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Evaluating post-fire vegetation regrowth in Brazil's Chapada Diamantina National Park using remote sensing

Avaliação da regeneração da vegetação pós-incêndio no Parque Nacional da Chapada Diamantina do Brasil através de sensoriamento remoto

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Abstract: Understanding fire dynamics in vegetation is essential for assessing the impacts caused by wildfire action, especially because biomass burning in ecosystems has been indicated as one of the main factors that impact climate and biodiversity. A current alternative to detecting fire via satellite data is cloud processing platforms such as Google Earth Engine (GEE). Given this context, this work aims to assess the degree of vegetation regrowth after a wildfire in an area included in the Chapada Diamantina National Park (Bahia - Brazil) based on applying the Normalized Burn Ratio (NBR) in Landsat Surface Reflectance Tier 1 data sets. The images were accessed and processed on the GEE platform. The NBR index was more sensitive to the pre- and post-fire displacements of the pixels affected by the fires between the Landsat NIR and SWIR image bands. We found that the NBR mean values decreased immediately after the fire occurrence in the entire study area. Then, following the wildfire, the NBR mean values returned to conditions similar to those that preceded the fire. We can conclude that the plant biomass had already recovered considerably nine months after the fire when checking the NBR values. Therefore, this study points out the need to better understand the wildfire

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dynamics in the Chapada Diamantina National Park region and the impact associated with these events, with respect to fire ecology.

Keywords: Google Earth Engine; Landsat 8; Vegetation regrowth; Forest fire; NBR.

Resumo: A compreensão da dinâmica do fogo na vegetação é essencial para avaliar os impactes causados pela ação dos incêndios florestais, especialmente porque a queima de biomassa nos ecossistemas tem sido indicada como um dos principais fatores que impactam o clima e a biodiversidade. Uma alternativa atual para detetar incêndios através de dados de satélite são as plataformas de processamento em nuvens, como o Google Earth Engine (GEE). Dado este contexto, o presente trabalho visa avaliar o grau de recuperação da vegetação após um evento de incêndio numa área incluída no Parque Nacional da Chapada Diamantina (Bahia - Brasil) com base na aplicação da Razão de Queimada Normalizada (NBR) em conjuntos de dados Landsat Surface Reflectance Tier 1. As imagens foram acessadas e processadas na plataforma GEE. O índice NBR revelou-se mais sensível aos deslocamentos pré e pós-fogo dos pixels afetados pelos incêndios entre as bandas de imagem Landsat NIR e SWIR. Verificou-se que os valores médios do NBR diminuíram imediatamente após a ocorrência do incêndio em toda a área de estudo. Após o incêndio, os valores médios do NBR foram apontando no sentido do retorno a condições similares àquelas que o precederam, indicando os valores de NBR que a biomassa vegetal, nove meses após o incêndio, já apresentava uma considerável recuperação. Neste sentido, este estudo demonstra a necessidade de se conhecer melhor a dinâmica dos incêndios na região do Parque Nacional da Chapada Diamantina e os impactes associados a estes eventos, no que respeita à ecologia do fogo.

Palavras-chave: Google Earth Engine; Landsat 8; Regeneração da vegetação; Incêndios florestais; NBR.

Introduction

Fire plays an essential role in the ecology of many ecosystems (Bento-Gonçalves *et al*., 2012). It can be considered a pivotal factor in justifying the distribution and dominance of savannas worldwide, even in places where climate and soil are capable of sustaining forests (Bond & Keeley, 2005; Santos *et al*., 2020). However, fire can significantly threaten many environments, being considered one of the most challenging issues in the environmental sciences field (Bento-Gonçalves *et al*., 2012; Bento-Gonçalves & Vieira, 2020; Granged *et al*., 2011).

In the history and development of humanity, fire has always been present, being used through time to establish communities and open clearings in the forest (whether for agriculture or pasture), among others. Hence, wildfire assumes the role of a crucial "ecological factor" in the development or regression of forest systems worldwide (Ferreira-Leite *et al*., 2013). Thus, fire can be understood as a natural ecological factor or not, influencing the structure and functioning of several ecosystems. However, when its control is lost, it can cause significant damage (Chuvieco *et al*., 2010).

The increase in fire frequency and intensity has been documented in several ecosystems worldwide and it represents a substantial impact on global warming, as wildfires often result in massive loss of biomass and carbon, which may alter the local climate (Chuvieco *et al*., 2010; French *et al*., 2008; Meng & Meentemeyer, 2011; Parker *et al*., 2015; Robichaud *et al*., 2007; Westerling *et al*., 2006). In 2015, the Chapada Diamantina National Park, a Brazilian Federal Conservation Unit (UC), was affected by wildfires from September to December, when fire typically occurs in the region, as shown by several authors (Franca-Rocha *et al*., 2017; Leite *et al*., 2017; Santos *et al*., 2020; Santos *et al*., 2017). Therefore, when managing conservation areas such as the Chapada Diamantina National Park, it is essential to analyze the impact of fires on the ecosystem and its regrowth process.

After a wildfire, various changes occur as the fire consumes the vegetation, leaving soil exposed and altering its moisture. The degree of fire-induced ecological change has been the focus of many studies around the world (Parks *et al*., 2018). These researches are usually based on metrics that use pre and post-fire data to quantify fire-induced change (Parks *et al*., 2018). Thus, remote sensing techniques are highly feasible and effective in describing patterns of wildfire occurrence in several ecosystems, considering that satellite images are crucial for delineating fire expansion boundaries and characterizing fire severity degrees (Key & Benson, 2006; Meng & Meentemeyer, 2011; Santos *et al*., 2021; Santos *et al*., 2006; Sunderman & Weisberg, 2011; Veraverbeke *et al*., 2014).

Assessing wildfire induced changes in vegetation patterns from a temporal perspective range from field observations to monitoring using Earth Observation Systems (Bento-Gonçalves, Vieira, *et al*., 2019; Santos *et al*., 2020; Soulard *et al*., 2016). Earth observation is critical for monitoring land cover dynamics at both regional and global scales (Johansen *et al*., 2015; Sonnenschein *et al*., 2011). Although their temporal, spatial, and spectral resolutions vary, Earth Observation Systems provide tools to evaluate vegetation conditions from different perspectives, such as spectral indices (Soulard *et al*., 2016). In addition, recent advances in computational methods and free access to satellite systems such as Sentinel and Landsat enable the development of time-series studies to monitor and identify disturbances (Soulard *et al*., 2016).

Consequently, using the Google Earth Engine (GEE) platform seems promising for developing such analyzes, given its extensive processing capacity, in a concise way (Alencar *et al*., 2022). Google Earth Engine is a cloud-based processing platform that provides online access to the global coverage of satellite imagery, including MODIS and Landsat. The latter is available for nearly 40-year time series (Alencar *et al*., 2022). GEE also provides tools for trusted testers to explore this image data file to detect changes, map trends, and quantify differences in the Earth's surface (Johansen *et al*., 2015).

GEE has been used in various applications, covering topics such as global forest change (Hansen *et al*., 2013) and post-fire vegetation regrowth (Soulard *et al*., 2016). It has also been integrated with several applications, such as climate monitoring and land-use change assessment (Gorelick *et al*., 2017). Therefore, fire detection from satellite images can be done through specific techniques, such as spectral index calculation. These metrics derived from orbital data are often produced using images from Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM +), and Operational Land Imager (OLI) sensors. This is due to its global coverage and temporal resolution.

Srivastava *et al*. (2013) consider that Landsat images may provide better methods for obtaining information on the behavior and effects of fire regimes. Based on the results described by Key and Benson (2006) in their study, we consider that the NBR index incorporates the reflectance of Landsat-8/OLI band 5, which reacts positively to the plant's leaf area. In parallel, the reflectance of Landsat-8/OLI band 7 responds positively to the drying of some characteristics of the surface without vegetation. In addition, band 7 has low reflectance on vegetation that is green and without moisture, including moist soil and cloud, the opposite of band 5.

A widely used spectral index in fire studies is the Normalized Burn Ratio (NBR) (Key & Benson, 2006). This index helps to identify burned areas as they have specific spectral responses. Vegetation removal and the deposition of coal by fire generally result in a decrease in post-fire near-infrared (NIR) reflectance and an increase in post-fire short-wave infrared (SWIR) reflectance (Key & Benson, 2006). These metrics typically have a high correspondence ($r2 \geq 0.65$) with measures of fire severity based on field observations (Parks *et al*., 2018), which makes them a viable alternative to collecting information in extensive environmental conservation areas, such as the Chapada Diamantina National Park (Santos *et al*., 2020).

Fire severity refers to how fire intensity affects ecosystems. While intensity describes the physical process of combustion and energy release from organic matter, fire severity refers to the magnitude of fires' direct and immediate impact, it reflects the total heat released from burning biomass. Fire intensity thus contributes to fire severity but only partially explains it (Bento-Gonçalves *et al*., 2019; Santos *et al*., 2020).

For all these reasons, and because of their spatial resolution and unique spectral characteristics, satellite image analysis is a valuable tool for mapping burned areas and monitoring vegetation cover (Escuin *et al*., 2008). The delineation of the perimeter of the burned area and the identification of its severity levels, contribute to the decision-making process regarding the regrowth of these areas. It also allows an analysis of the effects of fire on post-fire succession vegetation.

This paper aims to characterize the degree of regrowth of the vegetation cover in the Chapada Diamantina National Park after a wildfire event, using NBR values calculated in the GEE processing environment. To achieve this goal, we used Landsat-8 data to evaluate the vegetation regrowth in an area affected by wildfire in 2015, considering the years pre-and post-fire. NBR spectral index was used to diagnose the fire severity and the levels of regrowth (or vegetation regrowth). The regrowth process was evaluated by comparing the burned area with an unburned reference area in its surroundings.

The use of Google Earth Engine to run the methodology of this study represents an important contribution to planning actions to monitor wildfires. Parks *et al*. (2018) presented their work methods to produce fire severity metrics derived from Landsat data quickly. Therefore, the development of studies using methodologies in the GEE environment will allow the production of data sets and information on the areas affected by wildfires more quickly.

1. Materials and Methods

1.1. Study area

The Chapada Diamantina National Park is in the state of Bahia (Brazil) and corresponds to the extension of the Espinhaço Rift System, beginning in Minas Gerais State and penetrating Bahia. This protected area situates in the Sincorá mountain range, a plateau with altitudes ranging from 400 to 1700 meters. Therefore, altitude and relief diversity influence the occurrence of different climates. According to the Köppen Climate Classification System, hot and semiarid (BSwh), tropical highland (Cwb), and tropical monsoon (Am) climates prevail in the study area (Santos *et al*., 2017).

The Park is the federal conservation unit with the largest number of wildfires per season in Brazil, although it is not where the largest burning extensions occur (Gonçalves *et al*., 2011). In 2015, the conservation unit burned 33,390 hectares (Santos *et al*., 2017) in a fire season that lasted from September to December, a period when the occurrence of wildfires in the region is larger (Santos *et al*., 2017). Therefore, the development of this study is based on an area burned in 2015 in the Chapada Diamantina National Park (Figure 1). The park has a high floristic diversity associated with various vegetation types that include "Floresta estacional"[1], "campo limpo"[2] (savannah-type formations), and "campo rupestre"[3]. The Fire affected a small area of "matas ou floresta estacional", "campo limpo", and "campo rupestre" type vegetation.

The area's elevation varies between 1200 and 1600 meters, with Neosol and Latosol soil types. This burned area was chosen because it has a large tourism flow, and rich biodiversity of fauna and flora, besides being affected by frequent burnings (Gonçalves *et al*., 2011).

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[1] The "floresta estacional" may be encountered on the western slope of the mountain and is a small area in a valley carved into the anticlinal of the mountain. According to a survey conducted in 2011 in the Chapada Diamantina National Park, on the western edge, the canopy trees are 6 to 9m high with an understory with a high number of young species, this type of forest its trees lose their leaves during the dry season (Do Couto *et al*., 2011).

[2] The "campo limpo" vegetation type is a predominantly herbaceous physiognomy characteristic of the Cerrado Biome and can be found in various topographic positions with different humidity variations. However, it is most often found in humid and periodically flooded areas (Munhoz & Amaral, 2010).

[3] "Campo rupestre" stand out for their high plant richness and endemism (Araújo & Conceição, 2021; Silveira *et al*., 2016). The vegetation comprises a mosaic of plant communities with different physiognomies on rocky or sandy substrates. It generally occurs at altitudes above 900m, in areas with constant winds and extreme temperature variations, with hot days and cold nights (Munhoz & Amaral, 2010). On extensive rocky outcroppings, the vegetation is structured in small islands of herbs and shrubs sensitive to fire and tolerant to desiccation. On sandy soils, the vegetation is characterized by a continuous layer dominated by grasses and shrubs resistant to fire (Araújo & Conceição, 2021). The presence of endemic plant species with characteristics that allow them to survive some fire regimes suggests an ancient role of fire in the evolution of Rupestrian grasslands (Araújo & Conceição, 2021).

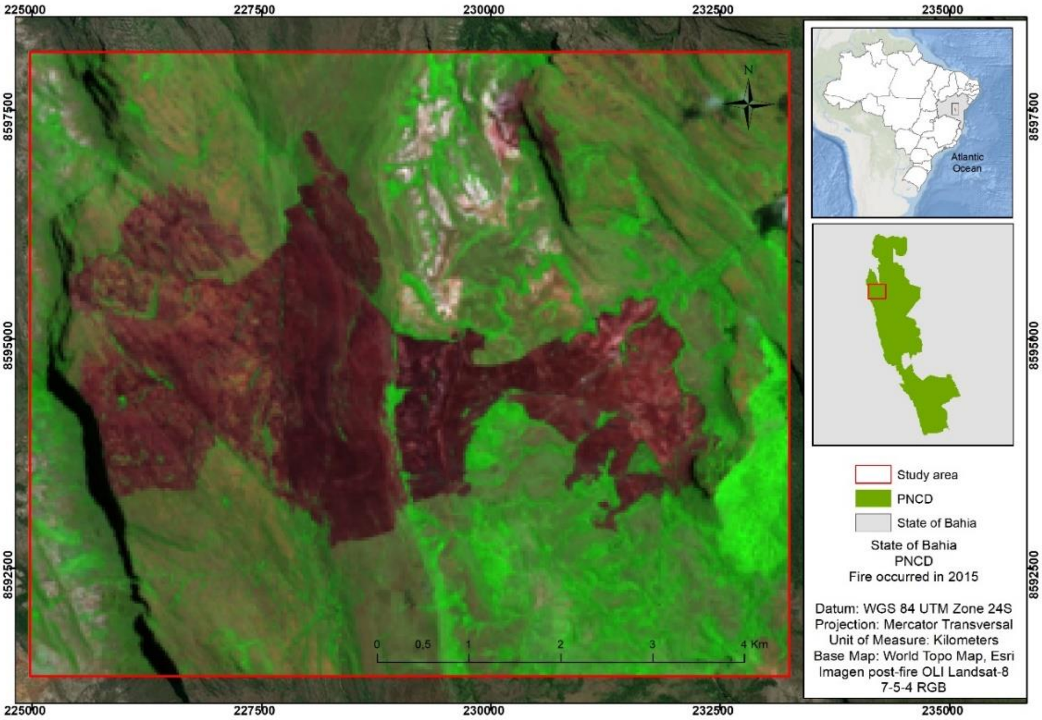

Figure 1: Location of the study area. In green, the Chapada Diamantina National Park is represented on the smaller map. The delimitation of the study area is shown in red. The post-fire image corresponding to the study area is the Landsat-8/OLI (R:7; G:5; B:4).
Source: NASA Landsat Program.

1.2. Database

By accessing the Google Earth Engine (GEE) platform, the Landsat Surface Reflectance Tier 1 data sets were used for running the NBR index and NDVI index. Initially, 111 Landsat-8 scenes ranging from April 2013 to November 2018 were identified for the study area. However, after applying a cloud filter of less than 30%, the collection has been reduced to 20 images. Despite this, there were still many clouds in these data, which meant that in the end, only 6 scenes were considered between 2013 and 2017 (Table I).

Table I: Characteristics of OLI / LANDSAT-8 images.

Satellite	Sensor Path/ row	Spatial resolution	Period	Product
Landsat	OLI 217/069	30 m	30/05/2013pre	NBR and NDVI
			22/09/2014pre	
			24/08/2015pre	
Landsat	OLI 217/069	30m	25/09/2015post	NBR and NDVI
			30/11/2016post	
			16/10/2017post	

To identify rainfall indices, maximum temperature, and humidity values, monthly accumulated values data from the meteorological station of Lençóis-Ba were used for

2015 (fire occurrence) and 2016 (post-fire). These data were obtained from the website of the National Institute of Meteorology (https://tempo.inmet.gov.br/).

The years 2013, 2014, 2016, and 2017 did not record any heat sources by the reference satellites, except for 2015, with four heat sources identified. These data come from sensors onboard the reference satellites used by the National Institute for Space Research (INPE) from Brazil, whose daily data on detected heat sources are used to build the time series over the years. Thus, the trend analysis may be carried out regarding the number of heat sources in different periods for the same study area. From 2010 to 2015, the reference sensor is MODIS (AQUA/TERRA), available in the Center for Weather Forecasting and Climate Studies (CPTEC) database.

1.3. Processing in Google Earth Engine

Landsat Surface Reflectance Tier 1 data sets include a quality evaluation mask to identify the pixels containing clouds, shade, and water (Parks *et al*., 2018). Such a process was performed using the FMask multi-pass algorithm, based on decision trees and described in detail by Foga *et al*. (2017) and Parks *et al*. (2018). When calculating the NBR index, the pixels identified as cloud, shade, and water were excluded.

To detect the area affected by the fire and to evaluate the post-fire vegetation regrowth, the Normalized Burn Ratio (NBR) index was calculated based on Landsat 8 data. This index normalizes the difference between the reflectance of Landsat-8/OLI band 5 and band 7, in which the burned areas are highlighted. To evaluate the bi-temporal change detection, the SWIR-NIR spectral interval was considered (see Figure 2) (Escuin *et al*., 2008; Key & Benson, 2006; S. Veraverbeke *et al*., 2010). The NDVI was calculated to help understand the vegetation condition, as it is a widely used index for studies in this line (Gouveia *et al*., 2010; Morresi *et al*., 2019).

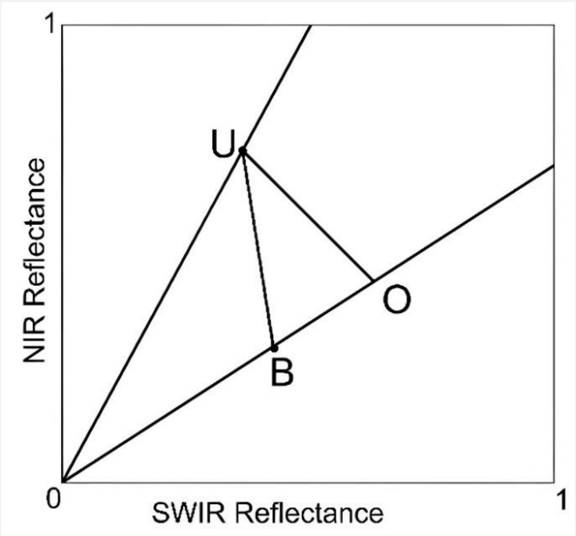

Figure 2: Example of a pre-and post-fire pixel trajectory in the SWIR-NIR feature space. A pixel moves from unburned (U) to burned (B). Point "O" resembles the position of a pixel optically detected and burned (Santos *et al*., 2020).

If a spectral index is appropriate for a given physical change, in this case, the reduction of fire-induced vegetation, there is a clear relationship between the shift and the direction of displacement in the bi-spectral feature space (Veraverbeke *et al*., 2010). In an ideal scenario, the bi-temporal trajectory of a pixel is perpendicular to the first bisector of the Cartesian coordinate system. This is illustrated in figure 2 for the displacement from unburnt (U) to optically (O) detected as burned (Escuin *et al*., 2008; Santos *et al*., 2020; Veraverbeke *et al*., 2010).

After selecting the scene collection, the NBR index (Key & Benson, 2006) was calculated based on a normalized difference function (Equation 1) and NDVI (Equation 2).

$$NBR = (NIR - SWIR)/(NIR + SWIR) \tag{1}$$

$$NDVI = (NIR - RED)/(NIR + RED) \tag{2}$$

Where,

- RED corresponds to Landsat-8/OLI band 4;
- NIR corresponds to Landsat-8/OLI band 5;
- SWIR corresponds to Landsat-8/OLI band 7.

NBR is a normalized index, its values range from -1.0 to +1.0. Key and Benson (2006) argue in their study that the response is positive when the reflectance in band 5 is greater than the reflectance in band 7, which is the case in productive vegetation areas. When the response is close to zero, the reflectance of both bands 5 and 7 are approximately equal, as with clouds, unproductive vegetation, bare soil, and rock outcrop. On the other hand, when NBR is negative, the reflectance in band 7 is higher than in band 5, suggesting high water stress on plants and the negative values representing burned areas (Leite *et al*., 2017; Santos *et al*., 2020).

After processing in GEE, the data was exported and converted to matrix format using ENVI 5.3 software. Descriptive statistics were calculated using R software, followed by the creation of boxplot graphs to represent the temporal variation of the observed burnt and unburnt area data. A transect was also applied to collect pixel information from unburned and burned areas; these data were used for calculation of Pearson correlation for NBR values.

2. Results

The fire occurred during September 2015 in the Chapada Diamantina National Park in a region called Gerais do Vieira. The affected vegetation was mostly “campo limpo”, “campo rupestre”, and a small area of seasonal forest. The area presented severity classes ranging from moderate-low severity to high severity (Santos *et al*., 2020).

The meteorological data indicate that September of 2015 presents favorable characteristics for fire occurrence. Low rainfall values (0,04 mm) associated with increased maximum temperature (32,7 ºC) and reduced air humidity (64%) were observed (see Figure 3).

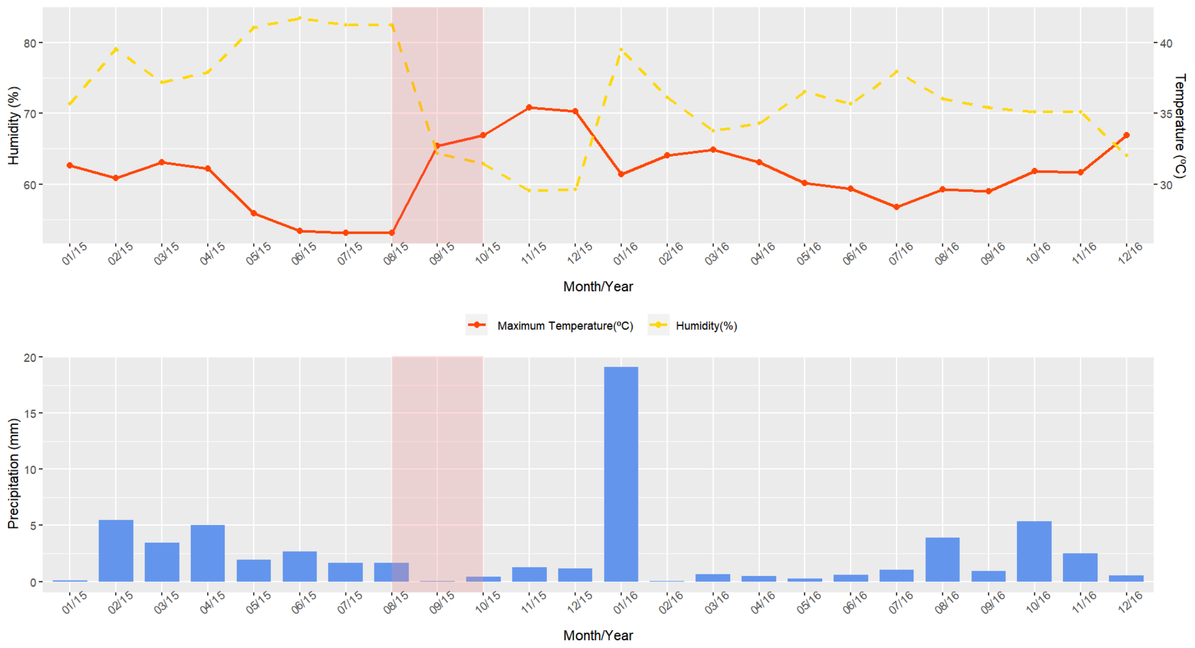

Figure 3: Mean precipitation (in blue), mean high temperature (in red) and minimum relative humidity (in yellow) monthly mean. The increase in temperature from August on, after months of little rainfall, favors the deflagration of vegetation fires (red column). Data source: INMET.

From the GEE, NBR images were obtained for the study area. The exclusion of the pixels corresponding to cloud, shade, and water resulted in a reduced number of Landsat-8 images to be processed. A variation of the NBR index values was observed from 2013 to 2017. It is worth highlighting that for 2015 the results showed more substantial effects (Table II).

Table II: NBR descriptive statistics, highlighting the year 2015, the year of the burning Data from the points before and after the fire.

Date	Min		Median		Mean.		SD		Max.	
	Fire	No Fire	Fire	No Fire	Fire	No Fire	Fire	No Fire	Fire	No Fire
30/05/2013	0.0655	-0.0135	0.1901	0.2396	0.2526	0.2647	0.1750	0.1691	0.6518	0.6789
22/09/2014	0.0219	-0.0533	0.1099	0.1825	0.1967	0.2120	0.1777	0.1695	0.6180	0.6411
24/08/2015	0.0716	0.0048	0.1704	0.3061	0.2486	0.2882	0.1711	0.1608	0.6549	0.6537
25/09/2015	**-0.4352**	**-0.0319**	**-0.2111**	**0.1911**	**-0.1405**	**0.2279**	**0.2589**	**0.1755**	**0.5235**	**0.6495**
30/11/2016	-0.0994	-0.0266	0.0474	0.1297	0.1488	0.2010	0.1971	0.1688	0.5946	0.6393
15/10/2017	-0.0681	-0.0536	0.1535	0.1122	0.1621	0.1838	0.1780	0.1675	0.6077	0.6255

Table III: NBR descriptive statistics, highlighting the year 2015, the year of the burning Data from the points before and after the fire.

Date	Min		Median		Mean.		SD		Max.	
	Fire	No Fire	Fire	No Fire	Fire	No Fire	Fire	No Fire	Fire	No Fire
30/05/2013	0.5092	0.5092	0.5825	0.5825	0.6139	0.6139	0.0985	0.0985	0.8422	0.8422
22/09/2014	0.4424	0.3853	0.5107	0.5385	0.5577	0.5597	0.1000	0.1104	0.7833	0.8424
24/08/2015	0.4858	0.3549	0.5535	0.6004	0.5912	0.6091	0.0972	0.1029	0.8178	0.8518
25/09/2015	**0.2181**	**0.2318**	**0.3315**	**0.5751**	**0.3851**	**0.5805**	**0.1497**	**0.1211**	**0.7470**	**0.8504**
30/11/2016	0.3491	0.4184	0.5172	0.5497	0.5526	0.5803	0.1197	0.1013	0.8060	0.8517
15/10/2017	0.4265	0.4099	0.5222	0.5214	0.5525	0.5598	0.0992	0.1002	0.7994	0.8365

Table II presents the descriptive statistics of the data. The mean NBR values were 0.2 in the study area, except for 2015, where a mean NBR equivalent to -0.1405 was recorded for the area burned in September.

For this scene, minimum values around -0.4 were identified, suggesting the occurrence of burns in this period. This result shows that from 2013 to 2017, the study area only presented NBR values indicating the wildfire in 2015.

Figure 4 shows pixel shifts in a time series for the datasets studied. The NBR values for September 2015 showed a higher concentration of negative pixels referring to the burned area. The mean NBR values for the entire study area indicate that the NBR values of September 2015 decreased immediately after the wildfire. Then, following the wildfire event, the NBR mean values returned to similar conditions to those preceding the fire.

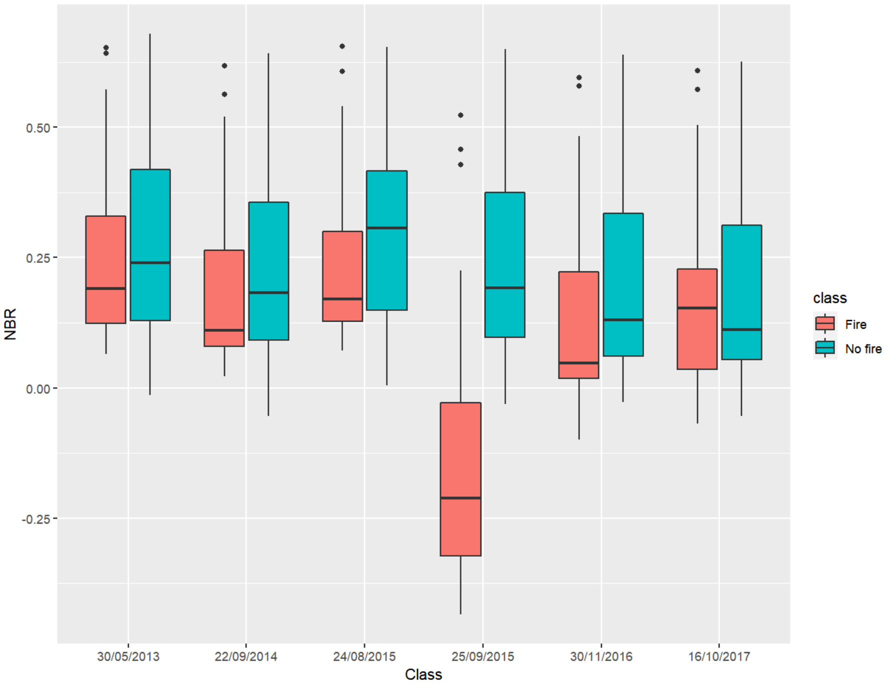

Figure 4: Boxplot of the NBR values based on Landsat-8 images. For pre- and post-fire scenes for burned and unburned areas.

Figure 5 brings NDVI index data to understand how the state of the vegetation was in the same period. In the 2016 image, we can see that the NDVI and NBR values of the burned area pixels return to similar conditions to the 2015 values (before the fire). We can relate the return of the photosynthetic conditions of the vegetation to the high rainfall values recorded in January 2016 (see Figure 3). The burnt and unburnt area presented the same type and conditions of vegetation, the fire was conditioned by action of firefighting and suppression of the fire by brigades working in the environmental preservation area.

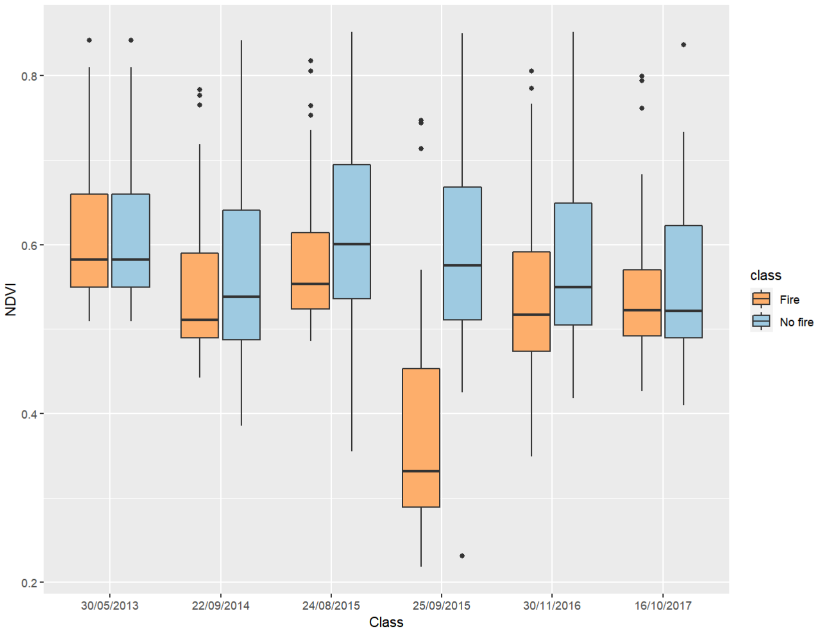

Figure 5: Boxplot of the NDVI values based on Landsat 8 images. For pre- and post-fire scenes for burned and unburned areas.

The temporal changes in the study area were obtained in the GEE environment using Landsat-8/OLI images in RGB (7-5-4) composition (Figure 6) and NBR (Figure 7). In the image of September 2015, the burn scar is highlighted in the brown pixels. In the image processing one year after the wildfire event, the plant regrowth is easily visible due to a change in the color of the targets.

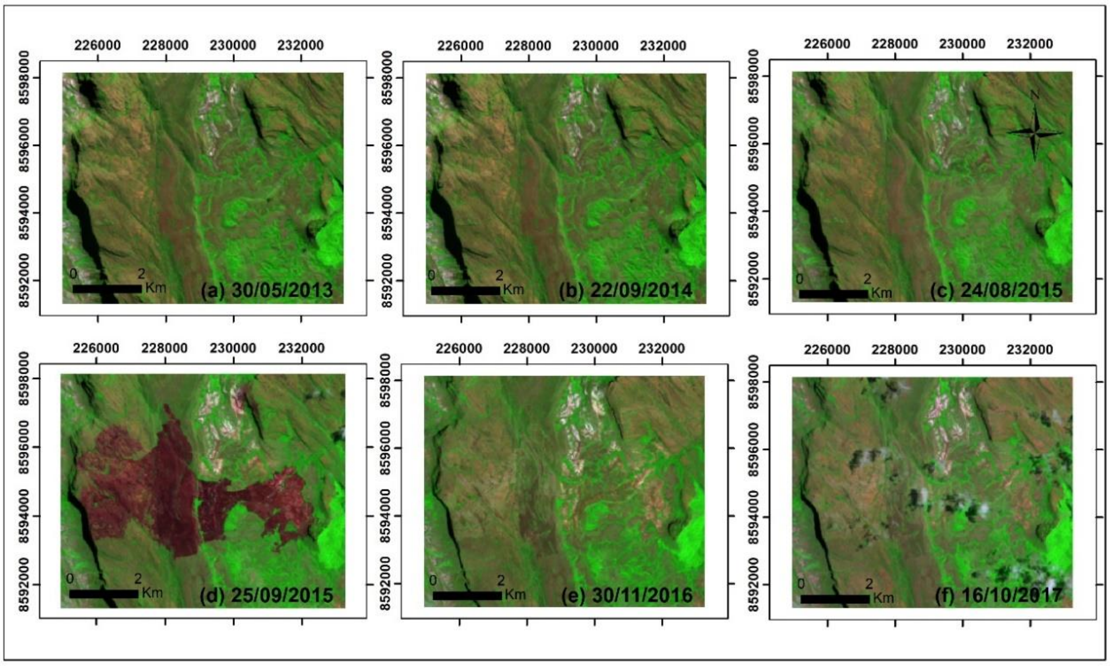

Figure 6: Landsat-8 RBG (7-5-4): (a) 30/05/2013; (b) 22/09/2014; (c) 14/08/2015; (d) 15/09/2015; (e) 30/11/2016; (f) 16/10/2017. In the image of September 2015 (image d), the burn scar can be observed in brown color. **Source:** NASA Landsat Program.

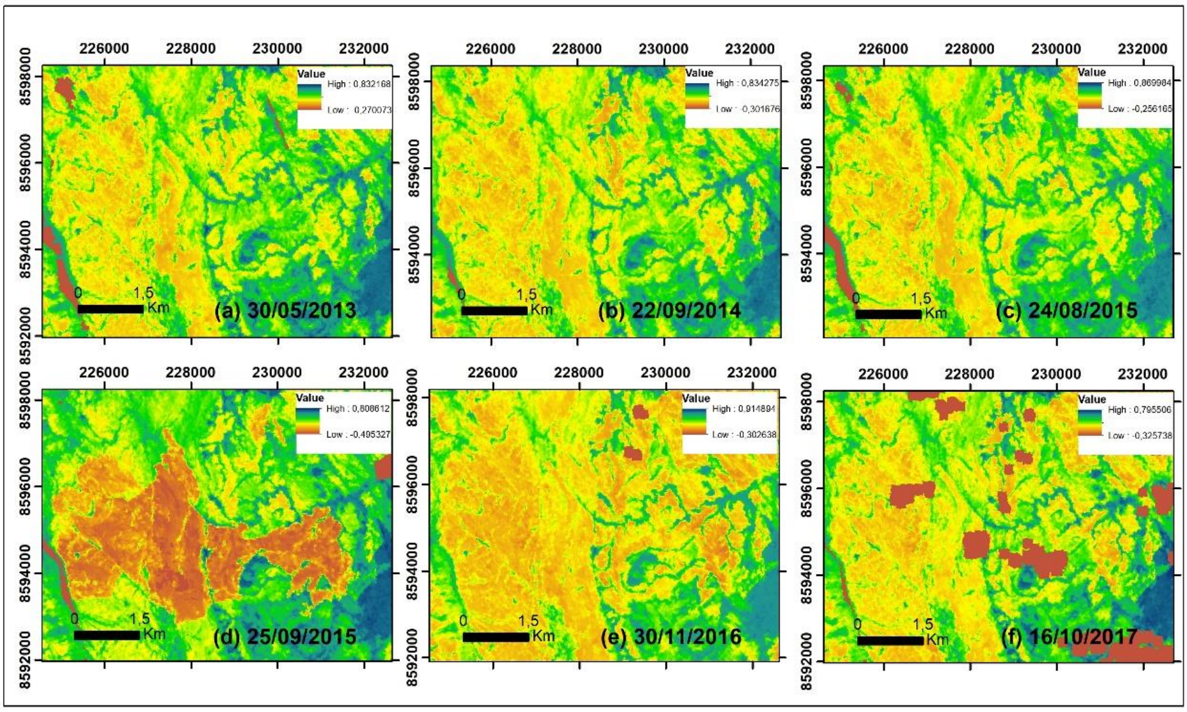

Figure 7: Index NBR: (a) 30/05/2013; (b) 22/09/2014; (c) 14/08/2015; (d) 15/09/2015; (e) 30/11/2016; (f) 16/10/2017. In the image of September 2015 (image d), the burn scar can be observed. **Source:** NASA Landsat Program.

The application of a transect on the image allowed us to verify the correspondence of NBR values before the fire (2014) and NBR regrowth (2016 and 2017) and to evaluate their correlation in different situations (Figure 8). The first correlates the NBR values before the fire and one year and two months after the wildfire, which resulted in a correlation of r = 0.93 (Figure 8a). And the second correlation, between pre-fire NBR and NBR regrowth two years and one month after the event, recorded an r = 0.94 (Figure 8b).

The Student's t-test to find out if the correlation is significant gave a p-value below 0.05, which shows that the correlation is significant. That means when the vegetation recovers, in short time periods, it continues at the same levels compared to before for the studied area with this type of vegetation.

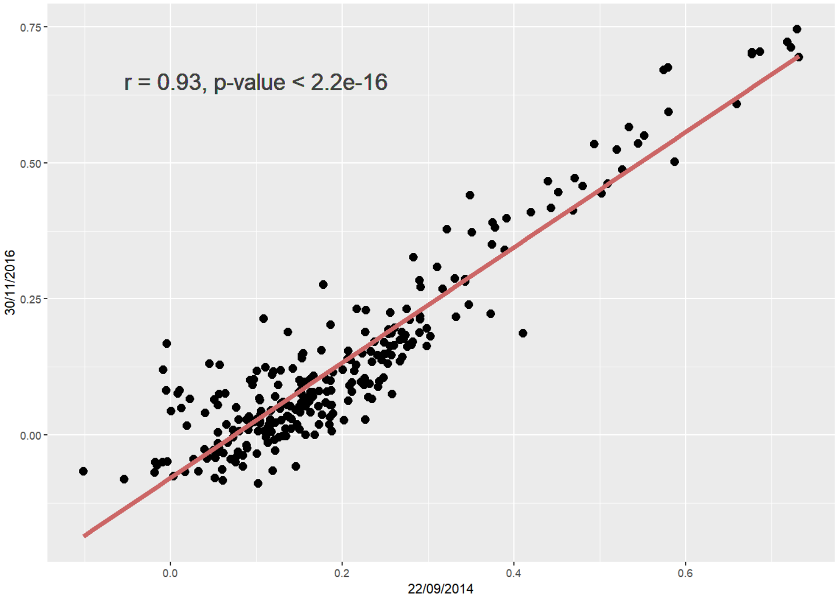

Figure 8a: Correlation between pre-and post-fire conditions (regrowth): NBR pre-2014 and NBR regrowth 2016.

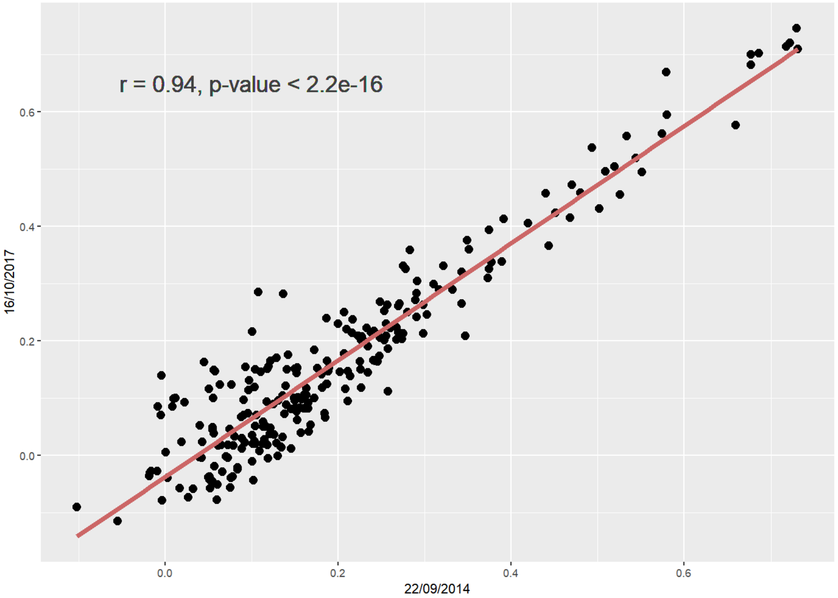

Figure 8b: Correlation between pre-and post-fire conditions (regrowth): NBR pre-2014 and NBR regrowth 10/2017.

3. Discussions

The calculation of the NBR index identified the area affected by the wildfire in the Chapada Diamantina National Park (Parks *et al*., 2018) estimates that the NBR measures the change in the spectral response caused by burned areas. Complementing this idea, Rogan and Yool (2001) consider that changes in the NIR reflectance typically indicate changes in the coverage of photosynthetic vegetation that are likely to be reduced by fire. In contrast, changes in SWIR reflectance usually mean changes in the exposure to bare soil, which is expected to increase after the influence of wildfire.

In 2015, the Chapada Diamantina National Park was devastated by several fires between September and December, a typical period for fires in the region(Santos *et al*., 2020; Santos *et al*., 2017). Studies indicate that the region is exceptionally favorable for the occurrence of fires between September and November (Santos *et al*., 2017). Data from the National Institute of Meteorology for 2015 show that the relatively low volume of rainfall and the increase in maximum temperature and reduction in humidity leads to the loss of photosynthetically active capacity of the vegetation cover, which facilitates the occurrence of fires.

In a study conducted in 2015 in the PNCD (Araújo & Conceição, 2021), in an environment with the same fire-prone vegetation type, spaces opened by fire can be quickly recovered by native plants (Araújo & Conceição, 2021; Neves & Conceição, 2010), mainly when the community is composed of resprouting species (Araújo & Conceição, 2021). Following this trend, the re-establishment of vegetation cover observed in the present study also occurred in a short period (16 to 20 months)(Araújo & Conceição, 2021), which corroborates the results found with the application of the NBR index. Leite *et al*. (2017) sought to identify fire-affected areas in 2008 and 2015 and compare the effectiveness of both NBR and NDVI spectral index for the same area as this study. The authors found that NBR attributed negative values to burned areas. Consequently, there is a decrease in the vegetation vigor density, which implies a negative spectral response in band 5 and an increase in the exposed soil substrate and burned materials, resulting in positive values for band 7. Key and Benson (2006) found that the results of recent fires usually present with negative NBR values close to zero for strongly negative NBR values (from 0 to -1), as it is observed in the boxplot of 09/25/2015 in figure 4.

Several authors also made similar observations in previous studies on this topic (Doerr *et al*., 2006; Key & Benson, 2006; Parker *et al*., 2015; Rogan & Yool, 2001; Sunderman & Weisberg, 2011; Wimberly & Reilly, 2007). Rogan and Yool (2001) highlighted the potential of NBR in characterizing fire-induced landscape changes. Parker *et al*. (2015) analyzed the effects of vegetation regrowth from the NBR calculation due to the latency time between the wildfire ignition and the date of the Landsat image acquisition. The authors noted that Landsat images captured 68 days after the ignition date indicated that the spectral signature of the burned was likely to have decreased, underestimating the severity of the fire, which can be attributed to the rapid regeneration of the vegetation, thus indicating its regrowth.

Santos *et al*. (2017) showed while assessing fire occurrence in a 10-year interval that the hot spots in the Chapada Diamantina National Park tend to increase considerably between September and December. Such an observation allows for considering the climatological factor in discussions of this nature, especially because fire occurrence has a particular seasonal pattern. Therefore, soon after this period, increased precipitation and reduced temperature between summer and fall may contribute to vegetation regrowth.

In this study, the NDVI values one year after the wildfire showed higher vigorousness compared with the data of the 2017 image. This increase may be related to a more notable plant activity in the study area between the months studied. Such a pattern is due to the influence of the rainy season. Given this result, we can consider that historical data derived from satellite imagery on fires can provide valuable information for more effective management of natural resources. These data represent a new insight into spatial and temporal patterns of fire regimes and fuel loads for supporting plans regarding flammable ecosystem management.

The NBR index can indicate pre-and post-fire vegetation conditions and is highly influenced by meteorology. In a study developed in South Korea, Ryu *et al*. (2018) observed that the annual meteorological variation strongly affects the vegetation and water conditions in a forest ecosystem. As a result, such phenomena directly impact the temporal patterns of forest regrowth indicated by NBR and NDVI.

Conclusions

This paper presented a useful methodology to characterize the vegetation regrowth after a wildfire event. The NBR index demonstrated higher sensitivity to the pre-and post-fire displacements of the fire-affected pixels in the interval based on comparing both Landsat NIR and SWIR bands. This study also found that the NBR mean values decreased immediately after the wildfire occurrence in the entire study area. After the wildfire event, the NBR mean values returned to conditions similar to those that preceded the wildfire occurrence. Thus, when checking the NBR values, we can conclude that the plant biomass had already recovered considerably 9 months after the fire.

When assessing vegetation regrow from Landsat imagery, historical data on fires must be considered to guarantee more consistent information for increasing the effectiveness of the management of natural resources. These data represent a new insight into both spatial and temporal patterns of fire regimes and fuel loads that can be used to support plans concerning the management of flammable ecosystems.

It is important to consider that the historical information on vegetation regrowth obtained from the Landsat images can provide valuable data for the effective management of natural resources. Studies should be encouraged to map the recurrence of fires in the area and understand the landscape patterns created by the fire and the monitoring of the regrowth of the affected areas and their relationship with severity.

With this study, we can realize that only with the application of the NBR index the Park managers can apply the technique and carry out the monitoring of the vegetation, being a simpler analysis that can be easily applied. We can also conclude that the vegetation characteristics in 1-2 years return to the spectral characteristics of the vegetation before the fire. This information will be valuable for forest managers to understand the consequences of even more acute fire regimes as observed for the area studied in 2008 and 2012. It will help in the implementation of effective restoration and environmental education actions. As a suggestion for future work, this study recommends further investigation into the dynamics of fires, their consequent ecological impacts, and recurrence in the Chapada Diamantina National Park.

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