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Research article

Devegetation is a widespread driver of fire in the Brazilian Cerrado

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A R T I C L E I N F O

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A B S T R A C T

The Cerrado is the largest tropical savanna in the world, featuring a wide range of vegetation types with different sensitivity to fire. The structure, functioning and rich biodiversity of the non-forest formations is intimately associated with the presence of fire, which historically has acted both as a natural disturbance and as a tool used by Indigenous communities. Currently, the Brazilian Cerrado is threatened by substantial devegetation (i.e., conversion of native vegetation to human land uses) and alterations in the fire regime (e.g., frequency, seasonality), negatively impacting biodiversity, local communities, and global climate regulation. Although it is known that land conversion can lead to fires in the Cerrado, the extent and proportion of burned area attributable to this process remain unclear. This study, covering the period 2003–2020, quantifies both the surface of native vegetation lost through land conversion (devegetation) and the area burned by fires ignited in converted areas, focusing on the portion of the Cerrado included in the state of Mato Grosso and the MATOPIBA region. Using geospatial data on devegetation (PRODES Cerrado), fires (Global Fire Atlas), and land use (MapBiomas), we classified individual fires into Devegetation Related Fires (DRF) or devegetation Independent Fires (IF). DRF were those ignited within or in close proximity to devegetated patches up to two years following the conversion, while IF included all other fires. We further examined differences in seasonality and size distribution between DRF and IF, and analysed DRF prevalence across different land tenures, including Indigenous Territories, Protected Areas, and private lands. Over the 18-year study period, DRF burned, with distinctive seasonality and reduced average fire size, approximately 20 million hectares within the study area, which represents about a quarter of the total native vegetation area. This accounts for approximately 12 % of the total burned area in the study region and is comparable to the size of the devegetated area during the same period (around 15 million hectares). Although governance systems like strictly Protected Areas and Indigenous Territories limited devegetation, they could not prevent impacts from DRF, which burned 12 % and 16 % of their total native vegetation area, respectively. These findings highlight the urgent need to halt devegetation and regulate fire use in the Cerrado through integrated fire management policies.

1. Introduction

The Cerrado is the second largest biome of South America, covering 24 % of the Brazilian territory (Rosan et al., 2022). It is the most biodiverse savanna in the world, harbouring over 1000 terrestrial vertebrates and more than 12,400 plant species (Arruda et al., 2018; Sano et al., 2019). The Cerrado vegetation is remarkably heterogeneous, ranging from fire-dependent grasslands and shrublands to fire-sensitive forest formations (Durigan and Ratter, 2016; Simon et al., 2009). The ecological relationships and biodiversity of the Cerrado are highly

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dependent on fire dynamics as they have co-evolved with fire (Durigan and Ratter, 2016; P. S. Silva et al., 2021; P. S. Silva et al., 2024). Different fire regime attributes, such as return interval, seasonality, and intensity, can influence ecosystem composition, structure, and productivity, with consequential effects on soil properties, water availability and local climate conditions (Arruda et al., 2018; Durigan and Ratter, 2016; Pivello et al., 2010, 2021; Rodrigues and Fidelis, 2022).

Anthropogenic pressures pose a serious threat to the Cerrado. The loss of native vegetation due to land conversion to anthropogenic uses, hereafter referred as *devegetation* (Machado and Aguiar, 2023), has been occurring in the Cerrado at an annual rate twice as high as that of the Amazon Forest biome (Da Conceição Bispo et al., 2023; Pivello, 2011; Schmidt and Eloy, 2020). As a result, 43 % of the Cerrado has been converted to other land use types (Luiz and Steinke, 2022; Sano et al., 2019). Although national policies, such as the Action Plan for the Prevention and Control of Deforestation and Fires in the Cerrado (PPCerrado), launched in 2010, have partially limited land conversion, their effectiveness has been compromised by government changes and the absence of regulations protecting non-forest vegetation (Machado et al., 2024;Da Conceição Bispo et al., 2023). The limited recognition of the social-ecological value of non-forest structures, has resulted in weaker conservation measures to curb devegetation in the Cerrado compared to those implemented in the Amazon. For instance, while 50.8 % of the Amazon is under some form of protection, only 13.1 % of the Cerrado is covered with similar safeguards, with a mere 3 % under strict protection (Da Conceição Bispo et al., 2023; Schmidt and Eloy, 2020). Similarly, sustainability policies such as the Soy Moratorium (a multi-party zero-devegetation agreement) were implemented exclusively in the Amazon and did not extend to the Cerrado (Da Conceição Bispo et al., 2023; Soterroni et al., 2019). Additionally, under the Brazilian Forest Code, private landowners in the Cerrado are permitted to convert between 65 % and 80 % of their land, whereas in the Amazon this percentage is limited to 20 % (Da Conceição Bispo et al., 2023). These regulatory imbalances have contributed to the displacement of devegetation pressures from the Amazon to the Cerrado (Trigueiro et al., 2020).

Beyond abrupt changes in land cover, devegetation can have unintended consequences such as impacting regional climate by raising temperatures and decreasing precipitation, increasing soil erosion, and altering both surface and groundwater circulation, limiting water availability (Hunke et al., 2015; Rodrigues et al., 2022). Land conversion is also a driver of fire in the Cerrado (Schmidt and Eloy, 2020; Silva et al., 2020; Silvério et al., 2019). Devegetation in this biome primarily occurs through the ‘slash and burn’ process, in which vegetation is mechanically removed, accumulated in piles, and subsequently burned to eliminate biomass (Pivello, 2011; Pivello et al., 2021; Schmidt and Eloy, 2020). Beyond direct burning, the increased human presence associated with land conversion raises the likelihood of both intentional and accidental fire ignitions (Silva et al., 2020). Fires associated with devegetation often spread beyond the boundaries of converted patches, burning surrounding vegetation (Oliveira et al., 2022; Pivello et al., 2021). Anthropogenic fires linked to modern human activities are not a natural ecological process and have negative impacts on the Cerrado fire regime and its ecological functions (Pivello et al., 2021;Silva et al., 2020). Distinctions from the natural fire regime may include altered characteristics such as fire size, seasonality, and frequency (Pereira Júnior et al., 2014).

Despite the anticipated relationship between devegetation and fire in the Cerrado, these interactions have been rarely quantified. Mataveli et al. (2021) observed a limited link between devegetation and fire emissions trends over the period 2002–2019, though only focused on two Protected Areas in the Brazilian state of Bahia. Oliveira et al. (2022) found that, between 2001 and 2019, proximity to deforested areas was a key factor influencing fire impact (intensity, size, return interval and timing) across the entire Cerrado. Finally, Ribeiro et al. (2024) identified a correlation between devegetation and fires over the period 1986–2020, though just focusing on fires occurring within converted areas, without accounting for the potential spread to adjacent areas. As a result, the extent to which devegetation drives fires in the Cerrado remains uncertain, including how much adjacent native vegetation is affected by fires associated with devegetation. Understanding this relationship requires considering broad scale land use regulating factors, with potential far-reaching implications for both fire patterns and land use changes.

Land governance, meant as the ensemble of public and private regulatory structures, including norms, strategies, and procedures concerning land management, plays a crucial role in influencing devegetation activities (Fischer et al., 2020; Giessen and Buttoud, 2014; Mataveli et al., 2021; Nolte et al., 2013; Pacheco and Meyer, 2022; Rocha et al., 2012). Effective governance, such as well-defined land ownership and use rights, has been proved to reduce devegetation (Fischer et al., 2020; Pacheco and Meyer, 2022), whereas weak governance, as seen in Brazil’s undesignated lands, where tenure rights remain unclear, tends to increase it (Pacheco and Meyer, 2022). Land governance also affects fire dynamics by implementing suppression policies, supporting fire management, and regulating land use transitions that create more or less flammable landscapes (Fidelis et al., 2018; Schmidt and Eloy, 2020; Spadoni et al., 2023). Consequently, governance approaches can mediate the relationship between land conversion and fire. Research indicates that in the Cerrado different land tenure types are associated with different governance models, which include various policies, regulations, and management practices, leading to different conservation and land use outcomes (Pacheco and Meyer, 2022). For instance, Françoso et al. (2015) showed that strictly Protected Areas substantially limit devegetation, while Fidelis et al. (2018) found that Protected Areas can greatly influence the fire regime through fire management plans or fire exclusion policies. In the Cerrado, the main land governance categories are: Indigenous Territories, Strictly Protected Areas, Sustainable use Protected Areas, Rural settlements, Public forests, Other public lands, and Private and other lands.

To the best of our knowledge, it is still unclear to what extent vegetation loss due to land conversion drives fires in the Cerrado, and how land tenure might mediate this relationship (Gomes et al., 2018). Here, we aim at clarifying some of the relationships that regulate this socio-ecological process by providing quantitative insights to the following research questions.

(a) To what extent is devegetation a driver of fires in the Brazilian Cerrado?
(b) How much native vegetation surface has been burned by fires associated with devegetation, beyond the area directly lost to land conversion?
(c) Do fires related to devegetation have distinct characteristics in terms of size distribution and seasonality?
(d) How does land tenure influence devegetation and its associated fires?

To address our research questions, we identified individual fires linked to devegetation by determining whether they were ignited within or up to 1 km from converted areas, within a period of maximum two years following the conversion. We focused on the portion of the Cerrado spanning Mato Grosso and the MATOPIBA region (Mataveli et al., 2021; Trigueiro et al., 2020), comprising Maranhão, Tocantins, Piauí and Bahia (Fig. 1). These five states have experienced the highest levels of land conversion in the Cerrado since 2000 (Parente et al., 2021; Rocha et al., 2012; Trigueiro et al., 2020). These regions have also recorded the highest number of fire events in the Cerrado between 1992 and 2015 (Arruda et al., 2018), accounting for approximately 60 % of the total burned area between 2001 and 2018 (Silva et al., 2020). Finally, this region features a diverse range of land tenure types, encompassing the main categories found in the Cerrado.

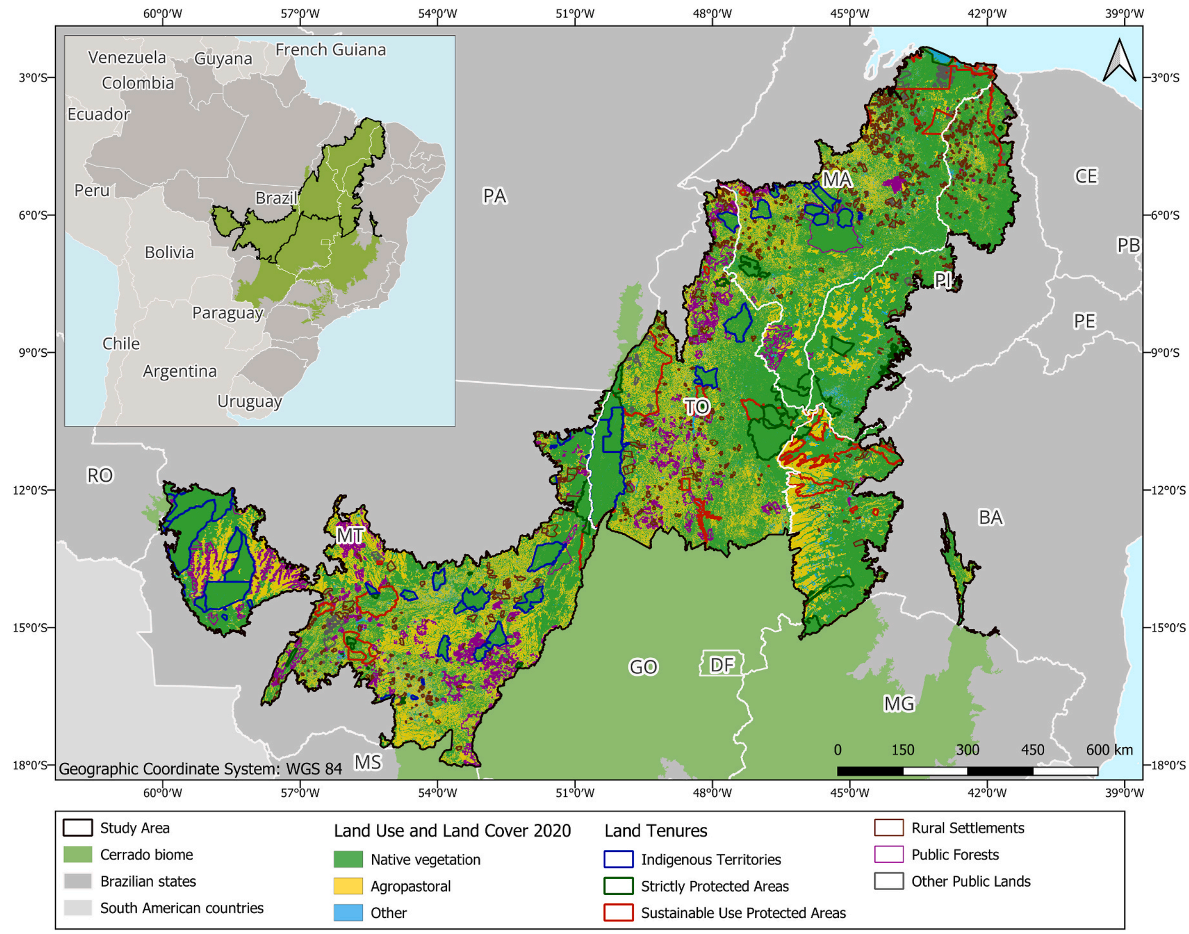

Fig. 1. Geographical representation of the study area, classified into three major land use and land cover classes, based on MapBiomas Collection 9 data for 2020, the last year of our study period. The map also shows the main land tenure categories considered in this study, along with the Cerrado ecoregion and the location of the study area within Brazil. Brazilian states abbreviations: BA, Bahia; CE, Ceará; DF, Distrito Federal; GO, Goiás; MA, Maranhão; MT, Mato Grosso; MS, Mato Grosso do Sul; MG, Minas Gerais; PA, Pará; PB, Paraíba; PE, Pernambuco; PI, Piauí; RO, Rondônia; TO, Tocantins.

2. Materials and methods

2.1. Study region

Our study area encompasses the northern portion of the Cerrado biome, spanning the states of Mato Grosso, Maranhão, Tocantins, Piauí and Bahia, with the latter four forming the MATOPIBA region (Mataveli et al., 2021; Trigueiro et al., 2020). Covering approximately 100 million hectares Table 2), the study area extends along a southwest-northeast axis that stretches for nearly 2000 km, from the Mato Grosso plateau, at the geodesic centre of South America, to the Atlantic coast of Maranhão (Fig. 1). The region experiences a tropical wet-dry climate (Köppen classification), with consistent intra-annual variability in precipitation, mostly concentrated from October to April. The average temperature is around 25 °C, peaking during the dry season (May–September; Salvador and De Brito, 2018; Silva et al., 2021). The physiognomy of the area is highly variable, shaped by climate, soil types and fire regimes, and includes fire-dependent savannas and grasslands, as well as fire-sensitive gallery forests and other moisture-dependent vegetation along riparian corridors (Oliveira and Marquis, 2002; Neri et al., 2013). This region has undergone extensive land conversion for agro-industrial expansion. Most of the devegetation in Mato Grosso happened between the 1970s and 1990s, with rates declining in the early 2000s. In contrast, in MATOPIBA, large-scale agricultural expansion accelerated following the 2007–2008 Brazilian food price crisis, making this area the Cerrado's last agricultural frontier (Rocha et al., 2012;Silva et al., 2020; Trigueiro et al., 2020). Devegetation in MATOPIBA has also been exacerbated by the displacement of land conversion pressures from the neighbouring Amazon biome, where stricter environmental enforcement was implemented (Trigueiro et al., 2020). Our study area, as the rest of the Cerrado, is predominantly fire dependent, having evolved with both natural wildfires and traditional burning by local populations (Da Silva Arruda et al., 2024; Silva et al., 2024; Welch, 2014). However, it is increasingly affected by anthropogenic fires linked to modern land use activities, including devegetation, most of which are illegally ignited (Arruda et al., 2024; Santos et al., 2021; Schmidt and Eloy, 2020). Unlike natural disturbance, these modern fires lead to disruptive ecological and social impacts (Pivello et al., 2021). This issue became particularly critical in 2024, when the Cerrado experienced a severe environmental crisis, marked by a 92 % increase in burned area compared to 2023, totaling 9.7 million hectares affected, 84 % of which occurred in natural areas (MapBiomas Brasil (n. d.); Arruda et al., 2024). Our study area included some of the most affected municipalities (Arruda et al., 2024). The study region consists of a diverse mosaic of land tenures, including 57 Indigenous Territories (7.12 % of the land), 84 Protected Areas (9.53 %), 860 Rural Settlements (3.32 %), over 4800 Public Forests and Other Public Lands (4.59 %), and Private Lands that, accounting for more than 75 % of the study area, are the predominant land tenure type (Fig. 1; Table S3).

2.2. Datasets

We used Global Fire Atlas (GFA) dataset for fire perimeters and associated ignition points (Andela et al., 2019; Andela and Jones, 2024).

GFA has a global coverage for the period 2002–2021 (Table 1; Jones et al., 2024). The GFA groups burned pixels from the Modis Collection 6.1 burned area (BA) dataset (Giglio et al., 2018) into individual fires. The output BA data has a spatial resolution of 500 m and daily temporal resolution (Table 1; Andela et al., 2019, 2022; Andela and Jones, 2024).

We used the PRODES (*Programa de Cálculo do Desflorestamento*) Cerrado to identify native vegetation areas that were converted to other land uses (Maurano et al., 2019), that is, the devegetated area. PRODES is a project led by INPE (National Institute for Space Research) and provides the official national estimates of devegetation in Brazil. The project involves manual mapping of devegetated areas using satellite imagery from various sources, including the Landsat series and Sentinel-2 (de Almeida et al., 2021). PRODES Cerrado has a 30 m spatial resolution and covers the period 2000–2022 (Table 1). From 2000 to 2012 the data is provided in biannual maps, while from 2013 to 2022 it provides annual maps. For the biannual resolution period, data referred to one year include all the surfaces converted in that year and the previous one, while, in the annual resolution period, yearly data refer to surfaces converted in that same year. PRODES Cerrado is the most accurate devegetation dataset available, reaching an overall accuracy exceeding 93 % (Mataveli et al., 2021; Parente et al., 2021).

We used MapBiomas Collection 8.0 data to describe the land cover of our study area (Alencar et al., 2020). This dataset provides, through the application of machine learning algorithms to Landsat images mosaics, annual maps of land use and land cover for the period 1985–2022, with a spatial resolution of 30 m (Table 1). We aggregated its original land cover classes into six macro classes: Native vegetation, Forest plantation, Pasture, Agriculture, Mosaic, and Other land uses (see Table S1).

Administrative boundaries for the five federal states, the Cerrado biome, Indigenous Territories and Protected Areas were obtained from Terrabrasilis (Sparovek, G. Terrabrasilis. (n.d.)). Perimeters of Rural settlements and Other public lands were obtained from the Brazilian National Institute for Colonization and Agrarian Reform Hunke, P. INCRA. (n.d.), and Public forests boundaries were retrieved from the National Public Forest Registry (Simon, M. F. SNIF. (n.d.)).

Despite differences in resolution, the datasets used provide the most complete and up-to-date records of the processes we analysed and are the most appropriate for our methodology (Andela and Jones, 2024; Mataveli et al., 2021; Parente et al., 2021). Specifically, we selected the Global Fire Atlas because, although its resolution is coarser than other satellite products providing burned areas at the pixel level, it offers data at the individual fire level, including estimated ignition points. As detailed in Section 2.4, this ignition point information was essential to our methodology.

2.2.1. Land tenures

We identified seven tenure categories, each representing a distinct land governance type, to assess their influence on devegetation and related fires: Indigenous Territories, Strictly Protected Areas, Sustainable use Protected Areas, Rural settlements, Public forests, Other public lands, and Private and other lands. Indigenous Territories were originally established to safeguard land and resources for Indigenous Communities, allowing them to uphold their traditional rights and ways of life, though today they also represent key spaces stewarded for ecological conservation and climate change mitigation (Garnett et al., 2018). Protected Areas were created for conservation and emissions reduction purposes, through curbing deforestation and devegetation. Strictly Protected Areas restrict resource extraction and human access, while sustainable use protection allows for some land use change, resource extraction, and human settlements (Nolte et al., 2013). Rural settlements are lands provided by the state agency National Institute for Colonization and Agrarian Reform (INCRA) to small landless farmers (Gosch et al., 2017). Public forests, also established for environmental protection purposes, may either be managed by a specific state agency, or remain without a defined destination, and known as Undesignated Public Forests (UPF; Cadastro Nacional de Florestas Públicas, n.d.). UPF are a prominent target for devegetation in Brazil, although being mostly found in the Amazon (Azevedo-Ramos et al., 2020; Sparovek et al., 2019). Other public lands include lands acquired, expropriated by, or donated to the state and may be allocated for various types of management, including settlement for small farmers, large landowners, or agribusiness companies (Terras Públicas, n.d.). Most of the Cerrado is privately owned (Pompeu et al., 2024; Schmidt and Eloy, 2020) and, according to the 2012 New Brazilian Forest Code, up to 65 % of the vegetation cover (referring to its extent in July 2008) on private properties in the Amazon-Cerrado transition zone, and up to 80 % in the rest of the Cerrado, can be legally converted, while just between 20 % and 35 %, known as "Legal Reserves", must be preserved (Bonanomi et al., 2019; Pinillos et al., 2021; De Marco et al., 2023; Pompeu et al., 2024). However, this regulation applies exclusively to properties registered in the Rural Environmental Registry (*Cadastro Ambiental Rural* - CAR), as would be required by law. Landowners illegally not registered in the CAR are often not only not defining Legal Reserves but also illegally occupying, and converting, other public lands (De Marco et al., 2023).

Strictly Protected Areas and Indigenous Territories are often associated with reducing devegetation, although their effectiveness largely depends on local law enforcement (Françoso et al., 2015; Mataveli et al., 2021; Nolte et al., 2013). In contrast, Sustainable use Protected Areas are much more vulnerable (Françoso et al., 2015). The effect of Protected Areas and Indigenous Territories on fires remains less clear, due to the uneven enforcement of exclusion policies, the use of fire for land management, and cultural burnings (Fidelis et al., 2018; Pivello et al., 2021). The role of Rural settlements in the devegetation process is uncertain: while they tend to be less devegetated than surrounding private lands, they are still highly impacted, aligned with regional patterns (Gosch et al., 2017). The effect of Public forests and Other public lands on devegetation and fires has yet to be examined, though our hypothesis is that their effectiveness is undermined by ambiguous management and a lack of monitoring. Finally, Private and other lands are expected to be the most impacted category, given that there devegetation is allowed to some extent.

Table 1
Description of the main datasets used in this study.

Variable	Dataset	Spatial coverage and resolution	Serie and temporal resolution	Main reference
Fire perimeters - Fire ignitions	Global Fire Atlas	global, 500 m	daily, 2002–2021	Andela and Jones (2024)
Devegetation perimeters	PRODES Cerrado	Cerrado biome, 30 m	annual/ biannual, 2000–2022	Maurano et al. (2019)
Land cover mosaic	MapBiomas	Brazil, 30 m	annual, 1985–2022	Alencar et al. (2020)

2.3. Data preparation

In this study, we focus on the 18-year period from 2003 to 2020, which was divided into 9 two-year time steps. This two-year time window was selected to temporally constrain the influence of devegetation on fire, and to ensure consistency in the time series, as PRODES data are provided biannually until 2012. The patterns observed across individual time steps were comparable (Table S4), allowing us to coherently resume findings from each step into the main results presented for the entire study period. Accordingly, we aggregated all the fire perimeters and associated ignitions into two-year steps. To characterise the land cover of the study area, within each biannual time step, we used the land cover layer available from the second year. Devegetation, fire, and land cover layers, as well as the land tenure ones, were cut for the study area.

To have a unique land tenure layer covering the entire study area, in case of contradictory overlaps among single tenure layers, we applied the following hierarchy: Indigenous Territories, Strictly Protected Areas, Sustainable use Protected Areas, Rural settlements, Public forests, Other public lands, and Private and other lands.

2.4. Data analysis

We analysed devegetation and fires separately for each two-year time step. According to Ribeiro et al. (2024), the influence of devegetation on fire activity in the Cerrado is of limited duration, rarely lasting for more than 2 years. This short duration influence should not be confused with the long-term impacts resulting from established agro-pastoral uses following land conversion, whose assessment, though, was not an object of our study. To assess if devegetation is a fire driver in the Brazilian Cerrado, we assumed that fires happening in the same time step in which land conversion has occurred and whose points of ignition lie within the converted area are directly linked to the land conversion process. Assuming that devegetation can trigger fire initiation beyond its boundaries, we applied a 1 Km buffer to the devegetation polygons, linking fires to devegetation if ignitions also occurred within this buffer zone. In the Brazilian Amazon, Silveira et al. (2020) found that one third of all active fires were up to 1 Km from deforested areas within one year, while C.A. Silva et al. (2021) observed a high fire activity up to 1.2 Km from devegetation frontiers, under the same conditions. Being the Cerrado more accessible (because of its less dense vegetation structure) and more flammable, compared to the Amazon, the 1 Km threshold seemed appropriate for this study. However, to avoid drawing buffers around small devegetated areas that could result in unrealistic influence zones, we applied a filter to exclude devegetation polygons smaller than 1 ha before using the 1 km buffer.

In this study, we focused on fires occurring in native vegetation areas. Thus, we filtered the fire dataset to select fires burning mainly native vegetation cover by overlapping fire perimeters with MapBiomas land cover layers from the corresponding time step. To do so, we reclassified the MapBiomas land cover classes and created a native vegetation macro class (as shown in Table S1). Individual fires with native vegetation as the most frequent land cover class within their perimeters were labelled as vegetation fires. Hence, we defined Devegetation Related Fires (DRF) as vegetation fires whose ignition point fell within a devegetation polygon, or its buffer zone, in the same time step. Conversely, we called devegetation Independent Fires (IF) all the vegetation fires whose ignition fell outside devegetation polygons and their buffer zones in the same time step (Fig. 2; Fig. S1).

The workflow adopted to identify DRF and IF is summarised in Fig. 2. The classification of the Global Fire Atlas (GFA) fire perimeters dataset into these two categories was based on the GFA ignition dataset, the PRODES Cerrado devegetation database, and the MapBiomas land use and land cover layers. The preliminary steps involved identifying fire ignitions contained into the devegetation influence zone, defined using the 1 ha dimensional filter and the 1 km buffer applied to devegetation polygons. Additionally, land cover layers were reclassified to establish a native vegetation macro-class. Fires predominantly spreading over native vegetation were filtered and linked to their corresponding ignitions. Based on the ignition's position relative to the devegetation influence zone, fires were then classified. This procedure was iterated over

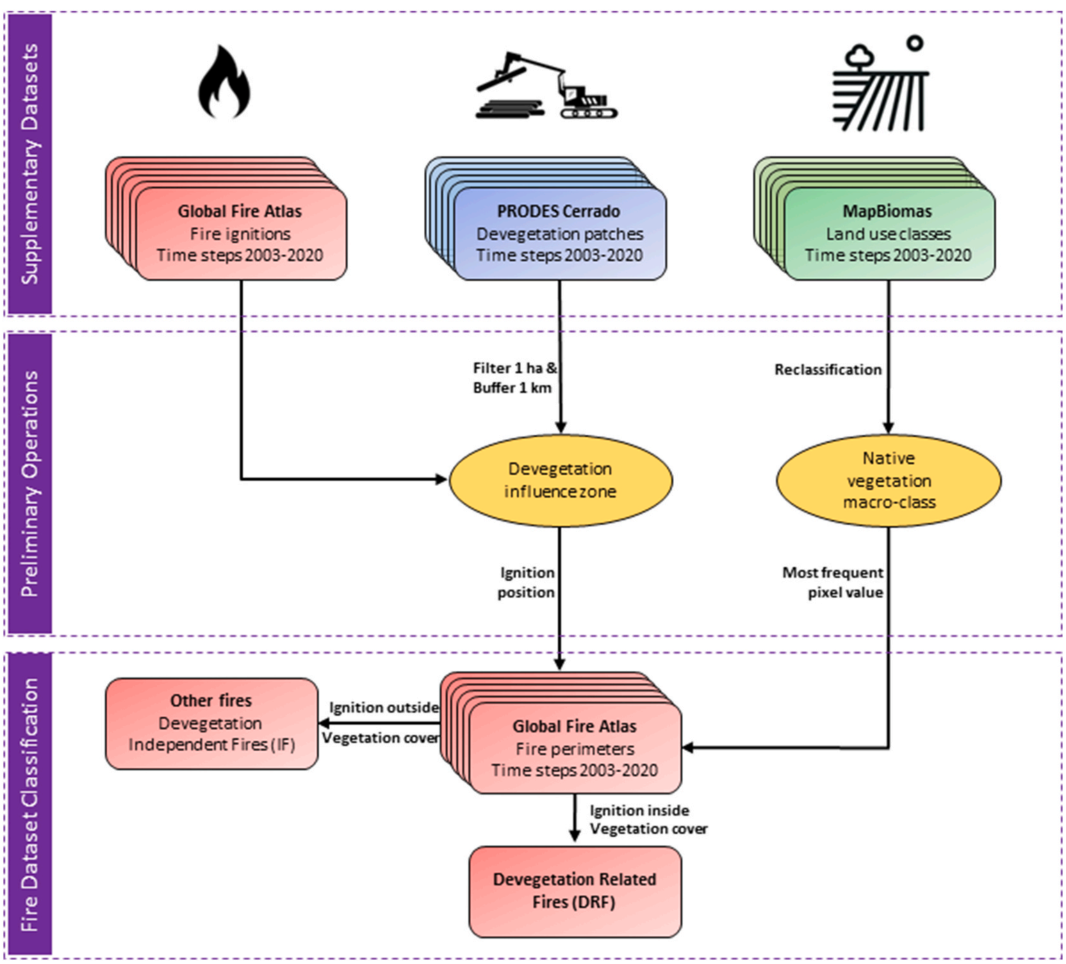

Fig. 2. Methodological workflow for the identification of Devegetation Related Fires (DRF) and devegetation Independent Fires (IF). Overlapping rectangles represent biannual datasets, black annotations beside the arrows represent GIS operations, ovals represent intermediate outputs, and single rectangles represent final output layers.

all time steps, with the final fire classes compiled as the aggregate of fires classified at each step.

To describe DRF, we evaluated both the total cumulative burned area and the number of fires within this class throughout the study period, comparing these measures to those of all fires (Table 2), to the metrics of devegetation (Fig. 3; Table 2), and to the native vegetation area (Fig. 3; Table 2). We also assessed the fire escape rate as the amount of DRF burned area not overlapping devegetated areas (i.e., mainly overlapping native vegetation surrounding devegetated areas) within the same time step, on the total DRF burned area (Table 2).

To assess how devegetation might alter the Cerrado's fire regime, we compared DRF fire size distribution (i.e., the distribution of individual fire sizes over the whole study period) and fire seasonality (i.e., the distribution of individual fire start days over the whole study period) with those of IF (Figs. 4 and 5). We assumed that IF represented different types of vegetation fires in the Cerrado, such as natural wildfires, cultural fires, prescribed burning, as well as other anthropogenic fires, and so IF were used as a control to perform the comparisons. We described the distributions using basic statistical parameters (mean, mode, skewness, kurtosis; Table S2). We applied a Welch's *t*-test to determine if mean fire sizes of DRF and IF were significantly different (Table S2; West, 2022). Since our sample sizes were very large (ranging from 3758 up to 48,130 events, depending on the fire class and state), the Central Limit Theorem ensures that Welch's *t*-test remains robust even when the data are not normally distributed (Dwivedi et al., 2017; Guo et al., 2011). To further support the results obtained from Welch's *t*-test, which assesses differences in means, we also conducted a Mann-Whitney *U* test to evaluate differences in medians (McKnight and Najab, 2010). We also applied a nonparametric two-sample Kolmogorov-Smirnov (K-S) test to assess if DRF and IF start day series follow the same distribution, considering their location and shape, even if their sample size is different, as in our case. To validate the results from the K-S test, we further evaluated distributional differences using the Anderson-Darling test. All tests were assumed significant at $p < 0.05$.

To evaluate the influence of land tenure on devegetation and associated fires, we performed intersections between spatial layers representing these processes and one depicting the seven main tenure categories considered in this study. For each tenure type, we assessed the absolute and relative areas affected by devegetation and DRF (Fig. 6; Table S3).

Table 2
Devegetation, Fires and DRF processes during the period 2003–2020 in the Brazilian Cerrado. Methods used to assess the variables are reported in section 2.3.[a] Relative to the native vegetation area;[b] relative to the total area;[c] relative to all fires burned area;[d] relative to the number of all fires;[e] relative to the total DRF burned area. Note: percentage values of burned area for all fires, reported as %[b], exceed 100 % since some surfaces within the study area burned multiple times between 2003 and 2020.

Process/Land	Variable	Unit	MT	MA	TO	PI	BA	TOT
Study area	area	ha	33,809,449	21,979,882	25,411,176	13,521,896	10,462,776	105,185,179
	native vegetation area	ha	20,333,576	17,124,942	19,203,451	11,715,064	8,399,120	76,776,153
Devegetation	area	ha	3,304,282	3,586,179	3,834,760	1,933,221	1,970,554	14,628,996
	area	%[a]	16.3	20.9	20.0	16.5	23.5	19.1
	polygon number	n°	150,476	339,037	211,041	143,188	45,243	888,985
All fires	burned area	ha	44,248,456	28,333,587	54,411,381	16,288,080	14,791,663	158,073,167
	burned area	%[b]	130.9	128.9	214.1	120.5	141.4	150.3
	number fires	n°	53,578	88,023	71,978	39,224	23,978	276,781
DRF	burned area	ha	4,801,919	4,574,873	6,351,242	2,108,111	1,812,054	19,648,199
	burned area	%[a]	23.6	26.7	33.1	18.0	21.6	25.6
	burned area	%[c]	10.9	16.1	11.7	12.9	12.3	12.4
	number fires	n°	3758	12,953	7696	4816	2380	31,603
	number fires	%[d]	7.0	14.7	10.7	12.3	9.9	11.4
	fire escape rate	%[e]	95.8	92.2	96.5	82.7	86.3	92.9

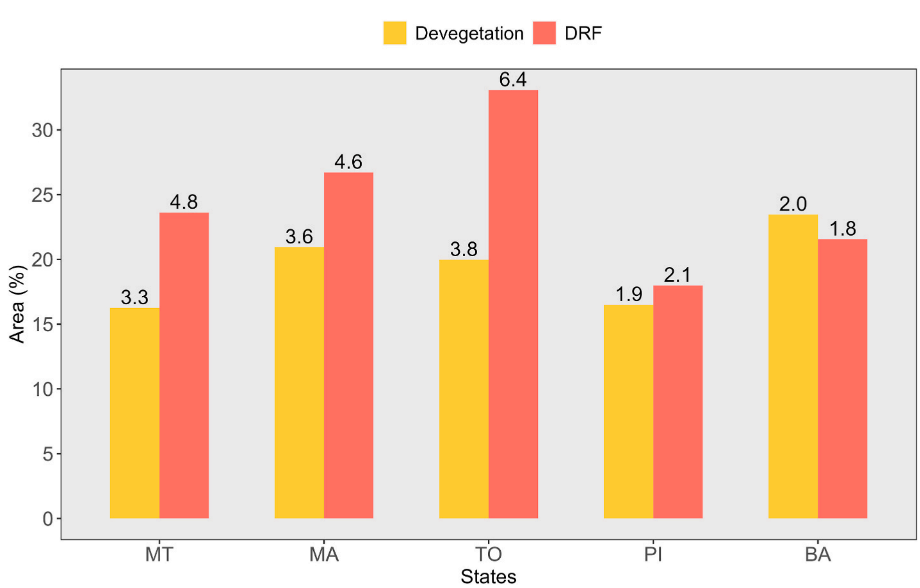

Fig. 3. Devegetation and Devegetation Related Fires (DRF) percentage related to total native vegetation area within each state (y-axis) and absolute values in million hectares (bars numbers), for each Brazilian state (Mato Grosso – MT, Maranhão – MA, Tocantins – TO, Piauí – PI, Bahia – BA). Both percentage and absolute measures represent cumulative totals over the whole study period. See Table 2 for precise values and results for the whole study area.

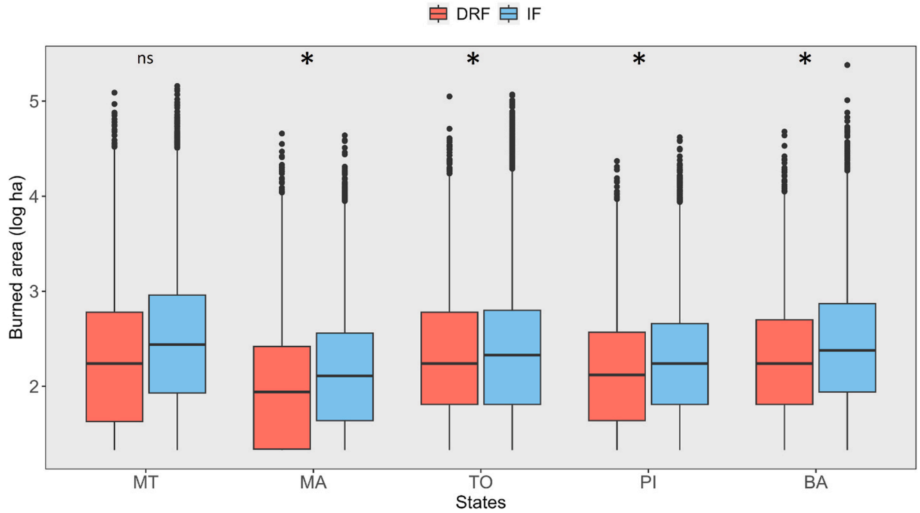

Fig. 4. Fire size distribution per fire class (Devegetation Related Fires – DRF, devegetation Independent Fires - IF) and by Brazilian state (Mato Grosso – MT, Maranhão – MA, Tocantins – TO, Piauí – PI, Bahia – BA). Asterisks indicate that differences in mean fire size between fire classes are significant according to Welch's *t*-test. See Table S2 for detailed results about statistical tests and mean fire size values for the different states and the whole study area.

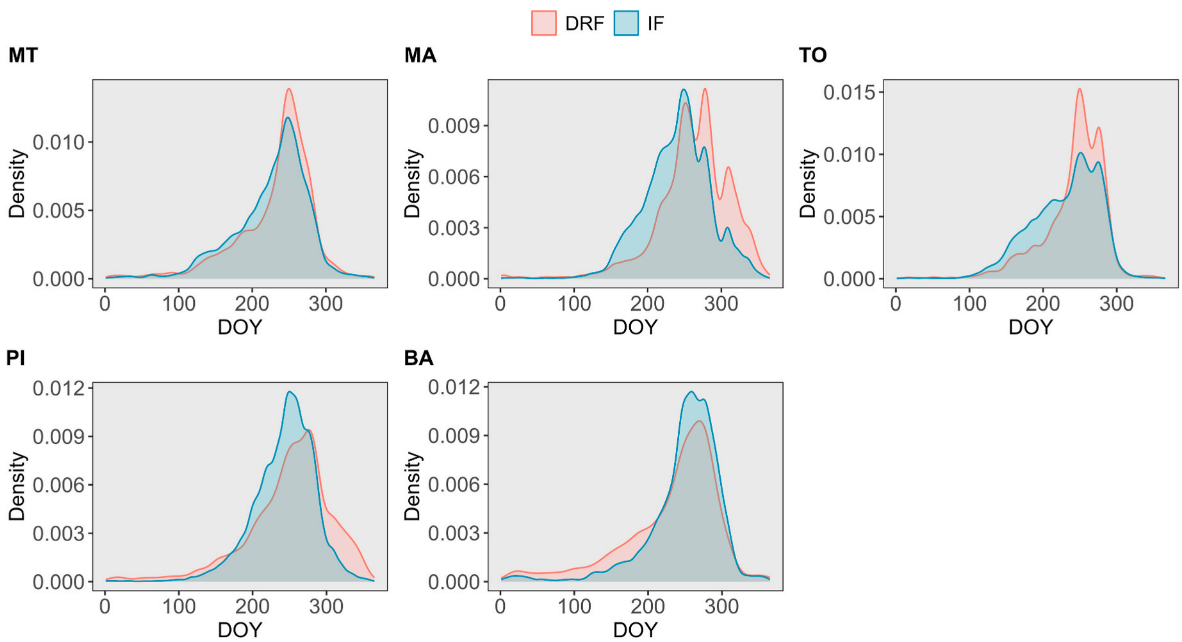

Fig. 5. Fire seasonality per fire class (Devegetation Related Fires – DRF, devegetation Independent Fires - IF) and state (Mato Grosso – MT, Maranhão – MA, Tocantins – TO, Piauí – PI, Bahia – BA). The y-axis shows the estimated probability density function, or the relative likelihood of observing given x values. Density was assessed by Kernel density estimation (KDE) method. See Table S2 for results about statistical tests and shape parameters for the different states and the whole study area.

3. Results

3.1. Devegetation and DRF statistics

Between 2003 and 2020, devegetation impacted 14.6 million hectares within the study area, ranging from 1.9 million hectares in Piauí and 2.0 million in Bahia to 3.3 million in Mato Grosso, 3.6 million in Maranhão, and 3.8 million in Tocantins (Fig. 3; Table 2). Within the same period, DRF burned a cumulative total of 19.6 million hectares within the study area, ranging from 1.8 million hectares in Bahia and 2.1 million hectares in Piauí, to 4.6 million hectares in Maranhão, 4.8 million in Mato Grosso, and 6.4 million in the state of Tocantins (Fig. 3; Table 2). DRF affected larger cumulative areas than devegetation in every state except Bahia (Fig. 3), with a ratio of 1.34 when considering the whole study area. In relative terms, devegetation affected 19.1 % of the native vegetation surface of the study area, with losses varying by state: 16.3 % in Mato Grosso, 16.5 % in Piauí, 20.0 % in Tocantins, 20.9 % in Maranhão, and 23.5 % in Bahia (Fig. 3; Table 2). On the other hand, throughout the study period, DRF affected 25.6 % of the native vegetation of the study area, ranging from 18.0 % in Piauí and 21.6 % in Bahia, to 23.6 % in Mato Grosso, 26.7 % in Maranhão, and 33.1 % in Tocantins (Fig. 3; Table 2). Tocantins was the state with the largest total areas of DRF and devegetation, as well as the highest percentage of native vegetation cumulatively burned by DRF, while Bahia experienced the highest percentage of devegetation (Fig. 3).

The ratio of DRF burned area not overlapping devegetated areas

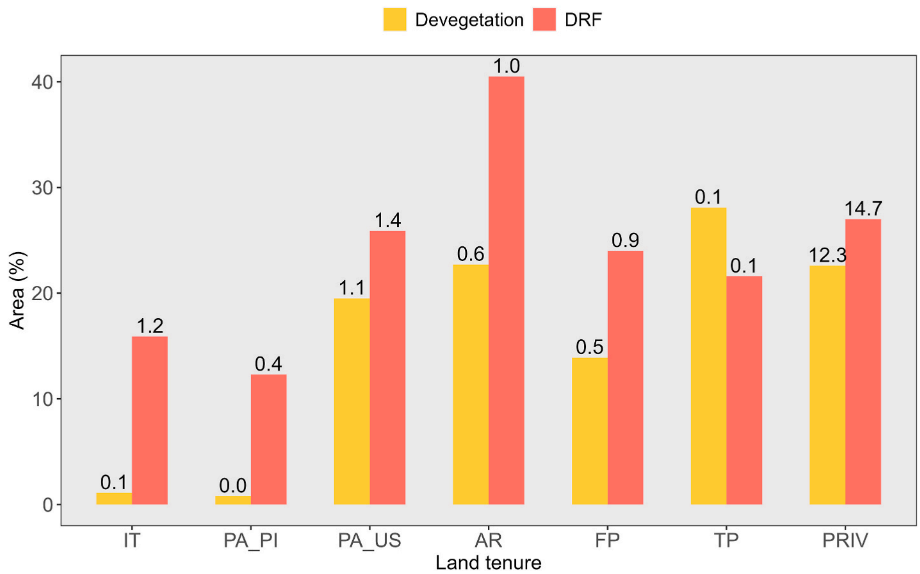

Fig. 6. Percentages of devegetation and Devegetation Related Fires (DRF) related to total native vegetation area (y-axis) and absolute values in million hectares (bars numbers) for each land tenure type (Indigenous Territories: IT, Strictly Protected Areas: PA_PI, Sustainable use Protected Areas: PA_US, Rural settlements: AR, Public forests: FP, Other public lands: TP, and Private and other lands: PRIV). Both percentage and absolute measures represent cumulative totals over the whole study period. See Table S3 for numeric results by state.

(within the same time step) to the total DRF burned area (fire escape rate henceforth) was 92.9 % within the study area, ranging from 82.7 % in Piauí and 86.3 % in Bahia, to 92.2 % in Maranhão, 95.8 % in Mato Grosso, and 96.5 % in Tocantins (Table 2). This ratio indicates that the large majority of DRF burned area did not affect devegetated patches but the surrounding native Cerrado vegetation. DRF accounted for 12.4 % of the total cumulative burned area and 11.4 % of the fires during the study period, where these values also represent the mean annual proportions, with a standard deviation of ±2 and ± 3 percentage points, respectively. These values differed slightly by state, with total cumulative burned area ranging from 10.9 % in Mato Grosso and 11.7 % in Tocantins, to 12.3 % in Bahia, 12.9 % in Piauí, and 16.1 % in Maranhão; and the total number of fires varying among 7.0 % (MT), 9.9 % (BA), 10.7 % (TO), 12.3 % (PI), and 14.7 % (MA; Table 2). Maranhão had the highest percentages of DRF compared to all fires, as well as the highest number of fire events, despite having a lower total cumulative burned area than Mato Grosso and Tocantins (Table 2).

3.2. DRF characteristics

The fire size distribution of DRF and IF followed a skewed distribution, in all the states, due to the frequent occurrence (up to ~ 500 and 900 occurrences, for DRF and IF, respectively) of small fires (~20–30 ha) with similar sizes and the much less frequent occurrence (single occurrence) of large fires (up to tens of thousands of hectares). The size of the largest fires varied by state, with fire events exceeding 100,000 ha in the states of MT, TO and BA (Fig. 4).

The p-values from Welch's t-tests suggest a significant difference between the mean size of DRF and IF (Table S2). For the whole study area, DRF mean size value (622 ± 2504 ha) was 20 % smaller than the one of IF (778 ± 3013 ha; Welch's *t*-test p-value <0.001). This trend was consistent across all states but Mato Grosso (Fig. 4; Table S2). However, differences in medians were found to be statistically significant by the Mann-Whitney *U* test across all states and the whole study area (Table S2). Mato Grosso exhibited the largest mean sizes for both DRF and IF, while Maranhão showcased the smallest mean sizes in both series (Fig. 4; Table S2).

Regarding the distribution of fires starting dates (i.e., the fire seasonality), both DRF and IF are concentrated during the dry season (May–September) with the maximum number of occurrences (up to ~ 500 and 2000 occurrences, for DRF and IF, respectively) at the end of the season. The Kolmogorov-Smirnov test indicate that the shapes of the start date distributions of DRF and IF are significantly different, and this result is corroborated by the Anderson-Darling test (Table S2). We found that DRF distributions are more left skewed (asymmetric), and sharper (concentrated around mean values) compared to IF distributions, in all states except Bahia (Table S2). That is, the DRF season is shorter and reaches its peak later in the year. Within the whole study area and study period, DRF reach their peak (576 fires) on October 2nd, while IF reach their peak (2007 fires) on September 3rd, that is 29 days earlier (Table S2).

3.3. Land tenure influence

We found that land tenure significantly affects the spatial distributions of devegetation and DRF (Fig. 6). Throughout the period 2003–2020, Private and other lands (PRIV) experienced the largest total areas of devegetation and DRF, 12.3 and 14.7 million hectares respectively, with a mean annual DRF burned area of 816 ± 258 ha (Fig. 6; Table S3). Nonetheless, when normalising by the total native vegetation area of each tenure, Other public lands (TP) was the land tenure type most impacted by devegetation between 2003 and 2020, with 28 % of its native vegetation area being lost to human land uses, while Rural settlements (AR) had the highest extent of DRF cumulative burned area with 41 % of their native vegetation burned (Fig. 6; Table S3). Sustainable use Protected Areas (PA_US) and Public forests (FP) also experienced extensive devegetation and DRF, relative to their native vegetation surface (Fig. 6). Indigenous Territories (IT) and Strictly Protected Areas (PA_PI) seemed to consistently limit devegetation, but not DRF, with 16 % and 12 % of their native vegetation area burned, respectively (Fig. 6; Table S3). Finally, TP was the only land tenure type where DRF affected a smaller area of native vegetation than that impacted by devegetation (Fig. 6).

4. Discussions

Our study aimed to quantify the contribution of devegetation to fire occurrence and assess the extent of native vegetation surface burned by devegetation related fires, focusing on the portion of the Brazilian Cerrado encompassing Mato Grosso and the MATOPIBA region during the period 2003–2020. Additionally, we examined whether fires associated with devegetation exhibit distinct characteristics in terms of size distribution and seasonality, potentially altering the Cerrado fire regime. We also investigated how different land tenure types influence the spatial patterns of devegetation and related fires. Our findings quantify the impacts of devegetation on native vegetation, both in terms of land converted and area burned by altered fires linked to the land conversion process, that were only partially mitigated by the presence of Protected Areas and Indigenous Territories.

4.1. Devegetation as a widespread fire driver in the Cerrado

Fires resulting from devegetation (i.e., Devegetation Related Fires - DRF) in our study area, from 2003 to 2020, accounted for 11.4 % of total number of fires and 12.4 % of total burned area (Table 2), indicating that devegetation is a relevant fire driver in the region. These findings corroborate previous qualitative assessments – mainly based on field experiences and geospatial data observation – that had already suggested this causal relationship between the two processes (Pivello et al., 2021; Schmidt and Eloy, 2020). Our results also extend prior quantitative results. They do not align with findings of Mataveli et al. (2021), who reported a limited connection between devegetation and fires, although their analyses were based on fire emissions and focused exclusively on two Protected Areas in Bahia. Conversely, our findings are consistent with the ones of Oliveira et al. (2022), who determined that devegetation accounts for 12 % of the variability in the location of fire activity, with fire occurrence and impact increasing in proximity to converted areas. Similarly, our results align with Ribeiro et al. (2024), who observed an increase in burned area over devegetated patches at the moment of conversion. However, these previous results were not expressed in terms of fire counts and burned area, nor did they examine the impacts on surrounding native vegetation, focusing instead solely on converted patches. Our fire-based approach reveals that burned area associated with devegetation extends beyond devegetated areas, impacting also surrounding native vegetation. Fire escape rates - the proportion of DRF burned area not overlapping devegetated areas relative to the total DRF burned area (Table 2) - showed that the fire activity within devegetated areas (i.e., 7.1 % of the total DRF burned area) was substantially lower than that occurring outside these areas (i.e., 92.9; Fig. 3; Table 2).

The state of Mato Grosso had the lowest devegetation-fires association, both in terms of number of fires and burned area, which is likely due to the lower relative devegetated area (16.2 %) during the period 2003–2020 compared to the other states in the study area (Table 2). Conversely, in Maranhão, our analyses reveal that devegetation led to a higher proportion of fires and burned area (Table 2), probably influenced by the fact that Maranhão experienced the second largest relative devegetated area (21.8 %; Table 2) and a high number of fires (88,023; Table 2). This may also be linked to the fact that Mato Grosso had the largest average fire size, whereas Maranhão had the smallest (Table S2), and the largest extent of Indigenous Territories in which many fires unrelated to devegetation happen (Carranza et al., 2014; Pivello, 2011).

4.2. Impacts of devegetation

Between 2003 and 2020, 19.1 % of the Cerrado native vegetation surface have been converted to other land uses in the states of Mato Grosso, Maranhão, Tocantins, Piauí and Bahia, with Bahia having nearly a quarter of its original native vegetation surface converted (Fig. 3). This extensive land conversion has negatively impacted biodiversity, ecosystem dynamics, and local communities (Assis et al., 2021). Furthermore, the increase in anthropogenic ignitions associated with the devegetation process has led to the occurrence of DRF, which burned 25.6 % of the native vegetation in the study area, corresponding to 1.34 times the area directly affected by devegetation (Fig. 3).

DRF are fires originated by anthropogenic processes of devegetation and hence leading to vegetation degradation and negative socio-ecological impacts (Pivello et al., 2021; Silva et al., 2020). The high rate of fire escape associated with DRF (92.9 %) indicates that these fires predominantly burn native vegetation surrounding devegetated patches (Table 2). In fact, the reduced overlap between devegetated and DRF areas may suggest that the combined direct (land conversion) and indirect (fire) impacts of devegetation affect more than twice the area typically accounted for in devegetation estimates. This highlights the extensive and far-reaching consequences of devegetation on the ecosystem.

Tocantins is the most impacted state by devegetation and DRF in absolute terms (Fig. 3; Table 2), consistent with previous findings (Drost et al., 2019; Parente et al., 2021). This extensive impact likely contributes to Tocantins being the state most affected by DRF relative to its total vegetation area (Table 2) and having the highest rate of fire escape (96.5 %; Table 2). Conversely, Bahia is the state most affected by devegetation in relative terms (Fig. 3), which can be attributed to its smaller overall native vegetation cover and the extensive land conversion undergone in the past, albeit concentrated in a few municipalities (Parente et al., 2021; Pompeu et al., 2024). This concentrated land conversion may also explain why Bahia is the only state where DRF covered a smaller area than devegetation, as there may have been less vegetation available to burn.

4.3. Devegetation related fires characteristics

Devegetation related fires showed statistically significant differences in fire size distribution and seasonality compared to devegetation Independent Fires (IF; Table S2). This suggests that devegetation, through DRF, might alter the fire regime in the Cerrado, particularly in terms of fire size and seasonality. However, these differences were moderate (Fig. 4; Fig. 5), possibly due to the high rate of fire escape. Once DRF spread into the surrounding native vegetation, their behaviour may not differ considerably from that of IF.

The (20 %) smaller average size of DRF (Fig. 4) was expected, as these fires may spread into more fragmented landscapes compared to IF (Hantson et al., 2015). IF, which include cultural and natural fires, often occur in Indigenous Territories and Protected Areas, where the native vegetation cover is more continuous, and fires are often left burning, when conditions are favourable (Garnett et al., 2018; Hantson et al., 2015). The inverse relationship between fire size and frequency of occurrence, observed in both DRF and IF, is a well-established trend in fire science (Hantson et al., 2015b). Fires size is driven by multiple factors, including meteorological conditions, fuel connectivity, and the availability of resources and expertise, as well as the willingness to suppress fire or allow it to spread (Hantson et al., 2015b; Jones et al., 2022). In the case of DRF, the prevalence of smaller fires may result from reactive suppression of unintentional fires, as well as from other socio-environmental factors, such as landscape mosaic patterns or population density (Hantson et al., 2015b; Jones et al., 2022).

DRF occurring (29 days) later in the dry season and being more concentrated within the same period (Fig. 5; Table S2) was also expected, as conversion fires typically occur at the end of the dry season, within precise time frames determined by land use practices (Da Silva Arruda et al., 2024; Le Page et al., 2010). This finding is concerning, as fires occurring at the end of the dry season, when vegetation is at its driest, spread more rapidly, increasing the risk of becoming uncontrollable (Arruda et al., 2024). For this reason, fire management practices, such as prescribed burning, are mostly implemented at the beginning of the dry season (Franke et al., 2024).

4.4. Influence of land tenure on devegetation and DRF

Devegetation and DRF primarily happened in the Private and other lands tenure class (Fig. 6), where the native vegetation cover is one or more orders of magnitude larger than in other tenure categories (Table S3). Private lands are in most cases still legally convertible (see Section 2.1.1), making them easily exploitable by small and medium landowners, as well as by agribusiness companies. Fire use, which should be restricted to Protected Areas and Indigenous Territories (Durigan and Ratter, 2016; Schmidt and Eloy, 2020), is also occurring on private lands and other tenures (Fig. 6).

In relative terms, Other public lands, Rural settlements and Public forests were widely impacted by devegetation and DRF, suggesting that a lack of proper management and monitoring by designated state agencies may be contributing to the loss of native vegetation in these areas. Similarly, devegetation and DRF occurrence levels in Sustainable use Protected Areas are comparable to those of Other public lands, Rural settlements and Public forests, indicating that overall they may not be as effective in mitigating the direct and indirect impacts of devegetation, as shown by previous studies (Françoso et al., 2015).

Our results show that devegetation in Indigenous Territories and Strictly Protected Areas was limited, emphasizing the effectiveness of these governance models in halting the loss of native vegetation (Carranza et al., 2014; Françoso et al., 2015). However, these areas appeared more vulnerable to indirect impacts from devegetation, as DRF affected large areas within these lands. These findings highlight the need to enhance monitoring efforts in Indigenous Territories and Protected Areas, particularly along their borders (Ricketts et al., 2010), as devegetation from neighbouring areas can indirectly affect them through DRF.

4.5. Limitations of the study

The main limitations of this study stem from the temporal and spatial resolution of the datasets used to identify Devegetation Related Fires. First, we associated fires with devegetation based on the location of ignition points within 2-year windows, reflecting the biannual temporal resolution of the PRODES devegetation dataset until 2012. Greater temporal precision of land conversion data would improve fire classification, ensuring that Devegetation Related Fires are identified only when fires occur after the land has been converted. Second, the 500m resolution of the Global Fire Atlas fire ignition data introduced a consistent level of uncertainty in the fires classification process.

Additional limitations are related to the analysis of Devegetation Related Fires characteristics. We used devegetation Independent Fires as a control group to assess if Devegetation Related Fires exhibited distinct characteristics, with potential alteration effects of the Cerrado fire regime. To enhance this assessment, filtering devegetation Independent Fires, such as by isolating lightning-ignited fires and excluding agricultural fires, would yield a more accurate control group. Furthermore, incorporating other fire attributes such as fire severity, duration, or rate of spread, when available, would offer a more comprehensive analysis.

5. Conclusions

This study shows that devegetation is a widespread driver of fires in the Brazilian Cerrado, being linked to approximately 12 % of the total burned area within our study area, spanning Mato Grosso and the MATOPIBA region, between 2003 and 2020. The fires we termed Devegetation Related Fires burned around a quarter of the study area's total native vegetation surface, over the 18-year period, amounting to approximately 20 million hectares, and to 1.34 times the area lost to devegetation. Moreover, these fires exhibited smaller average sizes and distinct seasonality compared to those not associated with devegetation, posing a risk of altering the Cerrado fire regime. Our results also suggest that Devegetation Related Fires are severely impacting Cerrado's public lands, including Protected Areas and Indigenous Territories, despite their crucial role in preventing devegetation. These altered fires should be recognised as a significant additional degradation effect of land conversion. Reducing the rate of devegetation in the Cerrado is crucial for preserving the ecological integrity of the biome and limiting the occurrence of such anthropogenic fires. Efforts in fire governance, particularly through Integrated Fire Management, should prioritize areas with high devegetation rates. Management of public lands such as Public forests should be strongly strengthened as they appear particularly vulnerable to land conversion and related fires. Monitoring of Protected Areas and Indigenous lands should focus on their borders to prevent Devegetation Related Fires from encroaching from adjacent areas. We also recommend increased public and private investment in the development, enhancement, and continuity of devegetation and fire monitoring systems, such as PRODES and the Global Fire Atlas. These investments would provide essential technical support for fire management and lay the foundation for future research into the complex interactions between devegetation and fire. Improving the spatial and temporal resolution of monitoring products, as well as their coverage, could help overcome some of the main limitations of this study and enhance the identification of Devegetation Related Fires. Further research should also expand our findings to the rest of the Cerrado and to other biomes, while stratifying results by vegetation types with varying degrees of adaptability to fire.

CRediT authorship contribution statement

Gian Luca Spadoni: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Jose V. Moris:** Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation. **Carlota Segura-Garcia:** Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Ana Carolina Pessoa:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Matthew W. Jones:** Writing – review & editing, Supervision, Methodology, Data curation. **Manoela S. Machado:** Writing – review & editing, Validation, Supervision, Formal analysis. **Renzo Motta:** Writing – review & editing, Visualization, Supervision, Conceptualization. **Ane Auxiliadora Costa Alencar:** Writing – review & editing, Supervision, Conceptualization. **Davide Ascoli:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Imma Oliveras Menor:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.125637.

Data availability

Data will be made available on request.

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