Four-Decade Analysis of Fire Behavior in the Brazilian Caatinga Biome 1985-2023

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Abstract

The Caatinga, unique in northeastern Brazil, has species adapted to the semi-arid climate. Recurrent fires put its biodiversity at risk, highlighting the need for urgent measures to protect this fragile ecosystem. This study analyzed four decades of fire behavior in the Caatinga biome (1985-2023) using data from the MapBiomas Fire project and spatial analysis, revealing a worrying dynamic of fires that affected approximately 10.9 million hectares (12.74% of the biome). The results showed an increasing trend in the frequency and intensity of fires, with critical peaks between August and November, particularly in October where historical maximums were reached in the period 2020-2023 (60.34%). Spatial distribution showed significant concentrations in the western and southern regions of the biome, especially in the states of Bahia and Piauí, mainly linked to human activities. The temporal analysis revealed a progressive accumulation of burned areas, with a notable increase towards the end of the period studied. The recurrence of fires presented a heterogeneous distribution, with up to 39 events at the same point in critical areas, affecting mainly forest formations and herbaceous-bush vegetation. The research underlines the vulnerability of the Caatinga ecosystem to these recurrent events, highlighting the urgent need to implement land management and fire management measures, including continuous monitoring programs and regional adaptive strategies that combine agricultural productivity with ecosystem conservation. This study contributes to the understanding of fire dynamics in tropical semiarid biomes, providing crucial information for decision-making in conservation and sustainable management policies.

Keywords: Burned area; Fires; Vegetation cover; Semiarid; MapBiomas.

1. Introduction

Fire is a key natural element in the dynamics of many ecosystems around the world, playing a fundamental role in maintaining their structure and functioning. From boreal forests to tropical savannas, fire acts as a renewal agent, eliminating invasive species, reducing the accumulation of dead biomass and promoting the regeneration of plant species adapted to this disturbance (BOND; KEELEY, 2005). However, when fires are too frequent or intense, they can drastically alter ecosystems, causing biodiversity losses and vegetation changes (PAUSAS; KEELEY, 2019).

The Caatinga biome is exclusive to northeastern Brazil, characterized by its xerophytic vegetation adapted to semi-arid climatic conditions and high temperatures (DE OLIVEIRA et al., 2012). The hot and dry climate of the Caatinga drives unique adaptations in its biodiversity, fostering the evolution of specific physiologies and reproductive behaviors in its species (DA SILVA VIEIRA; SANTANA; ARZABE, 2009). This biome is characterized for being the most extensive and humid in the world, covering 10% of Brazil's territory.

Has ecosystems such as thorny scrub with cacti in poor soils, semi-arid forests in sediments and deciduous forests in more fertile soils, each adapted to specific conditions of moisture and nutrients (DA SILVA; LACHER, 2020). Likewise, this biome stands out for offering diverse ecosystem services, such as provisioning, regulation and cultural aspects. Its conservation is vital for biodiversity, the well-being of local communities and climate change mitigation (ANDRÉIA; NIKO, 2024).

However, despite these attributes, it faces serious deforestation problems, having already lost half of its original vegetation (DA SILVA VIEIRA; SANTANA; ARZABE, 2009). In addition, between 2001 and 2021, the Caatinga recorded an average of 17 thousand fire outbreaks per year, concentrated mainly between October and December, being the months with the highest activity during this period (BELLO; VASQUES FREITAS; MARIA VIEIRA, 2023). Forest fires are recurrent in this biome, affecting between 10 % and 47 % of its surface, with repeated burns in various sectors (MARTINS et al., 2024). This biome is highly vulnerable to fires due to recurrent droughts and human activities such as agriculture, cattle ranching and deforestation, which increase their frequency and extent (FRANCA ROCHA et al., 2024).

Studies that allow the analysis of a long time series of burned areas are essential to better understand the dynamics of these events. This evidences the urgent need to optimize fire management and strengthen conservation strategies in Brazil, requiring a comprehensive analysis of the spatio-temporal dynamics of fire in the Caatinga (DE OLIVEIRA-JÚNIOR et al., 2022). “MapBiomas Fire” is an initiative derived from the MapBiomas project, focused on monitoring and mapping forest fires mainly in

Brazil. It uses satellite imagery, artificial intelligence and platforms such as Google Earth Engine to detect, quantify and analyze areas burned by fires over time (MAPBIOMAS, 2024). This project provides data to understand historical patterns and fire dynamics, supporting environmental management and public policies.

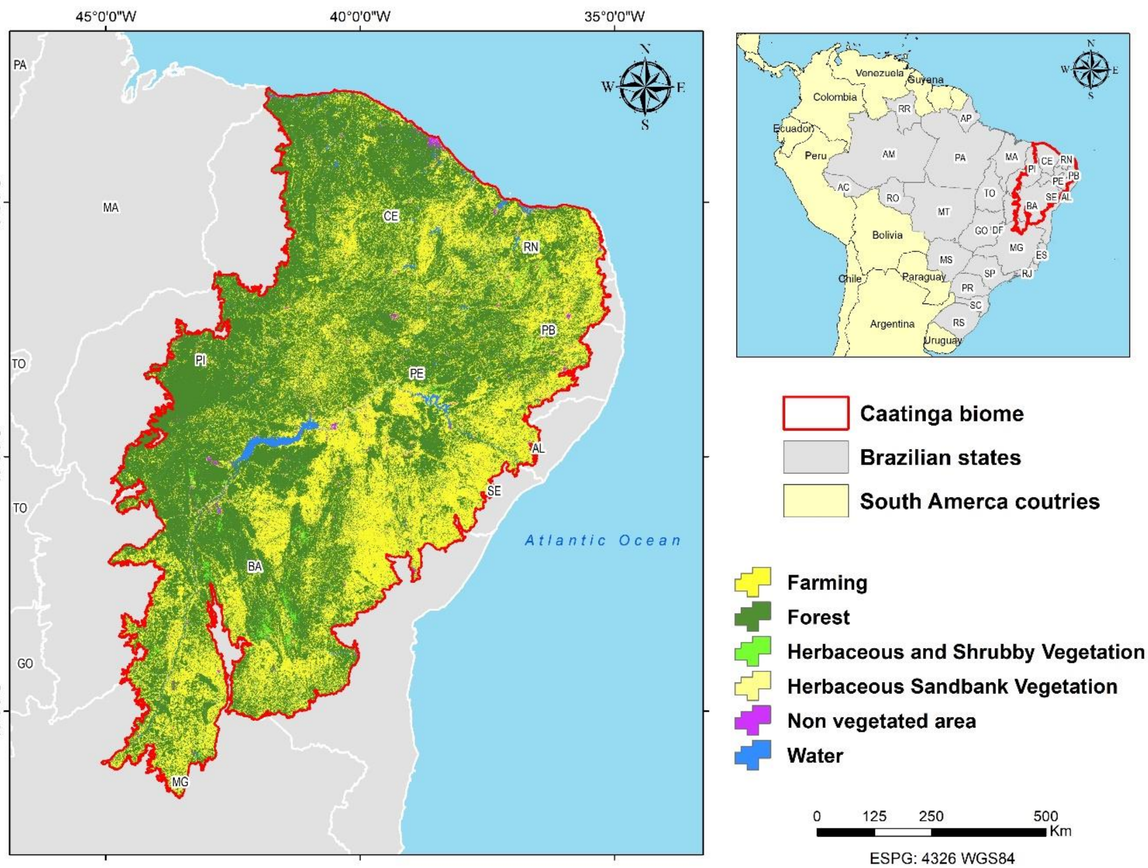
The objective of this study is to analyze four decades of fire behavior in the Brazilian Caatinga biome 1985-2023 from MapBiomas Fire data, in addition to producing vital information from spatial fire analysis. This study is expected to provide information on the spatial and temporal patterns of burned areas in the Caatinga, in support of effective fire management and prevention strategies.

2. Materials and methods

2.1 Study area

The Caatinga biome, located mainly in northeastern Brazil, is a semi-arid ecosystem characterized by its xerophytic vegetation adapted to low rainfall and high temperature conditions. This biome covers approximately 11% of the Brazilian territory and harbors significant endemic biodiversity, with species adapted to seasonal aridity (SILVA; LEAL; TABARELLI, 2017). According to (ACCIOLY; FARIAS; ARRUDA, 2024), the Caatinga presents a diverse plant structure, including thorny shrubs, cacti and deciduous plants, reflecting its ability to survive in extreme conditions. In addition, this biome is crucial for the maintenance of ecosystem services, such as water supply and climate regulation, although it faces significant threats due to deforestation and climate change (NIEMEYER; VALE, 2022). Recent studies highlight the need to implement more effective conservation strategies, considering both the ecology of the biome and the human communities that depend on its resources (ARAUJO et al., 2023).

Figure 1- Location map of the studied area



Source: based on IBGE (2022) and MAPBIOMAS (2024)

Average annual temperatures range between 24 °C and 28 °C, with maximums that can exceed 38 °C during the hottest months (SILVA; LEAL; TABARELLI, 2017). average annual precipitation ranges between 240 and 1500 mm concentrated mainly in a few months of the year (December to April) (RITO et al., 2017), Also, the vegetation of the Caatinga biome has about 5,000 species, of which about 300 are considered to be endemic (RICARDO et al., 2018). This biome is adapted to certain natural fire regimes, but the increasing frequency and intensity of fires in recent decades have exceeded its resilience (SILVA; LEAL; TABARELLI, 2017).

2.2 Data acquisition

We used the geographic database of fire scars from the MapBiomas Fire Collection 3 project (ALENCAR et al., 2022), which were accessed through the fire module of the Biomas Brasil project (https://brasil.mapbiomas.org/metodo-mapbiomas-monitor-do-fogo/). The database includes monthly information from 1985 to 2023 on burned areas in Brazil, with a resolution of 30 m, obtained from Landsat sensors, covering natural, forest and man-made fires (DA SILVA ARRUDA et al., 2024). For this study, data corresponding exclusively to the geographic extension of the Caatinga biome were used, ensuring a specific and detailed focus on this region. With an overall accuracy of 89.35%, the datasets were created by supervised classification. Annual Landsat mosaics and spectral samples of burned/unburned pixels were used as training data for the model (ALENCAR et al., 2022). Data management and analysis was done using a GIS, ArcGIS 10.8.

Annual maps with land cover and land use information from MapBiomas Collection 9 (http://mapbiomas.org), available for the same time series and spatial resolution as the burned areas (MAPBIOMAS, 2024), were also used. With an accuracy of 85.8%, it is a multi-institutional initiative that generates annual land cover and land use maps since 1985, using semi-automatic classification (Random Forest) on 30 m Landsat images in Google Earth Engine (GEE) (SOUZA et al., 2020). For data analysis and data acquisition of MapBiomas, we used the GEE platform, which has a great capacity to process and analyze large datasets (GORELICK et al., 2017).

2.3 Spatial analysis of fires

The analysis of fires in the Caatinga biome included the estimation of the following parameters: A) monthly and annual burned area; this refers to the measurement of the areas affected by fires in a given period, either month by month (monthly) or accumulated over a year (annual). This indicator is essential to understand the dynamics of fires in an ecosystem and to evaluate their environmental impact. At the monthly level, it allows identifying seasonal patterns, such as burning peaks associated with drier periods, when vegetation is more vulnerable due to low humidity and high temperatures (DA SILVA ARRUDA et al., 2024). On the other hand, the annual analysis provides a broader view on the magnitude and trend of fires, revealing how climatic factors or human activities influence in the long term (OTÓN et al., 2021).

B) cumulative burned area; refers to the sum total of the areas affected by fire over a period of time. This indicator is fundamental for evaluating the cumulative impact of fire on an ecosystem and allows the identification of long-term trends in fire dynamics (FRANCA ROCHA et al., 2024). The cumulative burned area was estimated based on annual increments. C) fire recurrences; refers to the frequency with which a specific area is affected by fires in a given period. This parameter is fundamental to evaluate the ecological impact of fires, since a high recurrence can exceed the natural regeneration capacity of ecosystems (DA SILVA ARRUDA et al., 2024). This parameter was evaluated by adding the annual products of burned area.

D) fire scar size refers to the total extension of the area affected by a fire, evidenced as a “scar” in the landscape. This indicator is crucial for assessing the ecological and environmental impacts of fires, since larger affected areas may imply greater losses of biodiversity, soil disturbance and carbon emissions (DA SILVA ARRUDA et al., 2024; MCLAUCHLAN et al., 2020). To evaluate the distribution of fires as a function of land use and land cover classes, a spatio-temporal overlap analysis was implemented (DA SILVA ARRUDA et al., 2024). This approach made it possible to identify the main patterns of fire dynamics, linking them to the vegetation cover of the Caatinga.

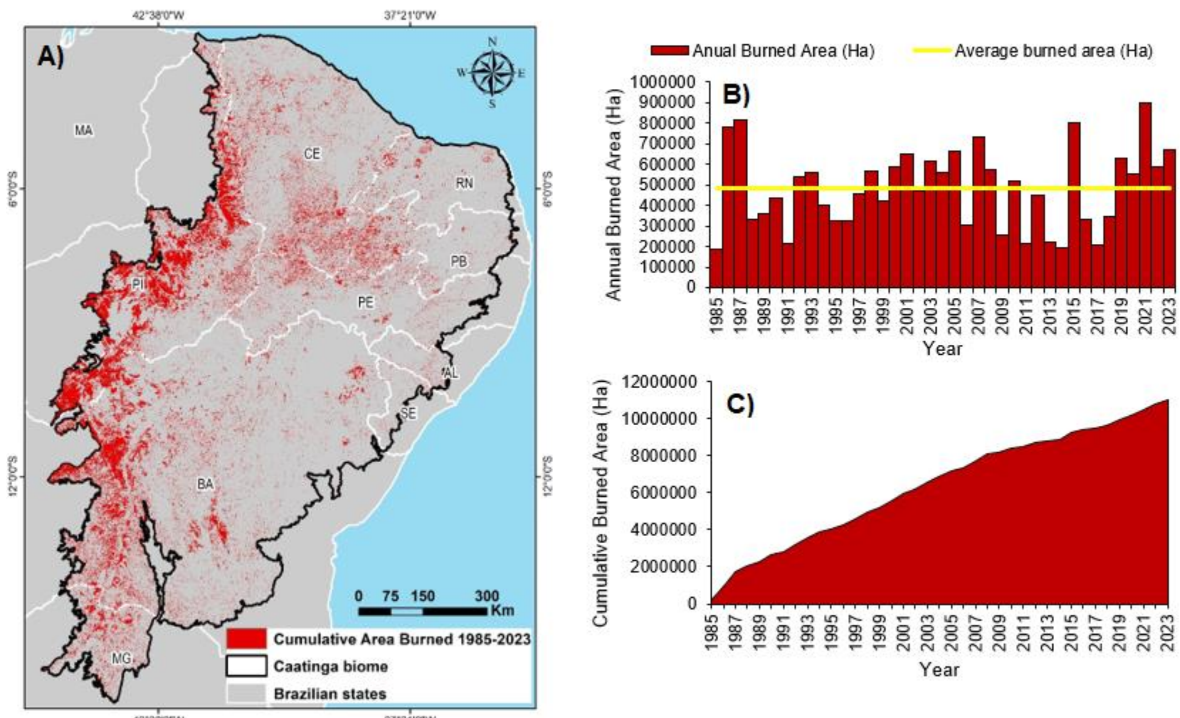
To better understand fire dynamics over time, 4-time intervals were used; 1985-1999, this period represented a baseline. 2000-2010, this period represented the change to the 21st century influenced by population growth and intensification of human activities. 2011-2019, this period represented the increased availability of satellite data and possible climate change impacts and 2020-2023 represents recent trends. In addition, the variation in the size of the scars in each time interval was analyzed.

3. Results

3.1 Annual variability of burned area

During the period analyzed (1985-2023) the burned data set showed high fire activity with a total of 10989284 ha (approximately ≈12.74% of the total biome) burning at least once in 39 years, A significant concentration of fires was observed in the western and southern areas of the biome, especially in the states of Bahia and Piauí (Figure 2A). Also, an average of 480972.95 ha (≈0.56% of the total biome) were determined to be affected by fire action each year (Figure 2B). On the other hand, the estimates of burned area varied between years, the year 1985 presented the lowest burned area with 183510 ha compared to the year 2021 which presented the highest burned area with 898831 ha. Other years with a higher incidence of fires were 1986, 1987 and 2015, while 1991, 2014 and 2017 presented less incidence of burned areas. The general trend of the accumulated area indicated a progressive increase in the accumulation of areas burned by fires (Figure 2C), suggesting an increase in the frequency of these events as the period analyzed progresses.

Figure 2- Spatial and temporal distribution of burned area in the Caatinga biome



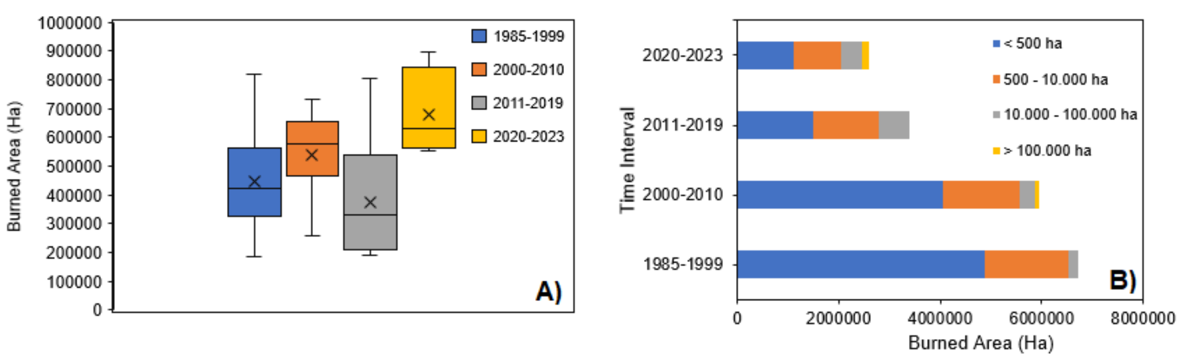
A) Spatial distribution of total burned area between 1985 and 2023 in Brazil. B) annual burned area between 1985 and 2023 and C) cumulative burned area between 1985 and 2023. Source: Author (2025)

The analysis of the distribution of the burned area in different time periods reveals an increasing trend in the extent of fires over time. Between 1985 and 1999, the median burned area was around 400,000 ha, with a remarkable variability. In the

2000-2010 period, the median increased to approximately 500,000 ha, while between 2011 and 2019, a decrease in the median to about 350,000 ha was observed, accompanied by a greater dispersion in the data. Finally, the period 2020-2023 had the highest median (~600,000 ha) and lower variability, suggesting greater consistency in the magnitude of recent fires.

The analysis of burned areas shows a significant evolution between the periods analyzed. In the first years (1985-1999), smaller areas (< 500 ha) predominated, with an accumulated total of 4873679.08 ha. From 2000 onwards, an increase in larger fires (> 100,000 ha) was observed, reaching 86340.42 ha between 2000-2010. On the other hand, in 2020-2023, smaller areas decreased, while very large areas (> 100,000 ha) increased notably to 130876.44 ha, reflecting an increase in the severity of recent fires.

Figure 3- Distribution of burned area according to time intervals and size categories



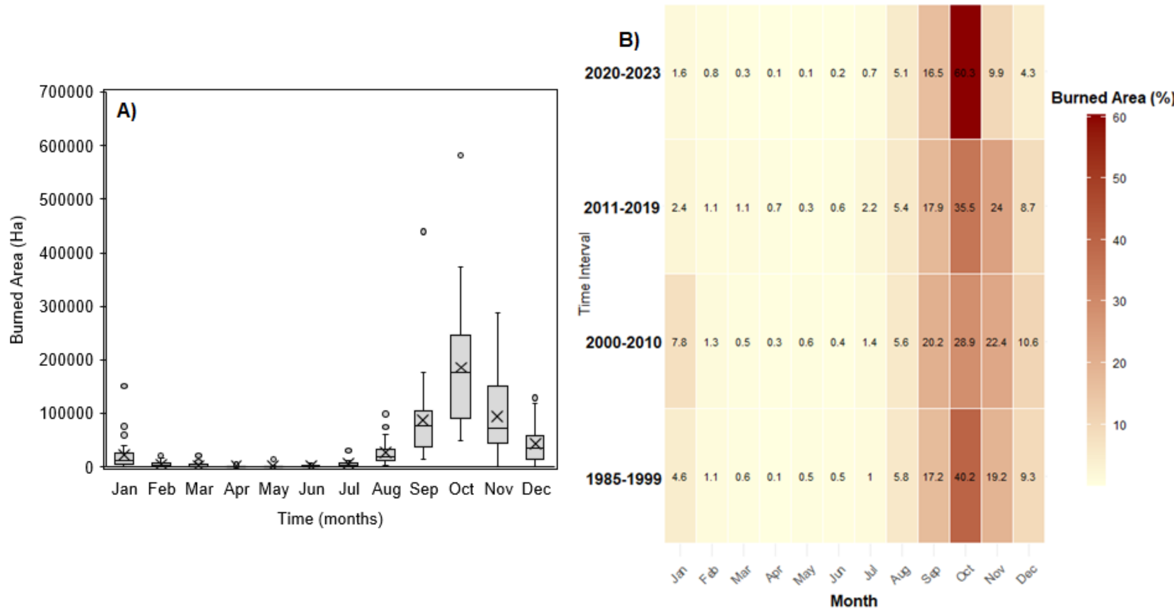
A) Boxplot of the variability of burned areas per period and B) Evolution of accumulated burned areas per period.

3.2 Changes in the monthly burned area in Caatinga

The box-and-whisker plot analysis revealed a clear seasonality in the distribution of burned areas throughout the year. During the first months (January to July), burned areas are generally low, with medians close to the horizontal axis and narrow interquartile ranges, indicating little variability. However, from August onwards, a significant increase in burned areas is observed, reaching a maximum in October and November. These months present higher medians and wider interquartile ranges, reflecting both an increase in the frequency and severity of fires. In addition, the presence of outliers in October and November highlights the occurrence of extreme events of large burned areas (Figure 3A).

The analysis of Figure 3B revealed a clear seasonal pattern in the dynamics of fires in the Caatinga ecosystem, with peaks of burned area concentrated between the months of August and November. Throughout the evaluated time intervals, a general trend towards an increase in fire severity was observed, especially in the months of October, with the highest percentages of burned area in all periods, reaching its highest point in the interval 2020-2023 with 60.34%, which shows an intensification of fires in recent years. In months such as July, prior to the critical season, the burned area values decreased from 0.99% (1985-1999) to 0.74% (2020-2023), indicating a slight reduction of fires outside the period of greatest risk.

Figure 4 - Monthly distribution of burned area according to time intervals

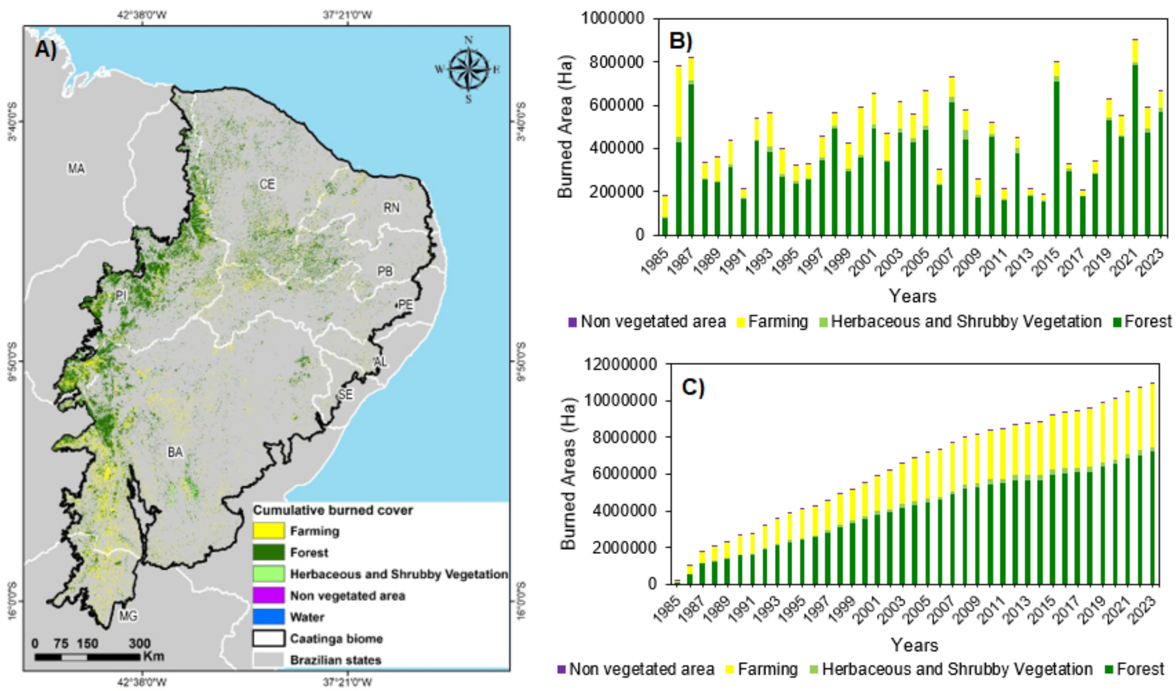


A) Monthly variations in burned area (ha) for the Caatinga between 1985-2023 and B) Average burned area in the Caatinga for different periods, together with the monthly percentage of area affected in each interval.

As shown in Figure 4A in the distribution of the cumulative coverage of burned areas, the fires mainly affected regions of herbaceous and shrub vegetation, as well as agricultural areas, concentrated in the states of Bahia, Piauí and Minas Gerais. The forest areas in the Caatinga, represented in dark green, were located mainly in western Bahia and southern Piauí, where there is a transition with the Cerrado biome. On the other hand, within the annual analysis of burned cover, years such as 1987, 2015 and 2021 stand out, where the highest peaks of fires were obtained (Figure 4B).

The years 1985, 1991, 2014 and 2017 were also highlighted for having the least damage. Likewise, the areas burned with the forest category were significantly higher than the Farming category in all periods. Towards the end of the analyzed period, a considerable increase in burned areas is detected for both coverages, especially for forests. On the other hand, the accumulation of burned areas in the forest and farming categories showed an increasing trend throughout the analyzed period (Figure 4C). Forest fires and burning events have been progressively increasing in both coverages. Forests showed much higher values than farming, indicating that forests are more affected by recurrent burning events.

Figure 5. Spatial and temporal distribution of burned area by type of vegetation cover



A) area burned by fires in the different land covers, B) annual burned area between 1985 and 2023 for the different land covers and C) accumulated burned area between 1985 and 2023 for the different land covers.

3.3 Fire recurrence

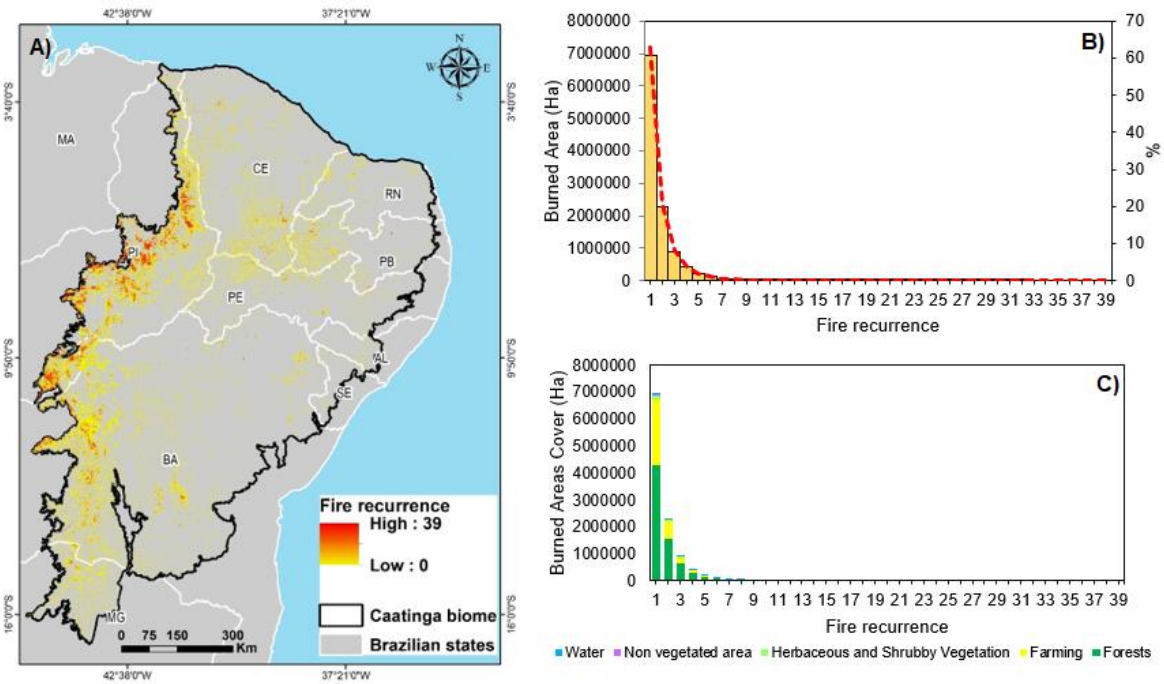
Fire recurrence in the Caatinga biome presents a heterogeneous spatial distribution, with significant concentrations in western Piauí and Bahia, as well as in areas of

Minas Gerais. These regions exhibit the highest values of fire repetition, reaching up to 39 events at a single point (Figure 5A). In contrast, states such as Ceará, Paraíba and Rio Grande do Norte present lower recurrence, indicating a lower frequency of events.

The distribution of fire recurrence in the Caatinga biome revealed that 63% of the burned areas have experienced fires at least once (Figure 5B). Most of the affected area corresponds to fires with a recurrence between 1 and 3 events (92%), progressively decreasing as the frequency increases. Figure 5C shows the distribution of fire recurrence in the Caatinga biome, differentiated by cover type.

It was observed that most of the burned area corresponds to low recurrence events (between 1 and 3 fires), with a progressive decrease as recurrence increases. In particular, forest (62.10%) and farming (34.71%) burned only once, while other cover types, such as Herbaceous and Shrubby Vegetation presented a smaller extension. The Savanna Formation cover is one of the most affected, being burned up to 32 times.

Figure 6 - Spatial distribution and analysis of fire frequency in the Caatinga biome



A) Fire recurrence in the Caatinga from 1985 to 2023. B) distribution of burned area among recurrence classes. C) fire recurrence categorized by covers.

4. Discussion

Analyzing fire scars over 39 years reveals key data on the distribution and impact of burned areas in the Caatinga, essential for understanding fire dynamics, its influence on land use and the state of the semiarid ecosystem in northeastern Brazil (FRANCA ROCHA et al., 2024). The results obtained in this study evidence a worrying fire dynamic in the analyzed biome during the period 1985-2023. The magnitude of the affected areas, which reached a total of 10.9 million hectares (≈12.74% of the biome), this underlines the vulnerability of the ecosystem to these recurrent events. This finding coincides with previous studies that point to increasing anthropogenic and climatic pressure as key factors in the spread of fires in tropical and semiarid regions (BELLO; VASQUES FREITAS; MARIA VIEIRA, 2023). Most of the fires in the region are of human origin, mainly linked to agricultural activities and land management practices, highlighting the direct influence of human actions in their occurrence (FRANCA ROCHA et al., 2024).

On the other hand, the progressive trend in the accumulation of burned areas, evidenced by an increase in fire frequency towards the end of the period, suggests a possible cumulative effect of multiple factors. This includes climate change, which has increased dry and warm conditions, along with landscape fragmentation, which facilitates fire spread (JOLLY et al., 2015). The spatial concentration of fires in the western and southern regions of the biome, particularly in the states of Bahia and Piauí, indicate a direct relationship with human activities such as agricultural expansion, burning of pastures for livestock and deforestation (DE OLIVEIRA et al., 2012). Municipalities such as Barra (BA), Pilão Arcado (BA) and Pimenteiras (PI) have accumulated up to one million hectares burned, making it necessary to implement urgent territorial management and fire management measures that include the creation of continuous monitoring programs (FRANCA ROCHA et al., 2024).

Analysis of the distribution of burned area revealed complex temporal dynamics in the occurrence and magnitude of fires, with trends that reflect changes in both the frequency and severity of these events. Between 1985 and 1999, medians (~400,000 ha) and the prevalence of small burned areas (<500ha) indicate less intense or fragmented fires, probably influenced by environmental conditions or management practices typical of that period (ABATZOGLOU; WILLIAMS, 2016). Between 2000 and 2010, the median increased (~500,000 ha) and larger fires

(>100,000 ha) emerged, evidencing a key alteration in fire patterns, possibly linked to climate change, expansive agriculture, or deficiencies in preventative measures. This is consistent with research indicating how extreme conditions resulting from climate change, such as heat waves and water deficits, promote catastrophic fires (SAYEDI et al., 2024).

Between 2011 and 2019, median decreased (~350,000 ha) and dispersion increased, possibly due to mitigation efforts or climate variability. However, it does not indicate improvement, as the dispersion reflects large fires. Between 2020-2023, the highest median (~600,000 ha) and lowest variability was observed, indicating more severe and widespread fires. This increase would reflect the influence of climate change, ecosystem degradation and human activities, suggesting a loss of environmental resilience and greater challenges for fire management. Ecological degradation and human actions, such as deforestation, weaken environmental resilience, leading to larger and more difficult to manage fires (COCHRANE, 2003).

The results obtained in this study show a marked seasonality in fire dynamics in the Caatinga ecosystem, with critical peaks between August and November, for example Sutomo & van Etten, (2023) noted that dry weather conditions, typical of the end of the dry season in semi-arid regions, increase fire susceptibility. On the other hand, the low activity observed from January to July can be attributed to the longer rainy season, relative humidity and the lower availability of combustible dry biomass during these months. Since August, there has been a notable increase in areas affected by fires, showing greater frequency and severity. This is related to the accumulation of dry biomass due to prolonged drought and uncontrolled agricultural burning (CONCIANI et al., 2021).

The increasing trend in fire severity, particularly in October, where record highs were reached in the period 2020-2023 (60.34%), suggests a direct impact of climate change and human activities on the dynamics of semiarid ecosystems (ARGIBAY; SPARACINO; ESPINDOLA, 2020). Between June and October, the absence of rainfall, dry weather and intense winds created conditions conducive to fires (MARTINS et al., 2024).

The results showed that fires in the Caatinga mainly affect areas of forest formation. According to Franca Rocha et al. (2024), fires focus mainly on savanna vegetation, especially in the transition zones with the Cerrado, showing critical patterns in these interface areas. Likewise, Martins et al. (2024) identified that savannas and rocky outcrops are the main factors driving the occurrence of fires in the Caatinga biome, highlighting their influence on fire dynamics in this semiarid region. These fires generally occur due to land preparation for agriculture, highlighting the importance of sustainable strategies that combine agricultural productivity with ecosystem conservation (FRANCA ROCHA et al., 2024).

Years such as 1987, 2015 and 2021 showed significant peaks, which may be related to climatic events such as El Niño, which increase drought and favor the spread of fires (MARENGO et al., 2011). The notable increase in burned areas towards the end of the period analyzed suggests a worrying trend, possibly exacerbated by climate change and the intensification of human activities (FRANCA ROCHA et al., 2024).

This study also evidenced a heterogeneous spatial distribution of fire recurrence in the Caatinga biome, with significant concentrations in regions such as western Piauí, Bahia and areas of Minas Gerais. The high frequency of events in these areas could be associated with extensive agricultural practices, burning of pastures for livestock and drier climatic conditions, which favor the spread of fire (ANTONGIOVANNI et al., 2020). Fire damage varies according to the type of cover: forest and agricultural areas show more low-recurrence burns, while herbaceous and shrublands show smaller areas. Areas with high fire recurrence (up to 39 events) reflect critical points that alter the resilience and natural regeneration of the ecosystem (HOFFMANN et al., 2012).

The results presented here are part of an approach and complement to the work done by (FRANCA ROCHA et al., 2024), which allows a deeper understanding of the fire dynamics in the Caatinga biome. Furthermore, the Caatinga biome is considered a fire-independent biome, so the flora and fauna lack adaptation to frequent fires (PIVELLO et al., 2021). Human activities have increased fires in this biome, causing its degradation (ALTHOFF et al., 2016), which could transform it into an ecosystem sensitive to being affected by fire (PIVELLO et al., 2021). This integration of findings reinforces the need for regional adaptive strategies, contributing to fire mitigation and conservation of semiarid ecosystems. Finally, it is worth highlighting that the high susceptibility of the Caatinga to fire is crucial in its ecological dynamics, highlighting the importance of expanding historical analyses to understand the dynamics for decision making (ALTHOFF et al., 2016; DE SANTANA et al., 2024).

5. Final considerations

The analysis of four decades of fire behavior in the Brazilian Caatinga biome (1985-2023) revealed a worrying dynamic of progressive increase in the frequency, severity and extent of fires, affecting approximately 12.74% of the biome and evidencing a significant loss of ecological resilience. The results highlighted a marked seasonality in the occurrence of fires, with critical peaks between August and November, associated with dry climatic conditions and agricultural practices, while the spatial distribution shows significant concentrations in regions such as western Piauí and Bahia. The combined influence of climate change, landscape fragmentation and human activities have considerably increased the vulnerability of the ecosystem, particularly in areas of transition with the Cerrado, where a high recurrence of fire events (up to 39 events at a single point) is observed. These findings underscore the urgent need to implement regional adaptive strategies that integrate continuous monitoring, sustainable land management and specific conservation policies to mitigate the negative impacts of fire in this fragile semi-arid ecosystem.

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