Revista Brasileira de Cartografia
ISSN 1808-0936 | https://doi.org/10.14393/revbrascartogr
Sociedade Brasileira de Cartografia, Geodésia, Fotogrametria e Sensoriamento Remoto

Evaluation of Spectral Indices for Mapping Burned Areas using Unsupervised Classification in Different Ecosystems using Spectral Indices from Sentinel-2 images

Avaliação de Índices Espectrais para o Mapeamento de Áreas Queimadas usando Classificação não Supervisionada em Diferentes Ecossistemas usando Índices Espectrais de Imagens Sentinel-2

Juarez Antônio da Silva Júnior[1] e Admilson da Penha Pacheco[2]

1 Universidade Federal de Pernambuco, Recife, Brasil. juarez.silvajunior@ufpe.br
ORCID: https://orcid.org/0000-0002-2898-0309
2 Universidade Federal de Pernambuco, Recife, Brasil. admilson.pacheco@ufpe.br
ORCID: https://orcid.org/0000-0002-3635-827X

Recebido: 02.2023 | Aceito: 06.2023

Abstract: Fire is one of the natural agents that has the greatest impact on the terrestrial ecosystem and plays an important ecological function in a huge portion of the Earth's surface. Remote sensing is an important source for mapping and monitoring forests as well as environmental damage to the landscape caused by fire.To estimate the severity of the fire, the temporal distinction between the spectral indices before and after the fire is critical. This study examines the performance of spectral indices derived from Sentinel-2 Multi Spectral Instrument (MSI) bands for the detection of fire-affected areas in forest fires in regions with different ecosystems located in Brazil, the United States, and Portugal. Separability Index (M) and the Reed-Xiaoli Detection (RXD) Anomaly automatic classifier allowed us to assess the spectral separability and the thematic accuracy of the burned area for the different spectral indices. The analysis parameters were based on spatial dispersion with validation data, Commission Errors (CE), Omission Errors (OE), and Sorensen–Dice Coefficient (DC). The results indicated that the indices based exclusively on the longer shortwave infrared (SWIR1), shorter SWIR (SWIR2), and red-edge bands showed a high degree of separability and were more suitable for detecting the burned areas, although it was observed that the diversity of land use affects the performance of the indices. The evaluation of the performance of the spectral indices based on Sentinel-2 data was important in the analyzes of potentialities and limitations in the detection of burned areas in the face of the different global biomes.
Keywords: Forest Fires. Remote Sensing. Sentinel-2. Spectral Indices.

Resumo: O fogo é um dos agentes naturais de maior impacto no ecossistema terrestre e desempenha importante função ecológica em grande parte da superfície terrestre. Para regular e avaliar os danos ambientais, o sensoriamento remoto é uma técnica importante para mapear e monitorar as mudanças nas paisagens florestais produzidas por incêndios. Para estimar a severidade do incêndio, a distinção temporal entre os índices espectrais de severidade ordenados antes e depois do incêndio é crítica. Este estudo examina o desempenho de vários índices espectrais derivados das bandas Sentinel-2 MSI (Multispectral Instrument) para a detecção de áreas afetadas por incêndios florestais em regiões com diferentes ecossistemas localizadas no Brasil, o Estados Unidos e Portugal. O índice de separabilidade (M) e o classificador automático Reed-Xiaoli Detection (RXD) Anomaly permitiram avaliar a separabilidade espectral e a precisão temática da área queimada para os diferentes índices espectrais. Os parâmetros de análise foram baseados na dispersão espacial com dados de validação, Erros de Comissão (CE), Erros de Omissão (OE) e Coeficiente de Sorensen-Dice (DC). Os resultados indicaram que os índices baseados exclusivamente no infravermelho de ondas curtas mais longo (LSWIR), SWIR mais curto (SSWIR2) e bandas de borda vermelha apresentaram alto grau de separabilidade e foram mais adequados para detectar as áreas queimadas, embora tenha sido observado que o a diversidade de uso da terra afeta o desempenho dos índices. Os índices fornecidos pelos dados multitemporais do Sentinel-2 permitiram auxiliar o manejo florestal para o monitoramento espacial das cicatrizes de incêndio estudadas, adaptando-se aos diferentes biomas interligados.
Palavras-chave: Incêndios florestais. Sensoriamento remoto. Sentinela-2. Índices Espectrais.

1 INTRODUCTION

Biomass burning is a major disturbance in almost all terrestrial ecosystems. Forest fires have important biophysical and ecological consequences at various scale levels. On a global scale, vegetation fires attest to a significant contribution to the emission of trace gases into the atmosphere and play an undeniable role in global climate cycles (CHUVIECO et al., 2019). Forest fires partially or entirely remove the vegetation layer at the landscape level and affect post-fire vegetation composition. Accordingly, monitoring and assessing the fires' impacts on the natural ecosystem are necessary to plan the post-fire management of damaged areas. (VERAVERBEKE et al., 2011; FARHADI et al., 2022).

Earth Observation (EO) has proven to be a suitable technology for identifying areas affected by fires from global to local scales. From this perspective, EO data have been used to identify active fires, delimit perimeters of burned areas, monitor vegetation recovery after the fire event, and determine the distribution of the plume in the atmosphere (CHUVIECO et al., 2019; FORKEL et al., 2019). In recent years, the wide availability of high-resolution optical data, equipped with spectral information in the red-edge domain, which is one of the best radiance-based descriptors of chlorophyll content, has paved the way for the development and application of new spectral indices to discriminate burn severity (GIGLIO et al., 2016). Recent studies have assessed burn severity using Sentinel-2 spectral indices from pre-fire and post-fire satellite acquisitions. These studies showed good performance in the red edge band, suggesting the need for further research on the systematic development of mapping burned areas (CAMPAGNOLO et al., 2021; LIU et al., 2020; FILIPPONI et al., 2018).

Spectral indices (SI) are a viable alternative for discriminating between burned and unburned areas in single images. Despite the common use of SI, it is still a challenge to identify which one is the most appropriate for each case. Furthermore, research studies often evaluate the performance of spectral indices in ideal case studies - i.e. wildfires occurring during the summer dry season when vegetation is still photosynthetically active - without demonstrating whether they perform well under different environmental conditions. (PICOTTE et al., 2020; BA et al., 2019). Some of these studies report that spectral indices have different behaviors for different biomes. The Normalized Burn Ratio (NBR) and Burn Area Index (BAI) indices proposed by Key and Benson (1999) and Chuvieco et al., (2002), respectively, are used worldwide with functionalities of mapping and modeling forest fire predictions.

The BAI index, uses the reflectance values in the red and Near-Infrared (NIR) part of the spectrum to identify the areas of the land affected by the fire. It emphasizes the coal signal in post-fire images. BAIS2 is an adaptation of the BAI index based on the Sentinel-2 red edge bands (FILIPPONI, 2018). Trigg and Flasse et al. (2011) developed the MIRBI Index for shrub-savannah vegetation, where NIR wavelengths are less efficient because of the senescent condition of the plant during the fire event. The index was created in the SSWIR1/SWIR2 spectral space, and its performance in savannah ecosystems was shown to be fairly stable different seasons. The NBR index was initially developed for use with Landsat TM and ETM+ bands 4 and 7 but can be used with any multispectral sensor with NIR bands between 0,76 and 0,9 µm and SWIR between 2.08 and 2.35 µm. It was proposed by Key and Benson (1999). The NIR and SWIR2 spectral regions are used instead of the red region by NDVI (BASTARRIKA et al., 2014). The water content in plants or soils absorbs significant radiation in the SWIR2 band. After a fire, scorching, drying, or dry soil exposure increases SWIR2 reflection, lowering the NBR index (KEY; BENSON, 1999; PLENIOU; KOUTSIAS, 2013).

Numerous approaches have been developed to solve this problem. Many anomaly detection algorithms based on traditional statistical methods have emerged in recent decades. The Reed Xiaoli algorithm (RXD) is an important milestone in anomaly detection (Reed and Yu, 1990). An approximate representation of the background statistical model can be obtained by estimating the mean and covariance matrix of all pixels. The probability that each pixel belongs to an anomaly can be identified by calculating the Mahalanobis distance. As RXD is not only simple but also effective, many improved algorithms are derived from it, such as local RX detector (LRXD) and kernel RX detector (KRXD) (RAO et al.,2022).

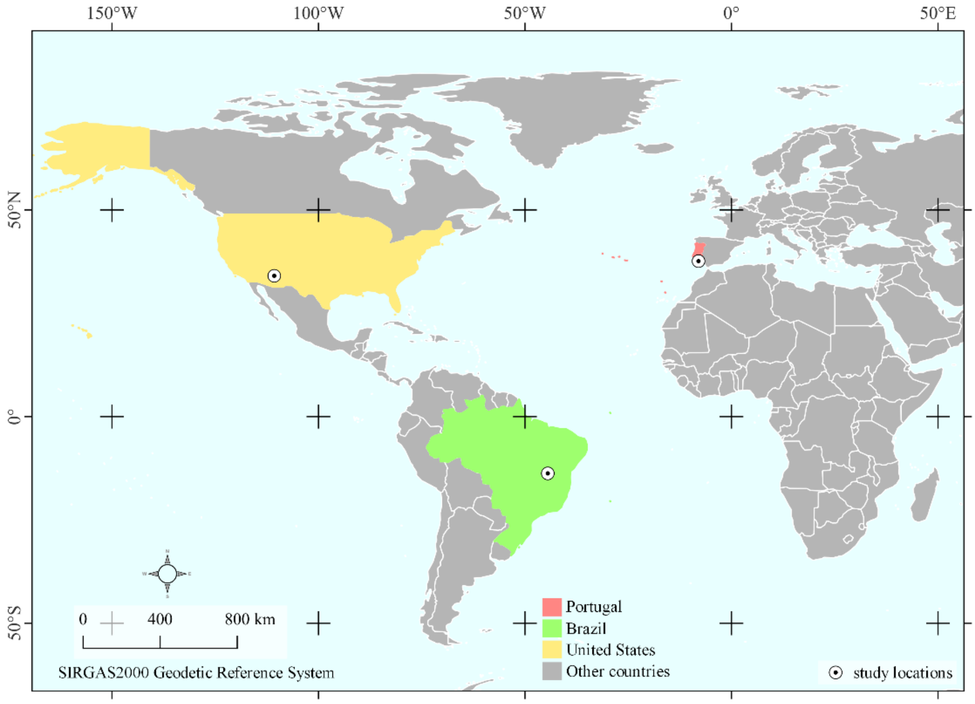
This article presents an analysis of the behavior of the spectral indices BAI, BAIS2, MIRBI, NBR and NBR2 obtained from Sentinel-2 images and their ability to discriminate burned areas using the RXD anomaly detector in protected areas with different ecosystems in Brazil, United States United States and Portugal.

2 MATERIALS AND METHODS

2.1 Study Areas

Study sites include protected areas in Brazil, the United States and Portugal. In Brazil, the fire was located in the Wildlife Refuge Veredas do Oeste Baiano (RVS) with geographic coordinates centroid 14°06'09.47"S, 45°17'36.05" W in the WGS84 reference system. The RVS is a federal conservation unit in Brazil, located in the state of Bahia and created by Presidential Decree on December 13, 2002. It is categorized as a wildlife refuge. The RVS is part of the Cerrado biome and aims to protect natural environments where conditions for the existence or reproduction of species or communities of local flora and resident or migratory fauna are ensured (MMA, 2007). The region's climate is semi-humid tropical with 4 to 5 dry months and an average temperature above 18 °C, the rainy season takes place from November to March. The predominant vegetation in the municipalities is savanah. However, there are areas of lower regions where seasonal deciduous forests are found and where there is still great natural wealth despite the constant deforestation. In these forests, hardwoods such as jacaranda, mastic, peroba, cedar, pau d'arco, umburana, and several other plant species are still found, even on a small scale (SOUZA, 2017).

Figure 1 – Location of study areas



Source: The Authors (2023).

The second study area is located on The Tonto National Forest, which covers 11.627 km², is the largest of Arizona's six national forests, and is the ninth largest national forest in the United States. Tonto is managed by the USDA Forest Service and is headquartered in Phoenix. The Bush Fire occurred in 2020/07/01, burned 193.455 acres, making it the fifth largest Arizona fire on record, prompting the Incident Management Team to transition control to the Forest Service, which subsequently conducted a Burned Area Emergencies (BAER) to initiate rehabilitation efforts. Investigators determined that the fire was man-made (U.S. Forest Service, 2020).

The study area in Portugal is located in the southern sector of the country in the state of Faro with coordinates 37°17′17.7″N 07°35′17.2″W in the WGS84 reference system and an extension of 67.20 km². The location has a temperate Mediterranean climate, with hot, dry summers and mild winters; precipitation is unevenly distributed throughout the year, concentrated in the autumn and spring months. According to the Institute for the Conservation of Nature and Forests (ICNF) the fire occurred on 16/08/2021, approximately

6.5 km from the Odeleite water dam and 4.20 km from the Beliche water dam and was considered intentional due to anthropic action. The northern sector of the fire area reached areas considered Ecological Corridors, being important for ensuring the movement of animals and the dispersion of seeds between these areas (ICNF, 2023).

2.2 Data and pre-processing

Sentinel-2 Level-2A data from 2020 and 2021, before and after the fire events, were used in our analysis. These data were processed using Sentinel Application Platform (SNAP) managed by the European Space Agency (ESA). Table 1 shows the date of the MSI images used.

Table 1 – Sentinel-2 images over Brazil, the United States, and Portugal used in this study.

Country	**Tile**	**Date**
Brazil	T23LME	12/08/2021 (before) 21/09/2021 (after)
EUA	T12SVC	08/06/2020 (before) 08/07/2020 (after)
Portugal	T29SPB	10/08//2021(before) 20/08/2021 (after)

Source: The Authors (2023).

The Sentinel-2 acquisitions are multispectral images composed of 13 bands, mainly in the near/visible infrared (VNIR) and Short-Wave Infrared (SWIR) spectral range. The Level 2A processing that includes a level 1C orthoimage with Top of the Atmosphere (TOA) conversion performed in Sen2Cor. The main output of Sen2Cor is a background corrected reflectance (BOA) product with a spatial resolution of 10 m by the upsampling method (ESA, 2023).

2.3 Spectral indices

Five spectral indices (BAI, BAIS2, MIRBI, NBR and NBR2) were calculated from Sentinel-2/MSI bands to detection of burned and unburned areas (Table 2).

Table 2 -Analyzed Spectral indices used in this study.

Name	**Acronym**	**Formula**	**Reference**
Burned Area Index	BAI	$1/[(0{,}1 - B4)^2 + (0.06 - B8)^2]$	Chuvieco et al. (2002)
Burned Area Index for Sentinel 2	BAIS2	$\left(1 - \sqrt{B6 \times B7 \times B8A/B4}\right) \times \left((B12 - B8A)/\sqrt{B12 + B8A} + 1\right)$	Filipponi (2018)
Mid-Infrared Burn Index	MIRBI	$(10 * B12) - (9.8 * B11) + 2$	Trigg e Flasse (2001)
Normalized Burn Ratio	NBR	$(B8 - B12)/(B8 + B12)$	Key and Benson (1999)
Normalized Burn Ratio 2	NBR2	$(B11 - B12)/(B11 + B12)$	Key and Benson (1999)

Source: The Authors (2023).

Where B4 is the Red band; B6 is the Vegetation red-edge 1 band; B7 is the Vegetation red-edge 2 band; B8 is the near infrared band; B8A is Vegetation red-edge band; B11 is Short Wave Infrared band-1 (SWIR1) and B12 is Short Wave Infrared band-2 (SWIR2).

2.4 Separability Analysis

The separability M index proposed by Kaufman and Remer (1994) allows us to analyze the degree of discrimination between classes, in this case, vegetation, and fire. The M index is a statistical test that calculates the difference between the averages of the reflectance values of the pixels of the two categories, normalized by the sum of the standard deviations (KAUFMAN and REMER, 1994). The M index is an estimator of the signal/noise ratio. It consists of the absolute difference between the mean values of the two classes, associated with their variability, and the sum of the standard deviations that represent the noise (RODRIGUES et al., 2018). Values lower than 1 indicate that the two classes do not show spectral differences from each other and, therefore, are not distinguishable (low separability), while values larger than 1 indicate that the spectral responses of the two classes are different and, thus, the classes can be unambiguously identified (high separability) (PEREIRA et al., 2016; LIBONATI et al., 2015). The separability index (M) has great potential in remote sensing, useful in analyzing the discrimination of classes of interest. It is calculated according to Equation (1), as Kaufman and Remer (1994):

$$M = \frac{m(b) - m(unb)}{a(b) + a(unb)} \tag{1}$$

Where $m(b)$ is the mean of burned pixels and $m(unb)$ is the mean of unburned pixels, $a(b)$ is the standard deviation of burned pixels and $a(unb)$ is the standard deviation of unburned pixels for each spectral index.

2.5 Unsupervised Anomaly Change Classification (RXD Anomaly)

Automatic classifications of burned areas obtained by spectral indices before and after the fire were generated by the RXD algorithm. It was proposed by Reed and Yu (1990) to extract signatures unique from the surroundings without requiring a priori knowledge. These anomalies are detected as outliers due to: (i) spectral signatures that differ from adjacent pixels; and (ii) a low likelihood of occurrence (BELENGUER-PLOMER et al. 2019). As a result, RXD differentiates burned areas from the rest of the image as they are identified as anomalous changes from other generalized changes, such as seasonal trends which occur regularly and span over large parts of the image (DABBIRU et al., 2012). The Mahalanobis Distance between a given pixel and the average of surrounding pixels is calculated by RXD using the covariance matrix. As a result, the anomalous change score (AC) for any pixel x is computed using Equation (2) (REED and YU, 1990):

$$AC(x) = (x' - \mu)^{\top} C^{-1} (x' - \mu) \tag{2}$$

where x, μ represents the mean of each band and C is the bands' covariance matrix.

2.6 Accuracy Analysis and Validation

For the classification validation in the Brazil study area, the mapping product developed by the Forest Fires Monitoring Program of the National Institute for Space Research (INPE) was used as a reference. This product is available free of charge at http://queimadas.dgi.inpe.br (INPE, 2021). The monitoring uses images from the Landsat, CBERS-4, CBERS-4A series, and field visits. The data are available in vector format and operationally and automatically estimate the burned surface, generating digital maps, temporal comparisons, and support products to manage and assess the impact of fire use on vegetation. In this way, it enables regular detection and quantification of the burned area through satellite images of the extent of burned vegetation in the country.

In the case of the United States fire, the Burn Severity Trend Monitoring Program (MTBS) assesses the frequency, extent, and magnitude of all major wildfires in the United States for the period from 1984 to 2020. MTBS produces a series of geospatial data obtained from Landsat and Sentinel-2 imagery (as of 2018) for analysis at various spatial, temporal, and thematic scales and is intended to meet information needs that require consistent environmental data. This map layer is a vector polygon shapefile of the location of all currently inventoried fires between 1984 and 2020 (USGS, 2021; PICOTTE et al., 2020).

Finally, the validation product utilized as a reference for the study area in Portugal was the 2019 annual burned areas atlas from the National Institute for Nature Conservation and Forests (ICNF) of Portugal (http://www.icnf.pt/) (ICNF, 2023). The data are available in a shapefile. They consist of a collection of burned areas represented by polygons accompanied with information about the date and duration of the fire, the area, and the causes that provoked it. The global map of all the fires in the Portuguese territory is composed of geospatial files generated by semi-automatic classifications using 10 m resolution Sentinel-2 data (ICNF, 2023).

In this work, the classification assessment metric used is the Sørensen–Dice Coefficient (DC) (SØRENSEN et al.,1948). The DC Coefficient is used to compare the similarity between two samples, such as the results of the classification of burned pixels and the reference map, in addition to being widely used as a spatial evaluation parameter (PÉREZ-LUQUE et al., 2022; AL-DABBAGH and ILYAS, 2023). It is calculated according to Equation (3), as (DICE, 1945):

$$DC = \frac{2}{2 + \frac{OE}{1 - OE} + \frac{CE}{1 - CE}} \tag{3}$$

The Error of Omission (OE) and Error of Commission (EC) can be calculated through the simple ratio between burned and unburned pixels in a given classification. However, it is necessary to assess the accuracy of each validation scar for a more accurate analysis. OE reflects the proportion of burn scars not correctly classified by the classifier. On the other hand, the CE is the error produced when a pixel is assigned to a certain class, actually belonging to some other class. DC is an estimate of accuracy and ranges from 0 to 1, where values close to or equal to 1 represent the proportion of overlapping pixels labeled as burned in the reference map that was really classified as burned. In contrast, values close to or equal to 0 correspond to no overlap in the current category (LIBONATI et al.,2015).

3 RESULTS AND DISCUSSION

3.1 Separability analysis of burned and unburned areas for spectral indices

Table 3 shows the M index values between the images before and after the fire for the different spectral indices used in this study.

Table 3 -Analyzed Spectral indices used in this study with M_{mean} values.

Spectral Index	Brazil	USA	Portugal	M_{mean}
BAI	1.54	1.05	1.24	1.28
BAIS2	1.17	1.96	1.54	1.56
MIRBI	2.00	1.69	2.00	1.90
NBR	1.70	1.92	1.35	1.66
NBR2	1.88	1.88	1.85	1.87

Source: The Authors (2023).

The NBR2 showed similar separability in the three study areas, with an average separability (M_{mean}) of 1.87, unlike the other indices that differed slightly between areas. The BAIS2 showed almost maximum separability in the USA and low in Brazil, compared to the other indices, which resulted in a Mmean of 1.56. Like the NBR2, the MIRBI showed good separability in all countries, with the maximum value in Brazil and Portugal, consequently reaching the highest Mmean 1.90 of the set. The BAI in the USA presented the set's lowest separability and the lowest M_{mean} (1.28), while for NBR was 1.66. Despite this, both indices followed the trend of all indices, with separability above 1. The results found in this article agree with Veraverbeke et al. (2011) and Ba et al. (2019), where low separability values and high detection errors were reported for the BAI index in wildfires in the United States. In this study, the separability values of the BAI index were moderate, close to 1. On the other hand, they disagree with the statements of Mpakairi et al. (2020) on the performance of BAI. These authors revealed that forest ecosystems require spectral indices of burned areas that can explain soil reflectance. Thus, the BAI index, which uses the red band, can detect soil reflectance and, thanks to the NIR and the red bands, the loss of vegetation. In Mediterranean ecosystems, where most burning leaves coal residues, the BAI index has been especially applied in fire studies. In Brazil, the BAI index showed low performance, which may be related to the studies by Smith et al. (2005).

These authors argue that using BAI in savanna ecosystems characterized by low albedo surfaces

 DOI: http://dx.doi.org/10.14393/rbcv75n0a-68307

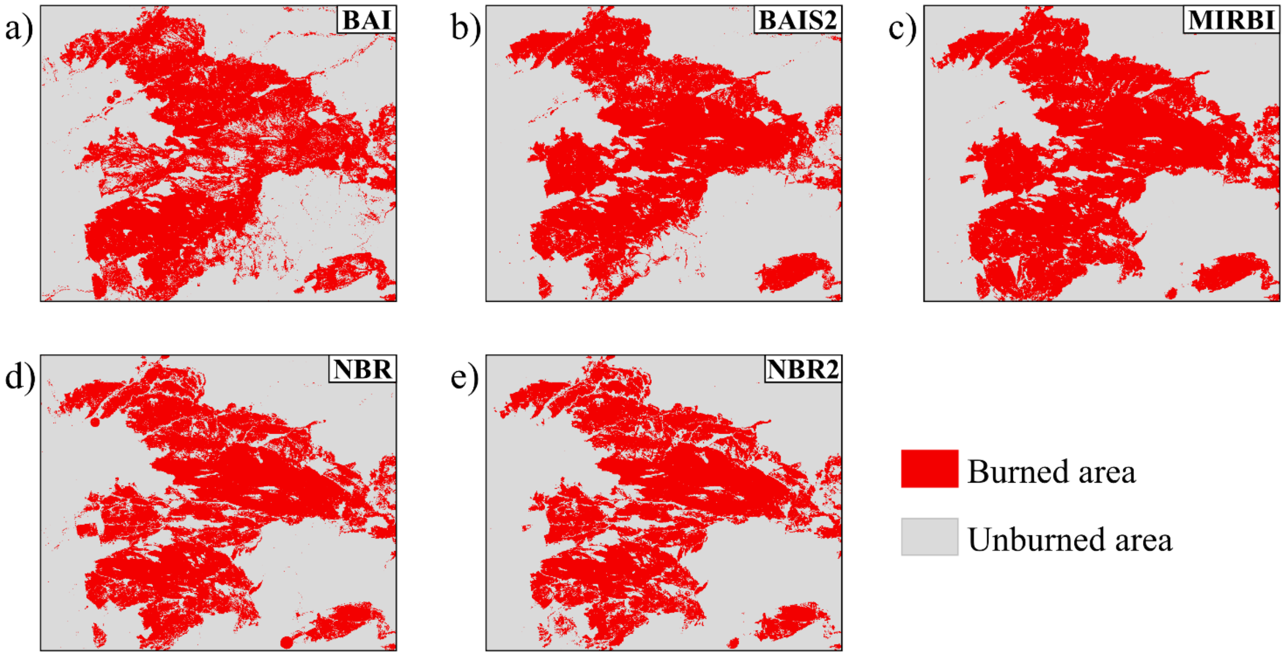
(plowed soil) may overestimate the burned areas. In another study, Pereira et al. (2016) also did not find good results using BAI to discriminate fires in the Brazilian Cerrado, which can be explained by the characteristic differences between the local vegetation and the vegetation of countries located in the Europe Mediterranean region, where the study by Chuvieco et al. (2002) was developed. In general, the indices based on red-edge, LSWIR, and SSWIR showed the greatest separation between the burned and unburned areas. In contrast, the indices with the spectral region of the VNIR in their calculation showed different performances depending on the particularities of the fire location, such as shown in Table 3.

3.2 Accuracy Analysis

Figures 3, 4, and 5 show the burned area detected by each spectral index for each study area and the histograms of the OE and CE regarding the correctly classified burned areas.

In the Brazil fire case (Figure 3), the BAIS2 index presented more balanced errors concerning all the indices. Despite this, the MIRBI showed the set's lowest CE estimation with an overestimated burned area of approximately 3.23 km² while the BAIS2 was 23.6 km². The BAI and NBR2 indices showed the most considerable overestimation, with spatial estimations of 82% and 87%, respectively, concerning the reference area. In total, OE was concentrated below 15%, with the best performance for BAIS2 and the worst performance for BAI. That is, BAIS2 incorrectly classified approximately 22.6 km² while BAI was 52.80 km², and NBR and NBR2 presented similar underestimations.

Figure 3 – Spatial distribution of the burned area detected by each spectral index in the Brazil case study. Histograms for the OE and CE regarding the correctly classified pixels as burned area.



Source: The Authors (2023).

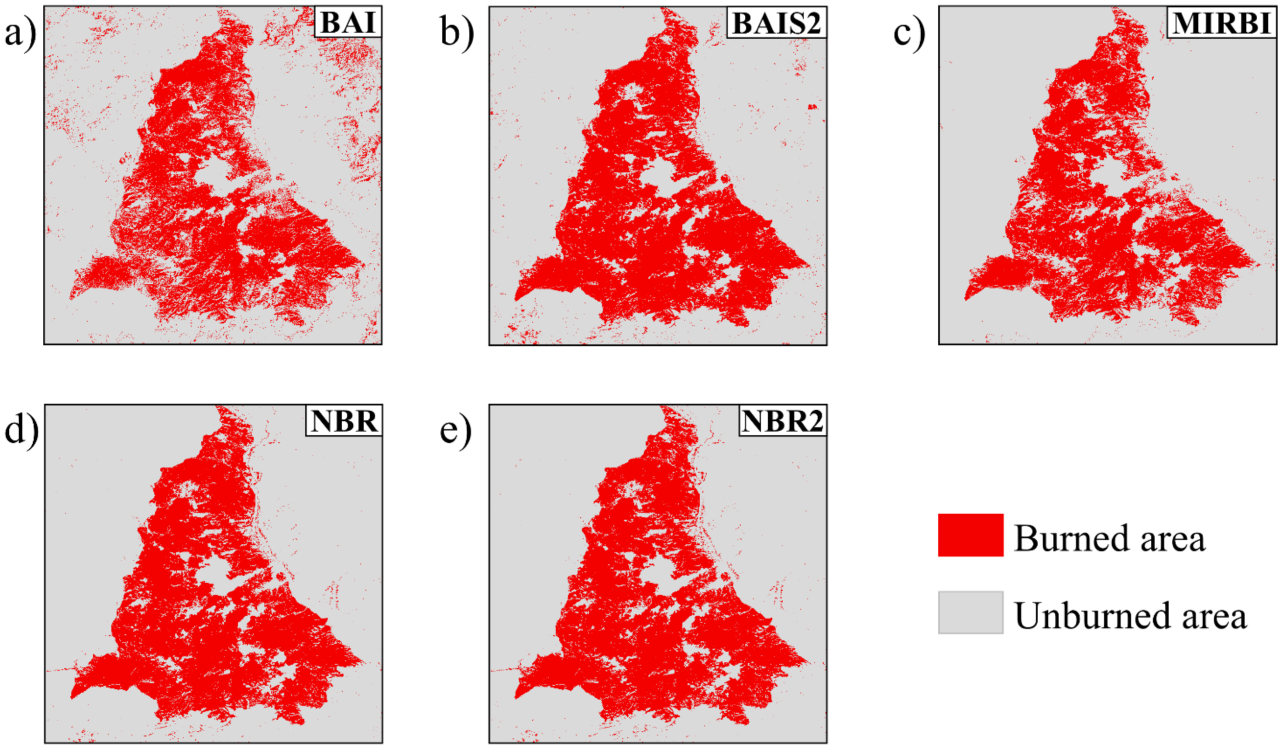
Table 3 – DC estimates for each spectral index based on CE and OE values for Brazil, the United States, and Portugal.

Indices	OE (%)	CE (%)	DC
BAI	14.50	10.70	0.87
BAIS2	4.90	4.70	0.95
MIRBI	11.30	0.67	0.91
NBR	6,90	9.90	0.91
NBR2	5.70	12.40	0.91

Source: The Authors (2023).

For the United States case study (Figure 4), the BAI index presented the highest OE and CE estimation, with a spatial coincidence of 86% concerning the reference map. The MIRBI and NBR indices showed similar error values, with 89% spatial coincidence with the reference area. The BAIS2 presented the lowest estimate of OE and underestimated approximately 182.8 km² of truly burned area. However, it presented a coincidence of 95%, being behind only the NBR2 index with 97.8%. The indices based on the combination NIR-SWIR1-LSWIR generally showed good performance based on CE concentrated below 2.5%, with emphasis on MIRBI and NBR, with burned area overestimations below 10 km². On the other hand, the NBR2, despite the significant OE, incorrectly classified approximately 195.3 km², the MIRBI was 296.19 km², and the NBR 257.8 km². The indices generated by the red bands (BAI and BAIS2) showed high EC values, possibly showing a tendency of spectral indices to overestimate the burned areas in Brazil.

Figure 4 – Spatial distribution of the burned area detected by each spectral index in the USA case study. Histograms for the OE and CE regarding the correctly classified pixels as burned area.



Source: The Authors (2023).

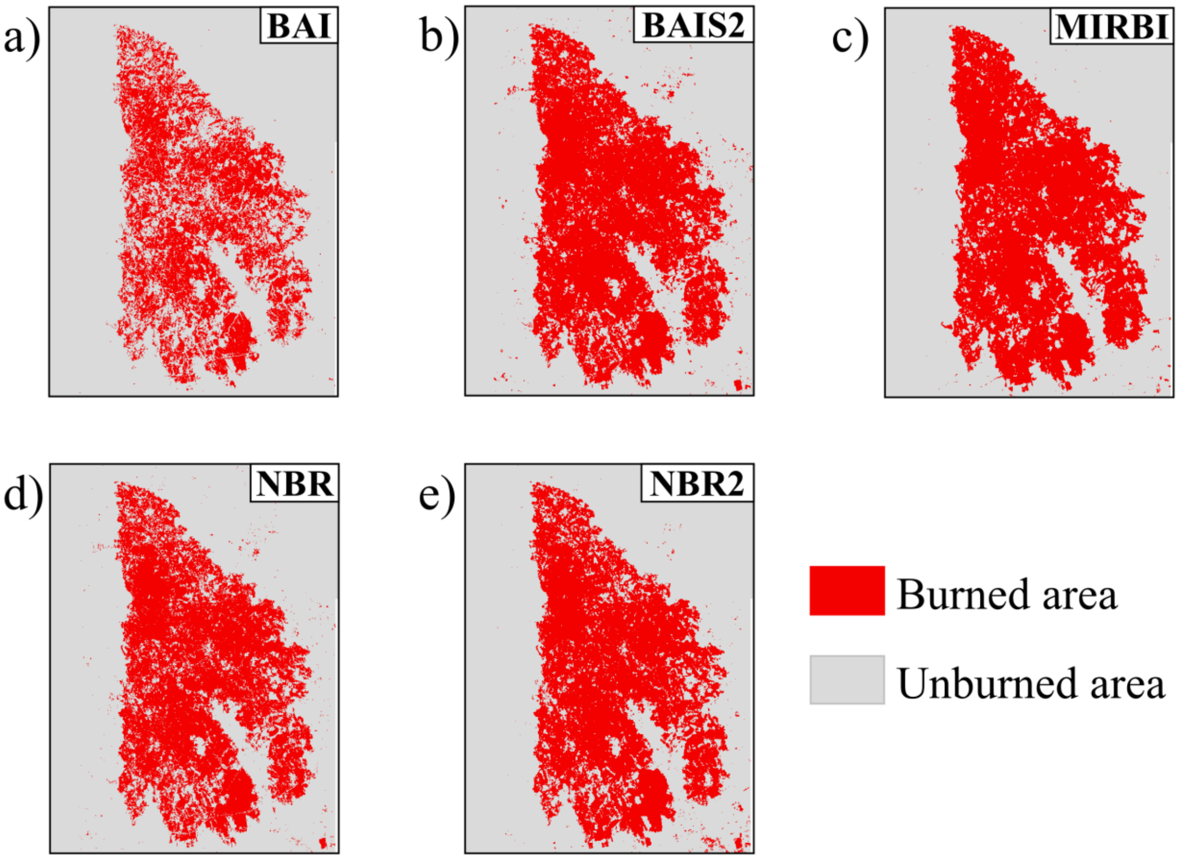
Table 4 – DC estimates for each spectral index based on CE and OE values for Brazil, the United States, and Portugal.

Indices	**OE (%)**	**CE (%)**	**DC**
BAI	32.00	13.00	0.86
BAIS2	17.00	5.00	0.93
MIRBI	28.50	1.20	0.83
NBR	25.00	1.30	0.86
NBR2	19.00	2.30	0.91

Source: The Authors (2023).

Finally, regarding the Portugal case study (Figure 5), BAI results presented the largest OE concerning the other indices, with approximately 24.7 km² of underestimated burned area. On the other hand, it showed a CE close to zero. For the other indices, OE was concentrated below 8% and 5.1 km² of an area without correctly attributing the burned area. Based on OE, the NBR index showed the best performance. However, showing an inverse behavior to the BAI, presenting the highest CE estimation among the other indices. The BAIS2 and MIRBI indices presented balanced values between CE and OE, but the MIRBI stood out with the lowest error estimates and a coincidence of 95.8% with the reference map, while the BAIS2 showed a 92.3% spatial coincidence. The NBR2 presented the second position in the lowest CE performance and overestimated approximately 3.7 km² of the burned area.

Figure 5 – Spatial distribution of the burned area detected by each spectral index in the Portugal case study. Histograms for the OE and CE regarding the correctly classified pixels as burned area.



Source: The Authors (2023).

Table 3 shows the DC estimates for the spectral indices in the different study areas.

Table 4 – DC estimates for each spectral index based on CE and OE values for Brazil, the United States, and Portugal.

Indices	OE (%)	CE (%)	DC
BAI	36.70	0.70	0.76
BAIS2	7.60	9.00	0.92
MIRBI	4.20	5.40	0.95
NBR	3.90	15.60	0.90
NBR2	6.00	12.90	0.90

Source: The Authors (2023).

Based on DC, all indices obtained estimates close to 0.90, except for BAI. NBR2 and BAIS2 appeared with close values in the three study areas, while NBR and MIRBI decreased slightly in the USA. The same similarity was seen for the BAI but with a decrease in the fire in Portugal. In general, BAIS2 obtained the best performance of the set with an average DC of 0.93. On the other hand, the indices based on NIR-LSWIR-SSWIR obtained similar values (NBR2 = 0.91; MIRBI = 0.90; NBR = 0.89), while BAI showed the lowest mean DC (0.83).

3.3 Overview and some limitations

This study provides an assessment of the effectiveness of spectral indices to discriminate burned areas between one S2 scene pre-fire and one post-fire, supporting previous findings that spectral indices exclusively based on the red-edge, NIR, LSWIR, and SSWIR bands provide high discrimination of burned areas in a variety of ecosystems, including, for example, the Brazilian Savana in Campagnolo et al. (2021); Pereira et al. (2016); Libonati et al. (2015), the United States desert in Esque et al. (2013); Cain et al. (2005), and Mediterranean in (GARCIA; CHUVIECO, 2004; VAN ECK et al., 2016). On the other hand, this study also reinforces the fact that the detection performance of the indices can vary between different ecosystems. Thus, mapping burned areas by spectral indices becomes even more challenging, mainly when performed on a continental scale and its different ecosystems, diversity of land uses, and fire regimes. The ephemeral characteristics that the fire scars leave on satellite images are a complicating factor for detecting burned areas (ALENCAR et al.2022). Depending on the image acquisition date, it is possible to lose the spectral signature of fire in the landscape (MELCHIORRE et al., 2018).

The overall general accuracy of the burned areas obtained by the spectral indices revealed satisfactory results of the burned areas, being approximately 91.00% for Brazil and 87.90% for the United States, and 88.60% for Portugal, with more OE than CE, indicating a conservative extent of the burned area over time for reference datasets using annual multi-sensor mapping and field data. Strategies to improve overall accuracy and reduce CE and OE with unattended applications include, for example, the use of water masks, mainly in Brazil and the United States, where they have a large number of water bodies of different extensions and the change in the number of classification sub-regions based on land use dynamics, environmental characteristics and geomorphologies.

3.4 Behavior of spectral indices for the detection of burned areas

Based on the implementation of MIRBI, it proved to be a reliable spectral index to detect burned areas in the different environments analyzed, emphasizing the fire in Portugal and Brazil, showing high separability (Table 3) and DC above 97% and low estimates of CE and OE. This result is in agreement with Liu et al. (2020), who reported that the reflectance values in SWIR1 and SWIR2 present in MIRBI, show distinct differences between the characteristics and humidity of the vegetation and the state of the soil, which provided a greater possibility of discrimination and the variation of the degree of severity of the fires in the United States. Its performance was moderate compared to the other indices, which aligns with the findings of Malambo and Heatwole (2020), who stated the low detection capability of MIRBI in boreal forests and regions with rugged terrain. However, this approach can be adapted to other spectral indices, such as the NBR2 (KEY and BENSON, 1999).

Previous studies have reported a high performance of NBR2 in detecting burned areas in different biomes, such as the Atlantic Forest in Sacramento at al. (2020), Savannas in Huang et al. (2016) and the Amazon (SANTANA et al., 2018). Van Dijk et al. (2018) found high separability values in the spectral indices for the burned and unburned area, thus showing sensitivity to spectral changes caused by burning. On the other hand, Arruda et al. (2021) used the active fire product (MCD64A1) generated by the NBR2 index in conjunction with other measures to generate cumulative maps in the collection of burned and unburned samples in the Cerrado biome, obtaining an overall accuracy of 97% (GIGLIO et al., 2016). In an approach based on fuzzy sets theory for mapping burned areas in Portugal, the inclusion of NBR2 decreased the CE from 59.50% to 1.30% and increased the overall accuracy from 42.60% to 91.30% (STROPPIANA et al., 2012). In this study, NBR2 provided the important results of classification accuracy, with low error coefficients, high separability and stable DC of approximately 0.91 for the three study areas. However, the moderate estimation of OE in the United States case study was caused by poor detection of small polygons within the fire scar, whereas the CE in Brazil and Portugal were caused by the detection of degraded soils and areas of removal of native vegetation such as burned areas. Trigg and Flasse (2014) reported that spectral indices based on LSWIR and SSWIR create artificial signals that confuse the spectral responses of ash with dry areas whose spectral signature of the burned area disappears within a few weeks.

The NBR index is widely used for mapping burned areas globally. Here the NBR performed well in the study sites, reaching high estimates of separability coefficient and DC, but it presented the highest CE of the set in Portugal. First, some of these errors would be due to internal islands (unburned areas within the fire) that the reference image detects, in addition to errors on dark ground surfaces (BOSCHETTI et al., 2010). It is also important to note that the results are best when a post-fire image is used as close as possible to the fire extinguishing date (over time, weather factors such as rain can disrupt the results). As in the latter the geographic context involved is not the same, the difference observed, for example, in the accuracy estimates of the NBR is mainly a consequence of the change in the time of the post-fire spectral signal and spectral peculiarities of different land covers (STROPPIANA et al., 2009). In Brazil and the USA case studies, the estimates were better, which may be related to the large extension of the burned area, which are generally due to more intense fire events and are characterized by a more persistent spectral signal.

The BAIS2 uses data in the red edge spectral domain of vegetation which is one of the best descriptors based on radiance of chlorophyll content, a combination of bands based on this spectral region make BAIS2 an index a valuable instrument for post-fire monitoring. This index showed significant high performance values in the detection metrics applied in the three study areas. This performance was also found in previous studies as in Filipponi et al. (2019) where they showed lower CE in forest fires in southern Italy compared to NBR, while Farhadi et al. (2022) stated that the precise determination of vegetation classes and the elimination of water zones in the burned area map led to a considerable increase in the accuracy of the final map obtained from the BAIS2 spectral index. Van Dijk et al. (2021), in California, found that the BAIS2 index, the Sentinel-2 band 11 were less affected by temporal sensitivity, suggesting that this index is more sensitive to the flare signal that prevailed over longer time periods. Brovkina et al. (2020) observed that BAIS2 was able to differentiate the carbonization of the sparse and dense grass cover class from other soil covers during the vegetation period. The authors stated that BAIS2 separated the burned forest area after nine post-fire growth seasons and demonstrated a stability of BAIS2 to identify a burned area irrespective of the vegetation period from the satellite data acquisition. The best estimate for BAIS2 in this study may be related to the temporal proximity of the fire event due to the existence of purely burned pixels and the detection of more compact features of burned areas. On the other hand, it was possible to identify that BAIS2 erroneously detected unidentified water resources in the mask layer and shadows caused by uneven topography in the three study areas.

According to Smiraglia et al. (2020), who evaluated the performance of the composite index in several areas with varying conditions, the NBR2 performed generally well under all conditions and the MIRBI index performed well in the dry season. Brovkina et al. (2020) revealed that the BAIS2 composite index was stable in detecting burned areas regardless of the vegetation period. Stroppiana et al. (2009) stated that the combination of NBR can distinguish very well burnt areas with soil and shadows. The BAI index showed the highest sensitivity to discriminate burned areas from other types of land cover in Spain according to Garcia and Chuvieco (2004) but low performance using Sentinel-2 images in Turkey (CHUVIECO et al., 2019). Finally, it was observed in this study that all indices overestimated burned areas with water polygons in the three study areas, which is quite common in the literature and is an input of investigations for researchers (DESHPANDE et al., 2022; STROPPIANA et al., 2012).

Overall, the OE found are mainly due to small areas not detected; very small patches are often lost and contaminated by spectral mixing, although these events represent a small proportion of the total area burned and may not interfere with overall accuracy. Another factor for the occurrence of OE may be related to the inadequacy of the indices in mapping low-severity burned areas, which may result in unwanted noise and the identification of inappropriate thresholds in the automatic classification algorithms, although this work was not encouraged to precisely identify different fire severities. On the other hand, the 5-day temporal resolution MSI allowed an improved mapping of fires of different severities on a precise spatial and spectral scale, making it possible to reduce temporal incompatibilities with the validation data used in this study.

4 CONCLUSION

In this study, we present an assessment of the efficacy of the spectral indices BAI, BAIS2, MIRBI, NBR, and NBR2 to discriminate burned areas in Brazil, the United States, and Portugal using Sentinel-2 satellite images. This study also indicates that the behavior of indices can vary between different ecosystems, suggesting that functionally different forest types have different spectral responses. Therefore, the same index may not have the same performance in detecting the burned area. The Sentinel-2 MSI, in particular the red-edge and SWIR bands with 10 m spatial resolution, allows for more detailed spatial and spectral monitoring of fires, possibly reducing temporal incompatibilities with the validation data used in this study.

The BAIS2, MIRBI, and NBR2 indices outperformed other indices in the three study areas. Therefore, we recommend indices based on the red-edge, SSWIR, LSWIR bands for detection of burned areas. These indices were better compared to the NBR, which is globally known due to its high discriminatory power. The BAI index showed moderate separability between burned and unburned areas, important CE and OE compared to the other indices, but showed an important performance with low levels of overestimation in the burned area of Portugal. Despite that, finally, BAI showed a deficiency in detection and low sensitivity in densely hilly regions due to shadows and water resources, reflecting caution in its application.

The classification method based on bi-temporal anomalous changes (RXD Anomaly) proved to be effective in enhancing the burned area in terms of temporal change and executing an unsupervised detection without depending on ground truth. It was applicable under different environmental systems by remote sensing images without the need for a priori information and fixed thresholds, in addition to representing a tool to link spectral indices and spatial dynamics. On the other hand, the main limitations of RXD were observed in non-abrupt changes of burned areas and not burned, which is very common in fires with low severity. In addition, the method was not tested for the classification of several fire features distributed in a scene, which can cause important spatial interferences due to a possible complexity of land cover elements in the analyzed biomes.

The results obtained in this study were able to provide critical information to algorithms for mapping fires and for an accurate spatial estimation after the fire in temperate forests and dry ecosystems. The proposed method provided a perspective on the use of detection by remote sensing in local fires inserted in environmentally fragile areas. Such information is essential for environmental studies, mainly in the spatial dynamics of areas susceptible to fire, preservation of fauna and flora, regeneration, and greenhouse gas emissions.

Interest Conflicts

The authors declare no conflict of interest.

Author Contributions

Conceptualization, J.A.d.S.J., A.d.P.P.; Data curation, A.d.P.P., J.A.d.S.J.; Formal analysis, A.d.P.P., J.A.d.S.J.; Investigation, A.d.P.P., J.A.d.S.J; Methodology, A.d.P.P., J.A.d.S.J.; Supervision, A.d.P.P., J.A.d.S.J.; Validation, A.d.P.P., J.A.d.S.J.; Writing–original draft, A.d.P.P., J.A.d.S.J.; Writing–review & editing, A.d.P.P., J.A.d.S.J. All authors have read and agreed to the published version of the manuscript.

Acknowledgment

The research was supported by the project “Remote Sensing Applied to the Study of Hot Spots in Forests in Brazil and the Iberian Peninsula” from the Department of Cartographic Engineering and Surveying (DECart) at the Federal University of Pernambuco (UFPE/Brazil).

References

AL-DABBAGH, Ali Mahdi; ILYAS, Muhammad. Uni-temporal Sentinel-2 imagery for wildfire detection using deep learning semantic segmentation models. Geomatics, **Natural Hazards And Risk**, [S.L.], v. 14, n. 1, p. 200-225, 5 abr. 2023. Informa UK Limited. http://dx.doi.org/10.1080/19475705.2023.2196370.

ALENCAR, Ane A. C.; ARRUDA, Vera L. S.; SILVA, Wallace Vieira da; CONCIANI, Dhemerson E.; COSTA, Diego Pereira; CRUSCO, Natalia; DUVERGER, Soltan Galano; FERREIRA, Nilson Clementino; FRANCA-ROCHA, Washington; HASENACK, Heinrich. Long-Term Landsat-Based Monthly Burned Area Dataset for the Brazilian Biomes Using Deep Learning. **Remote Sensing**, [S.L.], v. 14, n. 11, p. 2510, 24 maio 2022. MDPI AG. http://dx.doi.org/10.3390/rs14112510.

ARRUDA, Vera L.s.; PIONTEKOWSKI, Valderli J.; ALENCAR, Ane; PEREIRA, Reginaldo S.; MATRICARDI, Eraldo A.T.. An alternative approach for mapping burn scars using Landsat imagery, Google Earth Engine, and Deep Learning in the Brazilian Savanna. **Remote Sensing Applications:**

Society and Environment, [S.L.], v. 22, p. 100472, abr. 2021. Elsevier BV. http://dx.doi.org/10.1016/j.rsase.2021.100472.

BA, Rui; SONG, Weiguo; LI, Xiaolian; XIE, Zixi; LO, Siuming. Integration of Multiple Spectral Indices and a Neural Network for Burned Area Mapping Based on MODIS Data. **Remote Sensing**, [S.L.], v. 11, n. 3, p. 326, 6 fev. 2019. MDPI AG. http://dx.doi.org/10.3390/rs11030326.

BASTARRIKA, Aitor; CHUVIECO, Emilio; MARTÍN, M. Pilar. Mapping burned areas from Landsat TM/ETM+ data with a two-phase algorithm: balancing omission and commission errors. **Remote Sensing of Environment**, [S.L.], v. 115, n. 4, p. 1003-1012, 15 abr. 2011. Elsevier BV. http://dx.doi.org/10.1016/j.rse.2010.12.005

BELENGUER-PLOMER, Miguel A.; TANASE, Mihai A.; FERNANDEZ-CARRILLO, Angel; CHUVIECO, Emilio. Burned area detection and mapping using Sentinel-1 backscatter coefficient and thermal anomalies. **Remote Sensing of Environment**, [S.L.], v. 233, p. 111345, nov. 2019. Elsevier BV. http://dx.doi.org/10.1016/j.rse.2019.111345.

BROVKINA, Olga; STOJANOVIć, Marko; MILANOVIć, Slobodan; LATYPOV, Iscander; MARKOVIć, Nenad; CIENCIALA, Emil. Monitoring of post-fire forest scars in Serbia based on satellite Sentinel-2 data. **Geomatics, Natural Hazards And Risk**, [S.L.], v. 11, n. 1, p. 2315-2339, January 1. 2020. Informa UK Limited. http://dx.doi.org/10.1080/19475705.2020.1836037.

BOSCHETTI, Mirco; STROPPIANA, Daniela; BRIVIO, Pietro Alessandro. Mapping Burned Areas in a Mediterranean Environment Using Soft Integration of Spectral Indices from High-Resolution Satellite Images. **Earth Interactions**, [S.L.], v. 14, n. 17, p. 1-20, 1 nov. 2010. American Meteorological Society. http://dx.doi.org/10.1175/2010ei349.1.

CAMPAGNOLO, M.L.; LIBONATI, R.; RODRIGUES, J.A.; PEREIRA, J.M.C.. A comprehensive characterization of MODIS daily burned area mapping accuracy across fire sizes in tropical savannas. **Remote Sensing of Environment**, [S.L.], v. 252, p. 112115, jan. 2021. Elsevier BV. http://dx.doi.org/10.1016/j.rse.2020.112115.

CAIN, James W.; JOHNSON, Heather E.; KRAUSMAN, Paul R.. WILDFIRE AND DESERT BIGHORN SHEEP HABITAT, SANTA CATALINA MOUNTAINS, ARIZONA. **The Southwestern Naturalist**, [S.L.], v. 50, n. 4, p. 506-513, dez. 2005. Southwestern Association of Naturalists. http://dx.doi.org/10.1894/0038-4909(2005)050[0506:wadbsh]2.0.co;2.

CHUVIECO, Emilio; MOUILLOT, Florent; WERF, Guido R. van Der; MIGUEL, Jesús San; TANASE, Mihai; KOUTSIAS, Nikos; GARCÍA, Mariano; YEBRA, Marta; PADILLA, Marc; GITAS, Ioannis. Historical background and current developments for mapping burned area from satellite Earth observation. **Remote Sensing of Environment**, [S.L.], v. 225, p. 45-64, maio 2019. Elsevier BV. http://dx.doi.org/10.1016/j.rse.2019.02.013.

CHUVIECO, E.; MARTÍN, M. P.; PALACIOS, A.. Assessment of different spectral indices in the red-near-infrared spectral domain for burned land discrimination. **International Journal of Remote Sensing**, [S.L.], v. 23, n. 23, p. 5103-5110, jan. 2002. Informa UK Limited. http://dx.doi.org/10.1080/01431160210153129

DESHPANDE, Monish Vijay; PILLAI, Dhanyalekshmi; JAIN, Meha. Agricultural burned area detection using an integrated approach utilizing multi spectral instrument based fire and vegetation indices from Sentinel-2 satellite. **Methodsx**, [S.L.], v. 9, p. 101741, 2022. Elsevier BV. http://dx.doi.org/10.1016/j.mex.2022.101741.

DICE, Lee R.. Measures of the Amount of Ecologic Association Between Species. **Ecology**, [S.L.], v. 26, n. 3, p. 297-302, jul. 1945. Wiley. http://dx.doi.org/10.2307/1932409.

ESA, S.-2. M. G. Sentinel-2 - Missions - Sentinel Online - **Sentinel Online**.(2023). Available in: <https://sentinel.esa.int/web/sentinel/missions/sentinel-2/>

ESQUE, Todd C.; WEBB, Robert H.; WALLACE, Cynthia S. A.; VAN RIPER, Charles; MCCREEDY, Chris; SMYTHE, Lindsay. Desert Fires Fueled by Native Annual Forbs: effects of fire on communities of plants and birds in the lower sonoran desert of arizona. **The Southwestern Naturalist**, [S.L.], v. 58, n. 2, p. 223-233, jun. 2013. Southwestern Association of Naturalists. http://dx.doi.org/10.1894/0038-4909-58.2.223.

FARHADI, Hadi; MOKHTARZADE, Mehdi; EBADI, Hamid; BEIRAMI, Behnam Asghari. Rapid and automatic burned area detection using sentinel-2 time-series images in google earth engine cloud platform: a case study over the andika and behbahan regions, iran. **Environmental Monitoring And Assessment**, [S.L.], v. 194, n. 5, p. 100-115, 16 abr. 2022. Springer Science and Business Media LLC. http://dx.doi.org/10.1007/s10661-022-10045-4.

FILIPPONI, Federico. Exploitation of Sentinel-2 Time Series to Map Burned Areas at the National Level: a case study on the 2017 italy wildfires. **Remote Sensing**, [S.L.], v. 11, n. 6, p. 622, March 14. 2019. MDPI AG. http://dx.doi.org/10.3390/rs11060622.

FILIPPONI, Federico. BAIS2: burned area index for sentinel-2. **The 2Nd International Electronic Conference On Remote Sensing**, [S.L.], v. 5, n. 1, p. 27-37, March 22. 2018. MDPI. http://dx.doi.org/10.3390/ecrs-2-05177.

FOOD AND AGRICULTURE ORGANIZATION (FAO). Global Forest Resources Assessment 2010 — Main Report; FAO Forestry Paper 163; **FAO**: Rome, Italy, 2010. Available online: http://www.fao.org/3/i1757e/i1757e.pdf (accessed on January 24 2021).

FORKEL, Matthias; ANDELA, Niels; HARRISON, Sandy P.; LASSLOP, Gitta; VAN MARLE, Margreet; CHUVIECO, Emilio; DORIGO, Wouter; FORREST, Matthew; HANTSON, Stijn; HEIL, Angelika. Emergent relationships with respect to burned area in global satellite observations and fire-enabled vegetation models. **Biogeosciences**, [S.L.], v. 16, n. 1, p. 57-76, January 11. 2019. Copernicus GmbH. http://dx.doi.org/10.5194/bg-16-57-2019.

GARCIA, Mariano; CHUVIECO, Emilio. Assessment of the potential of SAC-C/MMRS imagery for mapping burned areas in Spain. **Remote Sensing of Environment**, [S.L.], v. 92, n. 3, p. 414-423, ago. 2004. Elsevier BV. http://dx.doi.org/10.1016/j.rse.2004.04.011.

GIGLIO, Louis; SCHROEDER, Wilfrid; JUSTICE, Christopher O.. The collection 6 MODIS active fire detection algorithm and fire products. **Remote Sensing of Environment**, [S.L.], v. 178, p. 31-41, jun. 2016. Elsevier BV. http://dx.doi.org/10.1016/j.rse.2016.02.054.

HUANG, Haiyan; ROY, David; BOSCHETTI, Luigi; ZHANG, Hankui; YAN, Lin; KUMAR, Sanath; GOMEZ-DANS, Jose; LI, Jian. Separability Analysis of Sentinel-2A Multi-Spectral Instrument (MSI) Data for Burned Area Discrimination. **Remote Sensing**, [S.L.], v. 8, n. 10, p. 873, 22 out. 2016. MDPI AG. http://dx.doi.org/10.3390/rs8100873.

INPE. **INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS**. Disponível em: https://queimadas.dgi.inpe.br/queimadas/aq30m/

ICNF. Defesa da Floresta Contra Incêndios. **Instituto da Conservação da Natureza e das Florestas**, Lisboa, 2023.

KAUFMAN, Y.J.; REMER, L. Remote sensing of vegetation in the mid-IR: The 3.75 µm channels. **IEEE Geoscience and Remote Sensing Letters**. v 32, p. 672-683, 1994.

KEY, C. H., & BENSON, N. C. **The Normalized Burn Ratio (NBR): A Landsat TM radiometric measure of burn severity**. U.S. Department of the Interior, Northern Rocky Mountain Science Centre. 1999.

LIBONATI, Renata; DACAMARA, Carlos; SETZER, Alberto; MORELLI, Fabiano; MELCHIORI, Arturo. An Algorithm for Burned Area Detection in the Brazilian Cerrado Using 4 µm MODIS Imagery. **Remote Sensing**, [S.L.], v. 7, n. 11, p. 15782-15803, 24 nov. 2015. MDPI AG. http://dx.doi.org/10.3390/rs71115782.

LIBONATI, Renata; DACAMARA, Carlos C.; PEREIRA, José Miguel C.; PERES, Leonardo F.. On a new coordinate system for improved discrimination of vegetation and burned areas using MIR/NIR information. **Remote Sensing of Environment**, [S.L.], v. 115, n. 6, p. 1464-1477, jun. 2011. Elsevier BV. http://dx.doi.org/10.1016/j.rse.2011.02.006.

LIU, Sicong; ZHENG, Yongjie; DALPONTE, Michele; TONG, Xiaohua. A novel fire index-based burned area change detection approach using Landsat-8 OLI data. **European Journal of Remote Sensing**, [S.L.], v. 53, n. 1, p. 104-112, January 1. 2020. Informa UK Limited. http://dx.doi.org/10.1080/22797254.2020.1738900.

MALAMBO, Lonesome; HEATWOLE, Conrad D.. Automated training sample definition for seasonal burned area mapping. **Isprs Journal of Photogrammetry And Remote Sensing**, [S.L.], v. 160, p. 107-123, fev. 2020. Elsevier BV. http://dx.doi.org/10.1016/j.isprsjprs.2019.11.026.

MINISTÉRIO DO MEIO AMBIENTE (MMA). **Relatório Parametrizado – Unidade de Conservação Refúgio de Vida Silvestre Veredas do Oeste Baiano**. 2007. Disponível em: <http://sistemas.mma.gov.br/cnuc/index.php?ido=relatorioparametrizado.exibeRelatorio&relatorioPadrao=true&idUc=219>.

MELCHIORRE, Andrea; BOSCHETTI, Luigi. Global Analysis of Burned Area Persistence Time with MODIS Data. **Remote Sensing**, [S.L.], v. 10, n. 5, p. 750, 14 maio 2018. MDPI AG. http://dx.doi.org/10.3390/rs10050750.

MPAKAIRI, Kudzai Shaun; NDAIMANI, Henry; KAVHU, Blessing. Exploring the utility of Sentinel-2 MSI derived spectral indices in mapping burned areas in different land-cover types. **Scientific African**, [S.L.], v. 10, p. 100-112, nov. 2020. Elsevier BV. http://dx.doi.org/10.1016/j.sciaf.2020.e00565.

PACHECO, Admilson da Penha; SILVA JUNIOR, Juarez Antonio da; RUIZ-ARMENTEROS, Antonio Miguel; HENRIQUES, Renato Filipe Faria. Assessment of k-Nearest Neighbor and Random Forest Classifiers for Mapping Forest Fire Areas in Central Portugal Using Landsat-8, Sentinel-2, and Terra Imagery. **Remote Sensing**, [S.L.], v. 13, n. 7, p. 1345, 1 abr. 2021. MDPI AG. http://dx.doi.org/10.3390/rs13071345

PÉREZ-LUQUE, Antonio J.; RAMOS-FONT, María Eugenia; BARBIERI, Mauro J. Tognetti; PÉREZ, Carlos Tarragona; RENTA, Guillermo Calvo; CRUZ, Ana Belén Robles. Vegetation Cover Estimation in Semi-Arid Shrublands after Prescribed Burning: field-ground and drone image comparison. **Drones**, [S.L.], v. 6, n. 11, p. 370, 21 nov. 2022. MDPI AG. http://dx.doi.org/10.3390/drones6110370

PEREIRA, Allan; PEREIRA, José; LIBONATI, Renata; OOM, Duarte; SETZER, Alberto; MORELLI, Fabiano; MACHADO-SILVA, Fausto; CARVALHO, Luis de. Burned Area Mapping in the Brazilian Savanna Using a One-Class Support Vector Machine Trained by Active Fires. **Remote Sensing**, [S.L.], v. 9, n. 11, p. 1161, 14 nov. 2017. MDPI AG. http://dx.doi.org/10.3390/rs9111161

PEREIRA, A. A.; TEIXEIRA, F. R.; LIBONATI, R.; MELCHIORI, E. A.; CARVALHO, L. M. T. Avaliação de índices espectrais para identificação de áreas queimadas no cerrado utilizando dados landsat tm. **Revista Brasileira de Cartografia**, v. 68, n. 8, 16 out. 2016.

PEREIRA, J.M.C.. A comparative evaluation of NOAA/AVHRR vegetation indexes for burned surface detection and mapping. Ieee Transactions On Geoscience And Remote Sensing, [S.L.], v. 37, n. 1, p. 217-226, 1999. **Institute of Electrical and Electronics Engineers (IEEE)**. http://dx.doi.org/10.1109/36.739156.

PICOTTE, Joshua J.; BHATTARAI, Krishna; HOWARD, Danny; LECKER, Jennifer; EPTING, Justin; QUAYLE, Brad; BENSON, Nate; NELSON, Kurtis. Changes to the Monitoring Trends in Burn Severity program mapping production procedures and data products. **Fire Ecology**, [S.L.], v. 16, n. 1, p. 100-115, June 25. 2020. Springer Science and Business Media LLC. http://dx.doi.org/10.1186/s42408-020-00076-y.

PLENIOU, Magdalini; KOUTSIAS, Nikos. Sensitivity of spectral reflectance values to different burn and vegetation ratios: a multi-scale approach applied in a fire affected area. **Isprs Journal of Photogrammetry And Remote Sensing**, [S.L.], v. 79, p. 199-210, maio 2013. Elsevier BV. http://dx.doi.org/10.1016/j.isprsjprs.2013.02.016.

REED, I.s.; YU, X.. Adaptive multiple-band CFAR detection of an optical pattern with unknown spectral distribution. Ieee Transactions On Acoustics, Speech, And Signal Processing, [S.L.], v. 38, n. 10, p. 1760-

1770, 1990. **Institute of Electrical and Electronics Engineers (IEEE)**. http://dx.doi.org/10.1109/29.60107.

RAO, Weiqiang; QU, Ying; GAO, Lianru; SUN, Xu; WU, Yuanfeng; ZHANG, Bing. Transferable network with Siamese architecture for anomaly detection in hyperspectral images. **International Journal Of Applied Earth Observation And Geoinformation**, [S.L.], v. 106, p. 102669, fev. 2022. Elsevier BV. http://dx.doi.org/10.1016/j.jag.2021.102669.

RODRIGUES, J.A.; LIBONATI, R.; PERES, L.F.; SETZER, A.. Burned Area Mapping on Conservation Units of Mountains Region of Rio de Janeiro Using Landsat-8 Data During the 2014 Drought. **Anuário do Instituto de Geociências - Ufrj**, [S.L.], v. 41, n. 1, p. 318-327, 16 maio 2018. Instituto de Geociencias - UFRJ. http://dx.doi.org/10.11137/2018_1_318_327.

SACRAMENTO, Iorrana Figueiredo; MICHEL, Roberto Ferreira Machado; SIQUEIRA, Rafael Gomes. Análise bitemporal de áreas queimadas na Mata Atlântica. **Sociedade & Natureza**, [S.L.], v. 32, p. 565-577, 14 ago. 2020. EDUFU - Editora da Universidade Federal de Uberlandia. http://dx.doi.org/10.14393/sn-v32-2020-53339.

SANTANA, Níckolas; CARVALHO JÚNIOR, Osmar de; GOMES, Roberto; GUIMARÃES, Renato. Burned-Area Detection in Amazonian Environments Using Standardized Time Series Per Pixel in MODIS Data. **Remote Sensing**, [S.L.], v. 10, n. 12, p. 1904, 29 nov. 2018. MDPI AG. http://dx.doi.org/10.3390/rs10121904.

SILVA JUNIOR, Juarez Antonio; PACHECO, Admilson da Penha. Avaliação de incêndio em ambiente de Caatinga a partir de imagens Landsat-8, índice de vegetação realçado e análise por componentes principais. **Ciência Florestal**, [S.L.], v. 31, n. 1, p. 417-439, 15 mar. 2021. Universidad Federal de Santa Maria. http://dx.doi.org/10.5902/1980509843818.

SORENSEN, T. A Method of Establishing Groups of Equal Amplitude in Plant Sociology Based on Similarity of Species and Its Application to Analyses of the Vegetation on Danish Commons. **Kongelige Danske Videnskabernes Selskab**, 5, 1-34, 1948.

SMITH, Alistair M.s.; WOOSTER, Martin J.; DRAKE, Nick A.; DIPOTSO, Frederick M.; FALKOWSKI, Michael J.; HUDAK, Andrew T.. Testing the potential of multi-spectral remote sensing for retrospectively estimating fire severity in African Savannahs. **Remote Sensing of Environment**, [S.L.], v. 97, n. 1, p. 92-115, jul. 2005. Elsevier BV. http://dx.doi.org/10.1016/j.rse.2005.04.014.

STROPPIANA, D.; BOSCHETTI, M.; ZAFFARONI, P.; BRIVIO, P.A.. Analysis and Interpretation of Spectral Indices for Soft Multicriteria Burned-Area Mapping in Mediterranean Regions. Ieee Geoscience And Remote Sensing Letters, [S.L.], v. 6, n. 3, p. 499-503, jul. 2009. **Institute of Electrical and Electronics Engineers (IEEE)**. http://dx.doi.org/10.1109/lgrs.2009.2020067.

STROPPIANA, D.; BORDOGNA, G.; CARRARA, P.; BOSCHETTI, M.; BOSCHETTI, L.; BRIVIO, P.A.. A method for extracting burned areas from Landsat TM/ETM+ images by soft aggregation of multiple Spectral Indices and a region growing algorithm. **Isprs Journal Of Photogrammetry And Remote Sensing**, [S.L.], v. 69, p. 88-102, abr. 2012. Elsevier BV. http://dx.doi.org/10.1016/j.isprsjprs.2012.03.001.

SOUZA, Cláudia de. Nos interstícios da soja: resistências, evoluções e adaptações dos sistemas agrícolas localizados na região do Refúgio de Vida Silvestre das Veredas do Oeste Baiano. 2017. 311 f., il. **Tese (Doutorado em Desenvolvimento Sustentável)**—Universidade de Brasília, Brasília, 2017.

SMIRAGLIA, Daniela; FILIPPONI, Federico; MANDRONE, Stefania; TORNATO, Antonella; TARAMELLI, Andrea. Agreement Index for Burned Area Mapping: integration of multiple spectral indices using sentinel-2 satellite images. **Remote Sensing**, [S.L.], v. 12, n. 11, p. 1862, 8 jun. 2020. MDPI AG. http://dx.doi.org/10.3390/rs12111862

STROPPIANA, Daniela; BORDOGNA, G.; BOSCHETTI, M.; CARRARA, P.; BOSCHETTI, L.; BRIVIO, P. A.. Positive and Negative Information for Assessing and Revising Scores of Burn Evidence. **IEEE Geoscience And Remote Sensing Letters**, [S.L.], v. 9, n. 3, p. 363-367, maio 2012. Institute of Electrical and Electronics Engineers (IEEE). http://dx.doi.org/10.1109/lgrs.2011.2167953.

TRIGG, S.; FLASSE, S.. An evaluation of different bi-spectral spaces for discriminating burned shrub-savannah. **International Journal of Remote Sensing**, [S.L.], v. 22, n. 13, p. 2641-2647, jan. 2001. Informa UK Limited. http://dx.doi.org/10.1080/01431160110053185.

USGS, **Landsat 8 Data Users Handbook**. 2019 Department of the Interior U.S. Geological Survey.https://landsat.usgs.gov/sites/default/files/documents/Landsat8DataUsersHandbook.pdf

VAN DIJK, Daan; SHOAIE, Sorosh; VAN LEEUWEN, Thijs; VERAVERBEKE, Sander. Spectral signature analysis of false positive burned area detection from agricultural harvests using Sentinel-2 data. **International Journal Of Applied Earth Observation And Geoinformation**, [S.L.], v. 97, p. 102296, maio 2021. Elsevier BV. http://dx.doi.org/10.1016/j.jag.2021.102296.

VAN ECK, Christel M.; NUNES, Joao P.; VIEIRA, Diana C. S.; KEESSTRA, Saskia; KEIZER, Jan Jacob. Physically-Based Modelling of the Post-Fire Runoff Response of a Forest Catchment in Central Portugal: using field versus remote sensing based estimates of vegetation recovery. **Land Degradation & Development**, [S.L.], v. 27, n. 5, p. 1535-1544, 22 abr. 2016. Wiley. http://dx.doi.org/10.1002/ldr.2507.

VERAVERBEKE, S.; HARRIS, S.; HOOK, S.. Evaluating spectral indices for burned area discrimination using MODIS/ASTER (MASTER) airborne simulator data. **Remote Sensing Of Environment**, [S.L.], v. 115, n. 10, p. 2702-2709, out. 2011. Elsevier BV. http://dx.doi.org/10.1016/j.rse.2011.06.010.

Main author biography

Juarez Antônio da Silva Júnior was born in Recife, PE – Brazil. He holds a degree in Cartographic Engineering and Surveying from the Federal University of Pernambuco (2021). He is part of the research group “Orbital Remote Sensing Applied to the Study of Hot Spots in Forests in Brazil and the Iberian Peninsula”. Interested in the following topics: Remote Sensing; Machine Learning and Deep Learning and; Geospatial data quality.