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Hot spots and their climatic, environmental, and social determinants in the Cuiabá River Headwaters Environmental Protection Area, Brazil

Focos de calor e seus determinantes climáticos, ambientais e sociais na Área de Proteção Ambiental das Cabeceiras do Rio Cuiabá, Brasil

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ABSTRACT

The State Environmental Protection Area of the Cuiabá River Headwaters, located in the Cerrado biome, experiences recurrent wildfires that threaten its ecological integrity. This study analyzes the spatiotemporal dynamics of fire activity between 2010 and 2019, focusing on the relationship between climatic variables and the occurrence of hot spots. Data on hot spots were sourced from the fire database of the Brazilian National Institute for Space Research, while climate variables — precipitation, air temperature, and relative humidity — were obtained from the Brazilian National Institute of Meteorology database. Monthly fire activity was statistically correlated with climatic conditions using Spearman's correlation, and the number of consecutive dry days was calculated to assess drought severity. The results revealed a significant increase in hot spot density during the dry season (August to October), strongly associated with low precipitation, high temperatures, and critically low relative humidity. Among these variables, relative humidity showed the strongest and most consistent correlation with fire incidence, evidencing its role as an immediate meteorological trigger. Spatial analysis using kernel density estimation confirmed the concentration of fire activity in areas with recent land use changes, particularly agricultural expansion zones. These findings highlight the role of compound drought–fire dynamics in shaping fire regimes in the Cerrado and support the adoption of climate-informed fire management strategies to reduce wildfire risk in protected areas.

Keywords: Cerrado biome; Brazilian Conservation Units; wildfire; kernel density.

RESUMO

A Área de Proteção Ambiental das Cabeceiras do Rio Cuiabá, localizada no bioma Cerrado, enfrenta recorrentes incêndios que ameaçam sua integridade ecológica. Este estudo analisa a dinâmica espaço-temporal da atividade do fogo entre 2010 e 2019, com ênfase na relação entre variáveis climáticas e a ocorrência de focos de calor. Os dados sobre os focos de calor foram obtidos do banco de dados de queimadas do Instituto Nacional de Pesquisas Espaciais, enquanto as variáveis climáticas — precipitação, temperatura do ar e umidade relativa — foram extraídas da base de dados do Instituto Nacional de Meteorologia. A atividade mensal de fogo foi correlacionada estatisticamente com as condições climáticas por meio da correlação de Spearman, e o número de dias secos consecutivos foi calculado para avaliar a severidade da seca. Os resultados revelaram um aumento significativo na densidade de focos durante a estação seca (agosto a outubro), fortemente associado à baixa precipitação, altas temperaturas e umidade relativa criticamente baixa. Entre essas variáveis, a umidade relativa apresentou a correlação mais forte e consistente com a incidência de fogo, evidenciando seu papel como gatilho meteorológico imediato. A análise espacial por estimativa de densidade kernel confirmou a concentração da atividade de fogo em áreas com mudanças recentes no uso da terra, especialmente zonas de expansão agrícola. Esses achados destacam o papel da interação entre seca e fogo na modulação dos regimes de queima no Cerrado e reforçam a necessidade de estratégias de manejo do fogo baseadas em dados climáticos para reduzir o risco de incêndios em áreas protegidas.

Palavras-chave: bioma Cerrado; Unidades de Conservação brasileiras; incêndios florestais; densidade kernel.

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Introduction

Brazil holds one of the largest networks of protected areas in the world, encompassing approximately 18% of its national territory (Barros-Rosa et al., 2025). However, only a small fraction of these areas is strictly protected, classified under categories I to III of the International Union for Conservation of Nature (IUCN), accounting for about 6% of all Conservation Units (Rodrigues et al., 2024). In this context, Environmental Protection Areas (EPAs, Áreas de Proteção Ambiental), categorized as sustainable use units, represent the majority and are frequently more exposed to anthropogenic pressures such as deforestation, agricultural expansion, and fire.

Conservation Units in Brazil are regulated by the National System of Nature Conservation Units (SNUC), which classifies them into two main groups: strictly protected units, aimed exclusively at nature preservation and allowing only indirect use of natural resources, and sustainable use units, which aim to reconcile conservation with controlled resource use, often benefiting local communities (Rodrigues et al., 2024). Strictly protected units include Ecological Stations, Biological Reserves, National Parks, Natural Monuments, and Wildlife Refuges, while sustainable use units include EPAs, Areas of Relevant Ecological Interest, National Forests, Extractive Reserves, Fauna Reserves, Private Natural Heritage Reserves, and Sustainable Development Reserves.

The Cuiabá River Headwaters EPA, located in the Cerrado biome, is one such territory. Created to conserve biodiversity, protect water resources, and regulate land use in a region of increasing agricultural interest (Davidson et al., 2012), it was established by Law nº 7161/1999 (Mato Grosso, 1999).

The Cerrado is a fire-adapted savanna biome where fire has historically played a crucial role in maintaining ecological balance. Although fire is a natural ecological process in Cerrado ecosystems, the increasing frequency and intensity of wildfires pose a growing threat to biodiversity and ecological functions, particularly within Conservation Units (Spadoni et al., 2025). The Cerrado biome encompasses a mosaic of distinct vegetation classes, or phytophysiognomies, ranging from open grasslands to closed-canopy woodlands. Within the Cuiabá River Headwaters EPA, predominant formations include *Cerrado* sensu stricto, *Cerradão*, *campo sujo*, *campo limpo*, and *vereda formations*. These phytophysiognomies differ markedly in structure, species composition, fuel load, and flammability, influencing fire behavior and ecosystem resilience in diverse ways. Recognizing this internal heterogeneity is essential for interpreting fire regimes and formulating effective conservation and fire-management strategies within protected areas such as EPAs (Arruda et al., 2024).

Fires in the Cerrado can be broadly classified as either natural or anthropogenic, depending on their ignition source and compatibility with ecological cycles. Natural fires are generally triggered by lightning during seasonal transitions and occur with low frequency and intensity, contributing to nutrient cycling and vegetation renewal. These events follow the biome's historical fire regimes and are regulated by climatic factors and fuel moisture (Oliveras Menor et al., 2025). Natural fire regimes in the Cerrado are primarily shaped by climatic conditions, where the interaction between accumulated precipitation and seasonality determines both the buildup of fuel during the rainy season and its desiccation during the dry season (Alvarado et al., 2020). These regimes are marked by natural ignitions aligned with the adaptive cycles of vegetation.

In contrast, anthropogenic fires are initiated by human activities, such as land clearing, pasture renewal, or accidental ignitions, and tend to occur outside the natural fire season, with greater frequency, intensity, and spatial extent (Bird et al., 2024). These characteristics often result in ecological disruption and decouple fire behavior from its historical context (Shen, 2025).

Monitoring changes in fire regimes is therefore essential for the conservation and effective management of the Cerrado, a biome increasingly fragmented and under multiple threats (Conciani et al., 2021; Hoki et al., 2021). Although their effects are often destructive, wildfires can also play beneficial ecological roles when occurring within historical fire regimes, aiding in vegetation renewal, invasive species control, and biodiversity maintenance (Pausas and Keeley, 2019).

Land use and land cover changes have intensified fire occurrence and undermined ecological integrity (Santos et al., 2023). Studies conducted in the state of Goiás confirm the multifactorial complexity of wildfires, highlighting that variables such as land cover, proximity to roads, and population density are significantly associated with increased fire risk (Aires et al., 2025).

In Brazil, systematic wildfire monitoring began in the mid-1980s, with the National Institute for Space Research (INPE) using data from the National Oceanic and Atmospheric Administration meteorological satellite series to conduct daily hot spot detection across virtually the entire national territory. This advance enabled the quantification and geolocation of fire occurrences based on thermal signatures detectable by orbital sensors (França and Setzer, 2001).

Although satellite sensors detect thermal anomalies, such as any heat signal above a defined threshold, they do not distinguish between fire types. Thus, it is crucial to differentiate prescribed burning (or planned burning) from wildfires (or uncontrolled fires). Prescribed burns are human-induced, regulated ignitions conducted under controlled meteorological and environmental conditions, usually for pasture renewal or fuel load reduction. In contrast, wildfires are uncontrolled events occurring in natural or semi-natural vegetation, often caused by accidental human actions or lightning strikes, and typically result in significant ecological damage. Satellite-derived hot spots may include both types of events, and accurate classification generally requires field validation and knowledge of the local context (Morelli et al., 2009; Fesomade et al., 2025; Hsu et al., 2025).

Fire event characterization must consider the spatial clustering of multiple hot spots, which, when concentrated in time and space, represent active wildfires in natural or anthropogenic vegetation.

Thus, spatial analysis methods, such as clustering algorithms, are essential to distinguish actual fire events from isolated detections. This identification must be validated in the field, based on territorial context knowledge and local practices (Morelli et al., 2009). When combined with meteorological monitoring, this integrated approach allows for greater accuracy in fire detection and prevention, especially in extensive regions with limited ground surveillance capacity (Yuan, 2025).

Recent studies confirm that climate change has significantly increased the frequency and severity of wildfire-promoting conditions worldwide, including within Brazilian biomes. In the Cerrado, these changes have exacerbated fire intensity and lengthened the dry season, increasing fuel flammability and undermining ecosystem resilience (Santoset al., 2023; Kariuki et al., 2025).

Based on the observed fire seasonality in the Cerrado and the known influence of climatic extremes on fire behavior, we hypothesize that prolonged drought conditions and rainfall deficits significantly increase fire occurrences in the Cuiabá River Headwaters EPA. While anthropogenic and land-use factors also influence ignition patterns, this study primarily focuses on climatic drivers and their interaction with the spatial and temporal distribution of fire over a ten-year period. The objective is to assess how climatic and seasonal factors influence the occurrence and spatial distribution of hot spots in the Cuiabá River Headwaters EPA from 2010 to 2019, using kernel density estimation and meteorological data. The period from 2010 to 2019 was selected for analysis in order to ensure temporal consistency and data integrity. This period coincides with a significant institutional shift in fire management policy in the state of Mato Grosso, marked by the creation of the Environmental Emergency Battalion and the restructuring of the State Fire Management Committee. These developments aimed to enhance wildfire prevention and response, particularly for human-induced ignitions, and provide important context for interpreting fire dynamics during the decade analyzed.

Material and Methods

Study area

The study area was located in the Cuiabá River Headwaters EPA, in South-Central Mato Grosso, Brazil, within the Cerrado biome. This protected area spans 473,410.6 hectares across six municipalities and encompasses portions of the Teles Pires, Juruena, and Upper Cuiabá River basins (Mato Grosso, 1999) (Figure 1, top panel).

Land cover classification indicates 249,102 hectares of forest, 40,413 hectares of non-forest natural formations, 169,049 hectares of agricultural land, 14,252 hectares of non-vegetated areas, and 265 hectares of water bodies (https://plataforma.brasil.mapbiomas.org/). The region is characterized by a tropical savanna climate with high annual temperatures and a well-defined seasonal regime: a rainy season from October to April and a dry season from May to September (Alvares et al., 2013).

Cartographic base

The cartographic datasets used to delimit and locate the study area were obtained from the Brazilian Institute of Geography and Statistics (IBGE, Instituto Brasileiro de Geografia e Estatística) and the INPE through the TerraBrasilis platform (http://terrabrasilis.dpi.inpe.br, accessed October 22, 2023).

Additional data regarding the road network and Indigenous lands were sourced from the Land Institute of Mato Grosso (INTERMAT, Instituto de Terras de Mato Grosso, https://intergeo.intermat.mt.gov.br, accessed May 2, 2024), while settlement program maps were provided by the National Institute of Colonization and Agrarian Reform (INCRA, Instituto Nacional de Colonização e Reforma Agrária, https://certificacao.incra.gov.br/csv_shp/export_shp.py, accessed May 2, 2023).

These geospatial datasets were used to evaluate potential anthropogenic and infrastructural pressures within the EPA.

Hot spot data

Hot spot data were obtained from the Burning Program Database (BDQueimadas) of the INPE (http://www.inpe.br/queimadas/bdqueimadas), derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor onboard the AQUA satellite. The MODIS sensor operates with a revisit time of approximately 1–2 days and detects thermal anomalies using bands 21 (3.929–3.989 μm) and 31 (10.780–11.280 μm), which are sensitive to high-temperature events such as active fires. Detection is based on an automated algorithm that identifies thermal contrasts on the surface, applying thresholds to differentiate active fires from other heat sources (Giglio et al., 2003).

The dataset has a native spatial resolution of 1 km and a temporal resolution of one observation per day (with local overpass time around 1:30 p.m.), covering the period from January 2010 to December 2019. Only high-confidence hot spots (detection confidence ≥30%), classified as vegetation fires, were considered in this analysis to reduce commission errors. Data pre-processing and spatial filtering were performed using the BDQueimadas platform and verified through INPE's quality control procedures.

To account for potential anthropogenic influences near the EPA, a 10 km buffer zone was established around its boundaries. This buffer incorporated adjacent settlement projects and Indigenous territories into the analysis (Figure 1, bottom panel).

Mapping of hot spots

The spatial and temporal analysis of hot spots within the Cuiabá River Headwaters EPA was conducted using interpolation methods in Quantum Geographic Information System (QGIS) software version 2.28.1 (QGIS Development Team), applying the kernel density estimator over the period from 2010 to 2019, with the objective of characterizing hot spot distribution patterns across the region.

The use of kernel density estimation for wildfire occurrence mapping was originally introduced by Koutsias et al. (2004) as a technique

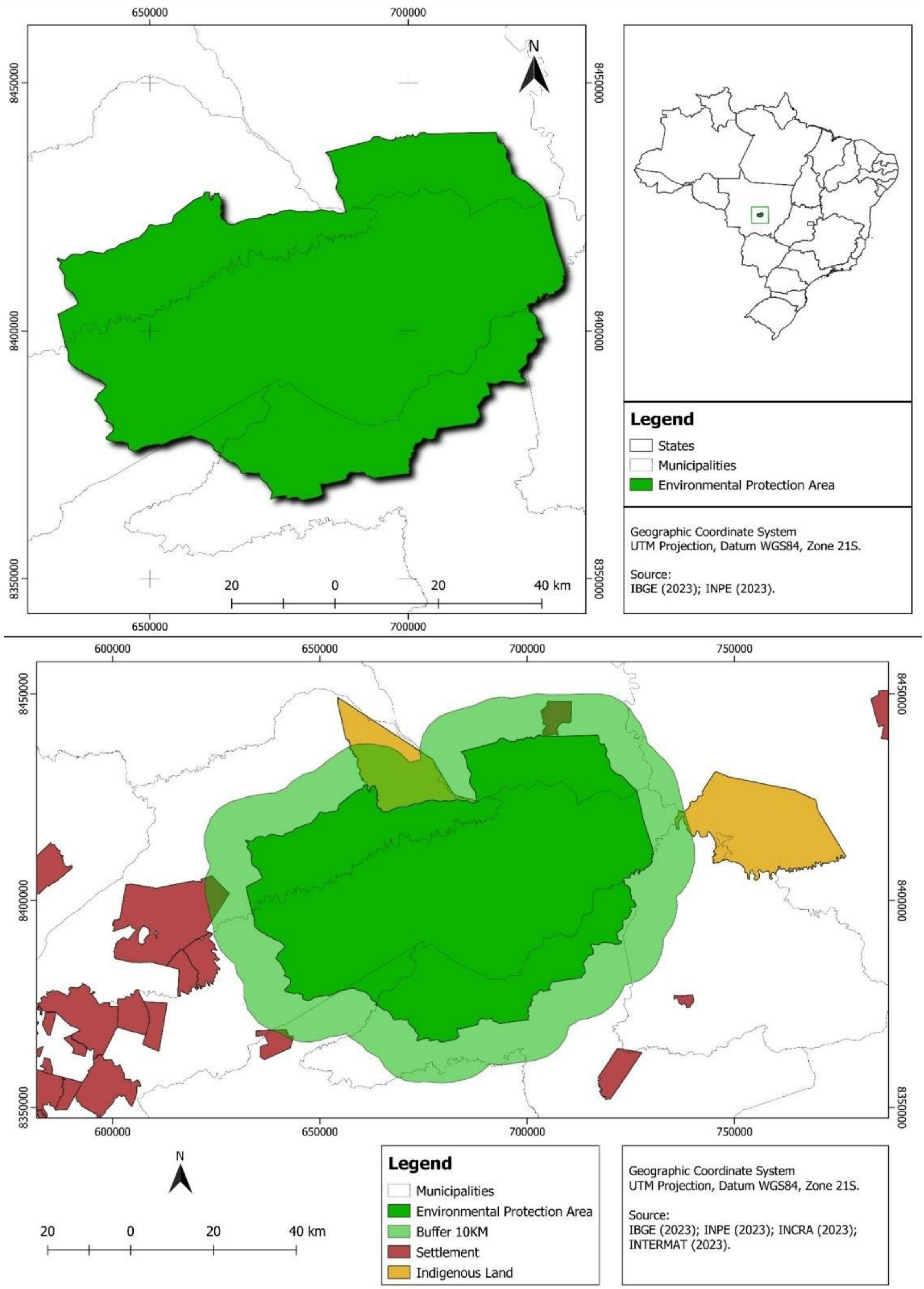

Figure 1 – Location map of the State Environmental Protection Area of the Cuiabá River Headwaters, in the state of Mato Grosso, Brazil (top panel), with a 10 km buffer and areas of settlements and Indigenous lands (bottom panel).

to address the inherent positional inaccuracies associated with recorded wildland fire ignition points. For instance, Aires et al. (2025) mapped wildfire risk in Rio Verde, state of Goiás, and found that proximity to highways and land use changes, especially conversion to agriculture, significantly increased fire hazard areas. Since then, it has been widely adopted due to its advantage in producing continuous density surfaces that are not affected by grid size or localization effects (Koutsias et al., 2014). For this study, the EPA was classified into five categories of hot spot intensity: very low (green), low (yellow), medium (orange), high (red), and very high (dark red) (Cunha Neto, 2021). The resulting kernel density estimation maps were classified into five intensity levels and compared across selected years to identify spatial patterns.

Climatic variables

Climatological data, including maximum temperature, relative humidity, and precipitation, were obtained from the Diamantino weather station (code 83309), located approximately 70 km from the study area and operational since 1931, as part of the Brazilian National Institute of Meteorology database (BDMEP, https://bdmep.inmet.gov.br/, accessed April 26, 2025). Although the Diamantino station is not within the EPA boundaries, its long historical series and data consistency justify its use. The data cover the period from January 2010 to December 2019, are recorded at one-hour intervals, undergo consistency checks, and are considered reliable representations of regional climatic conditions.

The original records are available at a daily resolution and undergo automated quality control procedures before public release.

For the purposes of this study, precipitation data were aggregated into monthly totals, while air temperature and relative humidity values were averaged by month for each year (i.e., monthly means across the 2010–2019 period). These transformations ensured temporal consistency across all variables and allowed for comparative statistical analysis with monthly fire data.

To assess the influence of rainfall scarcity on wildfire occurrence, the number of consecutive dry days (CDD) was evaluated. Daily precipitation data were classified as either dry days (rainfall $\leq$0 mm, coded as 1) or wet days (rainfall >0 mm, coded as 0). The CDD was computed by counting the maximum number of CDDs per month. This approach helps identify the intensity and duration of drought events in each location monthly.

The annual CDD was categorized into six drought severity classes, as shown in Table 1.

Data collection and statistical analyses

Data sources included published articles, Brazilian federal legislation, and technical reports developed under fire management projects associated with the Cuiabá River Headwaters EPA.

To support the interpretation of the statistical findings, a land cover change analysis was also performed using MapBiomas data (https://brasil.mapbiomas.org/), quantifying the conversion of natural vegetation into agricultural land and pasture from 2010 to 2019. This spatiotemporal perspective was critical to contextualizing the fire hotspot patterns observed and strengthening the discussion on the interplay between land use and climate drivers. This analysis considered land use and land cover conversion from the beginning of the period in 2010 to the year 2019.

Analytical procedures involved examining the spatial and temporal patterns of the number of hot spots and their relationships with monthly average air temperature, relative humidity, and accumulated monthly rainfall, for the period 2010–2019. Initially, the Shapiro-Wilk normality test was applied, which indicated that the data did not follow a normal distribution ($p<0.050$). Due to this non-normality, non-parametric tests were employed.

To evaluate significant differences between groups over time, a one-way repeated measures analysis of variance (ANOVA) was applied, followed by its non-parametric counterpart, the Friedman repeated-measures ANOVA by rank. Post hoc comparisons were conducted using Dunn's test with Bonferroni correction to identify significant differences between monthly distributions. The results were presented using medians and interquartile ranges (IQR 25 and 75%), considering the total number of observations and the absence of missing data.

All statistical analyses were performed using Jamovi software, version 2.3.21 (Jamovi, 2022).

Additionally, Spearman's rank correlation coefficient (ρ) was applied to examine monotonic relationships between the number of hot spots and selected climatic variables, including monthly precipitation (mm), mean air temperature (°C), and relative humidity (%). Also, Spearman's rank correlation coefficient (ρ) was applied to examine the relationship between CDD and hot spots per year.

Spearman's rank correlation was used to assess the statistical association between monthly

CDD values and the number of fire hot spots per month for each year.

Results

Land use and land cover dynamics

Land use and land cover were classified into five categories: forest, non-forest natural formations, agricultural land, non-vegetated areas, and water bodies. These categories were mapped (Figure 2) and quan-

Table 1 – Drought severity class based on consecutive dry days.

Drought severity class	Consecutive dry days
Very short drought	1–5
Short drought	6–10
Moderate drought	11–20
Long drought	21–30
Very long drought	31–60
Extremely long drought	> 60

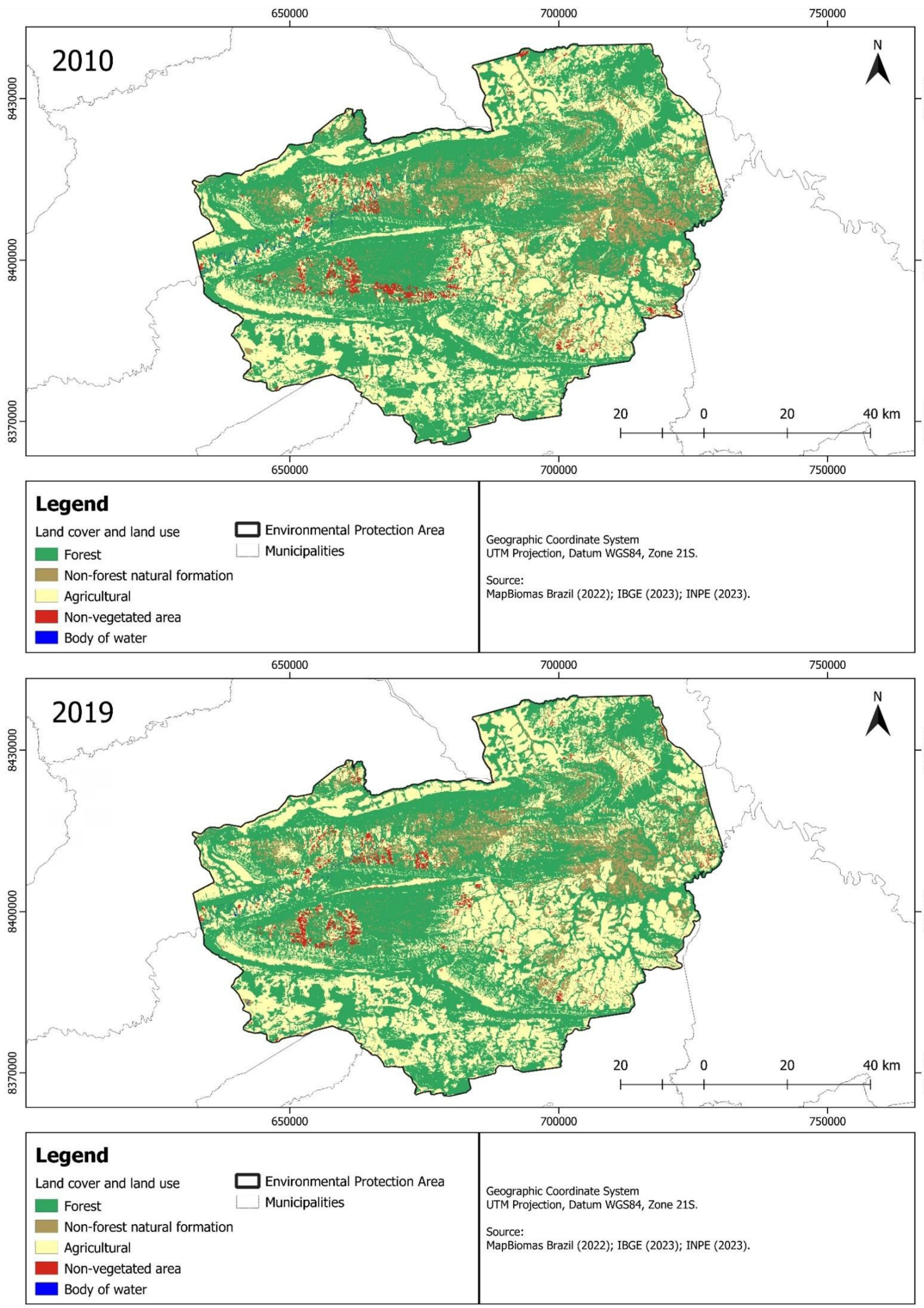

Figure 2 – Land cover and land use in the State Environmental Protection Area of the Cuiabá River Headwaters in the years 2010 (top panel) and 2019 (bottom panel).

tified for the years 2010 and 2019, marking the beginning and end of the study period, respectively (Table 1). Changes in land cover and land use were subsequently assessed by calculating increases and decreases in area, expressed in both hectares and percentages, from 2010 to 2019. A positive Δchange indicates a net gain in land cover, while a negative Δchange represents a net loss (Table 2).

Climatic patterns

Between 2010 and 2019, the annual accumulated rainfall in the study area ranged from 1,560 mm to 2,002 mm. The monthly distribution of rainfall exhibited a characteristic seasonal pattern, with lower values recorded from April to September (dry season) and higher values recorded from October to February (rainy season) (Figure 3).

Table 2 – Land cover and land use classification in the State Environmental Protection Area of the Cuiabá River Headwaters for the years 2010 and 2019, and corresponding changes (Δchange, in hectares and percentage)

Class	Land area 2010	Land area 2019	Δchange 2010–2019
Forest	259,832 ha (54.92%)	249,948 ha (52.83%)	-9,884 ha (-2.09%)
Non-forest natural formation	43,236 ha (9.14%)	37,321 ha (7.89%)	-5,915 ha (-1.25%)
Agricultural	160,325 ha (33.89%)	177,909 ha (37.61%)	+17,584 ha (+3.72%)
Non-vegetated area	9,348 ha (1.98%)	7,678 ha (1.62%)	-1,670 ha (-0.35%)
Body of water	339 ha (0.072%)	224 ha (0.050%)	-115 ha (-0.020%)

Source: https://plataforma.brasil.mapbiomas.org/.
Negative Δchange values represent a reduction in area, while positive values indicate an expansion.

Box plot analysis of air humidity and air temperature (Figure 4), combined with descriptive statistics, confirmed a pronounced seasonal behavior for both variables. August showed a marked decrease in relative humidity, averaging around 65%, while September recorded the highest average temperature, reaching 36.8°C.

Figure 5 illustrates the interannual distribution of dry spells categorized by the CDD approach from 2010 to 2019. Very short drought events (1–5 days) predominated throughout the period, accounting

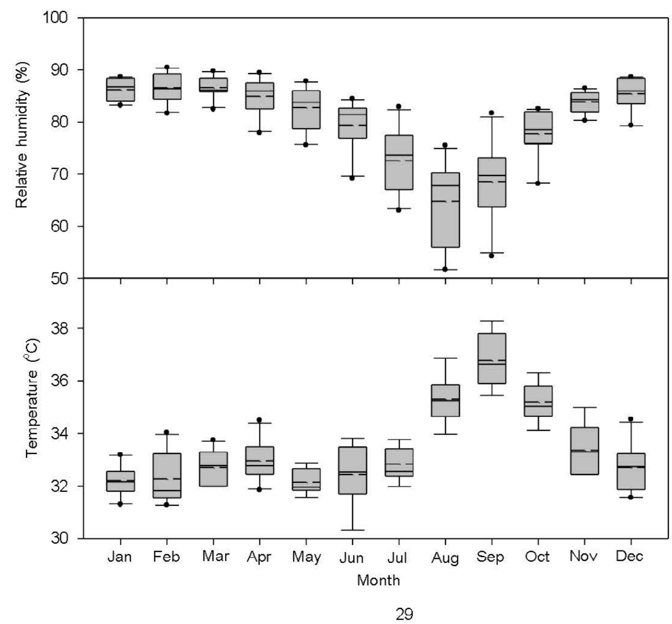

Figure 4 – Boxplots of average monthly air temperature (°C) and relative humidity (%) in the State Environmental Protection Area of the Cuiabá River Headwaters, Mato Grosso, Brazil, for the period 2010–2019. The boxplots represent the median (solid line), the mean (dashed line), the maximum and minimum values, and the first and third quartiles, represented by the vertical boxes with error bars.

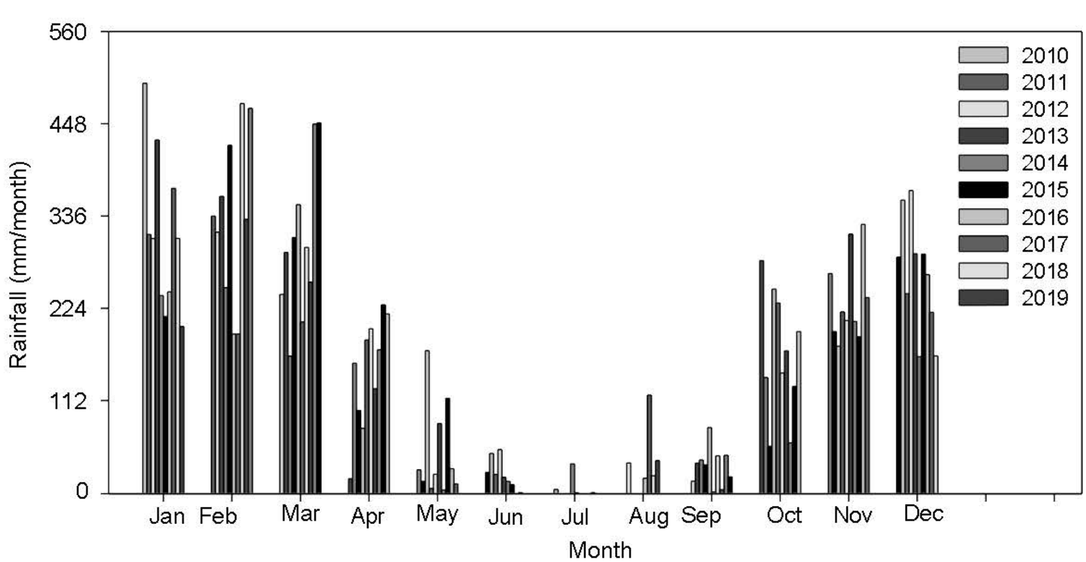

Figure 3 – Monthly rainfall (mm/month) in the State Environmental Protection Area of the Cuiabá River Headwaters, Mato Grosso, Brazil, for the period 2010–2019.

for the highest percentage of occurrences each year. In contrast, longer drought categories, especially very long and extremely long CDDs, occurred less frequently, although their presence is noticeable in specific years, such as 2010, 2011, and 2014. These variations highlight the temporal heterogeneity in drought duration and suggest a predominance of short-term dry events in the region throughout the study period.

Consecutive dry days and spatiotemporal patterns of hot spot density

Between 2010 and 2019, a total of 1,924 hot spots were recorded within the Cuiabá River Headwaters EPA, with an annual mean of 192 hot spots and a high standard deviation (±168), indicating substantial interannual variability in fire activity. According to records from the Authorization for Controlled Burning Sector of Mato Grosso State Department of the Environment (SEMA, Secretaria de Estado de Meio Ambiente do Mato Grosso), no permits for controlled burning were issued within the study area during this period.

Among the ten years analyzed, only four (40%) recorded hot spot totals above the annual mean, while six years (60%) remained below it. The highest number of hot spots occurred in 2010 (615 occurrences), followed by 2017 (255 occurrences), which represents approximately 2.5 times fewer than the 2010 peak. In contrast, the lowest hot spot counts were observed in 2018 (19 occurrences) and 2013 (68 occurrences) (Figure 6, bottom panel). The difference between the highest and lowest annual values during the period from 2010 to 2018 represents a range of 596 occurrences.

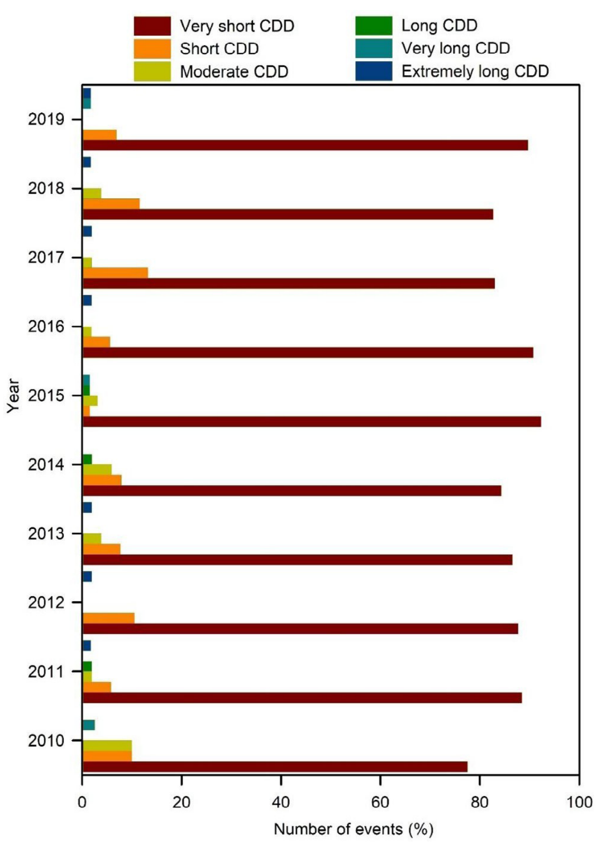

Figure 5 – Interannual distribution (%) of drought events by consecutive dry days (CDD) category in the State Environmental Protection Area of the Cuiabá River Headwaters, Mato Grosso, Brazil, for the period 2010–2019.

Figure 6 presents the annual number of CDD from 2010 to 2019, showing a variation between 230 and 256 days per year. Despite the observed trend, the Spearman correlation between CDD and the number of hot spots was not statistically significant at the 5% level (ρ=0.541; p=0.098).

Figure 7 presents the kernel density estimation mapping of hot spots in the Cuiabá River Headwaters EPA, from 2010 to 2019, categorized into five intensity levels: very low, low, medium, high, and very high. This method was used to convert hot spot occurrences into a continuous raster surface, spatially aligned with the administrative boundaries of the EPA. The resulting analysis indicates that high-density clusters of hot spots predominantly coincide with non-vegetated areas, as shown in Figure 3.

Climatic drivers and seasonality of fire activity

In 2010, during the dry season, the region experienced one of the lowest total rainfall amounts (75 mm), the lowest average relative humidity, and a prolonged dry spell without significant precipitation (Figure 8). These combined conditions contributed to the highest number of hot spots recorded during the study period. In the subsequent years with above-average hot spot occurrences (namely 2012, 2016, and 2017), at least two adverse climatic conditions were also present. An exception was observed in 2019, which, despite presenting three adverse climatic factors, recorded a hot spot count below the overall average.

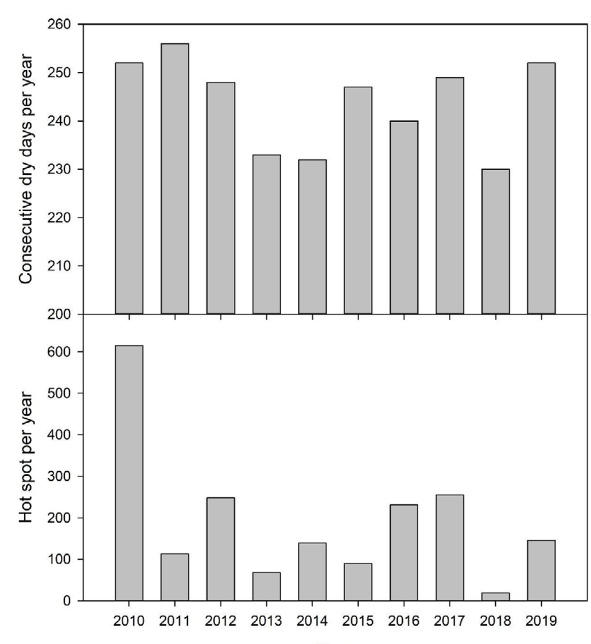

Figure 6 – Annual number of hot spots and of consecutive dry days in the State Environmental Protection Area of the Cuiabá River Headwaters, Mato Grosso, Brazil, from 2010 to 2019.

On average, 84% of the hot spots recorded during the study period occurred in the dry season (May to September), whereas approximately 16% were detected during the rainy season. In certain years, the intensity of the dry season was even more pronounced — for instance, in 2011 and 2012, when about 93% of the annual hot spots were concentrated within this period.

The consecutive three-month period of August–September–October accounted for the highest concentration of hot spots within the Cuiabá River Headwaters EPA, representing 78% of all fire occurrences in a given year. September was particularly critical, with an average of 61% of annual hot spots and a peak of 75% recorded in 2011 alone.

July stood out as the fourth month with the highest incidence of hot spots, registering 133 occurrences. When July is combined with the previously mentioned August–September–October period, this extended four-month window accounted for approximately 85% of the total annual hot spots, reaching up to 91% in specific years such as 2012. This pronounced temporal concentration of fire activity within a relatively short period of the year poses significant challenges for fire response and management operations.

Statistical analysis of fire-climate relationships

A significant negative correlation was identified between total monthly precipitation and the number of hot spots, as determined by Spearman's rank correlation. Temperature and relative humidity showed weaker but still significant associations (Table 3).

A Friedman repeated-measures ANOVA by rank was conducted to assess whether there were significant differences in the distribution patterns between monthly hot spot counts and total precipitation, based on 120 paired observations from 2010 to 2019. The normality assumption was violated, as indicated by the Shapiro–Wilk test ($p<0.050$), which justified the use of the non-parametric alternative.

The analysis revealed a statistically significant difference in the distributions ($\chi^2=50.675$; df=1; $p<0.001$). The median monthly number of hot spots was 1.0 (IQR: 0.0–4.0), whereas the median monthly precipitation was 165.55 mm (IQR: 20.83–254.10 mm), indicating distinct seasonal behaviors. Post hoc multiple comparisons were performed using Dunn's test with Bonferroni correction, confirming that the observed difference was statistically significant.

These results corroborate the expected inverse seasonal relationship between precipitation and fire activity in the region, where lower rainfall values coincide with higher frequencies of fire events. This reinforces the seasonal dynamics already observed in the descriptive analysis and Spearman's correlation.

Table 4 presents the results of Spearman's correlation between the monthly number of fire hot spots and the monthly average air tem-

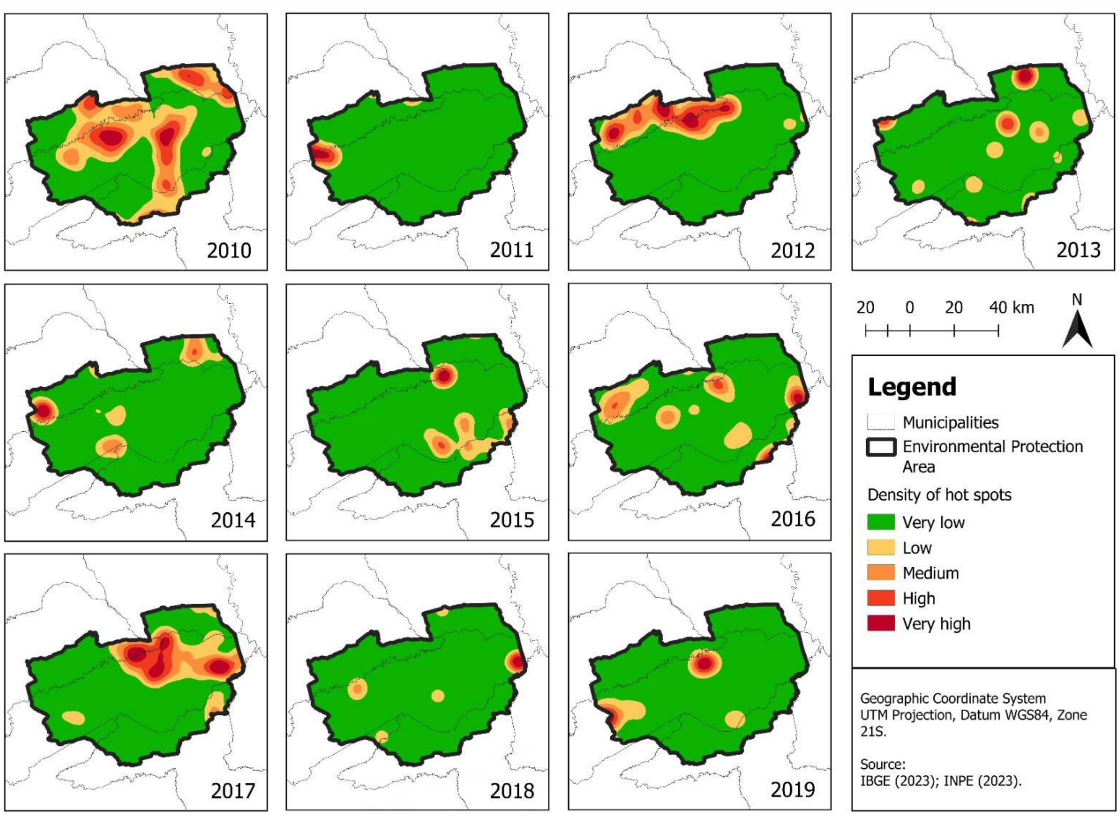

Figure 7 – Spatial distribution of hot spot density in the State Environmental Protection Area of the Cuiabá River Headwaters, Mato Grosso, Brazil, from 2010 to 2019.

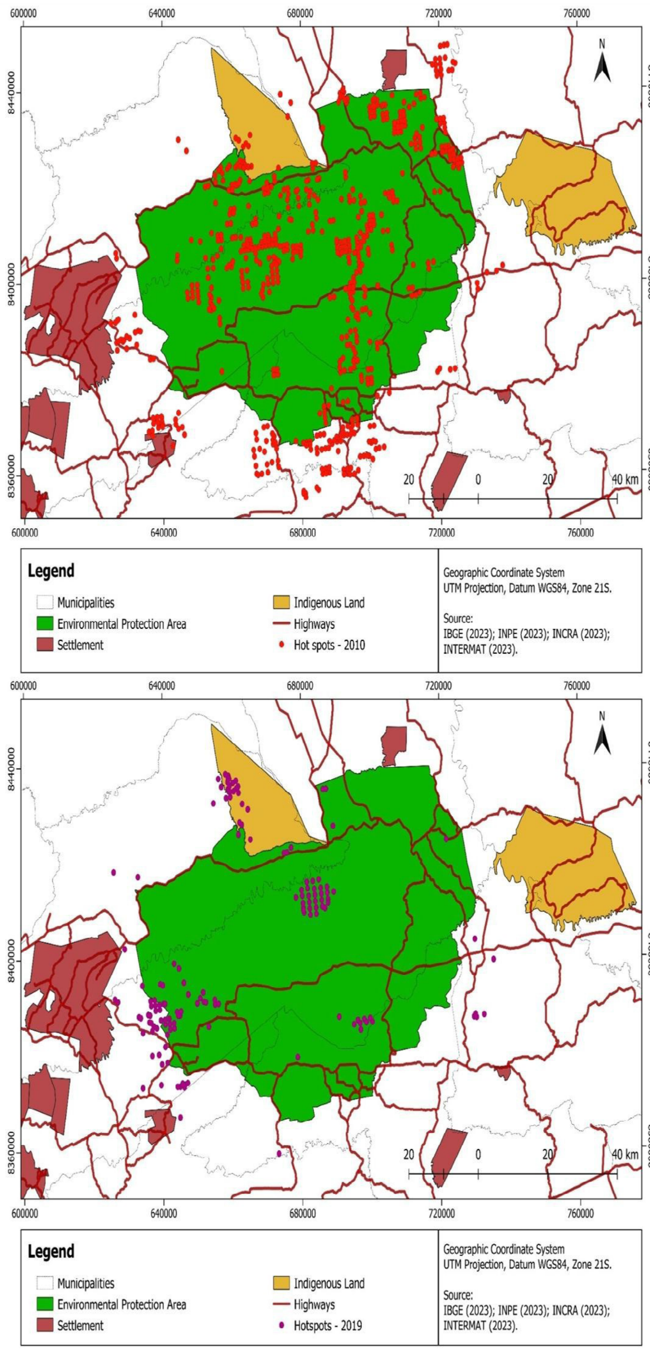

Figure 8 – Spatial distribution of hot spots and zones of human settlement and occupation, including highways, settlement areas, and Indigenous lands, in the State Environmental Protection Area of the Cuiabá River Headwaters and its surrounding areas, for the years 2010 (top panel, n=615 hot spots) and 2019 (bottom panel, n=146 hot spots).

perature, relative humidity, and accumulated precipitation for each year from 2010 to 2019. A significant negative correlation between precipitation and the number of hot spots was observed in several years, particularly in 2010, 2013, 2015, 2016, and 2017 ($p<0.05$).

Table 3 – Spearman's correlation between monthly number of hot spots and monthly accumulated precipitation, average air temperature, and relative humidity (n=120) for the period 2010–2019.

Variable pair	Spearman's correlation (ρ)	p-value	Significance (p<0.05)
Hot spot vs. precipitation	-0.484	0.0000000289	yes
Hot spot vs. air temperature	0.489	0.0000000511	yes
Hot spot vs. relative humidity	-0.595	0.000000200	yes

Table 4 – Spearman's correlation between monthly number of hot spots and monthly accumulated precipitation, average air temperature, and relative humidity (n=12) for each year in the period 2010–2019.

Variable pair	Year	Spearman's correlation (ρ)	p-value	Significance (p<0.05)
Hot spot vs. precipitation	2010	-0.676	0.0139	yes
	2011	-0.477	0.1110	no
	2012	-0.502	0.0892	no
	2013	-0.580	0.0446	yes
	2014	-0.526	0.0749	no
	2015	-0.688	0.0126	yes
	2016	-0.804	0.00036	yes
	2017	-0.738	0.00466	yes
	2018	-0.102	0.7330	no
	2019	-0.124	0.6830	no
Hot spot vs. air temperature	2010	0.539	0.0663	no
	2011	0.641	0.0222	yes
	2012	0.371	0.2240	no
	2013	0.872	2.000×10^{-7}	yes
	2014	0.374	0.2240	no
	2015	0.455	0.1300	no
	2016	0.378	0.2150	no
	2017	0.522	0.0749	no
	2018	0.676	0.0139	yes
	2019	0.630	0.0263	yes
Hot spot vs. relative humidity	2010	0.816	2.000×10^{-7}	yes
	2011	-0.702	0.0101	yes
	2012	-0.820	2.000×10^{-7}	yes
	2013	-0.687	0.00126	yes
	2014	-0.694	0.0113	yes
	2015	-0.739	0.466×10^{-2}	yes
	2016	-0.799	0.664×10^{-3}	yes
	2017	-0.792	1.00×10^{-3}	yes
	2018	-0.911	2.000×10^{-7}	yes
	2019	-0.651	0.0203	yes

Spatial overlay with human occupation

Figure 8 overlays hot spot distributions with human infrastructure, including settlement areas, highways, and Indigenous lands, within and around the EPA. The data suggest a spatial correlation between fire occurrence and zones of anthropogenic pressure, highlighting critical areas for fire management interventions.

Discussion

Climatic influences on wildfire incidence

The study region features a tropical savanna climate, with distinct wet (October–April) and dry (May–September) seasons that directly influence wildfire occurrence. The dry season, particularly from July to September, is characterized by prolonged drought, low relative humidity, elevated temperatures, and minimal rainfall — conditions empirically associated with increased fire activity. For example, in 2010 — the driest year on record — over 600 hot spots were detected, representing the highest annual count in the study period.

This climatic pattern leads to a pronounced water deficit driven by synoptic systems, including the incursion of tropical Atlantic air masses during the wet season and polar air masses in the dry season, alongside geographic factors such as latitude and elevation (Mendes et al., 2019; Carvalho et al., 2021).

Among the climatic variables, relative humidity exhibited the strongest and most consistent relationship with fire occurrence. While precipitation reflects broader moisture availability, relative humidity acts as an immediate meteorological trigger controlling fine-fuel moisture and ignition potential. Low atmospheric humidity accelerates fuel desiccation — even following rain events — sustaining flammability and increasing fire risk. This explains why relative humidity often correlates more strongly with fire incidence than cumulative monthly precipitation (Volpato et al., 2023).

According to the findings, 84% of all hot spots occurred during the dry season, with September consistently registering peak fire activity. This month also showed the highest average air temperature (up to 36.8°C) and the lowest relative humidity (<65%). The cumulative effect of CDDs further amplified fuel flammability, supporting the hypothesis of compound drought–fire interactions in the region. Conversely, fire activity declined sharply during the wet season (Cunha Neto et al., 2021).

This seasonal fire pattern is consistent with that reported by Stephens et al. (2018), who found that drought-induced tree mortality can intensify fire behavior, even in fire-adapted ecosystems. The present study's data suggest that multi-year drought anomalies, compounded by changes in vegetation structure, may be pushing local fire regimes beyond their historical variability, leading to increases in both frequency and severity.

Air temperature also exhibited a positive correlation with fire occurrence ($\rho=0.388$; $p<0.001$), reinforcing its role in drying fine fuels and increasing ignition probability. As highlighted by Bezerra et al. (2021), elevated temperatures reduce fuel-moisture content, intensifying fire behavior even under marginal conditions.

Relative humidity frequently dropped below 65% in August and September, coinciding with elevated fire activity. Similarly, Cunha Neto et al. (2021) demonstrated that atmospheric dryness during extended dry spells is a critical driver of fire outbreaks in forest–agriculture transition zones.

Precipitation exerted the strongest overall influence, with a significant negative correlation with hot spot frequency ($\rho=-0.484$; $p<0.001$). As Silva et al. (2024) noted, under such conditions, fire events intensify and post-disturbance vegetation recovery is impeded, especially in ecosystems with low regenerative capacity.

Anthropogenic drivers of wildfire occurrence

Human activities are probably a key driver of wildfire incidence within the Cuiabá River Headwaters EPA, particularly during the dry season. In rural areas of the Cerrado, fire is routinely used for land clearing, crop preparation, and pasture renewal. These practices intensify toward the end of the dry season, when vegetation is dry and ignition conditions are most favorable. According to Rocha and Nascimento (2021), the October transition into the rainy season is strategically chosen by rural producers for burning, which aligns with the seasonal concentration of hot spots observed in this study data — 78% of all annual fire activity occurred between August and October.

The spatial analysis indicates that fire incidence is not distributed randomly, but rather in clusters in areas undergoing recent land cover changes. Between 2010 and 2019, the EPA experienced a 252% increase in agricultural land, alongside a loss of over 15,000 hectares of forest and non-forest natural vegetation. The overlay of hot spot density with zones of agricultural expansion reveals a strong spatial association. Similarly, Torres et al. (2011) found that fire activity in urban–rural interfaces is strongly correlated with ongoing deforestation processes.

This anthropogenic pattern is widely documented in the literature. Cunha Neto et al. (2021) demonstrated that fire occurrences in the Eastern Amazon are significantly higher in transitional zones where agricultural encroachment and pasture expansion replace native vegetation. This study's findings align with this pattern, as human-driven land use change within the EPA increases ignition sources and disrupts natural fire regimes.

Although climatic variability remains central, two dominant anthropogenic factors — deforestation and insufficient fire suppression infrastructure — have been identified as key modulators of fire regimes in the Cerrado (Schmidt and Eloy, 2020). This was particularly evident in years like 2010 and 2012, when prolonged drought coincided with accelerated land clearing, resulting in peak fire activity.

Furthermore, as McLauchlan et al. (2020) emphasized, anthropogenic disturbances not only elevate fire frequency but also decouple fire regimes from their historical ecological contexts, posing new risks to biodiversity and ecosystem resilience.

Institutional efforts and policy impacts

The analysis of fire suppression and land-use governance within the Cuiabá River Headwaters EPA must be contextualized within the regional development dynamics of municipalities such as Rosário Oeste and Nobres, which together comprise over 70% of the EPA. These municipalities are characterized by agricultural expansion and cattle ranching — sectors frequently associated with the use of fire for land management and renewal of pastures (SEMA, 2022; 2024).

A turning point in wildfire patterns occurred after 2010, the year that recorded the highest number of hot spots (615). This was followed by a decline in fire activity, coinciding with the institutionalization of fire management policies in the state of Mato Grosso. Key measures included the creation of the Environmental Emergency Battalion under Complementary Law nº 404/2010 (Mato Grosso, 2010), activated in 2014, and the restructuring of the State Fire Management Committee (Decree nº 513/2011, Mato Grosso, 2011), coordinated by the Mato Grosso State Military Fire Department (CBMMT, Corpo de Bombeiros Militar do Estado de Mato Grosso) and SEMA. At the federal level, the Integrated Fire Management (MIF, Manejo Integrado do Fogo) program, launched in 2014, introduced an approach integrating ecological, cultural, and socioeconomic factors (Schmidt and Eloy, 2020), and promoting prescribed burning and specialized brigades in fire-prone biomes such as the Cerrado.

Despite institutional advances, enforcement capacity and resources remained limited until 2016, when Action 2121 under SEMA's Program 393 secured budgetary autonomy for fire control (Sousa, 2020), thereby improving operational continuity. However, in 2019, fire activity resurged (from 19 to 146 hot spots), coinciding with the enactment of State Law Nº 10,713/2018, which authorized additional deforestation within the EPA. Although still below historical averages, this increase underscores how policy incoherence can undermine conservation goals. These findings suggest that institutional gains in fire control remain fragile and depend on consistent land-use regulation and coordinated action across governance levels.

Spatial patterns and land-use associations

The spatial distribution of hot spots within the Cuiabá River Headwaters EPA reveals persistent clustering in the Northern and Central regions, which correspond to areas of more intense land use change. An exception occurred in 2010, when fire activity was widespread across the EPA (Figure 7), coinciding with extensive drought and over 100,000 hectares of deforestation reported that same year by the Special Areas Monitoring Program.

Between 2010 and 2019, the Project for Monitoring Deforestation in the Legal Amazon by Satellite (PRODES, Projeto de Monitoramento do Desmatamento na Amazônia Legal por Satélite) documented approximately 400 km² of clear-cut deforestation within the EPA. When spatially correlated with the hot spot maps, these zones of vegetation loss showed a strong alignment with areas of high fire density, particularly in regions converted to pasture and agriculture.

Agricultural land within the EPA expanded by 252% between 2010 and 2019, primarily replacing native vegetation, while pasture declined by 13%. Nearly 15,800 hectares of forest and non-forest formations were lost. These changes corroborate those found by Santos et al. (2023), who reported that fire hot spots in protected areas are closely associated with recent land-use transitions. Spadoni et al. (2025) quantified this trend, showing that approximately 12% of fires in Mato Grosso and Matopiba — a region encompassing parts of the states of Maranhão, Tocantins, Piauí, and Bahia, representing Brazil's major agricultural frontier — occurred in recently devegetated zones between 2003 and 2020. According to the authors, these fires affected 20 million hectares, including 12% of such areas within protected areas and 16% within Indigenous lands.

Although the EPA was established in 1999, deforestation continued, totaling 893 km², with no official authorizations until 2018, when State Law nº 10,713/2018 (Mato Grosso, 2018) authorized new clearings. This legal shift raised concerns about the weakening of conservation goals. As noted by Joly and Padgursch (2019), such trends exemplify the structural vulnerabilities of Cerrado protected areas, which face mounting pressures despite their rich biodiversity — including over 12,000 plant species and 200 mammal species.

This trajectory mirrors global trends observed in fire-prone ecosystems. According to Bowman et al. (2020), large-scale wildfires are increasingly driven by the interplay between anthropogenic land conversion and climate extremes. Within the Cuiabá River Headwaters EPA, this interplay is evident in the spatial convergence of fire activity, agricultural expansion, and biodiversity threats, underscoring the urgent need for integrated fire and land-use governance strategies.

Influence of infrastructure and Indigenous lands

The spatial distribution of hot spots in the Cuiabá River Headwaters EPA showed clear clustering near roads, settlements, and Indigenous territories, indicating the influence of socio-spatial factors on fire ignition patterns. Similar associations between human infrastructure and fire activity were reported by Ganteaume et al. (2013) and Aires et al. (2025), reinforcing the role of human presence — particularly in areas such as Coqueiral, Quebó, and Ponte de Barro — in driving fire occurrence.

These patterns align with Costa et al. (2017), who reported increased fire activity along the influence zone of BR-163 in Mato Grosso — a dynamic that, although not directly involving the EPA, seems mirrored near local roads that facilitate land access and burning practices. Fire incidence was also notable near Indigenous lands, particularly within the Santana and Bakairi territories. During high-fire years (2010, 2012, and 2017), elevated hot spot densities occurred near these areas, indicating that fire vulnerability may reflect not only proximity but also broader territorial and policy-related factors.

Conclusion

The findings reveal that fire activity in the Cuiabá River Headwaters EPA is strongly seasonal and spatially concentrated. About 78% of hot spots occurred between August and October, aligning with the region's dry season and adverse climatic conditions, such as low precipitation, low relative humidity, and extended dry spells. These climatic factors — particularly relative humidity — showed statistically significant correlations with hot spot frequency, supporting the hypothesis that drought conditions influence hot spots.

Spatially, fire events were not random but associated with anthropogenic factors such as roads, settlement projects, and land use change. Between 2010 and 2019, agricultural land expanded by 252%, while forest and natural vegetation declined, highlighting the role of human-driven deforestation in modifying fire regimes.

Despite institutional efforts — such as the creation of the Environmental Emergency Battalion and implementation of fire management programs — policy contradictions, including legal authorizations for deforestation in protected areas, have weakened fire control strategies. The integration of climatic analysis, land cover change, and spatial mapping through a Geographic Information System (GIS) proved essential for understanding fire patterns and informing territorial management.

This study emphasizes the urgent need for integrated fire prevention and land use policies to protect biodiversity, control anthropogenic fire triggers, and enhance resilience in fire-prone ecosystems such as the Cerrado.

Authors' Contributions

Sanches, L.: conceptualization, data curation, investigation, methodology, visuali-zation, writing – original draft, writing – review & editing. **Anjos**, M.F.: data curation, formal analysis, writing – original draft. **Carmo Junior**, G.N.R.: project administration, writing – original draft. **Hoki**, V.S.P.: data curation, formal analysis. **Alves**, K.S.S.: methodology, data curation, formal analysis.

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