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Use of spectral indices in the characterization of vegetation cover in the Caatinga region of the Semiarid region of Bahia

Uso de índices espectrais na caracterização da cobertura vegetal em região de Caatinga do Semiárido Baiano

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Abstract: Given the importance to raise information that contributes to scientific dissemination, conservation of natural resources, and monitoring and planning of environmental policies in the Caatinga biome, this study aims to characterize the vegetation coverage and the carbon flow of the municipality of Central in the State of Bahia, which has an extensive area occupied by temporary crops. The characterization work was accomplished by applying the spectral indices NDVI, SAVI, EVI, and the CO_2Flux during the dry and rainy months of 2020. Images of Sentinel-2, processed in a GIS environment were used. The results showed the highest values based on these indices in the rainy season (0.50 ┤1) distributed over a large area (NDVI: ~88%; SAVI: ~90%, EVI: ~81%). In the dry season, the values between 0 and 0.50 prevailed (NDVI: ~96.8%; SAVI: ~95%, EVI: ~94.8%) with values above 0.50 limited to riparian forests and alluvial areas. The rainy EVI presented lower values than the NDVI and SAVI about lower saturation. The urban area has been properly detailed in the rainy season images. Based on the indices, lower altitude zones presented higher values while higher areas had lower values. The CO_2Flux showed that the carbon sequestration was more effective in the rainy period and presented a strong correlation among the indices.

Keywords: Vegetation indices; Sentinel-2; GIS.

Resumo: Diante da importância de levantar informações que contribuam com a divulgação científica, conservação dos recursos naturais, o monitoramento e o planejamento de políticas ambientais no bioma Caatinga, objetivou-se caracterizar a cobertura vegetal e o fluxo de carbono no município de Central/BA, que apresenta extensa área ocupada por lavouras temporárias. Tal caracterização se deu por meio dos índices espectrais NDVI, SAVI, EVI e CO_2Flux, para um mês seco e um chuvoso de 2020. Foram utilizadas imagens do Sentinel-2, processadas em ambiente SIG. Os resultados demonstraram os maiores valores para os índices no período chuvoso (0,50 ┤1) distribuídos por uma maior área (NDVI: ~88%; SAVI: ~90%; EVI: ~81%), e para o período seco os valores entre 0 e 0,50 predominantes (NDVI: ~96,8%; SAVI: ~95%, EVI: ~94,8%), estando valores acima de 0,50 limitados às áreas de mata ciliar e aluviões. O EVI chuvoso apresentou valores menores que o NDVI e SAVI, relacionado à menor saturação. A área urbana foi bem discriminada nas imagens do período chuvoso. Zonas de menor altitude apresentaram maiores valores para os índices e as de maior altitude menores valores. O CO_2Flux demonstrou um sequestro de carbono mais eficiente no período chuvoso e uma correlação bastante forte entre os índices.

Palavras-chave: Índices de vegetação; Sentinel-2; SIG.

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1. Introduction

Forest resources, especially in tropical forests, count on several processes for life maintenance, either directly or indirectly, in the distinct earth ecosystems. These resources are linked to primary ecosystem productivity, cycling of nutrients, water cycle, carbon sequestration for energy purposes, and agricultural viability, among several biotic, abiotic, and economic factors (SOUZA *et al*., 2019).

Caatinga is one of the Seasonally Dry Tropical Forests (SDTF) – a biome that presents a unique set of features that differentiate it from other vegetation formations. It's essential to bring to light its fauna and flora as much as its high degree of endemism. The flora dynamics presented in the caatinga are predominantly affected by edaphoclimatic factors, such as water availability and pedogenesis, which directly influence the vegetation behavior and the variation of phenological traits. Those dynamics need further exploration and scientific observation in different locations and contexts, especially considering that this biome is among the less protected and studied ecosystems, despite its uniqueness and importance (MMA, 2012; BARBOSA; CARVALHO; CAMACHO, 2017; BARBOSA *et al*, 2019; SOUZA *et al*., 2019).

Since the colonization process in the northeastern region of Brazil, the Caatinga biome has been changing due to land use and occupation practices as a consequence of anthropic activities, which lead the region to a degradation process. According to Lopes *et al*. (2020), it is estimated that anthropic effects – mainly extractivism and farming – in the Caatinga vegetation have already reached approximately 80%, resulting in altered areas in an initial or intermediate stage of ecological succession. Activities such as agriculture and cattle-raising have been causing impacts in these areas due to their establishment and maintenance, which have been altering areas of natural vegetation into areas of anthropic activities. These degradation factors can also lead to erosive processes, local changes in climate dynamics, and desertification – as it is a susceptible region – among other problems.

Therefore, Remote Sensing techniques stand out for enabling measuring physical parameters associated with, for example, biomass, plant development, soil cover, and vegetation assessment. That is possible by using ground, suborbital and orbital sensors with different spatial and temporal resolutions to explore the spectral properties of plants, especially their reflectance in visible and near-infrared regions, which are the main wavelengths that interact with microscopic structural elements that compose the leaves of plants (PONZONI; SHIMABUKURO; KUPLICH, 2012; LOPES *et al*., 2020; SILVA JUNIOR *et al*., 2021).

By using the results generated by sensors, it is possible to create mathematical models combining spectral bands, using or not adjustment coefficients, to quantify biomass or detect phenological changes present in vegetation. That system allows the characterization, mapping, and analysis of spatial, temporal, and seasonal behavior of vegetation degradation and the consequence of human and natural activities, etc. (LIMA JÚNIOR, *et al.* 2014; DONG *et al*. 2019; LOPES *et al*., 2020).

To obtain the flora spectral behavior, it is possible to process sensor images by using image processing techniques known as Vegetation Index (VI). Those techniques aim to explore the enhancement of scenes with different plant biomass densities (MENESES; ALMEIDA; BAPTISTA, 2019; SILVA JUNIOR *et al*., 2021).

Among the indices, some of those stand out such as 1) Normalized Difference Vegetation Index (NDVI), used for monitoring plant biomass to build seasonal and temporal profiles that allow inter-annual comparisons; 2) Soil-adjusted Vegetation Index (SAVI), which has similar application to NDVI, with the addition of an adjustment factor for soil effects, considering the diverse vegetation density; 3) Enhanced Vegetation Index (EVI), which also measures plant biomass seeking to reduce both the effects of soil and atmosphere in the results, being more sensitive to variations in the vegetation structure (PONZONI; SHIMABUKURO; KUPLICH, 2012; MENESES; ALMEIDA; BAPTISTA, 2019). The VI also helps to obtain other indices like the Carbon Forest Sequestration Index (CO_2Flux), which analyzes the efficiency of atmospheric carbon sequestration by the forest community.

Taking into consideration all the factors associated with the importance of the Caatinga biome in both national and global contexts and the information gathered to contribute to scientific dissemination, monitoring, conservation of natural resources, and planning of environmental policies and decision-making processes, this work focus in characterizing the vegetation coverage and the carbon flux of the municipality of Central in the State of Bahia, using the NDVI, SAVI, EVI, and CO_2Flux spectral indices. For this purpose, are considered spectral analysis, the carbon flux behavior, the forms of use and occupation of the soil, the terrain, the vegetation dynamics, and the correlation among results generated during the dry and rainy seasons in 2020.

2. Methodology

Study area

The municipality of Central is located in the north-central region of the State of Bahia, in the Brazilian semiarid region (Figure 1), between the geographic coordinates 11°1′19″S-11°15′43″S and 41°55′30″W-42°15′29″W. It occupies an area of 566.97km², with an estimated population of 17,280 inhabitants (IBGE, 2010). The climate is the BSh type according to the Köppen climate classification (ALVARES *et al*., 2013), the average annual temperature is 23.9ºC, and the average precipitation is 744.3 mm (SEI, 2014).

The city is part of the Depression Sertaneja Meridional Ecoregion, with natural vegetation predominantly Steppic Savanna, characteristic of the Caatinga biome and the BSh climate type. The municipality's GDP per capita is R$9,059.39, being farming and ranching one of the main economic activities, second only to services and industries, where prevails the planting of castor beans, corn, forage palm, and watermelon crops; and the raising of goats, sheep, cattle, and pigs (IBGE, 2017). Although agriculture is not the main activity, as observed in Figure 1, the land use for Temporary Crops covers a large territorial extension, which is an ongoing concern in protecting natural landscapes. The region is also a touristic site for its numerous archaeological sites, landscapes of rocky fields with records of ancient civilizations surrounded by canyons and caves of impressive beauty.

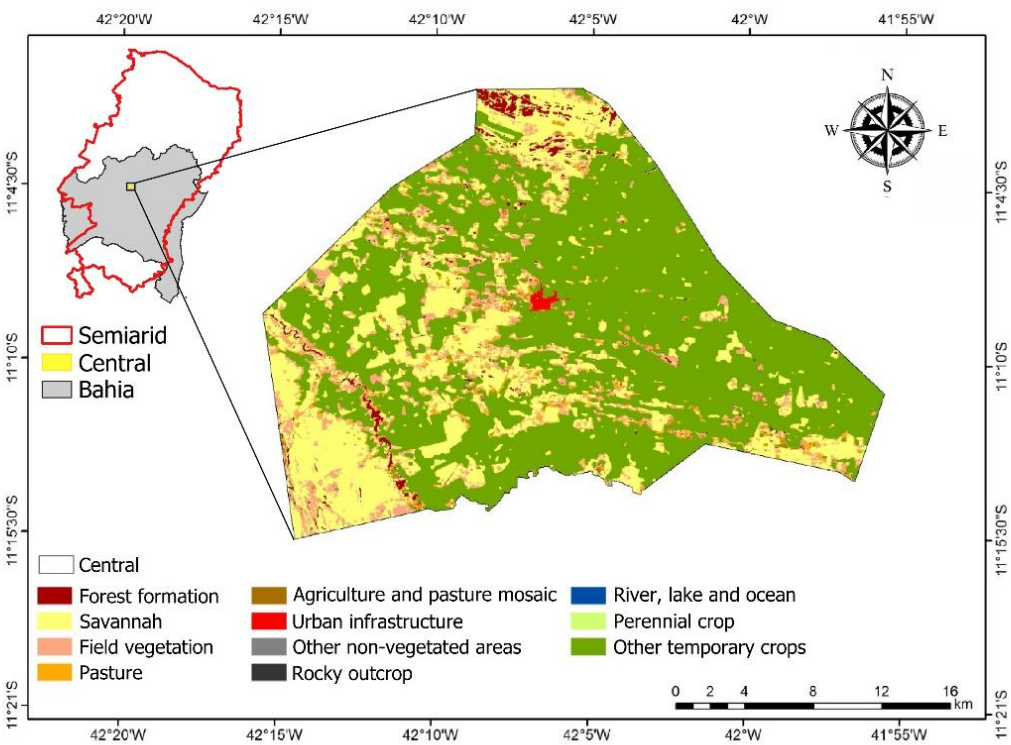

Figure 1 – Location map of the municipality of Central, in the semiarid region of Bahia.
Source: Authors (2021)..

According to Nepomuceno (2014), among the soil types found in the city prevails the Eutrophic Ta Haplic Cambissols, a typology characterized by low structural development, often with characteristics of the mother rock. There are also areas with Litholic Dystrophic Neosols in the extreme southwest of the region, with areas with larger slopes. This specific type presents low intensity of pedogenetic processes and a thin mantle of alteration. In geomorphological aspects, the city is located in the flatlands of the Jacaré and Salitre rivers, with a terrain composed of small plateaus and colluvial ramps and degrees of slope from weak to moderate (CPRM, 2006). The hypsometric map (Figure 2) represents the altitude variation of the study area.

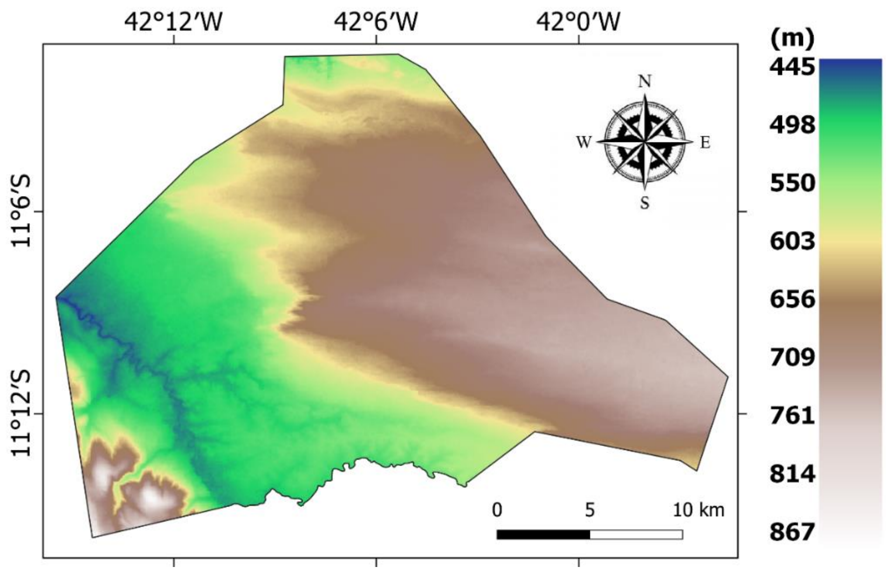

Figure 2 – Hypsometric map of the municipality of Central, in the State of Bahia, Brazil.
Source: Authors (2021).

Image acquisition and pre-processing

Satellite images have been selected from the MultiSpectral Instrument Sensor - MSI level 1C that is onboard the Copernicus Sentinel-2, developed by the European Space Agency (ESA) as part of the Copernicus program. To calculate the indices proposed here were used bands in visible and near-infrared regions, with a spatial resolution of 10 meters. The scenes used were the T23LRH and T23LQH of the year 2020, considering two study periods, one of higher and the other of lower rainfall (wet and dry, respectively), totaling four scenes, two for each period. The criterion for choosing the scenes was based on less cloud cover from March (03/27/2020) to October (10/03/2020).

The minimum, maximum and average rainfall values in the municipality of Central - BA in March and September are presented in Table 1, gathered by the Integrated Multi-satellite Retrievals for the Global Precipitation Measurement (IMERG) Version 6, Final Run. Studies by Asong *et al*. (2016), Tan and Duan (2017), and Gadelha (2018), comparing IMERG data with that from rainfall stations, showed good performance of the satellite to estimate precipitation, especially on monthly (used in this study) and annual time scales. As the scene obtained is from the dry season date 03/10/2020, the precipitation values observed relate to September

Table 1 – Minimum, maximum, and average rainfall data in the municipality of Central - BA in March and September 2020.

Precipitation (mm)		
	March 2020	**September 2020**
Minimum	205	10
Maximum	251	14
Average	235	12

Source: Authors (2021).

To After capturing them, the images underwent a radiometric/atmospheric correction process by converting Top-Of-Atmosphere (TOA) reflectance to Bottom-Of-Atmosphere (BOA) reflectance, using the SNAP 8.0 software and the Sentinel-2 Atmospheric Correction (Sen2Cor) algorithm. That is a necessary procedure for spectral characterization, which is essential for vegetation. The scenes were converted from JPEG2000 to GeoTIFF (easier processing format) using the GDAL/OSGeo4W command line.

Image processing

After completing the atmospheric correction, it was initiated the image processing in SIRGAS 2000 Datum, Zone 23S, using the QGIS 3.10 software. The scenes were merged and cut out based on the municipal mesh, data obtained through the Brazilian Institute of Geography and Statistics – IBGE (2020). To generate spectral indices – NDVI, SAVI, EVI, and CO_2flux –, the Raster Calculator was used to calculate the VI, according to the equations presented in Table 2.

Table 2 – Equations used to calculate spectral indices of the vegetation cover characterization in the Caatinga region of semiarid Bahia.

Index	**Equation**	**Reference**
NDVI – ***Normalized Difference Vegetation Index*** **(1)**	NDVI=(ρNIR- ρRED)/(ρNIR+ ρRED)	Rouse *et al.* (1973)
SAVI – ***Soil-adjusted Vegetation Index*** **(2)**	SAVI=((ρNIR- ρRED)×(1+L))/((ρNIR+ ρRED+L))	Huete (1988)
EVI – ***Enhanced Vegetation Index*** **(3)**	EVI=2.5×(ρNIR-ρRED)/(ρNIR+(C1×ρRED-C2×ρBLUE)+L)	Huete *et al.* (2002)
PRI – ***Photochemical Reflectance Index*** **(4)**	PRI=(ρBLUE- ρGREEN)/(ρBLUE+ ρGREEN)	Gamon, Serrano e Surfus (1997)
sPRI – ***Photochemical Reflectance Index rescheduled for positive values*** **(5)**	sPRI=(PRI+1)/2	Baptista (2003)
CO_2FLUX – ***Carbon Forest Sequestration Index*** **(6)**	CO_2Flux=sPRI ×NDVI	Rahman *et al.* (2000)

Legend: ρBLUE corresponds to the band in the blue region; ρGREEN in the green region; ρRED in the red region; ρNIR in the near-infrared region; C1 is the atmospheric correction factor for the red region (6); C2 is the atmospheric correction factor for the blue region (7.5); and L is the adjustment factor for the ground using 0.428, which is recommended by ESA for Sentinel-2 images.

Source: Authors (2021).

As to the area of study, only scenes from March to October showed cloud coverage to allow processing of the VIs, discarding scenes from the other months due to the strong presence of clouds. By applying the methodology, it was possible to generate maps that visually represent the indices' spatial distribution and their behavior in these months, one rainier and the other drier.

To compare the same scale between the VIs, the interval was rescaled to values between 0 and 1, with the values for the indices between -1 and 0 included in a single category (0). The other categories correspond to interval values, where each corresponds to a class of the VIs, starting at 0 with water bodies/clouds, following to exposed soil –0 ┤0.25 –, sparse vegetation – 0.25 ┤0.50 –, intermediate vegetation – 0.50 ┤0.75 –, and dense vegetation – 0.75 ┤1.0 –. For the CO_2Flux, values were also rescaled, but with a range varying between 0 and 0.30, which corresponds to the carbon flux from the lowest to the highest.

Correlation analysis

Aiming to assess the correspondence degree between the VIs, 200 pixels were sampled by applying the "create random points in the extension" feature of the QGIS 3.10 program. The data of the index scenes were extracted from these points by using the "Point Sampling Tool" plugin, in which data was exported and statistically analyzed in spreadsheets for each of the VIs.

The Shapiro-Wilk (1965) test of normality was performed based on the extracted information, and the correlation analysis among the VIs was performed as to Pearson's method (r), which expresses the degree of relationship among variables with normal distribution and values in the range -1 to 1 (Table 1). Thus, the closer to 1, the stronger the correlation (positive linear relationship); the closer it is to -1, the correlation is also strong (negative linear relationship).

Table 1 – Pearson's correlation coefficient reliability rating. Source: adapted from Veiga et al. (2019).

***r* value (positive or negative)**	**Interpretation**
0	Null
0.01 a 0.20	Little weak
0.21 a 0.40	Weak
0.41 a 0.60	Moderate
0.61 a 0.80	Strong
0.81 a 0.99	Little strong
1	Perfect

Source: Authors (2021).

3. Results and Discussion

NDVI, SAVI and EVI

The results presented in Figure 3 showed that the rain period had higher values in the VIs, especially NDVI and SAVI, with values higher than 0.50 and close to 1, and well-distributed pixels corresponding to this class interval, mainly in the portion that goes from the center to the west. The EVI in the rainy season presented lower values than in the mentioned indices, corroborating Nery, Moreira, and Fernandes's (2014) demonstration, in which the annual average values (2007 - 2012) of the EVI are always lower than those of the NDVI. The VIs of the dry season presented values predominantly lower than 0.50, however, in riparian forest regions, values higher than 0.50.

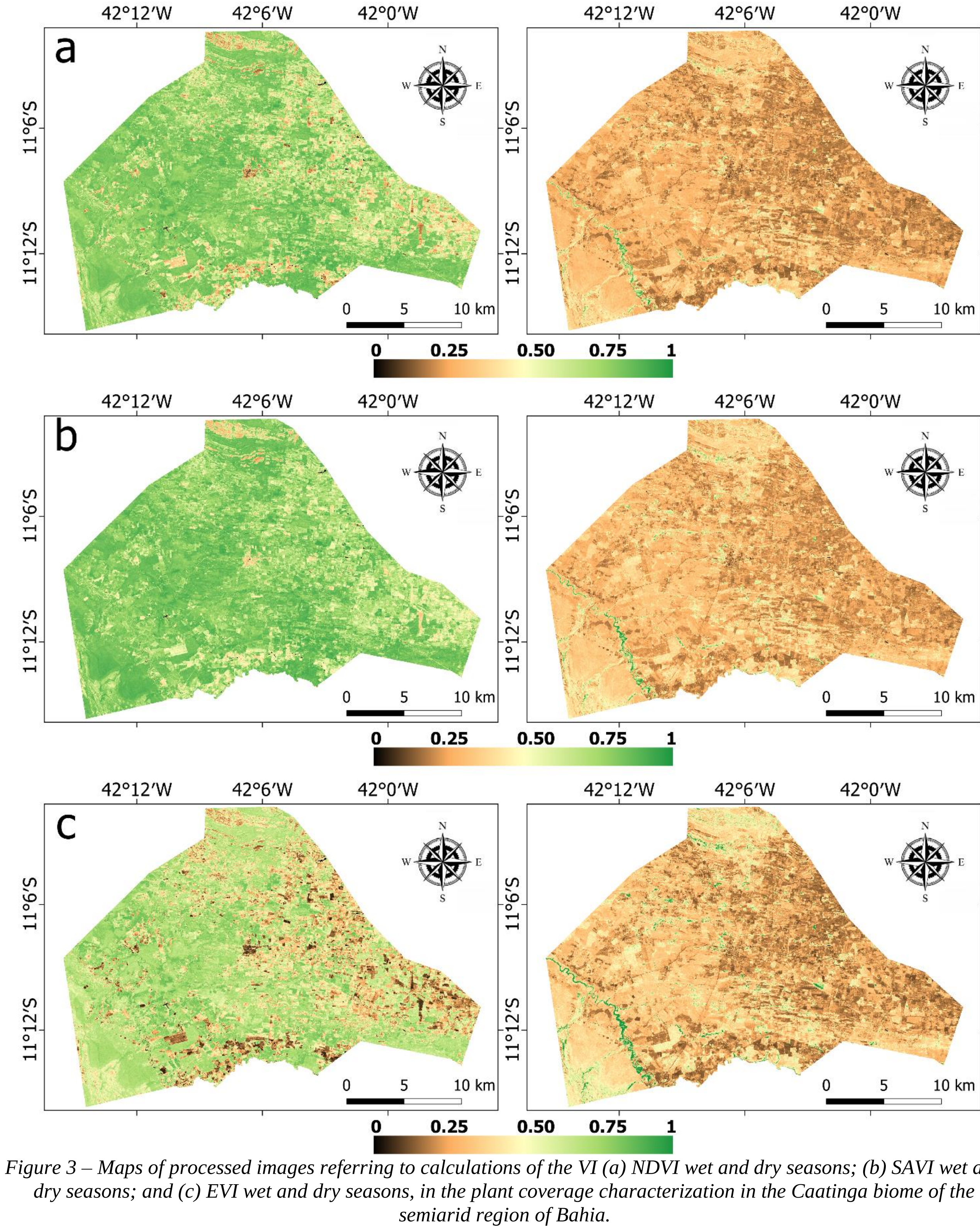

Figure 3 – Maps of processed images referring to calculations of the VI (a) NDVI wet and dry seasons; (b) SAVI wet and dry seasons; and (c) EVI wet and dry seasons, in the plant coverage characterization in the Caatinga biome of the semiarid region of Bahia.
Source: Authors (2021)

Table 3 shows the areas in percentages corresponding to each VI interval based on the total area of the city (566.97km^2). The divergences in the area distribution are demonstrated in the illustration with higher and lower values for each index and period.

Table 3 – Percentage of areas corresponding to each interval of the indices categories NDVI, SAVI, and EVI in the characterization of plant coverage in the Caatinga area of the semiarid region of Bahia.

	NDVI (%)		**SAVI (%)**		**EVI (%)**	
Intervals	**Rainy**	**Dry**	**Rainy**	**Dry**	**Rainy**	**Dry**
0	0.07	0.01	0.07	0.01	0.07	0.01
0 ┤ 0.25	1.76	43.21	1.52	33.86	3.66	41.37
0.25 ┤ 0.50	9.91	53.62	8.04	61.38	14.86	53.41
0.50 ┤ 0.75	31.28	2.65	20.04	0.81	37.36	4.01
0.75 ┤ 1	56.97	0.52	70.33	3.94	44.04	1.21

Source: Authors (2021).

By observing both Figure 3 and Table 3, it is noticeable that in the rainy season the distribution of the highest indices values – 0.50 ┤ 1 – comprises a larger area – NDVI: ~88%; SAVI: ~90%, EVI: ~81% – due to higher vegetation density and biomass concentration. During the dry season, the interval 0 ┤ 0.50 prevails and occupies a larger area (NDVI: ~96.8%; SAVI: ~95%, EVI: ~94.8%). The analysis of maps seen in Gameiro *et al*. (2016) and Wanderley *et al*. (2018) study areas with similar characteristics indicate the same pattern, corroborating with previous observations. Compared to the results of Gameiro *et al*. (2016), the intermediate and dense vegetation categories corresponded to ~63% of the area for the NDVI and ~62% for the SAVI in the rainy season; and the exposed soil and sparse vegetation categories to ~87.5% for the NDVI and ~87% for the SAVI in the dry season.

By analyzing the results gathered in the three indices, the regions in black (0) correspond to areas without vegetation, in this case, water bodies, whether natural or artificial or even clouds, if any in the scenes. The three indices in the rainy season discriminate small watercourses (0), whether intermittent, perennial, or small reservoirs, the temporary for example, a characteristic of semiarid regions. The locals – known as "sertanejos" – use these areas to store water during rainy periods. It is worth mentioning that the black "spots" are more noticeable in the NDVI and EVI, and less in the SAVI.

The gradient corresponding to the interval 0 ┤ 0.25 represents the regions colored in brown and orange hues, indicating areas of exposed soil (no plant coverage). The pixels distribution in this dry season intervals occurs mainly in the eastern and southernmost portions, as can be seen in Figure 3. In the wet season, the gradient interval is distributed in the same regions, covering a small area, in special for the NDVI and SAVI, as seen in Table 3. Note that in the EVI, the areas corresponding to the same interval are larger.

Also based on Figure 3, all indices considered show that the rainy season presented improved accuracy in the urban area compared to the dry. Central urban area can be seen in the center of the map in Figure 1 and its values during the rainy season drew near to 0 for the NDVI and EVI, while for the SAVI the values neared 0.5.

In this section, the yellowish corresponds to the interval between 0.25 ┤and 0.50 in the three indices, representing possible areas of deciduous vegetation, more creeping and sparse, such as the Gramineous Woody Savanna, or even cultivated pastures, or annual crops, which usually present low photosynthesis. In the dry season, the interval distribution – 0.25 ┤ 0.50 – covers a significant area (Table 3) and, in general, concentrates in the extreme north, southwest (area with relief presenting higher altitudes), and southeast (Savanna regions, as seen in Figure 1), according to Figure 3.

The spectral behavior pictured in the rainy season undergoes a more recurrent interval of 0.25 ┤ 0.50 on the right (east) of the maps for the NDVI and SAVI, which may be attributed to the presence of temporary crops, as observed in the city map of use and occupation (Figure 1). The farming of temporary crops is usually done in the rainy period, explaining the slight increase in vegetative vigor in this period scenes in the same regions set aside in the dry season. However, the spectral response is lower than that of natural vegetation, as local crops are mostly annual species of shrub, herbaceous, and graminoid habits. In the rainy EVI, the gradient is mainly concentrated in the extreme southwest (savanna) and some regions scattered over the map.

In general, the indices values in the dry period hardly exceeded 0.50 for the NDVI, SAVI, and EVI, indicating that much of the region is in a phytogeographic domain consisting of Hyperxerophilous Caatinga, with species adaptable to semiarid regions, such as thorns (Cactaceae), and total (deciduous) or partial (semideciduous) foliage loss, added to senescence and lower photosynthesis, which contribute to lower vegetative vigor. That process also indicates a few areas with irrigated crops. Furthermore, the radiation spectral response reflected by the plant coverage in drought may resemble that of other terrestrial targets, such as fallow and anthropized areas, and rocky outcrops (NEPOMUCENO, 2014).

The results presented are similar to those of Barbosa, Huete, and Baethgen (2006), who demonstrated in October a baseline ranging between ~0.25 and ~0.5 in the study of the NDVI temporal variation patterns in northeast Brazil, over 20 years (1982 - 2001). Chaves *et al*. (2013) highlighted low NDVI values in the dry period (<0.4) as an indication of Hyperxerophilic Caatinga vegetation; Wanderley *et al*. (2018) reinforced the predominance of classes lower than 0.50 in the Caatinga area of semiarid Paraiba in the NDVI values and lower than 0.30 in the SAVI. The subject area of these authors is similar to this study, as well as the VIs values. When compared to the characteristics of different study areas by Becerra, Shimabukuro, and Alvará (2009) (Cerrado of the Legal Amazon) and Nery, Moreira, and Fernandes (2014) (Deciduous Seasonal Forest), the first observed a distinct behavior with values higher than 0.60 throughout the year, both for the EVI and NDVI; and the second showed similar behavior with values below 0.50 in the driest months and higher in the rainiest.

The other scenes corresponded to VIs values >0.50, showing higher plant density and photosynthesis and indicating the distribution of remnant vegetation in these areas. Thus, that points to phytosociological regions of Steppe Savanna, with phytophysiognomies of Park and Wooded Savanna with interval values around 0.75 and of Forested Steppe Savanna with the highest values – around 1, also indicating areas with permanent and irrigated crops.

The value range corresponding to the 0.50 ┤ 1 in the rainy season has been distributed across the territory for the NDVI (~88%), SAVI (~90%), and EVI (~81%). In this way, the remnant vegetation was denser in the region due to the water availability in the soil facilitated by rainfalls, offering improved conditions for growing native vegetation. Therefore, defoliated deciduous and semi-deciduous plants can recover the foliage due to soil moisture, resulting in more active photosynthesis, which is better captured by sensors and facilitates the identification of features in the scenes (NEPOMUCENO, 2014). In addition, some crop cultivation areas, with larger sizes and better growing, can comprehend higher reflectance values and consistency in this class interval.

These results confirm Barbosa *et al*. (2019) findings correlated to rainy seasons by relating the NDVI with precipitation, corresponding the months with higher precipitation with those with higher index values, and the outcome gathered by Nery, Moreira, and Fernandes (2014) and Brito, Santos, and Morais (2020) showed accuracy. Chaves *et al*. (2013) observed that the NDVI values had increased significantly in almost all the classes in this period compared to the dry season, as Barbosa, Huete, and Baethgen (2006) observed in value patterns ranging between ~0.45 and ~0.7.

It was also noticed that the highest values in all the three indices (0.50 ┤ 1) were concentrated in few areas during the dry season and, compared to the results of Gameiro *et al*. (2016), that the vegetation classes corresponding to this interval and period were ~11% of the area in the NDVI and ~12% in the SAVI. These areas cover watercourses, either intermittent or perennial, and a creek known as Baixão do Gabriel to the west. In these regions, the soil characteristics contribute to moisture storage (presence of alluvium), enabling the maintenance of foliage and providing a perennial profile.

Similar results regarding denser vegetation near watercourses during the drier period were observed by Boratto and Gomide (2013) when characterizing the plant coverage of northern Minas Gerais, showing higher values in the NDVI and SAVI (between 0.48 and 0.81). Silva Junior *et al*. (2021), when analyzing the NDVI and EVI, found lower values in low vegetation areas and higher values concentrated in riparian forest areas during the lower precipitation season in the Caatinga region, similarly to the behavior seen in this study, as observed in Figure 3.

The relationship of the VIs with the hypsometry is a fundamental factor as well. The analysis of the geospatial distribution resulting from the indices classes allowed observing patterns of the vegetation coverage arrangement within the geographic space affected in phytogeographic terms by ecological variables (BARBOSA; CARVALHO; CAMACHO, 2017).

The results based on both the dry and the rainy periods showed higher VIs values to the west of the creek Baixão do Gabriel, located at an altitude of approximately 500 meters (Figure 2). This outcome may be related to climatic zones by altitude, in which altitudinal gradients are influenced by microclimatic characteristics, where may grow different types of plants, as well as to environmental gradients influenced, for example, by water table heights and the soil moisture in the watercourses surroundings (BARBOSA; CARVALHO; CAMACHO, 2017). It was observed the lowest VIs in areas to the east with an altitude higher than 700 meters where there is the highest concentration of temporary crops and a characteristic plateau terrain in a region known as the Plateau of Irecê.

By visual observation of the VIs maps, it was noticed the influence of phenological dynamics in the Caatinga physiognomic and methods of cultivation used during the rainy season. In the dry season, the spectral behavior of the targets has a different variation from most of the periods of higher rainfall rates (according to Table 1), just as environmental dynamics may change according to climatic characteristics.

CO_2FLUX

The carbon flux in the county, in both seasons, has its distribution represented in the maps illustrated in Figure 4.

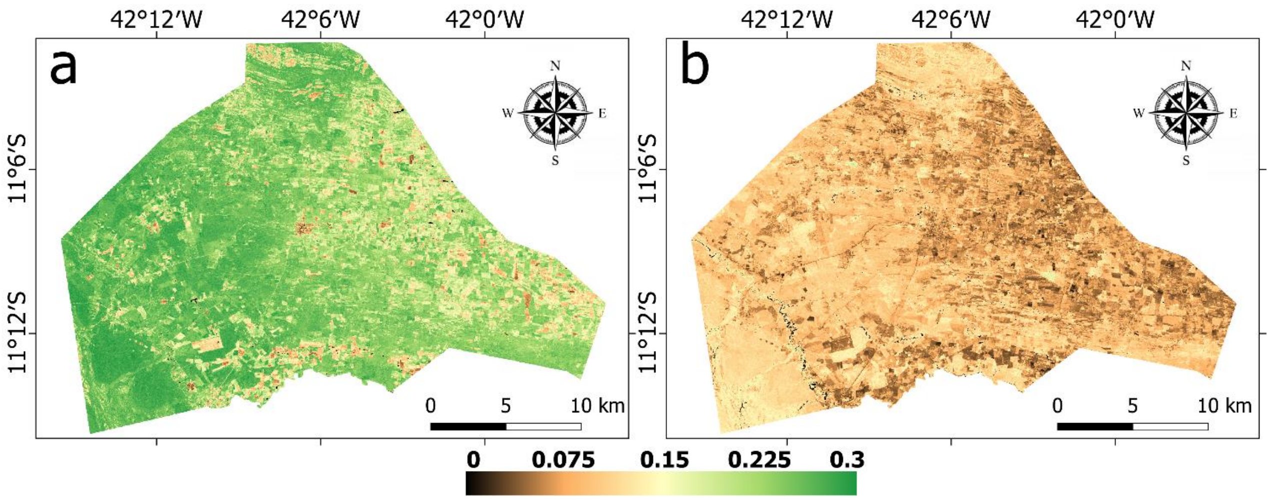

Figure 4 – Maps of the processed images referring to the calculation of CO_2FLUX in the two periods studied (a) rainy and (b) dry in the characterization of vegetation coverage in the Caatinga biome of the semiarid region of Bahia.
Source: Authors (2021).

Table 4 presents values corresponding to the area in percentage filled by each CO_2FLUX class interval in the total area of the municipality (566.97km^2).

Table 4 – Areas in percentage corresponding to each CO_2FLUX class interval in the characterization of the vegetation cover in the Caatinga biome of semiarid Bahia.

CO_2FLUX (%)		
Intervals	**Rainy**	**Dry**
0	0.074	0.007
0 ┤ 0.075	1.293	31.025
0.075 ┤ 0.15	8.918	67.411
0.15 ┤ 0.225	35.975	1.556
0.225 ┤ 0.30	53.740	0.002

Source: Authors (2021).

From the analysis of the spectral profile, in the rainy season (Figure 4a) the areas with higher vegetation and, consequently, photosynthesis (in the light phase of the process) showed higher values for carbon flux, ranging in most of the area – from 0.15 to 0.30 – what indicates that the carbon sequestration performed by the vegetation is more efficient in this period. As observed in the NDVI, SAVI, and EVI, these areas correspond to those with values >0.50, that is, vegetation remnants and areas of possible irrigated cultivation.

The rainy season has the highest values for being a time of intense vegetation, presenting greater biomass and leaf area. With this, photosynthesis reaches high levels and, as it is related to the use of atmospheric carbon, an element of access in the ecosystem, the CO_2 sequestration rate increases. The lowest values are observed in regions where temporary crops concentrate, indicating that the forest carbon sequestration is more efficient than that performed by the agricultural crop species used in the municipality.

As the dry season approaches, the CO_2FLUX tends to decrease due to climate conditions. The map shown in Figure 4b, corresponding to the CO_2FLUX, shows values below 0.15 in almost the entire area during the dry season, as observed in Table 4, where the largest areas correspond to classes >0 to 0.15.

The water stress caused by low rainfall in the dry season leads non-perennial species to lose their foliage, as already mentioned, leading to a reduction of plant biomass, leaf area, and photosynthesis, and all these factors lead to a drop in forest carbon sequestration rates. Furthermore, as observed in the wet season, the regions with temporary crops showed the lowest values also in the dry season. Regions of higher altitudes (Figure 2) with rupestrian fields to the north and southwest are prone to retain more moisture, covering these areas with natural savanna vegetation (Figure 1) characterized by distinct plant development, which raises the indices values in those areas.

In both seasons, the lowest values concentrate in villages, where the majority is fallow and presents spectral characteristics of exposed soil. In the areas described as rupestrian fields, there are zones distributed in the extreme north and southwest mainly where values approximate 0.15 in the dry season.

In the literature, there are similarities related to CO_2Flux. Carbon flux outcomes are similar to those of Grilo *et al*. (2011), who mapped the CO_2 flux in Caatinga environments and farming systems using orbital images. These authors found, in sectors composed of preserved and anthropized Caatinga, CO_2Flux values ranging from 0.186 to 0.305, and areas with lower CO_2 flux ranging from -0.175 to 0.158. The values here also corroborate Santos's work (2017), which demonstrated the pattern of the CO_2Flux index in dry and rainy periods and observed the decrease of values by modeling the carbon flux in areas of preserved and regenerating Caatinga. The values were higher in the rainy season when the vegetation turns into a carbon sink and were lower as the dry season arrives.

Correlation analysis

Table 5 and Table 6 show Pearson's correlation coefficients found in both study periods.

Table 5 – Pearson's correlation matrix between the indices shown in the rainy season in the vegetation coverage characterization in the Caatinga biome in the semiarid Bahia.

	NDVI	**SAVI**	**EVI**	**CO_2Flux**
NDVI	1			
SAVI	0.971	1		
EVI	0.925	0.838	1	
CO_2Flux	0.915	0.880	0.906	1

Source: Authors (2021).

Table 6 – Pearson's correlation matrix between the indices presented in the dry period in the vegetation coverage characterization in the Caatinga biome in the semiarid Bahia.

	NDVI	**SAVI**	**EVI**	**CO_2Flux**
NDVI	1			
SAVI	1	1		
EVI	0.973	0.973	1	
CO_2Flux	0.753	0.753	0.786	1

Source: Authors (2021).

The indices' outcomes expressed similarities considering the observation of the spectral profiles obtained through Pearson's coefficient of determination, which in two months of study led to values that confirmed that similarity. Most of the indices presented quite positive correlations in both periods, which means that their values presented a direct proportion rate, growing at a closely similar rate. The NDVI and SAVI indices presented the highest correlation coefficient with r = 0.971 in the rainy season and reached r = 1 in the dry season, rated as perfect, considering the equivalence of both indices.

The EVI showed a strong correlation with the NDVI and SAVI in the dry month – r = 0.973 –, as can be seen in Table 6, also with the three indices – NDVI, SAVI, and CO_2Flux – in the rainy month – r = 0.925, r= 0.838 and r = 0.915, respectively – as in Table 5. In this follow-up, the results indicated that the correlation of the CO_2Flux with other indices in the dry period achieved lower values, with r = 0.753 when related to the NDVI and SAVI, and r = 0.786 when related to the EVI, a strong correlation. In the humid period, it achieved again higher values for the coefficient (a little strong), being r = 0.915 for NDVI, r = 0.880 for SAVI, and r = 0.906 for EVI.

These results confirm Silva Junior *et al*. (2021) outcome, who obtained a quite strong Pearson's coefficient – 0.93 – when correlating both NDVI and EVI in the dry season using the Sentinel-2 MSI sensor. Those results also resemble Espig, Soares, and Santos's (2006), and Nery, Moreira, and Fernandes's (2014), who observed that the values of the EVI and NDVI indices behave similarly, showing a positive correlation.

In general, there were connections in comparing the indices in dry and rainy seasons. However, the EVI showed less saturation in areas of higher vegetative density in both periods, an inherent characteristic of this VI. The saturation of higher biomass values is one of the negative points of the NDVI, according to Meneses, Almeida, and Baptista (2019).

Also according to Meneses, Almeida, and Baptista (2019, p. 213), the EVI has higher sensitivity "[...] to variations in vegetation structure, that is, it has a high correlation with reflectance values in the NIR range", and it may present a better distinction of targets, as Silva Junior *et al*. (2021) point out. This factor may justify why the correlation between EVI and NDVI and SAVI showed lower values than the correlation between NDVI and SAVI, for example.

By observing Tables 5 and 6, is worth highlighting that the correlation between the EVI and the other indices in the rainy season is lower than in the dry season, possibly indicating a connection with the saturation shown in the other indices during this period in regions with higher vegetation density.

Based on the NDVI and EVI, Espig, Soares, and Santos (2006) and Nery, Moreira, and Fernandes (2014) highlighted a possible saturation in areas of dense vegetation compared to the NDVI values, explaining higher reflectance values compared to those shown by the EVI. Most of the values close to 1, fairly distributed in the study area, don't represent with accuracy the Caatinga physiognomies characteristics. As discussed, different spectral responses indicated different Caatinga typologies like arboreal physiognomies represented by higher VI intervals close to 1, and regions with creeping or sparse physiognomies – between 0.50 and 0.75. This relationship of different physiognomics in an environment with different spectral responses is represented in the EVI (Figure 3c).

4. Final considerations

The scenes processed in the four indices – NDVI, SAVI, EVI, and CO_2FLUX – allowed us to observe the distribution of different class intervals of vegetation coverage and carbon sequestration and characterize these factors in the region studied. Based on the spatial variability of the VI values in both periods (rainy and dry), the information on vegetation coverage showed spectral behavior variations in different areas, considering edaphoclimatic factors (such as precipitation and altitude) and vegetation coverage (phytophysiognomies, deciduousness, semi-deciduousness, evergreen, senescence, etc). The values related to the VIs were linked to water availability in soil, therefore, rainy period scenes showed greater homogeneity, but visually conceal areas with lower values characterized by soil exposure and degradation, possibly visualized in the eastern of the dry period images.

Among the VI, the EVI narrowed the vegetation biomass data compatibly with local circumstances, not saturating values like in the NDVI and SAVI, which means more sensitiveness to vegetation, soil, and atmosphere characteristics. However, all indices used for the study – NDVI, SAVI, and EVI – are important tools for managing and characterizing land coverage since there is a similar relationship, as shown through Pearson's coefficients.

The analysis of carbon sequestration (CO_2FLUX) allowed mapping areas with low sequestration levels, consequently, high levels of CO_2 in the lower atmosphere in the dry period, in contrast to the rainy season. With the invigorated plant biomass and high photosynthesis, atmospheric carbon sequestration became more efficient, reducing CO_2 levels in the lower atmosphere.

Mapping the spatial configuration of vegetation coverage in both periods is an essential scientific and environmental contribution as this data facilitates the preservation of native resources of the Caatinga remnants in the municipality of Central in Bahia. This mapping can assist the local government in planning environmental policies to stimulate decision-making processes by social actors, as well as to raise the population's awareness about the conservation need of natural resources.

To continue and refine the research in future studies is considered a deeper and longer investigation to pave the way to field investigations by using other reliable indices, new satellite images, and different sensors to acquire better resolution images, both spatial and temporal, also considering the use of Unmanned Aerial Vehicles (UAV) or other means of capturing images to obtain a vegetation coverage classification with a more accurate characterization.

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