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ORIGINAL ARTICLE

POST-FIRE REGENERATION OF CERRADO PHYTOPHYSIOGNOMIES IN SERRA DA CANASTRA NATIONAL PARK

Regeneração pós-fogo de fitofisionomias de Cerrado no Parque Nacional da Serra da Canastra

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Abstract
Brazil stands out for the diversity of its biomes, which form an extensive vegetation mosaic. However, extreme climatic events and anthropogenic pressures have intensified wildfires throughout the country. Serra da Canastra National Park is part of this context because it has been affected by recurrent fire events. This study aims to analyze the post-fire regeneration of Cerrado phytophysiognomies in Serra da Canastra National Park from 2013 to 2021. Spectral-temporal profiles of the Normalized Difference Vegetation Index were used based on Landsat 8 images processed on the Google Earth Engine platform. The results indicate that Cerrado stricto sensu requires, on average, 6 months for regeneration. Grassland requires approximately 9 months, whereas Rupestrian Grassland presents an average spectral regeneration period of 8 months. These results are expected to contribute to the assessment of post-fire regeneration in the studied phytophysiognomies and to support park management.

Keywords: Wildfires, Remote sensing, Google Earth Engine, MapBiomas, National System of Conservation Units (SNUC).

Resumo
O Brasil destaca-se pela diversidade de biomas que compõem um extenso mosaico vegetacional, todavia eventos climáticos extremos e pressões antrópicas têm intensificado os incêndios florestais em todo o país. O Parque Nacional da Serra da Canastra insere-se nesse contexto, por enfrentar incêndios florestais recorrentes. Objetiva-se analisar a regeneração pós-fogo das fitofisionomias de Cerrado no Parque Nacional da Serra da Canastra no período de 2013 a 2021. Utilizou-se a técnica de perfis espectro-temporais do Índice de Vegetação por Diferença Normalizada processados na plataforma Google Earth Engine, com imagens do Landsat 8. Resultados indicam que a fitofisionomia Cerrado sentido restrito requer, em média, 6 meses para regeneração. O Campo Limpo necessita

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aproximadamente de 9 meses. Por sua vez, o Campo Rupestre apresenta média de regeneração espectral de 8 meses. Almeja-se com estes resultados, contribuir para a avaliação da regeneração pós-fogo das fitofisionomias estudadas e gestão do parque.

Palavras-chave: Incêndios florestais, Sensoriamento remoto, Google Earth Engine, MapBiomas, SNUC.

1. INTRODUCTION

Brazil has accumulated a marked increase in wildfire records as a consequence of adverse climatic conditions, heat waves, and anthropogenic pressure for the expansion of agricultural, livestock, and mining activities, many of them near Conservation Units (CU) (Silva Junior *et al.,* 2020; Pivello *et al.,* 2021). In this sense, the establishment of protected areas has become one of the few mechanisms that still restrain anthropogenic expansion in Brazilian biomes since the creation of the National System of Conservation Units (Brasil, 2000).

One of these areas is Serra da Canastra National Park (PNSC), a Strict Protection Conservation Unit of great relevance both for biodiversity conservation and for protecting the headwaters of the São Francisco River. Nevertheless, the park faces several environmental threats, such as water erosion processes, extensive cattle ranching, land tenure irregularities, and recurrent wildfires. In relation to fires, understanding their impacts on different vegetation types and their consequences is essential for establishing command-and-control procedures aimed at mitigating future damage to biodiversity and natural resources in the region (Messias; Ferreira, 2019; Latuf *et al.,* 2022; Rios *et al.,* 2024).

The Cerrado, the predominant biome in PNSC, has a close relationship with fire (Fidelis; Zirondi, 2021), since several species depend on it for germination and nutrient cycling, which are essential for biodiversity maintenance (Saraiva *et al.,* 2024). However, anthropogenic fires disrupt this balance, reduce the resilience of phytophysiognomies, and require specific management measures for preservation (Pivello *et al.,* 2021).

In PNSC, the predominant phytophysiognomies are Grassland, represented mainly by grasses; Rupestrian Grassland, adapted to rocky and shallow soils; and Cerrado stricto sensu, a low shrub-tree vegetation type that reflects biodiversity and different forms of adaptation to fire (Coutinho, 2006; IBAMA, 2010).

The park's broad territorial extent, combined with its diversity of vegetation and geomorphological forms, makes field research difficult (Ab'sáber, 2003). In this context, geotechnologies provide a continuous view of large areas (Ponzoni *et al.,* 2015) and enable analyses on cloud processing platforms, such as Google Earth Engine (Gorelick *et al.,*

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2017). Spectral indices, such as NDVI and NBR, allow the identification of areas affected by fires and other disturbances. Derived from satellite imagery, these indices provide information on vegetation condition and support the monitoring of recovery in affected areas (Rouse *et al.,* 1974; Key; Benson, 2006). Studies such as those by Anderson et al. (2005), *Oliveira et al.* (2017), and Latuf *et al.* (2022) demonstrate the effectiveness of remote sensing in monitoring vegetation cover and analyzing fire scars.

In addition to disturbance detection, remote sensing makes it possible to monitor vegetation regeneration after events such as fires. This process, known as spectral regeneration, refers to the recovery of land surface spectral signatures that indicate vegetation return, although it does not reveal details about species structure or composition (Hird *et al.,* 2021).

Satellite images from programs such as Landsat and Sentinel, processed in environments such as Google Earth Engine (Gorelick *et al.,* 2017), have been used to assess changes in vegetation cover over time and monitor vegetation recovery, supporting ecosystem management and decision-making for preservation (Howe et al., 2022; Rios *et al.,* 2024). In this context, this study analyzes post-fire regeneration in different Cerrado phytophysiognomies in PNSC between 2013 and 2021, based on orbital imagery and the interpretation of spectral-temporal profiles.

2. STUDY AREA CHARACTERIZATION

PNSC is located in the South-Southwest Mesoregion of the state of Minas Gerais, Brazil, with an area of 197,787 ha (Brasil, 1972), of which approximately 93,000 ha are officially designated as a Strict Protection Conservation Unit (BRASIL, 2000) (Figure 1).

Regarding geology, PNSC is located at the convergence between the southern portion of the Brasília Fold Belt and the southwestern margin of the São Francisco Craton. In this region, NW-SE lineaments are observed, which give rise to normal and thrust faults, in addition to causing lithological variations modified by denudational processes (Mauro; Valadão, 2018; Salgado; Santos; Paisani, 2019).

The park presents a landscape marked by plateaus, steep slopes, and incised valleys. Two regions stand out: the plateau of the Canastra Massif, the predominant physiognomy covered by grassland formations and known as Chapadão da Canastra; and Chapadão da Babilônia, which has more rugged relief. Altitudes vary between 700 and 1,400 meters in both formations (Brasil, 2005; Salgado; Santos; Paisani, 2019).

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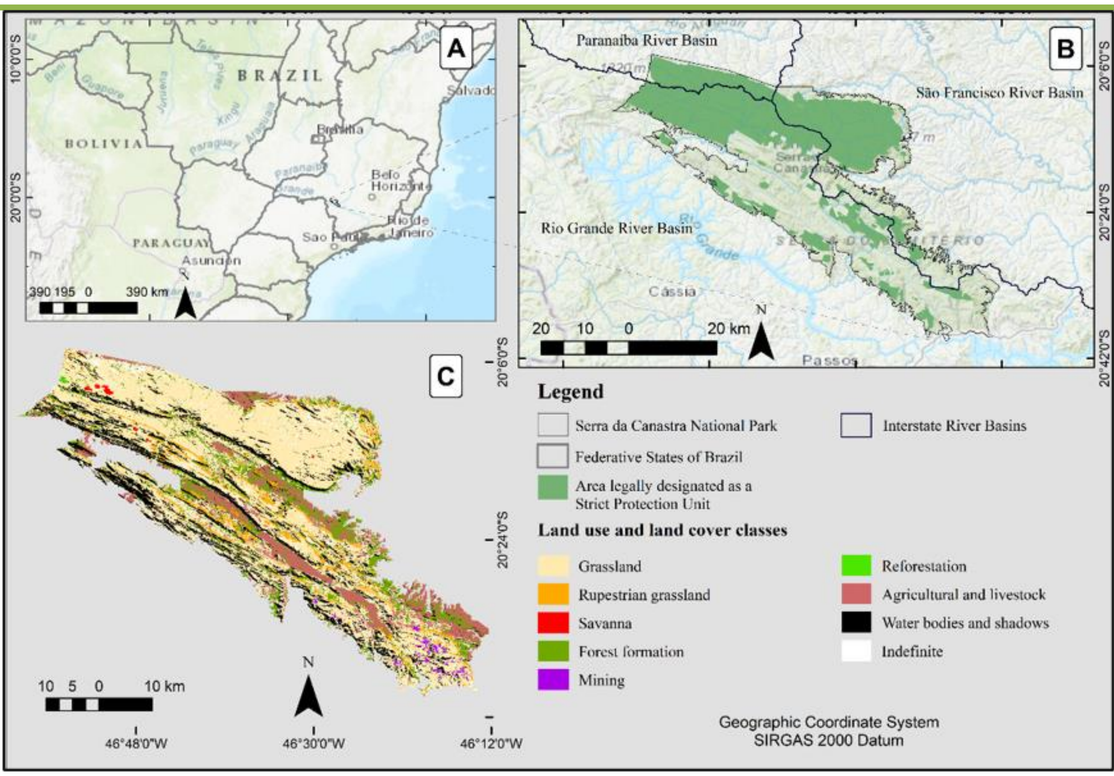

Figure 1 - Location of Serra da Canastra National Park.
Source: Authors, 2023.

According to the Köppen classification, the regional climate corresponds to the Cwa (humid subtropical) and Cwb (highland subtropical) types, characterized by hot summers and mild winters, with mean temperatures between 18 °C and 22 °C (Alvares *et al.,* 2013). Annual rainfall, estimated by the CHIRPS 2.0 satellite product, ranges from 1,000 to 1,800 mm (Funk *et al.,* 2015), while winds predominate in the north-south direction, especially in the afternoon, and can reach up to 80 km/h in some months (IBAMA, 2007). The seasonal regime includes a rainy period from October to March, with a monthly mean of 213 mm, and a dry season from April to September, with only 35 mm on average (Alves; Nóbrega, 2011; Silva; Escobar; Reboita, 2020). This seasonality directly affects fire dynamics, since the end of the rainy period coincides with the completion of regeneration after fires from the previous year, while most new fire outbreaks occur during the dry months (Alves; Nóbrega, 2011; Setzer; Ferreira, 2021).

The park and its surroundings are located within the Cerrado phytogeographic domain. According to the nomenclature proposed by Coutinho (2006), Serra da Canastra is predominantly covered by grassland formations, such as Rupestrian Grassland, Rupestrian Cerrado, Grassland, Shrub Grassland, Cerrado stricto sensu, Gallery Forest, and Wet Grassland. This phytophysiognomic diversity, conditioned by climate and fire dynamics, defines vegetation as a central element for understanding ecological processes in PNSC.

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3. METHODOLOGICAL PROCEDURES

The methodological workflow was organized into five stages (Figure 2). In the first stage, vector data in shapefile format were obtained: Federative Units (IBGE, 2021), PNSC boundaries (SISEMA, 2021), the soil map of Minas Gerais (UFV, 2010), the hydrographic network of the São Francisco, Grande, and Paranaíba river basins (ANA, 2021), and the phytophysiognomic map of PNSC (BRASIL, 2005). All geospatial data were processed in ArcMAP™ 10.6.1 software (ESRI, 2018).

In the second stage, fire recurrence and fire scar data in PNSC were obtained from the MapBiomas Fire Project, available on the Google Earth Engine (GEE) platform through its toolkit (MAPBIOMAS, 2021).

Regarding orbital products, the Landsat 8 collection, OLI sensor, paths/rows 219/74 and 220/74, Collection 2, Level 2, with 30 m spatial resolution (USGS, 2021), was used with geometric and atmospheric corrections by the LaSRC version 3.0 method (Zanter, 2019). Scale factor correction was processed in Google Earth Engine (GEE), followed by the application of the cloud and cloud-shadow mask generated by the Fmask algorithm (Zhu; Woodcock, 2014).

In the third stage, conditioning factors capable of altering NDVI were considered (Elmore *et al.,* 2000), such as proximity to watercourses (Furquim *et al.,* 2018) and the presence of rocky outcrops. To reduce these influences, a 60 m buffer was delimited around outcrop areas and the hydrographic network.

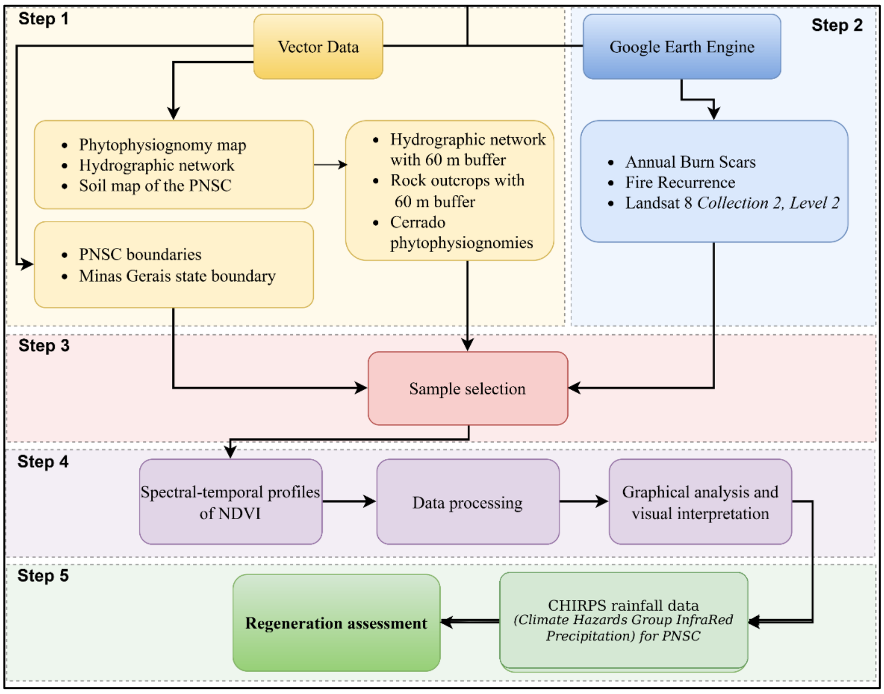

Figure 2 - Methodological flowchart.
Source: Authors, 2023.

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Six samples were selected for each Cerrado phytophysiognomy (Grassland, Rupestrian Grassland, and Cerrado stricto sensu), in 3 × 3 pixel windows, corresponding to 90 × 90 m grids (8,100 m²). In addition to stratification by phytophysiognomy, the fire recurrence map from the MapBiomas Fire Project was considered, with three samples allocated to high-recurrence areas (more than three records) and three to low-recurrence areas (up to two records) for each phytophysiognomy (Table 1). With the three low- and high-recurrence samples (six in total) in each phytophysiognomy, the statistical difference between mean regeneration times was assessed by Student's t-test at the 95% probability level, in RStudio version 1.3.1073 (R CORE TEAM, 2020).

Table 1: Recurrence classes for each Cerrado phytophysiognomy in PNSC (2013-2021).

Phytophysiognomy	Low recurrence	High recurrence
Grassland	1 to 2 occurrences	6, 7, and 8 occurrences
Rupestrian Grassland	1 to 2 occurrences	4, 5, and 6 occurrences
Cerrado stricto sensu	1 to 2 occurrences	3 and 4 occurrences

Source: Authors, 2023.

In the fourth stage, JavaScript code was developed to process orbital images on the Google Earth Engine platform (GORELICK et al., 2017), with the objective of obtaining spectral-temporal NDVI profiles (Equation 1) for the samples between 2013 and 2021, based on regeneration after the 2020 fires. The results were later processed in a spreadsheet. The code is available at: https://code.earthengine.google.com/0dfb0e560d99066be34790541d11ce17.

$$NDVI = (NIR - R) / (NIR + R) \quad \text{(Equation 1)}$$

where: NDVI: Normalized Difference Vegetation Index (dimensionless); NIR: Near-infrared surface reflectance (dimensionless); R: Red surface reflectance (dimensionless).

Graphical analysis made it possible to identify the interval between the fire, confirmed by visual inspection of the images in each sample through a click on the chart generated by the script, and the return of NDVI to previous values. This return was defined by a baseline calculated from the mean pre-fire NDVI, with spectral regeneration defined as recovery up to this line. Visual inspection used the false-color composite R6/G5/B4 for pre-fire and regeneration images, and R7/G5/B4 for post-fire images, which facilitated scar identification (Liu *et al.,* 2006).

In the fifth stage, vegetation regeneration was assessed based on an adaptation of the spectral regeneration concept by Hird *et al.* (2021). Because water availability interferes with

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the spectral response, monthly rainfall data from the CHIRPS satellite product (Funk *et al.,* 2015) were used to assess hydrological dynamics in PNSC. The park has no station registered in the hydrometeorological network of the National Water and Basic Sanitation Agency (ANA). The data were obtained from: https://data.chc.ucsb.edu/products/CHIRPS-2.0/global_monthly/tifs/.

4. RESULTS AND DISCUSSION

Climatic conditions directly influence wildfire dynamics because they affect vegetation moisture (Brando *et al.,* 2014). Increased precipitation is inversely correlated with the number of scars, confirming the influence of climate on the occurrence of these events (Setzer; Ferreira, 2021). Climatic seasonality, associated with anthropogenic factors such as land-use changes, reinforces the complexity of interactions among climate, vegetation, and human activities in fire spread and frequency (Aragão *et al.,* 2008).

Species diversity in Cerrado phytophysiognomies also affects post-fire regeneration times. This study did not address the detailed floristic composition of each phytophysiognomy, which limits the understanding of regeneration dynamics. Many species have adaptive mechanisms, such as resprouting from roots or regeneration from seeds, which result in different responses to fire (Brasil, 2005; IBAMA, 2010). The absence of this analysis may lead to generalizations and highlights the need for future research on species composition to better elucidate interactions among fire, biodiversity, and vegetation regeneration in the Cerrado. The results for each analyzed phytophysiognomy are presented below.

In all samples of the Grassland phytophysiognomy, there was agreement between the recurrence map from the MapBiomas Fire Project (Beta version) and the NDVI calculated in this study, indicating the effectiveness of the index for identifying fires in PNSC.

The predominance of herbaceous vegetation, with few shrubs and absence of trees, favors the reestablishment of vegetation indices after fire, which in some cases can exceed values in unaffected areas. Burning releases nutrients in the surface soil layers, increasing their availability to grasses, which regenerate rapidly due to their high photosynthetic rate (Coutinho, 2006). Variations in soil moisture, depth, and fertility also influence the process and accelerate vegetation recovery in environments with these characteristics.

Table 2 presents the estimated regeneration time for each of the six Grassland samples, considering low and high fire recurrence.

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Table 2: Number of days required for regeneration in Grassland in PNSC.

Grassland	Samples					
	Low recurrence			High recurrence		
	1	2	3	4	5	6
Fire 1	74	113	209	625	193	280
Fire 2	170	-	-	-	600	168
Fire 3	-	-	-	161	273	645
Fire 4	-	-	-	984	577	273
Fire 5	-	-	-	263	-	305
Fire 6	-	-	-	193	-	241
Average per sample	122	113	209	445	411	319
Low recurrence average	142					
High recurrence average	385					
Overall average	263					

Source: Authors, 2023.

Nineteen fire occurrences were identified in the Grassland phytophysiognomy at the sampled site. In low-recurrence areas, the mean regeneration time was 142 days (4.7 months; n = 4), ranging from 74 to 209 days. In high-recurrence areas, the mean was 385 days (13 months; n = 15), ranging from 319 to 445 days. The mean for the six samples (n = 19) was 263 days (8.7 months).

Student's t-test indicated a statistically significant difference between regeneration times in the recurrence classes at the 5% level (p = 0.0025). The mean difference was 243 days (8.1 months), confirming that low-recurrence areas regenerate more rapidly than high-recurrence areas.

The first analysis refers to the red rectangle in the time series (Figure 3a), in a low-recurrence area. The process began on 05/06/2014, with an NDVI of 0.59 (indicator A). The value declined until 10/13/2014, when the scar was detected (indicator B), with a mean NDVI of 0.16. Regeneration was the fastest among the three low-recurrence Grassland samples, with recovery detected after 74 days (indicator C), when NDVI values exceeded pre-fire levels.

Sample 4, located in a high-recurrence area (Figure 3b), required the maximum regeneration time compared with all samples, with fire detected on 08/08/2016 (indicator B in the profile) and regeneration detected only on 04/18/2019 (indicator C in the profile), that is, nearly three years after the event. In the first and third analysis periods, a second fire occurred before the NDVI value returned to the previous pattern, showing that high fire recurrence changes the natural cycle of ecological succession, as shown by Burton *et al.* (2020).

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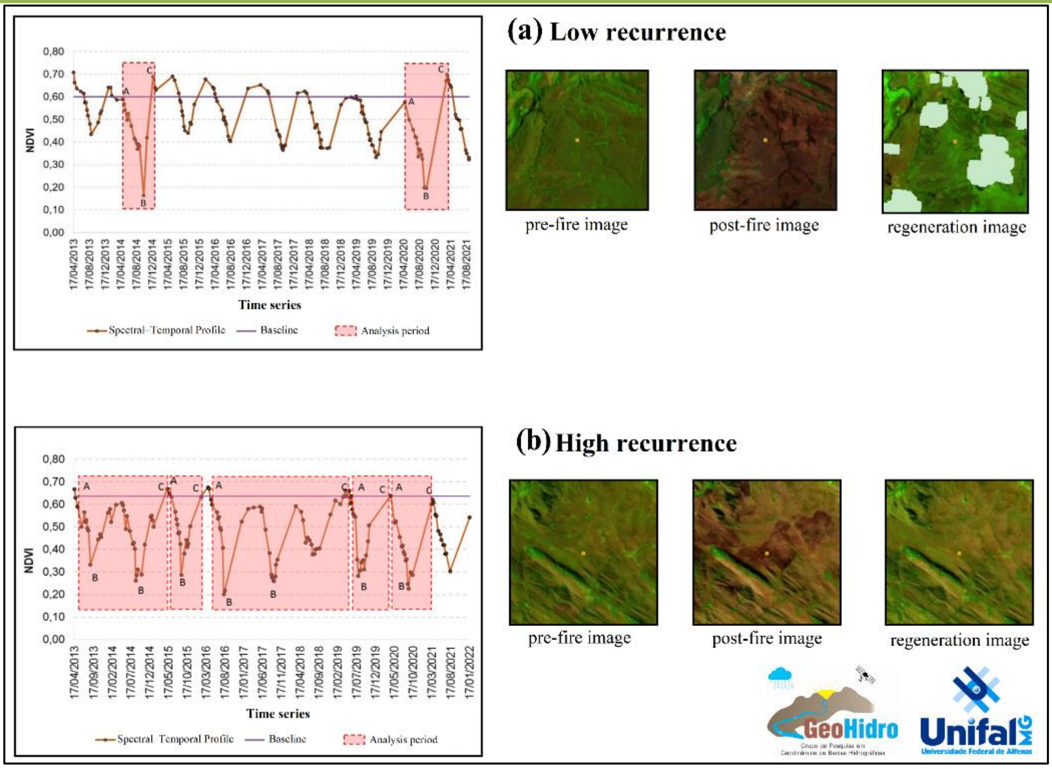

Figure 3 - Spectral-temporal profile and pre-fire, post-fire, and regeneration images (samples 1 and 4).
Source: Authors, 2023.

Rupestrian Grassland comprises a vegetation type made up of herbaceous-shrub communities. Due to conditioning factors such as topography, pedology, and climate, this phytophysiognomy has strong landscape heterogeneity, which favors a rich floristic composition with many endemic species (Brasil, 2005; Neves; Conceição, 2010).

In the selected samples, both low and high recurrence, agreement was observed between the recurrence map acquired from the MapBiomas Fire Project (2021) and the NDVI calculated in this study. Six samples were analyzed in low- and high-recurrence areas, as well as the time required for post-fire regeneration (Table 3).

Table 3: Number of days required for regeneration in Rupestrian Grassland in PNSC.

Rupestrian Grassland	Samples					
	Low recurrence			High recurrence		
	7	8	9	10	11	12
Fire 1	184	209	74	161	241	273
Fire 2	241	200	154	184	289	161
Fire 3	-	-	-	593	184	200
Fire 4	-	-	-	-	266	193
Fire 5	-	-	-	-	154	545
Average per sample	213	205	114	313	227	274
Low recurrence average	177					
High recurrence average	265					
Overall average	237					

Source: Authors, 2023.

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A total of 19 fire events were detected from 2013 to 2021, according to MapBiomas Fire. The mean regeneration time for this phytophysiognomy in low-fire-recurrence areas was 177 days, or 5.9 months (n = 6), ranging from 74 to 241 days. In high-recurrence areas, the mean was 265 days, or 8.9 months (n = 13), ranging from 154 to 545 days. The mean obtained for all six samples was 237 days, or 7.9 months (n = 19).

Regarding statistical differentiation between regeneration times in different recurrence classes (low and high), Student's t-test indicated no statistical difference between sample means at the 5% significance level, with p-value = 0.0734. This shows that the regeneration "rate" between low- and high-recurrence samples does not present a statistical difference according to the t-test.

Figure 4(a) represents the spectral-temporal profile and images referring to sample 7 in Rupestrian Grassland, which had two fire occurrences. In the second analysis period, it presented an NDVI of 0.58 in the pre-fire image dated 05/31/2020 (indicator A in the profile), with a fire on 07/18/2020 (indicator B in the profile), registering an NDVI of 0.29. Regeneration was detected on 03/15/2021 (indicator C in the profile), with an NDVI of 0.61 and an estimated time of 8 months (241 days). It is noted that the spectral-temporal profile varies with lower-amplitude values in periods when seasonality is determinant; however, when fires were recorded, the sample presented marked reductions in the NDVI index.

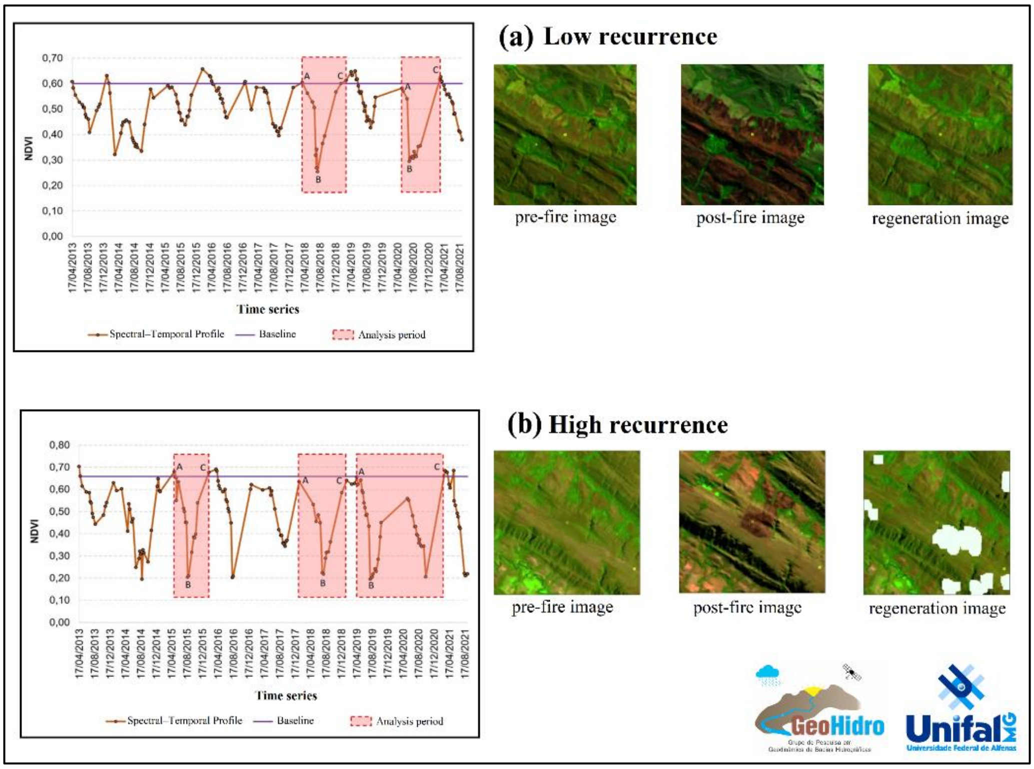

Figure 4 - Spectral-temporal profile and pre-fire, post-fire, and regeneration images (samples 7 and 10).
Source: Authors, 2023.

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Sample 10, in the Rupestrian Grassland phytophysiognomy, is located in a high-fire-recurrence area. The spectral-temporal profile shows a large amplitude in NDVI values, explained both by climatic seasonality — low values outside the red rectangles — and by fire occurrences (Figures 4a and 4b). Seasonality, however, does not explain all NDVI declines, which do not always correspond to fires.

In the third analysis period, which began on 05/20/2019 (indicator A), the NDVI was 0.66. The post-fire image from 08/01/2019 (indicator B) had a value of 0.20. Regeneration was recorded only on 03/15/2021 (indicator C), with an NDVI of 0.68. This interval resulted in the longest regeneration time for the Rupestrian Grassland phytophysiognomy in a high-recurrence area, with 19.7 months (593 days).

Cerrado stricto sensu is characterized by low, tortuous trees with irregular and twisted branches, as well as spaced shrubs and subshrubs. Its species have perennial underground organs that allow resprouting after burning. This phytophysiognomy occurs in deep clayey soils in flat and gently undulating terrain (Brasil, 2005).

Table 4 summarizes the regeneration time of the six samples of the Cerrado phytophysiognomy in PNSC between 2013 and 2021, considering low and high fire recurrence.

Table 4: Number of days required for regeneration in Cerrado stricto sensu in PNSC.

Cerrado stricto sensu	Samples					
	Low recurrence			High recurrence		
	13	14	15	16	17	18
Fire 1	193	193	193	177	145	188
Fire 2	193	193	193	145	145	145
Fire 3	-	-	-	193	193	193
Average per sample	193	193	193	172	161	175
Low recurrence average	193					
High recurrence average	169					
Overall average	179					

Source: Authors, 2023.

In the Cerrado phytophysiognomy, 1 to 3 fire events per sample were detected between 2013 and 2021 in PNSC, based on the MapBiomas Fire Project (Beta version, 2021), totaling 15 events. In low-recurrence areas, the mean regeneration time was 193 days (6.4 months; n = 6), with similar behavior among samples.

In high-recurrence areas, the mean was 169 days (5.6 months; n = 9), ranging from 145 to 193 days. The overall mean was 179 days (6 months; n = 15), corresponding to one rainy cycle in the Tropical climate. In these areas, regeneration was faster, associated with vegetation adaptation to fire (Simon; Pennington, 2012).

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Student’s t-test indicated a statistically significant difference between recurrence classes at the 5% level (p = 0.017), even with low variation in mean times.

In sample 13, in a low-recurrence area, NDVI variation throughout the series was relatively low, except during fire events. During periods of water stress, vegetation presented NDVI values higher than those of other phytophysiognomies, possibly due to root system depth (Figure 5a). Two fires were observed: the first between 08/15/2016 (indicator B) and 02/23/2017 (indicator C), and the second between 09/11/2020 (indicator B) and 03/22/2021 (indicator C). Both presented a regeneration time of 193 days (6.4 months).

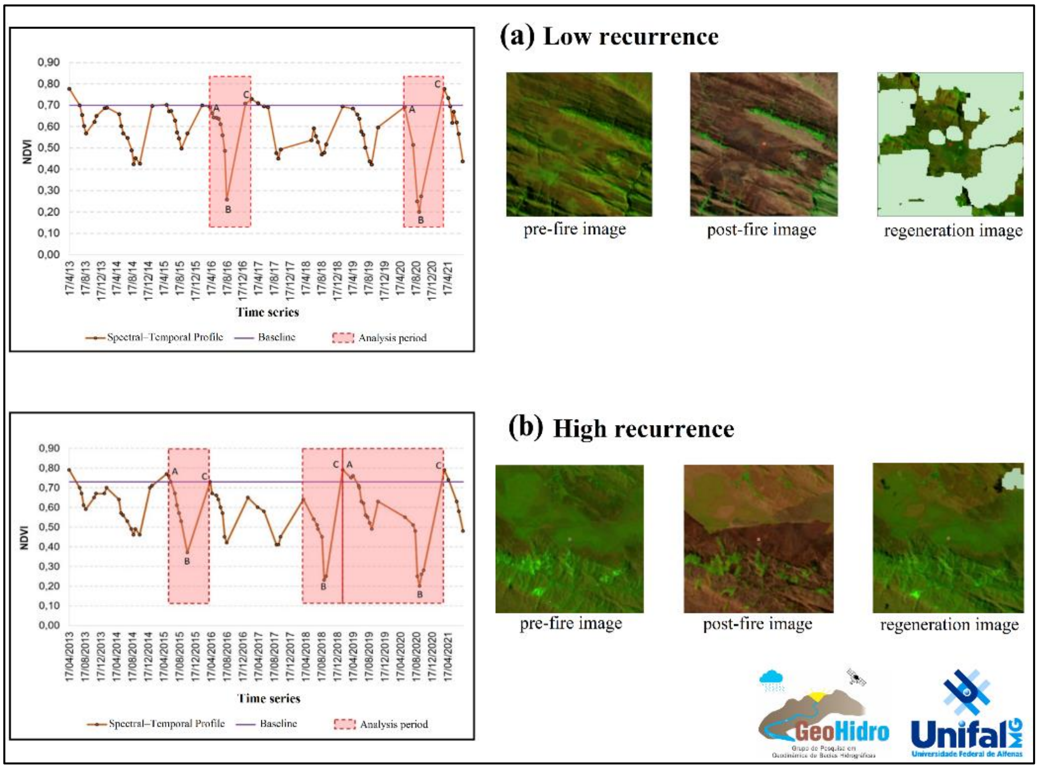

Figure 5 - Spectral-temporal profile and pre-fire, post-fire, and regeneration images (samples 13 and 16).
Source: Authors, 2023.

Sample 16, in an area with high fire occurrence, recorded three events. The minimum regeneration time occurred in the second event (145 days) and the maximum in the third (193 days), with an amplitude of 48 days. The first period began on 07/12/2015 (indicator A), with NDVI of 0.73. The post-fire image from 10/16/2015 (indicator B) presented 0.37 NDVI, while regeneration was recorded on 04/09/2016 (indicator C), with NDVI of 0.73, totaling 177 days (Figure 5b).

This process is related to the tree species of the Cerrado, which present phenological variation in leaf production and leaf fall. During periods of severe drought, there is a greater proportion of deciduous species, which lose leaves as a function of climatic seasonality

(Williams; Cook; Moore, 1999). Resprouting, however, is less influenced by seasonality and can occur in both rainy and dry periods (Gouveia; Felfili, 1998).

5. CONCLUSIONS

Post-fire regeneration showed significant differences between recurrence classes in Grassland and Cerrado stricto sensu, while in Rupestrian Grassland there was an increase in mean time in high-recurrence areas, but without statistical difference at the 5% level.

In Grassland, mean regeneration was 5 months under low recurrence and 13 months under high recurrence, showing a strong contrast.

In Rupestrian Grassland, mean times were 6 months under low recurrence and 9 months under high recurrence, suggesting a trend toward increased regeneration time, although without a statistically significant difference at the 5% level.

In Cerrado stricto sensu, mean regeneration was 6 months, with 6.4 months under low recurrence and 5.6 months under high recurrence, reflecting adaptations to fire.

Rainfall analyses showed that climatic seasonality interferes with NDVI and may induce fires. Visual inspection of the charts was essential for detection accuracy.

Overall, fire recurrence strongly influences recovery times, reinforcing the need for appropriate prevention and management strategies.

The comparative analysis highlighted the complexity and diversity of vegetation responses, emphasizing the importance of specific approaches for each phytophysiognomy.

There was agreement between the recurrence map from the MapBiomas Fire Project and the calculated NDVI, confirming the effectiveness of the index in identifying fires.

Google Earth Engine proved suitable for spectral-temporal analysis and interpretation of regeneration patterns, providing consistent information on mean recovery times.

This study focused on the spectral analysis of vegetation, but full regeneration also involves interactions between flora and fauna.

The results provide support for environmental management and conservation of PNSC, in addition to supporting broader analyses of ecosystem dynamics.

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