Biodiversidade Brasileira
Revista Científica

SCIENTIFIC ARTICLE

Toward management in conservation landscapes: an open-source framework for fire regime gradient analysis

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Como citar:
Costa CF, Cunha CS, Ramos Pereira MJ. Toward management in conservation landscapes: an open-source framework for fire regime gradient analysis. Biodivers. Bras. [Internet]. 2026; 16(3): e2961. doi:10.37002/biodiversidadebrasileira.v16i3.2961

Recebido em 07/05/2026 – Aceito em 10/08/2026

Editor temático: Romário de Oliveira de Santana

ABSTRACT – Wildfires have become a significant environmental challenge, exacerbated by climate change. Remote sensing technologies have advanced, but their use for monitoring fire frequency and severity remains limited, particularly in resource-constrained regions. To address this, we developed an open-source tool on Google Earth Engine that generates fire regime maps, combining fire frequency and severity data, thus allowing a temporal assessment of fire severity. The tool utilizes freely available satellite data, including MapBiomas Fire data (1985–2023) and fire spectral indices (NBR, dNBR) from Sentinel-2A imagery (2019–2023). Applied to two conservation units in Brazilian savannas, the tool revealed contrasting fire regimes: in the CGEPA Chapada dos Guimarães, 68% of burned areas showed low frequency and low severity, consistent with fire-adapted cerrado vegetation, while higher-intensity regimes were concentrated in pasturelands; in the RPPN SESC Pantanal, 90% of the burned area was affected by moderate to high severity, strongly influenced by the exceptional wildfire events of 2019 and 2020. The tool offers a cost-effective, scalable, and replicable solution for monitoring fire dynamics, identifying priority areas for management intervention, and supporting informed decision-making in conservation units. Its open-source nature and reliance on freely available satellite data democratize environmental monitoring, making it accessible even in resource-limited settings. This approach aligns with global strategies to mitigate the impacts of climate change and contributes to broader scientific and policy initiatives aimed at wildfire mitigation and sustainable ecosystem management.
Keywords: dNBR, fire severity, NBR, open-source tool, savannas.

Rumo à gestão em paisagens de conservação: um *framework* de código aberto para análise de gradientes do regime de fogo

RESUMO – Os incêndios florestais se tornaram um grande desafio ambiental, agravado pelas mudanças climáticas. Embora as tecnologias de sensoriamento remoto tenham avançado, o seu uso para monitorar a frequência e a severidade dos incêndios ainda é limitado, especialmente em regiões com poucos recursos. Para resolver isso, desenvolvemos uma ferramenta de código aberto no Google Earth Engine que gera mapas de regimes de incêndio, combinando dados de frequência e severidade de incêndios. A ferramenta utiliza dados de satélite acessíveis gratuitamente,

incluindo o MapBiomas Fogo (1985–2023) e índices de incêndio (NBR, dNBR) da imagem do Sentinel-2A (2019–2023). Aplicada a duas unidades de conservação em savanas brasileiras, a ferramenta revelou regimes de fogo contrastantes: na APA Chapada dos Guimarães, 68% das áreas queimadas apresentaram baixa frequência e baixa severidade, consistentes com a vegetação de cerrado adaptada ao fogo, enquanto regimes de maior intensidade se concentraram nas pastagens; na RPPN SESC Pantanal, 90% da área queimada foi afetada por severidade moderada a alta, fortemente influenciada pelos eventos excepcionais de 2019 e 2020. A ferramenta oferece uma solução de baixo custo, escalável e replicável para monitorar a dinâmica de incêndios, identificar áreas prioritárias para intervenção e apoiar a tomada de decisões em unidades de conservação. Seu caráter de código aberto e o uso de dados satelitais gratuitos democratizam o monitoramento ambiental, tornando-o acessível mesmo em contextos com recursos limitados. Essa abordagem se alinha às estratégias globais de mitigação dos impactos das mudanças climáticas e contribui para iniciativas científicas e políticas voltadas à mitigação de incêndios e ao manejo sustentável dos ecossistemas.
Palavras-chave: ferramenta de código aberto, dNBR, NBR, savanas, severidade do fogo.

Hacia la gestión en paisajes de conservación: una plataforma open source para el análisis de gradientes del régimen de incendios

RESUMEN – Los incendios forestales se han convertido en un gran desafío ambiental, agravado por el cambio climático. Aunque las tecnologías de teledetección han avanzado, su uso para monitorear la frecuencia y la severidad de los incendios sigue siendo limitado, especialmente en regiones con recursos limitados. Para abordar este problema, desarrollamos una herramienta de código abierto en Google Earth Engine que genera mapas de regímenes de incendios, combinando datos de frecuencia y de severidad. La herramienta utiliza datos satelitales de acceso gratuito, incluyendo el MapBiomas Fogo (1985–2023) y los índices de incendio (NBR, dNBR) derivados de imágenes de Sentinel-2A (2019–2023). Aplicada a dos unidades de conservación en sabanas brasileñas, la herramienta reveló regímenes de fuego contrastantes: en el APA Chapada dos Guimarães, el 68% de las áreas quemadas presentó baja frecuencia y baja severidad, consistente con la vegetación de cerrado adaptada al fuego, mientras que los regímenes de mayor intensidad se concentraron en pastizales; en la RPPN SESC Pantanal, el 90% del área quemada fue afectada por severidad moderada a alta, fuertemente influenciada por los eventos excepcionales de 2019 y 2020. La herramienta ofrece una solución rentable, escalable y replicable para monitorear la dinámica del fuego, identificar áreas prioritarias para intervención y apoyar la toma de decisiones en unidades de conservación. Su carácter de código abierto y el uso de datos satelitales gratuitos democratizan el monitoreo ambiental, haciéndolo accesible incluso en contextos con recursos limitados. Este enfoque se alinea con las estrategias globales para mitigar los impactos del cambio climático y contribuye a iniciativas científicas y políticas orientadas a la mitigación de incendios y al manejo sostenible de los ecosistemas.
Palabras clave: herramienta de código abierto, dNBR, NBR, sabanas, severidad del fuego.

Introduction

Fire is a natural event in many ecosystems worldwide, often playing a crucial ecological role. Savannas, grasslands, mediterranean shrublands, tropical dry forests, heathlands and peatlands are some ecosystems where fire occurs naturally [1, 2, 3]. Fire is a powerful eco-evolutionary force, influencing a wide range of processes; it shapes organismal traits, regulates population sizes, mediates species interactions, and determines community composition [4]. Fire also plays a key role in carbon and nutrient cycling, ultimately driving ecosystem function. However, even in fire-prone ecosystems, increasingly destructive wildfires driven by criminal activities or human-induced landscape changes demand urgent attention. Measuring fire severity is crucial for understanding its impact on ecosystems and guiding effective management strategies. Fire severity influences vegetation recovery, soil stability, and the redistribution of carbon and nutrients, which are essential for maintaining ecosystem function [2, 5]. High-severity fires can disrupt natural cycles, leading to biodiversity loss, soil degradation, and altered water dynamics, while low-severity fires often support ecological processes in fire-adapted systems [6]. Quantifying fire severity allows researchers and land managers to assess the ecological consequences of fires, evaluate post-fire recovery, and develop strategies to mitigate risks associated with both intense wildfires and fire suppression in fire-dependent ecosystems.

Fire is a natural ecological event typical of brazilian savannas, occurring periodically and shaping the structure and dynamics of the local biota [7, 8, 9]. However, land use changes, mostly resulting from the conversion of native vegetation caused by large-scale agriculture, mineral extraction and livestock production [10], provide opportunities for large fires to occur in these environments and also in typically forested areas. In addition, the relaxation of environmental inspection and financing policies in Brazil has facilitated irresponsible practices and rhetoric that weaken environmental protection, leading to an increase in criminal fires [11]. In South America, Brazil stands out for having the highest incidence of wildfires [12, 13], with at least 19.6% of its territory having experienced burning at least once from 1985 to 2023 [14]. During this period, most wildfires occurred in the Amazon and Cerrado ecoregions, while the Pantanal registered the highest proportion of the burned area. In most of these fires, native vegetation was significantly affected by the flames [14]. Unlike the Amazon, which is primarily forested, the Cerrado and Pantanal encompass a mosaic of landscapes, including predominantly savannas and open areas, as well as forested areas [15, 16, 17]. These ecosystems are largely classified as fire-dependent due to the array of adaptations that their plant and animal species have evolved [18, 19]. Changes in fire intensity, spatial extent and periodicity can significantly impact biodiversity, directly and indirectly, at different spatial and temporal scales [20].

The Cerrado stands out for its exceptional biodiversity, surpassing all other savannas worldwide in the variety of plant and animal species [21, 22]. However, by 2020, it is estimated that it has lost 50% of its native vegetation cover [10]. The Pantanal, a large seasonal floodplain located in the heart of South America, covers 1.8% of Brazil's territory [10], making it the largest floodplain in the world. Climatic changes associated with land use and cover alterations in the Cerrado include rising temperatures and reduced air humidity [23]. Additionally, the decline in precipitation, primarily linked to shifts in atmospheric circulation caused by global climate change, affects both the Cerrado and the Pantanal. This decrease in rainfall is particularly pronounced during the dry season (june-september) and the onset of the rainy season (october-november), periods that coincide with the majority of wildfires [24, 25, 14]. While both ecoregions exhibit seasonal flooding patterns, the Cerrado is predominantly situated in elevated areas with well-drained soils that do not experience flooding [26]. In contrast, the Pantanal is subject to significant climate shifts, particularly reductions in rainfall and river flow [27]. Intense flooding periods foster the development of biomass-accumulating plants, and when the dry season arrives, this vegetation tends to become fuel, facilitating the spread of large fires in the region [28, 29]. The incidence of wildfires increased significantly in 2020 [30], marking the largest series of fires in the Pantanal in the last 20 years. During august and september, the Pantanal recorded approximately 22,000 fire outbreaks [31]. Nearly 30% of the total area of the Pantanal was consumed by fire, with an estimated minimum of 17 million vertebrates perishing as a direct consequence of those fires [32]. The continuous conversion of native areas, combined with climatic factors, is altering the seasonal dynamics of these ecosystems, prolonging dry periods and increasing the risk of wildfires in the future.

Affected areas show a distinct spectral response that can be monitored with remote sensing data [33]. In this context, several platforms are dedicated to monitoring the brazilian territory through satellite imagery. The Fire Database [31] is the official monitoring system that provides data used by the brazilian government to demonstrate its compliance with international agreements. It is an important tool for identifying and monitoring fire outbreaks, enabling the anticipation of risks in vegetative areas. The Terra Brasilis Portal also offers resources for querying, analyzing, and disseminating geographical data generated by monitoring projects such as PRODES and DETER [34], all developed and maintained by the National Institute for Space Research (INPE). In addition, the MapBiomas Fire Project [14] makes a significant contribution by validating these data and mapping fire scars across brazilian territory from 1985 to 2023, with data captured at both monthly and annual intervals [14]. This comprehensive mapping effort is complemented by the Google Earth Engine, a cloud-computing platform developed by Google specifically designed to analyze and process of extensive geospatial datasets [35]. These platforms primarily document fire occurrence and extent; however, characterizing the ecological impact of fire also requires quantifying its severity – that is, the degree of change imposed on the ecosystem by the burning event.

Recent studies have employed spectral indices, such as Normalized Burn Ratio (NBR) and Difference Normalized Burn Ratio (dNBR), derived from satellite imagery available through these platforms, to detect changes, pre and post-disturbance and, quantify wildfire occurrence, frequency, and severity [36]. The NBR index is suitable for detecting changes in the landscape affected by fire and is considered effective in identifying burned areas [37]. Variations in near-infrared (NIR) reflectance can indicate changes in photosynthetically active vegetation, while changes in shortwave infrared (SWIR) reflectance can signal reduced photosynthetically active vegetation, moisture content, ash deposition, and increased soil exposure. In studies related to forest fires in conservation units, it has been observed that the dNBR enhances the changes between NBR images, highlighting the presence of fire [37]. The dNBR is obtained by subtracting the post-fire NBR image from the pre-fire NBR image [38].

Despite the growing availability of remote sensing platforms and spectral indices for fire monitoring, their integration into systematic analyses combining fire frequency and severity over long time series remains incipient in the brazilian context, with few studies addressing both dimensions simultaneously [39, 40]. Studies on fire dynamics in the brazilian Cerrado using satellite-derived burned area products have been performed mostly on limited areas, with little known about the behavior of those products across different land use and cover classes [41]. Furthermore, an official spatial database that systematically accounts for fire-affected areas combining frequency and severity at local and regional scales is not yet available in Brazil, with current monitoring in conservation units still largely based on active fire data from moderate-to-low spatial resolution sensors [39]. The translation of these tools into operational, routine use within conservation units, however, faces persistent barriers: although recent advances in Integrated Fire Management in protected areas in the Cerrado are evident, budget cuts in environmental management and research have undermined these efforts, limiting the implementation of standardized fire monitoring protocols [11]. The analysis of fire-affected conservation areas in the Pantanal further highlights limitations in the implementation of conservation policies, particularly in terms of governance and enforcement, underscoring the need for adaptive management strategies that can respond to evolving threats such as fire regimes and land-use changes [42]. In this context, accessible, replicable, and scalable tools are essential to support fire monitoring and adaptive management in protected areas.

Our primary aim was therefore to develop an open-source code within Google Earth Engine capable of generating a temporal fire severity assessment, combining fire severity derived from Sentinel-2A (2019–2023) imagery with historical fire frequency data from the MapBiomas Fire Project (1985–2023) [14]. Specifically, we sought to: (i) describe the methodological framework of the tool, including its design, inputs, and outputs; (ii) demonstrate its applicability by applying it to two conservation units in brazilian savannas, one in the Cerrado and one in the Pantanal ecoregion, both with documented fire histories and active fire management programs; and

(iii) discuss the ecological implications of the observed fire regimes in each area, with emphasis on their relevance for conservation planning and adaptive management.

Materials and Methods

Focal areas

Our focal areas were two conservation units in Brazil: Chapada dos Guimarães Environmental Protection Area (CGEPA), in the Cerrado ecoregion and the SESC Pantanal Private Natural Heritage Reserve (RPPN), situated in the Pantanal ecoregion (Figure 1). Both are located in the state of Mato Grosso and have a history of fire. These areas were selected due to their ecological relevance, documented fire dynamics, and the need for improved tools to support fire management, providing a suitable context to test the applicability of the proposed approach in conservation units.

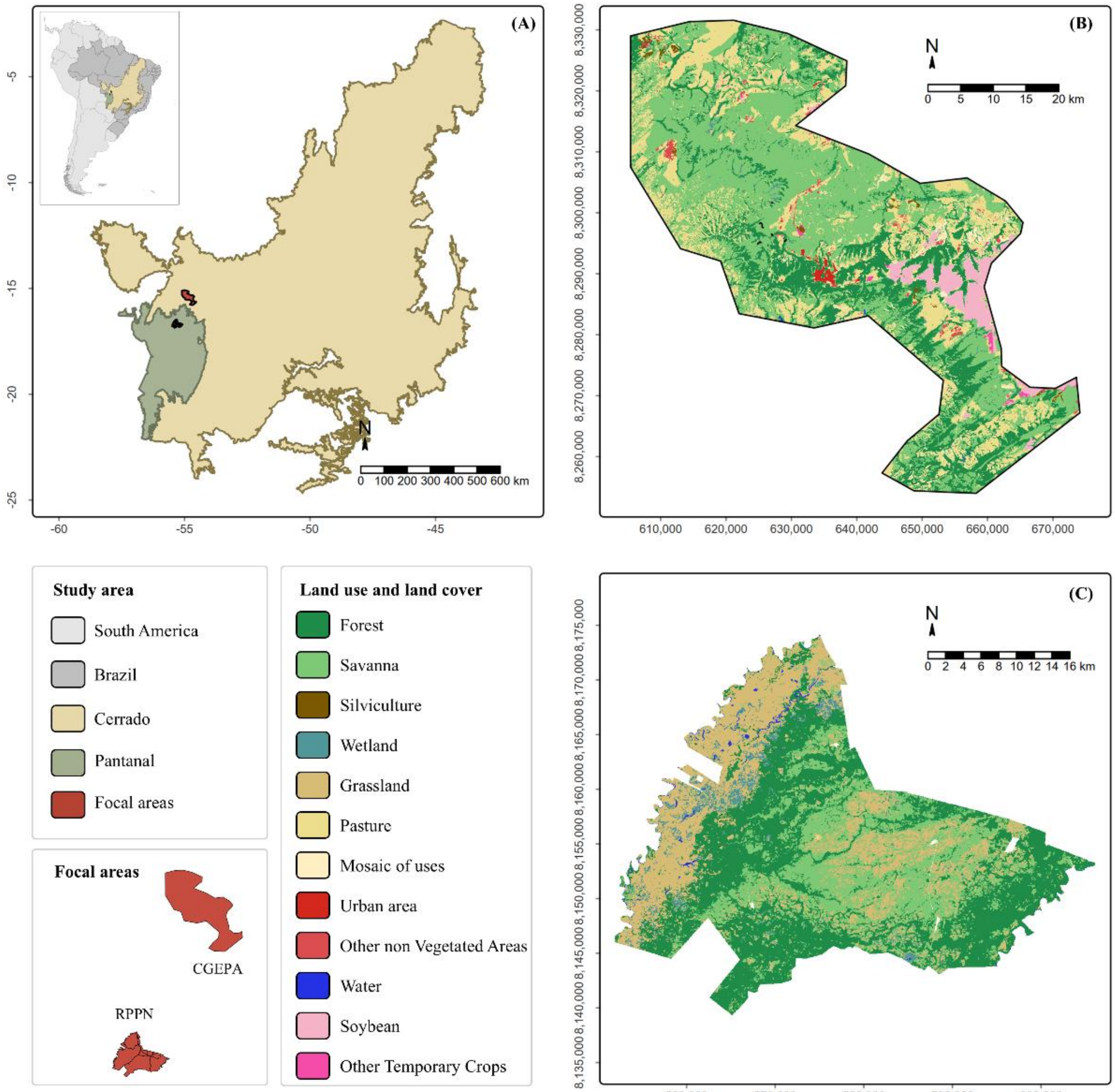

Figure 1 – Map of Brazil (A) highlighting the Cerrado ecoregion (dark yellow–gold) and the Pantanal ecoregion (olive green), indicating the two sampling areas. Insets show detailed land use and land cover maps for 2023 of the Chapada dos Guimarães Environmental Protection Area (CGEPA) (B) and the SESC Pantanal Private Natural Heritage Reserve (RPPN) (C) [43].

Chapada dos Guimarães Environmental Protection Area (CGEPA)

The protected area extends over 251,848 hectares and consists of a set of conservation units, such as the Chapada dos Guimarães National Park, the Cuiabá-Chapada dos Guimarães-Mirante Park Road, the Quineira State Park, and the Natural Monument of the Geodesic Center of Latin America. The area features well-preserved ecosystems, including riparian forests, gallery forests, dry forests, and Cerrado stricto sensu, as well as savanna formations, palm swamps, and grassland systems [15, 16]. Additionally, the protected area features sections that have been converted into pastures and agricultural lands, inherited from before the implementation of its designation in 2002 [44] (Figure 1). The area is influenced by the rainy season, from october to march, is followed by dry periods from april to september, resulting in an average annual rainfall of 1500 mm [45]. One of the region's most significant features is its preservation of vital water resources, including springs, rivers, and recharge areas of the Guarani Aquifer, one of the world's primary freshwater reserves [46].

SESC Pantanal Private Natural Heritage Reserve (RPPN)

Considered the largest Private Natural Heritage Reserve in Brazil, spanning 108,000 hectares in the municipality of Barão do Melgaço, Mato Grosso, the RPPN is located amidst extensive areas of relatively preserved native vegetation, with some pastoral areas (Figure 1). The region is characterized by a tropical climate with dry winters and rainy summers, receiving annual rainfall ranging between 1000 mm and 1600 mm [47]. The high biodiversity of the Pantanal results from the integration of flora and fauna elements from the Cerrado, Chaco, Amazon, and Atlantic Forest. Additionally, the diversity of habitats in the Pantanal is closely linked to geomorphological variations and the unpredictability of flooding, which creates distinct environments: permanently flooded areas (such as forests dominated by Cambará trees), rarely flooded areas (such as fields with murundus - elevated mounds in floodplain landscapes), non-flooded areas (such as forests with acuri palm trees), and zones with annually variable dynamics [17, 48, 49]. The flooding cycle also annually replenishes soil nutrients, boosting ecosystem productivity and supporting unparalleled population abundance [50].

Open-source code and outputs

The code supporting this study is publicly available in a dedicated repository, ensuring transparency, reproducibility, and accessibility for validation and future applications. Access details are provided in the Data Availability section. The stages of code development and the final outputs are discussed in detail in the following sections. The overall methodological workflow is summarized in Figure 2, which illustrates the three main stages of the analysis: (i) the generation of the fire frequency map from MapBiomas Fire data; (ii) the generation of the fire severity map from Sentinel-2A imagery using NBR and dNBR indices; and (iii) the integration of both layers in QGIS [51] to produce the fire regime gradient map.

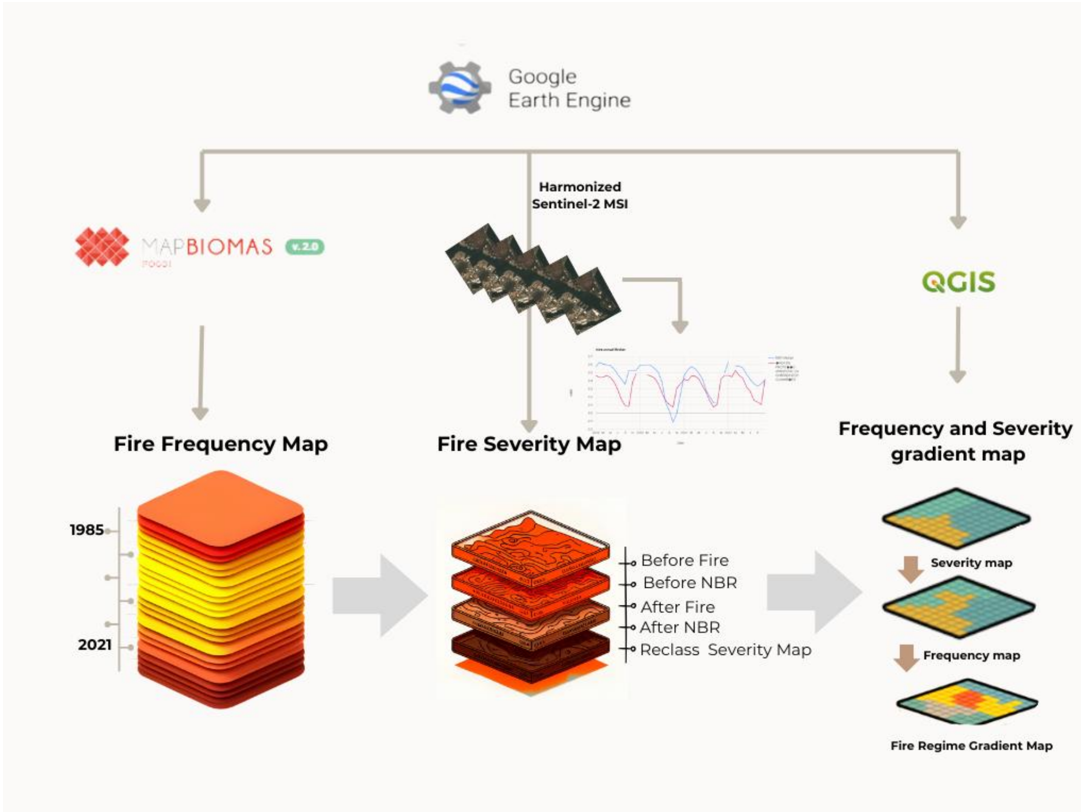

Figure 2 – Flowchart of the activities and processes carried out for the development of the fire regime gradient map, representing the temporal assessment of fire severity for the Chapada dos Guimarães Environmental Protection Area (CGEPA) and the SESC Pantanal Private Natural Heritage Reserve (RPPN), Mato Grosso, Brazil.

Fire frequency map

Using data sourced from the MapBiomas Fire Project [14], accessed through the Google Earth Engine via toolkit, we created a map depicting the frequency of wildfire events. The term 'fire frequency' denotes the number of occurrences a specific location experiences fires within a defined timeframe. We processed a collection of images containing annual burned area and fire frequency data. For the fire frequency analysis from 1985 to 2023, we assigned a binary value to each pixel, 1 if it burned during the year and 0 if it did not. We then summed these values across years, normalized the result for each pixel to a scale of 0 to 1, and multiplied by 100 to express the values as percentages, converting the final results to integers. We then summed all the annual layers into a single layer. The fire frequency product enabled us to estimate the recurrence of events in the studied pixels. Subsequently, we classified the fire frequency data into six distinct categories: No fire record, low fire record, moderate-low fire record, moderate fire record, moderate-high fire record and high fire record.

Fire intensity map

Fire intensity quantifies the energy released during a fire, typically measured as heat per unit area. Our analysis of wildfire indices utilized Sentinel-2A imagery from the 'COPERNICUS/S2_SR_HARMONIZED' collection, covering the period from March 2019 to January 2023. This high-resolution multispectral imaging mission, conducted by Copernicus Sentinel-2A, provides extensive coverage to support land monitoring studies. The mission enables the observation of various environmental factors, including vegetation, soil, water cover, inland water bodies, and coastal regions, with a revisiting time of five days. To identify burned areas, we applied the Normalized Burn Ratio (NBR) index, following the methodology described by [36].

$$NBR = \frac{(\mathrm{NIR} - \mathrm{SWIR})}{(\mathrm{NIR} + \mathrm{SWIR})}$$

High NBR values indicate healthy, dense vegetation, while values near zero reflect exposed soil or sparse vegetation with lower NIR and SWIR reflectance. Negative values indicate the presence of water, which reflects less in the NIR. In the context of fires, areas with reduced NBR values post-fire indicate degraded vegetation and exposed surfaces. The next step of the code then involves applying the add NBR function within our designated areas of interest, leveraging the NIR (B8) and SWIR-2 (B12) bands from Sentinel-2A imagery. Furthermore, we used the maskCloudAndShadowsSR function to mask out clouds and shadows present in the images. Following the definition of the image collection for computing and interpreting the indices, we advanced to the image processing phase. This entailed filtering based on date, location, and the proportion of cloudy pixels. We executed the cloud and shadow masking function, chose pertinent bands, and computed the NBR. Subsequently, we merged the images by date using the mosaicByDate function. We reduced the data to a monthly resolution and generated a time series graph of the intra-annual median NBR (Figure 4).

When we analyzed the time series graph of the NBR for the conservation units, we noticed the presence of seasonalities with both positive and negative NBR values (see Figure 4). We decided to select the period with the lowest NBR (negative NBR) to define the post-fire area and an image with a higher NBR for the pre-fire period (positive NBR). The calculation of pre-NBR and post-NBR enables the study of change detection through multi-temporal visual analysis. In other words, it becomes possible to compare the alterations occurring between a period before and after the event (Appendix Figure A1). Subsequently, we used the dNBR, to identify changes between pre-fire and post-fire periods.

$$\mathrm{dNBR} = \mathrm{NBRpre} - \mathrm{NBRpost}$$

After calculating the dNBR, we reclassified the pixels using the methodology outlined by the United States Geological Survey (USGS). The following classes were adopted: Unburned, Low intensity, Moderate-low intensity, Moderate-high intensity, and High intensity.

Fire regime gradient map

After generating the fire frequency and fire intensity maps, both layers were integrated in QGIS [51] using a pixel-based decision matrix to produce a final fire regime severity map. The resulting classification combined information on the historical recurrence of fire events and their spectral intensity, allowing the identification of areas subjected to distinct levels of fire pressure. Pixels with no fire record in either layer were assigned to class 0 (no fire record), whereas the remaining classes – low (1), moderate-low (2), moderate (3), moderate-high (4), high (5), and severe (6) – represented increasing levels of fire regime severity. Higher classes occurred only where both fire frequency and fire intensity were simultaneously elevated. This approach prevents extreme values in a single dimension from dominating the final classification, ensuring that the resulting map reflects the combined effects of recurrent and intense fire events. Both variables contributed equally to the final classification, with no weighting applied to either fire frequency or fire intensity.

Results and Discussion

Open-source tool for analyzing temporal fire severity using Google Earth Engine

Our open-source code, available on Google Earth Engine, provides a robust tool for analyzing temporal patterns of fire severity in any region of interest. In the context of conservation units, this tool represents a practical and accessible approach to support fire monitoring and adaptive management. By enabling the identification of spatial and temporal patterns of fire frequency and severity, it provides relevant information for decision-making processes, including the prioritization of areas for monitoring, prevention, and management interventions. Due to its high adaptability, it only requires the substitution of the area of interest to initiate the analysis. Users can achieve personalized results for their study areas by making minimal adjustments to the cloud cover percentage, which varies by region. The flexible adaptation of the code also allows it to be integrated with other geospatial databases, such as land use change maps, enhancing its applicability in multidimensional studies. For example, it is possible to correlate fire patterns with soil and vegetation health indicators, providing a broader understanding of the ecological impacts of wildfires. This multidisciplinary approach is particularly relevant in the context of climate change, where data-driven adaptive management is essential. Savannas and other regions worldwide are experiencing rapid changes in land use [52]. Understanding how these transformations affect, or are affected by, the occurrence and intensity of fires is crucial for interpreting how species and ecosystems respond to these pressures. Through time series analysis of fire patterns and landscape changes, we identified areas with a higher likelihood of fire occurrence and greater vulnerability to loss. This enables a more efficient allocation of resources, focusing on strategic areas for monitoring, prevention, and mitigation.

Our tool has been developed to assist both researchers and decision-makers. It can serve as a foundation for identifying the most vulnerable sites that require greater attention in planning-controlled fire management and developing fire prevention actions. From the identified patterns and critical areas, it is possible to establish sampling grids ranging from low to high intensity and frequency of fire regime, allowing continuous monitoring of fire behavior and its impacts on flora and fauna populations and communities. In conservation units, this approach can support the establishment of management zones and guide the implementation of fire management strategies, such as prescribed burning and restoration actions.

Sentinel-2A stands out for its high spatial resolution, with visible, near-infrared (NIR), and shortwave infrared (SWIR) bands available at 10, 20, and 60 m. This makes it ideal for detecting detailed patterns in land use and cover, such as assessing wildfire severity. Its revisit interval of five days, enabled by the operation of two satellites, allows for near-continuous monitoring and increases the likelihood of acquiring cloud-free images. Sentinel-2A also offers a wide range of spectral bands, including the Red Edge band, which is particularly useful for advanced vegetation and soil analyses. For these reasons, and considering the focus of our case study, we selected Sentinel-2A. However, users of the code can choose longer time series or access specific information from previous years using Landsat satellite data. The choice between Sentinel-2A and Landsat satellites for remote sensing analyses should consider the project scope, as well as the required temporal and spatial scales, by evaluating the strengths and limitations of each sensor.

Landsat provides a long record of Earth observation, with data available since 1972, enabling historical studies and long-term analyses of environmental changes. While its spatial resolution of 30 meters is lower, it remains suitable for regional-scale studies, it remains adequate for regional-scale analyses. Its revisit frequency of 16 days can limit image availability in areas with frequent cloud cover. To use Landsat, the data processing code must be adjusted. This involves changing the data source to specific collections, such as Landsat Collection 2 Tier 1 or Tier 2, and adapting spectral indices to the corresponding bands, as their nomenclature differs from Sentinel-2A. For example, Sentinel-2A's band 8 (NIR) corresponds to band 5 in Landsat 8. Steps in the code that depend on specific resolutions or revisit frequencies must be modified to ensure compatibility. The lower revisit frequency of Landsat may require the use of composite data over longer periods to compensate for reduced image availability. Thus, the decision between Sentinel-2A and Landsat depends on the study's priorities, and it is essential to adapt analytical tools to maximize the advantages of each sensor.

Fire regime gradient maps

The integration of fire frequency and fire intensity layers generated the final fire regime gradient maps for both conservation units (Figure 3). The resulting products summarize the cumulative effects of fire recurrence and fire intensity, allowing the identification of areas subjected to different levels of fire pressure and ecological disturbance.

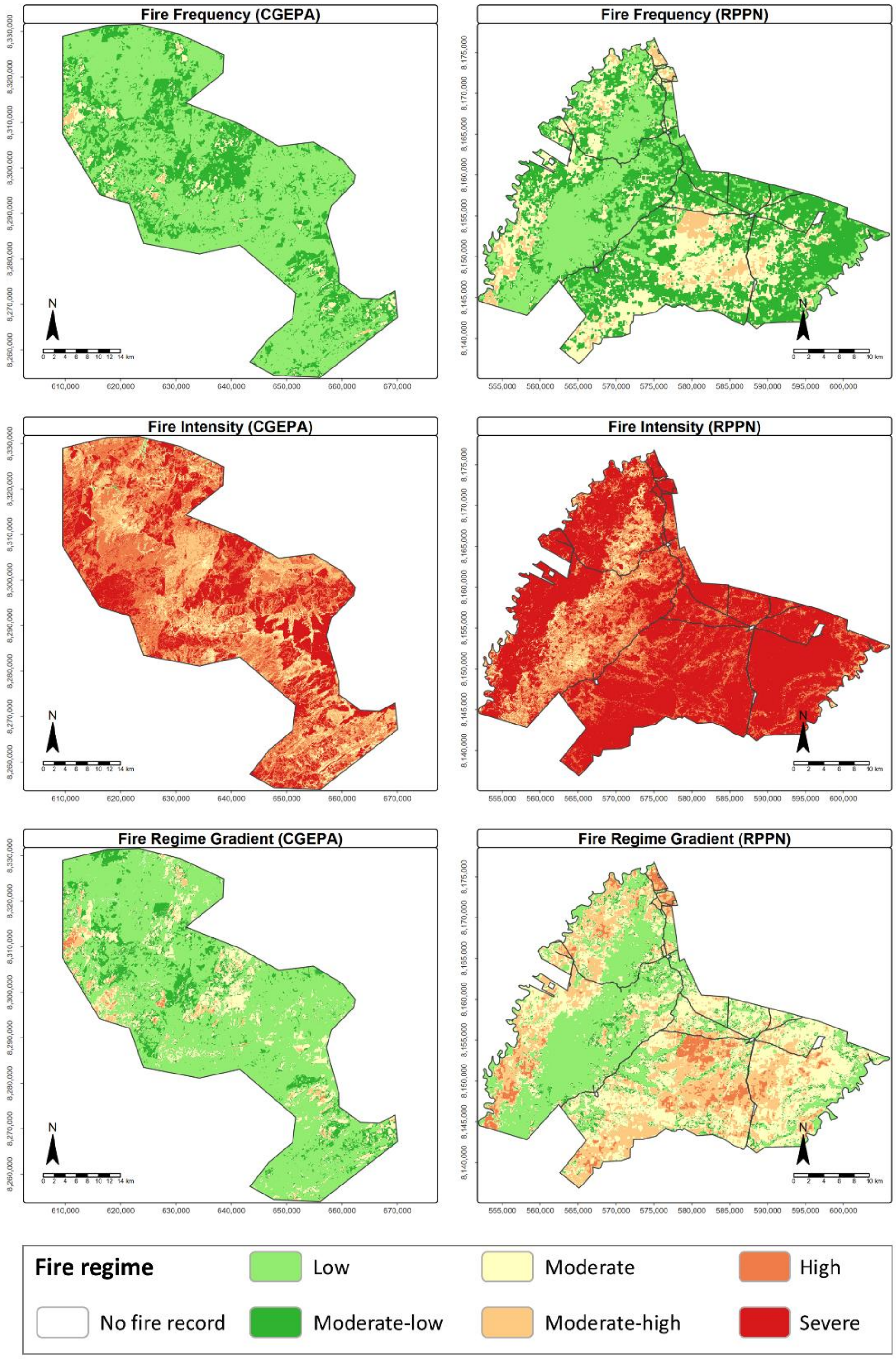

Figure 3 – Fire frequency maps (1985–2023), fire intensity maps derived from dNBR (2019–2023), and the resulting fire regime gradient maps for the Chapada dos Guimarães Environmental Protection Area (CGEPA) and the SESC Pantanal Private Natural Heritage Reserve (RPPN), Mato Grosso, Brazil. The fire regime gradient integrates historical fire recurrence and spectral fire intensity into a single measure of cumulative fire pressure.

The fire regime gradient maps revealed marked differences between the two protected areas (Figure 3). In the CGEPA, approximately 68% of the area was classified as low fire regime severity, reflecting a predominance of low-frequency and low-intensity fire events. Only 1% of the area was affected by high-frequency and high-intensity fire regimes. In contrast, the RPPN SESC Pantanal exhibited substantially higher fire regime severity, with approximately 62% of the area classified as moderate fire regime severity and nearly 90% of burned areas affected by moderate to severe fire regimes. Severe fire regimes were concentrated in areas affected by the exceptional wildfire events of 2019 and 2020.

Temporal assessment of fire severity in brazilian savannas

To complement the spatial analyses, we evaluated temporal variation in vegetation condition using intra-annual median NBR time series for both conservation units (Figure 4). These trajectories provide an overview of vegetation responses to fire events and subsequent recovery dynamics throughout the study period.

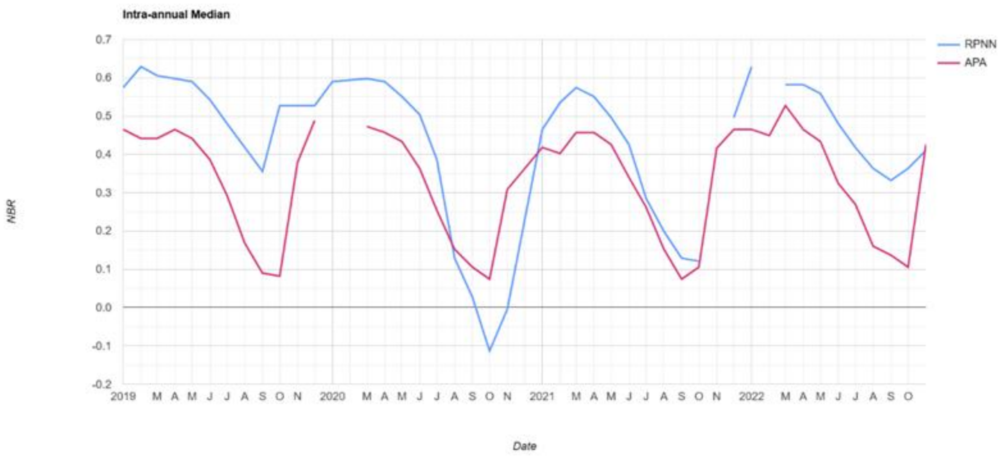

Figure 4 – Graphical representation of the intra-annual median time series of the Normalized Burn Ratio (NBR) for the Chapada dos Guimarães Environmental Protection Area (CGEPA), depicted in red, and the SESC Pantanal Private Natural Heritage Reserve (RPPN), in blue, both located in Mato Grosso, Brazil.

Our assessment of the fire frequency maps revealed overlaps during the analyzed period (1985–2023), allowing us to identify the frequency at which the areas were affected by wildfires. The frequency of those fires varied, ranging from 1 to 5 times for the Chapada dos Guimarães Environmental Protection Area (CGEPA) and from 1 to 4 times for the SESC Pantanal Private Natural Heritage Reserve (RPPN). In the CGEPA, ca. 68% of the total burned areas experienced fire once, while approximately 30% of the area suffered two or three fire occurrences. Only a small fraction, less than 1%, was affected by fires 4 to 5 times. Fire recurrence was higher in pasturelands, followed by savanna formations. In the RPPN, most burned areas experienced fire at least twice, comprising 42% of the total burned area. Around 26% were burned once or three times, while 5% were affected on four occasions. Fires impacted native grasslands and savanna formations with greater severity. It is also noteworthy that wetland areas burned three times, whereas forested areas experienced fires twice, although in much smaller proportions.

In terms of intensity, fires ranged from low to high intensity across both areas. Moderate to high-intensity fires affected 70% of the CGEPA and 90% of the RPPN, spanning all land use and land cover classes within these protected areas. These results highlight a significant effect on both areas, with over 155,000 hectares suffering high-intensity fires. Notably, this timeframe encompassed the wildfires of 2019 and 2020, the largest recorded in both areas in recent decades, which represented an unprecedented departure from the historical fire regime [30].

The predominance of low-severity fire regimes in the CGEPA suggests that fire occurrence remains largely within the historical ecological range expected for fire-adapted Cerrado ecosystems. Such systems have evolved under recurrent low- to moderate-intensity fires and generally exhibit high resilience to these disturbance regimes [53]. However, the occurrence of moderate and moderate-high fire regimes in pasturelands indicates localized anthropogenic pressures associated with land-use conversion and fuel accumulation, highlighting specific management challenges within the protected area. However, it is noteworthy that a small part of the area exhibited moderate or moderate-high intensity regimes, particularly in pastureland. This pattern suggests that, in general, fire dynamics within the conservation unit may still be within the expected ecological range for fire-adapted systems, particularly in areas dominated by native vegetation. However, the concentration of higher intensity regimes in pasturelands indicates the influence of anthropogenic pressures, especially in areas with previous land use conversion, highlighting potential challenges for management. While fire dynamics in areas dominated by native vegetation appear to remain within the expected ecological range for fire-adapted systems, the concentration of higher-intensity regimes in pasturelands reflects the influence of anthropogenic land use conversion and highlights specific management challenges in those zones.

Recent estimates from MapBiomas show that between 1985 and 2023, the conversion of native vegetation in the Cerrado for agriculture and pastureland increased by 6.2 times [43]. These land use and land cover changes, coupled with more frequent and intense droughts and reduced rainfall [10, 54], highlight the urgent need for careful fire management in the region to prevent devastating wildfires, such as those experienced in 2019 and 2023. In the CGEPA, annual prescribed burns are conducted by firefighting agencies, municipal authorities and park managers. These activities aim to reduce fuel accumulation, control invasive plants, promote native vegetation regeneration, and mitigate the risk of uncontrolled fires [55, 56]. When well-planned and consistently implemented, prescribed fire can be an effective tool for maintaining the fire regime within ecologically appropriate bounds and preserving biodiversity [55]. These results highlight the importance of integrating spatially explicit fire regime data, such as those generated by the proposed tool, into management plans to improve the effectiveness of prescribed fire practices.

Like CGEPA, the RPPN maintains a longstanding fire monitoring and combat program. In contrast to the Cerrado site, the Pantanal exhibited a predominance of moderate to high fire regimes, reflecting the exceptional wildfire events recorded during recent years and the increasing vulnerability of the region to large-scale fires. Moderate-intensity fires represent a complex combination of surface and crown fire behavior [57], while high-intensity fires are characterized by vigorous and rapid combustion consuming large amounts of vegetation within a short period [58]. These fires tend to spread rapidly under favorable weather conditions, including strong winds, low humidity, and terrain features [59], causing substantial damage to native vegetation, animal communities, and natural habitats, while also posing risks to nearby human settlements [60, 61]. Post-fire recovery in these areas may require extended periods, and vegetation may not fully regenerate between successive fire events, potentially leading to long-term shifts in plant and animal community structure [62, 63]. In this context, tools capable of identifying areas with higher fire intensity and recurrence are essential to support emergency response, restoration planning, and biodiversity conservation in protected areas.

Over the past decades, the Pantanal has been severely affected by land use conversion, with a significant expansion of areas allocated for pasture [10]. Between 1985 and 2023, pastureland expanded threefold, leading to a net loss of 10% of native vegetation in the region [10]. This pattern of environmental degradation, including unsustainable agricultural practices [64] and indiscriminate pesticide use [65, 66], not only threatens local biodiversity but also poses significant risks to human communities that depend on the Pantanal's natural resources

[67]. The areas surrounding the RPPN SESC Pantanal already reflect this broader regional trend, underscoring the urgency of spatially targeted conservation and fire management efforts.

Overall, the integration of fire frequency and severity into a single analytical framework provides a valuable basis for supporting evidence-based management in conservation units. By translating complex remote sensing data into actionable information, the proposed tool bridges the gap between scientific research and practical management, supporting more effective and adaptive conservation strategies in fire-prone ecosystems.

Conclusion

Our tool offers a robust, efficient, and replicable approach for assessing fire severity through time in any area of interest, with significant implications for both environmental management and public policies. Although the proposed workflow is fully automated and based exclusively on freely available datasets, some limitations should be acknowledged. The accuracy of the resulting products depends on the quality and temporal availability of the MapBiomas Fire database and Sentinel-2 imagery, particularly in regions affected by persistent cloud cover. Furthermore, the fire regime classification proposed here was developed for brazilian savanna ecosystems and may require threshold adjustments when applied to regions with distinct vegetation structure or fire dynamics. Nevertheless, the open-source implementation and modular structure of the workflow facilitate future adaptations and improvements for different ecological contexts.

Applied to two conservation units located in distinct brazilian savanna ecosystems, the proposed workflow revealed contrasting fire regimes with direct implications for conservation management. The Cerrado site exhibited predominantly low-severity fire regimes compatible with the expected ecological dynamics of fire-adapted vegetation, whereas the Pantanal site showed evidence of increased fire pressure associated with recent extreme wildfire events and ongoing landscape transformation. These findings demonstrate the ability of the proposed framework to identify spatial patterns of fire pressure and support management decisions related to prescribed burning, restoration priorities, and fire prevention strategies.

The innovative feature of this methodology lies in its automation and accessibility. By leveraging open-source tools and freely available satellite imagery, it democratizes environmental monitoring, offering a cost-effective solution for protected area managers, even in resource-limited settings. Its open-source design encourages collaboration, continuous improvement, and broad applicability across regional and global scales.

The data generated by our tool can inform public policies aimed at mitigating the environmental impacts of fires. By providing clear, quantifiable, and spatially explicit information, it supports informed decision-making and helps develop sustainable management strategies for vulnerable ecosystems. By combining methodological innovation with practical applicability, this tool strengthens the integration between scientific research and conservation management in fire-prone ecosystems, aligning with global agendas for biodiversity monitoring and climate adaptation.

Despite the limitations inherent to remote sensing products and ecosystem-specific classification thresholds, the proposed workflow provides a transparent, reproducible, and easily adaptable framework for fire monitoring in protected areas. Future developments incorporating additional fire regime dimensions, such as seasonality, fire duration, fire size and time since the last fire event, together with ecosystem-specific calibrations, may further expand its applicability across fire-prone landscapes worldwide.

Acknowledgements

We would like to express our gratitude to the Rufford Foundation for supporting the project Effects of Fire on Bat Diversity and Occupancy in the Megadiverse Brazilian Savannas through the Small Grant (ID 41558-2). We also thank the Brazilian Biodiversity Fund (FUNBIO; Grant 014/2023), Bat Conservation International (BCI) for awarding the 2023 Student Research Scholarship, and the Brazilian Society for the Study of Bats (SBEQ) for its support through the Small Grants in Biology, Ecology, and Bat Conservation program. We thank the Brazilian National Council for Scientific and Technological Development (CNPq) for awarding a Research Productivity Fellowship to MJRP. This work was also supported by the Coordination for the Improvement of Higher Education Personnel (CAPES), Brazil, through doctoral scholarships awarded to CC and CSC (Funding Code 001).

Declaration of artificial intelligence use

ChatGPT (OpenAI) was used solely for grammatical corrections in the manuscript.

Conflict of interest statement

The authors declare no financial, institutional, or personal conflicts of interest related to this manuscript.

Author Contributions (CRediT Taxonomy)

Papel CRediT	**Descrição**	**Autores**
Conceptualization	Project ideation and formulation of the research	Cíntia Fernanda da Costa, Maria João Ramos Pereira
Data curation	Data management, cleaning, and maintenance	Cíntia Fernanda da Costa, Christhian Santana Cunha
Formal analysis	Application of statistical or mathematical techniques	Cíntia Fernanda da Costa, Christhian Santana Cunha Maria João Ramos Pereira
Funding acquisition	Obtaining financial support	Cíntia Fernanda da Costa, Maria João Ramos Pereira
Investigation	Conducting the study, data collection, and experiments	Cíntia Fernanda da Costa, Maria João Ramos Pereira
Methodology	Development or design of methods and procedures	Cíntia Fernanda da Costa, Christhian Santana Cunha, Maria João Ramos Pereira
Project administration	Management and coordination of the project	Cíntia Fernanda da Costa, Maria João Ramos Pereira
Resources	Provision of materials, reagents, and equipment	Cíntia Fernanda da Costa, Maria João Ramos Pereira
Software	Development of software, code, or algorithms	Christhian Santana Cunha, Cíntia Fernanda da Costa
Supervision	Overall project guidance and supervision	Maria João Ramos Pereira

Validation	Verification of the accuracy and consistency of results	Cíntia Fernanda da Costa, Christhian Santana Cunha, Maria João Ramos Pereira
Visualization	Preparation of figures, graphs, and visual representations	Cíntia Fernanda da Costa, Christhian Santana Cunha, Maria João Ramos Pereira
Writing – original draft	Preparation of the initial manuscript	Cíntia Fernanda da Costa, Christhian Santana Cunha, Maria João Ramos Pereira
Writing – review & editing	Critical review and editing of the manuscript	Cíntia Fernanda da Costa, Christhian Santana Cunha, Maria João Ramos Pereira

Data availability

The Google Earth Engine scripts used to generate fire frequency and fire intensity maps are openly available at: https://github.com/Kejorureu/Temporal-assessment-of-fire-severity. The repository includes the original scripts, documentation and instructions for reproducing the analyses presented in this study.

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Appendix

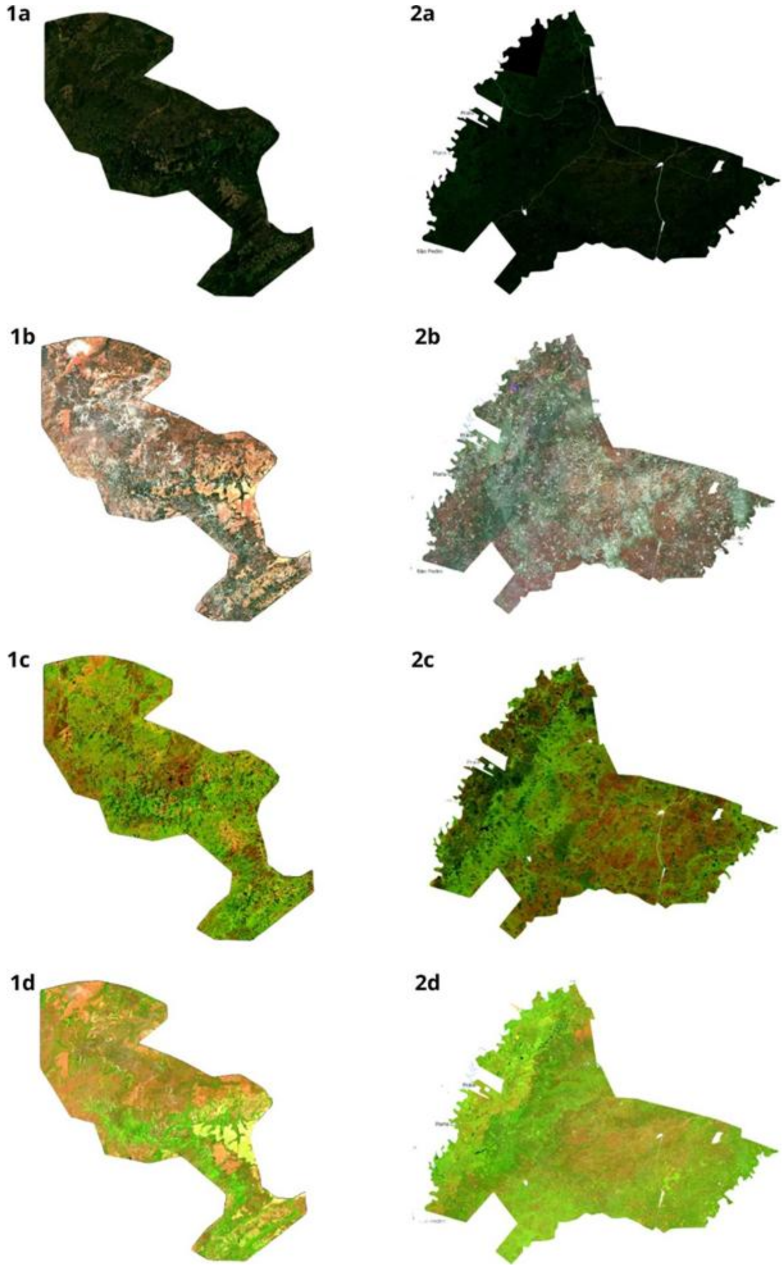

Figure A1 – Sentinel-2 image mosaic representing: 1 for the Chapada dos Guimarães Environmental Protection Area (CGEPA) and 2 for the SESC Pantanal Private Natural Heritage Reserve (RPPN). In: a) Color composition (RGB) of the period with a low number or absence of fire events; b) Recording of fire-affected pixels during the analyzed period; c) and d) False-color compositions, composed of SWIR, NIR, and red bands.

Biodiversidade Brasileira
Fluxo Contínuo
v. 16 n.3, 2026
https://revistaeletronica.icmbio.gov.br/index.php/BioBR/
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ISSN: 2236-2886