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Desertification trends in the Northeast of Brazil over the period 2000–2016

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ABSTRACT

Information about changes in land use and land cover is useful to address issues related to drylands management, as well as to support decision-making related to the sustainable use of soils. Since drylands are frequently affected by accelerated soil erosion, land degradation and desertification associated with vegetation cover losses, constant monitoring of land use and land cover changes are required. However, land use and land cover maps are often not available, making it difficult to monitor degradation. Therefore, in this work, we developed an efficient mapping method to monitor bare soil areas, which are indicative of land degradation in the case of the Northeast of Brazil, using Normalized Difference Vegetation Index images. The proposed methodology was field calibrated and applied to the region using 17-year (2000–2016) NDVI maps, with a spatial resolution of 250 m. Based on bare soil mapping, we estimated the degree of degradation using an index calculated from the persistence and frequency of bare soil during the study period. The results indicated that the degraded areas increased in the period of the study, mainly in areas of pasture and *Caatinga*. This expansion has been accelerated due to the severe drought that affected the region since 2011.

1. Introduction

After five centuries of disordered occupation, the Brazilian semiarid have been degraded by inadequate land management, such as slash and burning agriculture, overgrazing and overexploitation of woody resources as a fuel source (Menezes et al., 2012; Vieira et al., 2015).

The natural vegetation that dominates the Brazilian semiarid region is a savanna-steppe known as *Caatinga*. *Caatinga* vegetation has a high spatial variability, both floristically and physionomically (Andrade-Lima, 1981), mainly determined by the amount and seasonality of rainfall. Physiognomic types are locally denominated shrubby, woody, shrubby/woody and park (Araújo et al., 2007), and can reach heights of up to 20 m. It is very difficult to determine how much of the variability is due to differences in other local physical conditions, for example soil type, or to human interference, since the semiarid zone of Brazil has been inhabited for more than 10,000 years (Sampaio, 1995). *Caatinga* vegetation is rich in therophyte species, which remain as seeds in the soil during the unfavorable season, vegetating only in the rainy period. The woody species, classified as phanerophytes and chamaephytes, typically shed their leaves during the dry season (Costa et al., 2007).

In addition, traditional agricultural practices involve slash-and-burn and shifting cultivation. Burning of the vegetation occurrs by the end of the dry season, when the wood debris lost most of their humidity (Mamede and Araújo, 2008). Such fallow-farming system have converted Caatinga vegetation in a mosaic of regenerating forest patches with different ages (Sobrinho et al., 2016).

Based on data of secondary growth of the *Caatinga* vegetation, Araújo Filho (2013) concluded that the fallow time of agricultural land should be 40 years, but the anthropic pressure has reduced this period to ten years and even shorter periods, not giving sufficient time for the recovery of the soil and vegetation. It is important to mention that the region is considered to be the Brazilian ecosystem most vulnerable to climate change due to the reduction of rainfall deficit and increased aridity over the next century (Marengo et al., 2016).

Previous studies (Helldén, 2008) recognized that areas with bare soil over a long period of time are a good proxy of desertification since they are more vulnerable to degradation considering that unprotected topsoils are susceptible to severe erosion (Hill et al., 1995). Araújo Filho (2013) showed that it is mainly the *Caatinga* areas of bare luvisols and argisols, which cover 25%–64% of the whole area, that are generally exposed to high rates of soil erosion. It was estimated that the whole region has annual soil losses of approximately 50 t ha^{-1} (Araújo Filho,

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2013).

Remote sensing products have frequently been used in land degradation studies since the 1980s (Tripathy et al., 1996; Schmidt and Karnieli, 2000; Maldonado et al., 2002; Zhang et al., 2008; Nkonya et al., 2011; UNEP, 2012; Fensholt et al., 2013; Dardel et al., 2014, among others). On a global scale, one of the most common indicators in the assessment of degradation / desertification are the vegetation indices derived from satellite images, such as the Normalized Difference Vegetation Index – NDVI. This is the most frequently used index by the United Nations Convention to Combat Desertification - UNCCD (UN, 2001). Multi-temporal analysis of NDVI data allows the detection of desertification trends based on the relationship between NDVI and vegetation greenness and cover (Zhang et al., 2008; Purkis and Klemas, 2011; Dardel et al., 2014; Higginbottom and Symeonakis, 2014). In areas where biomass productivity is lower, NDVI values tend to be lower, indicating a larger proportion of bare soil surface (Nicholson and Farrar, 1994; Bai et al., 2008).

Together with the identification of bare soil, the characterization of the different tree strata and biomass has also been used as an indicator of the degree of desertification (Le Houerou, 2006; Barbero-Sierra et al., 2015; Torres et al., 2016). According to Zhang et al. (2016), areas with tree and shrub coverage greater than 50%, or where there is more than 70% forage coverage of the surface, are less susceptible to soil degradation process.

Because the Brazilian *Caatinga* is a complex ecosystem with a large variety of trees, shrubs and pastures that are unequally distributed, with highly fragmented landscape due to several anthropic land uses, it produces a wide range of spectral responses. Consequently, to determine the threshold responses of bare soil, we related NDVI values to a biomass index used extensively in local field surveys. Using this relationship, we determined threshold NDVI values correspondent to bare soil areas and mapped areas without vegetation for the period of 2000–2016.

It is important to note that severe droughts, deforestation for firewood production, and the slash and burning agriculture result in very low values of NDVI, similar to those of bare soil, that recover with the return of regular rainfall. Unless regenerated patches, degraded areas show little or no signs of re-greening in the wet season. Therefore, we proposed a degradation index based on the frequency and persistence of bare soil, which was used to characterize the degradation/desertification extension and intensity during the study period.

2. Materials and methods

2.1. Study site

With an extension of approximately 1 797 123 km^2, approximately 20% of the total Brazilian territory, the study area is located in the equatorial zone (1–21 °S, 32–49 °W, Fig. 1). The region is characterized by intense solar radiation, low cloudiness and relative humidity, high potential evapotranspiration, rainfall that ranges from less than 800 mm y^{-1} within the semi-arid region to more than 1500 mm y^{-1} in the rainy zone along the eastern coast, precipitation concentrated over 2–5 months during the wet season, and a high degree of spatial and temporal variability (Cunha et al., 2015). A large fraction of the area (approximately 982 563 km^2) is classified as semiarid climate (Alvares et al., 2013).

2.2. NDVI data

In this work, we used 1552 MODIS images from the Earth satellite, available at http://modis.gsfc.nasa.gov/, with a spatial resolution of 250 m, corresponding to the four tiles that encompass the study area (h13v9, h14v9, h13v10, and h14v10) for 388 imaging dates from 2000 through 2016. The product used was MOD13Q1, which is the NDVI vegetation index produced every 16 days, which has been corrected for atmospheric effects. NDVI is a quantitative measurement based on vegetation spectral properties and related to biomass and vegetation vigor. It is indicative of plant photosynthetic activity related to leaf area index and the fraction of PAR absorbed by vegetation. For this reason, high values of NDVI identified healthy vegetation, while low values are associated with stressed or diseased vegetation. The index is obtained through the relationship between the reflectance (ρ) of the near infrared (IVP) and red (V) bands using the following equation:

$$NDVI = \frac{\rho IVP - \rho V}{\rho IVP + \rho V} \tag{1}$$

2.3. Defining wet and dry seasons and estimating NDVI annual means

Several studies have shown that vegetation responds to climate variability (Zhou et al., 2014). Consequently, NDVI values present subtle temporal variations on large scales, making it difficult to interpret the results of this type of study (Bégué et al., 2011). Thus, to interpret NDVI trends due to changes in land use and land cover, rainfall variability, which is the main factor of the NDVI variation, has been considered (Hickler et al., 2005).

Rainfall in the Brazilian semiarid region shows high spatial and temporal variability (Marengo et al., 2016), split over 3–4 months of the wet season, followed by a long dry season during the remainder of the year. We determined the onset and demise of the wet and dry seasons based on the analysis performed by Cunha et al. (2015). Using data of 1974 meteorological stations for the period 1970–2012, they identified the months of the year with a high frequency of rainy days and divided the area into five regions, which are entirely consistent with the different rainfall regimes of the study area described by Kousky (1979). For the purpose of this study, we treated the remaining months as the dry season, excluding a two-month interval prior to the onset and the end of the wet season to minimize potential interferences in the NDVI values associated with inter-annual shifts in the wet season onset/demise.

Considering the months corresponding to each season, the average NDVI values were calculated for each season, resulting in two images for each year. Thus, the original dataset was reduced to 34 images, referring to the mean values of NDVI for the dry and humid season of the 17 year-period analyzed.

2.4. Calibration of NDVI values for bare soil

The spatial variability of soil and plant reflectance requires extensive in situ measurements, which is not feasible in most studies (Montandon and Small, 2008). Thus, due to the extension of the study area, field analyses were conducted in an eastern region of the study area from September 11 to 16, 2016, in an area of approximately 4908.20 km^2. The region is known as Alto Sertão Sergipano, is located between the coordinates 9°30′S to 11°30′S and 36° 'W to 38°30′W and is one of the priority areas of the United Nations Development Program - UNDP for recovery from degradation. The period chosen for conducting field evaluations was the dry season because it was the most favorable time to map *Caatinga* vegetation (Guimarães, 2009; Lopes et al., 2010; Chaves et al., 2012). The field data sampling technique used was non-random (selective): we collected 170 ground-truth points, with large extensions of bare soil and different degrees of vegetation density, pasture and agriculture, to serve as training samples for the classification of a wide range of NDVI values. Using Landsat 8 images, we drew polygons around each point and assigned the polygon to a land use and land cover class (bare soil, pasture, agriculture and forest). In order to determine the degradation history of each field point, we applied questionnaires to the local community to verify for how long the area remained as bare soil. Training samples (number of locations and number of pixels) were then associated to the NDVI range for bare soil classification.