly and annual aggregations were conducted by each municipality to assess inter- and intra-annual analyses.

Kernel density estimation

To characterize the spatial distribution of fire activity during the dry season, we applied Kernel Density Estimation (KDE) (Bailey; Gratell, 1995). KDE is a non-parametric spatial analysis method that calculates the density of events (in this case, fire hot spots) over a continuous surface, enabling the identification of clusters and high-risk areas.

KDE outputs were generated using the ArcGIS software with a default search radius (bandwidth) calculated based on the spatial configuration and quantity of input points. This calculation was implemented to address the issue of spatial outliers. The Quartic Kernel function (Silverman, 1986) (see below) is employed to

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calculate the density, where: i = 1,…,n are the hotspots points within the search radius; pop_i is the value of point i, which is an optional parameter, and $dist_i$ s the distance between point i and the location (x,y).

$$Density = \frac{1}{radius^2} \sum_{i=1}^{n} \left[.pop_i \left(1 - \left(\frac{dist_i}{raio} \right)^2 \right)^2 \right] \text{ (Equation 1)}$$

The resultant data were then categorized into five distinct risk levels: very low (0-1000 hot spots per year), low (1001-2000), medium (2001-6500), high (6501-10000), and very high (10001-100000), based on the annual fire occurrence. In order to analyze the monthly data, the aforementioned limits were divided by 12.

Temporal clustering of fire occurrences was also examined to identify seasonal patterns and interannual variability. A Geographic Information System (GIS) analysis was conducted to visualize the annual spatial shift of high-density fire areas. To this end, Kriging density-based (KDE) maps were generated for different months and subsequently compared to ascertain their geographic concentration.

Land use and land cover classification

The data concerning land use and land cover (LULC) from 2012 to 2021 were obtained from the MapBiomas Project – Collection 7 (MapBiomas, 2021). MapBiomas is a source of annual LULC classifications for Brazil, with a spatial resolution of 30 meters. These classifications are derived from Landsat imagery and automated classification algorithms.

Each fire hotspot was spatially overlaid on the corresponding LULC map for the year of occurrence to quantify the number and density of fire events by land use class. This approach facilitated the identification of LULC types that were most affected by fires. It also supported the interpretation of spatial fire patterns in relation to anthropogenic and natural landscapes.

Statistical analyses

In order to assess whether the occurrence of fires presents a non-random spatial pattern, we employed Moran's I index, which was applied to the hotspot density maps for all years. This index is designed to quantify spatial autocorrelation, defined as the phenomenon in which similar values (high or low) are observed to occur in geographically proximate locations. The magnitude of Moran's I is indicative of the extent of spatial clustering, with higher values indicating more pronounced patterns. The test also provides a p-value, which indicates the probability that the observed pattern occurred by chance. A value of $p < 0.05$ indicates statistical significance of the clustering. The analysis was executed using ArcGIS Pro software.

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In order to assess the distribution and differences in hotspot density among land use classes, a preliminary normality check of the data by group was performed using the Shapiro-Wilk test. In cases with more than 5,000 observations, random sampling was applied. Given the non-normal distribution of the data, the Kruskal-Wallis test with Wilcoxon pair-wise comparisons was employed to assess the mean fire density among various land uses (forest, pasture, and others) across each year.

III. Results

Hotspot detection

From 2012 to 2021, a total of 194,490 fire hot spots were documented across the 27 municipalities along the Carajás Railway. The annual values reached their zenith in 2015 (particularly in Pará's municipalities) and 2017 (particularly in Maranhão's municipalities) (Figure 2A). The first one was associated with strong El Niño episodes that intensified drought conditions.

Among the municipalities, Marabá (Pará) exhibited the highest number of hotspots during the analyzed period, with over 38,000 recorded across the 10-year period (Figure 2A). Given the municipality's area (15,128 km²), this corresponds to an average of 0.25 hotspots per year per km². However, when only unprotected areas are considered, the municipality of Parauapebas leads the municipalities of Pará with 0.58 hotspots per year per km² of unprotected municipal area. In Maranhão, higher densities were observed, notably in the municipality of Buriticupu, which had an average of 0.69 hotspots per year per km² (Figure 2B).

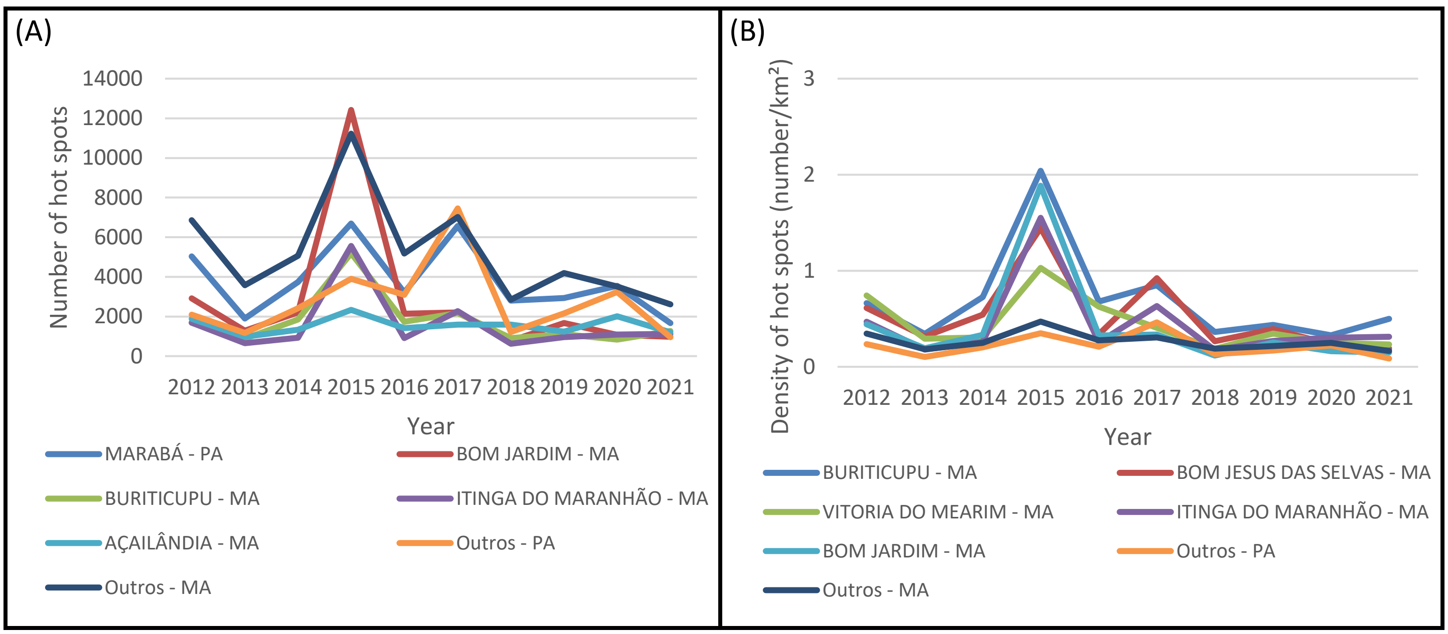

Figure 2 – (A) Total number and (B) density of hotspots in municipalities along the Carajás railway in Pará and Maranhão from 2012 to 2021. The five municipalities with the highest average values are presented, and the rest are grouped by state: Pará (PA) and Maranhão (MA).

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A close examination of the data reveals a notable seasonal pattern in the occurrence of fires. The majority of detections—approximately 92%—occurred between August and December. This period, which corresponds to the critical trimester in Pará's municipalities, is particularly salient. In contrast, the months of August through October—the critical trimester in Maranhão's municipalities—experienced a significant surge in fire activity (Figure 3). In most years, October alone accounts for 26% of the annual fire activity. Notwithstanding the occurrence of interannual variations, the dry-season pattern demonstrated consistency across the span of the decade.

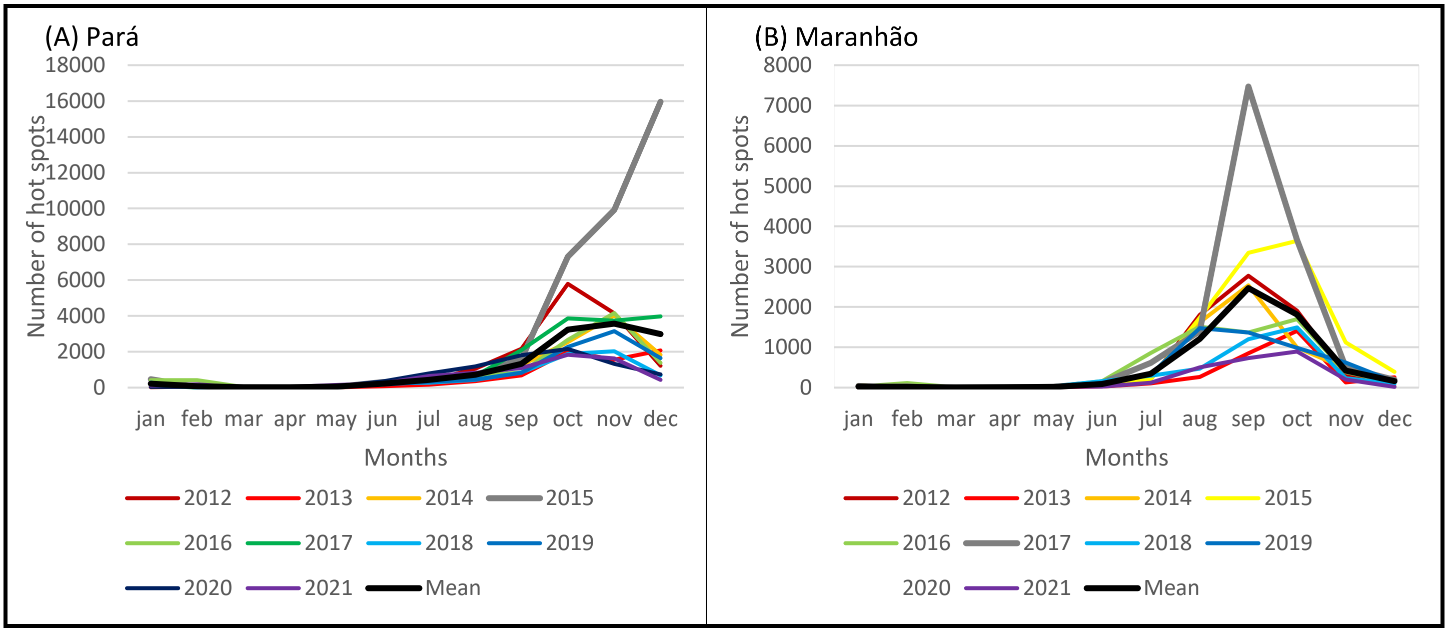

Figure 3 – Number of hotspots per month for municipalities along the Carajás highway in the states of Pará (A) and Maranhão (B). The mean monthly values (black) and the values for the year with the highest number of hotspots (dark gray) are highlighted.

Hot spots density maps

Given the minimal incidence of fires in the study region during the initial six months of the year, the majority of the region was designated as having an extremely low risk of fire occurrence. In January, May, and June, only minor regions were designated as having a moderate risk.

During the second semester, KDE revealed distinct spatial patterns in fire occurrence, with high-density areas shifting across the railway corridor throughout the dry season. From July to September, high and very high fire risk zones were predominantly concentrated in the southwestern segment of the railway, primarily in Pará state. In October, the vast majority of the region is classified as being in a high-risk category, with the exception of the areas designated as protected (Figure 4). From November to December, a notable shift in the spatial

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concentration of fire risk was observed, with a notable increase in risk observed in the northeastern portion of the corridor, particularly in the western region of Maranhão.

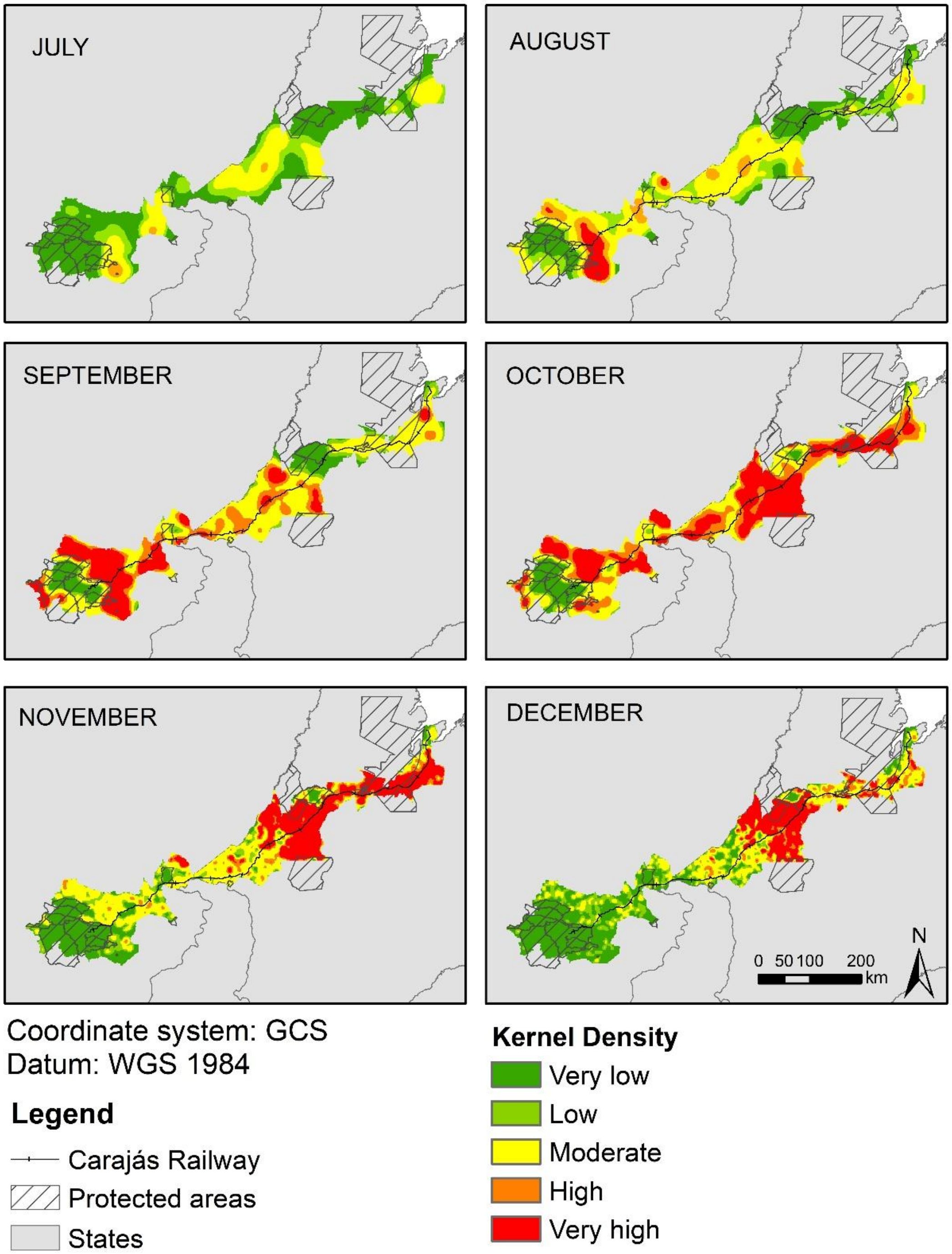

Figure 4 – Fire risk, as determined by the density of historical hotspot occurrences, is examined from July to December within the municipalities of the Carajás Railway Corridor.

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The results of the annual kernel density analyses demonstrate that in the years with the highest occurrence of hotspots (2015 and 2017), these were concentrated in the central region of the CR in the municipalities of Itinga do Maranhão, Bom Jardim, and Buriticupu, and in the southern portion of the study area in the municipalities of Marabá and Curionópolis. In 2013 and 2021 (Figures 5C and 5D), which had the lowest totals of hotspots, there were only small areas with a high to very high occurrence rating in the central region.

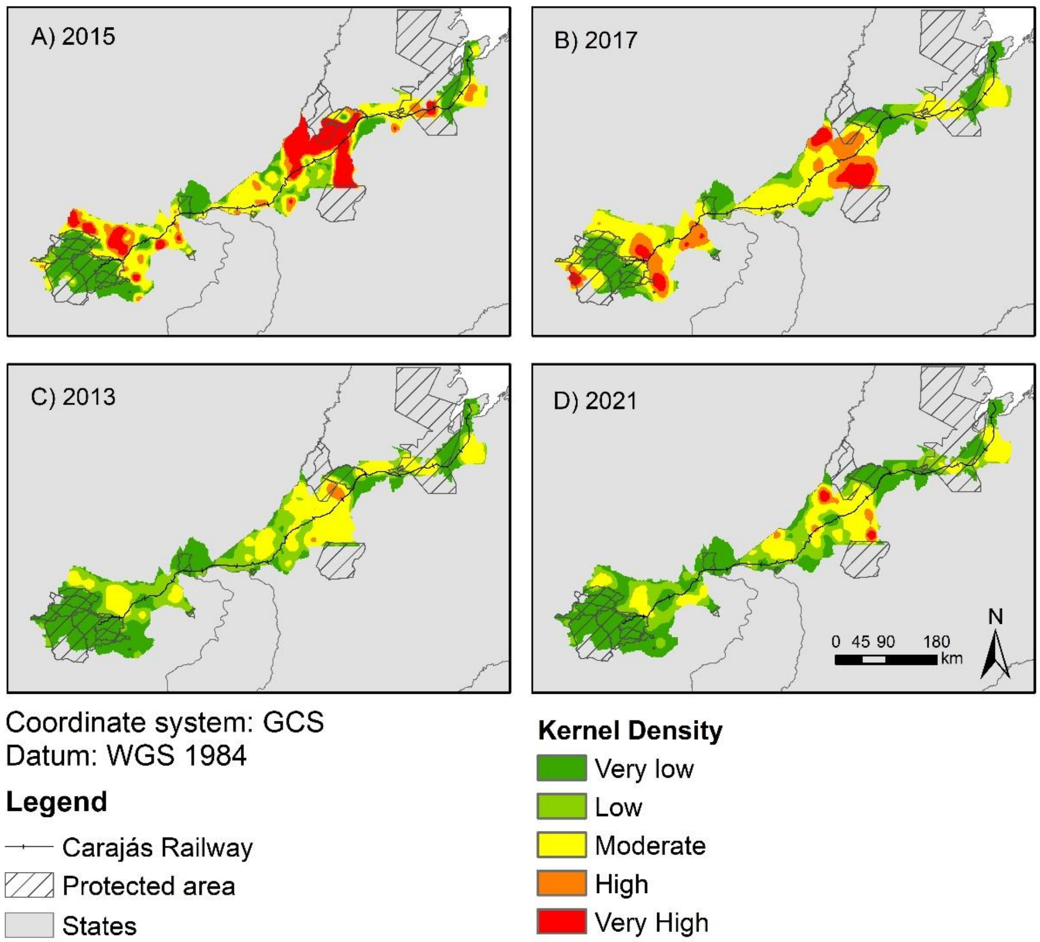

Figure 5 – Kernel density maps for years with the highest occurrence of hotspots: A) 2015 and B) 2017; and for years with the lowest occurrence of hotspots: C) 2013 and D) 2021.

Furthermore, the Moran's I index, when applied to the EDK map for all years analyzed, was approximately 0.99, indicating a strong pattern of positive spatial autocorrelation. The findings indicate that fire outbreaks exhibit a high degree of spatial clustering, with a probability of less than 1% that this pattern is attributable to chance ($p < 0.01$).

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Fire incidence by land use and land cover

From 2012 to 2021, forest formations encompassed approximately 31,800 km² of the basin, while pastures constituted around 29,300 km² (Figure 6A). A subsequent analysis of fire hot spots by LULC indicated that pastures accounted for the largest share of detections, with 98,185 hot spots recorded over the study period, an average of 0.32 hot spots/km²/year. Forest formations still accounted for 62,079 hot spots, with a mean density of 0.20 hot spots/km²/year, highlighting the vulnerability of both anthropogenic and native vegetation types. For both primary categories of land use, the highest concentrations of hotspots were observed in the same years: 2015, 2017, and 2012. The remaining LULC categories exhibit a significantly lower frequency and greater variability in classes with higher detection errors. Consequently, they will not be addressed in this study.

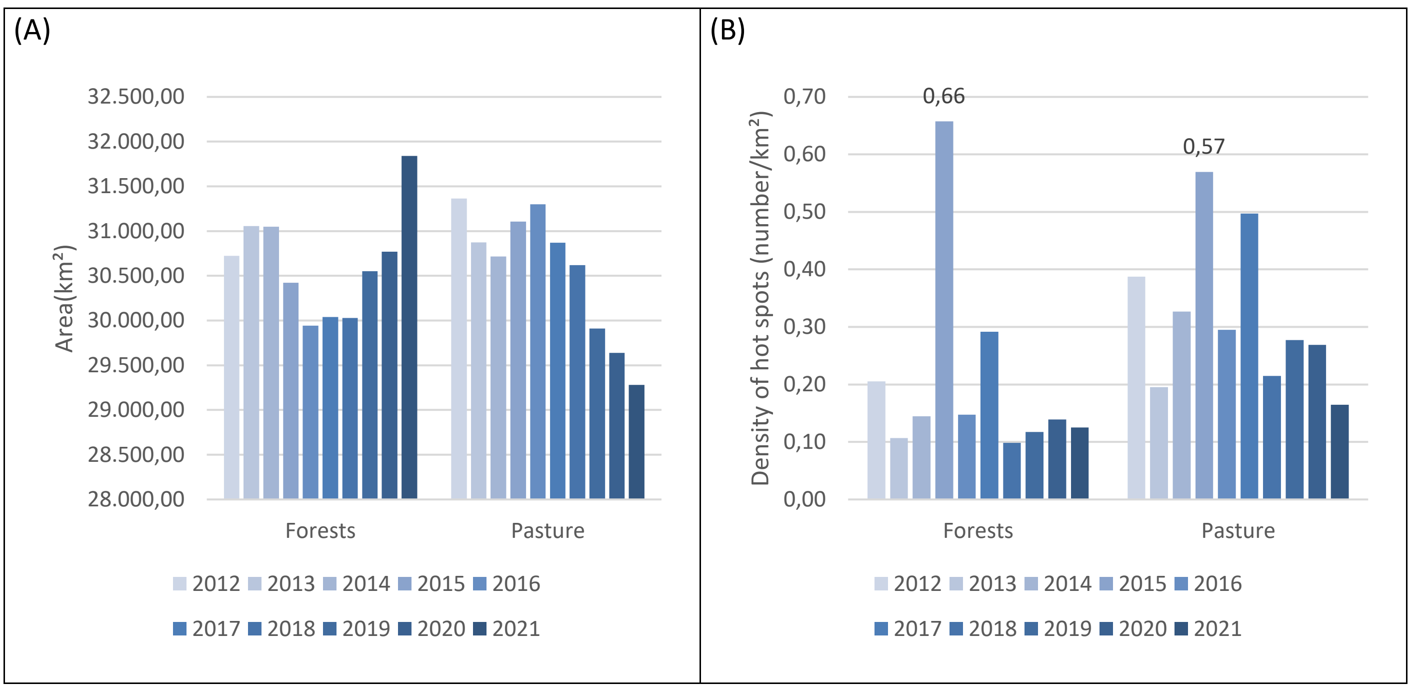

Figure 6 – (A) Pasture and forest area and (B) density of hotspots for these land use classes in the CR municipalities for the years 2012 to 2021.

A higher density of hot spots was observed in pasture areas compared to forest areas for all years analyzed, with the exception of 2015. Areas exhibiting different LULC classes generally demonstrated an intermediate level of hotspot density, situated between the two aforementioned extremes. A statistically significant discrepancy was identified between the groups under consideration (p-value < 0.05) in all annual assessments.

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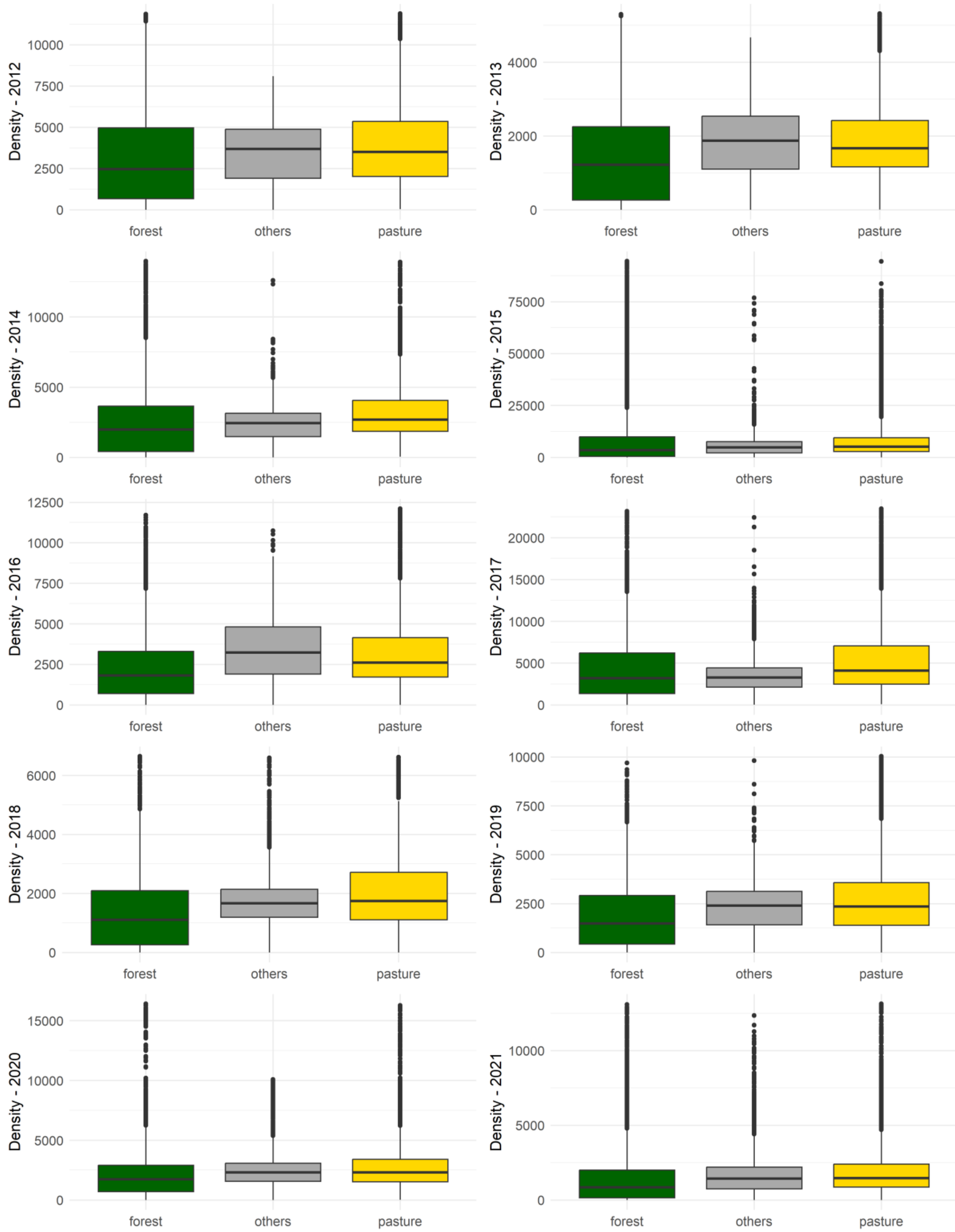

Figure 7 – Annual box plot of heat source density by land use class in EFC municipalities between 2012 and 2021. Average density is indicated by an asterisk.

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IV. Discussion

The results of the study indicate a distinct pattern of seasonal variability in fire occurrences across the CR municipalities, with the majority of events occurring between August and October. This finding is consistent with earlier research on the eastern Amazonian fire regime (Aragão et al., 2018) and with nationwide data (MapBiomas Fogo, 2025).

The periods of heightened fire activity observed in 2015 and 2017 correspond with documented El Niño events, which have been demonstrated to intensify drought conditions and elevate the risk of wildfires across the Amazon Basin (Chen et al., 2011; Alencar et al., 2015). The years from 20015 to 2017 exhibited the highest burned areas in the Amazon during the analyzed period (MapBiomas Fogo, 2025), thereby reinforcing the climate sensitivity of fire dynamics.

The analysis by land use class confirms that the majority of fires occurred in pastureland, a phenomenon attributable not only to the extent of pastureland but also to the common practice of using fire for land clearing (Moura et al., 2020). However, the high number of fire hot spots in forest areas during drought years reveals ongoing threats to native vegetation. In the southern region of Pará, an increase in the duration and intensity of the dry season is anticipated due to climate change (Pontes et al., 2022), which may lead to an escalation in forest fires.

The mean annual hotspot density recorded for forested regions was approximately 0.2 hotspots/km²/year, which is regarded as elevated in comparison to Amazon rainforest areas (e.g., Rosan et al., 2017). This figure is influenced by the sharp increase in hotspots in forested areas observed during the severe drought of 2015 but may also reflect the landscape fragmentation and forest degradation, the clearing of secondary forest areas, and the spread of fires along forest edges. This year, the hot spot density exhibited an even higher level of intensity compared to that observed in previous years. A similar pattern was also observed for the municipality of São Felix do Xingu in Pará following the 2010 drought (Rosan et al., 2017). The intensification of wildfires during El Niño years has been shown to significantly contribute to increased carbon emissions and long-term forest degradation (Aragão et al., 2018). This phenomenon has become a chronic problem in the fight against climate change and the reduction of emissions from the land use sector. Tropical old forests are less prone to fire, but secondary forests (Adorno et al., 2025) and degraded forests, which predominate in fragmented landscapes, are more vulnerable to fire (Guedes et al., 2020). Forest degradation caused by fire also impacts biodiversity, particularly in cases of recurring fires (Xaud et al., 2013).

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The southwest-to-northeast progression of fire density during the dry season is indicative of spatial variability in rainfall patterns, vegetation types, and ignition sources. This phenomenon was initially documented by Fonseca et al. (2021) in the states of Maranhão and Tocantins, while Pereira et al. (2014) reported it in Pará. The high-density clusters found in municipalities such as Buriticupu and Marabá are consistent with their history of land-use pressure, including pasture expansion and road-driven deforestation fronts.

The recurrence of fires underscores the necessity for educational programs that promote alternative land management strategies, as well as investments in training communities for fire control and prevention to mitigate the uncontrolled spread of fire. Monitoring systems and platforms that use geospatial data capable of capturing this seasonal and spatial concentration of fire outbreaks can be efficient alternatives for directing prevention efforts, particularly in pasture-dominated zones before August, to curb the escalation of fires during the core dry season, and especially in El Niño years. This is particularly salient in regions such as Buriticupu, which exhibited the highest average fire density across the decade and should be accorded with priority in future fire mitigation strategies. Moreover, monthly spatial analyses from EDK can function as a strategic instrument for identifying regions that merit increased allocation of resources for environmental surveillance, firefighting, and enforcement. This is particularly relevant for regions proximate to conservation units, indigenous lands, and traditional communities, which have been shown to be more susceptible to the deleterious effects of fire. Within the context of the study area, the Gurupi Biological Reserve and the Caru Indigenous Land, both in the state of Maranhão, deserve particular attention.

The analysis of the spatial dynamics of land use and fire occurrence revealed a significant opportunity to enhance fire mitigation actions among municipalities and even between states in eastern Amazonia. For instance, assets utilized for prevention and firefighting activities can be allocated to the southernmost municipalities in the study region at the onset of the dry season and subsequently transferred to the northernmost municipalities at the conclusion of the season. Federal Law 14.944 of 2024, which established the National Policy for Integrated Fire Management, includes among its guidelines the participatory and shared management among federative entities, organized civil society, indigenous peoples, quilombola communities, other traditional communities, and the private sector (Brazil, 2024). This shared responsibility, in conjunction with the necessity for coordination to develop programs and plans that promote integrated fire management, is also emphasized in the State Program for the Prevention and Combat of Wildfires and Forest Fires of the state of Pará (Decree 4.739 of 2025). The integration of ecological, cultural, socioeconomic, and technical dimensions

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in the planning and management of forest fires, while acknowledging the significance of traditional and adaptive fire use, is a hallmark of these models. During the period of highest fire occurrence, the clustering of fires indicates that prevention and monitoring actions should be developed in the vicinity of the locations where the first fires are detected. In addition, the incorporation of seasonal climate forecasts into the territorial planning of these municipalities and fire risk management has the potential to enhance the preparedness of government agencies and the private sector, thereby reducing the impacts caused by wildfires.

Furthermore, coordination with companies operating along the railway is imperative, as their operations intersect with high-risk areas. A potential benefit of public-private collaboration would be the enhancement of fire detection, reporting, and suppression infrastructure across railway municipalities.

V. Conclusion

The findings of this study indicate that fires along the Carajás Railway exhibit well-defined seasonal patterns, which are significantly influenced by climatic events and land use. The maximum fire detection period is from August to October in the southwestern municipalities (PA) and from October to December in the northeastern municipalities (MA). The analysis reveals a tendency for fire occurrence to cluster in specific regions, with areas demonstrating a history of high fire activity exhibiting a higher incidence of fires in pasture areas. However, in the driest year of the analyzed historical series, the density of fires in forest areas exceeded that of pastures, indicating a loss of resilience and a change in patterns. Consequently, analyses of fire density and its relationship with land use enable the early identification of critical areas, optimize resource use, and guide focused actions at both the municipal and intermunicipal scales.

This information must be systematically incorporated into fire prevention, monitoring, and control plans, considering seasonality, climatic triggers (e.g., El Niño), and local land-use pressures. It is imperative to recognize the significance of collaborative efforts among governments, the private sector, and civil society, grounded in spatial intelligence, to mitigate the environmental and social ramifications of fire in Eastern Amazonia. The integration of monitoring systems with public policies and local actions is not merely a technical recommendation; rather, it constitutes a strategic imperative for the region's sustainability.

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