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Spatiotemporal analysis of wildfires in the municipality of Rio de Contas, Chapada Diamantina

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Abstract

Wildfire occurrences annually affect different vegetation regions, generating environmental, economic, and social impacts. The municipality of Rio de Contas, located in Chapada Diamantina, Bahia, constitutes one of these vulnerable areas. In this context, the use of geotechnologies such as remote sensing is essential for monitoring and analyzing affected territories. This study was developed to evaluate wildfire occurrences on a spatiotemporal scale in Rio de Contas from 2010 to 2024, using satellite imagery and geoprocessing techniques. Data on fire outbreaks were obtained from the Wildfire Program of the National Institute for Space Research (INPE), whereas burned area data were extracted from NASA's Reverb platform and the University of Maryland. Meteorological information was provided by the National Institute of Meteorology (INMET). Analyses were performed on QGIS, applying Kernel density estimation. Of the 101 wildfire outbreaks identified, 48.5 % occurred within conservation units. Its highest incidence was recorded in September, with an average burned area of 394.18 ha, associated with low rainfall rates. Spatial analysis indicated a concentration of fire outbreaks in areas above 1000 meters in altitude, predominantly in grassland savanna. Thus, the most prone periods to wildfires and their association with local climatic variables were identified. These findings highlight the relevance of geotechnologies in environmental planning and management, providing support for wildfire prevention and mitigation strategies.

Keywords: Conservation Areas. Geotechnologies. Geoprocessing. Forest Fires. Remote Sensing.

Introduction

Wildfires in vegetation areas can cause serious damage to the environment such as negative impacts on fauna, flora, and human beings, including loss of life. Additionally, these events bring about considerable economic consequences, generating significant financial costs for the control and recovery of affected areas. Uncontrolled wildfires, especially in conservation areas, represents an important mechanism for biodiversity extinction and interruption of natural ecological processes (SILVA *et al.*, 2021).

Studies on forest fires, fire location, critical areas of recurrent wildfire and temporal variability allow for a systematic approach in terms of managing and planning preventive and fire control actions (MOUILLOT *et al.*, 2014). Planning and implementing forest fire management can therefore be based on spatial and temporal mapping resulting from remote sensing techniques, presenting high potential for monitoring fire-affected vegetation (FRANKE *et al.*, 2018; SANTOS *et al.*, 2018).

Technological advancements like use of satellite imagery and remote sensors enable detecting and locating fire outbreaks in real time. Brazil has invested in technologies that allow for the rapid monitoring and control of hotspots, aiding in the effective fight against wildfires (GRANEMANN, CARNEIRO, 2009). In this context, the National Institute for Space Research (INPE) has been developing and improving the Amazon Forest Fire Monitoring, Prevention and Control System (PROARCO) since 1980 to monitor and combat wildfires. PROARCO uses space-based sensors to track wildfires across Brazil, providing free data from polar and geostationary satellite imagery. Once these images are processed, INPE provides information on the detected hot spots (BATISTA, 2004).

Southwestern Chapada Diamantina presents relevant geological and tourist potential due to its geological formations, biodiversity and hydrography, which provide beautiful landscapes, besides its rich historical character (BARRETO, 2007). Although the region's rocky fields occupy areas where ecotourism is the main economic activity, this type of vegetation has been altered by various disturbances such as deforestation, grazing, wildfire, and extraction of native species for commercialization (CHIAPETTI, 2009).

Part of the municipality lies within the Serra do Barbado Environmental Protection Area (APA), represented by the varied nuances of the Caatinga biome like the Gerais, high-altitude rocky fields, and the Cerrado with varied vegetation (INEMA, 2002). In January 2002, the municipality established the Serra das Almas Municipal Natural Park (PNSA), an important area for biodiversity preservation (BRASIL, 2024). Leite *et al.* (2012) warn that the park faces significant limitations in its conservation, management, and enforcement activities, although it is classified as a protected area. Consequently, unregulated land occupation, improper use of fire, and unregulated tourism pose persistent threats to the integrity of this ecosystem.

Recent research has applied multitemporal analyses to understand the dynamics of wildfires in ecological transition regions, highlighting correlations between climate variability and fire intensity (CAMPANHARO *et al.*, 2021; SETZER *et al.*, 2021). In a study on the spatiotemporal patterns of wildfires in the Gran Chaco and Pantanal, Vidal-Riveros *et al.* (2024) evinced the combined influence of climatic variables, such as temperature and rainfall, and anthropogenic factors, such as land use and the presence of livestock, on wildfire occurrence.

In analyzing over 2.2 million hot spots detected between 2011 and 2022 across Brazilian biomes, Pimentel *et al.* (2024) underscored the importance of temperature and humidity as determinants in wildfire frequency. Such quantitative approach provides support for comparisons between different regions and periods, enabling more robust analyses of the phenomenon.

Regional-specific research also brings relevant contributions. Santos *et al.* (2020) assessed the severity of burned areas and post-fire regeneration in the Chapada Diamantina National Park using spectral indices (dNBR and RdNBR), highlighting the heterogeneity of environmental impacts. Oliveira *et al.* (2021), in turn, analyzed fire occurrences and their relationship with atmospheric variables between 2015 and 2020 in the same park, reinforcing the strong association between prolonged drought and increased incidence of wildfires.

Given this context, this work analyzed, based on a spatiotemporal scale, wildfire occurrences in the municipality of Rio de Contas, Bahia, from 2010 to 2024. For this purpose, data were collected from INPE's Wildfire Program, the MCD64A1 product—generated and made available by the National Aeronautics and Space Administration (NASA)—, and geoprocessing techniques were used to analyze spatial information.

Material and methods

The study area was the municipality of Rio de Contas, located in south-central Bahia, 742 km from the state capital Salvador, situated between latitude 13° 35' S and longitude 41° 48' W, with a total area of 1,115.252 km^2 (Instituto Brasileiro de Geografia e Estatística – IBGE, 2025). Part of its Northwest region is located within the Serra do Barbado Environmental Protection Area (APA) (INEMA, 2002), whereas the Serra das Almas Municipal Natural Park (PNSA) is located in the Southwest region.

Data on fire outbreaks in the municipality were acquired from the Wildfire Program database developed by INPE (2024). Tabulated and shapefile data from 2010 to 2024 were used. Data were analyzed using spatial and temporal criteria, considering annual and monthly periods. For this study, data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor, aboard the Terra and Aqua satellites, were used. The period from 2010 to 2024 was selected to investigate possible influences of interannual climate variations on fire outbreaks, encompassing a range of years with distinct meteorological patterns, including extremes associated with the El Niño and La Niña phenomena.

Information geoprocessing and map creation were performed using the free software QGIS 3.26.3. Fire outbreaks were spatially analyzed using the statistical method of density estimation via Kernel algorithm to assess their distribution and intensity across the study area.

Data on burned areas were provided by NASA, specifically by the MCD64A1 product, generated from MODIS sensor images with a 500-m resolution. These data is freely available in shapefile format through Reverb (NASA) and the University of Maryland. NASA's burned area data were processed for projection system conversion, cropped to the municipality's area. Subsequently, the spatial analysis was compared with relief and vegetation information obtained from the IBGE platform.

Meteorological information on rainfall, temperature, and wind speed was obtained from the automatic station located in the municipality of Piatã, provided by INMET (2024), the meteorological station closest to the study area. Temporal analysis of the data was compared with the meteorological conditions of temperature, wind speed, and rainfall, obtaining a linear correlation.

Results and discussion

From 2010 to 2024, INPE's program registered 101 fire outbreaks in the municipality of Rio de Contas (Figure 1), of which 48.5 % occurred within environmental protection areas (Serra do Barbado and Serra das Almas Park).

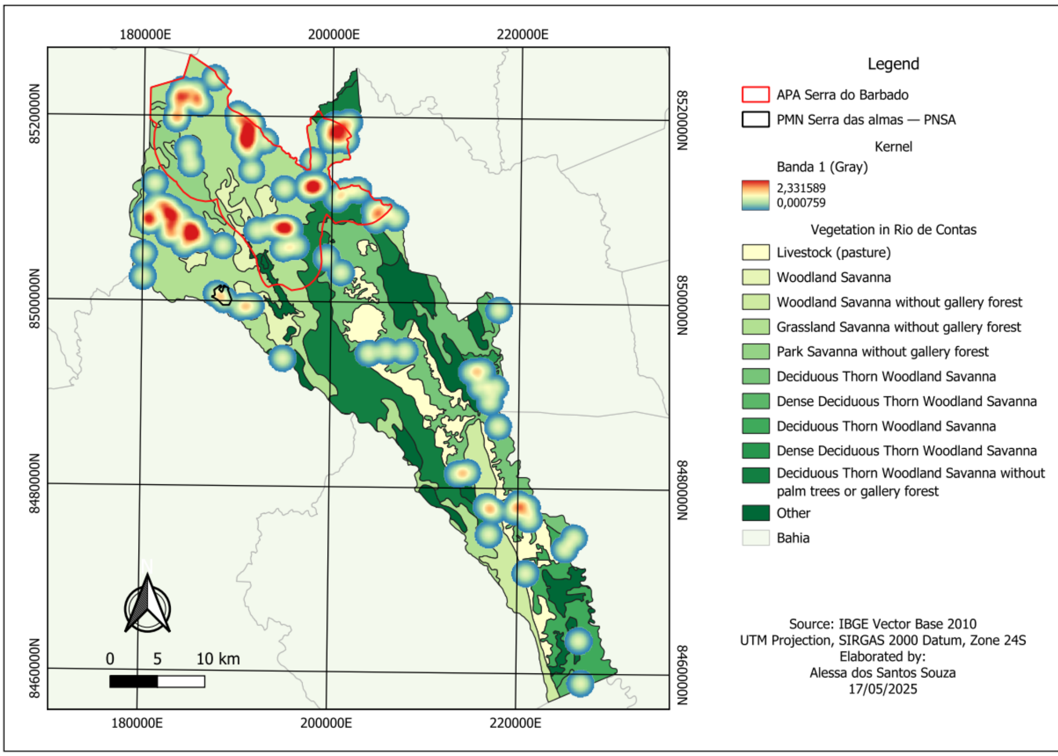
Setzer *et al.* (2021) found a similar result in protected areas of the Caatinga biome, where the density of fire outbreaks in Federal Conservation Units (UCFs) was higher than that recorded in unprotected areas. According to the authors, this pattern may be related to the fact that approximately 98 % of sustainable use UFCs is located in protected areas, where certain human activities are permitted.

In theory, these areas are intended to enable a balance between human presence, their socioeconomic interests, and the conservation of natural resources. However, the population residing in the APAs frequently resorts to slash-and-burn for land clearing and agricultural practices, violating current legislation and more frequently than in unprotected areas (SETZER *et al*., 2021).

September saw the highest number of wildfires (27 hotspots), coinciding with the period of lowest average monthly rainfall (15.0 mm) (Table 1). This reduced rainfall intensified the drought and increased the environment's susceptibility to larger-scale fires. Thus, environmental preservation areas were most affected during September, with an average burned area of 242.8 hectares per year.

Pimentel *et al*. (2024) found similar results when analyzing more than 2.2 million hotspots nationwide, identifying rainfall and humidity as determining variables in wildfire occurrence, thereby reinforcing the direct influence of extreme climatic conditions. Similarly, Vidal-Riveros *et al.* (2024), in a study on the Gran Chaco and Pantanal, showed that climatic

Figure 1. Spatial distribution and density of fire outbreaks from 2010 to 2024 in the municipality of Rio de Contas, Bahia.



Source: Elaborated by the authors with INPE data (2024)

Table 1. Fire outbreaks, Burned area in Rio de Contas (ha); Burned area in the Serra do Barbado APA (ha); Burned area in the Serra das Almas Park (ha); Days with rainfall; Average Monthly rainfall (mm); Average Temperature (°C) and Average Wind Speed (m/s) in the municipality of Rio de Contas, BA, from 2010 to 2024.

Month	Fire Outbreaks	Burned area in Rio de Contas (ha)	Burned area in Serra do Barbado APA (ha)	Burned area in Serra das Almas Park (ha)	Days with rainfall	Average Monthly Rainfall (mm)	Average temperature (°C)	Average Wind Speed (m/s)
Jan	3	988.16	555.26	0.00	10	90.2	20.9	2.4
Feb	0	416.55	416.55	0.00	12	78.6	21.0	2.4
Mar	9	23.14	23.14	0.00	11	92.4	21.2	2.3
Apr	3	23.12	0.00	0.00	12	91.7	20.3	2.4
May	2	0.00	0.00	0.00	12	39.8	19.0	2.4
June	0	0.00	0.00	0.00	12	38.3	17.7	2.7
July	6	23.14	23.14	0.00	13	45.6	16.9	3.0
Aug	11	2,241.64	0.00	0.00	10	36.3	17.5	3.0
Sept	27	5,912.74	3,641.35	0.00	6	15.0	19.1	2.9
Oct	21	3,792.01	2,394.45	572.90	6	47.7	20.7	2.7
Nov	7	2,350.13	2,123.03	140.51	12	93.0	19.0	2.0
Dec	12	1,998.57	866.53	0.00	10	86.5	18.2	2.1

Source: Elaborated by the authors with INPE (2024) and INMET (2024) data.

seasonality associated with land use (extensive livestock farming and deforestation) intensifies fires, corroborating the seasonal pattern detected in Rio de Contas.

Overall, wildfires in Brazil are concentrated during the dry season and prolonged periods of drought, mainly in deforested areas. Notably, most of these events are anthropogenic in origin, being associated with practices like preparation and maintenance of cultivated areas, pasture renovation, burning of residues, and pest and disease control (SETZER *et al.*, 2021).

In the Caatinga biome, this seasonality occurs mainly between August and October—the dry season (CAMPANHARO *et al.*, 2021). At the regional level, the findings align with Oliveira *et al.* (2021), who analyzed the period from 2015 to 2020 in the Chapada Diamantina National Park, finding a higher wildfire frequency in the dry months and a strong association with prolonged droughts.

Spearman's correlation matrix analysis evinced several correlations between the meteorological variables and fire outbreaks and burned area. Analysis reveals that the burned area is moderately correlated with the number of fire outbreaks ($r = 0.43$, $p < 0.01$), suggesting that regions with more fire outbreaks tend to have a larger total burned area (Table 2). Fire outbreaks also correlated with the month ($r = 0.28$, $p < 0.01$), showing that the number of fire outbreaks is directly proportional to the month of the year, and the burned area increases as the number of fire outbreaks recorded in the same period rises. Carvalho *et al.* (2017) also observed a strong linear relation between hot spots and burned area.

Average temperature exhibits a moderate positive correlation with burned area ($r = 0.31$, $p < 0.01$), suggesting that periods of higher temperatures may increase wildfire spread and lead to large areas burned.

Table 2. Estimates of Spearman's linear correlation coefficients between Months of the year, Fire outbreaks, Burned area, Days with rainfall, Monthly rainfall, Average temperature and Average wind speed, in the municipality of Rio de Contas, BA.

Correlation Matrix: Spearman	Month	Fire outbreaks	Burned area (ha)	Days with rainfall	Monthly rainfall (mm)	Average temperature (°C)
Fire outbreaks	0.28^{**}					
Burned area (ha)	0.27^{**}	0.43^{**}				
Days with rainfall	-0.19^{*}	-0.25^{**}	-0.34^{**}			
Monthly rainfall (mm)	-0.09^{ns}	-0.11^{ns}	-0.18^{**}	0.72^{**}		
Average temperature (°C)	-0.19^{*}	0.14^{ns}	0.31^{**}	-0.25^{**}	0.17^{*}	
Average wind speed (m/s)	0.18^{*}	0.10^{ns}	0.13^{ns}	-0.11^{ns}	-0.36^{**}	-0.50^{**}

**Significant at 1 % probability by t-test.

**Significant at 5 % probability by t-test.

^{ns}Not significant.

Source: authors (2025).

Number of days with rainfall presented a significant negative correlation with the number of fire outbreaks ($r = -0.25$, $p < 0.01$) and burned area ($r = -0.34$, $p < 0.01$), indicating that for the same period, the fewer days with rainfall, the greater the number of fire outbreaks and the greater the burned area. Burned area also showed a significant negative correlation with monthly rainfall ($r = -0.18$, $p < 0.05$), indicating that the lower the rainfall during the month, the greater the wildfire.

Rainfall reduces the potential for wildfires to occur and spread, even to zero, depending on the amount of rainfall (SOARES, 2000). Wildfire occurrence and regime are influenced by meteorological and climatic conditions, particularly lightning strikes, wind speed, and fuel moisture. This last variable is directly related to elements such as rainfall, relative humidity, temperature, and solar radiation (SETZER *et al.*, 2021).

These results highlight the complex interactions between meteorological factors and wildfires, emphasizing the importance of considering multiple parameters when developing strategies for preventing and fighting forest fires. Most fire outbreaks occurred in 2011, 2012 and 2024, registering 14, 13 and 15 occurrences, respectively (Table 3). Additionally, 2020 presented the highest rainfall, being one of the years with the lowest number of recorded fire outbreaks.

Largest burned areas in the municipality were recorded in 2012, 2019, and 2024, with 4,123.28, 3,048.80, and 2,912.55 hectares,

Table 3. *Fire outbreaks, Burned area in Rio de Contas (ha); Burned area in Serra do Barbado APA (ha); Burned area in Serra das Almas Park (ha); Days with rainfall; Average annual rainfall (mm); Average annual temperature (°C) and Average wind speed (m/s) in the municipality of Rio de Contas, BA, from 2010 to 2024.*

Year	Fire Outbreaks	Burned area in Rio de Contas (ha)	Burned area in Serra do Barbado APA (ha)	Burned area in Serra das Almas Park (ha)	Average Monthly Days with rainfall	Annual rainfall (mm)	Average annual temperature (°C)	Average Wind Speed (m/s)
2010	6	0.00	0.00	0.00	13	1,12060	19.63	2.57
2011	14	23.14	23.14	0.00	13	939.80	19.16	2.47
2012	13	4,123.18	2,991.16	0.00	10	672.20	19.74	2.56
2013	9	1,203.17	1,203.17	0.00	13	1,039.40	19.83	2.45
2014	4	0.00	0.00	0.00	11	938.40	19.32	2.59
2015	9	1,780.52	1,251.84	0.00	10	757.60	20.14	2.51
2016	4	0.00	0.00	0.00	4	42.40	20.00	2.47
2017	1	432.90	0.00	0.00	6	73.00	19.45	2.52
2018	7	2,411.08	0.00	0.00	14	1,133.60	19.67	2.33
2019	4	3,048.81	2,209.89	713.41	10	665.20	20.18	2.69
2020	1	532.21	532.21	0.00	15	1,432.80	19.12	2.89
2021	4	24.84	0.00	0.00	8	519.60	16.01	2.24
2022	1	34.52	34.52	0.00	11	567.20	19.02	2.76
2023	9	1,242.26	1,242.26	0.00	8	522.00	20.11	2.64
2024	15	2,912.55	555.26	0.00	11	900.00	17.98	2.29

Source: Elaborated by the authors with INPE (2024) and INMET (2024) data.

respectively. These years exhibited below-average annual rainfall, and followed years with above-average rainfall. This corroborates Campanharo *et al.* (2021), who comment that wildfire occurrences and the alternation of long rainy and dry periods generate events of greater magnitude in subsequent years. Years with above-average rainfall tend to contribute to biomass recovery and, consequently, promote the occurrence of fires in subsequent years.

In 2012, the Serra do Barbado APA registered a burned area equivalent to 2,991.16 ha. In 2019, both the Serra do Barbado APA and the Serra das Almas Park were affected, with 2,209.89 ha and 713.41 ha burned, respectively (Figure 2). Serra das Almas Park recorded a burned area only in 2019. No burned areas were recorded in 2010, 2014, 2016, 2017, 2018, and 2021, in the studied preservation areas (Figure 2).

Most wildfires in the municipality occurred in grassland savanna areas without gallery forests. Considered one of the most vulnerable to wildfires, its grassy character is the primary reason for its high susceptibility to fire. Grasses produce a significant amount of fine, well-ventilated combustible material, resulting in highly flammable vegetation during drought periods (SILVA, 2018).

Most outbreaks and burned areas in the municipality occurred in higher altitude regions, above 1,000 m, and within environmental protection areas (Figure 3). Altitude is an environmental factor that influences the risk of wildfires due to its relationship with relative air humidity. However, this factor should not be considered in isolation and needs to be evaluated alongside other variables.

Similarly, Santos *et al.* (2020) showed that, in addition to occurrence, the severity of wildfires in Chapada exhibits great spatial heterogeneity, influenced by relief and vegetation type. This observation is consistent with the present study, in which Kernel density estimation revealed a higher concentration of wildfires in high-altitude areas, predominantly covered by grassland savanna vegetation.

Understanding wildfires is essential to mitigating their devastating impacts. As highlighted by Chang *et al.* (2015), a vast number of factors influence fire ecology. Regional climate plays a key role, as atmospheric conditions like temperature, humidity, and wind patterns affect the susceptibility of areas to wildfires and determine their intensity. Moreover, the amount of biomass available, which can be influenced by factors such as vegetation density and prolonged droughts, plays a critical role in fire spread. Land use is also a significant component, as agricultural, forestry management, and urbanization practices can alter the landscape, influencing fire propagation and behavior. Relief, including slope and altitude, plays an important role in shaping wind patterns and creating microclimates, which can influence fire spread and complexity. In addition to physical variables, socioeconomic and political factors can also play a significant role in wildfire occurrence and management. Hence, understanding the complex interaction of these factors is crucial for developing effective strategies for preventing and managing wildfires.

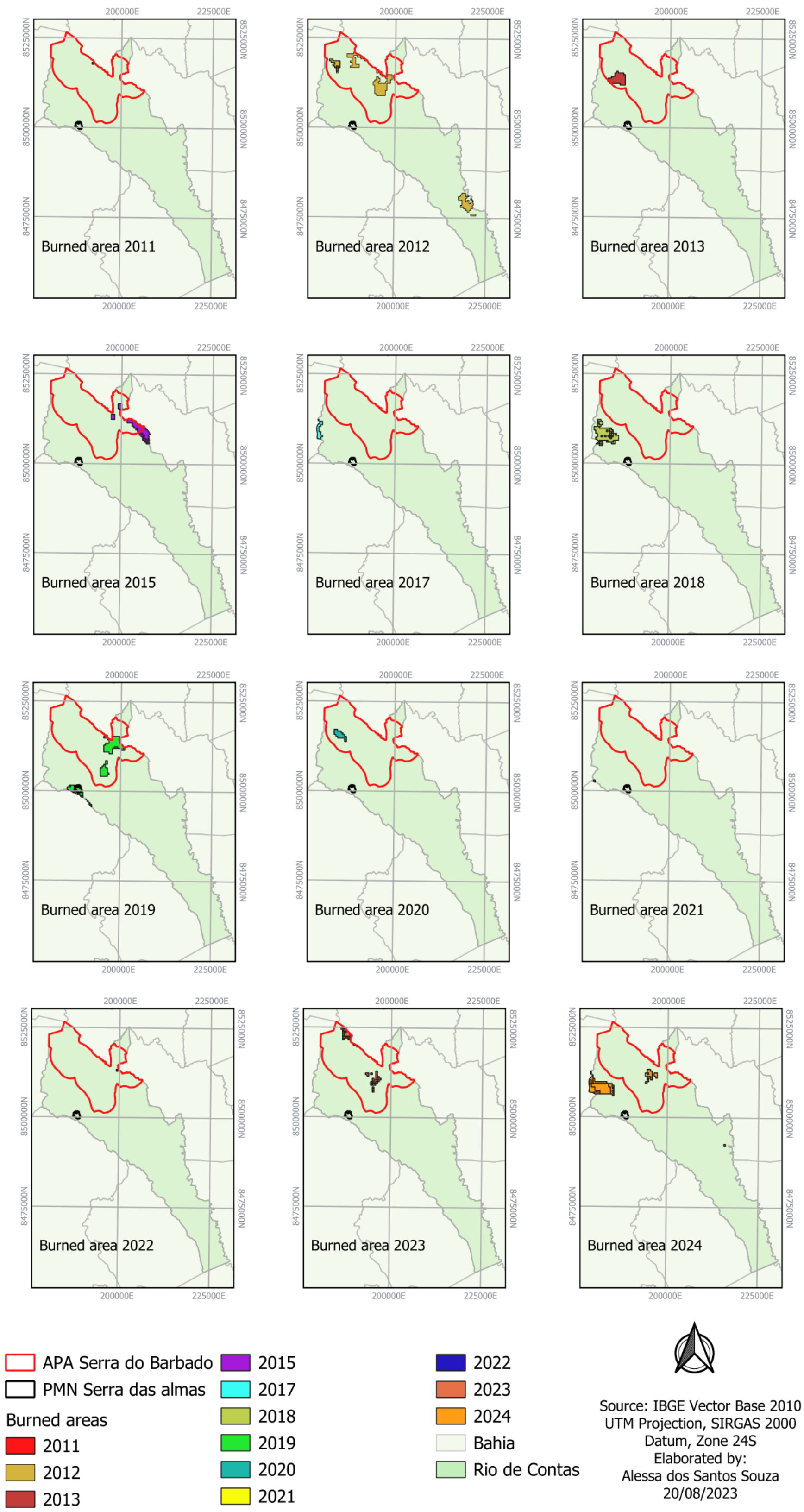
Conclusions

September is a critical month for forest fires, recording the highest numbers of outbreaks and burned areas. Factors contributing to this pattern include low rainfall and high average wind speeds, which facilitate the rapid fire spread.

Hot spots present highest density in environmental protection areas, regions above 1000 m in altitude, and with savanna-type vegetation characteristics.

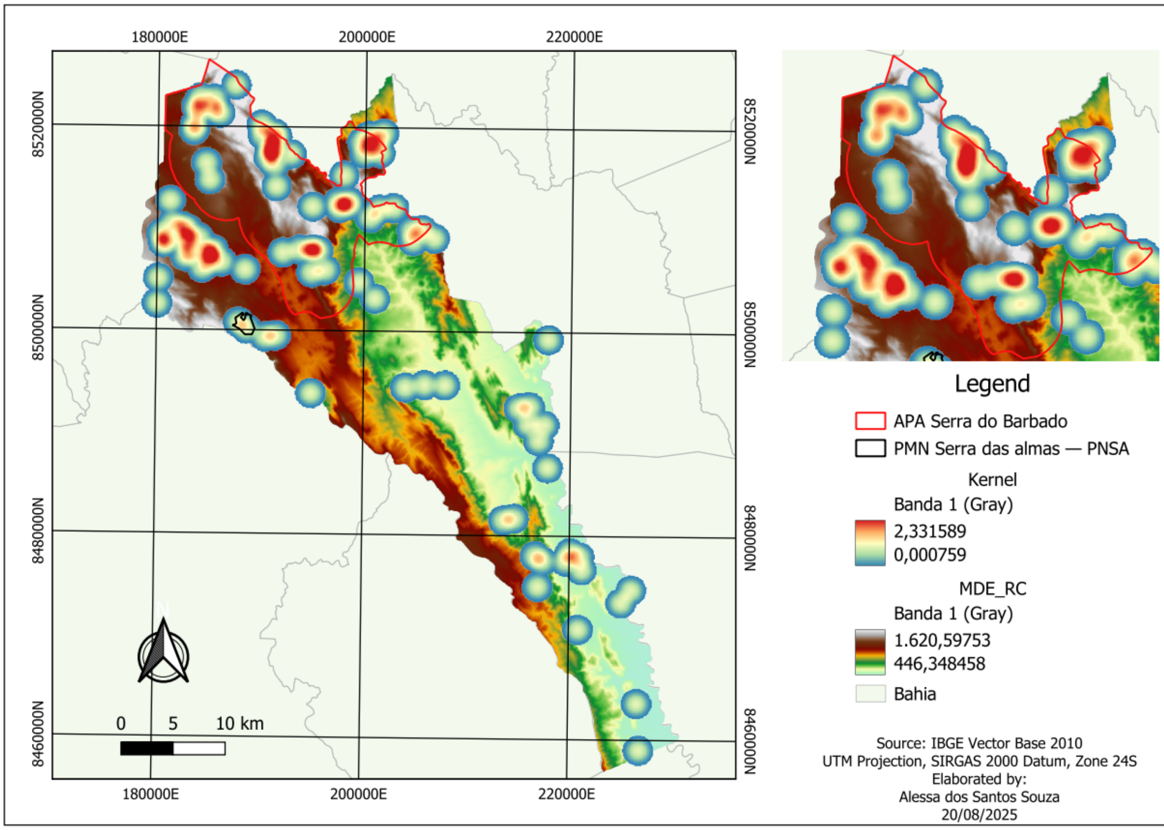
Fire outbreaks reached their highest numbers in 2011, 2012 and 2024, whereas the largest

Figure 2. Burned areas in the municipality of Rio de Contas, BA, from 2010 to 2024.



Source: Elaborated by the authors with MODIS (2025) data.

Figure 3. Digital Elevation Model (DEM) and density of fire outbreaks from 2010 to 2024 in the municipality of Rio de Contas, BA.



Source: authors (2025).

burned areas were recorded in 2012, 2019 and 2024. Interestingly, these years follow periods with above-average rainfall.

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