Ecological Indicators 117 (2020) 106579

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

# Analysis of areas undergoing desertification, using EVI2 multi-temporal data based on MODIS imagery as indicator

F.G.S. Bezerra[a,*], A.P.D. Aguiar[a], R.C.S. Alvalá[b], A. Giarolla[a], K.R.A. Bezerra[a], P.V.P.S. Lima[c], F.R. do Nascimento[d], E. Arai[e]

[a] *National Institute for Space Research – INPE, Earth System Science Center – CCST, Avenida dos Astronautas, 1758, Jardim da Granja, 12227-010 São José dos Campos, SP, Brazil*

[b] *National Center for Monitoring and Early Warning of Natural Disasters – CEMADEN, Rodovia Presidente Dutra, Km 40, 12630-000 Cachoeira Paulista, SP, Brazil*

[c] *Federal University of Ceará – UFC, Center for Agricultural Science – CCA, Av. Mister Hull, 2977 – Campus do Pici, Bloco 826, 60440-970 Fortaleza, CE, Brazil*

[d] *Federal University of Ceará – UFC, Science Center – Campus do Pici, 60440-900 Fortaleza, CE, Brazil*

[e] *National Institute for Space Research – INPE, Remote Sensing Division – DSR, Avenida dos Astronautas, 1758, Jardim da Granja, 12227-010 São José dos Campos, SP, Brazil*

ARTICLE INFO

*Keywords:*
Desertification
Land degradation
Monitoring of desertification
Semiarid
Trajectory
Vegetation index

ABSTRACT

Desertification is a global problem that impacts a significative part of the Earth's surface, which cause a large environmental and social losses in several regions of the world. The Brazilian semiarid region, located mainly in the northeast part of the country, includes areas of moderate to very high susceptibility to desertification. In order to contribute to a comprehension of the dimensions of desertification in the Brazilian semiarid region, this paper aimed to develop a potential indicator for the evaluation and monitoring of this area, considering an appropriate temporal and spatial scales. For this objective, satellite data were used for the identification and monitoring of sub-areas potentially undergoing degradation/desertification. Thus multitemporal series of Enhanced Vegetation Index 2 (EVI2) covering the period between 2000 and 2016 was used, which were calculated from data provided by the MODIS sensor carried aboard the Terra satellite. Besides, previous samples were selected for the calibration and validation of the methodology. The results show an increase of areas potentially undergoing degradation/desertification, covering an area equal to 167,814.24 $km^2$ at the end of the period analyzed (around 16.7% of the study area). Approximately 23.63% of the total degraded area comprises both the Very High Degradation Trajectory and High Degradation Trajectory. The proposed methodology contributed to the determination of the degree of the degradation through the determination of Degradation Trajectories, which differentiates it from the ones proposed in other studies; however, it is emphasized that this approach must be analyzed in association with additional information, such as trends and climatic scenarios of land use and land cover, as well as retrospective analyses of the landscape, soil erosion, field recognition, socioeconomic conditions, among others.

## 1. Introduction

Desertification, a process known as land degradation in arid, semi-arid and dry sub-humid areas, resulting from various factors, including climatic variations and human activities (UN, 1994, p. 4; United Nations - UN, 1992, paragraph 12.2), is a global problem that impacts 20–25% of the earth's surface (Grainger, 2013; Lambin et al., 2002; Ramankutty et al., 2006; Reynolds et al., 2007; Sietz et al., 2011). The term "land degradation" includes the degradation of soil, water resources, vegetation and biodiversity, which significantly reduces the quality of life of populations affected by this process (Bakr et al., 2012). Thus, studies related to environmental issues have focused on this process, as it constitutes one of the major obstacles to the development of dry regions of the planet (Adeel et al., 2007; Brasil, 2004; Cavalcanti et al., 2006; Cornet, 2002; Rêgo, 2012). This is partly due to the impacts generated by human activities to meet the basic needs of local populations in different regions susceptible to desertification, which ultimately acts as facilitators of the degradation process due to direct exploitation or overuse of natural resources (Zhou et al., 2015).

Desertification is an environmental and social risk, being considered by de Nascimento (2015) one of the biggest environmental problems of contemporary times Annually, there is an estimated loss of 5,300

* Corresponding author.
*E-mail address:* francisco.gilney@inpe.br (F.G.S. Bezerra).

https://doi.org/10.1016/j.ecolind.2020.106579
Received 17 September 2019; Received in revised form 6 May 2020; Accepted 26 May 2020
1470-160X/ 

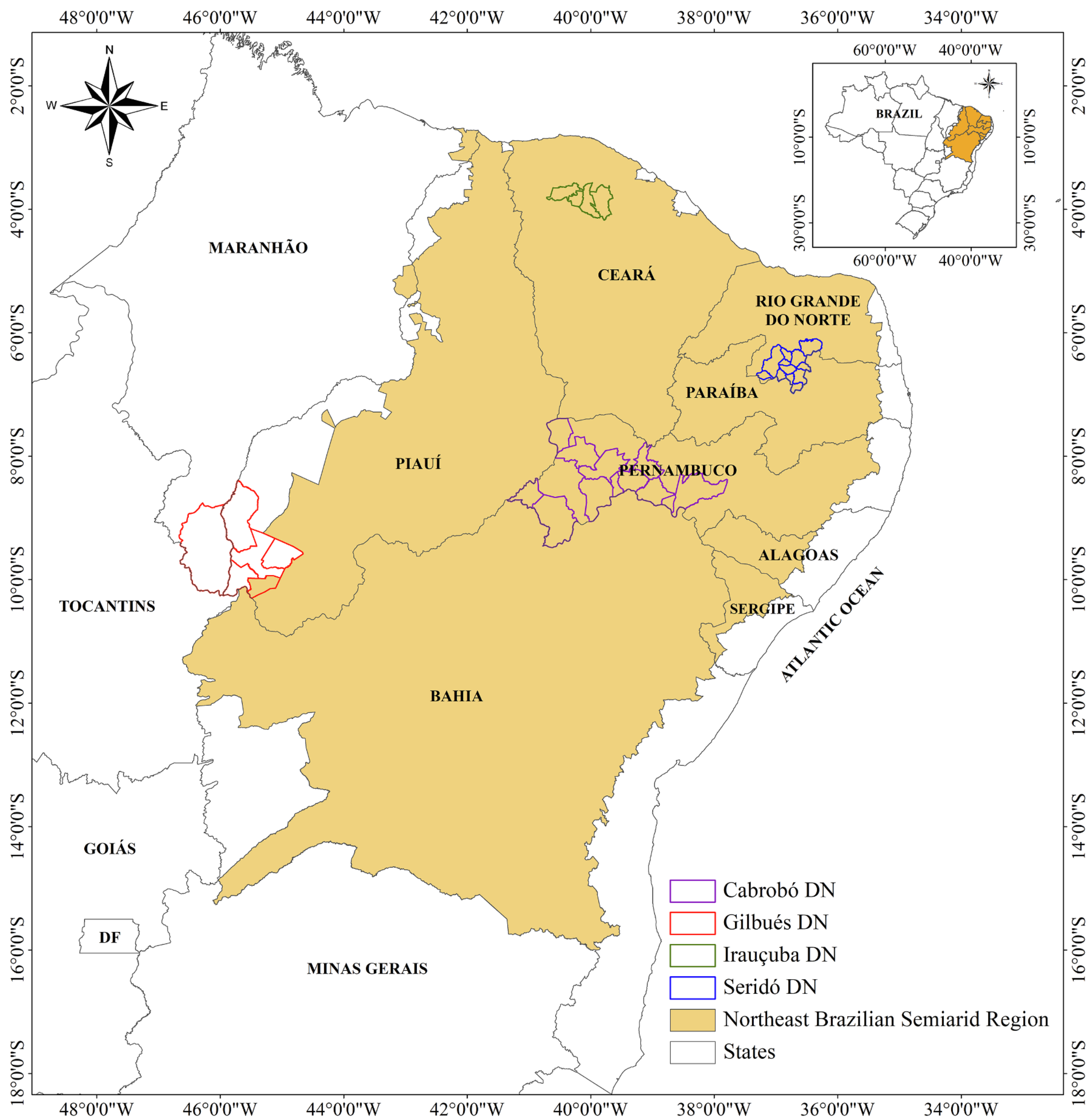


**Fig. 1.** Study area – Northeast Brazilian Semiarid Region (NBSR) and Desertification Nuclei.

million tons of fertile soil and 8 million tons of plant nutrients worldwide due to different desertification processes (Dharumarajan et al., 2018). According to data released by the United National Convention to Combat Desertification - UNCCD, about 2.1 billion people (40% of the world's population) live in dry regions. Of this total, 90% live in developing countries that are most vulnerable to climate variability, water availability and climate change (D'Odorico et al., 2013; Krol et al., 2006). Approximately 20% of Brazilian territory has degraded areas (UNEP, 2010, p. 72), the Northeast is the region that presents the greatest environmental problems of land degradation and desertification, with a total of 1,143,491 km$^2$ of susceptible areas desertification (ASD). Approximately 26 million people live in the Northeast Brazilian Semiarid Region (NBSR), which is equivalent to 46% of the population of the Northeast and 13% of the national population (IBGE, 2018), making it one of the most populous dry regions in the world (Ab'Saber, 1985; Marengo, 2008; Rêgo, 2012).

On the other hand, previous studies on desertification processes in the Northeast Brazilian Semiarid Region focused mainly on areas known as Desertification Nuclei (DN), identified in the studies by Vasconcelos Sobrinho (1982) and classified as at high risk of desertification. These nuclei are Gilbués (PI), Irauçuba (CE), Seridó (RN) and Cabrobó (PE) (BRASIL, 2004), as shown in Fig. 1. As already highlighted by Lin et al. (2009), it is necessary to reassess the spatial distribution of areas at risk of desertification. In addition, considering that the processes that contribute to desertification are dynamic, it is essential to use monitoring techniques to identify changes quickly, practically and efficiently (Gül and Erşahin, 2019; Helldén and Tottrup, 2008).

Remote sensing data is an affordable and cost-effective alternative source compared to traditional field survey techniques that demand more time, are cost and labor-intensive, making systematic monitoring on a larger scale more costly and difficult to implement (Chen et al., 2013; Higginbottom and Symeonakis, 2014).

The use of multitemporal vegetation index (VI) series records from remote sensing data has contributes and presentes itself as an important tool for land surface monitoring and characterization (Javzandulam et al., 2005; Jiang et al., 2008; Lambin and Linderman, 2006), in particular with different types of land cover and land use (Moreira, 2005;

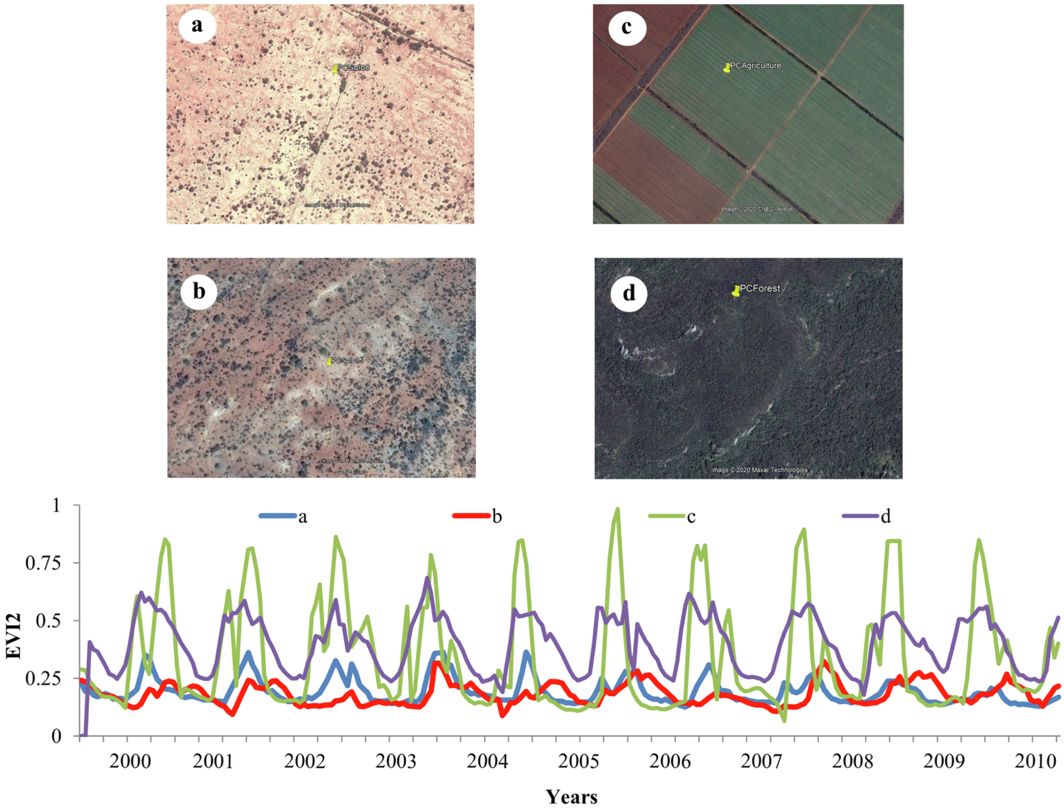


**Fig. 2.** Examples of samples which present a certain degree of degradation and the time series the EVI2 for a sample point: a) Xique-Xique (7°28′59.51″S, 36°35′24.94″O, Datum WGS84) – Bahia state and b) Serra Branca (10°51′35.76″S, 42°33′16.11″O, Datum WGS84) – Paraíba state; Examples of sample areas from: Agriculture (c) Quixeré (5°10′26.43″S, 37°53′55.64″O, datum WGS84) – Ceará state and Native Vegetation (d) Serra Talhada (8° 15′35.02″S, 38°10′47.62″ O, Datum WGS84) – Pernambuco state.

Silva, 2013). Vegetation indices result from the mathematical combinations of different spectral bands which are almost always from the visible and near-infrared regions of the electromagnetic spectrum (Viña et al., 2011). Several studies have been conducted to identify, evaluate and monitor desertification in arid and semiarid lands, considering vegetation index (Albalawi and Kumar, 2013; Barbosa et al., 2013; Chen et al., 2013; Diouf and Lambin, 2001; Erasmi et al., 2006; García-Gómez and Maestre, 2011; Lanfredi et al., 2003; Lin et al., 2009; Lin and Chen, 2010; Olsson et al., 2005; Paruelo et al., 2005; Piao et al., 2005; Sternberg et al., 2011; Symeonakis and Drake, 2004; Tomasella et al., 2018; Zhang et al., 2008). Particularly for Latin America, vegetation index has been considered an important indicator for desertification assessment and monitoring, mainly from the discussions established during the project to develop a unified methodology for desertification assessment and monitoring in Latin America in the 1990s (Matallo Junior, 2001; Santibañez and Pérez, 1998) and reaffirmed during the 13th Conference of the Parties (COP13) of the United Nations Convention to Combat Desertification (UNCCD) in Ordos, China (UN, 2017, p. 9). Despite the relevance of using vegetation index for studies of regions characterized by desertification processes, there are few studies considering the evaluation of the Northeast Brazilian region.

In this context, the objective of this work was to develop a potential indicator for the evaluation and monitoring of desertification in large surface areas, in appropriate temporal and spatial scales, considering satellite data, for the identification and monitoring of areas potentially undergoing degradation/desertification (AUD).

## 2. Materials and methods

### *2.1. Study area*

The study area corresponds to the Northeast Brazilian Semiarid Region (Fig. 1), whose official delimitation was based on three criteria: a) average annual rainfall of 800 mm or less; b) aridity index (Thornthwaite, 1941) up to 0.5 and c) daily percentage of water deficit equal to or greater than 60% (BRASIL, 2017a, 2017b). The Northeast Brazilian Semiarid Region has an area of 1,007,120 km$^2$ and is made up of significant parts of the states of Bahia, Sergipe, Alagoas, Pernambuco, Paraiba, Rio Grande do Norte, Ceará, Piaui, and Maranhão. Most of the region is covered by the Caatinga biome, the only biome exclusively Brazilian due to its endemic biodiversity. The region also includes portions of the Cerrado and Atlantic Forest biomes, thus being the most diverse in terms of biomes in all of Brazil.

The dry and warm climate of the region is characterized by the high spatial and temporal variability of the precipitation regime, directly related to the interannual sea surface temperature (TSM) variability of the tropical oceans, especially the Tropical Atlantic and Equatorial Pacific oceans. The region is also marked by the recurrence of droughts (Marengo et al., 2011), leading to social problems such as economic loss, famine, migration and family disintegration, etc. In addition, climate change studies project temperature increases, rainfall reductions and a tendency for longer periods with consecutive dry days, which would lead to more frequent/intense droughts and a tendency to aridification in the region (Marengo, 2008; Marengo et al., 2017a,b). Thus, the combined effects of biophysical and socioeconomic conditions make the Brazilian semiarid region a *hotspot* of vulnerability to both

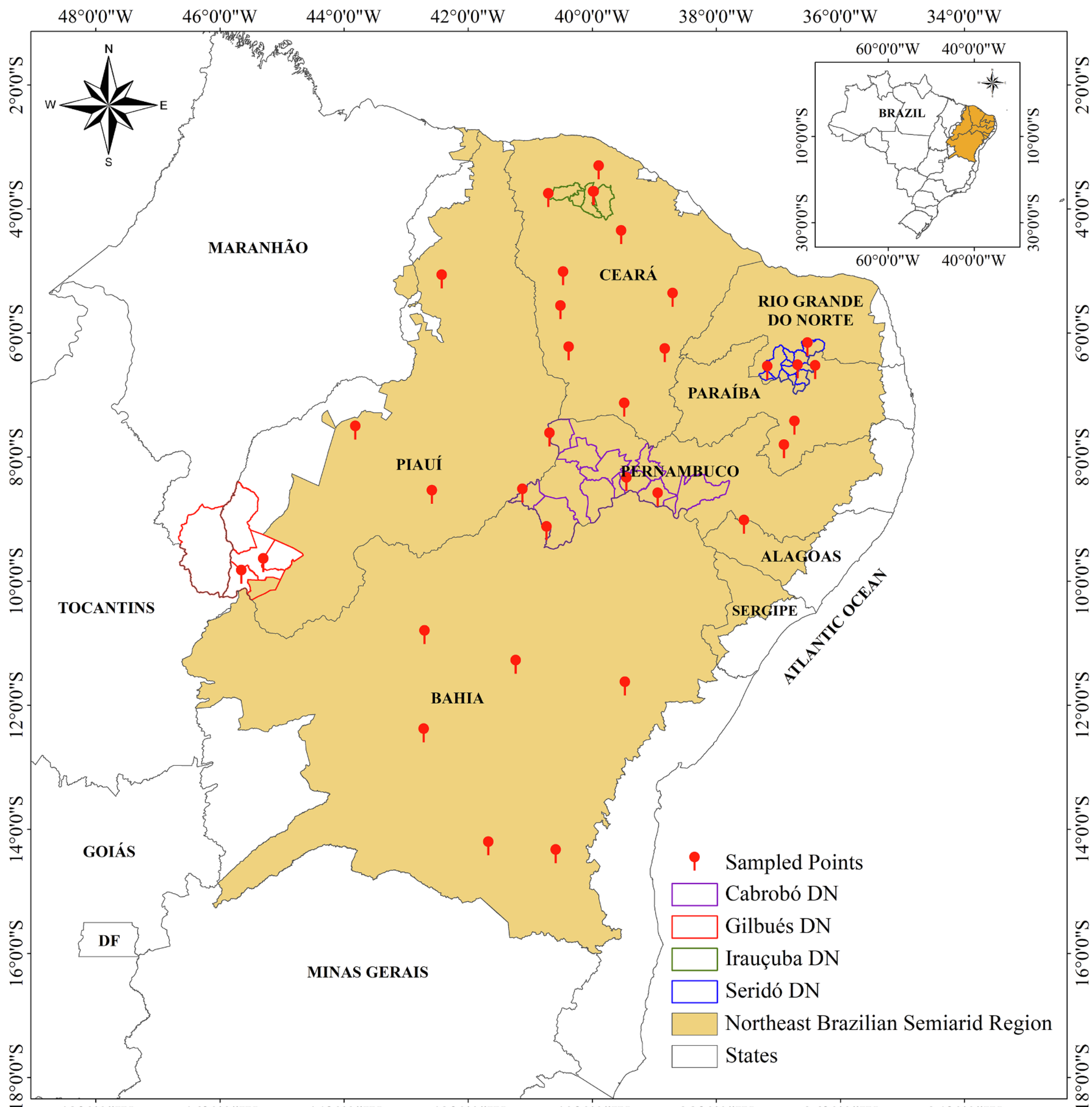


**Fig. 3.** Location of the sample points (elements).

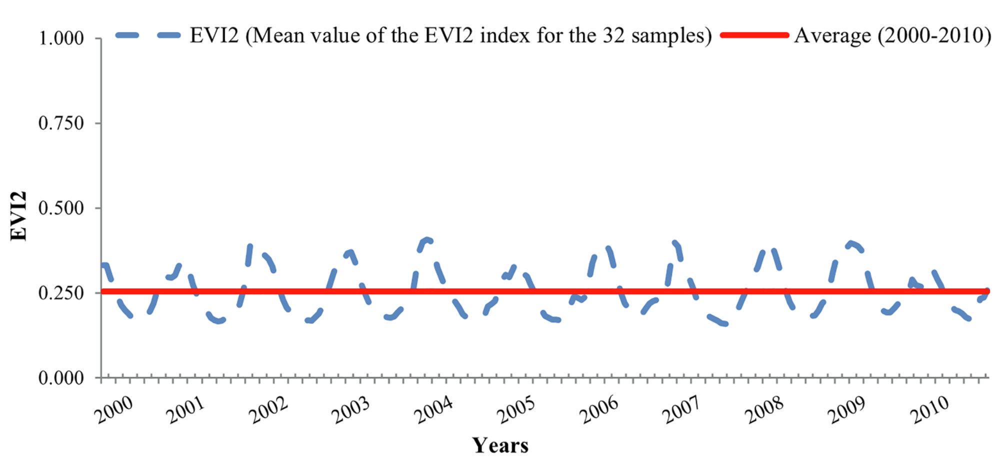


**Fig. 4.** Value of the EVI2 index for the 32 samples.

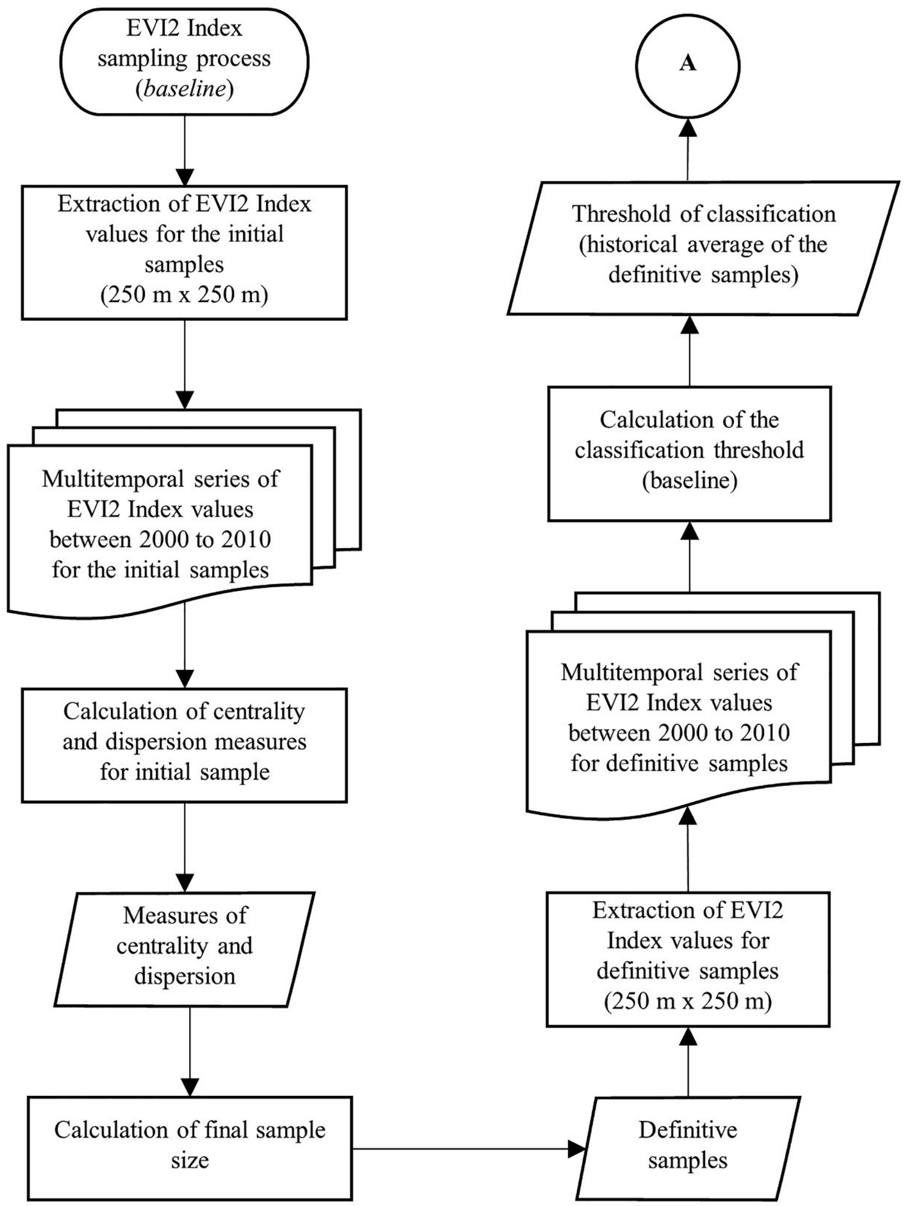


**Fig. 5.** Flow diagram for the identification of the classification threshold (*baseline*).

climate change and desertification.

### *2.2. Change Analysis.*

The proposed method used compositions of multitemporal images of vegetation index EVI2 (Enhanced Vegetation Index 2) calculated using data from the MODIS instrument carried aboard the Terra spacecraft and aimed to characterize the behavior of this index in areas potentially undergoing degradation/desertification. In general, these areas showed (i) heavily degraded or an absence of vegetation cover, (ii) low vegetation response to precipitation, (iii) signs of soil erosion and (iv) absence of productive activities (e.g. agriculture). Although the NDVI (Normalized Difference Vegetation Index) is generally used more frequently in works with this theme (Yengoh et al., 2015), we chose to use EVI2. The EVI2 presents adjustment in the signal/noise that minimize the influences of the soil and the sensitivity and linearity of the vegetation, thus avoiding the saturation found in the EVI and other vegetation indices, in addition to minimizing atmospheric distortions, since the band blue is not used. EVI2 can still reveal the dynamics of different types of vegetation, especially when reflectance values in the red band are low, and NDVI becomes saturated (Jiang et al., 2008).

#### *2.2.1. EVI2 overview*

The EVI2 (Enhanced Vegetation Index 2) index, developed by Jiang et al. (2008), highlights the variation in land cover (Freitas, 2011) and is based on the use of vegetation data from the sensor platforms of the Moderate Resolution Imaging Spectroradiometers (MODIS) aboard Terra and Aqua satellites. For the calculation of EVI2 only the surface reflectance of the *Red* and *NIR* (near-infrared) spectral bands were used, according to the following equation:

$$EVI2 = 2.5\frac{NIR - Red}{(NIR + 2.4Red + 1)} \quad (1)$$

In the current study the MOD13Q1 product from the MODIS/TERRA sensor collection 5 was used, since its temporal and spatial resolutions were considered sufficient for our purpose. This product is composed of globally registered imagery during a 16 day period, with a spatial resolution of 250 m.

### 2.2.2. EVI2 processing

*Step 1* – Sampling process and extraction of classification thresholds (*baseline*)

The objective of this step was to determine a classification threshold to be used as a *baseline* in the identification of areas with degraded vegetation cover, that is, with some disturbance in their natural behavior and, thus, to enable the monitoring of these areas. Therefore, it was decided to extract samples (250 m × 250 m) in areas that presented evidence of degradation/desertification. Fig. 2 presents examples of areas sampled with evidence of degradation/desertification (a and b), compared to the areas of Agriculture (c) and Native Vegetation (d). The initial sample consisted of seven sample points, for which a multi-temporal series of EVI2 was obtained from 2000 to 2010. This period was chosen due to the availability of the data, as well as for presenting neutral conditions in relation to the possible impacts of the El Niño and La Niña phenomena.

The time series for each sample consisted of 250 EVI2 values, acquired for the months from January to December every 16 days for 11 years. These samples were obtained from an online time series visualization tool applied to the analysis of land use and changes in coverage provided by the Remote Sensing Laboratory Applied to Agriculture and Forest (LAF) of the National Institute for Space Research (INPE), available at https://www.dsr.inpe.br/laf/series/index.php (Freitas, 2011).

From this initial sampling, it was possible to estimate the size of the definitive sample, calculated by the expression:

$$n = \left(\frac{t_{n_0-1,\alpha/2} \cdot s}{e}\right)^2 \quad (2)$$

where $\boldsymbol{n}$ is the size of the sample to be determined; $t_{\alpha/2}$ corresponds to the critical $\boldsymbol{t}$ value for the given significance level $\boldsymbol{\alpha}$ (5%) and $\boldsymbol{n_0}$**-1** degrees of freedom; $\boldsymbol{e}$ (0.094) is the error of the estimation of the population mean, based on the sample of size $\boldsymbol{n_0}$ (7); and $\boldsymbol{s}$ is the standard deviation of the pilot sample. After computing the final sample size, $\boldsymbol{n_0}$ was added to $\boldsymbol{n}$, totaling 32 sample points, which are distributed as shown in Fig. 3. The distribution of the sample points followed the same criteria as the initial sample, that is, areas with evidence of degradation/desertification reported in the literature and empirical knowledge were considered.

After analyzing the metrics to determine the threshold for the areas potentially undergoing degradation/desertification classification (for example the difference between the maximum and the minimum observed annual EVI2 value; analysis of the dry season EVI2 values, among others), we decided to use the historical average of EVI2 as detailed in section *Step 2*. The historical average was adopted after verifying that there was no significant difference (p-value < 0.50) between the analyzed averages, in addition to the EVI2 values, in the analyzed areas, they remain near the average value found. The estimated threshold was then calculated from the mean EVI2 values for the 32 sample points (Fig. 4). The threshold for detecting areas potentially

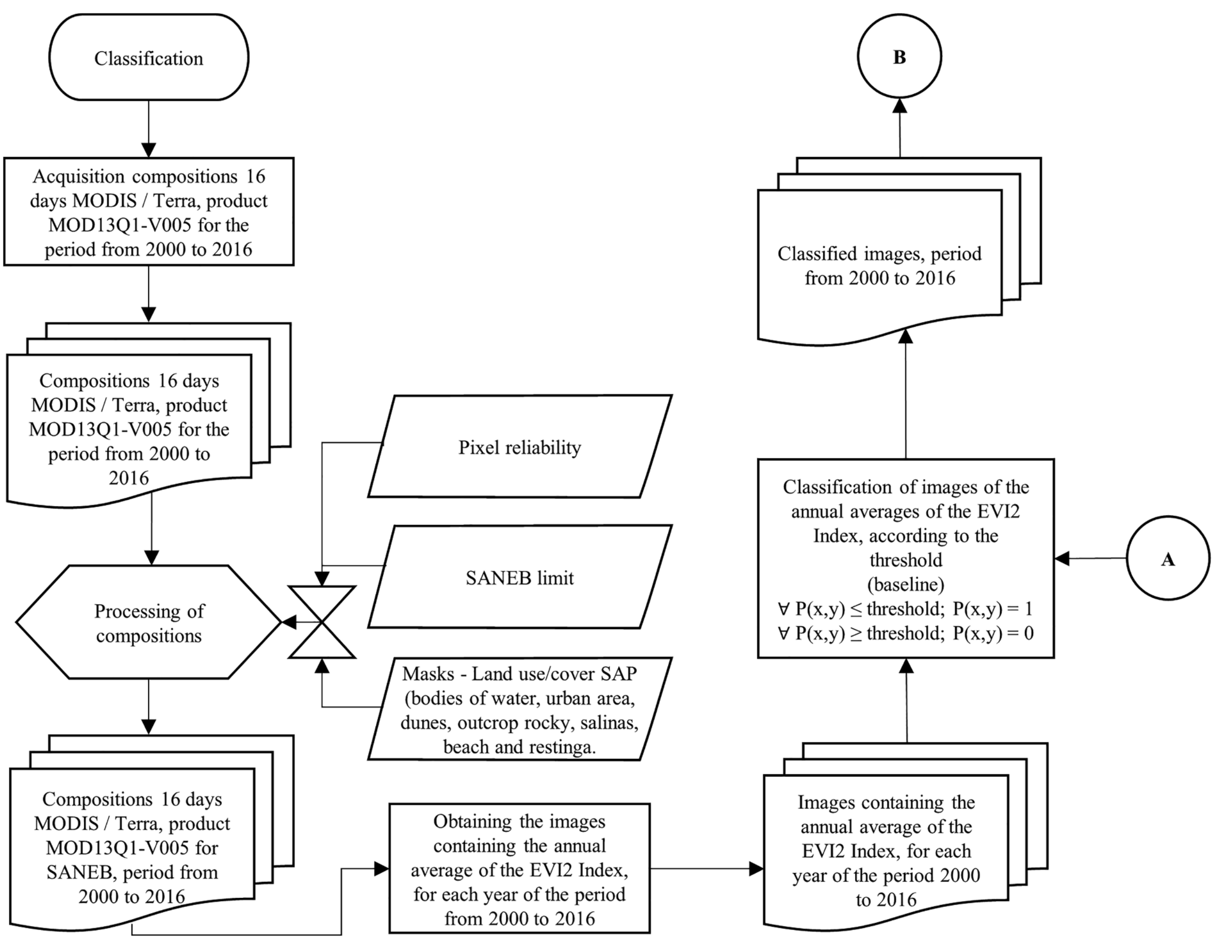


**Fig. 6.** Flow diagram for the identification of areas potentially undergoing degradation/desertification (AUD) and areas not potentially undergoing degradation/desertification (NAUD).

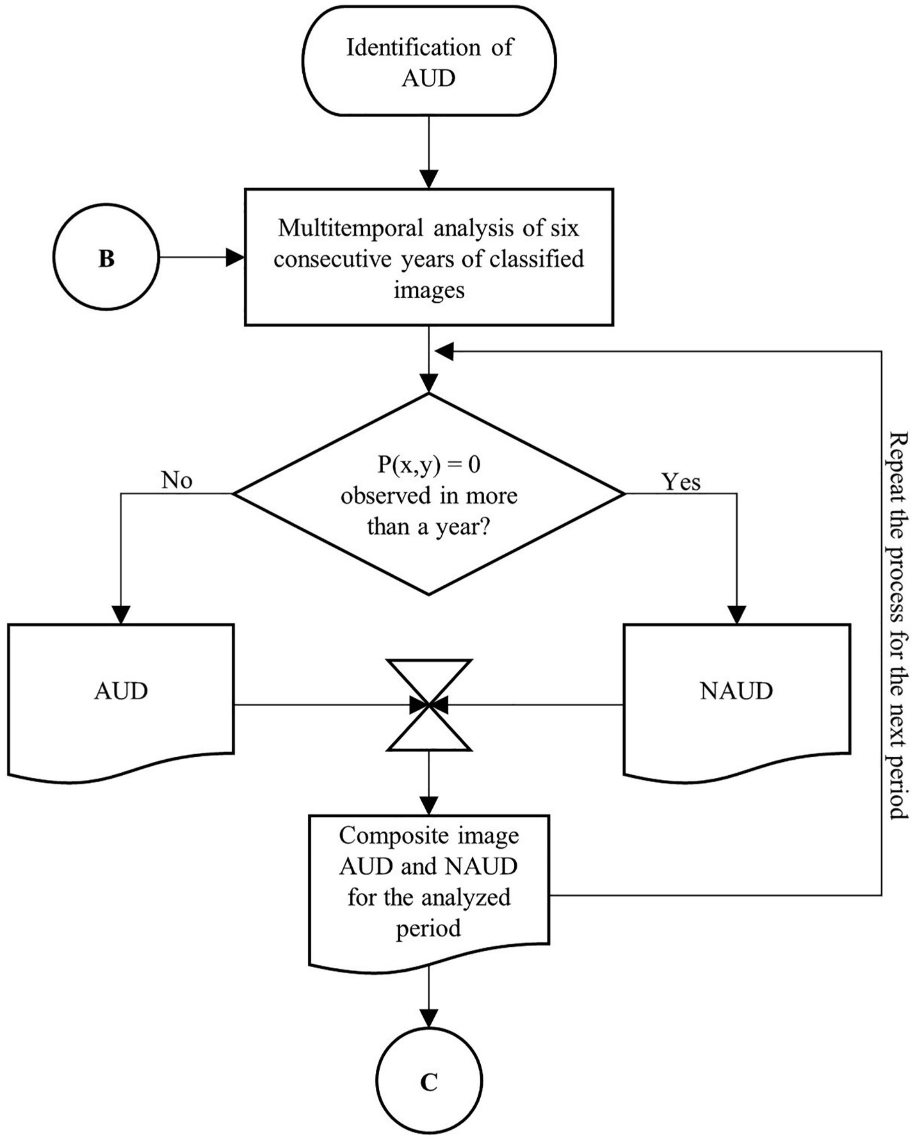


**Fig. 6.** (*continued*)

undergoing degradation/desertification in the Northeast Brazilian Semiarid Region was estimated at EVI2 = 0.254. Areas with a value below or equal to the threshold were classified as areas potentially undergoing degradation/desertification. Fig. 5 summarizes the flowchart of the classification threshold determination process.

*Step 2* – Classification

After calculating the threshold (*baseline*), the images from 2000 to 2016 were processed to identify areas potentially undergoing degradation/desertification. In order to obtain information for the whole area of interest, four tiles (h13v9, h13v10, h14v9 and h14v10) were considered for each date. The data was extracted from the site http://reverb.echo.nasa.gov/reverb. Initially, the image compositions were converted from the original HDF (Hierarchical Data Format) format, sinusoidal projection (Datum WGS84), to GeoTIFF format and geographic coordinate system, keeping the same datum, as recommended by Freitas (2011).

Fig. 6 shows the flow of the areas potentially undergoing degradation/desertification identification procedure. First, to remove from the analysis any information that brings noise and compromises the reliability of the result, masks were created containing spatially distributed information from: a) water, b) urban areas, c) dunes, d) rocky outcrops, e) salt flats, f) beach and e) sandbanks. This information originates from the land use and land cover classification provided by the Early Warning System (SAP, 2015). Furthermore, the Reliability images of the MOD13Q1 product (250 m) were considered to classify the good pixels. After this process, the images were extracted with annual average values for each year from 2000 to 2016. Following the calculation of the annual average values, the images were classified based on the threshold (*baseline*), where the pixels had a value less than or equal to the threshold were classified as areas with some disturbance in their natural behavior. The next step was the multitemporal analysis of six consecutive years of classified images (2000 to 2005, 2001 to 2006, …, 2011 to 2016), which resulted in 12 periods for analysis. The use of a period of six consecutive years aimed to remove from the analysis the effect of interannual variation of change and fallow land (since studies indicated that from the fifth year of fallow land in this region, it favors the restoration of soil quality under Caatinga. (Nunes et al., 2009).

The analysis by period verified the number of years that the value of EVI2 remained below or equal to the threshold (0.254) and then the areas potentially undergoing degradation/desertification were

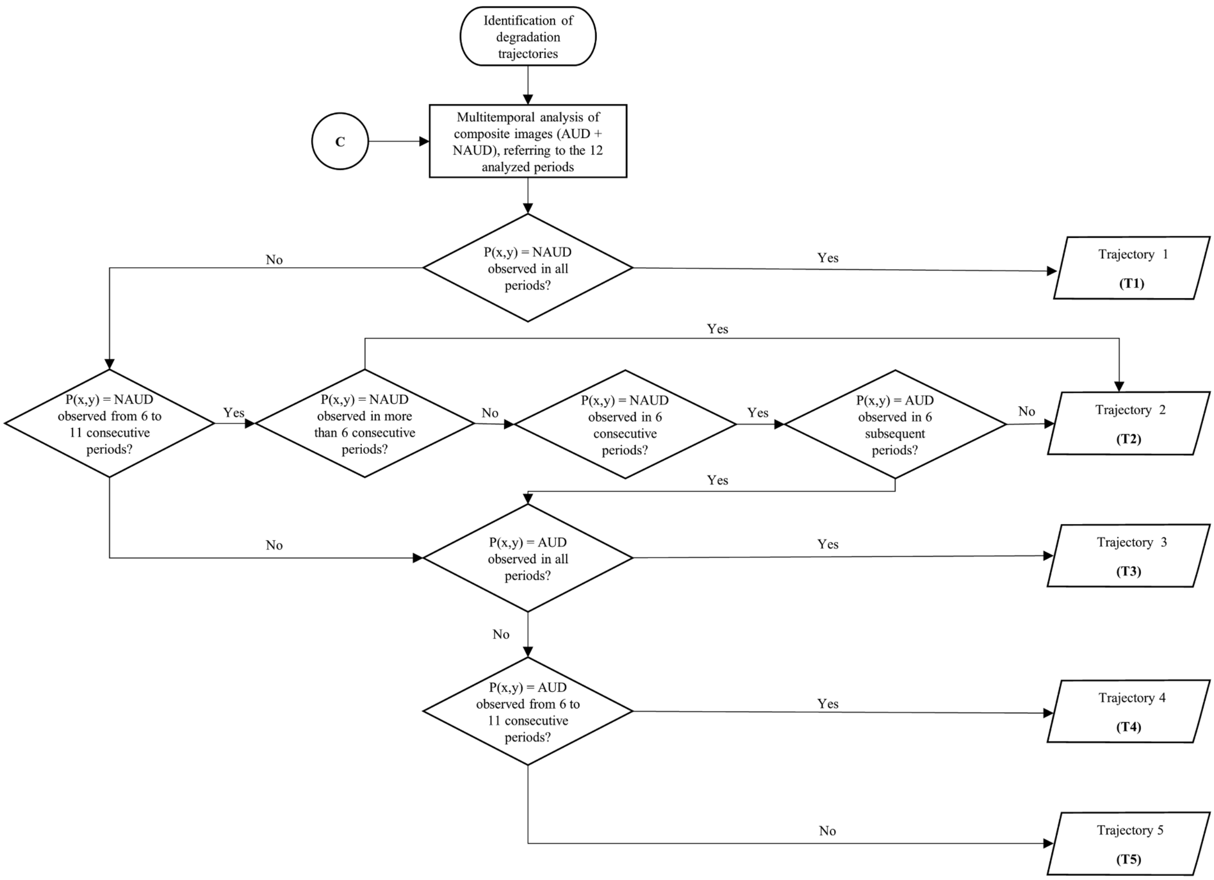


**Fig. 7.** Flow diagram for the identification of degradation trajectories for the Northeast Brazililan Semiarid Region.

identified.

### 2.3. Identification of degradation trajectories

In addition to the identification of areas potentially undergoing degradation/desertification, the degradation trajectories for the period 2000 to 2016 were analyzed with the specific objective of understanding the processes associated with degradation in the region. For the definition of the degradation trajectories, the multitemporal analysis of the composite images (AUD + NAUD), referring to the 12 analyzed periods was performed. For this step, we considered: (i) number of periods in which the pixel was classified as areas potentially undergoing degradation/desertification, ie, when the disturbance was observed in is natural condition, (ii) the order of occurrence of these disturbances, whether randomly or sequentially and (iii) persistence of the disturbances. Fig. 7 summarizes the flowchart of trajectory identification.

## 3. Results

This section presents the results on maps of the areas potentially undergoing degradation/desertification, from 2000 to 2016. Section 3.1 presents the identification of areas potentially undergoing degradation/desertification areas. Section 3.2 presents an analysis of changes in the areas identified between 2000 and 2016, while section 3.3 discusses the results associated with the Degradation Trajectories.

### 3.1. Identification of areas potentially undergoing degradation/desertification from 2000 to 2016

Fig. 8 illustrates the spatial distribution of areas potentially undergoing degradation/desertification (AUD) during the years 2000 to 2016. The results are presented in 12 clusters of six years. Most of the areas are located in the central region of the study area, characterized by tropical-arid or semiarid-tropical climates, where the Caatinga biome predominates.

### 3.2. Changes in the degradation/desertification patterns considering the period 2000 and 2016

In Period 1 (2000–2005), approximately 6.1% (60,976.29 km$^2$) of the study area was classified as an area potentially undergoing degradation/desertification. From Period 7 (2006–2011), there was the beginning of an increase in these areas. However, only during Period 10 (2009–2014), did the identified percentage have a significant increase. Between 2000 and 2016 there was an increase of 175% (106,846.80 km$^2$) of areas potentially undergoing degradation/desertification, totaling 167,814.24 km$^2$ (an area corresponding to 16.7% of the study area – Fig. 9).

Fig. 10 shows the areas potentially undergoing degradation/desertification transitions between 2000 and 2016, from which three situations can be observed: a) areas that in Period 1 were classified as areas not potentially undergoing degradation/desertification, being later considered areas potentially undergoing degradation/desertification (NAUD - AUD); b) areas that remained as areas potentially undergoing degradation/desertification during the analyzed periods (AUD

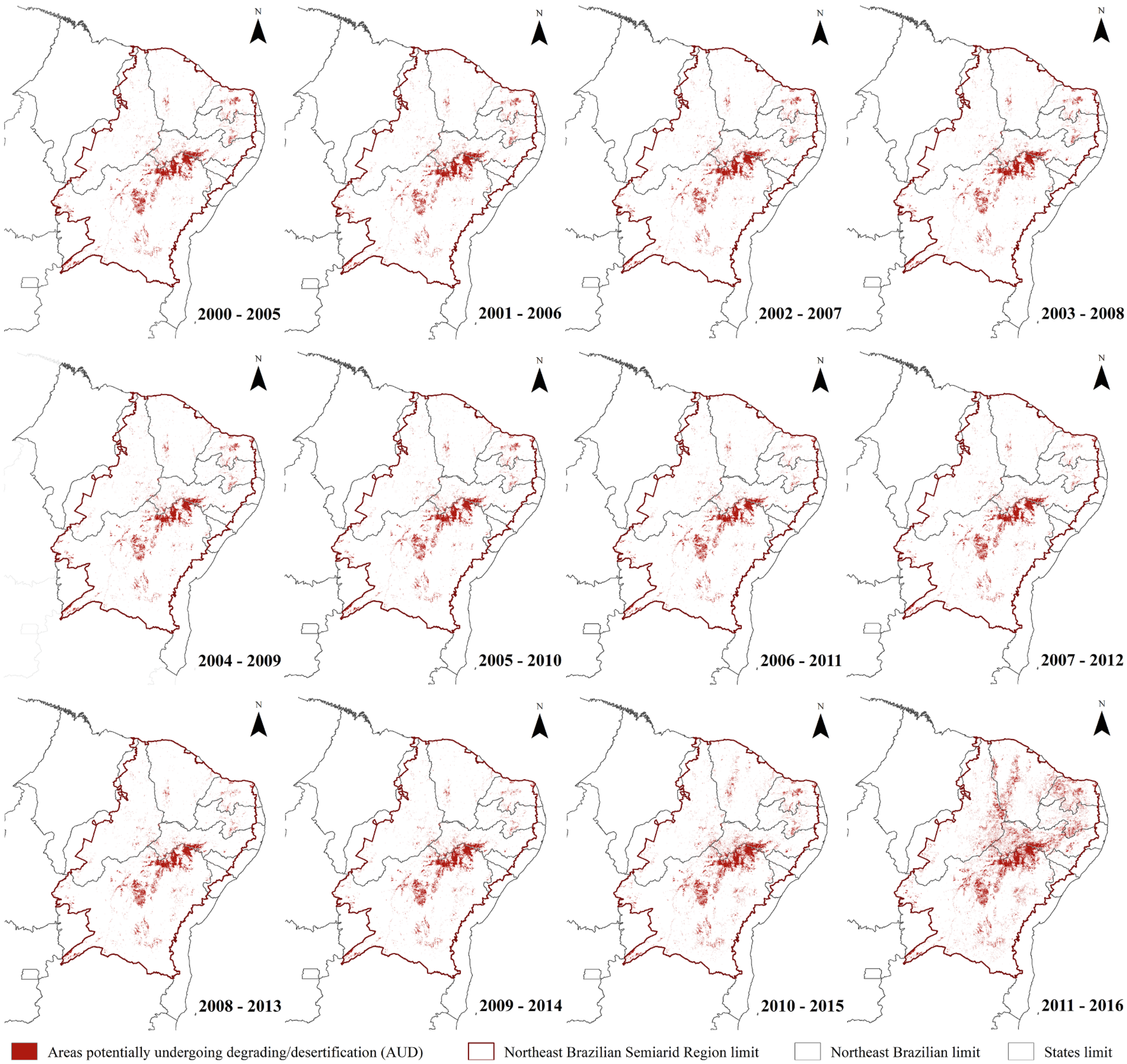


**Fig. 8.** Areas potentially undergoing degradation/desertification in the Northeast Brazilian Semiarid Region between 2000 and 2016, according to the analyzed period.

- AUD); and c) areas that migrated from areas potentially undergoing degradation/desertification to areas not potentially undergoing degradation/desertification (AUD - NAUD).

As shown in Fig. 10, approximately 5.1%, on average, of the northeastern semiarid areas, considered as areas potentially undergoing degradation/desertification, maintained this condition throughout the analyzed period (2000–2016). This result indicates that these areas have been under degradation processes for a long period. However, for the last analyzed period, it was observed n increase in the areas that remained and/or were considered as potentially degraded /desertifying areas. The increase in AUD-AUD was mainly associated with the increase in NAUD-AUD observed in the previous period (P10-P11). In these areas, there is the predominance of non-arboreal natural vegetation, especially transformed to grazing (natural pastures). On the other hand, to a lesser extent, approximately 0.5% on average of areas previously considered as areas potentially undergoing degradation/desertification did not maintain the same condition.

Table 1 shows the distribution of the percentage change in transitions, in relation to the semiarid area of each state. The results show an increase in areas potentially undergoing degradation/desertification in the NBSR during the period from 2000 to 2016, with marked intra-regional variations. The state of Bahia presented a greater extension of areas that remained as AUD in the analyzed period (32,014.77 km$^2$), followed by Pernambuco (8,596.39 km$^2$) and Rio Grande do Norte (50,98.78 km$^2$). In terms of the semiarid area of each state, Rio Grande do Norte, is the most affected, since approximately 10.39% of its area (5,098.78 km$^2$) has remained under intense degradation process (Table 1).

The increase of the areas potentially characterized by degradation/desertification was observed mainly in the states of Pernambuco (23,942.45 km$^2$), Rio Grande do Norte (11,521.91 km$^2$) and Paraíba (10,045.15 km$^2$). In the last period analyzed, all of these states presented approximately 34.05, 32.17 and 24.59% of the total area of the state as areas potentially undergoing degradation/desertification, if we consider the semiarid area of the states, 38.68, 34.62 and 27.07%, respectively.

The results also show the increase of areas potentially undergoing degradation/desertification in the desertification nuclei of Cabrobó (Pernambuco), Irauçuba (Ceará) and Seridó (Paraíba and Rio Grande do Norte) (Fig. 11). In addition to these three nuclei officially recognized by the Ministry of the Environment, as previously presented, the National Institute of Semiarid - INSA considers that two other areas can

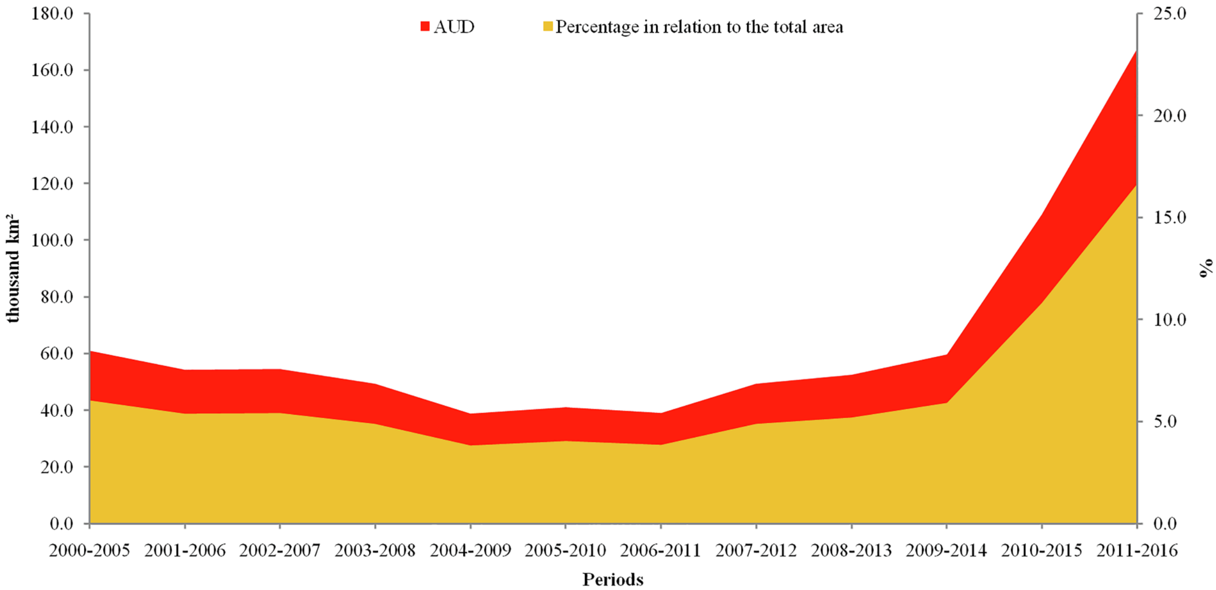


**Fig. 9.** Estimation of areas potentially undergoing degradation/desertification (AUD) (thousand km$^2$) between the periods evaluated; differences between periods and percentage of the study area affected (%).

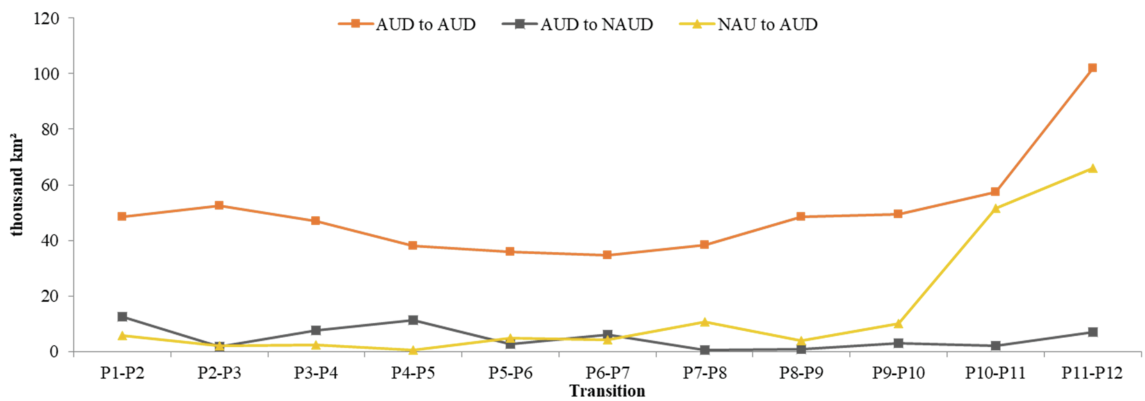


**Fig. 10.** Transitions of areas identified as areas potentially undergoing degradation/desertification (AUD) between 2000 and 2016, in consecutive six-year periods.

also be called desertification nuclei, Inhamuns and Jaguaribe, both in the state of Ceará (Fig. 11). In these two areas, a significant increase in areas potentially undergoing degradation/desertification was observed, mainly in the area surrounding the core of the Inhamuns.

### *3.3. Degradation trajectories for the Northeast Brazilian semiarid region (NBSR)*

Fig. 12 presents the (a) spatial distribution of the degradation trajectories in the Northeast Brazilian Semiarid Region. Low Degradation Trajectory, characterized by areas with no or low degradation, corresponds to approximately 81.17% of the region. By contrast, the Very High Degradation Trajectory (heavily degraded areas potentially in the process of desertification) and the High Degradation Trajectory (degraded areas potentially in the process of desertification), when taken together, are distributed in 4.22% of the region and correspond to 23.63% of the areas potentially undergoing degradation/desertification identified in the last period analyzed. These trajectories are mostly distributed in the central portion (backcountry) of the region.The state of Bahia is the largest with 30,278,958 km$^2$ of its territory covered by the Very High Degradation Trajectory and High Degradation Trajectory Trajectories, followed by the states of Pernambuco (4,514,695 km$^2$) and Rio Grande do Norte (2,754,841 km$^2$). By analyzing the semiarid area of each state, it can be observed that Bahia has the highest percentage, approximately 6.79%, followed by Rio Grande do Norte (5.61%) and Pernambuco (5.23%). The analysis of the Very High Degradation Trajectory and High Degradation Trajectory identified the municipalities of Juazeiro (BA), Curaçá, Campo Formoso (BA), Sento Sé (BA), Cocos (BA), Floresta (PE), Chorrochó (BA), Itaguaçu da Bahia (BA), Abaré (BA) and Xique-Xique (BA) as those with the highest percentages of semiarid areas of the municipality as areas potentially undergoing degradation/desertification, indicating that these should be pilot areas for insertion of public policies for the region to combat degradation/desertification.

Moderate Degradation Trajectory, areas with moderate degradation, are mainly distributed in the states of Bahia (49,666,480 km$^2$), Pernambuco (29,101,495 km$^2$) and Ceará (15,342,230 km$^2$), considering the extension, and in Pernambuco (33.71%), Paraíba (31.15%) and Rio Grande do Norte (25.70%), when considering the proportion of the state's semiarid area. Mixed Degradation Trajectory is characterized by areas with a constant oscillation of occurrences and the persistence of disturbances. These are areas with productive exploitation characteristics, with a predominance of well-defined disturbance cycles (eg every two years). Proportionally, the state of Bahia has most of the areas identified with this trajectory, approximately 62.37% (3,762,068 km$^2$), followed by the states of Pernambuco 16.60% (1,001,264 km$^2$) and Piauí 5.49% (331,244 km$^2$).

**Table 1**
Percentage of transitions by semiarid area of each state between 2000 and 2016.

| State | P1 | | P12 | | Percentage change between P1 and P12% | |
|---|---|---|---|---|---|---|
| | Area of the state with AUD | | | | | |
| | km$^2$ | % | km$^2$ | % | | |
| Alagoas - AL | 215.24 | 1.71 | 715.28 | 5.69 | ↗ | 4.55 |
| | | | | | → | 1.13 |
| | | | | | ↘ | 0.58 |
| Bahia - BA | 37,448.25 | 8.40 | 71,905.07 | 16.12 | ↗ | 8.94 |
| | | | | | → | 7.18 |
| | | | | | ↘ | 1.22 |
| Ceará - CE | 1,938.19 | 1.32 | 15,463.63 | 10.53 | ↗ | 9.41 |
| | | | | | → | 1.12 |
| | | | | | ↘ | 0.20 |
| Maranhão - MA | 41.931 | 1.19 | 61.08 | 1.73 | ↗ | 1.01 |
| | | | | | → | 0.72 |
| | | | | | ↘ | 0.47 |
| Paraíba - PB | 3,842.42 | 7.49 | 13,887.57 | 27.07 | ↗ | 20.28 |
| | | | | | → | 6.79 |
| | | | | | ↘ | 0.70 |
| Pernambuco - PE | 9,451.34 | 10.95 | 33,393.79 | 38.68 | ↗ | 28.72 |
| | | | | | → | 9.96 |
| | | | | | ↘ | 0.99 |
| Piauí - PI | 2,498.80 | 1.25 | 15,092.90 | 7.52 | ↗ | 6.57 |
| | | | | | → | 0.95 |
| | | | | | ↘ | 0.29 |
| Rio Grande do Norte - RN | 5,469.01 | 11.15 | 16,990.92 | 34.62 | ↗ | 24.23 |
| | | | | | → | 10.39 |
| | | | | | ↘ | 0.75 |
| Sergipe - SE | 6.27 | 0.56 | 304.00 | 2.74 | ↗ | 2.38 |
| | | | | | → | 0.36 |
| | | | | | ↘ | 0.20 |
| NBSR | 60,967.44 | 6.05 | 167,814.24 | 16.66 | ↗ | 11.40 |
| | | | | | → | 5.26 |
| | | | | | ↘ | 0.80 |

* ↗ = NAUD to AUD; → = AUD to AUD; e ↘ = AUD to NAUD.

## 4. Discussion

The present study focused on the proposition of a methodology on the determination of a potential degradation/desertification indicator, based on the limit value of EVI2, with the purpose to use it for spatial and temporal analysis. A premise was to develop a methodology to estimate areas under degradation in order to contribute for the debate on two issues related to the planning of strategies to combat desertification on a regional scale: (i) mapping areas under desertification process and generating reliable information to support the definition of subregion-specific priorities and needs (Gül and Erşahin, 2019; Sepehr and Zucca, 2012); and ii) identifying trends and monitoring changes in the process of desertification (Bakr et al., 2012). We believe that this approach is relevant in the context of the efforts to meet sustainable objectives (SDGs), particularly in the scope of the SDG 15, as well as indicators of soil degradation neutrality (LDN). The presented approach differs from the other ones previously presented, for example by Erasmi et al. (2006) and Tomasella et al. (2018), among others, since it includes the degradation trajectories; thus, establishes the level of degradation of the identified areas and the dynamics of this degradation in each identified trajectory. Thus, the proposed approach intends to go beyond the analysis of trends in indices and the identification of degraded areas. Although robust, it is highlighted that the detection of disturbances in degraded areas is from the spectral signal of vegetation, that is, a phenological signal of vegetation. Therefore, abrupt changes caused by large deforestation, recurrent fire and/or severe drought, can harm the entire technique. On the other hand, it is highlighted the adoption of the validation techniques by the use of high-resolution images, as proposed in the literature, mainly due to the size of the study area.

For the specific spatial analysis of the Northeast Brazilian Semiarid Region, the presence of areas with differentiated degradation/desertification processes was observed with heterogeneous distribution of productive areas, with or without disturbances. Similar behavior was found by Colantoni et al. (2015) and by Salvati and Bajocco (2011), whose studies focused on analyses in areas of degradation in Italy. In addition, it was possible to visualize degradation trajectories, thus establishing the degradation level of the identified areas. The multi-temporal analysis of EVI2 (identified mean value 0.254) was presented as a baseline to assist in monitoring the degradation dynamics in already identified areas. However, we must highlight that this average value may vary according to the region in which the methodology will be applied. This may be because each semiarid region on the planet has its specificities in terms of climate, soils, vegetation, land uses, agricultural practices; therefore, the methodology can be replicated to obtain specific threshold values, according to the region studied. The increase of desertification in the analyzed period, besides demonstrating the permanence of this phenomenon in the region, can be seen as a warning for the need to implement urgent measures capable of guaranteeing the sustainability of the region's ecosystem.

The results show that the advancement of the areas potentially undergoing degradation/desertification occurred mainly in the areas considered as highly susceptible to desertification (Bezerra, 2016; Vieira et al., 2015). These areas mostly present: i) aridity index, classified as semiarid, ii) geology and pedology classified as highly susceptible (Bezerra, 2016) and iii) low levels of socioeconomic development, which are associated with two main causes of desertification (Bakr et al., 2012; Ge et al., 2016; Xu et al., 2019; Zhou et al., 2015). In addition, there are other factors that determine desertification, such as rugged terrain conditions, diversity of vegetation cover and poor water availability.

The observed increase of the areas potentially under degradation/desertification in and around desertification centers indicates the need for effective, efficient and permanent strategies of monitoring. Despite studies and measures developed over the years focusing on these areas, as well as institutional efforts to mitigate desertification in the Northeast Brazilian Semiarid Region, such as the State Desertification Combat Plans (PAE), no transformations have been observed in the interaction between productive actions and the natural resources of these areas, as highlighted by Perez-Marin et al. (2012).

According to Bezerra (2016), which corroborates the studies conducted by Sales (2004) and by Lima et al. (2009), the relations of production and exploitation of natural resources established in the Brazilian semiarid region, in addition to contributing to the current state of degradation of this region, continue to act as a catalyst for desertification processes. As quoted by de Nascimento (2013), these relationships develop due to the non-observance of environmental and development policies, especially regarding the occupation of productive activities, putting at risk the pedobioclimatic capacity, the maintenance of the vegetation, the health of the water resources and, therefore, the environmental quality.

Concerning the last period of the analysis, there was a considerable increase in areas potentially undergoing degradation/desertification. Although the focus of the study was not intended to evaluate the effect of climate extremes on degradation/desertification processes, the results suggest that intense drought (considered the most severe ever recorded in this region (Brito et al., 2018)) contributed considerably for the intensification of degradation, reducing the response capacity of naturally fragile areas. Marengo et al. (2017a,b) point out that the conditions of this drought began to intensify in 2012 and that the conditions of the La Niña event in 2013 were not sufficient to compensate for the established drought conditions, and this situation worsened with the occurrence of the El Niño event in 2015. It should be noted that drought, although not the cause of desertification itself, exacerbates the human impact on soil degradation and leads to the

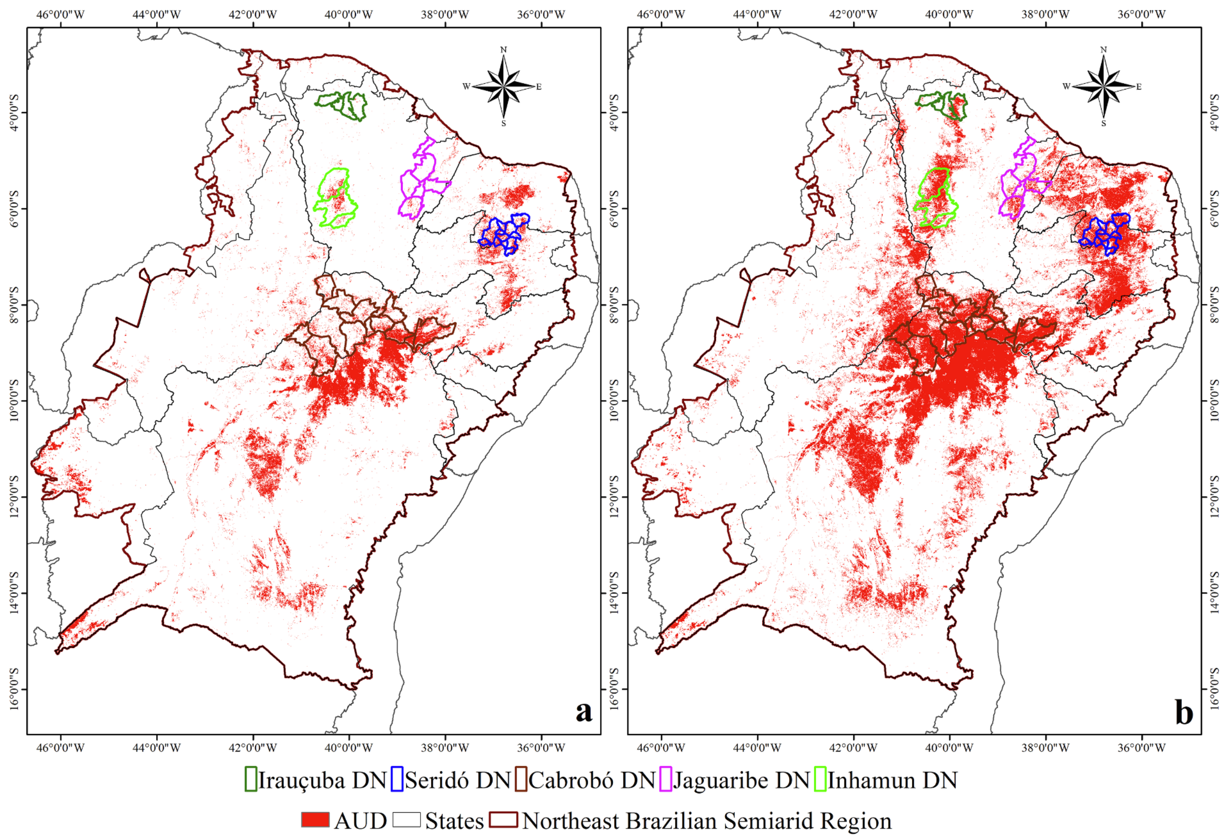


**Fig. 11.** Areas potentially undergoing degradation/desertification in P1(a) and P12(b) versus Desertification Nuclei in the Northeast Brazilian Semiarid Region.

advance of desertification (Cornet, 2002; Zhou et al., 2015).

The definition of the Degradation Trajectories presented in this research, and, consequently, the degree of degradation of the areas potentially undergoing degradation/desertification, can contribute, in this context, to the direction of mitigating measures and strategies to cope with the degradation/desertification process, as well as the responsiveness of the population in establishing priority areas. Regions where a disturbance in the natural condition of the ecosystem has persisted, such as the areas mainly comprised of Very High Degradation Trajectory and High Degradation Trajectory, tend to have increased vulnerability and decreased response capacity, especially in cases of extreme events, as has been observed in recent decades in this region. In addition, the analysis of the degradation trajectories allowed us to understand the degradation behavior of the Northeast Brazilian Semiarid Region and suggests that decision making is not based solely on the current situation of a region/area. The analysis of the trajectories also made it possible to verify that in the areas where the degradation is consolidated (Very High Degradation Trajectory), the dynamics of land use change and land cover have remained practically constant, with slight alterations. In other words, no significant changes have been observed in these areas. The changes have been concentrated mainly in the Trajectories of Moderate Degradation Trajectory, High Degradation Trajectory and Mixed Degradation Trajectory, which can be partly explained by the fact that these areas still have higher responsiveness, especially in relation to crop production (e.g. agriculture, pasture, etc).

The loss of vegetation cover observed in the analyzed areas increases the risk of soil erosion and, consequently, land degradation, especially in areas where degradation processes are advanced, as in areas comprised by Very High Degradation Trajectory. However, it should be noted that attention to other areas is essential, as most changes in land use and land cover have occurred mainly in these areas, including the suppression of plant cover. In this context, the results of the analyses of degraded areas and their trajectories, presented in this paper, corroborate with other studies that identified that soil degradation in semiarid regions is the result of the combination of semiarid climate with the most severe drought events in certain years and human activities, such as inappropriate land use, as highlighted by Bertrand (2004), Bezerra (2016), Ge et al. (2016), Lima et al. (2009), de Nascimento (2013), Sá et al. (2010), Sales (2004), Vieira et al. (2015), Xue et al. (2019), among others.

## 5. Conclusions

In the present study, a new methodology to provide a potential degradation/desertification indicator, considering the use of the EVI2 MODIS time series, was proposed. The research demonstrated the feasibility of using the records of multitemporal series of vegetation indexes to identify areas potentially undergoing degradation/desertification in semiarid regions and the degree of degradation by determining the Degradation Trajectories, which differentiates it from other studies that aimed only to identify degraded areas.

According to the results presented, it is emphasized that the dynamics of land degradation processes in the study region are not homogeneous, especially concerning the spatialization and location of areas undergoing desertification. The multitemporal analysis also indicated that the degradation/desertification processes are still present, despite the efforts made in recent decades, leading to a considerable increase in areas undergoing desertification, as well as the permanence of already degraded areas.

The proposed methodology proved to be useful, timely and efficient in the scope of development of a potential indicator capable to identify and monitoring areas under the influence of degradation and desertification processes; thus, relevant to assist in actions to combat and recover areas undergoing desertification and maintaining biodiversity, thus aligned with international agreements.

It should also be noted that the method of analyzing multitemporal

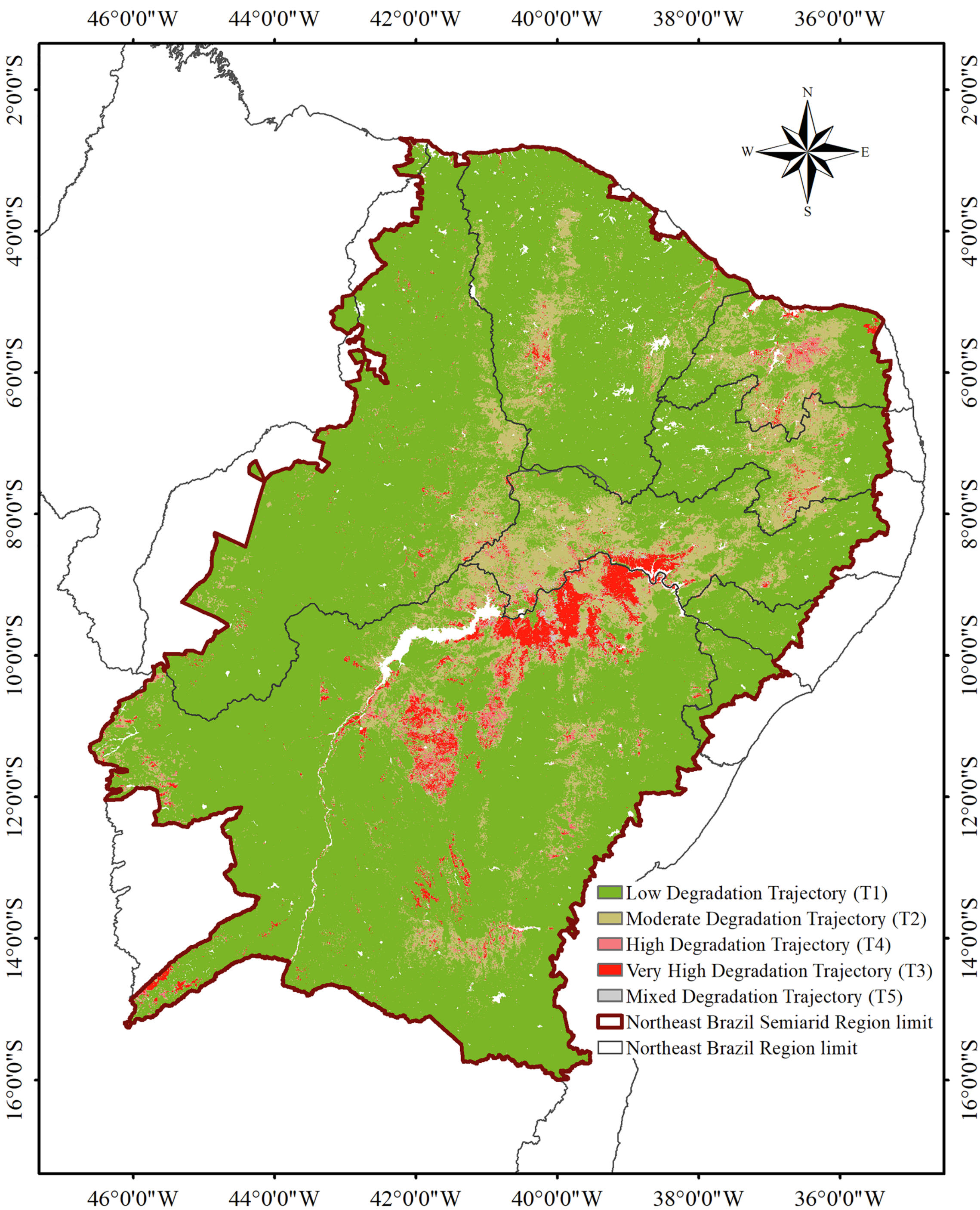


**Fig. 12.** Degradation Trajectories in Northeast Brazilian Semiarid Region.

series of vegetation indices is useful; however, it must be complemented with additional information, such as trends and climatic scenarios of land use and land cover with retrospective analysis of the landscape, soil erosion, field recognition, and socioeconomic information, among others.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

The authors thank Coordination for the Improvement of Higher Education Personnel (CAPES), National Council for Scientific and Technological Development (CNPq), Earth System Science Center of the National Institute for Space Studies (CCST-INPE) by support the development of work, Laboratory of Remote Sensing in Agriculture and Forestry (LAF) and researchers Ana Paula Martins do Amaral Cunha, André Lima, Camilo Daleles Rennó, Corina da Costa Freitas and Rita Marcia da Silva Pinto.

## References


Ab'Saber, A.N., 1985. Os sertões: a originalidade da terra. Ciência Hoje 3, 42–47.
Adeel, Z., Bogardi, J., Braeuel, C., Chasek, P., Niamir-fuller, M., Gabriels, D., King, C., Knabe, F., Kowsar, A., Salem, B., Schaaf, T., Shepherd, G., Thomas, R., 2007. Overcoming One of the Greatest Environmental Challenges of Our Times: Re-thinking Policies to Cope with Desertification. Hamilton.
Albalawi, E.K., Kumar, L., 2013. Using remote sensing technology to detect, model and map desertification: a review. J. Food Agric. Environ. 11, 791–797.
Bakr, N., Weindorf, D.C., Bahnassy, M.H., El-Badawi, M.M., 2012. Multi-temporal assessment of land sensitivity to desertification in a fragile agro-ecosystem: Environmental indicators. Ecol. Indic. 15, 271–280. https://doi.org/10.1016/j.ecolind.2011.09.034.
H. Barbosa C. Tote T.V. Lakshmi Kumar Y. Bamutaze . SILVERN, S., YOUNG, S. Environmental Change and Sustainability. INTECH 2013 91 121.
Bertrand, G., 2004. Paisagem e geografia física global. Espoço metodológico. Raega - O Espaço Geográfico em Análise 141–152.
Bezerra, F.G.S., 2016. Contribuição de fatores socioeconômicos, biofísicos e da agropecuária à degradação da cobertura vegetal como "proxy" da desertificação no semiárido do nordeste do brasil. (sid.inpe.br/mtc-m21b/2016/05.11.23.36-TDI) - Tese (Doutorado em Ciência do Sistema Terrestre) – Instituto Nacional de Pesquisas Espaciais. São José dos Campos. doi:sid.inpe.br/mtc-m21b/2016/05.11.23.36-TDI.
BRASIL, 2017a. Resolução no 107/2017, de 27 de julho de 2017. Recife, Brasil. Avaliable in: http://www.in.gov.br/web/dou/-/resolucao-n-107-de-27-de-julho-de-2017-19287788?inheritRedirect = true.
BRASIL Resolução no 115/2017, de 23 de novembro de 2017 2017 Brasil Avaliable In: http://www.in.gov.br/materia/-/asset_publisher/Kujrw0TZC2Mb/content/id/739568/do1-2017-12-05-resolucao-n-115-de-23-de-novembro-de-2017-739564.
BRASIL Programa de acão nacional de combate à desertificação e mitigação dos efeitos da seca Pan-Brasil 2004 Avaliable MMA/SRH, Brasília In: https://www.mma.gov.br/estruturas/sedr_desertif/_arquivos/pan_brasil_portugues.pdf.
Brazilian Institute of Geography and Statistics - IBGE, 2018. Population Estimates. Avaliable in: https://www.ibge.gov.br/en/estatisticas/social/population/18448-estimates-of-resident-population-for-municipalities-and-federation-units.html? = &t = o-que-e.
Brito, S.S.B., Cunha, A.P.M.A., Cunningham, C.C., Alvalá, R.C., Marengo, J.A., Carvalho, M.A., 2018. Frequency, duration and severity of drought in the Semiarid Northeast Brazil region. Int. J. Climatol. 38, 517–529. https://doi.org/10.1002/joc.5225.
Cavalcanti, E.R., Coutinho, S.F.S., Selva, V.S.F., 2006. Desertificação e desastres naturais na região do semi-árido brasileiro. Rev. Cad. Estud. Sociais 22 (1), 19–31.
Chen, W., Sakai, T., Moriya, K., Koyama, L., Cao, C.X., 2013. Estimation of Vegetation Coverage in Semi-arid Sandy Land Based on Multivariate Statistical Modeling Using Remote Sensing Data. Environ. Model. Assess. 18, 547–558. https://doi.org/10.1007/S10666-013-9359-1.
Colantoni, A., Ferrara, C., Perini, L., Salvati, L., 2015. Assessing trends in climate aridity and vulnerability to soil degradation in Italy. Ecol. Indic. 48, 599–604. https://doi.org/10.1016/J.ECOLIND.2014.09.031.
Cornet, A., 2002. La Désertification à la croisée de l ' environnement et du développement Un Problème qui nous concerne, in: Barbault, R., Cornet, Antoine, Jouzel, J., Mégie, G., Sachs, I., Weber, J. (Eds.), Johannesburg 2002. Sommet Mondial Du Développement Durable. Quels Enjeux ? Quelle Contribution Des Scientifiques ? Ministère des Affaires étrangères, pp. 1–32.
D'Odorico, P., Bhattachan, A., Davis, K.F., Ravi, S., Runyan, C.W., 2013. Global desertification: drivers and feedbacks. Adv. Water Resour. 51, 326–344. https://doi.org/10.1016/j.advwatres.2012.01.013.
Dharumarajan, S., Bishop, T.F.A., Hegde, R., Singh, S.K., 2018. Desertification vulnerability index-an effective approach to assess desertification processes: A case study in Anantapur District, Andhra Pradesh. India. L. Degrad. Dev. 29, 150–161. https://doi.org/10.1002/ldr.2850.
Diouf, A., Lambin, E.F., 2001. Monitoring land-cover changes in semi-arid regions: remote sensing data and field observations in the Ferlo, Senegal. J. Arid Environ. 48, 129–148. https://doi.org/10.1006/jare.2000.0744.
Erasmi, S., Bothe, M., Petta, R.A., 2006. Enhanced filtering of MODIS time series data for the analysis of desertification processes in Northeast Brazil. Kerle, N. Ski. A. Remote Sens. From Pixels to Process. Proc. ISPRS/ITC-Midterm Symp. 8–11.
Freitas, R.M., 2011. Virtual laboratory of remote sensing time series: visualization of MODIS EVI2 data set over South America. J. Comput. Interdiscip. Sci. 2, 57–68. https://doi.org/10.6062/jcis.2011.02.01.0032.
García-Gómez, M., Maestre, F.T., 2011. Remote sensing data predict indicators of soil functioning in semi-arid steppes, central Spain. Ecol. Indic. 11, 1476–1481. https://doi.org/10.1016/j.ecolind.2011.02.015.
Ge, X., Dong, K., Luloff, A.E., Wang, L., Xiao, J., 2016. Impact of land use intensity on sandy desertification: An evidence from Horqin Sandy Land. China. Ecol. Indic. 61, 346–358. https://doi.org/10.1016/J.ECOLIND.2015.09.035.
Grainger, A., 2013. The threatening desert : controlling desertification. Routledge, Hoboken.
Gül, E., Erşahin, S., 2019. Evaluating the desertification vulnerability of a semiarid landscape under different land uses with the environmental sensitivity index. L. Degrad. Dev. 30, 811–823. https://doi.org/10.1002/ldr.3269.
Helldén, U., Tottrup, C., 2008. Regional desertification: A global synthesis. Glob. Planet. Change 64, 169–176. https://doi.org/10.1016/J.GLOPLACHA.2008.10.006.
Higginbottom, T., Symeonakis, E., 2014. Assessing land degradation and desertification using vegetation index data: current frameworks and future directions. Remote Sens. 6, 9552–9575. https://doi.org/10.3390/rs6109552.
Javzandulam, T., Tateishi, R., Sanjaa, T., 2005. Analysis of vegetation indices for monitoring vegetation degradation in semi-arid and arid areas of Mongolia. Int. J. Environ. Stud. 62, 215–225. https://doi.org/10.1080/00207230500034123.
Jiang, Z., Huete, A., Didan, K., Miura, T., 2008. Development of a two-band enhanced vegetation index without a blue band. Remote Sens. Environ. 112, 3833–3845. https://doi.org/10.1016/j.rse.2008.06.006.
Krol, M., Jaeger, A., Bronstert, A., Güntner, A., 2006. Integrated modelling of climate, water, soil, agricultural and socio-economic processes: A general introduction of the methodology and some exemplary results from the semi-arid north-east of Brazil. J. Hydrol. 328, 417–431. https://doi.org/10.1016/j.jhydrol.2005.12.021.
Lambin, E.F., Chasek, P.S., Downing, T.E., Kerven, C., Kleidon, A., Leemans, R., Lüdeke, S. D., Prince, S.D., Xue, Y., 2002. The interplay between international and local processes affecting desertification, in: Global Desertification: Do Humans Cause Deserts? Dahlem University Press, Berlin, pp. 387–401.
Lambin, E.F., Linderman, M., 2006. Time series of remote sensing data for land change science. IEEE Trans. Geosci. Remote Sens. 44, 2005–2007. https://doi.org/10.1109/TGRS.2006.872932.
Lanfredi, M., Lasaponara, R., Simoniello, T., Cuomo, V., Macchiato, M., 2003. Multiresolution spatial characterization of land degradation phenomena in southern Italy from 1985 to 1999 using NOAA-AVHRR NDVI data. Geophys. Res. Lett. 30, 1069. https://doi.org/10.1029/2002GL015514.
Lima, P.V.P.S., Queiroz, F.D. de S., Mayorga, M.I. de O., Cabral, N.R.A.J., 2009. A propensão à degradação ambiental na mesorregião de Jaguaribe no Estado do Ceará, in: CARVALHO, E.B.S.C., C, H.M., BARBOSA, M.P. (Eds.), Economia Do Ceará Em Debate 2008. IPECE, Fortaleza, pp. 27–43.
Lin, M.-L., Chen, C.-W., 2010. Application of fuzzy models for the monitoring of ecologically sensitive ecosystems in a dynamic semi-arid landscape from satellite imagery. Eng. Comput. 27, 5–19. https://doi.org/10.1108/02644401011008504.
Lin, M.-L., Chen, C.-W., Wang, Q.-B., Cao, Y., Shih, J.-Y., Lee, Y.-T., Chen, C.-Y., Wang, S., 2009. Fuzzy model-based assessment and monitoring of desertification using MODIS satellite imagery. Eng. Comput. 26, 745–760. https://doi.org/10.1108/02644400910985152.
Marengo, J.A., 2008. Vulnerabilidade, impactos e adaptação à mudança do clima no semi-árido do Brasil. Parcerias Estratégicas 13, 149–176.
Marengo, J.A., Alves, L.M., Aalvala, R.C., Cunha, A.P., Brito, S., Moraes, O.L.L., 2017a. Climatic characteristics of the 2010–2016 drought in the semiarid Northeast Brazil region. An. Acad. Bras. Cienc. 90, 1973–1985. https://doi.org/10.1590/0001-3765201720170206.
Marengo, J.A., Alves, L.M., Beserra, E.A., Lacerda, F.F., 2011. Variabilidade e mudanças climáticas no semiárido brasileiro, in: Gheyi, H.R., Paz, V.P. da S., Medeiros, S. de S., Galvão, C. de O. (Eds.), Recursos Hídricos Em Regiões Áridas e Semiáridas. INSA, Campina Grande, pp. 383–422.
Marengo, J.A., Torres, R.R., Alves, L.M., 2017b. Drought in Northeast Brazil—past, present, and future. Theor. Appl. Climatol. 129, 1189–1200. https://doi.org/10.1007/s00704-016-1840-8.
Matallo Junior, H., 2001. Indicadores de Desertificação : histórico e perspectivas, Unesco. UNESCO, Brasília.
Moreira, M.A., 2005. Fundamentos do sensoriamento remoto e metodologia de aplicação, 3rd ed. UFV, Viçosa.
de Nascimento, F.R., 2015. Os semiáridos e a desertificação no brasil. Rev. Eletrônica do PRODEMA 9, 7–26.
de Nascimento, F.R., 2013. O fenômeno da desertificação. Editora UFG, Goiânia.
Nunes, L.A.P.L., de Araújo-filho, J.A., Menezes, R.I. de Q., 2009. Impacto da queimada e do pousio sobre a qualidade de um solo sob caatinga no semi-árido Nordestino. Rev. Caatinga 22, 131–140.
Olsson, L., Eklundh, L., Ardö, J., 2005. A recent greening of the Sahel—trends, patterns and potential causes. J. Arid Environ. 63, 556–566. https://doi.org/10.1016/j.jaridenv.2005.03.008.
Paruelo, J.M., Piñeiro, G., Escribano, P., Oyonarte, C., Alcaraz, D., Cabello, J., 2005. Temporal and spatial patterns of ecosystem functioning in protected arid areas in southeastern Spain. Appl. Veg. Sci. 8, 93–102. https://doi.org/10.1111/j.1654-109X.2005.tb00633.x.
Perez-Marin, A.M., Cavalcante, A. de M.B., Medeiros, S.S. de, Tinôco, L.B. de M., Salcedo, I.H., 2012. Núcleos de desertificação no semiárido brasileiro : ocorrência natural ou antrópica ? Parcerias Estratégicas 17, 87–106.
Piao, S., Fang, J., Liu, H., Zhu, B., 2005. NDVI-indicated decline in desertification in China in the past two decades. Geophys. Res. Lett. 32, L06402. https://doi.org/10.1029/2004GL021764.
Ramankutty, N., Graumlich, L., Achard, F., Alves, D., Chhabra, A., DeFries, R.S., Foley, J. A., Geist, H., Houghton, R.A., Goldewijk, K.K., Lambin, E.F., Millington, A., Rasmussen, K., Reid, R.S., Turner II, B.L., 2006. Global Land-Cover Change Recent Progress, Remaining Challenges, in: Lambin, E.F., Geist, H. (Eds.), Land-Use and Land-Cover Change: Local Processes and Global Impacts. Springer, Berlin, p. 220.
Rêgo, A.H. do, 2012. Os sertões e os desertos: o combate à desertificação e a política externa brasileira. FUNAG, Brasília.
Reynolds, J., Maestre, F., Kemp, P.R., Stafford-Smith, D.M., Lambin, E., 2007. Natural and human dimensions of land degradation in drylands: causes and consequences, in: Terrestrial Ecosystems in a Changing World. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 247–257. doi:10.1007/978-3-540-32730-1_20.
Sá, I.B., Cunha, T.J.F., Heriberto, A., Teixeira, D.C., Antonio, M., 2010. Desertificação no. Semiárido brasileiro.
Sales, M.C.L., 2004. Panorama da Desertificação no Brasil, in: MOREIRA, E. (Ed.), Agricultura Familiar e Desertificação. João Pessoa, pp. 33–49.
Salvati, L., Bajocco, S., 2011. Land sensitivity to desertification across Italy: Past, present, and future. Appl. Geogr. 31, 223–231. https://doi.org/10.1016/J.APGEOG.2010.04.006.
Santibañez, F., Pérez, J., 1998. Metodología Unificada para la Evaluación y Monitoreo de

la Desertificación en América Latina. Indicadores de la Desertificación, FAO/PNUMA/AGRIMED, Chile.
Sepehr, A., Zucca, C., 2012. Ranking desertification indicators using TOPSIS algorithm. Nat. Hazards 62, 1137–1153. https://doi.org/10.1007/s11069-012-0139-z.
Sietz, D., Lüdeke, M.K.B., Walther, C., 2011. Categorisation of typical vulnerability patterns in global drylands. Glob. Environ. Chang. 21, 431–440. https://doi.org/10.1016/j.gloenvcha.2010.11.005.
Silva, B.B., 2013. Aplicações Ambientais Brasileiras de Geoprocessamento e Sensoriamento Remoto. EDUFCG, Campina Grande.
Sistema de Alerta Precoce Contra a Seca e Desertificação - SAP, 2015. Sistema de Alerta Precoce Contra a Seca e Desertificação (SAP). Instituto Nacional de Pesquisas Espaciais (INPE), São José dos Campos.
Sternberg, T., Tsolmon, R., Middleton, N., Thomas, D., 2011. Tracking desertification on the Mongolian steppe through NDVI and field-survey data. Int. J. Digit. Earth 4, 50–64. https://doi.org/10.1080/17538940903506006.
Symeonakis, E., Drake, N., 2004. Monitoring desertification and land degradation over sub-Saharan Africa. Int. J. Remote Sens. 25, 573–592. https://doi.org/10.1080/0143116031000095998.
Thornthwaite, C.W., 1941. Atlas of climatic types in the United States 1900–1939. G.P.O, Washington, D.C.
Tomasella, J., Silva Pinto Vieira, R.M., Barbosa, A.A., Rodriguez, D.A., de Oliveira Santana, M., Sestini, M.F., 2018. Desertification trends in the Northeast of Brazil over the period 2000–2016. Int. J. Appl. Earth Obs. Geoinf. 73, 197–206. https://doi.org/10.1016/j.jag.2018.06.012.
United Nations - UN United Nations Convention to Combat Desertification in those Countries Experiencing Serious Drought and/or Desertification 1994 Particularly in Africa Avaliable In: http://www.unccd.int/Lists/SiteDocumentLibrary/conventionText/conv-eng.pdf.
United Nations - UN, 1992. Agenda 21. Avaliable in: https://sustainabledevelopment.un.org/content/documents/Agenda21.pdf.
United Nations - UN, 2017. The Scientific Conceptual Framework for Land Degradation Neutrality. Ordos.
United Nations Environment Programme - UNEP Latin America and the Caribbean: Environmental outlook 2010 UNEP, Panama. Avaliable UNEP In: http://wedocs.unep.org/bitstream/handle/20.500.11822/8663/-Global_environment_outlook_Latin_America_and_the_Caribbean_GEO_LAC_3-2010Latinin_America_and_the_Caribbean_-_Environment_Outlook_3.pdf.pdf?sequence=3&isAllowed=y.
Vasconcelos Sobrinho, J., 1982. Processos de desertificação ocorrentes no Nordeste do Brasil: Sua gênese e sua contenção. SEMA/SUDENE, Recife.
Vieira, R.M.S.P., Tomasella, J., Alvalá, R.C.S., Sestini, M.F., Affonso, A.G., Rodriguez, D.A., Barbosa, A.A., Cunha, A.P.M.A., Valles, G.F., Crepani, E., de Oliveira, S.B.P., de Souza, M.S.B., Calil, P.M., de Carvalho, M.A., Valeriano, D.M., Campello, F.C.B., Santana, M.O., 2015. Identifying areas susceptible to desertification in the Brazilian northeast. Solid Earth 6, 347–360. https://doi.org/10.5194/se-6-347-2015.
Viña, A., Gitelson, A.A., Nguy-Robertson, A.L., Peng, Y., 2011. Comparison of different vegetation indices for the remote assessment of green leaf area index of crops. Remote Sens. Environ. 115, 3468–3478. https://doi.org/10.1016/j.rse.2011.08.010.
Xu, D., You, X., Xia, C., 2019. Assessing the spatial-temporal pattern and evolution of areas sensitive to land desertification in North China. Ecol. Indic. 97, 150–158. https://doi.org/10.1016/J.ECOLIND.2018.10.005.
Xue, J., Gui, D., Lei, J., Sun, H., Zeng, F., Mao, D., Jin, Q., Liu, Y., 2019. Oasification: An unable evasive process in fighting against desertification for the sustainable development of arid and semiarid regions of China. CATENA 179, 197–209. https://doi.org/10.1016/J.CATENA.2019.03.029.
Yengoh, G.T., Dent, D., Olsson, L., Tengberg, A.E., Tucker III, C.J., 2015. Use of the Normalized Difference Vegetation Index (NDVI) to Assess Land Degradation at Multiple Scales: current status, future trends, and practical considerations, SpringerBriefs in Environmental Science. Springer International Publishing, New York. doi:10.1007/978-3-319-24112-8.
Zhang, Y., Chen, Z., Zhu, B., Luo, X., Guan, Y., Guo, S., Nie, Y., 2008. Land desertification monitoring and assessment in Yulin of Northwest China using remote sensing and geographic information systems (GIS). Environ. Monit. Assess. 147, 327–337. https://doi.org/10.1007/s10661-007-0124-2.
Zhou, W., Gang, C., Zhou, F., Li, J., Dong, X., Zhao, C., 2015. Quantitative assessment of the individual contribution of climate and human factors to desertification in northwest China using net primary productivity as an indicator. Ecol. Indic. 48, 560–569. https://doi.org/10.1016/J.ECOLIND.2014.08.043.