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The climatic patterns that control regional fire activity in the Brazilian savanna

Patrícia S. Silva [a,b,c,*], Renata Libonati [b,a], Luiz G. Gonçalves [d], Carlos C. DaCamara [a]

[a] IDL - Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal
[b] Departamento de Meteorologia, Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brazil
[c] Yale School of the Environment, Yale University, New Haven, Connecticut, USA
[d] Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio), Brazil

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ABSTRACT

Fire activity in the Brazilian savanna (Cerrado) is heavily constrained by climate, however the climate patterns that lead to extreme fire seasons are not yet well understood. Climate conditions during the fire season determine fire weather, but climate patterns prior to the fire season months may also modulate fuel availability and condition. In the context of a changing climate, understanding the climatic patterns that lead to extreme fire events, and their mediating factors, is crucial to build resilient landscapes and inform decision-making. In this study, we propose to uncover the nature of these relationships for Cerrado. We evaluate the regional temperature and precipitation patterns that lead to severe and mild fire seasons for each of the 19 ecoregions of Cerrado. We identify two periods that show contrasting behaviours in both extremes: the concurrent climate conditions during the fire season months (August to October) and pre-conditions during the austral autumn (March to May). Despite noteworthy regional discrepancies, in general we find that severe fire seasons are preceded by hot and dry conditions during autumn and associated with hot and dry conditions during the fire season months. Mild fire seasons see the opposite pattern, with colder and wetter conditions both during and prior to the fire season. We further investigate the influence of these climatic patterns in extreme fire activity for each month of the fire season and find that, over most ecoregions, early fire season burned areas are influenced by pre-conditions during autumn, whereas late fire season burned areas rely on concurrent favourable meteorological conditions. These results contribute to the understanding of the regional fire-climate dynamics of the second largest biome in South America and provide a starting point for regional fire outlooks. We further provide regionally tailored information that, considering recent Brazilian policies, may prove useful for fire management.

1. Introduction

Climate is one of the main drivers of fire activity worldwide (Bedia et al., 2015; Jones et al., 2022). Weather conditions favourable to fire, commonly referred to as fire weather conditions, generally include high air temperatures, low soil moisture and air humidity, accompanied by strong winds, that provide appropriate conditions for fires to occur and spread (Aldersley et al., 2011; IPCC, 2021). The single or concurrent occurrence of extreme events, such as droughts and heatwaves (Zscheischler and Seneviratne, 2017), is also linked with severe fire seasons, such as the Pantanal 2020 fires (Libonati et al., 2022a, 2022b) or the Australian 2019/2020 bushfires (Abram et al., 2021; Squire et al., 2021). Additionally, climate modulates fuel amount and availability through direct and indirect effects on vegetation (Krawchuk and Moritz, 2011; Pausas and Ribeiro, 2013).

Within the Brazilian Cerrado, fire is a crucial feature. This savanna-like landscape covers 2 million km^2 and is the largest contributor to Brazil's and South America's annual burned area (Bilbao et al., 2020; UNEP, 2022). As a fire-dependent biome, Cerrado relies on its natural fire regime to maintain the ecosystem's functioning and structure (Pivello et al., 2021) and has been shown to sustain high pyrodiversity (Silva et al., 2021). Biome-wide studies point out that interannual burned area variability in Cerrado can be explained through precipitation (Libonati et al., 2015) and fire danger indexes (Li et al., 2021; Nogueira et al., 2017; Silva et al., 2019). However, this may not be the case at the smaller scales, as local studies have found that the climatic

* Corresponding author.
E-mail address: patricia.silva@yale.edu (P.S. Silva).

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drivers of fire highly depend on regional context. Large fires in Cerrado have been associated with high wind speeds and compound hot-dry conditions, with considerable discrepancies in the importance of these drivers regionally (Li et al., 2022; Libonati et al., 2022b). Vapour pressure deficit (VPD) is the main driver of fire spread and fire intensity in Cerrado's grasslands, forests and savanna regions (Gomes et al., 2020), whereas burned areas in mountainous regions, have been shown to be sparsely correlated with concurrent precipitation but better explained by drought during the dry season (Alvarado et al., 2017). Similarly, Conciani et al. (2021) found that, for three protected areas within Cerrado, precipitation did not explain the interannual variability of burned areas but, when considering human factors such as land use management and agropastoral activities, the variance explained increased substantially.

Recently, Segura-Garcia et al. (2024) showed that fire-climate relationships in Cerrado are modulated by human occupation. These relationships become increasingly complex when considering regions with high anthropogenic activity, such as the Arc of Deforestation and Brazil's latest agricultural frontier, MATOPIBA, the confluence of states Maranhão (MA), Tocantins (TO), Piauí (PI), and Bahia (BA). In the Upper Xingu basin, stretching across the Arc of Deforestation, the concurrence of air dryness and low precipitation drives fire occurrence (Ribeiro et al., 2022). In the state of Tocantins, de Andrade et al. (2021) have shown that burned areas are positively correlated with the duration of the dry season and negatively correlated with total rainfall, while Santana et al. (2020) pointed out that the synergies between fire recurrence in the Araguaia National Park and biophysical variables, including the enhanced vegetation index (EVI), gross primary production (GPP), and land surface temperature (LST), strongly depend on land cover type. Silva et al. (2020) found that, while a fire danger index explains 52 % of interannual variability of the total burned area in MATOPIBA, the relationship between the fire danger index and regional burned area varied greatly when considering MATOPIBA's 41 microregions.

Although the currently available literature on the climatic drivers of fire in Cerrado hints at complex relationships with high geographical variation, a comprehensive study on the regional climate controls of fire activity is still lacking. In this study, the goal is understanding the climate conditions that characterize extreme fire seasons and how they differ throughout Cerrado's 19 ecoregions. As per other studies (e.g. Abram et al., 2021; Pereira et al., 2013), we expect that climate conditions prior to the fire season play a role in modulating fire season burned areas due to its effect on vegetation (and thus fuel loads available to burn). Furthermore, we hypothesize that the importance of this pre-conditioned climate may vary per region and by month of the fire season. To explore these hypotheses, we compute the climate anomalies associated with mild and severe fire seasons and then dive on the specific climate patterns that influence each month of the fire season.

2. Data and methods

2.1. Study area

We partition Cerrado into 19 ecoregions as proposed by Sano et al. (2019). These ecoregions are unique in terms of landscape characteristics and were defined based on their physical attributes (elevation, rainfall, and soil), land use types, land cover classes and conservation status (protected areas and indigenous territories). The physical attributes, chosen due to their considerable influence on the composition and production of ecosystems (Sano et al., 2019), intend to reflect ecological differences amongst ecoregions.

Silva et al. (2021) studied fire behaviours within each ecoregion using several fire parameters (e.g. burned area, fire intensity, and size of individual fire events), and further updated the ecoregional map with regional fire characteristics. For the purposes of this study, we restricted to ecoregions that burn regularly. As such, the five ecoregions classified as low-burned areas in Silva et al. (2021) (namely, Alto São Francisco, Depressão Cárstica do São Francisco, Jequitinhonha, Paracatu, and Costeiro) were not considered in the present study.

We further categorize ecoregions based on geographical location into one of five classes (Fig. 1): North; Central-West (hereafter Central-W); Central-East (Central-E); West; and South.

2.2. Datasets and pre-processing

Burned area was obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) MCD64A1 Collection 6.1 product (Giglio et al., 2018), for the 2001–2023 period. Using the Fuoco server from the University of Maryland, the Win05–07 tiles were merged to obtain data for South America. Data were then reassigned to a binary classification according to unburnt/burnt pixels. Monthly and yearly sums of burned areas at 500-meter spatial resolution were computed over each ecoregion. The MODIS MCD64A1 product is known to perform well over the Brazilian savanna, but uncertainties are larger in southern Cerrado due to the prevalence of smaller and scattered fire scars (Campagnolo et al., 2021; Rodrigues et al., 2019).

Daily surface temperature at 16:00 UTC and hourly total precipitation were downloaded from the European Centre for Medium-Range Weather Forecasts' (ECMWF) ERA5 reanalysis (Hersbach et al., 2020), at a $0.25^\circ \times 0.25^\circ$ spatial resolution for the 2001–2023 period. Daily precipitation totals were computed. All data was masked per each ecoregion and spatial means were computed.

2.3. Methods

2.3.1. Composite analysis of extreme years

The fire season in Cerrado is fairly constant throughout ecoregions, with most annual burned area occurring during the austral winter from August to October (Silva et al., 2021). The annual fire regime is therefore heavily constrained by fires in this period. Accordingly, this study focuses on extreme fire seasons, defined as the months of August, September, and October (ASO).

To analyse the climatic conditions that lead to extreme fire season years, we followed the approach proposed by Pereira et al. (2013). We obtained, for each ecoregion, the top(bottom) burned area years, defined as those above (below) the 75^{th} (25^{th}) percentile of fire season burned areas over 2001–2023, henceforth referred to as severe(mild) fire years. Severe and mild fire years per ecoregion are shown in Fig. S1.

A composite analysis was performed to compare climatic conditions associated to severe and mild years. Composites consist of monthly averages over the years that define the severe and mild classes, per ecoregion, and composite anomalies are computed by subtracting the monthly average of the full time series (2001–2023). This analysis allowed to pinpoint two 3-month periods that may, to some extent, influence burned areas during the fire season: pre-conditions during the austral autumn (defined as March, April, and May; MAM); and the concurrent conditions of the fire season (ASO). Seasonal means (accumulated values) of temperature (precipitation) were estimated for these two periods, and composite anomalies computed in a similar manner to that previously explained. Standardized anomalies were also estimated by further dividing the composite anomalies by the corresponding standard deviation.

A similar procedure was employed to study the climatic conditions associated with severe/mild fire years per month of the fire season (ASO). For each month (August, September, and October), severe and mild fire years were defined in the same way as previously described for the fire season: by means of the 75^{th} (severe) and 25^{th} (mild) percentiles of the 2001–2023 time series (shown in Fig. S1). We further compute seasonal means (cumulative sums) of temperature (precipitation) during the austral autumn (MAM) to assess the influence of pre-conditioned climate on severe/mild burned areas of each month of the fire season and use the corresponding monthly mean (sum) of temperature

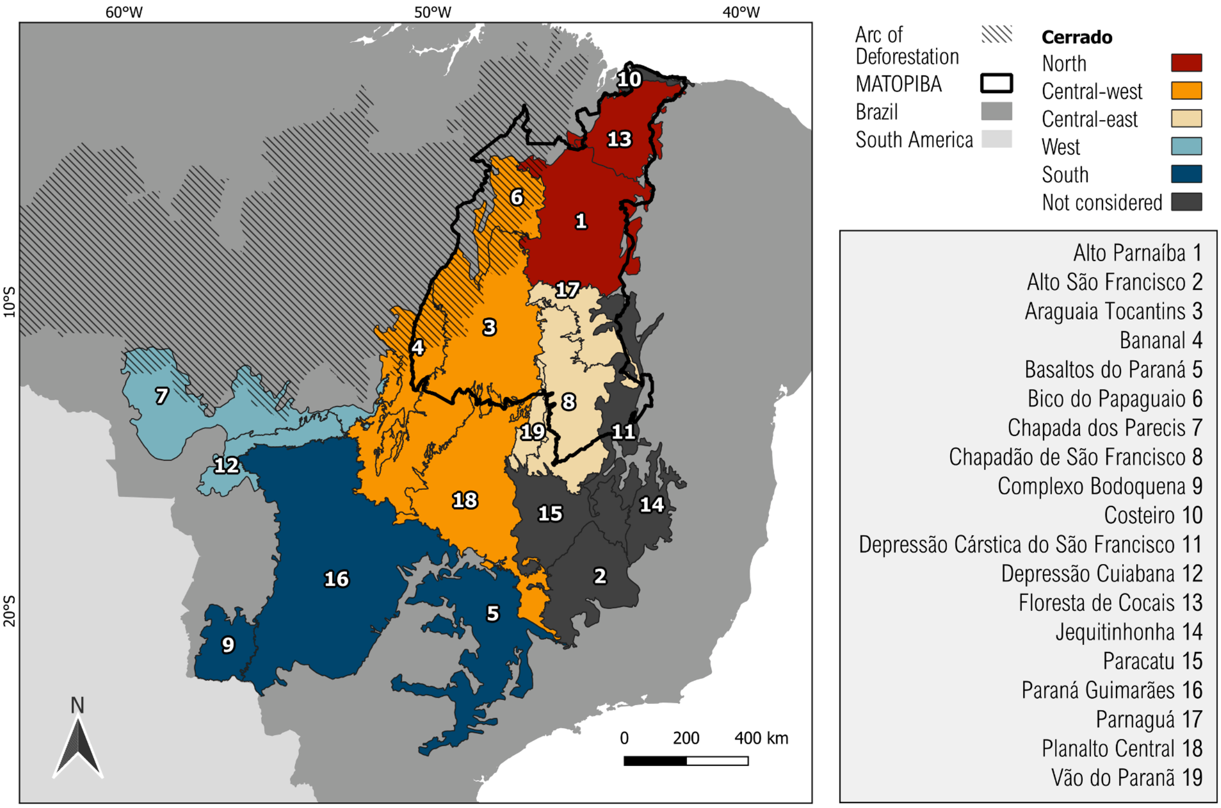

Fig. 1. Cerrado's location within Brazil (dark grey) and South America (light grey). The transition zone between the Cerrado and Amazon biomes, the Arc of Deforestation, is hatched and MATOPIBA, defined here as the intersection of states Maranhão, Tocantins, Piauí and Bahia, with Cerrado, is marked by a solid black line. Cerrado's 19 ecoregions (Sano et al., 2019) are shown and numbered, with the respective names listed in the column on the right. Cerrado's ecoregions are further categorized into 5 classes based on their geographical location within Cerrado: north (red); central-west (orange); central-east (yellow); west (light blue); and south (dark blue). Finally, ecoregions not considered in this study are numbered but shown in dark grey.

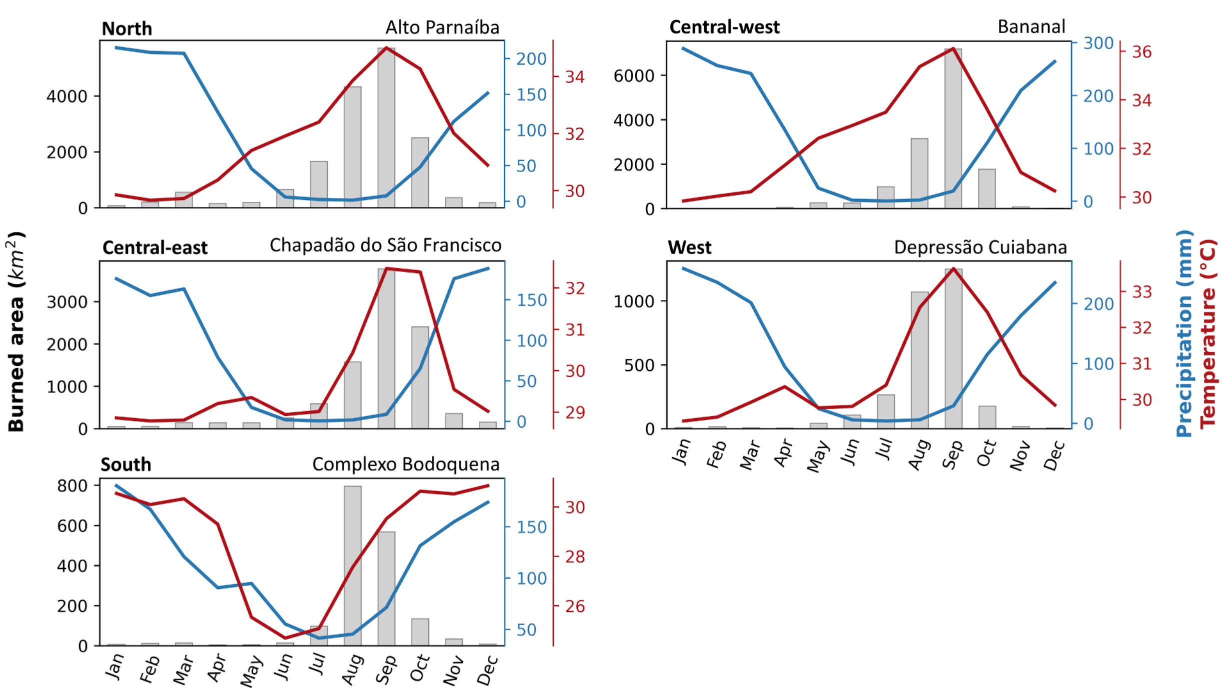

Fig. 2. Illustrative examples for regional seasonal cycles of burned area (left-hand axis in black pertaining to the grey bars, km^2), precipitation (right-hand axis in blue pertaining to the blue curve, mm) and temperature (right-hand axis in red pertaining to the red curve,°C) for the five geographical classes (North, Central-west, Central-east, West and South; according to Fig. 1). Values represent an average of monthly burned area and precipitation(temperature) totals(averages) over the 2001–2023 period.

(precipitation) to evaluate the influence of concurrent climate conditions.

2.3.2. Modelling regional fire-climate relationships

We investigated the regional relationship between fire and climate in each ecoregion through linear models that predict burned area (BA):

$$BA = \beta_0 + \beta_1 C_1 + \beta_2 C_2 + \varepsilon \quad (1)$$

where ε is the error of the regression, BA is the predictand, C_1 and C_2 are the two predictors (standardized values of either temperature or precipitation), that respectively represent concurrent conditions during the fire season (ASO) and pre-conditions during the austral autumn (MAM), and β_0, β_1, and β_2 are the regression coefficients. The significance of each predictor was evaluated through the corresponding p-values and considered significant if below the 5 % confidence level. The adjusted coefficient of determination (R^2) provided the total variance explained by the model. Regression models given by (1) were also used to model annual values of burned area in each individual month of the fire season (months of August, September, and October).

The Variance Inflation Factor (VIF) was computed to measure multicollinearity amongst predictors (Tables S1 to S4), with VIF values above 5 requiring re-assessment of predictors (Montgomery et al., 2012).

3. Results

3.1. Ecoregional climate and burned area patterns

Temperature and precipitation patterns vary considerably within ecoregions according to the vast latitudinal extent of the Cerrado (Fig. 2). Nevertheless, while the annual cycle of precipitation is somewhat similar throughout the Cerrado, there are distinct regional temperature patterns.

With the exception of Planalto Central, northern (Alto Parnaíba and Floresta de Cocais) and central-western (Araguaia Tocantins, Bananal, and Bico do Papagaio) ecoregions have unimodal annual cycles of temperature, growing steadily from April to September, when the annual maxima are reached. On the other hand, Planalto Central (central-west), much like central-eastern ecoregions (Chapadão do São Francisco, Parnaguá, and Vão do Paraná), experiences abrupt temperature increases from July onwards, reaching the annual maxima around September. These ecoregions, along with Depressão Cuiabana (west), also show a bimodal temperature distribution, with a secondary peak around April and May. Lastly, southern ecoregions present a unimodal cycle that is substantially different from that of northern and central-western ecoregions, with annual maxima from September to March, and a sudden drop in monthly temperatures from April to August.

Albeit with slight spatial discrepancies, Cerrado shows a marked dry season that spans from May to September. With the exception of southern ecoregions (Basaltos do Paraná, Paraná Guimarães, and Complexo Bodoquena) that see rainfall throughout the entire year, the austral winter months of June, July, and August, have virtually zero precipitation. Nevertheless, Floresta de Cocais, the northernmost ecoregion, shows a different annual precipitation cycle as its dry season seems to start later in August and last until November, peaking during March.

In general, the majority of burned areas occur during the months of August, September, and October (ASO). The fire season represents 51 to 92 % of annual burned areas in Cerrado's ecoregions. With the exception of Basaltos do Paraná (57 %) and Chapada dos Parecis (51 %), fire season (ASO) burned areas represent at least two-thirds of annual burned areas. Peaks in burned area occur in September for all ecoregions, with the exceptions of Complexo Bodoquena and Chapada dos Parecis, which see a peak in burned area one month earlier in August, and Bico do Papagaio, which sees a burned area peak one month later in October.

The interannual variability of yearly and fire season amounts of burned area per ecoregion is shown in Supplementary Material Fig. S3. Although extreme years vary greatly amongst ecoregions, there are noteworthy temporal and spatial patterns. The years 2007 and 2010 are marked as severe for all ecoregions considered, except for 2010 in Complexo Bodoquena. Ecoregions located in northern and central Cerrado all show 2012 as a severe year, whereas central-eastern ecoregions have 2010, 2011 and 2012 in common as severe fire years.

3.2. Identifying the climatic patterns of extreme fire seasons

Monthly anomalies for extreme fire-year composites find contrasting patterns in both temperature and precipitation in two distinct 3-month periods (Fig. S4): the austral autumn (MAM) representing preconditions; and the concurrent conditions of the fire season (ASO). Fig. 3 summarizes the temperature and precipitation anomalies during both these periods for severe and mild fire seasons.

During autumn (MAM), with the exception of Bico do Papagaio, all northern and central-western ecoregions show very distinct temperature anomalies, where severe (mild) fire seasons are marked by positive (negative) temperature anomalies. The remaining ecoregions show very low standardized temperature anomalies of the same signal, with the exception of the southern ecoregion Paraná Guimarães. Standardized temperature anomalies are higher in central-western ecoregions, namely Araguaia Tocantins, Bananal, and Planalto Central, along with Floresta de Cocais (north) and Depressão Cuiabana (west). Conversely, all ecoregions have contrasting behaviours in precipitation anomalies: severe (mild) fire seasons are associated with negative (positive) precipitation anomalies. Vão do Paranã (central-east) is the sole exception, with negative precipitation anomalies for both severe and mild fire seasons. Standardized anomalies are higher in western ecoregions, and Paraná Guimarães (south).

During the fire season (ASO), there are contrasting temperature and precipitation patterns for northern, central-western, and southern ecoregions: severe (mild) fire seasons are associated with positive (negative) temperature anomalies and negative (positive) precipitation anomalies. On the other hand, central-eastern ecoregions have very low standardized and absolute temperature anomalies during this period and often of the same signal. Regarding precipitation, central-eastern ecoregions show contrasting anomalies, with negative (positive) anomalies for severe (mild) fire seasons, where standardized anomalies for mild fire seasons are relatively high and standardized anomalies for severe fire seasons are very low. In the case of western ecoregions, Chapada dos Parecis and Depressão Cuiabana have very distinct climate patterns during the fire season (ASO): Chapada dos Parecis has very low standardized anomalies for both temperature and precipitation, and negative precipitation anomalies for both severe and mild fire seasons; on the other hand, Depressão Cuiabana has contrasting patterns for both temperature and precipitation, where severe (mild) fire seasons are associated with positive (negative) temperature anomalies and negative (positive) precipitation anomalies.

The strength of the relationship between yearly values of temperature and precipitation and yearly fire season burned areas is assessed by fitting bivariate linear models using temperature or precipitation values over the austral autumn (MAM) and the fire season (ASO) as predictors of annual fire season (ASO) burned areas (Table 1; Table S1).

The strength of these relationships varies greatly among Cerrado's ecoregions, with adjusted R^2 values ranging from 0.05 to 0.60 for temperature and from 0.07 to 0.41 for precipitation (Table 1). In general, temperature models perform best for northern and central-western ecoregions, whereas precipitation models achieve higher coefficients of determination for northern and western ecoregions.

In the case of temperature models, pre-conditions during autumn (MAM) are significant for only three ecoregions: Alto Parnaíba (north), Araguaia Tocantins (central-west), and Planalto Central (central-west).

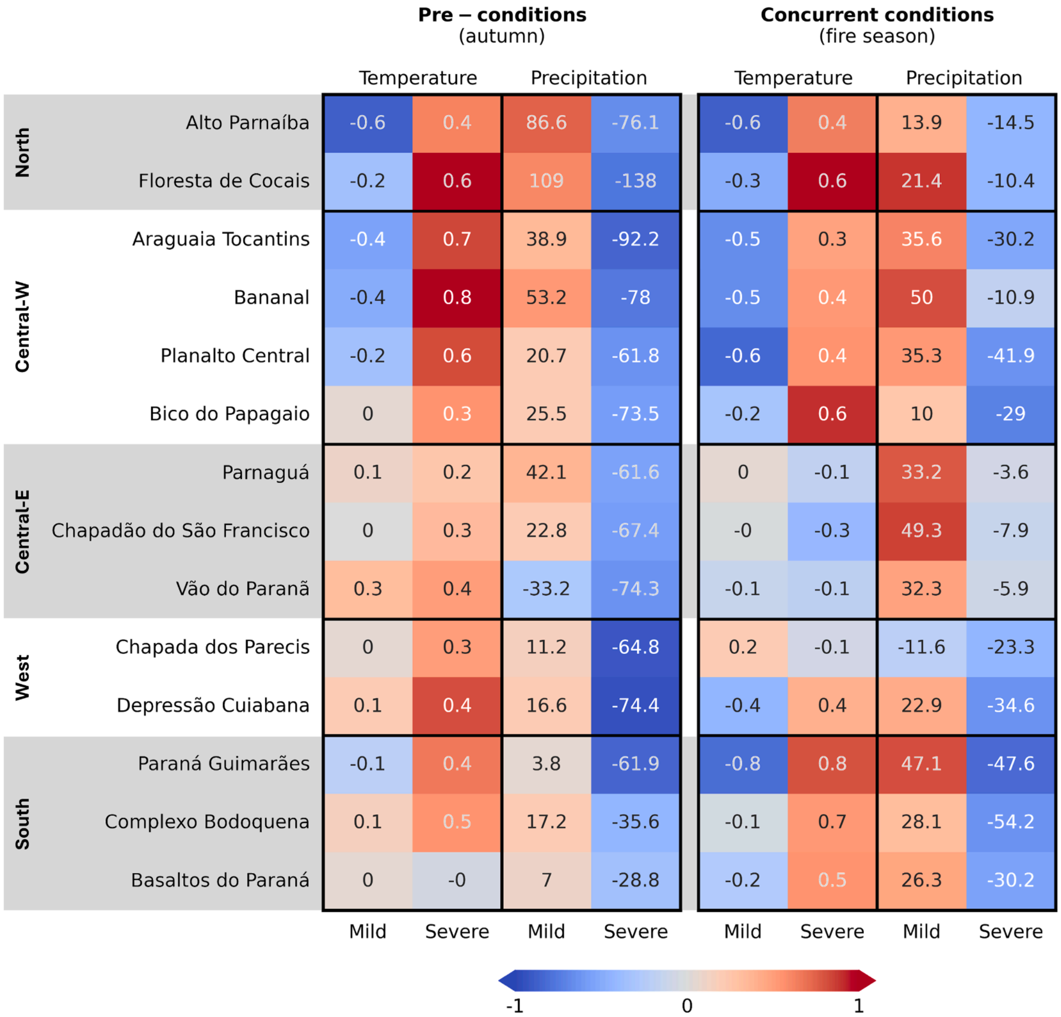

Fig. 3. Seasonal anomalies of temperature and precipitation for composites of extreme years along Cerrado's ecoregions for pre-conditions (autumn - MAM) and the concurrent conditions (fire season - ASO). Colours(numbers) represent standardized(absolute) anomalies of temperature (T,°C) and precipitation (P, mm). Anomalies are in respect to seasonal averaged temperatures and aggregated precipitation over the considered periods. Ecoregions are categorized geographically, according to Fig. 1: north, central-west (Central-W), central-east (Central-E), west, and south.

In turn, concurrent conditions during the fire season (ASO) are significant in three ecoregions: Floresta de Cocais (north), Bananal (central-west), and Planalto Central (central-west). Planalto Central is therefore the sole ecoregion where both predictors are significant but, as suggested by the standardized regression coefficients (Table S1), pre-conditions during autumn (MAM) have a slightly larger impact in yearly burned areas than concurrent temperatures during the fire season (ASO).

For precipitation models, in all northern and western ecoregions, along with Complexo Bodoquena (south), pre-conditions in autumn (MAM) are significant when modelling yearly fire season burned areas. Conversely, only Complexo Bodoquena achieves significance for concurrent rainfall during the fire season (ASO) and both predictors seem to translate in a similar amount of yearly burned area (Table S1).

3.3. The influence of seasonal climatic patterns on each month of the fire season

Given the lack of significance of pre-conditions during autumn (MAM) in modelling yearly fire season burned areas, and the contrasting patterns found for this period in the composite analysis, we investigated whether evaluating the entirety of the fire season could mask distinct monthly controls. Accordingly, we performed the same analysis, but using instead severe and mild composites of: August burned areas; September burned areas; and October burned areas. We then evaluated temperature and precipitation for pre-conditions during autumn (MAM) and the concurrent conditions of each month. Fig. 4 shows temperature and precipitation anomalies for pre-conditions during autumn (MAM) and concurrent conditions of each month (either August, September, or October) for composites of severe and mild years of each month of the fire season (either August, September, or October; see Methods).

Severe (mild) Augusts are in general associated with positive (negative) temperature anomalies and negative (positive) precipitation anomalies during autumn (MAM). Only four ecoregions show no contrast during autumn (MAM) between severe and mild Augusts, namely: Chapada dos Parecis (west), Complexo Bodoquena (south), and Basaltos do Paraná (south), in the case of temperature; and Vão do Paranã (central-east) and Basaltos do Paraná (south), in the case of precipitation. Severe (mild) Augusts are also associated with concurrent negative (positive) rainfall anomalies. Concurrent temperature anomalies do not present a consistent behaviour, with only southern and central-western ecoregions (excepting Planalto Central), and Floresta de Cocais (north), showing positive (negative) temperature anomalies for severe (mild) Augusts. The remaining ecoregions either show the opposite pattern with negative (positive) temperature anomalies for severe (mild) Augusts or there is no contrasting behaviour between August extremes.

In general, severe (mild) Septembers are marked by positive

Table 1
Bivariate linear models of annual Fire season (ASO), August, September, and October burned areas using temperature and precipitation. Goodness-of-fit is evaluated through the Adjusted R^2 (titled as R^2 in the table columns). Columns β_1 and β_2 correspond to the significance of regression coefficients associated with concurrent conditions of the evaluated period and pre-conditions during autumn (MAM), respectively, where a full dot denotes significant relationships below the 5 % level and the circle denotes relationships below the 10 % level. Ecoregions are categorized geographically, according to Fig. 1: north, central-west (Central-W), central-east (Central-E), west, and south.

		Fire season (ASO)						August						September						October					
		Temperature			Precipitation			Temperature			Precipitation			Temperature			Precipitation			Temperature			Precipitation		
		R^2	β_1	β_2	R^2	β_1	β_2	R^2	β_1	β_2	R^2	β_1	β_2	R^2	β_1	β_2	R^2	β_1	β_2	R^2	β_1	β_2	R^2	β_1	β_2
North	Alto Parnaíba	0.31		●	0.35		●	0.47	●	●	0.39	○	●	0.30		●	0.50	●	●	0.70	●		0.49	●	
	Floresta de Cocais	0.60	●		0.41	○	●	0.36	○		0.29		○	0.51		●	0.50	●	●	0.51	●		0.34	○	●
Central-W	Araguaia Tocantins	0.35		●	0.21			0.55	○	●	0.46	●	●	0.35	○	●	0.23			0.60	●		0.35	●	
	Bananal	0.43	●	○	0.22			0.52		●	0.28		●	0.33	●		0.18			0.53	●	○	0.29	●	
	Planalto Central	0.47	●	●	0.24	○		0.34		●	0.30	○	○	0.49	●	●	0.22	○		0.47	●		0.31	●	
	Bico do Papagaio	0.25	○		0.19			0.10			0.22		○	0.43	●		0.26	●		0.62	●		0.16		
Central-E	Parnaguá	0.09			0.14			0.58		●	0.16			0.06			0.39	●	●	0.33	●		0.14		
	Chapadão do São Francisco	0.05			0.17			0.34		○	0.26		●	0.04			0.20			0.51	●		0.50	●	●
	Vão do Paranã	0.08			0.07			0.07			0.08			0.12			0.18	○		0.41	●		0.31	●	
West	Chapada dos Parecis	0.15		○	0.35		●	0.15			0.36	○	●	0.21			0.47	○	●	0.15			0.30		●
	Depressão Cuiabana	0.14			0.39		●	0.03			0.29	○	○	0.28	●		0.59	●	○	0.32	●		0.33		●
South	Paraná Guimarães	0.19	○		0.27			0.08			0.31	●	●	0.34	●		0.34	●		0.33	●		0.22		
	Complexo Bodoquena	0.11			0.32	●	●	0.25			0.29	●	●	0.08			0.12			0.28	●		0.33	●	○
	Basaltos do Paraná	0.13			0.18	○		0.16			0.17	○		0.37	●		0.31	●		0.27	●		0.30	●	

(negative) temperature and negative (positive) precipitation anomalies, during both autumn (MAM) and September. Nevertheless, in autumn (MAM), two southern ecoregions show the opposite temperature pattern, and three other ecoregions, namely Bico do Papagaio (central-west), Vão do Paranã (central-east), and Chapada dos Parecis (west), show no contrasting temperature pattern for both severe and mild Septembers. Likewise, Bananal (central-west) and all southern ecoregions show no contrasting precipitation anomalies for severe and mild Septembers during autumn (MAM). When looking at concurrent temperature and precipitation anomalies, only Chapadão do São Francisco (central-east) shows a distinct pattern, with opposite temperature patterns and no diverging behaviour for severe and mild September in precipitation anomalies.

Lastly, severe and mild Octobers are associated with strong and contrasting concurrent anomalies in both temperature and precipitation. Only Chapada dos Parecis (west) and Paraná Guimarães (south) present no contrasting temperature and precipitation patterns, respectively. Both concurrent temperature and precipitation anomalies seem to be more pronounced for northern and central (both west and east) ecoregions. On the other hand, severe and mild Octobers obtain much lower temperature and precipitation anomalies during autumn (MAM) and three ecoregions do not show contrasting patterns for either climate variable. Nevertheless, the northern and western ecoregions, along with Vão do Paranã (central-east), Paraná Guimarães (south), and Complexo Bodoquena (south), show positive (negative) temperature anomalies and negative (positive) precipitation anomalies for severe (mild) Octobers.

As for the analysis for extreme fire seasons, we fit bivariate linear models that consider the pre-conditions during autumn (MAM) and the concurrent conditions of the evaluated month, for both temperature and precipitation, as predictor of yearly burned areas in each of the months of the fire season: August, September, and October (Table 1).

Models fitted for October burned areas using temperature as predictor achieve coefficients of determination that range from 0.15 to 0.70. Concurrent temperatures in October are significant for all ecoregions excepting Chapada dos Parecis (west), whereas pre-conditions during autumn (MAM) are not significant for any of the evaluated ecoregions. In the case of precipitation models for October, in which explained variance ranges from 0.14 to 0.50, 4 (8) ecoregions show significance for (pre-) concurrent conditions.

Conversely, for temperature models of August and September burned areas, the explained variance is generally lower than that obtained for October burned areas, ranging from 0.07 to 0.58 and 0.04 to 0.51, respectively. Nevertheless, in the case of August (September), 5 (4) ecoregions show pre-conditions during autumn (MAM) as a significant predictor, and 4 (6) ecoregions obtain the same result for concurrent conditions during August (September). Considering precipitation, models fitted for August (September) show coefficients of determination ranging from 0.08 to 0.46 (0.12 to 0.59), and significant regression coefficients for pre-conditions over 7 (4) ecoregions, whereas 3 (7) show concurrent rainfall in August (September) as significant.

4. Discussion

Seasonal precipitation patterns are similar throughout the Cerrado biome, with a marked dry season that peaks during the austral winter from June to August. There are, however, very distinct regional temperature patterns. In agreement with previous studies (Silva et al., 2021), our findings indicate that the vast majority of yearly burned areas occur within a 3-month period from August to October, which has often been considered as Cerrado's fire season. Throughout the vast majority of ecoregions, the fire season coincides with peaks in temperature, and

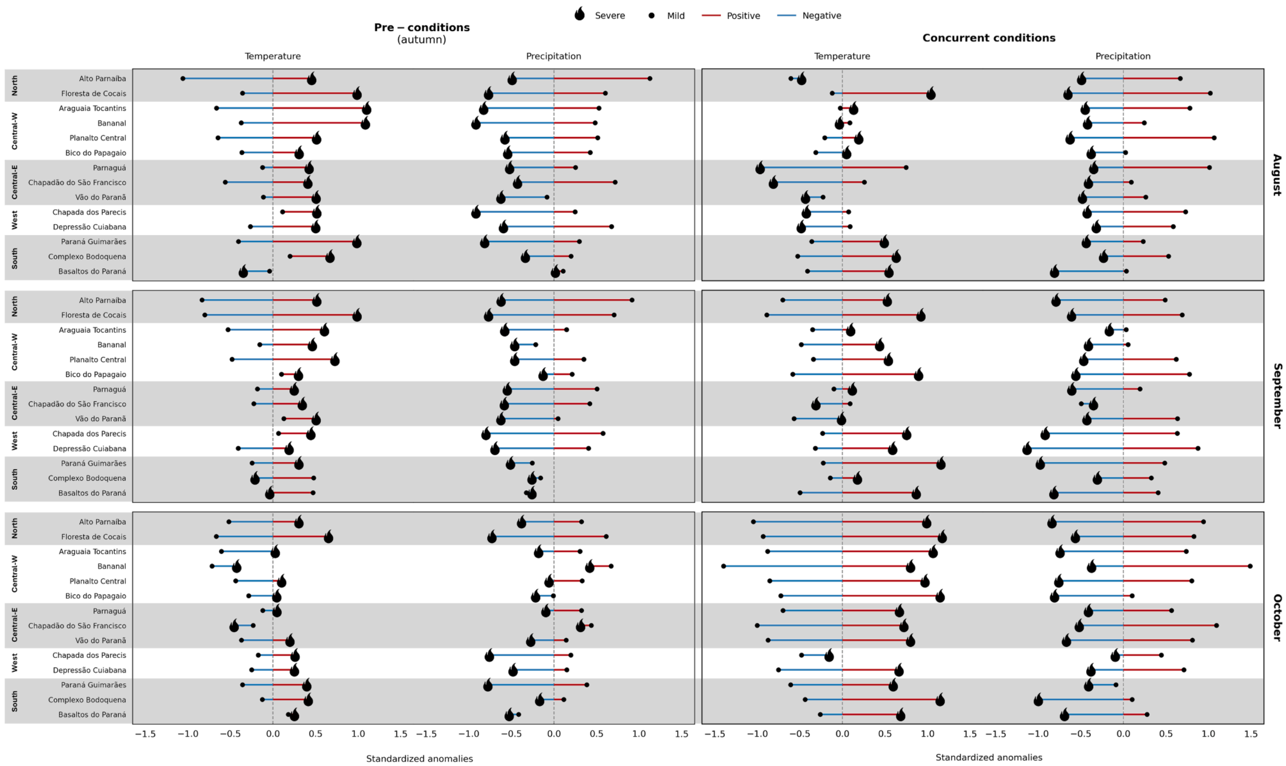

Fig. 4. Standardized anomalies of temperature and precipitation along Cerrado's ecoregions for composites of extreme monthly burned areas in August (top row), September (middle row), and October (bottom row). Standardized anomalies for both climate variables were computed for the austral autumn (MAM; left-hand plots) and the corresponding month (either August, September, or October; right-hand plots). Red(blue) lines represent positive(negative) standardized anomalies, while flame(dot) symbols pertain to composites of severe(mild) burned areas. Ecoregions are categorized geographically, according to Fig. 1: north, central-west (Central-W), central-east (Central-E), west, and south.

with the transition from the austral winter (June, July, and August) to spring (September, October, and November), which marks the start of the first rains in September and October. On the other hand, the months immediately prior to the fire season, June and July, are marked by the virtual absence of rainfall, with the exception of the southern ecoregions and the northernmost ecoregion (Floresta de Cocais). This slight mismatch between the fire season and the peak of the dry season in Cerrado has been reported previously (Alvarado et al., 2017; Silva et al., 2019).

This diversity in seasonal climate over Cerrado hints at distinct regional climate-fire relationships. An analysis of temperature and precipitation anomalies during severe and mild fire seasons provided an initial assessment of these regional interactions. Indeed, climate patterns during severe and mild fire seasons vary considerably along Cerrado's ecoregions, with similar patterns often aligning geographically. This spatial agreement might be due to a similar climate, but also that contiguous ecoregions may share the same extreme years. Precipitation patterns during extreme years are much more similar along Cerrado's ecoregions than those of temperature. Severe and mild fire seasons generally see large and contrasting precipitation anomalies during the austral autumn (March, May, and April). In the case of temperature anomalies, northern ecoregions show contrasting anomalies for extreme fire seasons throughout the entire year, while central-western ecoregions have two separate 3-month periods where discrepancies between severe and mild fire seasons are more pronounced: pre-conditions during the austral autumn and the concurrent conditions of the fire season. Central-eastern and western ecoregions present no clear distinction in temperature anomalies between severe and mild fire seasons throughout the year, with the exception of Depressão Cuiabana. Lastly, southern ecoregions show differences in temperature anomalies during the fire season only.

Nevertheless, most ecoregions show contrasting behaviours between severe and mild fire seasons to some extent during two distinct 3-month periods: the austral autumn from March to May; and the fire season months from August to October. Severe fire seasons show negative precipitation anomalies during the austral autumn in all ecoregions, which contrasts with positive anomalies during mild fire seasons. In the case of northern and central-western ecoregions, where three of the highest burning ecoregions are located (Alto Parnaíba, Araguaia Tocantins, and Bananal), temperature anomalies are also consistently high in this period during severe fire seasons. The austral autumn coincides with the growing season over most of Cerrado (Arantes et al., 2016), and it has been reported for several regions (Abram et al., 2021; Pereira et al., 2013) that hot and dry conditions during the growing season impact vegetation growth and health, resulting in dry fuel loads that, when exposed to favourable fire weather during the fire season, are more susceptible to burn.

However, these results for extreme fire seasons mask distinct monthly dynamics. In general, burned areas during the early fire season in August are much more constrained by pre-conditions of temperature and precipitation during the austral autumn, whereas late fire season burned areas in October rely on concurrent favourable climate conditions. This dynamic may be explained by the mediator effect of vegetation. In August, fuel moisture levels are generally high (Ramos-Neto and Pivello, 2000), hindering the occurrence of large burned areas even with favourable concurrent fire weather conditions; however, if fuel conditions deteriorate due to exposure to hot and dry weather during the growing season, it will be more susceptible to burning. On the other hand, by the end of the fire season vegetation stress is, in general, quite high due to several months of prolonged hot and dry conditions. September and October usually see the first rains, and their occurrence seems to be determinant for extreme burned areas during these months. These results are in line with previous assessments suggesting that fire activity in Cerrado is moisture-dependent (Alvarado et al., 2017), and that seasonal fire activity increases with a rapid drying of grasses or herbaceous fuel (Nogueira et al., 2017).

The importance of climate conditions during the austral autumn in preconditioning fuel dryness during the fire season months provides an opportunity for early warning of burned areas in August. In the case of high-burning ecoregions, such as Alto Parnaíba, Araguaia Tocantins, and Bananal, bivariate models show that both temperature and precipitation during the austral autumn influence the interannual variability of early fire season burned areas in August. The other two ecoregions that make up the top 5 high burning ecoregions in Cerrado (Silva et al., 2021), Parnaguá and Chapadão do São Francisco, also show importance for temperature and precipitation during the austral autumn, respectively. This means that monitoring climate conditions during the autumn months may provide a useful outlook for early fire season burned areas, as a measure of the fuel dryness during the fire season. On the other hand, results also show that for all ecoregions, and for both temperature and precipitation, the months immediately prior to the fire season (June and July) do not seem to be relevant to either severe or mild fire seasons. In the context of fire management, this assessment may assist in scheduling and defining the proper time and place for prescribed burning, a technique that is increasingly used to manage fuel loads in Cerrado landscapes (Schmidt et al., 2018). Controlled burns for agriculture also benefit from this outlook, as many large fires in Cerrado are agricultural burns that, often due to fire weather and stressed vegetation conditions, escalate to uncontrolled wildfires.

When looking at fire season burned areas, we find high regional variability in the explained variance of fire-climate models using either temperature or precipitation. However, when looking at bivariate models per month of the fire season, we find that August-burned areas are often linked with climate conditions prior to the fire season, whereas October-burned areas are associated with concurrent conditions. September seems to be a transitional month, where both preconditioned and concurrent climate may play a role. The primary aim of using bivariate models in this study was to explore relationships between regional fire activity and climate variables during and prior to the fire season. However, the very low coefficients of determination obtained with either temperature or precipitation, suggest that these variables may not be suitable for predictive purposes. Nevertheless, previous biome-wide studies found that precipitation can successfully model fire in Cerrado (Libonati et al., 2015; Mataveli et al., 2018). Given that the top 5 ecoregions contribute to, on average, 68 % of Cerrado's yearly burned areas (Silva et al., 2021), it may be that, when fitting models to total burned areas in the biome, these models mostly reflect the fire-climate relationships within the highest burning ecoregions. In this study, the best-performing models are indeed those of the highest burning ecoregions, such as Araguaia Tocantins and Bananal. Furthermore, several other studies have shown that meteorological fire danger indices are successful in predicting interannual burned areas in Cerrado (Nogueira et al., 2017; Silva et al., 2019). These complex indices take into account several other meteorological variables (such as relative humidity and wind speed), and mathematically reflect the influence of climate on several components of fire activity, such as fuel combustibility and fire spread. Additionally, the fact that both temperature and precipitation models perform worst when predicting August and September burned areas, in comparison to October burned areas, may reflect the importance of the mediating factors during these months (such as vegetation availability and condition, as previously hypothesized) and that they must be considered as well in modelling efforts.

Understanding the climatic drivers of burned areas in the biome, and their mediating factors, is crucial in light of ongoing and future climate change: there has been a steady increase in temperatures over the last 40 years in Cerrado (Hofmann et al., 2021; Marengo et al., 2022), and less rainfall during the dry season (Blázquez and Silvina, 2020; Zappa et al., 2021). As the highest contributor to Brazil's annual burned areas (UNEP, 2022), Cerrado is also responsible for a large portion of greenhouse gas (GHG) emissions. In the period of 1999 to 2018, Cerrado was responsible for emitting more than 2 500 Tg of carbon to the atmosphere, second only to the Amazon, and these rates are not expected to decrease (da Silva Junior et al., 2020). Brazil is amongst the largest carbon emitters worldwide (United Nations Environment Programme (UNEP), 2023) and plays a crucial role in combating climate change. On October 2023, Brazil made the first adjustment of its Nationally Determined Contribution (NDC) to the Paris Agreement, pledging to cut GHG emissions by half in 2030 and achieve carbon neutrality by 2050. Lowering fire emissions in Cerrado is a crucial step to achieve these goals, that must be achieved through appropriate fire management policies. With this study, we hope to provide regionally tailored information to assist in drafting these policies and inform decision-making.

Moreover, as shown for biomes worldwide, while climate acts as an enabler of fire, it does not preclude the importance of other bioclimatic and human controls (Jones et al., 2022). Over South America, in particular, the prevalence of anthropogenic burning now dominates extensive regions across the continent, not only altering natural fire regimes in fire-prone regions such as Cerrado but also inducing fires in fire-sensitive ecosystems (Libonati et al., 2021; Pereira et al., 2022). Ignitions in Cerrado are predominately anthropogenic (Schumacher et al., 2022), often associated with agricultural, land conversion, or traditional practices (Durigan and Ratter, 2016; Eloy et al., 2019). Moreover, land use associated with socio-economic factors vary greatly amongst Cerrado's ecoregions: southern Cerrado is characterized by severely altered landscapes and agricultural lands; while its northern region holds the last remnants of native vegetation cover and has high deforestation rates over the last few decades (Sano et al., 2019; Trigueiro et al., 2020). Relationships between land use and fire in Cerrado have been shown to be quite complex and highly dependable on regional context (Silva et al., 2020), and may, to a certain extent, explain the high regional variability of climate's influence on burned areas found in this study. As such, next steps in evaluating regional drivers of fire in Cerrado should include other bioclimatic variables and the anthropogenic component.

5. Conclusion

Fire weather is considered to be the dominant control in burned areas worldwide (Jones et al., 2022) and, in this study, we provide a first assessment of regional fire-climate dynamics throughout the Brazilian Cerrado. We analyse the climatic conditions (as evaluated through temperature and precipitation) that lead to severe and mild fire seasons in each of Cerrado's 19 ecoregions. Results show that there is high variability within the biome, but ecoregions with similar patterns align geographically. In general, we find contrasting behaviours in both temperature and precipitation for severe and mild fire seasons during two distinct 3-month periods: the pre-conditions during the austral autumn; and the concurrent conditions of the fire season. Ecoregions that burn the most show the largest contrasting behaviours during these periods and are also those for which bivariate models of temperature or precipitation perform best in predicting annual fire season burned areas.

We further assess the influence of pre-conditions during the austral autumn and concurrent conditions during the fire season in severe and mild years for each of the fire season months. For many ecoregions, we find that early fire season burned areas are constrained by pre-conditions during the austral autumn, whereas late fire season burned areas are linked to concurrent climate conditions. Severe (mild) burned areas in August are associated with hot and dry (cold and wet) conditions during the austral autumn, and severe (mild) burned areas in October are associated with hot and dry (cold and wet) concurrent conditions. September is an intermediate month, seemingly influenced by both pre-conditions and concurrent climate.

We hypothesize that the mediating effect of vegetation plays a crucial role in explaining these patterns. Hot and dry conditions during the growing season affect vegetation health and lead to highly curated fuel loads that are more susceptible to burning during the fire season.

Moreover, these results provide important information for fire management strategies, as we show that fire season months have different climatic constraints. Monitoring meteorological conditions during the austral autumn may provide useful outlooks for early fire season burned areas, while late fire season burned areas require a closer monitoring on concurrent meteorological conditions. Understanding the importance and dynamics of the mediating effect of vegetation in the fire-climate relationship is thus essential to better inform fire management in the Cerrado biome. As a severely disturbed biome that is subject to high anthropogenic pressure, future assessments of regional drivers in Cerrado should also consider the human influence on fire activity.

CRediT authorship contribution statement

Patrícia S. Silva: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Renata Libonati:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Luiz G. Gonçalves:** Writing – review & editing, Conceptualization. **Carlos C. DaCamara:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2025.110792.

Data availability

Data will be made available on request.

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