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Articles

Spatio-temporal dynamic of the fire focus observed in the Emas National Park: subsidy for integrated fire management and conservation of the Cerrado

Dinâmica espaço-temporal dos focos de calor observados no Parque Nacional das Emas: subsídio para o manejo integrado do fogo e conservação do Cerrado

Eugênio Ferreira da Silva[I]
Daniela Pereira Dias[I]

[I]Universidade Federal de Jataí, Jataí, GO, Brazil

ABSTRACT

The number of fire focus and their location may facilitate a process mapping of forest fire risk zones at a conservation unit. The objective of this paper was to analyze the spatio-temporal patterns of fire foci in the Emas National Park (PNE), identifying areas of recurrence and their relevance for integrated fire management and Cerrado conservation. The number and location of fire focus in PNE was obtained from 2013 to 2022. From the processing of fire foci data, Kernel density maps were produced each year, as well as considering the total period. In 10 years, there were 53,488 fire focus in the PNE area. Of these, more than 7,000 occurred in 2019, and in September, 18,891 fire focus (mean of 1,889.1). Using Kernel maps, the spatio-temporal variation of detected fire focus between 2013 and 2022 was verified. The south-southwest region of PNE presented a very high Kernel density, mainly due to the high concentration of fire focus observed in 2016 and 2021. The generated Kernel density map contributes to identifying priority locations for the implementation of integrated fire management actions and the planning of wildfire prevention actions in specific areas of the PNE, especially those with very high, high, or medium fire focus density.

Keywords: Brazilian savanna; Wildfire; Integrated fire management; Kernel map; Conservation unit

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RESUMO

A quantidade de focos de calor e sua localização podem facilitar o mapeamento de zonas de risco de incêndios florestais em uma unidade de conservação. O objetivo deste trabalho foi analisar os padrões espaço-temporais dos focos de calor no Parque Nacional das Emas (PNE), identificando áreas de recorrência e sua relevância para o manejo integrado do fogo e conservação do Cerrado. Foram obtidos o número e a localização dos focos de calor que ocorreram no PNE anualmente entre 2013 e 2022. A partir do processamento dos dados de focos de calor, foram produzidos os mapas de densidade de Kernel em cada ano, bem como considerando o período total. Em 10 anos, foram observados 53.488 focos de calor na área do PNE. Destes, mais de 7.000 ocorreram em 2019, e em setembro foram observados 18.891 focos (média de 1.889,1). Com os mapas de Kernel foi verificada a variação espaço-temporal dos focos de calor detectados entre 2013 e 2022. A região sul-sudoeste do PNE apresentou densidade de Kernel muito alta, sobretudo devido à elevada concentração de focos de calor observados em 2016 e 2021. O mapa de densidade de Kernel gerado contribui com o apontamento de locais prioritários para a implementação de ações de manejo integrado do fogo e o planejamento de ações de prevenção a incêndios florestais em áreas específicas do PNE, sobretudo naquelas com densidade de focos de calor muito alta, alta ou média.

Palavras-chave: Cerrado; Incêndios florestais; Manejo integrado do fogo; Mapas de Kernel; Unidade de conservação

1 INTRODUCTION

Emas National Park (ENP) is a strictly protected area (Conservation Unit) located in the states of Goiás and Mato Grosso do Sul, whose main objective is nature preservation, allowing only the indirect use of its natural resources, in accordance with Brazilian Law nº. 9,985 (Brasil, 2000). However, it exhibits an "island-like" layout surrounded by intensive agricultural activities (Albuquerque & Martins, 2023), such as soybean, sugarcane, cotton, and maize plantations, as well as pastures. Within the Cerrado biome, ENP is one of the largest protected areas, harboring high biodiversity and preserving significant samples of its wild flora and fauna, in addition to being recognized as a UNESCO World Natural Heritage site (UNESCO, 2001).

The grass-dominated physiognomies of the Cerrado present in ENP (Ramos Neto, 2000) accumulate high fuel loads during the dry season, which can promote the occurrence and propagation of catastrophic wildfires. Most Brazilian protected areas still struggle to control the threat of wildfires within their boundaries. The

implementation of Integrated Fire Management (IFM) reduces fuel accumulation, preventing large-scale, high-intensity wildfires. Fuel load mapping and monitoring assist in identifying priority areas for IFM interventions (Franke et al., 2018).

IFM is a planning and management framework that, in accordance with Brazilian Law No. 14,944/2024, integrates ecological, cultural, socioeconomic, and technical aspects into the implementation, integration, monitoring, evaluation, and adaptation of actions related to the use of prescribed and controlled burns, as well as wildfire prevention and suppression. This approach aims to reduce particulate matter and greenhouse gas emissions, conserve biodiversity, and mitigate wildfire severity while respecting traditional and adaptive uses of fire (Brasil, 2024). Environmental, economic, and social aspects are encompassed by IFM, represented by fire management (prevention, preparedness, suppression, and use of fire), fire culture (socioeconomic needs and impacts of fire), and fire ecology (benefits and damages of fire). In this context, the integrated operations of federal, community, and volunteer fire brigades, combined with remote sensing tools and risk forecasting, have strengthened emergency response capacity and enabled strategic prevention planning (Parente et al., 2025).

The identification and quantification of active fires (hotspots) via satellite remote sensing has been investigated through association with meteorological variables (Caúla et al., 2015; Dias & Corrêa, 2023; Ribeiro et al., 2021), spatio-temporal dynamics and their relation to local environmental and socioeconomic characteristics (Gois et al., 2020), fire danger indices efficiency (Soriano et al., 2015; Casavecchia et al., 2019; Gonçalves & Dias, 2020), and the development of Kernel density maps (Volpato et al., 2023). Kernel density estimation is highly useful in spatial analysis, enabling the visualization of areas with higher intensities of point phenomena, such as hotspots, for monitoring fire dynamics and wildfires (Barbosa et al., 2019).

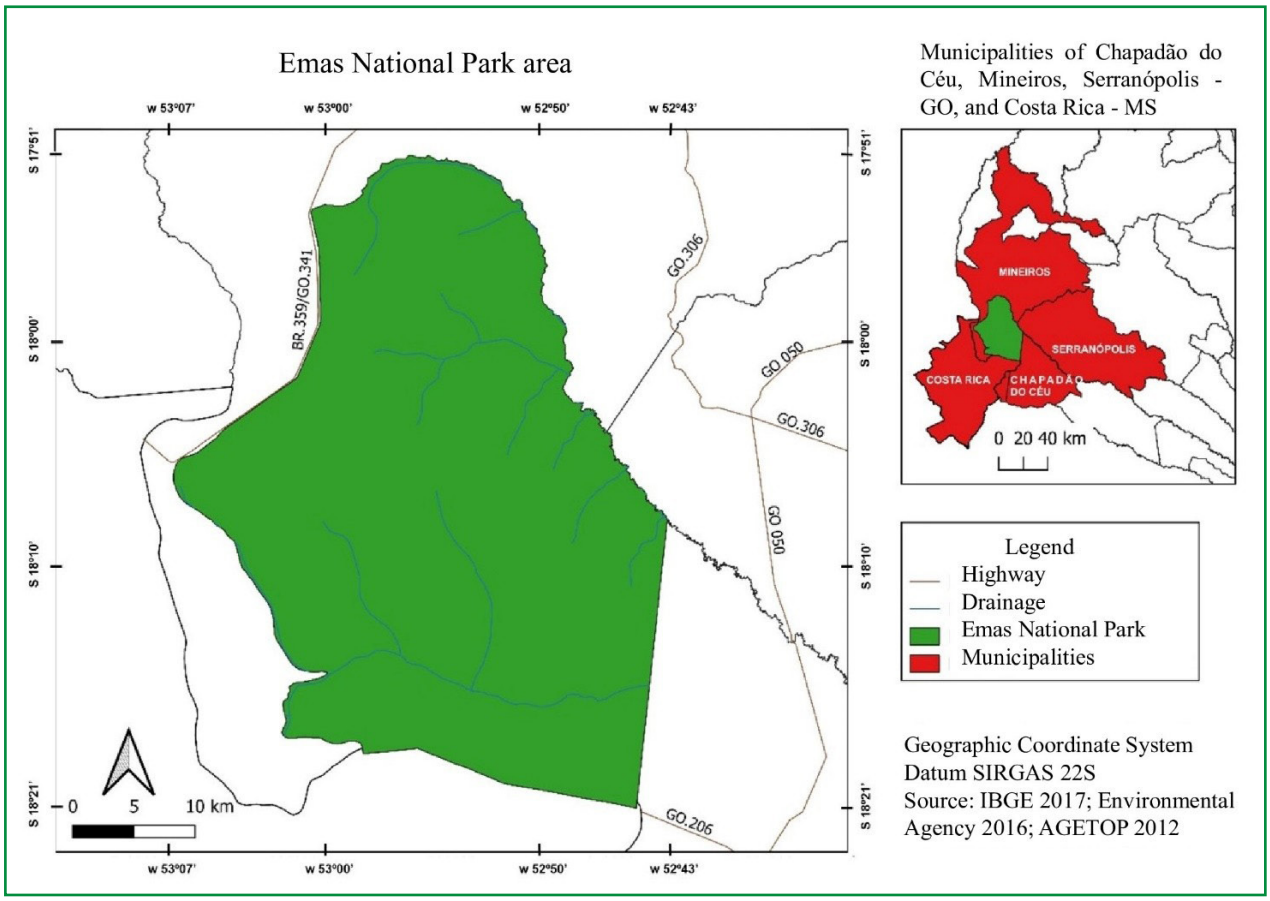
Identifying fire-affected areas and high fuel load zones, together with pinpointing hotspot concentrations, provides essential support for government decisions regarding enforcement, suppression, and fire management in protected areas (Borges et al., 2021). Therefore, this study aimed to analyze the spatio-temporal patterns of hotspots in Emas National Park, identifying areas of recurrence and evaluating their relevance for integrated fire management and Cerrado conservation.

2 MATERIALS AND METHODS

2.1 Description of the study area

Emas National Park (ENP) is located predominantly in the southwestern region of the state of Goiás, Brazil (Figure 1). Its area covers 132,000 hectares, distributed across the municipalities of Mineiros, Chapadão do Céu, and Serranópolis in Goiás, and Costa Rica in Mato Grosso do Sul. Its boundaries are located between latitudes 17°51’ and 18°21’S and longitudes 52°43’ and 53°07’W (Figure 1).

Figure 1 – Delimitation of the Emas National Park area, identifying municipalities in Goiás and Mato Grosso do Sul, and nearby highways



Source: IBGE (2017); Environmental Agency (2016); AGETOP (2012)

Almost all phytophysiognomical variations of the Cerrado biome are represented in ENP, ranging from open grasslands (*campo limpo*) to Cerrado *sensu stricto*. Open physiognomies (open grasslands / *campo limpo*, shrubby grasslands / *campo sujo*, and typical savannas / *campo cerrado*) predominate, occupying 78.5% of the area (104,359 ha), particularly on flat tablelands (Ramos Neto, 2000). Other Cerrado vegetation types present include wet grasslands (*campos* úmidos), earthmound fields (*campos de murundus*), and Mauritia palm swamps (*buritizais*), which account for 4.8% of the reserve (6,377 ha) and are associated with watercourse floodplains. Seasonally dry semideciduous forests and riparian forests occupy 2.9% (3,853 ha) and are associated with fertile soils and rivers, respectively.

ENP is situated on a tableland (*chapada*) characterized by flat to gently undulating terrain, with elevations ranging between 800 and 900 m above sea level. Dystrophic Dark Red Latosol (Oxisol) and dystrophic Red-Yellow Latosol (Oxisol) are the predominant soil types. The park is drained by rivers belonging to major Brazilian hydrological basins, such as the Formoso, Jacuba, and Sucuriú rivers (Paraná River Basin). The region features a warm, humid tropical climate (*Aw* according to the Köppen climate classification), characterized by a dry season spanning from May to September and a rainy season from October to April. It represents an important area for groundwater recharge. Average annual rainfall varies from 1,500 to 1,700 mm, with mean annual temperatures between 22°C and 24°C (Dubreuil et al., 2018).

2.2 Active fire data collection

Active fires (hotspots) are defined as polygons with a minimum area of 900 m² exhibiting surface temperatures above 47°C. They are reliable indicators of vegetation fire, though they do not guarantee a confirmed field-level wildfire. Thus, hotspots do not necessarily represent field-verified fires. The monthly number of hotspots observed in ENP was obtained from the BDQueimadas database of the National Institute for Space Research (INPE) for the 2013–2022 historical series. Monthly averages and total annual values were also calculated. In addition, the geospatial coordinates of these hotspots were retrieved from the database to generate Kernel density maps.

2.3 Generation of Kernel density maps

Kernel density maps were generated for each year between 2013 and 2022 using the ENP boundary map obtained from the State Geoinformation System (SIEG), along with hotspot locations from INPE. To construct the maps containing the spatial information of hotspots, data were imported into the open-source software QGIS (version 3.28.2). Subsequently, a point vector file in ESRI Shapefile format was generated, with the Coordinate Reference System defined as WGS 84 / UTM zone 22S.

Thus, annual hotspot locations served as the basis for the density maps. The Kernel density estimator from the QGIS Heatmap tool was utilized, calculating density based on the distance of points relative to a central value (Menezes et al., 2019). In this method, each sample point has a defined "neighborhood" (bandwidth) around it, and a weighting function is applied to determine the influence of neighboring points on the local estimate. The weighting function is selected based on the spatial distribution of the sample points, varying from 1 at the point's position to 0 at the neighborhood boundary. The value assigned to each cell is the sum of overlapping Kernel values divided by the area of the search radius (Oliveira & Oliveira, 2017).

To classify the annual Kernel maps from 2013 to 2022, a standard classification was applied, defining five concentration classes for hotspot density: very low, low, medium, high, and very high. Subsequently, a cumulative Kernel density map was generated by integrating data from the entire 10-year period to identify regions of higher or lower hotspot concentration in ENP. These areas are critical for guiding practical fire management strategies or wildfire preventive measures.

3 RESULTS AND DISCUSSIONS

3.1 Monthly and annual active ire variation

Over the 10-year study period (2013–2022), 53,488 hotspots were detected within the ENP boundaries (Figure 2A). Hotspot counts exceeded 4,700 per year during this period, except for 2013 and 2018. Lower values (3,984 hotspots) were reported in Jataí,

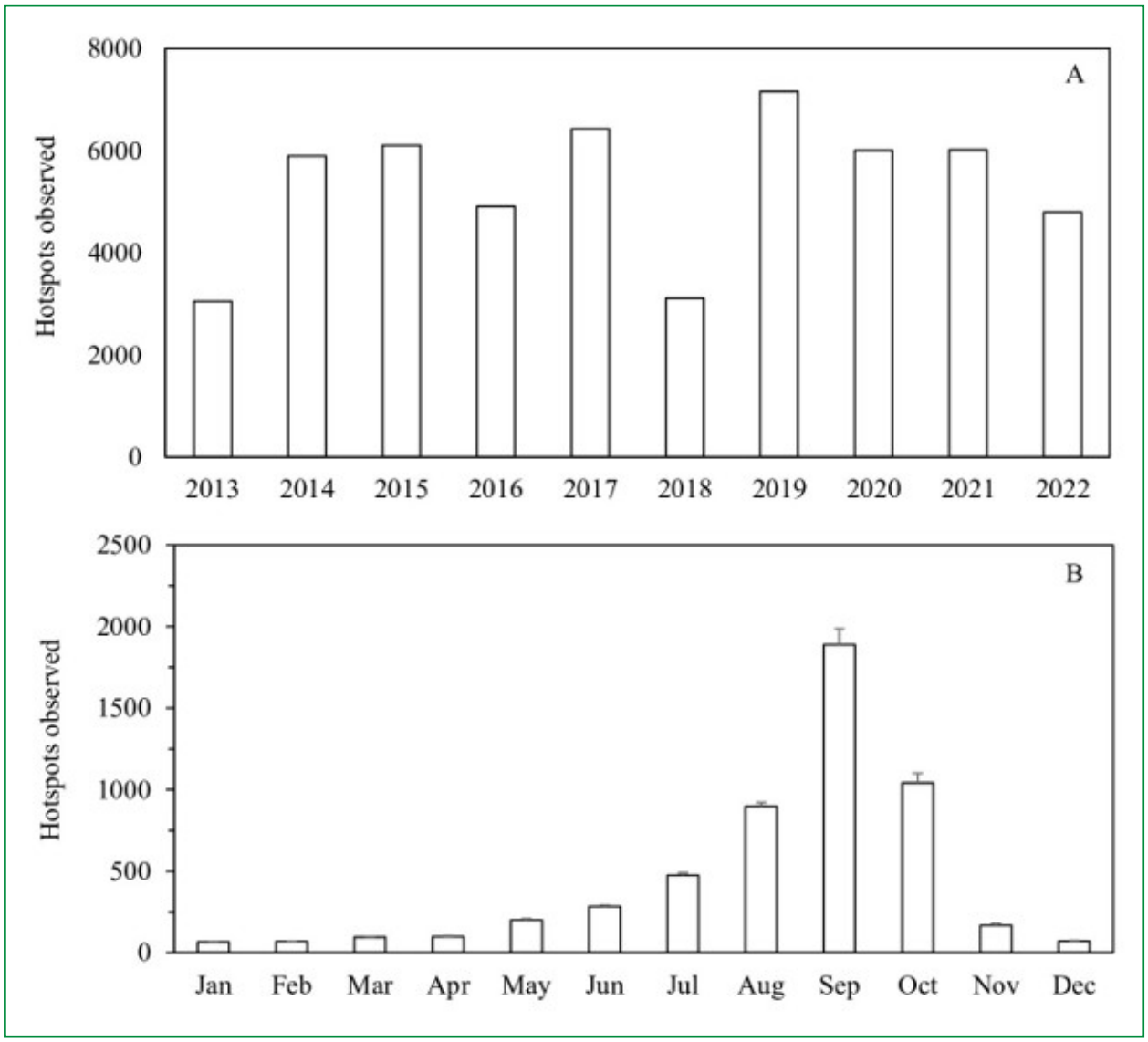
a municipality relatively close to ENP, over a 10-year period (2007–2016) (Gonçalves & Dias, 2020). Despite spatial and temporal differences, these data underscore the high density of thermal anomalies in ENP, indicating that satellites detected numerous surface temperatures reaching 47°C. While the number of detected hotspots does not always perfectly correlate with actual wildfire events, the probability of wildfire occurrence increases significantly when high concentrations of hotspots are registered in a single locality (Tomzhinski et al., 2011).

Within the analyzed period, 2019 registered the highest number of hotspots (7,160), followed by 2017 (6,428) and 2015 (6,107), as shown in Figure 2A. Conversely, the lowest numbers were recorded in 2013 and 2018 (3,050 and 3,110, respectively; Figure 2A). Interannual variability in hotspot occurrences can be related to meteorological fluctuations, human behavior—the primary driver of wildfire ignition in Brazil—and fuel availability (Lazzarini et al., 2012).

According to INPE (2025), the warmest years in Brazilian recorded history were 2024 (25.02°C), 2023 (24.92°C), 2015 (24.89°C), 2019 (24.83°C), 2016 (24.66°C), and 1998 (24.60°C), relative to the 1991–2020 historical climatological baseline of 24.23°C. Three of these warmest years fall within our study period (2015, 2019, and 2016); in two of them, major wildfires occurred, alongside the implementation of preventative firebreaks in ENP.

Across the 10-year series, September concentrated 18,891 hotspots (Figure 2B), with a monthly average of 1,889.1 hotspots (Figure 2B), followed by October (1,041.6) and August (896.2). These three months accounted for 71.55% of all hotspots detected in ENP, corresponding to the dry season and the onset of the rainy season. In Jataí, Goiás, Gonçalves and Dias (2020) observed that over 80% of hotspots occurred between July and October. The months with the highest hotspot records are characterized by heavy fuel accumulation on the ground (dry leaves and twigs), which becomes highly flammable due to reduced fuel moisture driven by drought and high temperatures, making these months the most critical for wildfire risk.

Figure 2 – Annual (A) and monthly (B) variation of active fires (hotspots) observed in Emas National Park between 2013 and 2022



Source: INPE (2023)

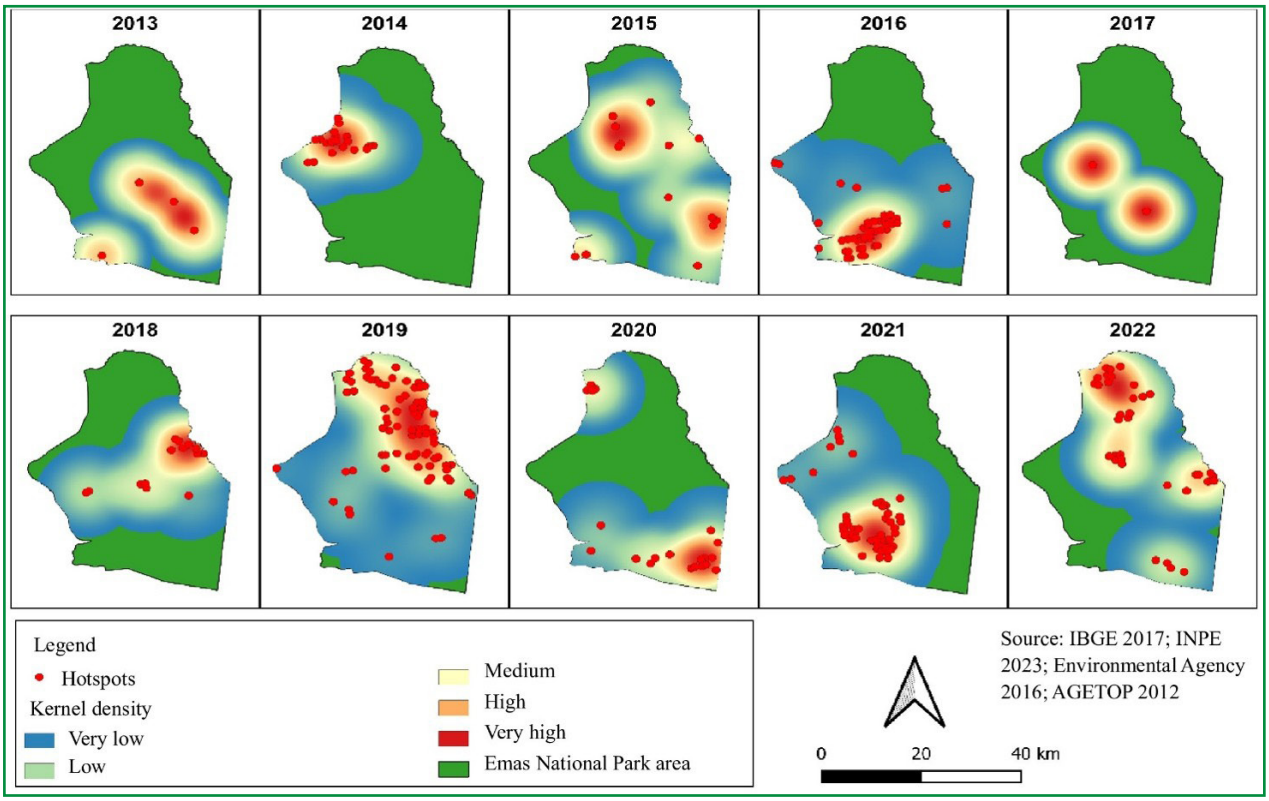
3.2 Kernel density maps

Kernel density maps captured the spatio-temporal dynamics of hotspots from 2013 to 2022 within ENP (Figure 3).

The areas exhibiting the highest hotspot densities (indicated in red, orange, and yellow) were not static over time, nor did they occur in the same locations (Figure

3). It is worth noting that the high-density spatial patterns in 2016 and 2021 were highly similar. Additionally, the green-colored areas in the maps for 2013, 2014, 2017, 2018, and 2020 reveal sectors where no hotspots were detected (Figure 3). In terms of geographical area and hotspot numbers, almost the entire ENP was occupied by varying hotspot densities (from very low to very high) in 2019 (Figure 3). It is crucial to emphasize that in this study, the Kernel maps do not depict the actual burned area, but rather the concentrations of detected thermal anomalies within ENP.

Figure 3 – Kernel density maps of active fires (hotspots) observed annually in Emas National Park from 2013 to 2022



Source: IBGE (2017); INPE (2023); Environmental Agency (2016); AGETOP (2012)

Higher hotspot concentrations may reflect areas with high temperatures, wildfires, or the execution of prescribed or controlled burns, particularly in 2016, 2019, and 2021. Land surface temperatures (LST) are lower in non-vegetated areas (32.2°C), followed by pastures (31.7°C), grain crops (30.8°C), and other croplands (30.6°C) within

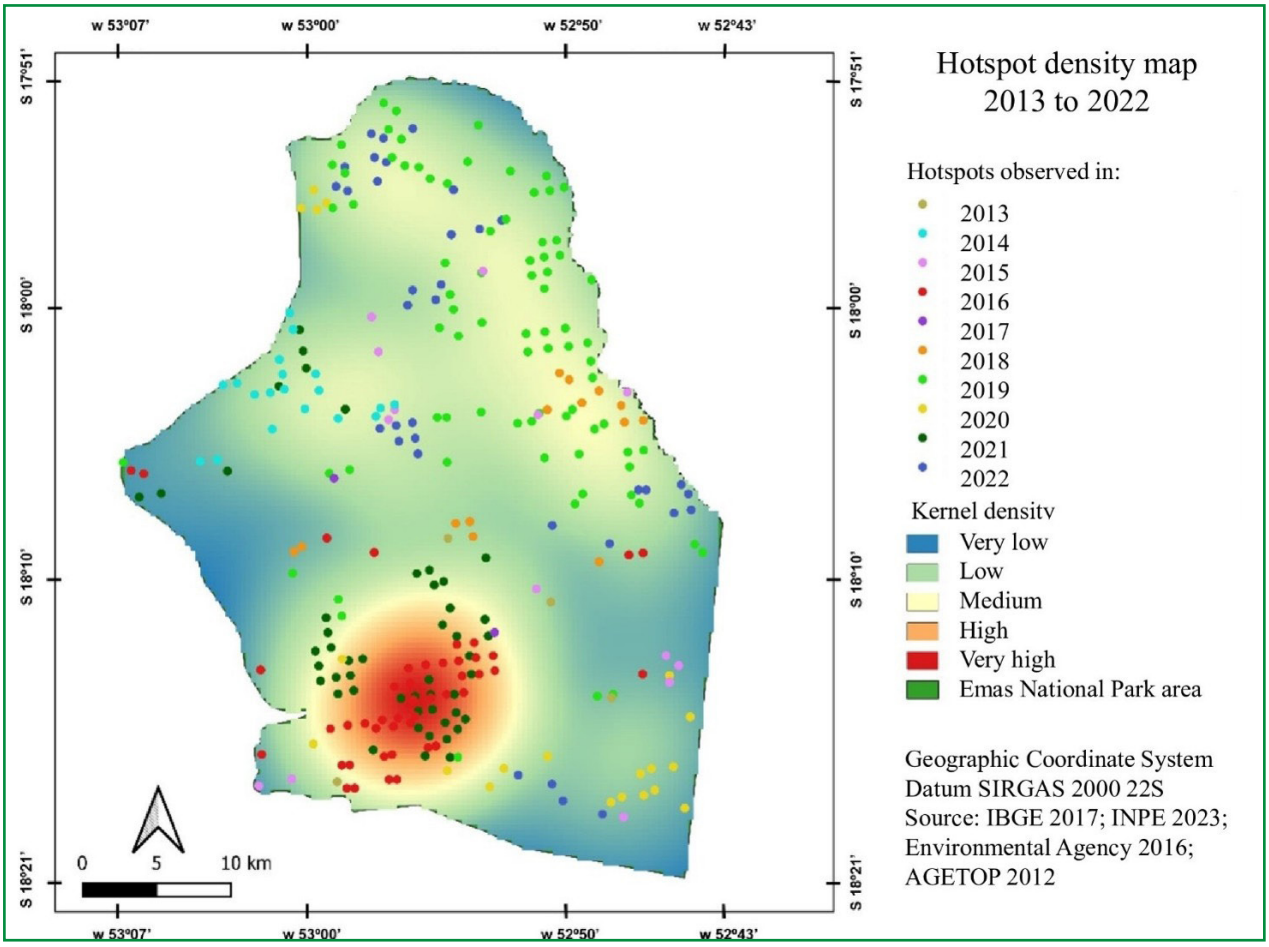
the ENP buffer zone. In contrast, Cerrado physiognomies exhibit milder LSTs: 27.5°C in forest formations, 28.8°C in savannas, and 30.8°C in open grasslands (Albuquerque & Martins, 2023).

In September 2016, protective firebreaks were established in ENP using fire to prevent large-scale wildfires. The burned buffer strip accounted for approximately 3% of the park's area, according to Amoury (2021), which aligns with the high hotspot counts during that period. In July 2021, a catastrophic wildfire affected nearly 28,000 hectares in ENP, triggered during firebreak maintenance when transport trucks caught fire (Amoury, 2021). In September 2019, a wildfire burned approximately 6,000 hectares in ENP (Schumacher & Setzer, 2022), contributing to the high hotspot density recorded that year. The dry weather in September caused the flames to spread rapidly, and the fire was brought under control during the night following a rainfall event (Lopes, 2019).

Between 2013 and 2022, ENP exhibited a major hotspot concentration, with very high Kernel density (red) surrounded by high (orange) and medium (yellow) densities in the south-southwestern region (Figure 4), adjacent to the municipality of Costa Rica, Mato Grosso do Sul (Figure 1). This region recorded recurrent hotspot concentrations in several study years, particularly 2016 and 2021 (represented by intense red and dark green points, respectively), demonstrating that this sector is highly vulnerable to wildfires.

The area with the highest Kernel density is dominated by Cerrado grassland formations, but also includes wet grasslands and palm swamps (*campos de murundus* and *buritizais*), which respond differently to fire (Albuquerque & Martins, 2023). Grassland formations (open grasslands / *campo limpo* and shrubby grasslands / *campo sujo*), characterized by fine grasses, provide conditions where fuel and ignition potential recover rapidly. Furthermore, frequent human activities in adjacent areas (edges, roads, neighboring properties) and flat topography favor ignition and rapid fire propagation. Thus, this area represents a critical zone for Integrated Fire Management, requiring both the reduction of anthropogenic ignitions (e.g., through reinforcing external firebreaks, enforcement, and fire-use protocols in the surroundings) and the strategic planning of prescribed burns to decrease late-season wildfire hazards.

Figure 4 – Kernel density map of cumulative active fires (hotspots) observed in Emas National Park from 2013 to 2022



Source: IBGE (2017); INPE (2023); Environmental Agency (2016); AGETOP (2012)

Since 86% of ENP is characterized by flat terrain with slopes below 6% (tablelands or *chapadões*) (Martins et al., 2020), wildfire propagation is heavily favored, especially when combined with high wind speeds and grass-dominated vegetation. Additionally, areas close to rivers face increased fire risk due to higher human presence associated with ecotourism. Because these areas are highly visited, controlled burns along the boundaries may be necessary.

Medium (yellow) and low (light green) Kernel densities were observed in the central and northern parts of ENP, whereas very low densities (blue) occurred along the western and northwestern edges (Figure 4). The northern sector experienced a

high number of hotspots in 2019 due to a wildfire near the park's border with the municipality of Mineiros, Goiás. According to Albuquerque and Martins (2023), this area presents a mosaic of vegetation types (savanna, forest, and grassland formations) and wetlands, which are naturally less flammable and associated with less frequent fire events (confined to extremely dry years, firebreak escapes, or lightning).

Spatially, some degree of hotspot density was registered across the entire ENP, implying that no area is entirely free from fire occurrence (Figure 4). This supports the established understanding of the Cerrado's evolutionary relationship with fire, where fire acts as a natural ecological driver that maintains structure, biodiversity, and ecosystem functioning (Durigan & Ratter, 2015; Schmidt et al., 2016). However, wildfires in Brazil are predominantly ignited by human activities, either intentionally or through negligence, and their propagation is governed by the interaction of topographic, climatic, and vegetative factors (Gomes et al., 2020; Patriota et al., 2017).

Nevertheless, the implementation of Integrated Fire Management has been proven to reduce wildfire size, greenhouse gas emissions, socio-environmental conflicts, and the associated social, economic, and public health costs (Parente et al., 2025), which is particularly critical given ENP's history of recurrent burning. Analyzing the spatio-temporal patterns of hotspot frequency provides valuable support for wildfire risk zoning in ENP, especially when integrated with topography, fuel load accumulation, road networks, and visitor flow.

4 CONCLUSIONS

The spatio-temporal dynamics of hotspots in ENP highlight areas with high historical fire recurrence. Combined environmental and anthropogenic factors drive hotspot concentrations in sectors highly vulnerable to fire propagation and wildfire events.

Hotspot distribution is highly heterogeneous across ENP, pointing to the south-southwestern region as a priority zone for intensive monitoring and wildfire

prevention techniques. Additionally, annual meteorological variations combined with anthropogenic activities influence hotspot frequency.

The generated Kernel maps effectively identify recurring patterns and high-priority zones for intervention in ENP. Consequently, the findings of this study support the implementation of Integrated Fire Management, strategic park monitoring, and the allocation of preventative techniques to promote Cerrado conservation.

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Authorship Contribution

1 Eugênio Ferreira da Silva

Forestry Engineer; Professor

https://orcid.org/0009-0008-5832-5197 • feugenio@discente.ufj.edu.br

Contribution: Conceptualization; Investigation; Methodology; Data curation; Formal analysis; Writing – original draft preparation

2 Daniela Pereira Dias

Professor

https://orcid.org/0000-0002-3541-1251 • danieladias@ufj.edu.br

Contribution: Conceptualization; Supervision; Data curation; Formal analysis Writing – original draft preparation; Writing – review & editing

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