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Assessing four decades of fire behavior dynamics in the Cerrado biome (1985 to 2022)

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Abstract

Background Fire significantly transforms ecology and landscapes worldwide, impacting carbon cycling, species interactions, and ecosystem functions. In the Brazilian Cerrado, a fire-dependent savanna, the interaction between fire, society, and the environment is evident. Given that wildfires significantly contribute to greenhouse gas emissions, our study aimed to analyze four decades of burned area data to understand changes in fire dynamics, using Collection 2 of annual MapBiomas Fire maps (1985 to 2022). Our study examined spatiotemporal patterns, fire recurrence, fire distribution across land uses, temporal changes in fire scar size, burned area variations across ecoregions, and their correlation with farming areas.

Results From 1985 to 2022, fire impacted 40% (792,204 km^2) of the Cerrado biome, with 63% burning more than once. Natural vegetation was the most affected, primarily due to human-driven ignition during the dry season. A noticeable trend of later peaks in fire activity, concentrated towards the end of the dry season, along with an increase in patch size over time, characterized a clear shift in the Cerrado fire regime. Recently, the MATOPIBA region and the northern biome exhibited significant fire clusters, with burned areas rising alongside farming expansion. The ecoregion-based analysis identified fire hotspots, with the "Bananal" ecoregion, the largest wetland area in the biome, exhibiting increased fire recurrence and larger patch size over time.

Conclusions Our four-decade analysis of fire dynamics in the Cerrado revealed human-induced changes in the fire regime, originally shifting from July to September to a new fire season from August to October. This shift poses several environmental threats given their overlap with the driest months of the year. This study improved our understanding of changes in fire patterns and their impacts on each ecoregion and land use. Wetlands experienced the highest relative burned area, highlighting their ecological importance and increased vulnerability. In the southern Cerrado, where farming is established and natural vegetation more fragmented, fire events tend to decrease; while in the north, with recent farming expansion, fire susceptibility rises. Conservation-oriented strategies, like the Brazilian Integrated Fire Management (MIF), are crucial for mitigating impacts while enhancing the Cerrado's resilience to climate change.

Keywords Brazilian savanna, Burned area, Cerrado, Fire regime, Land use and land cover change, Remote sensing

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Resumen

Antecedentes Los fuegos de vegetación transforman significativamente la ecología y los paisajes en todo el mundo, impactando en el ciclo del carbono, en las interacciones entre especies, y en el funcionamiento de los ecosistemas. En el Cerrado Brasileño, una sabana dependiente del fuego, las interacciones entre el fuego, la sociedad y el amiente es evidente. Dado que los incendios contribuyen significativamente a las emisiones de gases de efecto invernadero, nuestro estudio se enfocó a analizar cuatro décadas de datos de áreas quemadas para entender los cambios en la dinámica del fuego, usando la Colección 2 de los mapas anuales de fuego (MapBiomass) (1985–2022). Nuestro estudio examinó los patrones espacio-temporales, la recurrencia del fuego, la distribución de los incendios a través de los diferentes usos de la tierra, los cambios temporales en el tamaño e las cicatrices de fuego, y su correlación con áreas agrícolas.

Resultados Desde 1985 y hasta 2022, los incendios impactaron el 40% (792.204 km2) del bioma del Cerrado, con el 63% de su área quemándose más de una vez. La vegetación natural fue la más afectada, debido primariamente a las igniciones humanas durante la estación seca. Una tendencia destacable en los últimos picos de actividad del fuego, concentrada hacia el final de la estación seca, junto con un incremento con el tiempo en el tamaño de los parches de vegetación afectada, caracterizó un claro cambio en el régimen de fuego del Cerrado. Recientemente, la región de MATOPIBA y el bioma norte exhibieron clústeres de fuego significativos, con un aumento de las áreas quemadas en los alrededores de las zonas en las que se estaban expandiendo los campos agrícolas. El análisis basado en la ecorregión identificó también puntos calientes, con la ecorregión llamada "Bananal", el área de humedales más grande de la región, exhibiendo con el tiempo incrementos en la recurrencia del fuego y parches quemados cada vez más grandes.

Conclusiones Nuestro análisis de cuatro décadas sobre la dinámica del fuego en el Cerrado reveló cambios inducidos por la actividad humana sobre el régimen de los incendios modificándose desde julio a septiembre a una nueva estación de fuegos desde agosto y hasta octubre. Esta modificación implica algunas amenazas ambientales dado que se superpone con los meses más secos del año. Este estudio mejora nuestro entendimiento sobre los cambios en los patrones de incendios y sus impactos en cada ecorregión y en el uso de la tierra. Los humedales fueron los que experimentaron una mayor área quemada relativa, subrayando su importancia ecológica y el incremento en su vulnerabilidad. En el Cerrado del sur, donde las actividades agrícolas se han establecido y la vegetación natural está más fragmentada, los eventos de fuego tienden a disminuir; mientras que en el norte, con una expansión agrícola reciente, la susceptibilidad a los incendios aumenta. Las estrategias orientadas a la conservación, como el Manejo Integrado del Fuego en el Brasil (MIF), son cruciales para mitigar los impactos mientras se aumenta la resiliencia del Cerrado al Cambio Climático.

Background

Fire is a fundamental component of ecosystem dynamics and plays a key role in maintaining their patterns and processes worldwide (Bond and Keeley 2005; He et al. 2019). Savannas in particular are considered fire-adapted and fire-dependent ecosystems; they benefit from a fire regime that is naturally established during the rainy season through the ignition of lightning (Simon et al. 2009; Pivello et al. 2021). However, human activities have altered the natural fire regime for over 100,000 years (Bowman et al. 2009), leading to more frequent and severe wildfires under drier conditions (Bowman et al. 2011).

The Cerrado biome, a neotropical savanna in central Brazil, is a fine example of how fire dynamics have changed due to human activities. This biome is currently experiencing high wildfire rates during the dry season, caused by the use of fire for land clearing in agricultural activities (Arroyo-Kalin 2012). This practice, commonly employed in the Cerrado region, involves the deliberate burning of vegetation to prepare the soil for the cultivation of agricultural crops such as soybeans, corn, and cotton (Gomes et al. 2019). Additionally, fire is often used as a management tool for pastures, in order to control invasive species, promote grass regrowth, and improve forage quality for livestock (Durigan and Ratter 2016). Due to accumulated fuel (i.e., dry biomass) in the dry season, wildfires often get out of control and spread to adjacent areas, resulting in environmental damage, negative impacts on human health, and economic losses (Pivello et al. 2021).

Land conversion in the Cerrado is mainly driven by recurrent slash-and-burn practices that lead to habitat fragmentation, ecosystem degradation, and increased wildfire susceptibility (Menezes et al. 2022). This process is often associated with socioeconomic factors such as population growth and economic development and might involve several phases. It can either begin with a transition from natural vegetation to pasture, followed by the cultivation of crops, or start with a direct conversion of natural vegetation to agriculture (Garcia and Ballester 2016). Understanding the dynamics between fire and agricultural expansion is critical for effective fire management and maintaining ecosystem dynamics. This is especially the case for agricultural regions facing fast land conversion for commodity crops, such as the region formed by the states of Maranhão, Tocantins, Piauí, and Bahia (MATOPIBA) (Spera et al. 2016; Pires 2020).

The Cerrado is the most floristically diverse savanna in the world, where fire is essential to maintaining ecological, social, and environmental processes (Lewinsohn and Prado 2005; Munhoz and Felfili 2005; Bowman et al. 2011). As in all tropical savannas, the Cerrado has high interannual rainfall variability and a clearly defined dry season in winter, when rainfall can be close to zero (Alvares et al. 2013). However, drier conditions are increasing due to climate change (Hofmann et al. 2021), which, combined with human activities such as deforestation, agricultural expansion, and unsustainable land management practices, increases the frequency and extent of fires in the Cerrado. Consequently, these conditions have significant impacts on the fire regime, defined as the pattern, frequency, intensity, and seasonality of fires within a particular ecosystem (He et al. 2019; McLauchlan et al. 2020). In the Cerrado, the fire regime is essential for maintaining ecological balance by preventing woody vegetation encroachment, maintaining the savanna's open structure, and supporting biodiversity through nutrient cycling and the germination of fire-adapted species (Durigan and Ratter 2016). Changes in this fire regime can lead to land degradation, increased risk of biological invasions, and significant biodiversity loss (Pivello et al. 2021; Miranda et al. 2009).

Anthropogenic fires refer to fires ignited or influenced by human activities, often used as a tool for land clearing, deforestation, and land use management (e.g., maintaining crops and renewing pasture) (Pivello 2011; Libonati et al. 2021). In the Cerrado, most wildfires are of anthropogenic origin. These fires can escape control and pose a significant threat to fire-sensitive ecosystems rich in biological resources, such as forest areas and wetlands (Kumar et al. 2022). As a result, significant amounts of greenhouse gasses and aerosols are released into the atmosphere (Bustamante et al. 2012; Gomes et al. 2020), altering the water and carbon cycles and leading to climate shifts at regional and global scales (Li et al., 2017). Prescribed fires, on the other hand, refer to fires that are intentionally ignited under controlled conditions to achieve specific management objectives. In the Cerrado, prescribed fires are often used as an active fire suppression strategy to prevent uncontrolled wildfires in protected areas, especially in fire-sensitive vegetation (Schmidt et al. 2018). This practice helps to maintain ecological balance by reducing fuel loads and minimizing the risk of severe wildfires.

The spatial heterogeneity of the climate and fire patterns in the Cerrado leads to considerable regional differences in the spatial distribution of the size and frequency of burned areas and to regional differences in the intensity of forest fires (Arruda et al. 2018; Silva et al. 2021). Remote sensing plays a crucial role in monitoring burned areas at regional to global scales, often based on high temporal resolution data covering large areas (Liu et al. 2018). Mapping burned areas in the Cerrado has traditionally influenced decision makers in promoting and creating public policies for wildfire management while improving the effectiveness and efficiency of control measures (Arruda et al. 2021). Therefore, the availability of spatially-explicit data on annual burned area and fire dynamics in the Cerrado is crucial to assess human-driven impacts and thus, contributes to fire management and prevention actions while mitigating impacts on biodiversity (He et al. 2019; Alencar et al. 2022).

Regional studies on fire ecology in the Cerrado are mostly related to quantifying carbon budgets (Dionizio et al. 2020), understanding vegetation and climate dynamics (Silva et al. 2019; Li et al. 2022), estimating fire impacts (Nagel et al. 2023), evaluating patterns of fire occurrence (Santos et al. 2021), and characterizing fire regimes (Silva et al. 2021). Most of these studies rely on burned area products derived from sensors of short-revisit time covering large spatial extents, such as the Moderate Resolution Imaging Spectrometer (MODIS: Giglio et al. 2016) and the Geostationary Operational Environmental Satellite (GOES: Schmidt et al. 2012). Despite the advantage of a high temporal frequency, these sensors have a coarse spatial resolution (> 250 m) that does not allow the detection of small fire scars, which are necessary for estimating fire impacts on various land covers and land use types, as well as for a better understanding of recent shifts in fire regimes (Rodrigues et al. 2019). Sensors with higher spatial resolution (< 30 m), such as the Landsat series, have spatial and temporal characteristics that are suitable for delineating smaller fire scars over long time-series (Daldegan et al. 2019; Aslam et al. 2023). Moreover, most studies on fire dynamics and burned area mapping in the Cerrado are conducted at the local scale (Daldegan et al. 2014, 2019; Alvarado 2018; Rodrigues et al. 2021), leaving a significant knowledge gap in assessing fire dynamics at the regional scale.

In this context, we present a pioneering analysis of the spatiotemporal changes in fire dynamics across the ecoregions of the Cerrado biome. Our study uses a 38-year time-series of annual burned area data at a fine spatial resolution of 30 m, derived from Landsat sensors. This detailed and extensive dataset enables a novel examination of fire patterns and trends over an unprecedented temporal span and spatial detail. By analyzing these spatiotemporal changes in fire dynamics, we provide comprehensive insights into the fire ecology of the Cerrado that were not previously possible with coarser resolution data or shorter time spans. This approach addresses a knowledge gap by providing a comprehensive assessment of fire dynamics at both broad temporal and fine spatial scales, which is essential for understanding regional fire patterns and their impacts. Ultimately, our results aim to contribute to fire management strategies and policies at national and regional levels, thereby improving conservation and sustainability efforts in the Cerrado biome.

Materials and methods

Study area

The Cerrado biome covers an area of approximately two million square kilometers (km2), spatially located between the latitudes 2° S and 24.7° S and between the meridians 41.7° W and 60° W (Fig. 1). This biome is an important biodiversity hotspot, threatened by human pressure for commodity crops and pasture, which has led to the loss of almost half of its native vegetation (Myers et al. 2000; Alencar et al. 2020). The distribution of

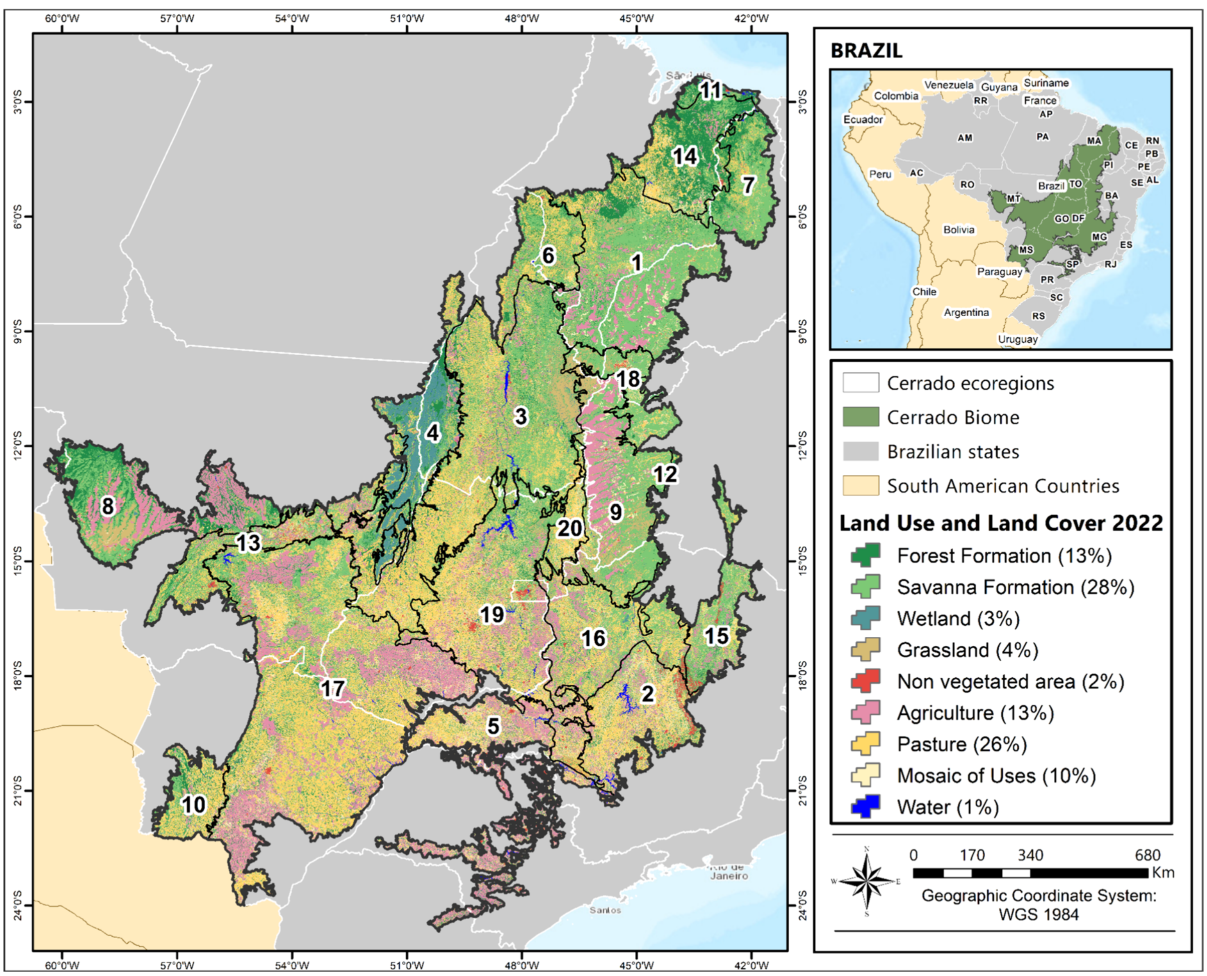

Fig. 1 Geographical representation of the Cerrado biome in Brazil, with the classes of land use and land cover according to the MapBiomas Collection 8 (MapBiomas Project 2023), with percentage assignment to each class in the legend. Including Ecoregions numbered as 1-Alto Parnaíba, 2-Alto São Francisco, 3-Araguaia Tocantins, 4-Bananal, 5-Basaltos do Paraná, 6-Bico do Papagaio, 7-Centro-norte Piauiense, 8-Chapada dos Parecis, 9-Chapadão do São Francisco, 10-Complexo Bodoquena, 11-Costeiro, 12-Depressão Cárstica do São Francisco, 13-Depressão Cuiabana, 14-Floresta de Cocais, 15-Jequitinhonha, 16-Paracatu, 17-Paraná Guimarães, 18-Parnaguá, 19-Planalto Central, 20-Vão do Paranã. And Brazilian states: AM Amazonas; AC, Acre; AL, Alagoas; AP, Amapá; BA, Bahia; CE, Ceará; DF, Distrito Federal; ES, Espírito Santo; GO, Goiás; MA, Maranhão; MT, Mato Grosso; MS, Mato Grosso do Sul; MG, Minas Gerais; PA, Pará; PB, Paraíba; PR, Paraná; PE, Pernambuco; PI, Piauí; RJ, Rio de Janeiro; RN, Rio Grande do Norte; RS, Rio Grande do Sul; RO, Rondônia; RR, Roraima; SC, Santa Catarina; SP, São Paulo; SE, Sergipe; TO, Tocantins

Cerrado vegetation types is directly related to the availability of water, soil nutrients, and distinct geomorphological and topographic features (Silva and Bates 2002). The spatial differences in the availability of resources favor a great diversity of vegetation types, ranging from closed-canopy forests to savannas and grasslands (Ribeiro and Walter 2002).

The Cerrado has a tropical climate (type Aw according to the Köppen climate classification) characterized by a rainy season from October to March and a dry season from April to September, which accounts for only 10% of the annual rainfall and is when most fire events are concentrated (Pereira Júnior et al. 2014). The average annual temperature is 22 °C, while annual precipitation ranges from 800 to 2000 mm (average 1500 mm) (Bustamante et al. 2012; Alvares et al. 2013). Some vegetation types in the Cerrado biome are adapted to the occurrence of fire and are partially dependent on it (Simon and Pennington 2012). Fires occur naturally as a result of lightning strikes during the rainy season or in the transition from the dry to the rainy season, affecting small areas and being quickly extinguished by rain (Ramos-Neto and Pivello 2000).

Data acquisition

To analyze the spatial distribution of fire events in the Cerrado, we used the fire scar database from MapBiomas Fire Collection 2 (Alencar et al. 2023), acquired from the MapBiomas project website (mapbiomas.org), as the main data used in this study. The fire scar database contains spatially explicit monthly burned area data available at 30-m resolution (derived from the Landsat sensors) from 1985 to 2022, encompassing all fires, including human-ignited fires, wildfires, and natural fires. The MapBiomas Fire data covers the entire extent of Brazil, but was clipped to the Cerrado extent for this study. With an overall accuracy of 89.3%, the datasets were developed through a supervised classification of annual Landsat mosaics and spectral samples of burned/non-burned pixels, which were used as training data for the classification model. The mosaics and training samples were prepared in Google Earth Engine (GEE) and exported to a Google Cloud Storage Bucket to be used as input for Deep Neural Network (DNN) models resulting in annual burned area maps developed over 38 years (Alencar et al. 2023).

We also used annual maps with land cover and land use information from the MapBiomas Collection 8 (acquired from http://mapbiomas.org), available for the same time-series and spatial resolution as the burned area database (Alencar et al. 2023). With an overall accuracy of 85.8%, the MapBiomas project is a multi-institutional initiative that develops annual maps (from 1985 to present) of land cover and land use from semi-automatic classification processes (Random Forest) applied to Landsat satellite imagery (30-m resolution) in Google Earth Engine (Souza et al. 2020). Finally, we used the Cerrado ecoregions data (Sano et al. 2019) to aggregate information on fire events in addition to the biome-level estimates (IBGE 2023).

For the geospatial analysis and MapBiomas data acquisition, we used the Google Earth Engine (GEE) platform, which has ample capacity for processing and analyzing large datasets (Gorelick et al. 2017). The main advantage of GEE is its accessibility and powerful computational resources, which allow for processing large amounts of geospatial data and statistical analyses over extensive geographic areas in the field of fire ecology (Jodhani et al. 2024).

Statistical analysis of fire behavior in the Cerrado in four decades

Our analysis of fire distribution in the Cerrado biome (Fig. 2) included estimating the following: (a) monthly and annual burned area; (b) cumulative burned area; (c) fire recurrence; and (d) fire scar size, all estimated at different time intervals and spatial units (biome, land use/land cover classes, and ecoregions).

The current study conducted annual and monthly area estimates of fire scars throughout the 1985–2022 time series and estimated the cumulative burned area based on annual increments. Estimating the cumulative area burned allows us to quantify how much of the Cerrado was affected by fire, resulting in total area and percentage estimates of the biome that experienced a fire event at least once. Fire recurrence was assessed by summing the annual burned area products, resulting in a consolidated map with 38 recurrence classes for the entire study period. To analyze fire distribution patterns across different land use and land cover classes, we used a temporal and spatial overlap approach that provides insights into the dominant patterns of fire dynamics. Annual burned area data were converted to vectors using the gdal_polygonize function to determine the size and individual area of fire scars (Open Source Geospatial Foundation (OSGeo) 2020). The uncertainties in this conversion process primarily arise from errors in digitization, including issues related to spatial resolution and boundary delineation. To minimize these uncertainties, we retained the original 30-m resolution during the vectorization process, preserving the spatial detail and accuracy of fire scars. The gdal_polygonize function was selected for its robustness and precision in handling raster-to-vector conversions, ensuring accurate delineation of burned area boundaries.

The fire scar size metric quantifies the area affected by a single fire event within a specific location, offering

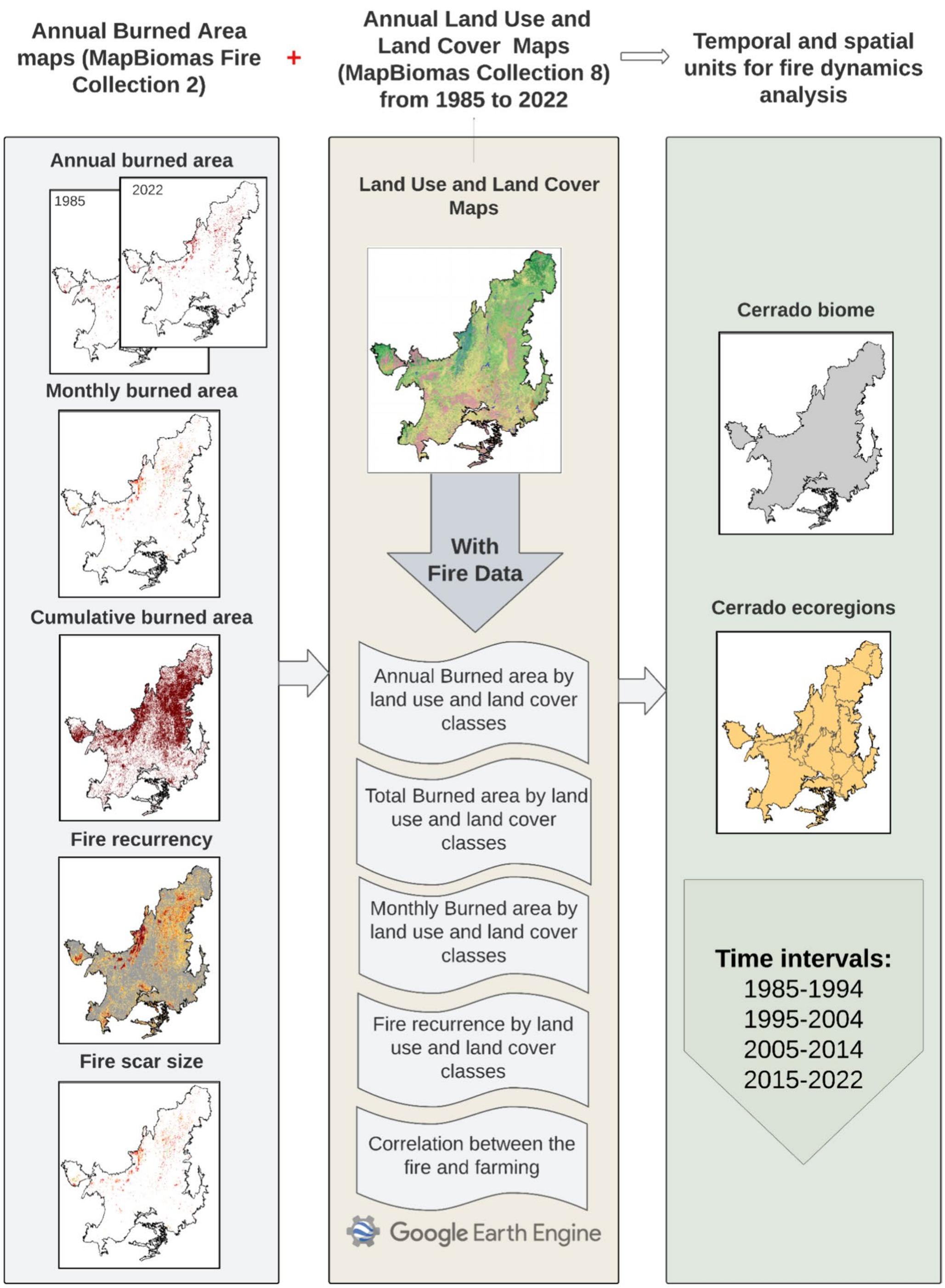

Fig. 2 Data-flow diagram with all fire data processed (in gray) and combined with Land Use and Land Cover Maps (in beige) at different temporal and spatial units in the Cerrado (in green). All data processing and analysis were performed in Google Earth Engine (GEE) platform

detailed insights for fine-scale analysis when assessing long-term trends in fire activity (McLauchlan et al. 2020). This metric is crucial for understanding whether individual fire events are increasing over time. In contrast, burned area provides a broader perspective by estimating the total area affected by fire, summing all fire scar sizes within a given period. This broader view is essential for landscape-level assessments, evaluating regional fire regimes, understanding broader ecological impacts, and informing resource management and fire mitigation strategies.

Our analysis, segmented into four distinct time intervals (1985–1994, 1995–2004, 2005–2014, and 2015–2022), aimed to better understand changes in fire dynamics over time. We analyzed the total burned area and the size of fire scars across these different time periods to assess variations in fire activity throughout the Cerrado biome.

To enhance our understanding of fire patterns over time and across ecoregions, we conducted comprehensive analyses, including the computation of the standardized annual anomaly of burned areas within the Cerrado ecoregions. This was achieved by comparing annual burned area with the average of the entire time frame and dividing it by its standard deviation $(X-\mu)/\sigma$. This approach results in a standard score with a mean of zero and a standard deviation of one, highlighting the relative importance of annual events in the time series.

In addition, we quantified the variation in fire scar size over the 9-year intervals for each ecoregion and determined the relative difference with the historical average. These analyses contribute to a comprehensive understanding of the dynamic patterns, considering both temporal and geographical aspects.

To deepen our understanding of the relationship observed between fire activity and land cover/land use changes, we used Pearson's correlation to analyze the annual correlation between burned area and farming area, and between average fire scar size and farming area, within each ecoregion. Farming areas encompass both pasture (non-indigenous grassland) and agricultural classes from MapBiomas's LULC Collection 8. A positive correlation between burned area and farming area suggests that regions with larger farming areas tend to experience more fire activity or larger fire events. This could indicate that agricultural practices and land management in these areas might contribute to increased fire incidence, either through intentional burning for land clearing and maintenance or through accidental ignitions. Conversely, a negative correlation indicates that regions with larger farming areas are associated with lower fire activity or smaller fire events. This could occur in areas with more mechanized agriculture, where the use of machinery reduces the need for burning, or it might indicate a displacement effect where farming activities reduce the availability of combustible vegetation, thereby limiting the spread of fires.

Results

Annual variability of burned area

Our analysis using the 38-year Landsat-based burned area dataset showed that the Cerrado biome experienced larger fire events over this period, totaling 792,204 km2 (or 40% of the Cerrado biome) of areas that burned at least once from 1985 to 2022 (Fig. 3A and C). In terms of temporal variability, we estimate that, on average, 79,144 km2 (4% of Cerrado) are affected every year by fire activity (Fig. 3B). However, annual burned area estimates varied over time, with the minimum annual area detected in 2009 (29,468 km2) and the maximum area mapped in 2010 (150,652 km2) (Fig. 3C). Other years of high fire occurrence were 1987, 1988, 1998, and 2007, while 2006, 2013, and 2018 showed a lower incidence of burned areas.

When examining the statistical analysis of the total yearly burned area over time (Fig. 3D and Table S1), no significant difference is observed ($p=0.546$), suggesting that there are no significant temporal trends in burned area from 1985 to 2022. However, the period from 1985 to 1994 exhibits the greatest total area burned (883,240 km2) and the period from 2005 to 2014 shows the highest standard deviation (±42,459 km2). One explanation for this interannual variability is related to the association between accumulated fuel material and more extreme climate conditions (e.g., El Niño Southern Oscillation—ENSO), which favors the occurrence of large fires (Aragão et al. 2018). Besides the accumulation of fuel materials and climate anomalies, there is also the presence of human-driven ignition sources, such as land use change, as a response to policy and economy (Schmidt and Eloy 2020).

Our analysis of fire scar size at different time-intervals (Fig. 3E) showed an increase of 18% in the size of fire scars, particularly in recent years (2015 to 2022) compared to the historical average (size of burned scars from 1985 to 2022), and a difference of 33% between the last (2015 to 2022) and the first interval (1985 to 1994). This significant increase suggests a changing trend in the fire dynamics within the analyzed time frame, with individual fire events becoming larger. This shift can be attributed to various factors, including changes in land use, climate conditions, or fire management practices (Wu et al. 2021).

Changes in Cerrado monthly burned area

Our monthly burned area estimates over the last 38 years helped establish the boundaries of the burning season in the Cerrado and understand how this is changing over time (Fig. 4A). Our results revealed that most fires occur during the dry season, with 89% happening from July to October; with September exhibiting the highest occurrence at 37%. Comparing the fire seasonality at different time intervals (every 9 years) revealed a shifting pattern in the peak of fire activity, consistently occurring later throughout the time series. Remarkably, the

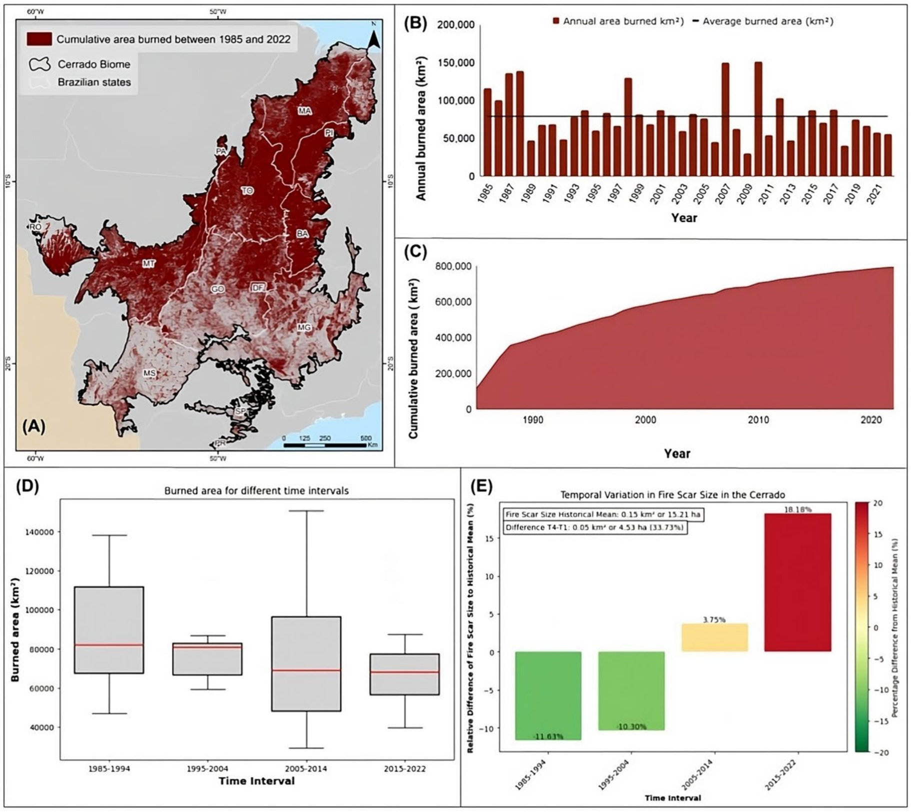

Fig. 3 **A** Spatial distribution of the total area burned between 1985 and 2022 in Brazil; **B** annual burned area from 1985 to 2022; **C** cumulative burned area between 1985 and 2022; **D** box plots illustrating the sum of burned area across distinct time intervals, representing the interquartile range (IQR) with the median highlighted in red; and **E** percentage difference of fire event size at different time intervals in the Cerrado biome, historical mean represents the average size of burned scars from 1985 and 2022, while the difference from T4 to T1 represents the variance between the means of fire scar size from 2015 to 2022 and from 1985 to 1994

highest concentration of fire events has shifted towards the end of the dry season, particularly in the month of September, and there has been a notable increase in the occurrence of fire activity in October (Fig. 4B). Fires, particularly those initiated by human activity during the dry season, exhibit distinct characteristics from natural fires in the rainy season or transitional periods (Ramos-Neto and Pivello 2000).

The increasing occurrence of fire activity towards the end of the dry season in the Cerrado may be influenced by climate change, human activities, and unsustainable land management practices. Climate change can lead to prolonged dry periods and higher temperatures, creating more favorable conditions for fires to ignite and spread (Libonati et al. 2022). Human activities, particularly agriculture, often involve the use of fire for land clearing and crop management. As the dry season progresses, the accumulation of dry vegetation increases the fuel load, making it easier for fires to start and spread. Unsustainable land management practices, such as deforestation and overgrazing, can degrade the land and reduce its resilience to fire, further exacerbating the situation (Ren et al. 2024). These combined factors contribute to the observed shift in fire occurrence towards the end of the dry season.

Our monthly analysis of burned areas across distinct land use and land cover classes showed a concentration of fire events predominantly from July to October (Fig. 4C). However, a more detailed analysis of the seasonal distribution of burned areas for each land use and land cover type revealed nuanced differences (Fig. S1): the largest burned area over grasslands, identified as the most flammable natural vegetation type in the Cerrado (Zanzarini et al. 2022) was identified in August, coinciding with minimal precipitation levels (Fig. 4A). In addition to burning during the dry season, forests were also impacted by fire events at the beginning of the rainy season. As for savannas and wetlands, the occurrence of fire events was high during the late dry season, particularly in September and October. In human-dominated land cover types, all land uses showed a larger concentration of fire scars in the dry season, with the class of agriculture

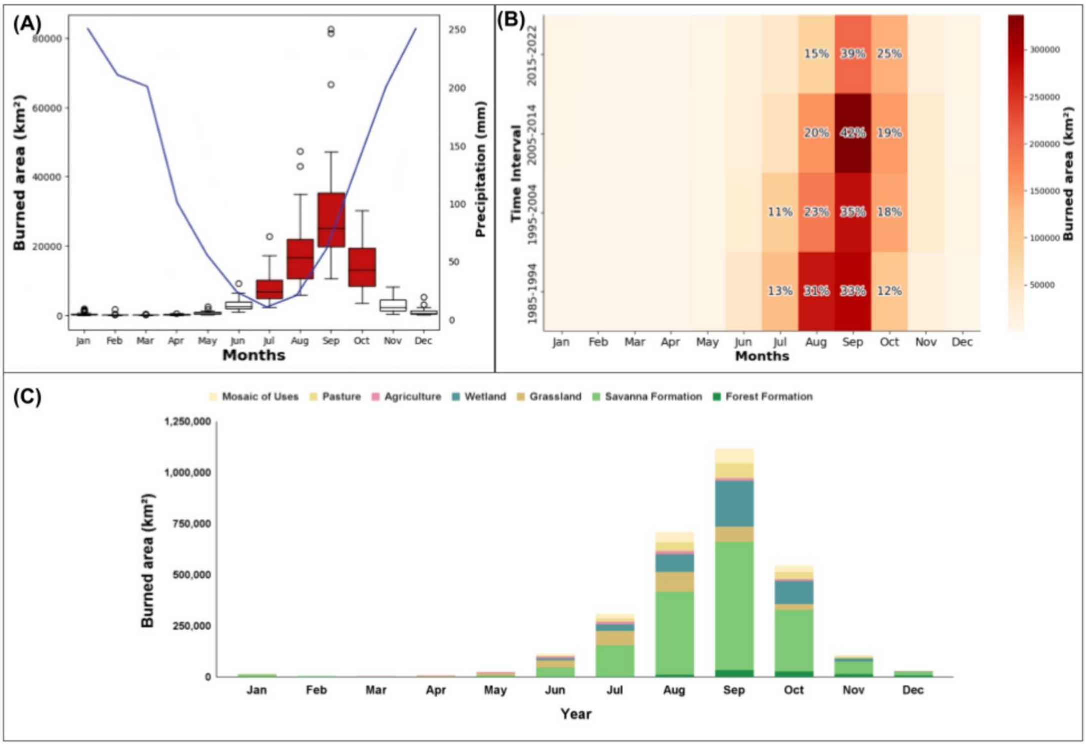

Fig. 4 **A** Monthly variations of burned area (hectares) and mean precipitation (measured in millimeters from the Tropical Rainfall Measuring Mission, TRMM) in the Cerrado, from 1985 to 2022; **B** mean burned area in the Cerrado for different time intervals and the percentage of burned area for each month within each time interval; **C** total monthly burned area categorized by land use and land cover from 1985 to 2022, with Jan—January, Feb—February, Mar—March, Apr—April, May—May, Jun—June, Jul—July, Aug—August, Sep—September, Oct—October, Nov—November, Dec—December

experiencing a peak in fire activities between July and September.

Fire recurrence

Our analysis of fire recurrence in the Cerrado biome revealed areas experiencing multiple fire events. The data range from 1 to 38, indicating the recurrence of annual fire events in specific locations throughout the study period (Fig. 5A). Most of the burned area in the Cerrado, approximately 503,832 km2 or 63%, experienced two or more fire events between 1985 and 2022 (Fig. 5B). Almost half (45%) of this area burned three times or more, with a fire return interval of up to 12 years; a small portion (3.5%) of the total burned area had a fire return interval shorter than 2 years when fire recurrence was higher than 15 times (Table S2). The spatial distribution of fire recurrence displayed significant heterogeneity, featuring high recurrence areas in the central and northern regions of the biome, especially in the MATOPIBA region. In contrast, the southern Cerrado region experienced less frequent and more discontinuous fire events.

Our subsequent analysis revealed a large variability in fire recurrence over land use and land cover classes (Fig. 5C; more details and percentages are in Fig. S2). Regarding native vegetation, forests exhibited the lowest fire recurrence, with 55% of the area burned once. In proportion, grasslands exhibited a higher recurrence, with 76% burned more than twice, compared to savannas where 64% experienced more than two burn occurrences in the same area. In contrast, wetlands showed the highest fire recurrence, with 35% of the area burned 10 times or more at intervals of up to 3 years. As for anthropogenic classes, pasture had the lowest recurrence, with 51% burned once.

Burned area by land cover and land use

Figure 6 illustrates the intersection between the cumulative burned area and the land use and land cover classes for 2022. The results revealed that, from 1985 to 2022, most burned areas (85%) in the Cerrado biome affected native vegetation classes (Fig. 6B), primarily savannas (54%), wetlands (16%), and grasslands (11%), with forests (3%) being affected to a lesser extent (Fig. 6A and B). It is worth noting that many of these natural areas experienced multiple fire events over this time period. The remaining fires (15%) occurred over farming, primarily

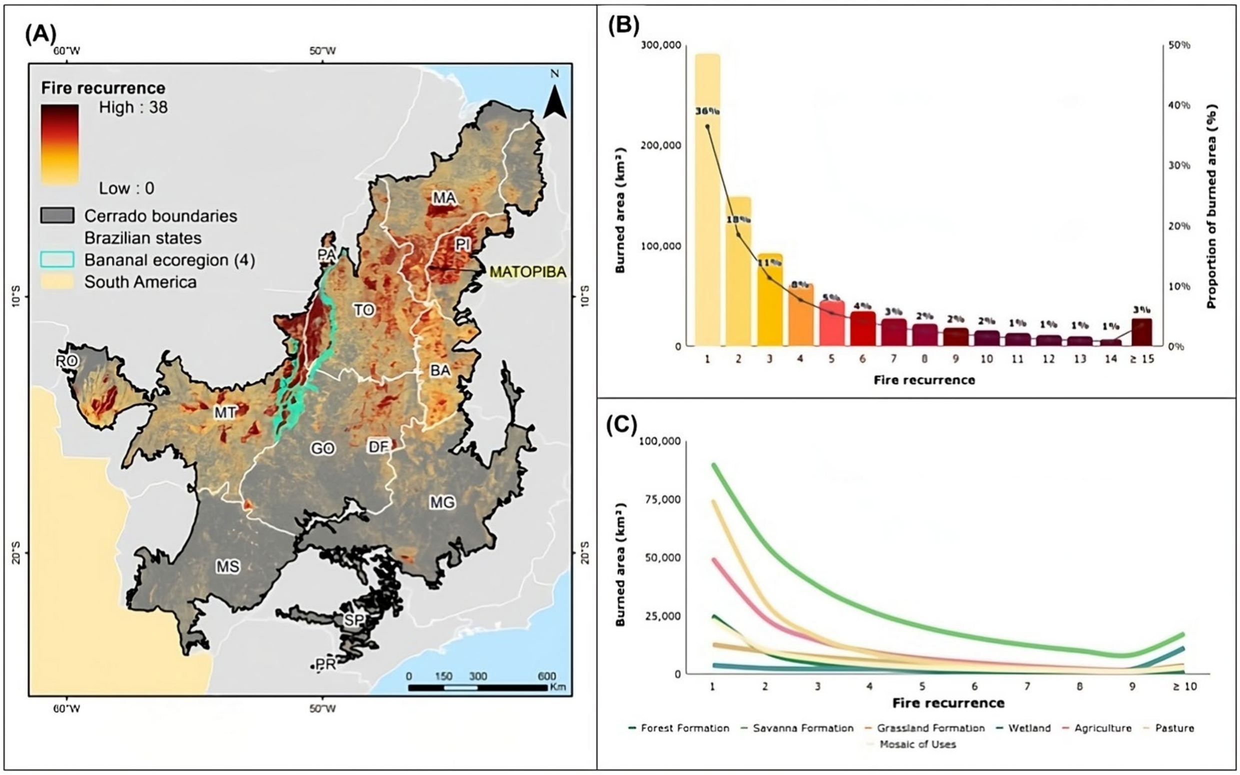

Fig. 5 **A** Spatial representation of fire recurrence in the Cerrado from 1985 to 2022, with the location of the Bananal ecoregion lEcoregion 4) and the Cerrado states, as well as the location of the MATOPIBA region (encompassing the states of Maranhão, Tocantins, Piauí, and Bahia); **B** area and percentage distribution of burned area across recurrence classes in the Cerrado; **C** fire recurrence categorized by land use and land cover classes in the Cerrado biome

pasture fields (6%), agriculture (2.4%), and mosaic of land uses (6%).

The analysis of annual burned area across land use and land cover classes revealed a persistent pattern in the Cerrado over time (Fig. 6D). In general, native vegetation classes experienced the highest increases in burned area during peak years (e.g., 1987, 1988, 1998, 2007, 2010, and 2012). However, when assessing land use in 2022 and burned area extent for each category, a distinct pattern is revealed: 72% of grasslands burned at some point in the last 38 years, along with 55% of savannas and 19% of forests (Fig. 6C). Although natural areas account for the highest proportion of burned land (85%), it is not possible to attribute these fire events exclusively to natural causes. In Fig. 6E, wetlands represent the native vegetation type experiencing the highest annual proportion of burning relative to its total area extent, followed by grassland and savanna. Among farming areas, the classes mosaic of uses and agriculture exhibit comparatively higher proportional burning rates, with agriculture showing a decreasing trend over the series.

Figure 7 illustrates the temporal variability of burned area patterns over time, proportionally to each land use and land cover class, providing insights into fire dynamics. The burned area is normalized, allowing to assess changes in burn extent relative to each class over time, while facilitating the understanding of fire impacts on different land types. Our findings revealed a significant increase in burned area within forests over time ($p = 0.057$). In relation to natural vegetation, wetlands experienced the highest proportion of burned area relative to their total extent. Despite a decrease in the area extent of savannas (i.e., 24 million hectares of the savanna ecosystem were lost over 38 years), burned areas did not show a reduction. A similar picture occurs in grassland ecosystems. Furthermore, our results revealed a decreasing trend in burned areas within agriculture ($p = 0.001$) and mosaic of land uses ($p = 0.025$), with statistical differences in burned area over time. The proportion of burned area in pasture remained constant over time.

Burned area patterns by ecoregions

The levels of human impact and preserved natural landscapes in the Cerrado vary across ecoregions, suggesting potential regional variations in fire dynamics and regimes. Among the Cerrado ecoregions, those with the

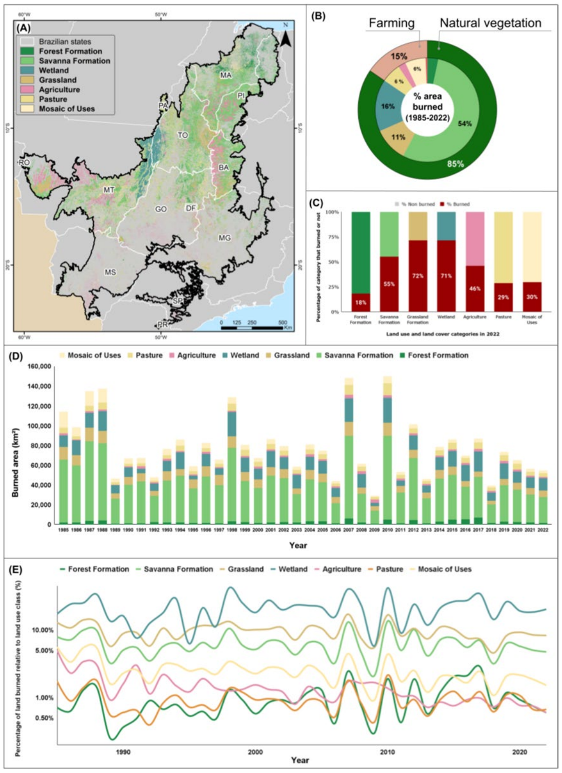

Fig. 6 **A** Burned area by land use and cover class in Cerrado from 1985 to 2022; **B** proportion (%) of the total area burned from 1985 to 2022 by land use and cover class in Cerrado; **C** categories of land use and land cover in 2022 and the proportion that burned at some point between 1985 and 2022 and the proportion that never burned; **D** Annual distribution of burned area by land use and land cover from 1985 to 2022; and **E** percentage of land cover burned in relation to the total areal extent of each land use and cover between 1985 and 2022, with the *y*-axis representing a logarithmic scale

largest farming areas are the following: Paraná Guimarães (74%), Alto São Francisco (71%), and Chapadão do São Francisco (36%). Conversely, the ecoregions with the highest proportions of natural areas are Costeiro (88%), Bananal (80%), and Planalto Central (34%). Table S3 provides a more detailed analysis of each ecoregion, including descriptive statistics (i.e., area estimates and percentages) of farming areas and natural vegetation for each ecoregion.

The analysis of spatiotemporal patterns of fire occurrences within each Cerrado ecoregion considered both the total burned area (Fig. 8A) and the normalized burned area, representing the percentage affected at some point between 1985 and 2022 (Fig. 8B). Four ecoregions (Araguaia Tocantins, Alto Parnaíba, Chapadão do São Francisco, and Paraná Guimarães) accounted for over half of the total burned area in the Cerrado biome, with an annual burned area average of 44,283 km2 (Fig. 8A and Table S4). Ecoregions such as Bananal (72%), Chapadão do São Francisco (71%), Alto Parnaíba (70%), and Parnaguá (60%) experienced burning in more than half of their territory throughout the entire study period. Given that all these ecoregions have more than 60% of their area covered by native vegetation, there is a potentially higher presence of fuel material susceptible to burning (Table S3).

The ecoregions in the central and northern parts of the Cerrado biome, including the MATOPIBA region, which encompasses the Cerrado portion in the states of Maranhão, Tocantins, Piauí, and Bahia, had approximately half of their territory burned. This region features the largest remnants of Cerrado's natural vegetation, as well as a well-established commodity-driven agricultural frontier. Meanwhile, the southern region contributes less to the total burned area.

The annual standardized anomaly of burned areas within each Cerrado ecoregion reveals both positive and negative trends over time and across space (Fig. 9). A positive anomaly is observed in the central and southern regions of the biome during the first 4 years of the time-series (1985 to 1988). Additionally, most regions exhibited positive burned area anomalies in 1998, 2007, and 2010. The years 2012 and 2015 stand out with particularly high positive anomalies in the regions surrounding the MATOPIBA, where trends in climate and land use factors have generally been intensified over the last two decades (Silva et al. 2020). On the other hand, most ecoregions display negative anomalies in the years before or after periods of significant positive anomalies, mainly due to a decrease in available fuel material, as seen in 2000, 2006, 2008, 2009, and 2013.

Figure 10 illustrates the temporal dynamics of fire scar patch size across Cerrado's ecoregions during different 9-year interval periods from 1985 to 2022. The findings revealed an increase in the extent of fire events, with the most significant rise occurring from 2015 to 2022 in most ecoregions. The ecoregion with the highest average burned area size is "Bananal" (47 hectares), and the ecoregion experiencing the most substantial increase in fire scar size is "Depressão Cárstica do São Francisco" (123.8%). This significant surge in wildfire size in recent years highlights the importance of having effective laws and fire management strategies to protect the biodiversity and ecological integrity of the Cerrado biome.

The correlation analysis conducted to assess the relationship between burned area and farming reveals contrasting patterns between fire regime and land cover and land use changes across the Cerrado biome. As expected, we observed negative correlations between annual burned area and farming (Fig. 11A), with higher strength in the southern Cerrado, pointing out that as

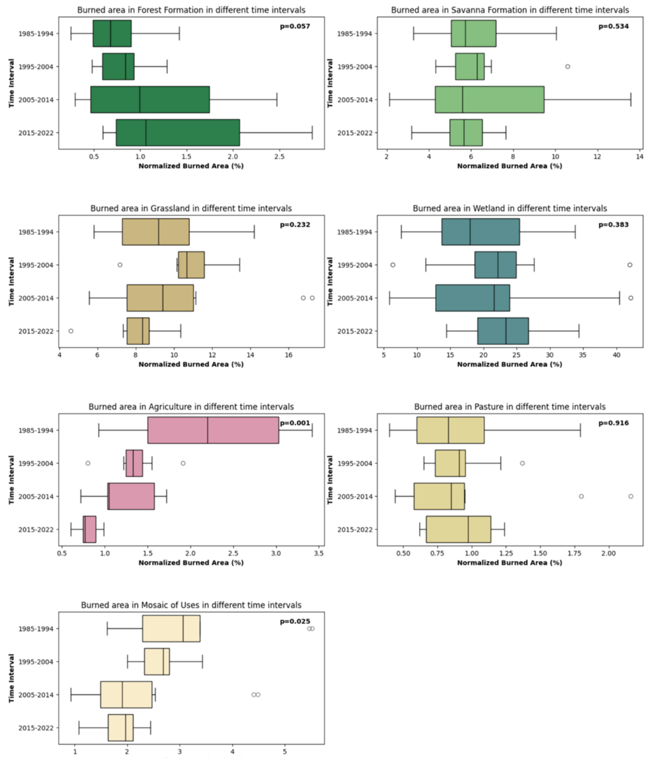

Fig. 7 Boxplots of the normalized burned area at different time intervals for each type of land use and land cover. The boxes represent the interquartile range (IQR), with medians represented by the black line. Black text upper each graphic represents the ANOVA *p*-value

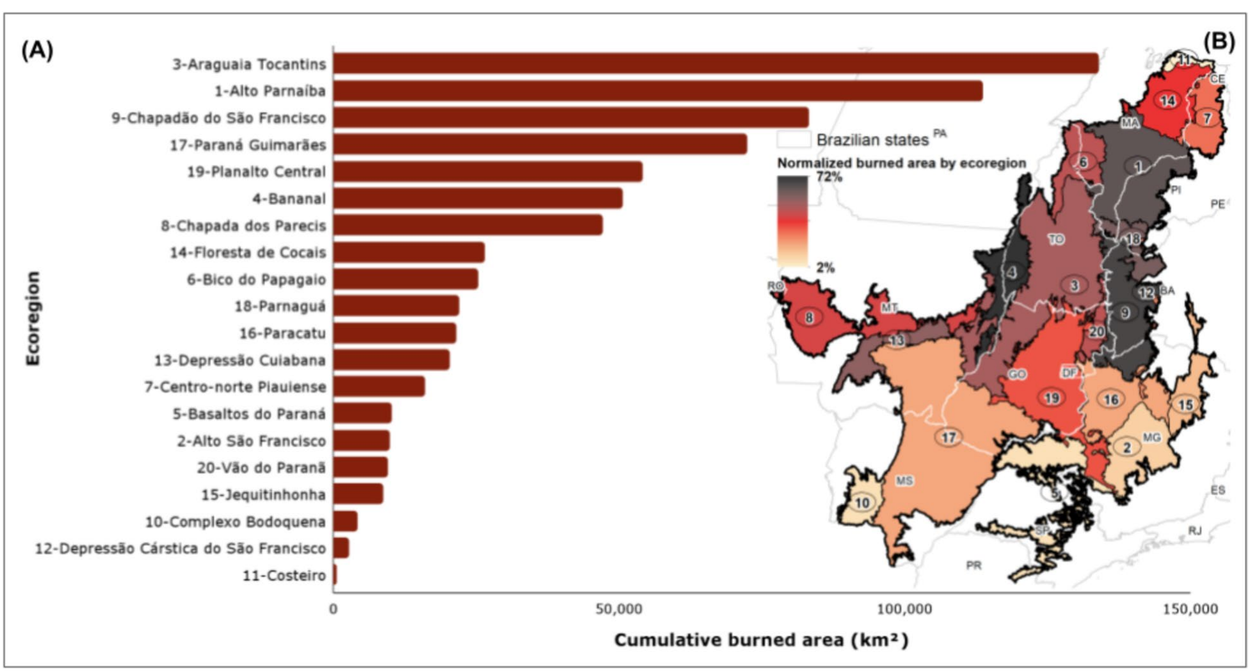

Fig. 8 **A** Total burned area for each Cerrado ecoregion. **B** Map illustrating the normalized total burned area for each ecoregion, with the darkest areas representing those that proportionally burned more. Both figures represent the period between 1985 and 2022

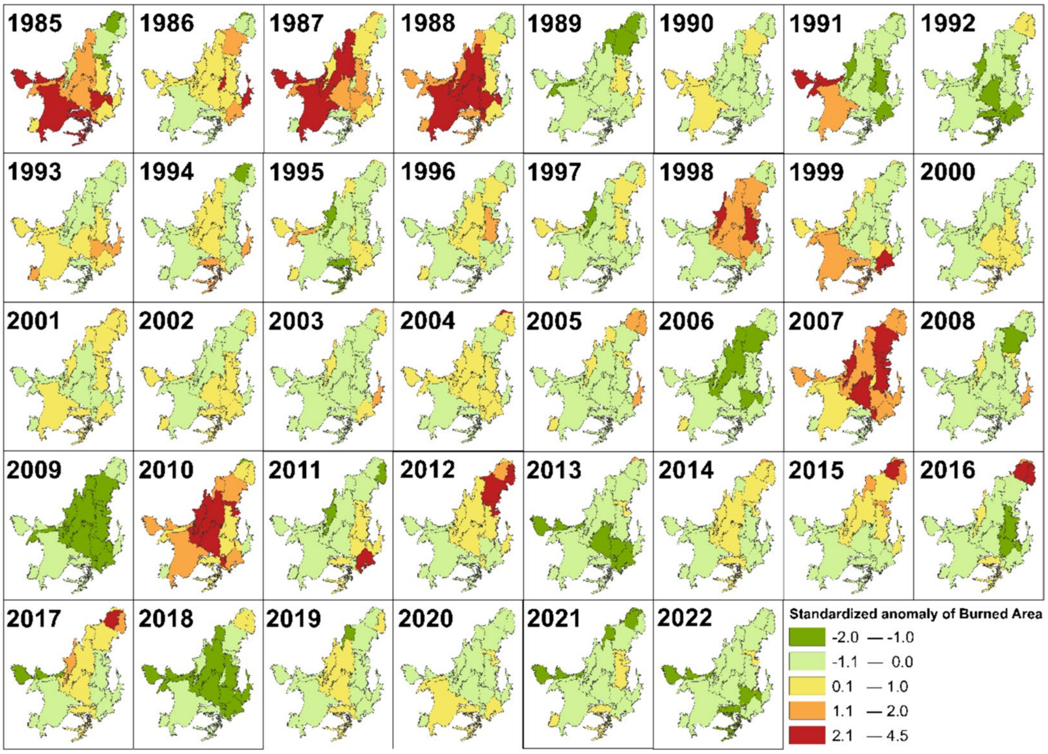

Fig. 9 Annually standardized anomaly of burned area in each ecoregion of the Cerrado biome from 1985 to 2022

the area used for farming activities increases, the burned area tends to decrease. Also, we found positive correlations in the northern Cerrado, including regions like Araguaia (ecoregion 4), Centro-norte Piauiense (7), Floresta de Cocais (14), and Parnaguá (18), indicating a regional pattern in which the expansion of farming activities leads to an increase in burned area.

Interestingly, correlations between fire scar size and farming (Fig. 11B) were positive in 16 of the 20 ecoregions, with higher values in central and northern Cerrado, emphasizing that the scar size tends to increase in ecoregions in which farming activities were expanded in the last four decades. On the other hand, neutral/weak, negative correlations were found in the southern portion of the biome, encompassing states like São Paulo (SP), Minas Gerais (MG) and Mato Grosso do Sul (MS).

Discussion

Our study analyzed the spatiotemporal patterns of fire dynamics in the Cerrado biome over the last four decades, revealing distinct patterns across ecoregions and improving our understanding of fire ecology in the Cerrado. By analyzing the past 38 years of monthly fire activity, our results demonstrate a clear shift in the burning season, with 89% of fire events occurring from July to October—with 37% concentrated in September. This concentration of fire activity during the dry season is primarily attributed to human activities, unlike natural fires caused by lightning in the wet season (Ramos-Neto and Pivello 2000), leading to more severe environmental and socioeconomic consequences (Pivello 2011). Analysis of 9-year intervals showed a later peak in fire activity, particularly in September and October. Results from prescribed burning experiments in an International Long-Term Environmental Research (ILTER) site in the Cerrado (known as "Projeto Fogo," conducted at the IBGE Ecological Reserve) indicate that a concentration of late-dry season fires results in higher tree mortality and more substantial impacts, driven by the vegetation's phenological peak in canopy renewal and reproduction during spring (Miranda et al. 2010). This shift in the fire regime highlights a need for fire management strategies that are adapted to both regional and local dynamics in the Cerrado, critical for safeguarding biodiversity and promoting the sustainability of local communities in the face of potential environmental and socioeconomic impacts.

Our detailed analysis of the seasonal distribution of fire activity across Cerrado's land cover and land use classes revealed nuanced differences, with the trend of peaks in fire activity occurring towards the end of the dry season, especially affecting native vegetation.

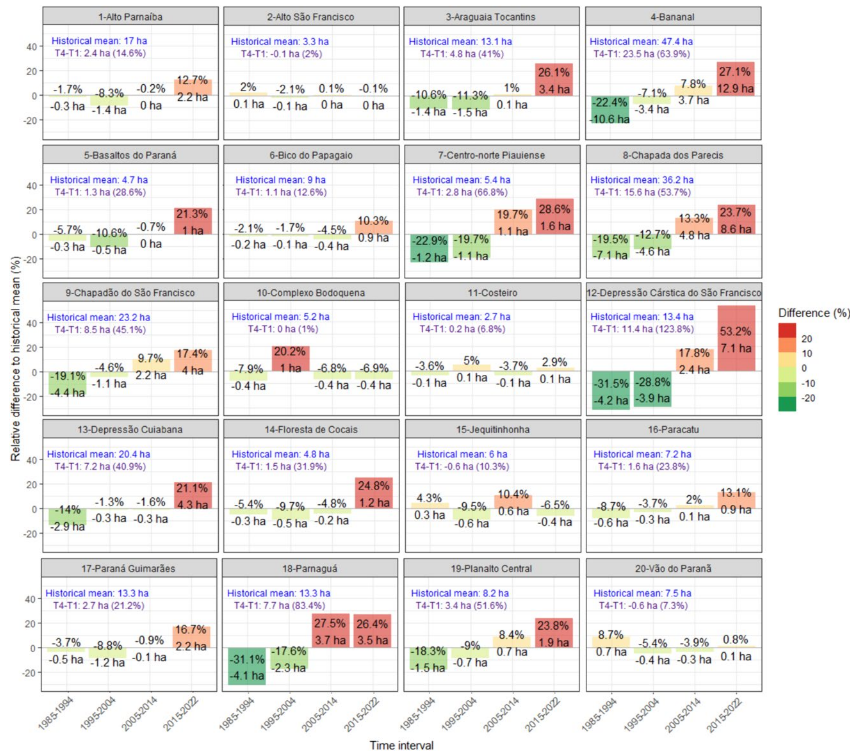

Fig. 10 Relative variation in mean fire scar size (*y*-axis) in the Cerrado across timeframes (*x*-axis) for each ecoregion. Each box represents an ecoregion, with colored bars indicating the variation in mean burn scar size per timeframe compared to the ecoregion's historical mean (indicated in blue text). The black text within each timeframe provides information on the variation (%) and absolute variation (hectares) per timeframe. Additionally, violet text in each box informs the absolute and relative difference between the last timeframe (T4 = 2015 to 2022) and the first (T1 = 1985 to 1994)

Grassland, a highly flammable vegetation type, showed peaks in fire in August. Savannas and wetlands experienced more fires in the late dry season, particularly in September and October, which can lead to serious ecological consequences for these ecosystems. Dry vegetation conditions increase the risk of fires spreading to adjacent areas, leading to a higher risk of uncontrolled fires. In this scenario, wetlands are of special concern given the specific aspects of their spatial distribution at the landscape scale and flammability due to their high rates of fuel build-up (Garcia et al. 2021). For instance, wetlands in the Cerrado are surrounded by riparian vegetation often dominated by forest species, which not only have a higher risk of severe wildfires but are also a fire-sensitive ecosystem that takes longer to recover from fire events (Nóbrega et al. 2019; Marques et al. 2022). Moreover, Cerrado wetlands are often surrounded by savanna-like vegetation, usually found under extremely dry conditions in the late dry season. This emphasizes the importance of Integrated Fire Management (MIF) strategies, especially early dry season management, to protect fire-sensitive ecosystems in the Cerrado biome (Schmidt et al. 2017).

Despite the efforts for fire suppression (Brazil National Law 2661/1998), fast land conversion for intensive and mechanized agriculture has significantly altered the fire regime in the Cerrado, leading to more frequent fire events at shorter intervals (Rodrigues et al. 2021). A significant portion of this biome, covering an area of 59,835 km2, has experienced recurrent fires, burning more than 11 times. This trend indicates a clear shift towards shorter intervals between successive fire events, resulting in consequences for natural vegetation such as increased mortality rates of woody and shrub species, reduced seedling development, and a rise in herbaceous vegetation, thereby impacting ecosystem functioning, water dynamics, and carbon flow (Miranda et al. 2009).

Approximately 40% of the biome witnessed at least one fire event during the timeframe analyzed, resulting in an annual average burned area of 79,144 km2, corresponding to 4% of the biome's total extent. In addition to frequency, analyzing the spatial patterns of fire recurrence can inform better management decisions focused on particular regions that burn often and over larger extents. Our results exhibited a spatially diverse distribution of burned areas, with regions such as the Bananal

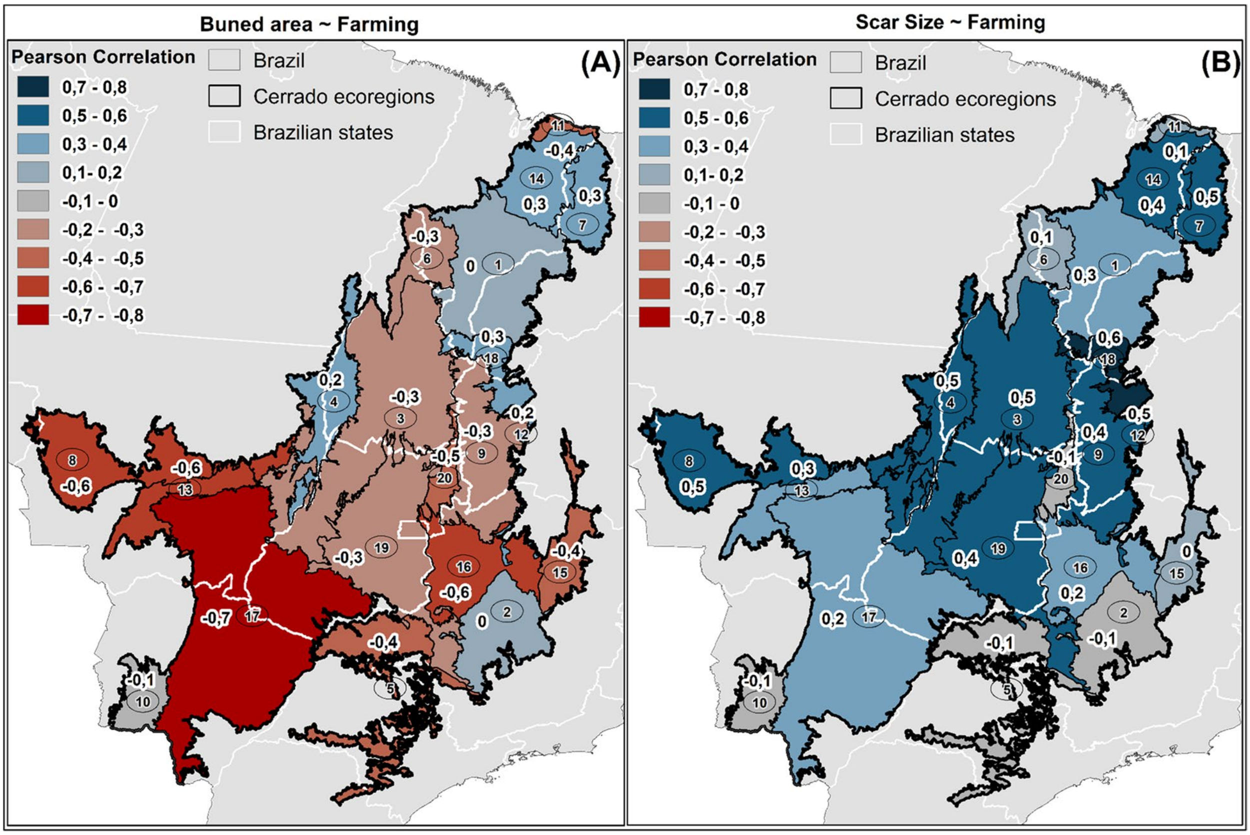

Fig. 11 **A** Map illustrating the correlation analysis between the total burned area and farming in each ecoregion. **B** Map illustrating the correlation analysis between mean fire scar size and farming. A negative correlation (shades of red) indicates an inverse relationship, pointing that as farming area increases, the total burned area and/or fire scar size decreases. Conversely, a positive correlation (shades of blue) indicates that as farming area increases, the total burned area and/or fire scar size also increases. Shades of red and blue represent the correlation strength, from light (weak) to dark (moderate/strong). For each ecoregion, small numbers in a circle inform the ecoregion ID (see Figs. 8 and 10), while the numbers in larger size represent the absolute correlation value

ecoregion (ecoregion 4) experiencing a higher frequency of fire events. A significant part of this region consists of wetlands, which are used as pastures by non-indigenous livestock farmers (Silva et al. 2021) and are thus subject to prescribed fires for management purposes, aiming to prevent large fires and reduce fuel material (Schmidt et al. 2017). Livestock farming, associated with high biomass production in humid areas, leads to the highest frequency of fire events (Pivello 2011). Thus, the increased fire recurrence in wetlands can have serious consequences, affecting not only the flora and fauna adapted to these ecosystems but also disrupting the balance of these environments and their essential ecological functions (Rivaben et al. 2021).

While natural areas account for the majority of burned land (85%), attributing these fires solely to natural causes is not possible; anthropogenic ignitions from farming activities are the primary drivers of wildfires in the Cerrado, which may subsequently spread into natural vegetation areas (Alvarado 2018). The increase in burned forests and the high proportion of burned wetlands suggest potential ecological impacts, influenced by factors like forest degradation, fragmentation, and land use change (Balch et al. 2015). Despite forests exhibiting smaller burned areas and fewer recurrent fire events due to their higher moisture content, their impact can be more devastating due to their lower adaptation to fire compared to savannas and grasslands (Miranda et al. 2010). This contributes to ecosystem impoverishment, exclusion of sensitive species, and reductions in nutrient and biomass stock in the tree and shrub layer (Gomes et al. 2020).

Despite savannas being the dominant ecosystem in the Cerrado, covering 28% of its landscape in 2022, they have undergone a substantial loss of approximately 24 million hectares over the 38-year period (Alencar et al. 2023). Despite that, savannas still contribute to the largest absolute burned area in the Cerrado biome. The prevalence of fires in grasslands and savannas can be attributed to the higher flammability of fine fuels found in herbaceous vegetation, abundant in these ecosystems, highlighting the feedbacks between fuel build-up and fire dynamics (Aleman and Staver 2018).

Wetlands in the Cerrado play a crucial role in fire ecology due to their significant contributions to water cycling and biodiversity (Schmidt et al. 2017). Our findings reveal that wetlands experience the highest relative burned area, with an annual mean burn rate of 22%. The Bananal ecoregion in particular, where most wetlands are located, exhibits the most substantial increase in fire scar size. Consequently, these wetlands are not only burning more frequently, but also experiencing larger fire events, possibly leading to ecosystem homogenization (Setterfield et al. 2010) and posing severe threats to biodiversity, habitat integrity, and ecosystem services. Therefore, conservation efforts in the Cerrado should prioritize the particularities of each vegetation type, implementing suitable fire management practices to ensure their long-term conservation (Durigan and Ratter 2016).

The MATOPIBA region is the last agricultural frontier in the biome and features the largest extent of remaining Cerrado vegetation (Alencar et al. 2020). This region has experienced extensive burning activity, particularly in its central and northern parts. Ecoregions with high fire recurrence are mainly situated in this region, where the use of fire is mostly driven by human activities such as management of different land uses, including crops and pastures, and land clearing for agricultural expansion (Silva et al. 2020). These activities have disrupted landscape connectivity and altered fuel conditions, consequently altering the microclimate while increasing the risk of degradation and intensity of fires due to the increase in edge areas (Aragão et al. 2008; Kumar et al. 2022; Ren et al. 2024).

The MATOPIBA region's agricultural practices, including slash-and-burn techniques and the use of fire for pasture renewal, have intensified fire recurrence. Additionally, deforestation and conversion of land for large-scale agriculture have reduced natural fire breaks, making the landscape more susceptible to uncontrolled fires. Policies and management strategies aimed at mitigating wildfire impacts could include strict enforcement of land use regulations, promotion of sustainable agricultural practices, and implementation of comprehensive fire prevention and management measures. Furthermore, engaging local communities in conservation efforts and sustainable land management practices could help reduce the frequency and severity of fires (Resende et al. 2020).

The southern Cerrado region features a highly fragmented landscape mainly shaped by farming activities, including row (i.e., soybean, rice, sugar cane) and perennial (i.e., coffee and citrus) crops (Souza et al. 2020), and anthropogenic fires (Conciani et al. 2021). The negative correlation observed in this southern landscape suggests that farming lands may act as a barrier against fire occurrence. This can be attributed to regulations prohibiting the use of fire in these areas (Ribeiro and Ficarelli 2010) and ecological reasons. For instance, landscape fragmentation can alter fire behavior and occurrence by creating barriers to fire spread or influencing local weather patterns (Barber et al. 2014; Balch et al. 2015). In contrast, the positive correlation observed in the northern Cerrado, characterized by recent land use changes and predominant row crops like soybean and sugarcane (MapBiomas Project 2023), highlights the susceptibility of these areas to fire. As land use expands, so does the extent of fire-affected areas and the magnitude of fire scars, likely influenced by ongoing land clearing and land conversion activities (Schneider et al. 2021). These distinct patterns in fire dynamics between the southern and northern Cerrado regions emphasize the importance of considering the local context and land use history in fire management strategies.

The annual anomalies of burned areas in each Cerrado ecoregion are consistent with those reported in Silva et al. 2021, which aimed to complement the ecoregional map of the Cerrado with information related to the fire component from 2000 to 2018. A noticeable north–south fire activity gradient was also observed, with the MATOPIBA region making substantial contributions. Additionally, there is a consensus between our study and Silva et al. 2021 regarding the ecoregions exhibiting the highest fire incidence, including Araguaia Tocantins, Alto Parnaíba, Chapadão do São Francisco, and Paraná Guimarães. The yearly variation in wildfires is linked to factors like the accumulation of combustible materials, climatic anomalies (such as El Niño), and changes in political and environmental policies (Miranda et al. 2010, 2014; Marengo et al. 2011; Aragão et al. 2018). Significantly in recent years (e.g., 2019), political changes in Brazil have led to weakened environmental law enforcement and reduced investments in safeguarding natural ecosystems, resulting in increased deforestation and heightened ignition for wildfires (Schmidt and Eloy 2020).

Fires in the Cerrado induce adaptations in woody plants (Silvério et al. 2015), with damage severity varying by fire frequency and seasonality (Miranda et al. 2010; Rodrigues et al. 2021; Souza et al. 2023). Despite its crucial ecosystem services, including water provision and carbon storage (Strassburg et al. 2017; Zimbres et al. 2021), the Cerrado faces climate change threats, with increasing temperatures and droughts (Hofmann et al. 2021). The increased frequency and extent of fires release stored carbon, contributing to greenhouse gas emissions (Silva et al. 2020), and directly impacting plant and animal mortality while leading to habitat fragmentation (Miranda et al. 2014; Bustamante et al. 2012).

Agricultural expansion exacerbates these challenges, disrupting the natural fire regime and affecting vast areas of native vegetation. Region-specific fire management policies are crucial to address these complexities, considering cultural and agricultural practices, flammable material introduction, ignition sources, and fire management practices. Implementing suitable fire management strategies is essential to mitigate the ecological consequences and ensure the long-term preservation of the Cerrado biome.

Conclusion

Our analysis of the annual burned area from 1985 to 2022 reveals a prevalence of fire events in the Cerrado biome, providing a comprehensive regional perspective of fire distribution over the past four decades. By assessing fire dynamics across ecoregions, this study offers valuable insights into seasonal and spatial variations of fire occurrence, highlighting the potential of integrating remote sensing data to improve our understanding of wildfire patterns. Our study demonstrates the importance of implementing effective fire management and conservation policies at the ecoregion scale while also considering factors such as land cover patterns, landscape fragmentation, and climate change impacts.

The observed trends in fire dynamics are complex and multifaceted, influenced by variables like climate conditions, land use changes, and fire management practices. While our analysis included the correlation of farming area with fire scar size and burned area, it is important to note that other drivers and parameters of the fire regime may play significant roles, which could be explored in future research. Additionally, while our focus was primarily on the Cerrado biome, extending similar analyses to other Brazilian biomes could provide a more comprehensive understanding of wildfires at a national scale. Future studies should also investigate the socio-economic and policy dimensions influencing fire occurrence, thereby improving the effectiveness of conservation strategies.

Our study characterized temporal shifts in the Cerrado fire regime, from natural fires in the wet season to anthropogenic fires in the dry season, while also assessing differences in fire recurrence across regions and land cover types. Given the pressures of deforestation and climate variability, understanding the nuances of fire dynamics is essential for shaping policies that balance ecological resilience with sustainable land use practices. By exploring the complex interactions between fire and land use, our research provides valuable insights for decision-making and policy formulation. These efforts are crucial for preserving the ecological integrity and resilience of the Cerrado biome in the face of escalating fire risks and anthropogenic pressures.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42408-024-00298-4.

Additional file 1: Supplemental Fig. S1. Total monthly burned area for each land use and land cover type individually, spanning from 1985 to 2022. Monthly abbreviations include Jan—January, Feb—February, Mar—March, Apr—April, May—May, Jun—June, Jul—July, Aug—August, Sep—September, Oct—October, Nov—November, Dec—December. Supplemental Fig. S2. Fire recurrence for each land use and land cover classes in the Cerrado biome, from 1985 to 2022. Supplemental Table S1. One-Way ANOVA evaluating significant differences in burned area (in km^2) among different time intervals within the Cerrado Biome, with corresponding p-values signifying statistical significance. Supplemental Table S2. Burned area (in square kilometers) and proportion of each recurrency class, for Cerrado biome. Supplemental Table S3. Total ecoregion area (km^2), Anthropogenic area (km^2), Natural areas (km^2), farming (%), and Natural area (%). Natural areas encompass MapBiomas Collection 8 classes: Forest Formation, Savanna Formation, Mangrove, Floodable Forest, Wooded Sandbank Vegetation, Wetland, Grassland Formation, Salt Flat, Rocky Outcrop, Herbaceous Sandbank Vegetation, and Other non-Forest Formations. Anthropogenic areas include Pasture, Agriculture, Forest Plantation, Mosaic of Uses, and Non-Vegetated Area.Supplemental Table S4. Area of each ecoregion (km^2), cumulative burned area (km^2), mean annual burned area (km^2), proportion of the total Cerrado's burned area for each ecoregion (km^2), and normalized burned area (%) that represents the percentage of the ecoregion that was burned at some point in the period, between 1985 and 2020.

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Authors' contributions
Contributions to this manuscript were made by all authors. All authors have read and approved the final manuscript.

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Availability of data and materials
The datasets analyzed in the current study are accessible through the MapBiomas Fire Collection 2 asset in Google Earth Engine. The specific path to access the data is as follows: projects/mapbiomas-workspace/public/collection7_1/mapbiomas-fire-collection2-monthly-burned-coverage-1.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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