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FOUR-DECADE ANALYSIS OF FIRE BEHAVIOR IN THE BRAZILIAN CAATINGA BIOME 1985-2023

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FOREST ECOLOGY

ABSTRACT

Background: 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 an alarming increase in fire activity, which affected approximately 10.9 million hectares (≈12.74% of the biome).

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 2015-2023 (48.1%). 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.

Conclusion: 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.

HIGHLIGHTS

Fires burned 10.9 million ha (12.74%) of the Caatinga from 1985-2023.
Fire frequency and severity have increased progressively over the last four decades.
Fire activity peaks between August and November, with highs in October.
Critical areas in Bahia and Piauí have burned up to 39 times in four decades.

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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 and Keeley, 2005). However, when fires are too frequent or intense, they can drastically alter ecosystems, causing biodiversity losses and vegetation changes (Pausas and Keeley, 2019).

The Caatinga biome, endemic to northeastern Brazil, is characterized by xerophytic vegetation adapted to semi-arid climates with high temperatures and seasonal droughts (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 et al., 2009). This biome is the most extensive semiarid region in the world, covering 10% of Brazil's territory.

The Caatinga includes 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 and 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 and Niko, 2024).

However, this biome faces severe deforestation problems, having already lost half of its original vegetation (Da Silva Vieira et al., 2009). In addition, the Caatinga recorded an average of 17,000 fire outbreaks per year between 2001 and 2021, concentrated mainly between October and December, months with the highest activity during this period (Bello et al., 2023). Forest fires are recurrent in this biome, affecting 10 % to 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).

Analyzing a long time series of burned areas is crucial to understanding the dynamics of fire events in the Caatinga biome. The urgent need to optimize fire management and strengthen conservation strategies in Brazil requires a comprehensive analysis of the spatio-temporal dynamics of fire in this threatened and fire-prone biome (De Oliveira-Júnior et al., 2022). The "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.

This study aims to analyze four decades (1985-2023) of fire behavior in the Brazilian Caatinga biome using MapBiomas Fire data to support effective fire management and prevention strategies. The hypothesize that fire frequency and recurrence have progressively increased in the Caatinga biome over the last four decades, mainly driven by anthropogenic activities and climatic variability.

MATERIALS AND METHODS

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; et al., 2017). According to Accioly et al. (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 and 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).

Average annual temperatures range between 24 °C and 28 °C, with maximums that can exceed 38°C during the hottest months (Silva et al., 2017). Average annual precipitation ranges between 240 and 1,500 mm concentrated mainly in a few months of the year (December to April) (Rito et al., 2017). 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 et al., 2017).

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 "MapBiomas 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 performed using ArcGIS 10.8 and R (v4.3.1) software.

Annual maps with land cover and land use information from MapBiomas Collection 9, 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).

Spatial analysis of fires

The analysis of fires in the Caatinga biome included the estimation of the following parameters:

A) Annual burned area: this refers to the measurement of the areas affected by fires in a given period (annual). This indicator is essential to understand the dynamics of fires in an ecosystem and to evaluate their environmental impact (Da Silva Arruda et al., 2024).

A statistical analysis was incorporated to identify extreme years of burned area. The mean and standard deviation (SD) of the annual series were calculated; years with values above the mean +1SD and below the mean −1SD were considered extreme. These were marked visually in the figure, while the dotted lines indicate the statistical thresholds. This approach highlights years with significantly higher or lower fire activity than the historical average.

B) Cumulative burned area: refers to the sum of the total area 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) Temporal analysis of the burned area: The annual series of burned area (1985–2023) was analyzed using the Mann–Kendall test to detect monotonic trends (Gilbert, 1987), Sen's estimator to quantify the slope (Sen, 1968), and Pettitt's test to identify points of change (Pettitt, 1979). LOESS smoothing with bootstrap resampling was applied to assess the visual significance of fluctuations (Cleveland et al., 1992). For comparisons between periods, windows of equal duration four 10-year intervals, (1985–1994, 1995–2004, 2005–2014, and 2015–2023) were defined, avoiding biases derived from arbitrary intervals and allowing medians and standard deviations to be estimated consistently.

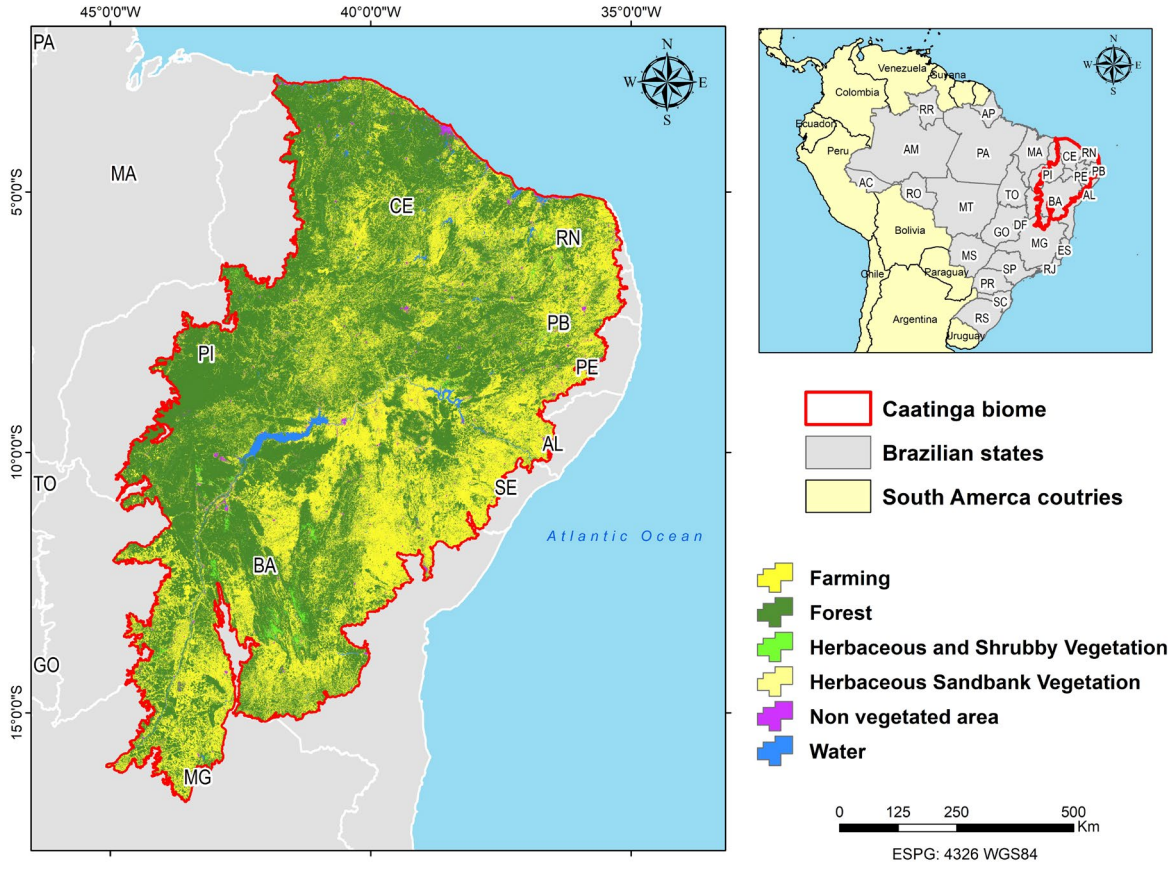

Figure 1: Location map of the studied area. Source: based on IBGE (2022) and MAPBIOMAS (2024).

D) Seasonal and fire recurrences: 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). 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).

E) To evaluate the distribution of fires as a function of land use and land cover classes (MapBiomas), a spatio-temporal overlap analysis was implemented (Da Silva Arruda et al., 2024). This approach was applied to identify the main patterns of fire dynamics, linking them to the vegetation cover of the Caatinga.

RESULTS

Annual variability of burned area

The burned data set showed high fire activity during the analyzed period (1985-2023), with a total of 10,989,823 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 481,609 ha (≈0.56% of the total biome) were determined to be affected by fire action each year (Figure 2B). The annual area burned between 1985 and 2023 showed high variability. Although most years remain close to the average (black line), there are several years with significantly higher values (purple bars), exceeding one standard deviation above the average (dotted gray line). This indicates that, although fires are recurrent, certain years present extreme events. 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.

The annual series of burned area between 1985 and 2023 showed high interannual variability, with extreme values in recent years (e.g., 2021 and 2023). The Mann–Kendall test did not show a significant monotonic trend (τ = 0.10, p = 0.36), and Sen's estimator indicated a slight positive slope (2,738 ha/year), without statistical significance. Pettitt's test did not identify any structural change points. LOESS smoothing with confidence bands revealed a moderate upward trajectory, although contained within historical variability (Figure 3). When segmented into 10-year intervals, a progressive increase in the median

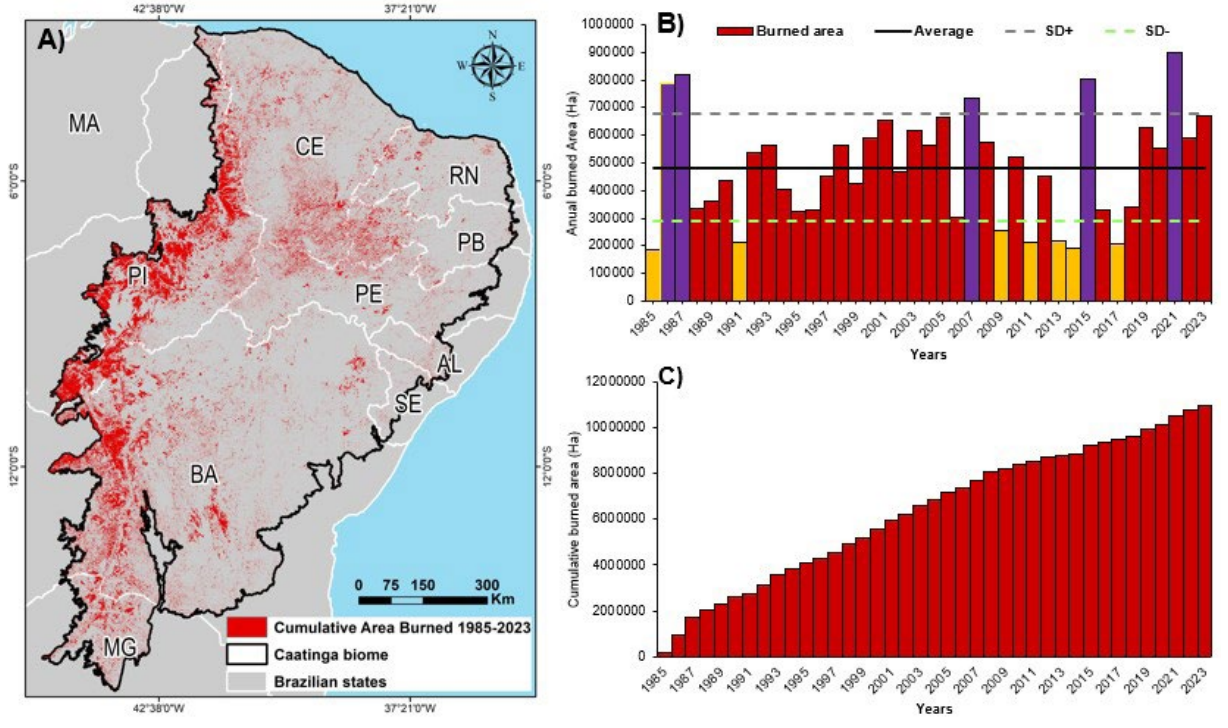

Figure 2: Spatial and temporal distribution of burned area in the Caatinga biome from 1985 to 2023. A) Spatial distribution of total burned area. B) annual burned area. The purple color shows years with above-average values (years with larger burned areas), while the orange colors indicate years with below-average values (years with smaller burned areas). C) cumulative burned area.

burned area was observed: from 418887.57 ha in 1985–1994 to 590201.62 ha in 2015–2023, accompanied by high dispersion in all periods.

Changes in the monthly burned area in Caatinga

The box plot of monthly burned area (in hectares) showed a marked concentration of fires in the second half of the year, with October having the highest median and variability, followed by September and December (Figure 4A). This pattern shows a consistent seasonal peak in fire intensity, likely influenced by climatic conditions and land use practices. In figure 4B shows a heat map of the percentage of burned area per month in four-time blocks, reinforcing this trend by showing that October consistently dominates fire activity, reaching 48.1% in the 2015-2023 interval. The progressive intensification of October fires in all blocks indicates a possible change in fire regimes, as in recent years, there has been a greater temporal concentration and, possibly, greater severity.

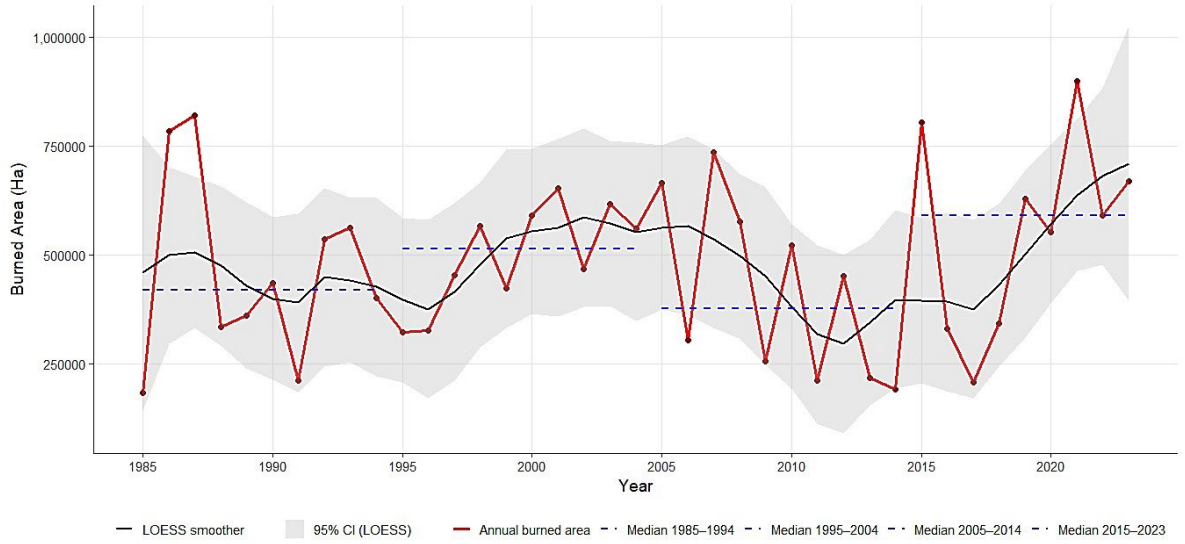

Figure 3. Annual burned area 1985 to 2023 (red), LOESS-smoothed trend (black), 95% confidence interval (gray), and median values for four decadal blocks (blue dashed lines). The LOESS curve highlights a moderate upward trend over time, while the segmented median lines reflect increasing fire activity across successive periods. Confidence intervals were derived from LOESS standard errors, and medians were calculated independently for each block.

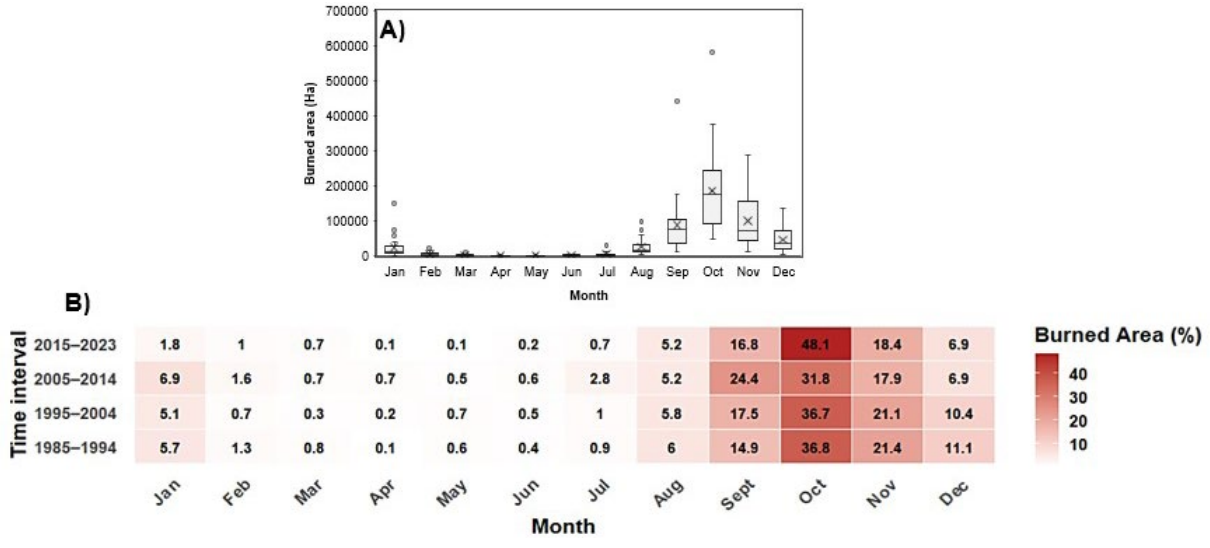

Figure 4. Seasonal fire patterns in the Caatinga biome (1985–2023). (A) Monthly burned area distribution, showing peaks in September, October, and November. (B) Percentage of burned area across four decadal intervals.

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" show lower fire 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. In 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.

In Figure 6A shows 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 6B).

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 6C). 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.

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

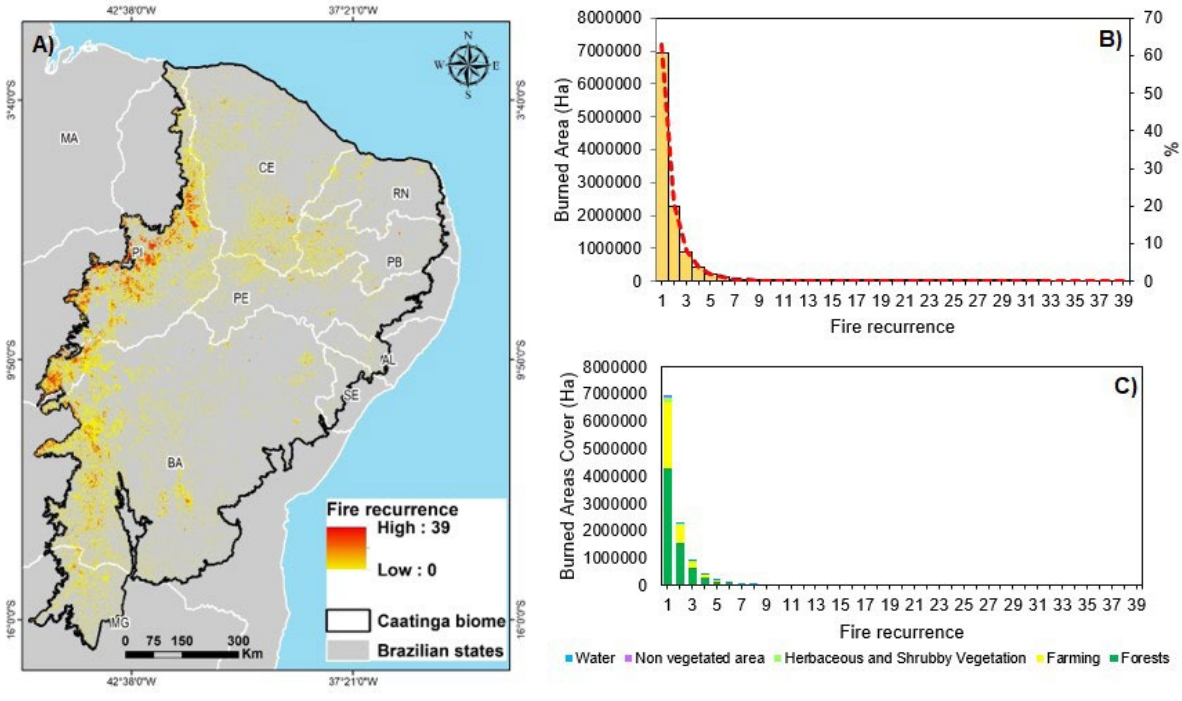

Figure 5: Spatial distribution and analysis of fire frequency in the Caatinga biome. A) Fire recurrence in the Caatinga from 1985 to 2023. B) distribution of burned area among recurrence classes. C) fire recurrence categorized by covers.

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), underlines the ecosystem's vulnerability to 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 et al., 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 1994, medians (≈418,000 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 and Williams, 2016). Between 2015 and 2023, the median increased (≈590,000 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).

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 and 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

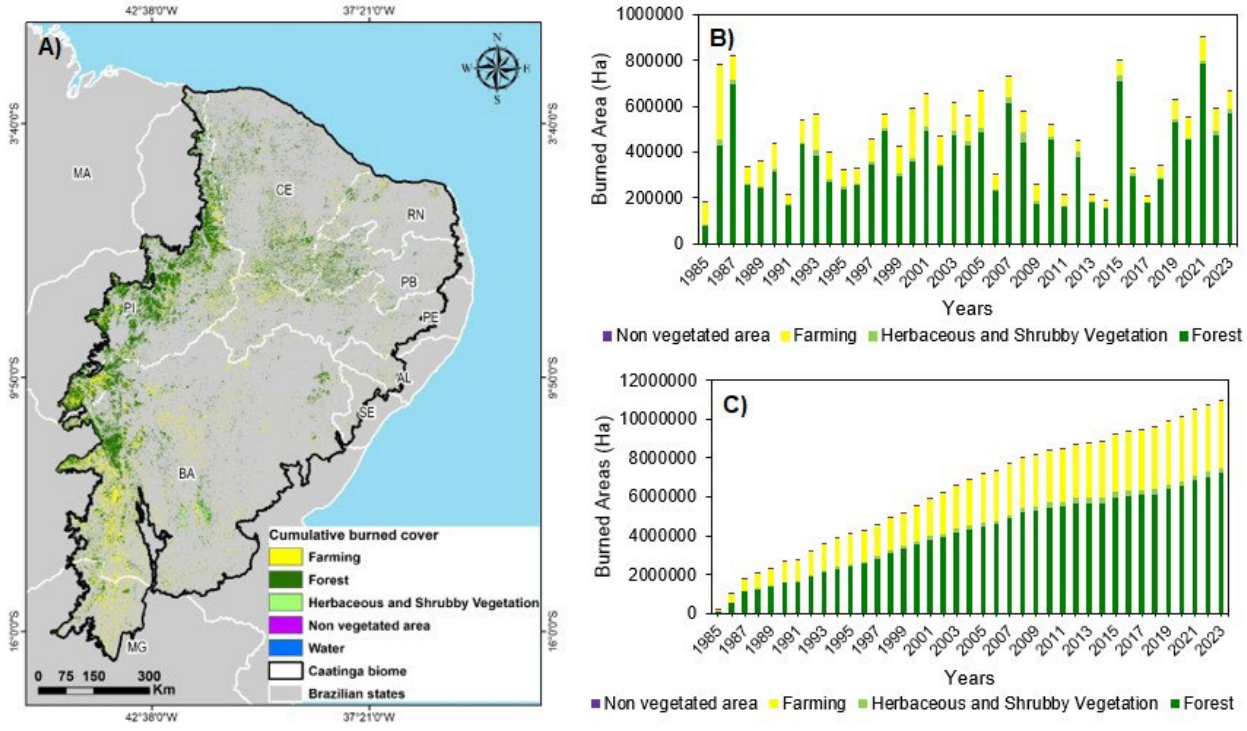

Figure 6: Spatial and temporal distribution of burned area by type of vegetation cover. A) area burned by fires in the different land covers, B) annual burned area between 1985 and 2023 for the different land covers and C) accumulated burned area between 1985 and 2023 for the different land covers.

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). October shows consistent increases in burned area across all decades, but significant highs were observed in the period 2015-2023 (48.1%), suggesting a direct impact of climate change and human activities on the dynamics of semiarid ecosystems (Argibay et al., 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 transition zones between the Caatinga and Cerrado biomes exhibited elevated fire incidence throughout the study period, driven by a combination of ecological and anthropogenic factors (Aparecido et al., 2024). These ecotonal regions host a mosaic of flammable vegetation types, such as savannas and shrublands, that accumulate dry biomass during the dry season and facilitate fire spread under drought and wind conditions. Additionally, these areas are subject to intense land-use pressures, including pasture burning and agricultural expansion, which increase ignition sources and reduce landscape heterogeneity. As highlighted by Da Silva Arruda et al. (2024), repeated fires in these zones may trigger a functional transition, where Caatinga vegetation, less adapted to fire, loses resilience and begins to resemble fire-adapted Cerrado physiognomies. This process threatens endemic biodiversity and alters ecosystem services. Therefore, ecotonal regions require differentiated fire management strategies, including native vegetation restoration, stricter regulation of agricultural burning and continuous monitoring of fire recurrence thresholds to prevent biome degradation (Pivello et al., 2021).

The presented results complement the work done by Franca Rocha et al. (2024), and provides 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).

CONCLUSIONS

This four-decade assessment reveals a progressive intensification of fire activity in the Caatinga biome, with increasing frequency, seasonal concentration, and recurrence, particularly in forested and transitional areas. The spatial and temporal patterns observed underscore the biome's growing vulnerability to fire, driven by climatic stressors and human land-use practices. These findings highlight the urgent need for adaptive fire management strategies that integrate ecological resilience, sustainable land use, and targeted monitoring in high-risk regions such as state of Bahia and Piauí. By providing a long-term perspective, this study contributes critical evidence to inform conservation policies and guide regional planning in Brazil's semiarid ecosystems.

AUTHORSHIP CONTRIBUTION

Project Idea: PA.
Funding: PA.
Database: PA.
Processing: PA.
Analysis: PA.
Writing: PA.
Review: PA.

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DATA AVAILABILITY

The datasets supporting the conclusions are included in the article.

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