Journal of Environmental Management 296 (2021) 113098

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Putting fire on the map of Brazilian savanna ecoregions

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ARTICLE INFO

Keywords:
Brazil
Cerrado
Remote sensing
Burned area
Fire radiative power
Scar size

ABSTRACT

The Brazilian savanna (Cerrado) is considered the most floristically diverse savanna in the world, home to more than seven thousand species. The region is a mosaic of savannas, grasslands and forests whose unique biophysical and landscape attributes are on the basis of a recent ecoregional map, paving the way to improved region-based strategies for land management actions. However, as a fire-prone ecosystem, Cerrado owes much of its distribution and ecological properties to the fire regime and contributes to an important parcel of South America burned area. Accordingly, any attempt to use ecoregion geography as a guide for management strategies should take fire into account, as an essential variable. The main aim of this study is to complement the ecoregional map of the Cerrado with information related to the fire component. Using remotely sensed information, we identify patterns and trends of fire frequency, intensity, seasonality, extent and scar size, and combine this information for each ecoregion, relying on a simple classification that summarizes the main fire characteristics over the last two decades. Results show a marked north-south fire activity gradient, with increased contributions from MATOPIBA, the latest agricultural frontier. Five ecoregions alone account for two thirds of yearly burned area. More intense fires are found in the Arc of Deforestation and eastern ecoregions, while ecoregions in MATOPIBA display decreasing fire intensity. An innovative analysis of fire scars stratified by size class shows that infrequent large fires are responsible for the majority of burned area. These large fires display positive trends over many ecoregions, whereas smaller fires, albeit more frequent, have been decreasing in number. The final fire classification scheme shows well defined spatially-aggregated groups, where trends are found to be the key factor to evaluate fire within their regional contexts. Results presented here provide new insights to improve fire management strategies under a changing climate.

1. Introduction

Fire is recognized as an essential component of the Earth system. Around 40% of the world's land surface, including grasslands, savannas, Mediterranean shrublands and boreal forests, owe their distribution and ecological properties to the fire regime (Bond et al., 2005). In recent decades, many aspects of the natural fire regime, such as frequency, extent and seasonality, have been extensively modified by human activity. Meaningful advances in Earth observation technology in recent decades have allowed the compilation of long-term fire datasets with

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https://doi.org/10.1016/j.jenvman.2021.113098
Received 10 February 2021; Received in revised form 12 May 2021; Accepted 14 June 2021
Available online 2 July 2021

reasonable spatial resolution and improved accuracy (Giglio et al., 2016). Newly developed tools and methodologies allow distinguishing individual fire events (Archibald and Roy, 2009; Balch et al., 2020; Oom et al., 2016) based on burn date, and provide accurate information on burning location and duration (Andela et al., 2019), fire shape complexity, orientation and elongation (Laurent et al., 2018; Nogueira et al., 2017a), and other fire characteristics related to fire patch size (Artés et al., 2019; Campagnolo et al., 2019; Hantson et al., 2015).

The Cerrado is the largest contributor to Brazil's annual burned area (BA) (Silva et al., 2019) and represents an important parcel of South America and even global BA (Bowman et al., 2020; Lizundia-Loiola et al., 2020). Recent studies highlight that Cerrado has strong spatial variability in BA (Campagnolo et al., 2021; Rodrigues et al., 2019; Santos et al., 2020), hinting that unique fire patterns may emerge within the biome, based on distinct landscape structure (Magalhães et al., 2020; Song et al., 2018), regional climate (Marinho et al., 2020; Mistry, 1998; Ratter et al., 1997) and fire policies (Durigan, 2020; Schmidt and Eloy, 2020). Contemporary fire patterns in Cerrado have been well documented based on field records (Alvarado et al., 2017; Coutinho, 1990; Gomes et al., 2018; Le Stradic et al., 2018; Ramos-Neto and Pivello, 2000; Rissi et al., 2017). However, *in situ* studies, given their limited geographical range, may present limited potential for biome-wide extrapolation (Arruda et al., 2018). A remote sensing approach fills this gap and allows the characterization of fire attributes within Cerrado with larger spatial coverage and temporal homogeneity compared to *in situ* methods (Chuvieco et al., 2008). Using satellite-derived datasets, various studies have striven to characterize fire activity in Cerrado (de Araújo et al., 2012; Junior et al., 2020; Mataveli et al., 2018; Rodrigues et al., 2019), allowing an increased understanding of existing fire patterns and behaviour.

A recent study partitioned Cerrado into 19 ecoregions, reflecting the environmental heterogeneity within the biome (Sano et al., 2019). These regions were classified based on physical characteristics (elevation, rainfall, and soil), patterns of human occupation (land use and land cover), and level of biodiversity conservation (conservation units and indigenous lands). The resulting classification allows the analysis of 19 unique ecoregions in terms of biophysical characteristics, protected areas, environmental liability, and priorities for biodiversity conservation, paving the way to improved region-based strategies for land management actions (Fig. 1). However, this classification did not consider fire activity, an undeniably important feature in Cerrado, as recognized by the authors of that study.

Relying on the most up-to-date satellite-derived datasets of BA, fire size, fire duration and fire intensity for 2001–2019, we mapped fire characteristics for each ecoregion of Cerrado. Fire was characterized by means of seasonal and interannual variability of the fire features, as well as their anomalies, frequency, and trends. Finally, as a guide to management and conservation policies, we produced a new Cerrado fire classification and map, based on BA, fire scar size, and fire intensity.

2. Data and methods

2.1. Study area

Despite being the most floristically diverse savanna in the world (Klink and Machado, 2005), with less than 3% of its original extent currently under strict protection (Ferreira et al., 2020), Cerrado (Fig. 1) rarely reaches a high level of attention within the international

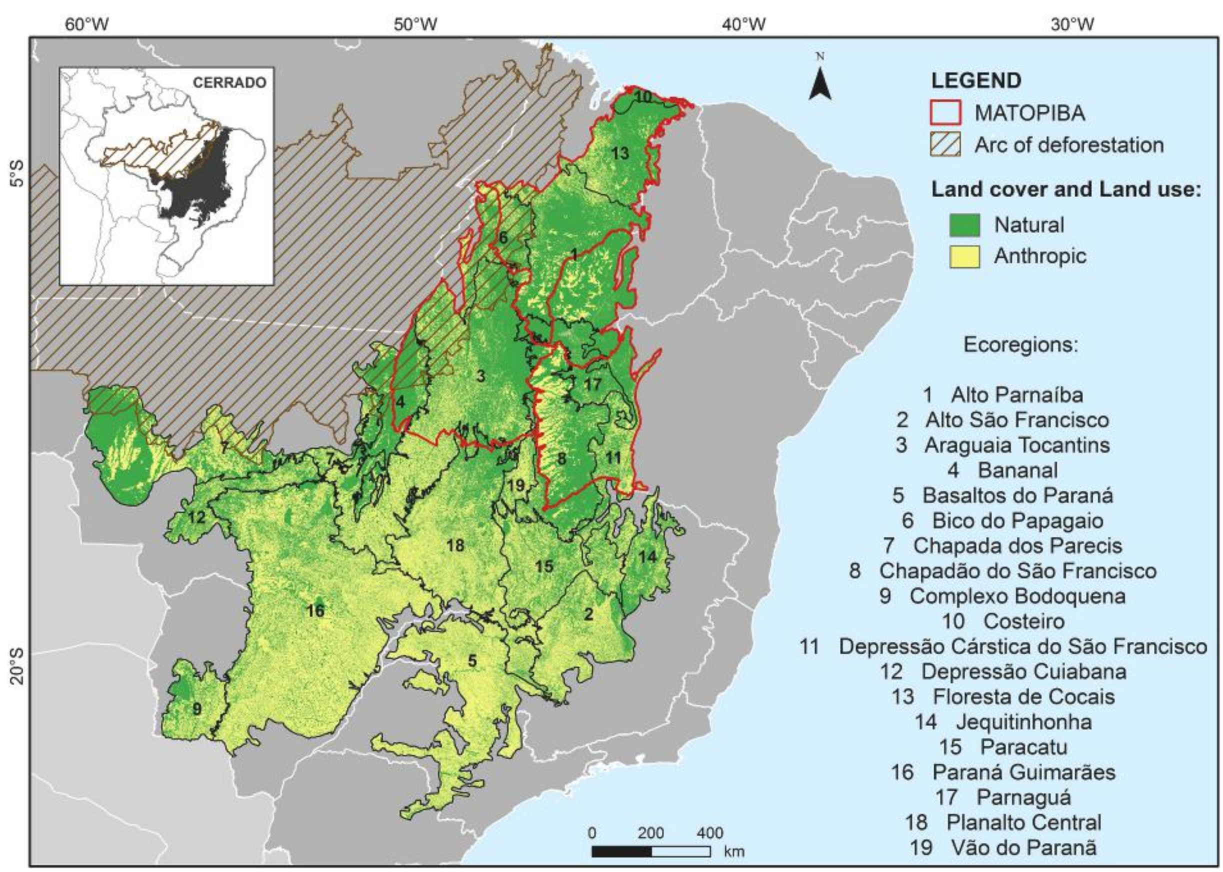

Fig. 1. Cerrado distribution within Brazil (top left panel) with its 19 ecoregions with their names in alphabetical order. Land cover and land use information from the MapBiomas Collection 5 (Project MapBiomas, 2020; Souza et al., 2020) is shown for the year 2019. The Cerrado main agrobusiness frontier, MATOPIBA, is delimited in red, whereas the Amazonian Arc of Deforestation is striped brown. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

community, especially when compared to its northern neighbour, the Amazon forest (Colli et al., 2020). The Cerrado is the second largest biome in Brazil, covering around 2 million km^2 (MMA, 2020). It has enormous importance for species conservation and the provision of ecosystem services, spanning three of the largest watersheds in South America and contributing to 43% of Brazil's surface water outside the Amazon (Strassburg et al., 2017). It is one of the most important global biodiversity hotspots (Klink and Machado, 2005; Overbeck et al., 2015), and relies on fire to shape its vegetation distribution, ecosystem functioning and ensure species survival (Abreu et al., 2017; de Miranda et al., 2014; Durigan et al., 2020; Ribeiro and Walter, 1998). It is a mosaic of soil types and topographic settings, resulting in a variety of water dynamics and different plant communities, including fire-resistant open grasslands and savannas, and fire-sensitive riparian forests (Ribeiro and Walter, 1998). As in all savannas, the Cerrado has high intra-annual variability in precipitation (Ratter et al., 1997), and a well-defined dry season in winter, generally from May to October (de Araújo et al., 2012; Grimm, 2011; Silva et al., 2019). Here, we define the dry season as lasting from June to October, while May is a transitional month with very little fire activity.

The Cerrado has been severely disrupted, with land conversion occurring mostly since the 1970's in the southern portion of the region. Since the 2010's, the newest agricultural frontier is concentrated in northern Cerrado, particularly in MATOPIBA (Fig. 1), the territory encompassing the states of Maranhão-MA, Tocantins-TO, Piauí-PI and Bahia-BA (Silva et al., 2020; Trigueiro et al., 2020). Eastern MATOPIBA partly overlaps the Cerrado-Amazon transition region, the so-called Arc of Deforestation (Fig. 1). Characterized by uncontrolled deforestation and land conversion to industrial agriculture (Marques et al., 2020), the Arc of Deforestation is the world's largest savanna-forest interface.

2.2. MODIS burned area, individual fire characteristics and fire radiative power products

We used three satellite-derived datasets; the MCD64A1 collection 6 burned area product (Giglio et al., 2018), the Global Fire Atlas database (Andela et al., 2019), and the MCD14ML collection 6 fire radiative power product (Giglio et al., 2016).

Developed by the National Atmospheric Space Agency (NASA), MCD64A1 is a monthly BA product derived from the MODIS (Moderate Resolution Imaging Spectroradiometer) sensors aboard the Terra and Aqua satellites, at 500 m spatial resolution (Giglio et al., 2018). Maps of BA in geographic projection (WGS 1984) covering the period 2001 to 2019 were obtained using the MODIS Reprojection Tool from NASA (Dwyer and Schmidt, 2006) to reproject the adjacent non-overlapping tiles of 10° by 10° (at the equator) with global sinusoidal projection.

The Global Fire Atlas (GFA) is a global fire database derived from MCD64A1 collection 6 that provides individual fire characteristics, such as timing (day of burn) and location of ignition points, fire size (km^2), fire duration (days), daily expansion ($km^2.day^{-1}$), fire line length (km) and speed ($km.day^{-1}$), and direction of fire spread (Andela et al., 2019). GFA classifies the individual events from daily MODIS data, based on a fire persistence threshold that determines how long a fire may take to spread from one 500 m grid cell into the next and to distinguish individual fires that are adjacent, but that occurred at different times in the same fire season. This threshold is presented as the final and initial date in the product. We obtained gridded 500 m layers over the study region from 2003 to 2018 to estimate fire size and day of burn.

Fire radiative power (FRP) is a measure of the instantaneous release of combustion energy and has been used as an effective estimator of the fire intensity (Laurent et al., 2019; Sperling et al., 2020). We use FRP data derived from NASA's MODIS Aqua + Terra Thermal Anomalies/Fire locations (collection 6) standard quality product (MCD14ML). For 2001 to 2019, we downloaded data in shapefile format from the Fire Information for Resource Management System (FIRMS, 2020). In order to minimize false alarms, only pixels with confidence level above 50%, and of type 0 (presumed vegetation fires) are analysed.

Limitations of the datasets are related to uncertainties associated with satellite-derived fire products. In the Cerrado, uncertainties in MCD64A1 product are large over the southern portion, consistent with small and fragmented fire scars associated with pasture and croplands, whereas uncertainties in the north are generally small due to the predominance of larger fires patches (Campagnolo et al., 2021; Rodrigues et al., 2019). Moreover, the GFA database considers individual fire events greater than 21 ha, the minimum fire size detected by MODIS sensors (Giglio et al., 2018) limiting the estimates of fire size smaller than this threshold. However, the advantage of MODIS data for mapping individual fire sizes is the daily temporal resolution, since the 16–day Landsat return interval is often not enough to individualize scars with separate ignitions that eventually coalesce into a single, large BA. This is a very common situation in savanna and grassland landscapes (Andela et al., 2019; Sá et al., 2003). Finally, the MODIS FRP product is limited by detection above the threshold of 9–11 MW (Schroeder et al., 2010). However, very low FRP occurs mainly away from the diurnal peak of fire activity in Cerrado (between 15 and 18 hours local time) (Giglio, 2007), thus the effect of MODIS FRP detection limit on the assessment of total landscape-scale FRP is negligible (Sperling et al., 2020).

2.3. Statistical analysis

We considered the total accumulated monthly and annual BA (km^2) for each of the 19 ecoregions (Fig. 1). Following the approach of Sousa et al. (2015), we also estimated the monthly Normalized Burned Area (NBA) for each ecoregion, defined as the ratio between the total amount of BA (km^2) in each ecoregion and its respective total area (km^2) (Table S1, 2nd column). We also evaluated interannual BA variability, using standardized anomalies based on a reference 19-year period (from 2001 to 2019).

Based on previous works (Pereira et al., 2017; Santos et al., 2020), single fire events from GFA were categorized into four classes according to fire scar size: I (0.21–1 km^2), II (1–10 km^2), III (10–50 km^2), and IV (>50 km^2). For each class of scar size, we calculated the respective total number of fire events (N scars), BA (km^2), and the distribution of the burn day (day of year) of each individual fire event.

We also analysed interannual trends in BA, fire intensity and fire size through slopes of linear regression for the study period. Given the short length of the time series, slopes were estimated using the Theil-Sen robust regression (Sen, 1968; Theil, 1950), and trend significance was assessed with the two-tailed Mann-Kendall non-parametric test (Gilbert, 1987; Kendall, 1975; Mann, 1945).

2.4. Evaluating fire patterns by ecoregion

For each of the 19 ecoregions, we evaluated satellite-derived historical fire data to identify similar fire patterns among ecoregions, considering the characteristics of the BA, fire intensity and fire size. We stratified the NBA and FRP values according to percentiles 25 (p25) and 75 (p75) for ecoregion's annual averages over the 2001–2019 period. Then, for each ecoregion, the BA totals for each scar size class were aggregated, and the size class with the largest contribution was chosen as the main contributor to the ecoregion's total BA.

Results from the above-described stratification were then represented by letters, leading to a 3-letter combination coding each ecoregion characteristics in terms of burned area (NBA), fire scar size, and fire intensity (FRP), respectively. The first uppercase letter distinguishes among ecoregions of low (L, < p25), moderate (M, between p25 and p75), and high (H, > p75) BA. The second lowercase letter indicates the scar type that most contributed to the total BA: small scars (s, 0.21–10 km^2) and big scars (b, > 10 km^2). The third lowercase letter denotes fire intensity characteristics, namely low (l, < p25), moderate (m, between p25 and p75) and high (h, > p75). Finally, positive (+) or negative (−) signs are added to indicate increasing and decreasing trends of BA over the 2001–2019 period, as estimated from the MCD64A1 product. A schematic description of the classification is provided in Table S2.

3. Results

3.1. Burned area patterns

Four ecoregions burn, on average, more than 8% of their area each year (Fig. 2a). In particular, the yearly BA in Bananal is twice that of the remaining ecoregions, with at least 24% of its area burning annually (equivalent to 16,114 km^2 per year), mostly during the dry season (23.4%). The highest five out of 19 ecoregions account for, on average, 67.4% of yearly BA in Cerrado, which translates to 81,522 km^2 per year (Fig. 2b). Conversely, the lowest five ecoregions just account for 2.7% of the yearly BA on average, about 3,305 km^2 per year. Spatial patterns of average yearly contributions to the total BA in Cerrado (Fig. 2b) show higher yearly contributions in the central-northern region and lower values in the south. Accordingly, ecoregions with BA classified as high (i.e. > p75, with NBA > 8%) are located in central and northern Cerrado, those classified with BA as low (i.e. < p25, with NBA < 2.3%) concentrate in the eastern and south-eastern Cerrado, and the remaining ecoregions, classified as moderate, occur mostly in the southern part (Fig. S3a). There is a marked spatial contrast in central-eastern Cerrado, where several ecoregions with high BA occur side by side with others with BA classified as low.

The dry season (June to October) accounts for more than 90% of the annual BA in all ecoregions in 2001–2019 (Fig. 2a), except Chapadão do São Francisco (89.6%), Costeiro (85.9%), Jequitinhonha (85.2%), Paraná Guimarães (85.1%), Basaltos do Paraná (82.3%), Chapada dos Parecis (78.2%) and Floresta de Cocais (73.6%). The months of August to October account for at least 64% of the BA, but six ecoregions (Alto de São Francisco, Paracatu, Complexo Bodoquena, Paraná Guimarães, Jequitinhonha and Depressão Cárstica de São Francisco) show an even shorter window with most fire activity occurring within a 2-month period (Fig. 2c). The case of Alto Parnaíba is worth noting since, although 90.2% of the BA occurs during the dry season, there is a secondary peak in March (Fig. 2c). A similar pattern is observed in Chapada dos Parecis, where BA is also recorded earlier in the year, from February to March.

In 2001–2019 (Fig. 3), most ecoregions display positive BA anomalies in 2007 and 2010 (18 and 14 ecoregions, respectively). The former was the most severe fire year for the biome, and only Costeiro did not show a positive anomaly, consistent with very low annual BA. Although not as widespread as in 2007, 2010 shows comparatively high anomaly values in the western Cerrado and recorded the highest anomaly in Paraná Guimarães. The year 2012 displays high positive anomalies in the ecoregions that encompass MATOPIBA. Conversely, many ecoregions show negative anomalies in 2009 and 2018 (11 ecoregions in both years), mostly over the central Cerrado.

Burned area trends show an overall decrease in most ecoregions (Fig. S1a), significant at the 5% level for Basaltos do Paraná, Chapada dos Parecis, Depressão Cuiabana and Costeiro. All ecoregions in the Arc of Deforestation display non-significant negative trends, except for Bananal and Floresta de Cocais, with non-significant positive trends, which were also found in Planalto Central and Alto Parnaíba.

3.2. Fire intensity

Ecoregions present large spatial heterogeneity in fire intensity (Fig. 4). The five regions classified with high fire intensity (i.e. > p75, with FRP > 63.7 MW) border other biomes, with Chapadão do São Francisco, Parnaguá and Depressão Cárstica do São Francisco being located in the border with the Caatinga biome, and Chapada dos Parecis and Bananal in the border with the Amazon (Fig. 4a, Fig. S3c). Chapada dos Parecis recorded the maximum value of fire intensity in a single event, reaching 11,334 MW in September 2003. Conversely, ecoregions with low fire intensity (i.e. < p25, with FRP < 42 MW) occur in Alto São Francisco, Planalto Central, Vão do Paranã, Costeiro, and Complexo Bodoquena (Fig. 4a). The heavy tails in FRP distributions in most regions show that a great majority of fires are predominantly of low intensity.

Most ecoregions show marked seasonality in fire intensity (Fig. 4b), with higher values towards the end of the dry season (in September and October). Alto Parnaíba and Chapada dos Parecis recorded BA values at the beginning of the year, which were not detected as active fires by the FRP product, suggesting that those relatively large BA correspond to fires with very low intensity.

Fire intensity trends show significant increase over Basaltos do Paraná, Paracatu, Paraná Guimarães and Planalto Central (Fig. S1b). Northern ecoregions (Alto Parnaíba, Costeiro and Floresta de Cocais) show a decreasing FRP over 2001–2019. Interannual variability (Fig. S2) displays a peak in total annual FRP in 2007 and 2010 for many ecoregions, namely Araguaia Tocantins and Bananal, further confirming

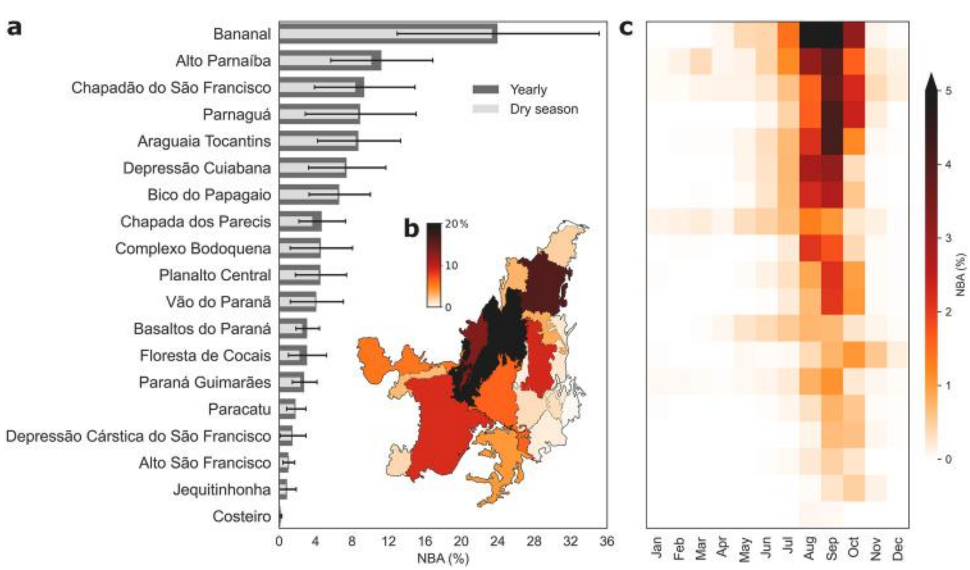

Fig. 2. a) Average normalized burned area (NBA) per year (dark grey bars) and dry season (light grey bars, representing months from June to October), with correspondent annual NBA variance (black whiskers); b) Ecoregion yearly contribution (%) to Cerrado's total BA during the 2001–2019 period; c) Heatmap of average monthly normalized burned area (NBA, %).

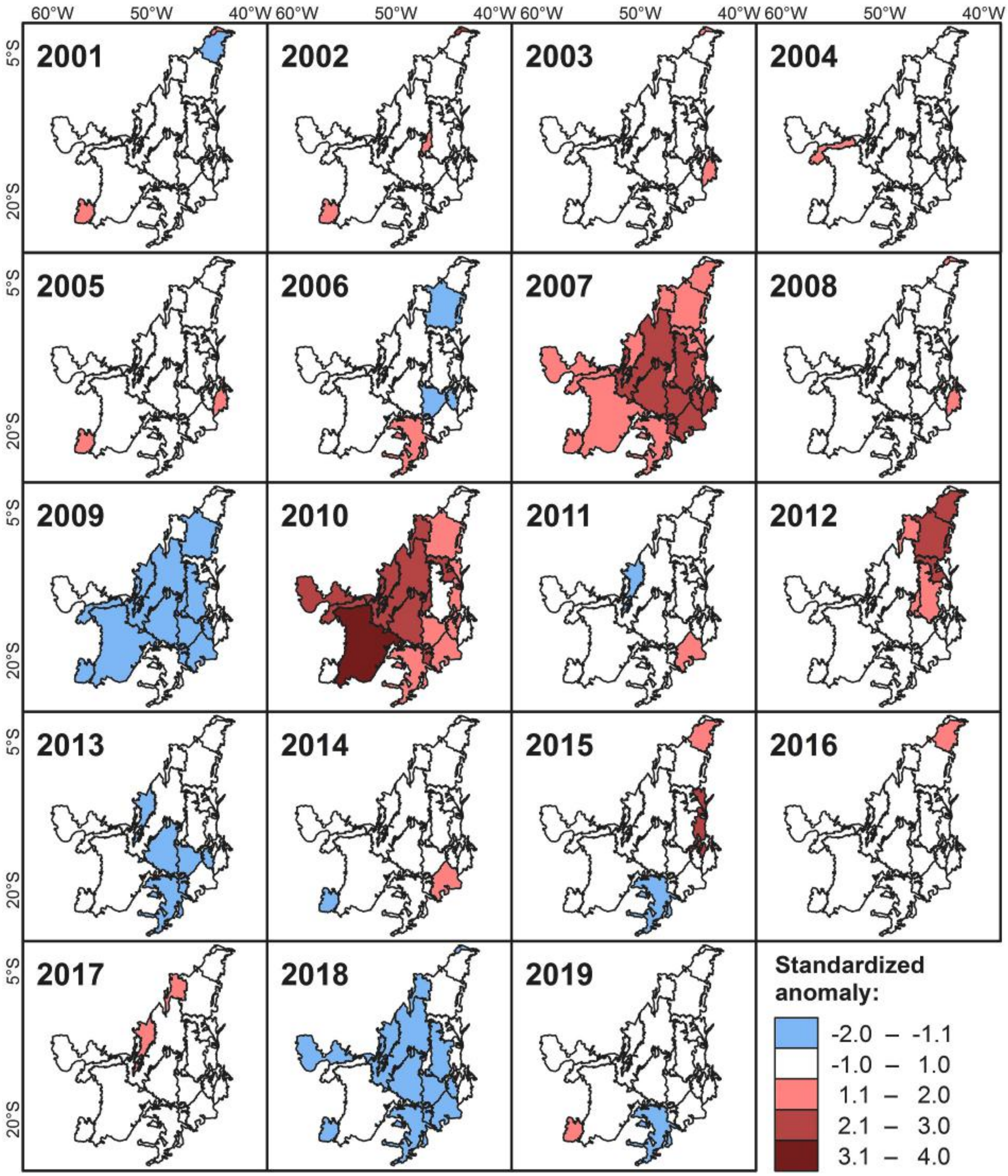

Fig. 3. Standardized anomaly of BA in each ecoregion of Cerrado from 2001 to 2019.

the 2 years as extremely severe for these ecoregions. Yearly FRP values closely track those of BA, with very high coefficients of determination ($R^2 > 0.8$) in the vast majority (14) of ecoregions.

3.3. Fire size patterns

Big scars (> 10 km^2) occur mainly in northern ecoregions (Fig. 5) and represent 20% (class III) and 10% (class IV) of the total number of fire scars, respectively. Although infrequent, they account for almost 90% of the total BA in the Cerrado. Conversely, small scars (< 10 km^2) are very common over the biome, and are much more evenly spread out over most ecoregions (Fig. 5); however their contribution to the biome total BA is small (10%).

All ecoregions show that more than 80% of their scars belong to the small class (Fig. 6). At least half of the total BA in ecoregions results from big scars. The exceptions are Floresta dos Cocais, Basaltos do Paraná and Costeiro that, along with Alto São Francisco, show a higher frequency of small scars that have a larger contribution to their total BA. By contrast, class IV scars represent more than 50% of the total BA in Araguaia Tocantins, Depressão Cuiabana, Complexo Bodoquena, Bananal and Depressão Cárstica do São Francisco. These regions burn extensively every year (Fig. 2a), suggesting that a very small number of big events is responsible for most of the Cerrado BA, a typical pattern for fire-prone environments (Campagnolo et al., 2021; Oom et al., 2016). The

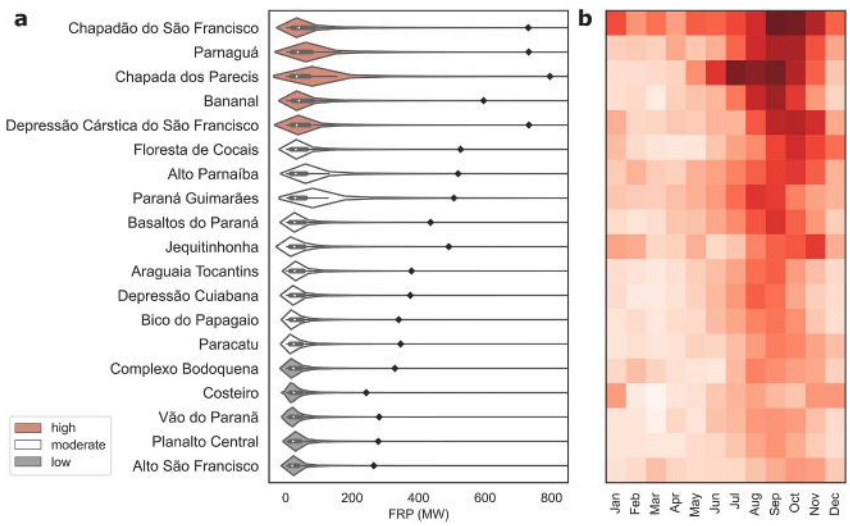

Fig. 4. a) Fire Radiative Power (FRP values in MW) per ecoregion for the 2001–2019 period; colours represent the fire intensity classes (low: < 42 MW; moderate: 42–64 MW; and high: > 64 MW) and black diamonds the 99th percentile of the FRP distribution. b) Monthly means of FRP values (MW) averaged over 2001–2019 for each ecoregion. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

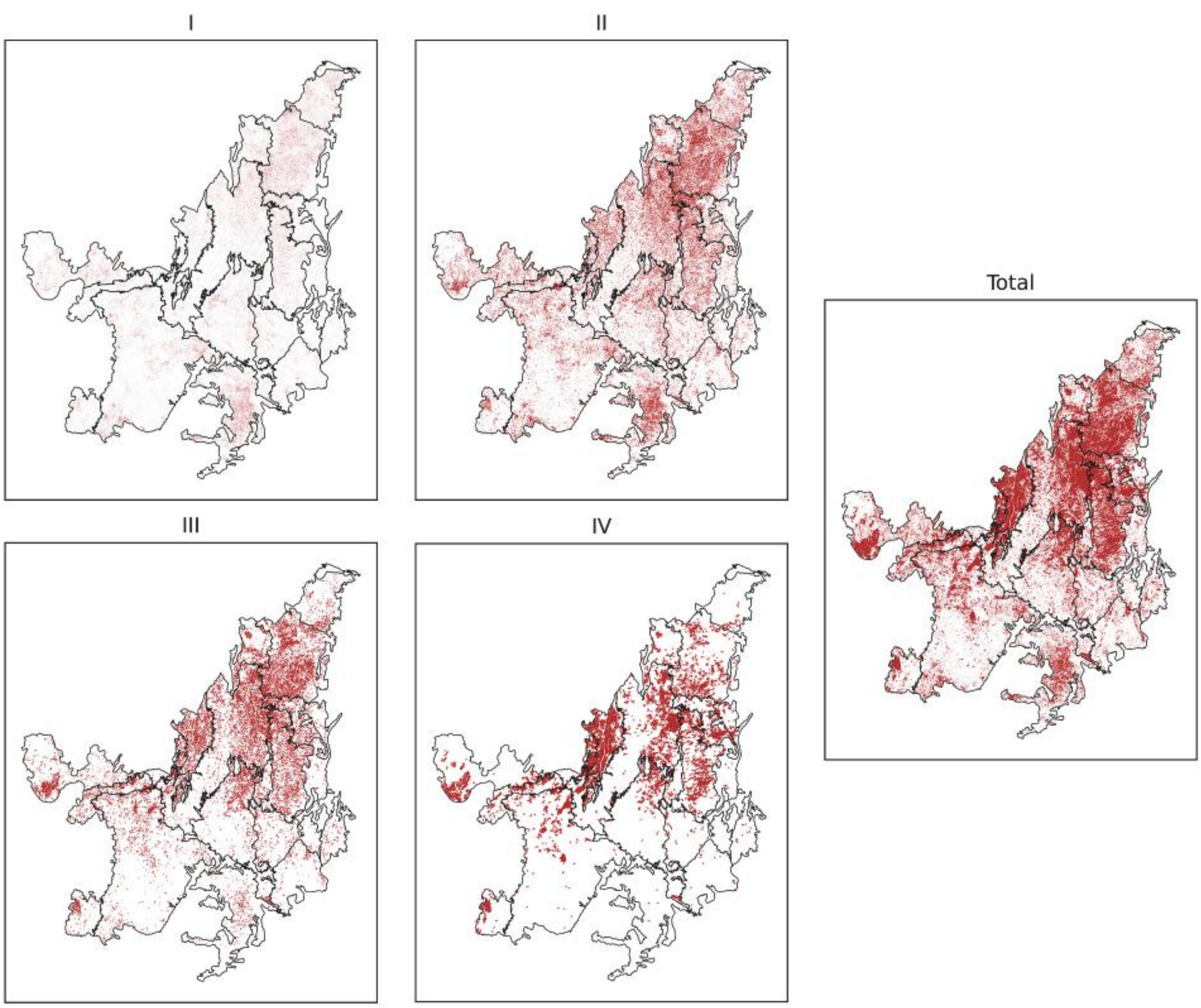

Fig. 5. Spatial distribution of fire size classes (I: 0.21–1 km^2; II: 1–10 km^2; III: 10–50 km^2 and IV: > 50 km^2) and all classes (Total), derived from GFA over the period of 2003–2018.

Fig. 6. Frequency (%) of the number of fire scars (bottom bars) and the corresponding total BA (top bars) over the 2003–2018 period according to fire size class (I: 0.21–1 km^2; II: 1–10 km^2; III: 10–50 km^2 and IV: > 50 km^2).

biggest disparity was found in Bananal, where 7% of the class IV scars account for 70% of its total BA. In turn, Basaltos do Paraná, Planalto Central and Chapada dos Parecis have many scars, but contribute much less to the total BA in the Cerrado.

There are considerable differences in fire seasonality when evaluating by fire size (Fig. 7). Overall, during the study period most fires occur in the dry season, and infrequent big fires show much less scattering than the remaining classes, concentrating mostly in August and September. Fires in classes I, II and III start to occur before the start of the dry season. This is particularly pronounced in Chapada dos Parecis, Basaltos do Paraná and, to a lesser extent, in Paraná Guimarães, where there is a marked contrast between large scars and the remaining size classes. In many ecoregions (Alto Parnaíba, Chapada dos Parecis, Chapadão do São Francisco, Depressão Cárstica do São Francisco, Floresta de Cocais, Paraná Guimarães and Planalto Central) small fires keep occurring after the end of the dry season.

When stratified by scar size (Figs. S1c–f), NBA rates of change and spatial patterns of trends deviate markedly from the total NBA (Fig. S1a). Annual NBA trends of class I fire patches show that almost all ecoregions display a decreasing rate, except for Complexo da Bodoquena. Class II fires show significant negative trends in Basaltos do Paraná, Chapada dos Parecis, Chapadão do São Francisco, Costeiro and Jequitinhonha. In turn, classes III and IV fire trends are positive over the central and north-western ecoregions, albeit non-significant. The most pronounced increase in NBA for class IV fire patches is seen over the Bananal ecoregion, while the highest positive rates of change for class III patches occur in Alto Parnaíba.

3.4. Putting fire on the ecoregional map

As described in Methods, the ecoregions were classified according to characteristics in the BA (Low, Moderate, High), fire size scar (small and big), and fire intensity (low, moderate, high). As shown in Fig. 8 and described in Table S2, when the different characteristics were assigned to the ecoregions, we obtained the following nine fire classes: Hbh, Hbm, Msm, Mbh, Mbm, Mbl, Lbh, Lbm, and Lsl.

Results show well-defined groups of similar fire characteristics over Cerrado (Fig. 8). Ecoregions classified as Hbh and Hbm are spatially aggregated over central-northern Cerrado. However, these ecoregions present distinct BA trends: although classified as Hbm, Alto Parnaíba and Araguaia Tocantins show opposite trends; and a similar contrast is observed in ecoregions classified as Hbh with Bananal presenting a positive trend and negative trends being displayed by Chapadão do São Francisco and Parnaguá. The contrast of Depressão Cárstica do São Francisco, the only ecoregion classified as Lbh, with the neighbouring Hbh ecoregions is worth being noted in what respects to BA even though they share similar characteristics in scar size and fire intensity. Ecoregions with low BA (Lbh, Lbm and Lsl) are also spatially aggregated in eastern Cerrado. The same does not happen with ecoregions of medium BA (Msm, Mbh, Mbm and Mbl), with patches spreading mostly over southern and south-western Cerrado and two ecoregions located in the northern part.

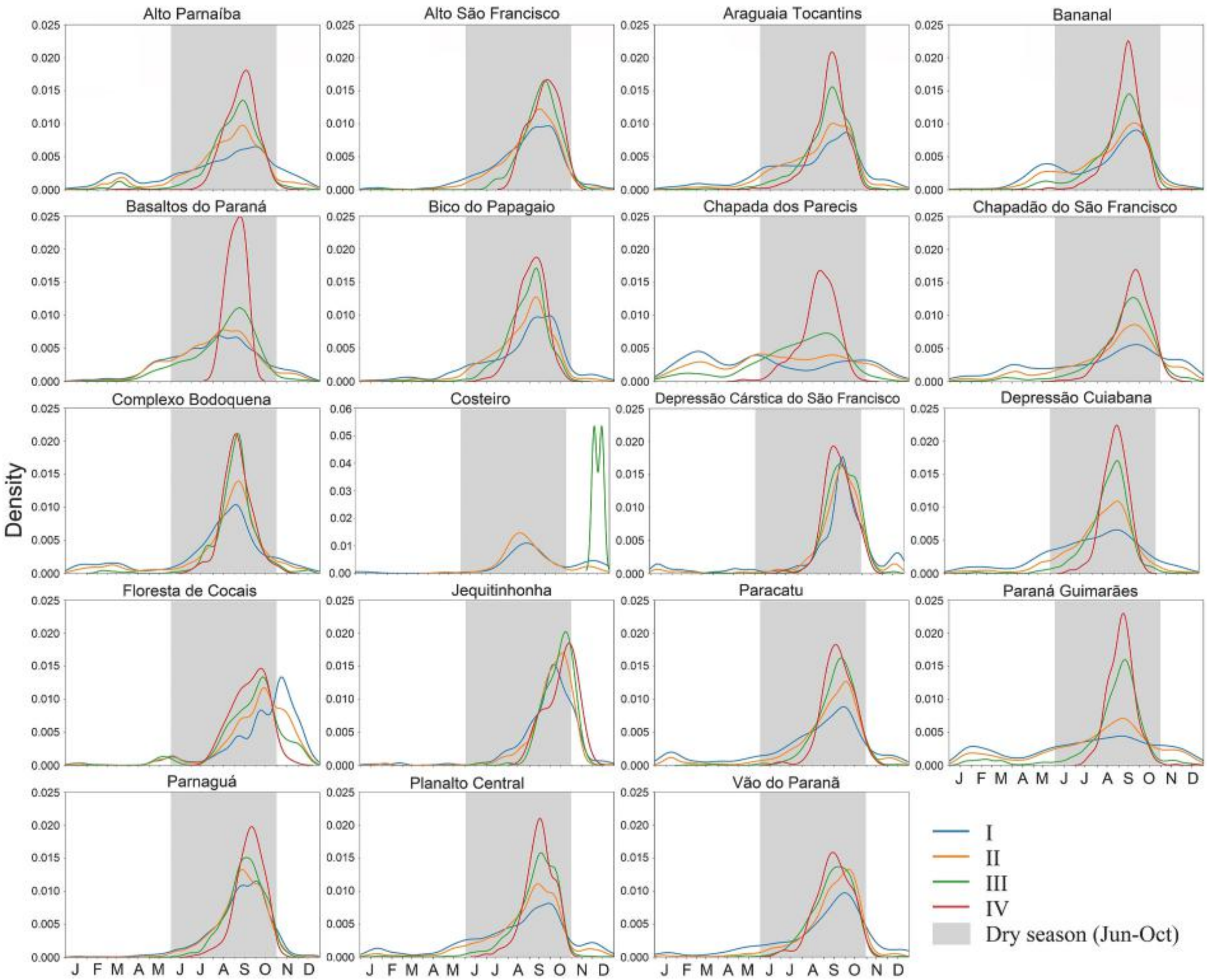

Fig. 7. Distribution of burn date (in julian day) according to fire size class (I: 0.21–1 km^2; II: 1–10 km^2; III: 10–50 km^2 and IV: > 50 km^2) for each ecoregion, considering the period from 2003 to 2018. Dry season between June and October is shaded in grey.

4. Discussion

4.1. Understanding the patterns of fire variability

The spatial heterogeneity of fire patterns within the Cerrado translate into considerable regional disparities in BA, fire intensity and distribution of fire size classes. Other parameters, such as fire seasonality, are consistent throughout the biome. The vast majority of ecoregions show increased fire activity and intensity from June to October, covering the Cerrado dry season (de Araújo et al., 2012; Silva et al., 2019). Although ignitions by lightning take place mainly at the transition between rainy and dry season (Ramos-Neto and Pivello, 2000), most ignitions are anthropogenic and fire is used mainly during the dry season for a variety of reasons, such as the management of species (Schmidt et al., 2007) and landscapes, cattle raising upon native or exotic pasturelands, subsistence and industrial agriculture (Eloy et al., 2019). The annual cycle of fire intensity is controlled by fuel availability (Oliveira et al., 2015; Wooster et al., 2005). In Cerrado, the growing period preceding the dry season tends to modulate the fire activity by affecting the accumulation of fine fuels (Krawchuk and Moritz, 2011) and, especially, fuel moisture (Nogueira et al., 2017b; Alvarado et al., 2020), which are also influenced by the hydrological regime, fire return interval and extent of area burned (Oliveira et al., 2021). Rate of fire spread is limited by high fuel moisture in the rainy season and early-dry season, and therefore fire intensity is low and fire size is small. Throughout the dry season, the fuel becomes drier and more intense fires potentially will spread more widely, depending on the landscape fragmentation level (Pyne et al., 1996). This explains the marked peak in fire intensity at the end of the dry season, in September and October, which extend into November. High FRP values towards the end of the dry season are consistent with a significant increase in fuel curing, leading to higher fire intensity, extent and severity in open savannas (Rissi et al., 2017; Rodrigues et al., 2021; Dos Santos et al., 2021). These late dry season wildfires commonly affect fire-sensitive vegetation, such as riparian forests, with high severity and negative impacts (Flores et al., 2020). However, the relationship between fire size and FRP in savannas and grasslands is complex, depending on the spatial fuel continuity, fuel load, fire season and moisture content (Laurent et al., 2019). Most active fires display low intensity, regardless of land cover and use and, therefore, location parameters of the FRP distribution, such as the mean or the median, are not adequate to characterize the different fire intensity distributions, differences only becoming apparent in the high quantiles (Hernandez et al., 2015; Luo et al., 2017; Oliveira et al., 2015), which better reflect heterogeneity in land use and land cover, landscape fragmentation, and land management across ecoregions (Libonati et al., 2021). In addition, when evaluating the distribution of burn dates by fire scar size (Fig. 7), significant differences in seasonal cycles emerge between those classified as big scars (classes III and IV) and small (classes I and II). Big scars (namely, class IV) have a narrow window of occurrence when compared to that of small scars, more evenly spread out during the year, in many cases preceding or continuing after the dry season. This behaviour is consistent throughout ecoregions and entails that major fire

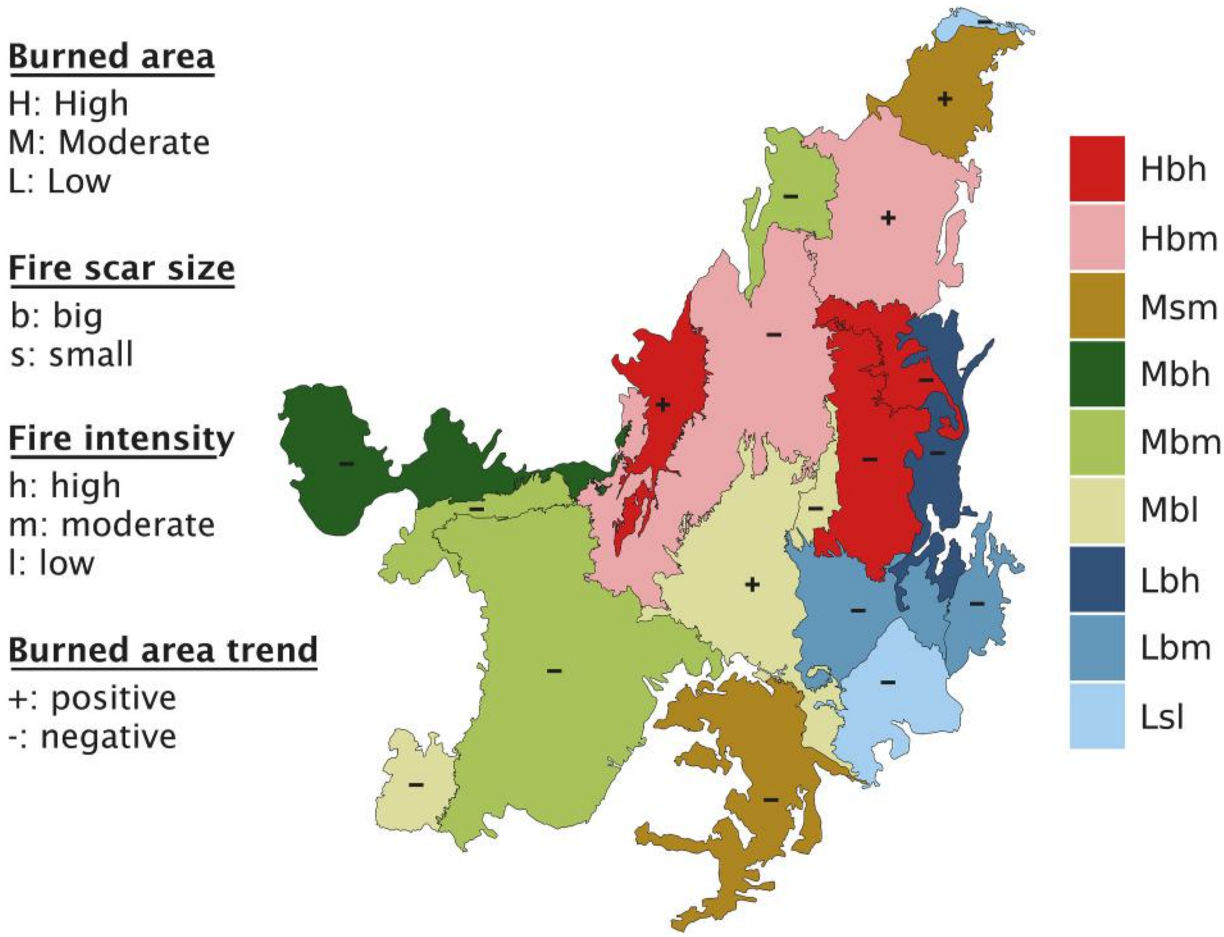

Fig. 8. Cerrado ecoregional map updated with main fire characteristics in each ecoregion. Spatial distributions of each fire characteristic are illustrated in Fig. S3. Description of each fire class (represented in the colour bar) are provided in Table S2. Plus and minus signs denote respectively, increasing and decreasing BA trends during the 2001–2019 period. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

events in Cerrado are fairly concentrated in a 2–3 month period within the dry season.

Fire activity in Cerrado also displays marked interannual variability associated with large-scale patterns of atmospheric variability. As the year with most extensive burning in the biome over the last two decades, 2007 is characterized by a severe drought induced by a La Niña event (de Araújo et al., 2012). In 2010, a strong positive phase of the Atlantic Multidecadal Oscillation (AMO) induced record drought conditions over the eastern and southern Amazon, and adjacent western Cerrado ecoregions (Andreoli et al., 2017) that reflected in high values of BA in almost all ecoregions. The extensive burning in 2012 in north-eastern ecoregions (Silva et al., 2020) is also in line with an extreme drought (Cunha et al., 2019; Jimenez et al., 2019; Marengo et al., 2013) which may have been aggravated by increased deforestation rates and incentives for land conversion resulting from changes to the Brazilian Forest Code that also took place in this year (federal law 12.651/2012). Conversely, the negative anomalies of BA in 2009 are associated to severe flooding, which occurred in western and central Amazon and the adjacent Cerrado (Marengo et al., 2012), and the global BA minimum since 1997 that was recorded in 2018 (Blunden and Arndt, 2019) relates to the wet conditions induced by the weak La Niña/neutral pattern early in the year. However, years such as these, marked by increased precipitation and flood events lead to higher biomass production and thus to a higher availability of fuel to burn in the following years (Schmidt and Eloy, 2020).

Large BA totals are found in parts of MATOPIBA, where most of the Cerrado native vegetation remains. This region has been experiencing high rates of deforestation and land conversion to agriculture and pasture (Spera et al., 2016), in which fire is widely used as an inexpensive and effective tool (Reddington et al., 2015; Zalles et al., 2019). Currently, 48% of Brazil's total soybean production comes from the Cerrado, and almost a quarter of this production area is located in MATOPIBA, mainly in the plateaus of the Chapadão do São Francisco and Alto Parnaíba (Sano et al., 2020). Unlike in Amazon where the Soy Moratorium between producers and the government prohibits the trading of soybean grown on recently deforested lands (Soterroni et al., 2019), the last undisturbed remnants of MATOPIBA are not protected by a consistent agreement but are indeed the target of governmental incentives for deforestation (Pitta et al., 2017). Within the study period, around 10% of the area of these two ecoregions burned annually (Fig. 2a) and an increase in fire activity and ecosystem disturbance is expected with further agricultural expansion in MATOPIBA (Soterroni et al., 2019). For instance, Depressão Cárstica do São Francisco, Chapadão do São Francisco and Parnaguá, three eastern ecoregions partly located in MATOPIBA, also show high fire intensities, and are considered at risk of very extensive land conversion between 2021 and 2050 (Soterroni et al., 2019). Partly located in MATOPIBA, Araguaia Tocantins is the highest contributing ecoregion to the Cerrado total BA (Fig. 2b). This ecoregion encompasses both the Xerente Indigenous Land, Jalapão State Park and most of the Serra Geral do Tocantins protected area, lands that had high fire activity until the implementation of a pilot project for integrated fire management in 2015 (Falleiro et al., 2016; Schmidt et al., 2016), and preliminary results point to a change of spatial fire patterns in some conservation units (Mistry et al., 2019).

However, the fire management program is restricted to protected areas, possibly limiting its impacts on fire patterns at the regional level. With low fire intensity and negligible BA that averages about 18 km^2 per year in the study period, Costeiro is an exception to the overall ecological and economical context of MATOPIBA (Table S1). This ecoregion is covered by sand dunes and low density of vegetation, which virtually does not burn (Françoso et al., 2015).

With intense fires and particularly high fire incidence, and with large extents of its area burning annually, Bananal is practically all within the Araguaia National Park and Indigenous Land. This ecoregion has the highest percentage of protected areas (46.3%) and of extremely high priority areas (26.8%) of all Cerrado ecoregions (Sano et al., 2019), an important feature since fire occurrence in these areas involves a complex dynamics of ownership land conflicts. Chapada dos Parecis, an ecoregion located within the Arc of Deforestation has recurrent, intense fires and displays the maximum recorded value of fire intensity in a single event. This ecoregion has high spatial discrepancies with large extents of savanna and forest in its western region (Gomes et al., 2018) and high anthropogenic use in the eastern region (Marques et al., 2020), especially due to soybean expansion in Mato Grosso state. Chapada dos Parecis and Alto Parnaíba show significant fire activity in March, most likely related to soil preparation for planting crops. Given that these fires occur during the Cerrado wet season (November to May), the scarce fuel after vegetation conversion and high relative humidity do not allow high intensity fires.

A very distinct picture is found in most of the southern ecoregions, with lower contributions to the BA in the Cerrado, smaller scars with low FRP values, associated with extensive areas of agriculture and pastures. Basaltos do Paraná and Paraná Guimarães show predominantly small fire scars: these are heavily deforested ecoregions where fire is mainly used for agricultural management. Large fire scars in these ecoregions are found within Indigenous Lands (Daldegan et al., 2019), where extensive areas of native vegetation remain and fire is traditionally used for many practices, including for hunting, for stimulating fructification, for managing biomass accumulation in grasslands, among others (Falleiro et al., 2016). Paraná Guimarães has not been subject to recent agricultural expansion, as it has been widely explored by farmers since the 1960s (Sano et al., 2020), given its highly fertile soils. Similarly, Basaltos do Paraná is a traditional agricultural region where fire is still used for cropland management, especially in already consolidated and historical lands producing sugarcane, soybean and maize (de Andrade et al., 2020; Loarie et al., 2011). Sugarcane production in this ecoregion has been expanding prompted by the biofuels market (Loarie et al., 2011). Many ecoregions in the southern Cerrado show negative BA trends, but increasing fire intensity, suggesting that agricultural activities historically developed in these regions have replaced the native vegetation with croplands and planted pastures, which tend to have small but intense fires in highly fragmented landscapes, unsuitable to the spread of large fires (Magalhães et al., 2020).

Recent advances in agricultural expansion may explain negative BA trends over most ecoregions (Fig. S1a). Fire activity tied to deforestation was high in earlier years. Later, controlled use of fire in agricultural landscapes led to a decrease in BA (de Oliveira et al., 2017; Eloy et al., 2019). Human activity was pinpointed as a driver of long-term global trends in BA (Andela et al., 2019), and similar trends due to land use change were found in the USA, Indonesia, and Australia (Bird et al., 2016; Field et al., 2016; Grégoire et al., 2013; Syphard et al., 2017; Taylor et al., 2016). Our results are also in line with those obtained using data derived from the Global Fire Emissions Database (GFED), where BA is found to be increasing over the north-eastern Cerrado and decreasing in the south (Andela et al., 2017; Chen et al., 2013; Forkel et al., 2019). However, BA trends vary substantially when the analysis is stratified by fire scar size. The observed distinct trends among fire size classes depend on regional underlying controls, such as local climate, population density, urban-rural interface, and fire management practices (Forkel et al., 2019; Hantson et al., 2015). Large scars occur mainly in northern ecoregions and in transitional areas between biomes, marked by high deforestation rates and land conversion, such as the Arc of Deforestation and MATOPIBA. In the northern ecoregions, the landscape is less fragmented and land clearing has intensified since 2002 as croplands expanded to MATOPIBA.

It may be argued that ecoregional differences in fire size and fire seasonality patterns should be also viewed in light of the recent paradigm shift from a no-fire policy (Durigan and Ratter, 2016) to an Integrated Fire Management program (IFM), that is occurring in the Cerrado (Schmidt et al., 2018). However, according to the National Center for the Prevention and Fighting of Forest Fires - PREVFOGO, less than 125, 000 km^2 are under IFM, therefore these changes are likely not enough to generate changes in fire patterns in any of the ecoregions.

4.2. Fire in the context of the ecoregional map and limitations

The proposed stratification of ecoregions into fire classes is especially pertinent, given the number and substantial variability of ecosystem types within Cerrado. The nine distinct combinations of fire characteristics obtained, namely Hbm, Hbh, Mbm, Mbh, Mbl, Msm, Lbm, Lbh and Lsl, reflect the natural constraints in the types of fire patterns present (Archibald et al., 2013). Large extensions of BA (Hbm, Hbh) are distributed over central-northern ecoregions, which currently concentrate most of the remnants of native Cerrado vegetation, and have been under high anthropogenic pressure (Alencar et al., 2020). Systematic fire activity, as seen in these regions during 2001–2019, may severely disrupt ecosystem functions. Conversely, ecoregions with low amounts of BA (Lbm, Lbh and Lsl) are located along the eastern and south-eastern portions of the biome, which have a longer history of land use. South-eastern ecoregions have considerably less native vegetation cover, a high level of landscape fragmentation and less land susceptible to burn (Souza et al., 2020). In the central-eastern Cerrado several ecoregions featuring high values of BA are side by side with others displaying low values, under very distinct regional contexts: Depressão Cárstica de São Francisco (Lbh) concentrates small landholder parcels dedicated to cattle ranching and subsistence farming and has distinct socio-economics characteristics compared to Chapadão do São Francisco (Hbh), an ecoregion dominated by commodity-driven and large-scale farms (IMAFLORA, 2018). Ecoregions with moderate BA (Mbm, Mbh, Mbl and Msm) have relatively more recent economic development (Rosa et al., 2016) and exhibit high deforestation rates from 2000 to 2008 (PPCDAm and PPCerrado, 2020). Basaltos do Paraná is an exception to that pattern, given that it is a traditional agricultural region with high landscape fragmentation that prevents the spread of large fires. Interestingly, Basaltos do Paraná and Floresta de Cocais, which have very distinct regional contexts, share the same fire classification (Msm). However, Floresta de Cocais is characterized by medium NBA values and an increasing BA trend, because it is an area of agricultural expansion in MATOPIBA (Araújo et al., 2019).

It's worth noting that when evaluating fire activity within ecoregions, we are driving our classification by biophysical parameters that ensure similar ecosystem types, and not by clusters of similar fire characteristics. This assumes homogeneity within ecoregions that vary significantly in size, and may mask patterns within. Sano's ecoregions have been defined based on rainfall patterns, topography and land cover, variables that have been shown to closely relate to fire activity (Libonati et al., 2015; Silva et al., 2019; Pausas and Ribeiro, 2013; Bowman et al., 2020), and thus we believe the assumption of similar fire features within ecoregions to be reasonable. Nevertheless, a proper evaluation of these drivers and of regional fire regimes in Cerrado would require that fire features drive the classification, which may or may not correspond to the ecoregional map. This, however, is beyond the scope of this work, which aimed to assess fire in the context of predefined Cerrado ecoregions.

5. Final remarks

We stratified the temporal and spatial characteristics of fire patterns in the ecoregions of Cerrado into nine classes of fire activity and added this information to the ecoregional map of Cerrado. Information includes the main components of fire activity, namely BA, fire intensity and fire size in regions with homogeneous biophysical and anthropogenic characteristics. An innovative approach classifying fire scars into distinct size classes revealed a diversity of fire patterns previously masked by generalized analysis, providing crucial and novel insights into the regional understanding of fire activity. By highlighting the differences in fire activity among the ecoregions and per fire size, our approach will be of use for decision-makers when planning locally-sensitive fire management and emergency actions, and when designing strategies to reduce emissions without compromising local biodiversity.

Although restricted to a period of 19 years due to satellite data availability, our analysis provides critical insights into regional fire activity in the Cerrado biome, at a time when both climate and land use are steadily changing. This is a crucial aspect, since fire activity in the Cerrado is closely linked to regional climate patterns (Libonati et al., 2015; Silva et al., 2019), and the biome is expected to become drier (Blázquez and Silvina, 2020) and warmer (Feron et al., 2019), further promoting conditions favourable to increased fire activity (Le Page et al., 2017). Fire seasons are also expected to expand (Flannigan et al., 2013) and fire danger may reach critical values much more frequently (Silva et al., 2016). Under these scenarios, disruptions in the historical fire regime may lead to an increase in BA over the Cerrado (Silva et al., 2019), with substantial and possibly irreversible consequences, including changes in ecological community composition (Krawchuk et al., 2009) and biome distribution (Lapola et al., 2009; Oyama and Nobre, 2003).

Considering ongoing and expected future agricultural expansion, particularly in MATOPIBA, consistent and robust environmental strategies are urgently needed to prevent further degradation of the Cerrado (Lahsen et al., 2016) and ensure the protection of native vegetation remnants (Soterroni et al., 2019). Thus, since neither climate nor the socioeconomic conditions in the Cerrado biome are expected to remain stable in the future, fire patterns are very likely to continue changing. Further research on realistic and adequate representation of fire patterns at a regional level is necessary to improve understanding of how the Cerrado ecosystems may respond to future changes.

Credit author statement

PSS, JAR, RL and CCD conceived and designed the study; PSS, JAR and FLMS performed the data analysis; PSS, RL, JAR and FLMS analysed the data; PSS, JN and RL wrote the paper; JMCP, CCD, GAD, AAP, LFP, IBS, JN and RL contributed to discussion; all authors revised the paper.

Funding

This work was developed under the scope of the Project Andura [CNPq grant number 441971/2018–0]; P.S.S. was supported by Fundação para a Ciência e a Tecnologia (FCT) [grant number SFRH/BD/146646/2019]; J.N. was supported by 'Women in Research'-fellowship program, Westfälische Wilhelms-Universität Münster (WWU Münster); J.A.R. was supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) [grant number 380779/2019–6]; F.LM.S. was early supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) [grant number 381461/2018–1] and is financed by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001 [grant number 88887.498119/2020–00]; I.B.S. was supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) [grant number 441951/2018–0]; R.L. was supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) [grant number 305159/2018–6] and FAPERJ [grant number E26/202.714/2019]; and FCT supports CEF [project UIDB/00239/2020] and IDL [project UIDB/50019/2020].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank Niels Andela for providing Global Fire Atlas data from 2017 to 2018, and Edson E. Sano for Cerrado ecoregion shapefiles. The authors would also like to thank the 5 anonymous reviewers for their insightful comments that contributed to improve the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.113098.

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