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Identifying areas susceptible to desertification in the Brazilian northeast

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Abstract. Approximately 57 % of the Brazilian northeast region is recognized as semi-arid land and has been undergoing intense land use processes in the last decades, which have resulted in severe degradation of its natural assets. Therefore, the objective of this study is to identify the areas that are susceptible to desertification in this region based on the 11 influencing factors of desertification (pedology, geology, geomorphology, topography data, land use and land cover change, aridity index, livestock density, rural population density, fire hot spot density, human development index, conservation units) which were simulated for two different periods: 2000 and 2010. Each indicator were assigned weights ranging from 1 to 2 (representing the best and the worst conditions), representing classes indicating low, moderate and high susceptibility to desertification. The results indicate that 94 % of the Brazilian northeast region is under moderate to high susceptibility to desertification. The areas that were susceptible to soil desertification increased by approximately 4.6 % (83.4 km^2) from 2000 to 2010. The implementation of the methodology provides the technical basis for decision-making that involves mitigating actions and the first comprehensive national assessment within the United Nations Convention to Combat Desertification framework.

1 Introduction

Drylands (arid, semi-arid and dry sub-humid areas) cover approximately 41 % of the Earth's surface and approximately 10 to 20 % of these regions are experiencing degradation processes (Deichmann and Eklundh, 1991; Reynolds et al., 2007), resulting in a decline in agricultural productivity, loss of biodiversity and the breakdown of ecosystems. According to the United Nations Conference to Combat Desertification (UNCCD), when land degradation happens in the world's drylands it often creates desert-like conditions. Land degradation occurs everywhere but is defined as desertification when it occurs in the drylands, resulting from various factors, including climatic variations and human activities (UN, 1979; UNCCD, 2012). The vegetation is composed of scrublands patches (high plant cover) interspersed with herbaceous patches (low plant cover)(Aguiar and Sala, 1999). This heterogeneity is induced by overgrazing, one of the main causes of the increase of bare soil that facilitates water and wind erosion and accelerates the desertification process (Cerdà and Lavee, 1999; Kröpfl et al., 2013; Pulido-Fernández et al., 2013; Ziadat and Taimeh, 2013).

Forty-four percent of global agricultural areas and almost 2 billion people are located over the drylands, and the majority (90 %) are in developing countries (D'Odorico et al., 2013). Overexploitation of natural resources in extremely vulnerable regions can accelerate land degradation and desertification process, affecting ecosystem functions and de-

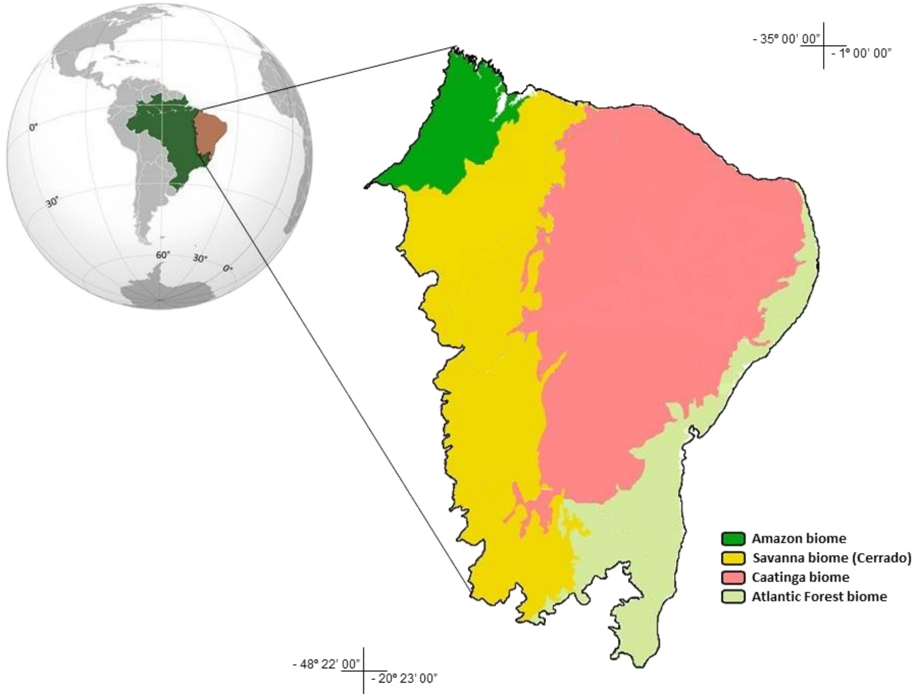

Figure 1. Study area location and its main biomes.

creasing productivity, biodiversity and landscape heterogeneity, and represents a major threat to the environment and human welfare (Mainguet, 1994; Reynolds and Stafford Smith, 2002; Montanarella, 2007; Salvati and Zitti, 2008; Cerdà et al., 2010; Santini et al., 2010; Kashaigili and Majaliwa, 2013; Pulido-Fernández et al., 2013; Bisaro et al., 2014).

In South America, the United Nations Convention to Combat Desertification report (ONU, 1997) concluded that, until 2025, one-fifth of the productive land could be affected by the desertification process. The most susceptible areas are located in Argentina, Bolivia, Chile, Mexico, Peru and Brazil (Arellano-Sota et al., 1996). In Brazil, the most critical desertification hot spots are located in the semi-arid northeast. In this region the climate is one of the factors that control the desertification process. Soil type, geology, landscape, vegetation, socioeconomic factors and land management also are considered important aspects of this process (IBGE, 2004). The main causes of desertification in this region are (i) deforestation to produce fuel wood and explore clay deposits; (ii) intensive land use employing poor agricultural methods, such as slash and burn, harvesting and land clearing; (iii) salinization; and (iv) extensive herding and overgrazing (Nimer, 1988).

Considering that the Brazilian semi-arid region is the world's most populous dry land region (Marengo, 2008), with more than 53 million inhabitants and a human population density of approximately 34 inhabitants per km^2 (IBGE, 2010), and that global climate change scenarios indicate that the region will be affected by increased aridity in the next century, this area is seen as one of the world's most vulnerable regions to climatic change (IPCC, 2007).

The UNCCD recognizes desertification as an environmental problem with huge human, social and economic costs (Hulme and Kelly, 1993).

The most accepted definition currently states that desertification is land degradation in arid, semi-arid and dry subhumid areas resulting from various factors, including climatic variations and human activities (UN, 1979). Due to the complex social interactions and the biophysical processes, the identification and assessment of the desertification areas have been addressed through a multidisciplinary framework across different spatial and temporal scales (e.g., Prince et al., 1998; Diouf and Lambin, 2001; Thornes, 2004; Santini et al., 2010).

Several methods have been successfully applied for desertification analysis based on indicators and indices (Kepner et al., 2006; Sommer et al., 2011). For instance, the MEDALUS methodology, developed for the European Mediterranean environment, is widely used because of its simplicity and flexibility. The MEDALUS methodology is based on the environmentally sensitive area index (ESAI; Parvari et al., 2011; Salvati et al., 2011; Izzo et al., 2013; Jafari and Bakhshandehmeh, 2013). In order to identify areas potentially affected by land degradation, the method analyzes four main variables: climate, soil, vegetation and land management (Kosmas et al., 1999, 2006; Lavado Contador et al., 2009). It has been validated on regional and local scales (Basso et al., 2000; Brandt et al., 2003; Salvati and Bajocco, 2011) and was

Table 1. Indicators of land degradation/desertification.

Indicators	Scale/Spatial resolution	Period	Source
Geology	1 : 500 000/90 m	2010	INPE/MMA
Geomorphology	1 : 500 000/90 m	2010	INPE/MMA
Pedology	1 : 500 000/90 m	2010	INPE/MMA
Land use and land cover	1 : 500 000/90 m	2000 and 2010	INPE/MMA
Aridity index	1 : 500 000/5 km	1970–2000	INMET/CPTEC
Slope angle	1 : 500 000/90 m	2010	INPE
Rural population density	Per municipality	2000 and 2010	IBGE
Livestock density	Per municipality	2000 and 2010	IBGE
Fire hot spot density	1 : 500 000/1 km	1999–2003 and 2008–2012	CPTEC
Human development	Per municipality	2000 and 2010	FJP
Conservation units	1 : 500 000/90 m	2010	MMA

CPTEC – Center for Weather Forecasting and Climate Research; INMET – National Institute of Meteorology; FJP – João Pinheiro Foundation, INPE – National Institute For Space Research; MMA– Ministry of the Environment; IBGE – Brazilian Institute of Geography and Statistics.

applied to quantify the impact of mitigation policies against desertification (Basso et al., 2012).

Symeonakis et al. (2014) estimated the environmental sensitivity areas on the island of Lesvos (Greece) through a modified ESAI, which included 10 additional parameters related to soil erosion, groundwater quality, demographic and grazing pressure, for two dates (1990 and 2000). This study identified areas that are critically sensitive on the eastern side of the island mainly due to human-related factors that were not previously identified.

Although several studies have been conducted to detect desertification or to identify the drivers (indicators) of the process in critical hot spots in the Brazilian northeast (Matallo Júnior, 2001; Lemos, 2001; Sampaio et al., 2003; Aquino and Oliveira, 2012), there have been no studies addressing the entire region.

Crepani et al. (1996) developed a methodology based on the concept of the eco-dynamic principles, proposed by Tricart (1977), and on the relationship between morphogenesis and pedogenesis to identify areas that are susceptible to soil erosion. The author provided an integrated view of the physical environment and the conceptual basis for developing human–nature relationships. However, this study did not include socioeconomic and management indicators as parameters that can influence soil loss.

Therefore, this paper presents a novel approach which integrates the MEDALUS project and the methodology developed by Crepani et al., 1996 to identify areas that are susceptible to desertification in the northeastern region of Brazil and the northern regions of the states of Minas Gerais and Espírito Santo by combining social, economic and environmental indices. This study was conducted considering two reference periods: early 2000s and 2010. The results will be useful for providing basic information for the diagnosis and prognosis of desertification in the region and providing subsidies for the technical support for mitigation and adaptation actions.

2 Study area

The study area is located in the equatorial zone (1–21° S, 32–49° W), totaling an area of 1 797 123 km^2, which corresponds to 20 % of the Brazilian territory (Fig. 1).

The climatology of the northeast of Brazil includes three different rainfall regimes: (i) in the south-southwest area, the rainy season occurs from October through February, which is associated with the displacement of cold fronts coming from the south; (ii) in the north of the region, rainfall occurs from February to May, which is associated with the southward movement of the Intertropical Convergence Zone; and finally, (iii) in a narrow area that is close to the coast at the east, the rainy season occurs from April through August, triggered by temperature differences between the oceans and the sea shore (Kousky, 1979; Marengo, 2008). The evaporation rate in the region is very high and can reach 1000 mm yr^{-1} in the coastal region and up to 2000 mm yr^{-1} in the interior (IICA, 2001), based on 11 stations distributed in the semi-arid region and on historical series (Molle, 1989). Annual evaporation average is 2700 to 3300 mm, with the highest values occurs from October to December and the lowest from April to June.

Because of the high evaporation rates and the short duration of the wet season, most of the rivers are temporary, and flash floods occur only during the rainy season (MMA-IBAMA, 2010).

In the northeast region of Brazil, natural vegetation includes rainforests, riparian forests, savannas and montane forests, among others (Foury, 1972). However, the natural vegetation that dominates 62 % of Brazilian semi-arid region is *caatinga* (MMA, 2007). *Caatinga* vegetation is composed of shrubs and small trees, usually thorny and decidu-

Table 2. Land use and land cover classes.

Land use and land cover classes	Description
Evergreen forest	Evergreen broadleaf closed/open
Water body	Rivers, streams, canals, lakes, ponds or puddles
Beach	Beach area
Seasonal forest	Type of forest characterized by trees that seasonally shed their leaves
Restinga	Herbaceous and arbustive vegetation, distributed along the coastal zone
Urban area	Cities and towns
Savanna (Cerrado)	Grasslands, shrublands and woodlands
Fluviomarine	Mangrove
Alluvial	Similar characteristics to the evergreen forest but differs because of its physiographical position (alluvial plain)
Campo Maior complex	Prevailingly herbaceous vegetation; presence of carnaubais (coconut type) in flood plains
Steppe Savanna (*caatinga*)	Vegetation typical of the Brazilian semi-arid region characterized by xeric shrubland and thorn forest that primarily consists of small, thorny trees that shed their leaves seasonally
Shrimp farming	Producing shrimp
Pasture	Pasture area (both natural and planted)
Agriculture	Cultivated areas (temporally and permanent crops)
Baixada Maranhense	Low plain area that is flooded in the rainy season, creating large lagoons
Bare soil	Bare soil areas without natural covering
Dunes	Sand dunes along the coast
Rock outcrops	Exposed rock areas
Salt fields	Areas where sea salt is produced

ous, that lose their leaves in the early dry season. *Caatinga* is a highly dynamic ecosystem that responds quickly to climatic conditions. The dominant factor that controls the structure and distribution of vegetation is the precipitation, with an annual mean of 500–800 mm and high spatial and temporal variability (Hastenrath and Heller, 1977; Oliveira et al., 2006). *Caatinga*, in comparison with other xeric areas in South America, presents climatic distinctiveness that resulted in numerous important morphological and physiological adaptations to aridity by many species of plants (Mares et al., 1985). Nowadays, more than 10 % of the semi-arid area has already undergone a very high degree of environmental degradation, being susceptible to desertification (Oyama and Nobre, 2004).

3 Methods

To identify areas susceptible to desertification, we evaluated 11 indicators of susceptibility to desertification (Table 1) based on previous studies of the area (Vasconcelos Sobrinho, 1978; Ferreira et al., 1994; Matallo Júnior, 2001; Lemos, 2001). From Table 1, each indicator was sub-divided into various uniform classes. Each class received a weight factor, related to the potential influence on desertification process, that ranged between 1 (low susceptibility) and 2 (high susceptibility), producing 11 susceptibility maps (SM). The weight factors were assigned based on previous analyses of the literature (Crepani et al., 1996, Torres et al., 2003; Alves, 2006; Santini et al., 2010; Symeonakis et al., 2013). These indicators were grouped into two groups as described below.

3.1 Physical indicators

3.1.1 Slope data, geology, geomorphology and pedology maps

The basic topographic data set used was a 30 m spatial resolution digital elevation model (DEM), derived from TOPADATA, which was developed based on Shuttle Radar Topography Mission data (Farr and Kobrick, 2000; Van Genderen et al., 1987). The DEM was processed to derive elevation and slope angle and used to identify breakline surface discontinuities where changes occurred in the vertical curvature which are linked to lithological, pedological, geomorphological and vegetation characteristics. Therefore, breaklines often indicate the boundary between adjacent units on a map.

Geomorphology and geology maps were extracted from RADAMBRASIL Project (Projeto RADAMBRASIL 1973–1981) and from the Geological Survey of Brazil (CPRM – Companhia de Pesquisa de Recursos Minerais), both with a spatial scale of 1 : 1 000 000. These basic maps were digitized and then rescaled to the scale of 1 : 500 000 using the processed DEM, following the procedure suggested by Valeriano and Rossetti (2012).

Soil maps (EMBRAPA, 1999) were rescaled from 1 : 5 000 000 to 1 : 500 000 based on the topographic map information. The Brazilian System of Soil Classification is based on soil pedogenetic characteristics, and also uses morphological, physical, chemical and mineralogical criteria (Camargo et al., 1987). The system is hierarchical and "opened" which allows the inclusion of new classes and enables the classification of all soil types that occur in Brazil.

3.1.2 Aridity index (AI)

The aridity index is considered to be one of the most important indicators of areas that are susceptible to desertification (UNESCO, 1979; Sampaio et al., 2003). In this study, the AI was obtained by the following formula:

$$\mathrm{AI} = P/\mathrm{PET}, \tag{1}$$

where P is the precipitation and PET is the potential evapotranspiration calculated using the Penman–Monteith equation (Monteith, 1965).

3.2 Socioeconomic indicators

3.2.1 Land use and land cover maps

Between 2000 and 2010, northeast Brazil was the fastest-growing economic (IBGE, 2010) region of the country and has been undergone severe land use and land cover changes. Therefore, it is crucial to asses if the combination of both effects – fast growth and severe land use changes – have impacted the susceptibility to desertification/degradation of the region. Thus, 90 Landsat-TM images (30 m resolution) of the dry period (July to September) of 2010 and 2011 were selected and geocoded based on the orthorectified Landsat images from the Global Land Cover Facility (NASA). These images were used to update the land use and land cover map derived by the ProVeg Project (Vieira et al., 2013), which was based on Landsat images from 2000. Additionally, land use and land cover maps from the PROBIO (Project for Conservation and Sustainable Use of Biological Diversity) (MMA, 2007) project, with a spatial scale of 1 : 500 000, and high-resolution images from Google Earth were used as auxiliary data. The land use and land cover classes mapped in this study are presented on Table 2.

3.2.2 Rural population density

These data were extracted from IBGE census data (available at http://downloads.ibge.gov.br/downloads_estatisticas.htm). The rural area boundaries and the number of inhabitants were defined considering information for both 2000 and 2010.

3.2.3 Livestock density

Livestock density data, based on the total number of cattle and goat herds per municipality in 2000 and 2010, were extracted from IBGE agricultural census.

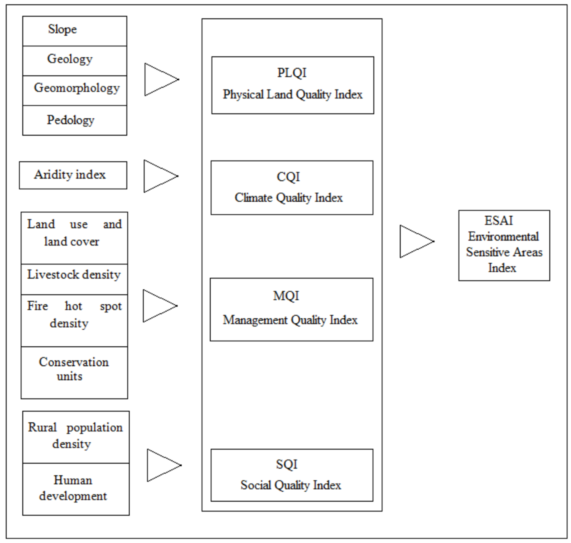

Figure 2. Combination of indicators for the determination of the ESAI; adapted from Benabderrahmane and Chenchouni (2010).

3.2.4 Fire hot spot density

Fire hot spot data were obtained from INPE's Fire Monitoring Project (INPE, 2012). Fire hot spot density maps were derived for two periods: (i) the average number of satellite hot spots from 1999 to 2003, which was used to represent the year 2000, and (ii) the average for the period 2008 to 2012, which was used as an indicator for the year 2010. To convert point data to continuous smooth surfaces, Kernel density estimation was applied to fire hot spots point using a 50 km radius (Koutsias et al., 2004; de la Riva et al., 2004). This estimator improves visualization and enables comparison with continuous environmental variables (Silverman, 1986).

3.2.5 Conservation units

Conservation unit data were obtained from the Ministry of the Environment. In the present study, the number of conservation units for 2000 and 2010 did not change. There are two basic categories of conservation units: integral protection units and the conservation units for sustainable use (Rocco, 2002). The former forbids the use of natural resources and includes national parks, ecological stations, biological reserves and wildlife sanctuaries. The latter includes national forests, extractive reserves and sustainable development reserves where the sustainable use and the management of natural resources are allowed under certain regulations.

3.2.6 Human development index (HDI)

The HDI indicators for the years 2000 and 2010 were obtained from the João Pinheiro Foundation (http://atlasbrasil.org.br/2013/). Population data, as well as HDI, are essential to understand the territorial dynamics. The calculation

Table 3. Classes and weights of parameters used for environment quality assessment.

Susceptibility class	Geomorphological types and features	Susceptibility weight
Low	Terrace formations structural and flat tops landforms; the roughness of the topographic relief is characterized by being very slightly dissected; flat relief and planation surface without intense erosive action.	1.00
	Flat and convex tops landforms; the roughness of the topographic relief is characterized by being lightly to moderately dissected; flat relief and planation surface with significant erosive action; slightly undulating relief with gentle slopes.	1.25
Moderate	Convex tops landforms; the roughness of the topographic relief is characterized by being moderately dissected; undulating relief with steep slopes.	1.50
High	Convex and sharp tops; the roughness of the topographic relief is characterized by being highly dissected; strong undulating relief with very steep slopes; karstic relief.	1.75
	Geology type	
Low	Quartzite, metaquartzite, banded iron formation, metagranodiorite, metatonalite	1.00
	Rhyolite, granite, dacite, metasyenogranite, monzogranite, syenogranite, magnetite, metadiorite, metagabbro	1.05
	Granodiorite, quartz-diorite, granulite	1.10
	Migmatite, gneiss, orthogneiss	1.15
	Nepheline syenite, trachyte, quartz-monzonite, quartz-syenite	1.20
	Andesite, basalt	1.25
	Gabbro, anorthosite	1.30
Moderate	Biotite, quartz-muscovite, itabirite, metabasite, mica schist	1.35
	Amphibolite, kimberlite	1.40
	Hornblende, tremolite	1.45
	Schists	1.50
High	Phyllite, metasiltite	1.55
	Slate rock, metargillite	1.60
	Marble	1.65
	Quartz arenites (sandstones), ortoquartizites	1.70
	Conglomerates	1.75
	Arkoses	1.80
	Siltstones, Argillite	1.85
	Shale	1.90
	Limestone, dolostone	1.95
	Unconsolidated sediments (colluvial and alluvial deposits, sandy deposits, etc.)	2.00

Table 3. Continued.

Susceptibility class	Geomorphological types and features	Susceptibility weight
	Soil type (EMBRAPA, 1999)	
Low	Latosols, organic soils, hydromorphic soils, humic soils	1.00
Moderate	Podzolic soils, brunizem, planosol, brunizem, structured dusky red earth	1.33
High	Cambisol Non-cohesive soils, immature soils, laterites, rocky outcrop	1.66 2.00
	Slope (%)	
Low Moderate High	2–6 6–18 > 18	1.00 1.50 2.00

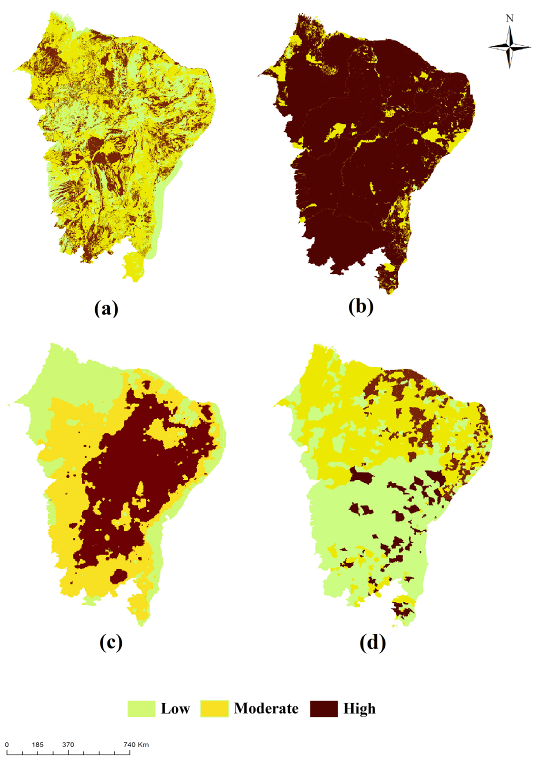

Figure 3. (a) Physical land quality index; **(b)** management quality index; **(c)** climate quality index; **(d)** social quality index.

of the HDI includes three kinds of data: longevity, education and economic income. HDI scale ranges from 0 to 1, where values from 0 to 0.49 represent low HDI, 0.5 to 0.59 medium HDI, 0.60 to 0.79 high HDI, and 0.8 to 1.0 very high HDI. According to the Atlas of Human Development of Brazil 2013, developed by a partnership between United Nations Development Program (UNDP, 2010), the Institute of Applied Economic Research and the João Pinheiros Foundation the Brazil have reduced the inequalities between its sub-indices of education, income and longevity in 2010.

3.3 Environmentally sensitive area index

The methodology used to map susceptible areas to desertification was based on the MEDALUS methodology (Mediterranean Desertification and Land Use, by Kosmas et al., 1999), which uses geometric means of environment-state and response indicators. Each index is estimated from a combination of indicators of desertification, which depends on geology, pedology, land management, human occupation and conservation policies (Fig. 2).

These maps were then grouped according to four quality indexes (Kosmas et al., 1999).

– Physical land quality index (PLQI):

$$\mathrm{PLQI} = (I_\mathrm{s} \cdot I_\mathrm{g} \cdot I_\mathrm{gm} \cdot I_d)^{1/4}, \quad (2)$$

where I_s is the soil SM, I_g is the geology SM, I_gm is the geomorphology SM and I_d is the slope SM.

– Management quality index (MQI):

$$\mathrm{MQI} = (I_\mathrm{uc} \cdot I_p \cdot I_\mathrm{fq} \cdot I_\mathrm{ucob})^{1/4}, \quad (3)$$

where I_uc is conservation units SM, I_p is the livestock density SM, I_fq is the fire density SM and I_ucob is the land use and land cover SM.

– Climate quality index (CQI):

$$\mathrm{CQI} = I_\mathrm{a}, \quad (4)$$

where I_a is the aridity index SM.

Table 4. Classes and weights of parameters used for management quality assessment.

Susceptibility class	Land use/land cover change classes	Susceptibility weight
Low	Evergreen forest, water body, beach, urban area	1.00
	Deciduous forest	1.40
	Restinga	1.45
Moderate	Savanna (Cerrado), fluviomarine pioneer, alluvial pioneer	1.50
	Complex of Campo Maior, Baixada Maranhense	1.55
	Caatinga	1.60
	Shrimp farming, pasture	1.80
	Agriculture	1.90
High	Bare soil, dunes, rocky outcrop	2.00
	Livestock density data	
Low	0 to 30	1.00
Moderate	30 to 75	1.50
High	above 75	2.00
	Fire density data	
Low	0 to 1000	1.00
Moderate	1000 to 2000	1.50
High	above 2000	2.00
	UC data	
Low	Integral protection units	1.00
Moderate	Conservation units for sustainable use	1.50
High	Without conservation unit	2.00

– Social quality index (SQI):

$$\mathrm{SQI} = (I_{\mathrm{HDI}} \cdot I_{\mathrm{Pop}})^{1/2}, \tag{5}$$

where I_{HDI} is the human development index SM and I_{pop} is rural population density SM.

The geo-database was developed using SPRING (Câmara, et al., 1996).

Finally, to obtain an ESAI, the geometric mean is calculated among the variables inside each factor through the following equation:

$$\mathrm{ESAI} = (\mathrm{PLQI} \cdot \mathrm{MQI} \cdot \mathrm{CQI} \cdot \mathrm{SQI})^{1/4}. \tag{6}$$

Based on these calculations, three types of ESAs were assigned: (a) low-susceptibility areas (ESAI $1.00 \geq 1.25$), (b) moderate-susceptibility areas (ESAI $1.25 \geq 1.50$) and (c) high-susceptibility areas (ESAI > 1.50).

Table 5. Classes and weights of parameters used for climate quality assessment.

Susceptibility class	Climate types	Susceptibility weight
Low	Wet sub-humid (AI above 0.65)	1.00
Moderate	Dry sub-humid (AI between 0.51 to 0.65)	1.50
High	Semi-arid (AI between 0.21 to 0.50)	2.00

3.4 Validation

In this study, the 2010 susceptibility map was validated using the method proposed by Van Genderen et al. (1978). This method assumes that the probability of making f interpretation errors when taking x samples from a remote-sensing-based classification map follows a binomial probability distribution function. The method allows the determination of the minimum sample size required for validating the map, avoiding the risk of accepting a map with low accuracy.

Based on this methodology, 110 random samples were selected from the low-, medium- and high-susceptibility classes and compared with high-resolution images from Google Earth (Ginevan, 1979; Congalton and Green, 1999) and in situ images. Thus, the points from high-susceptibility classes were compared to their corresponding images to observe the degraded areas of exposed soil.

4 Results and discussion

This work presents the first effort to identify the areas that are most susceptible to desertification in the semi-arid region of Brazil through a system that enables continuous and integrated analysis of the factors that provide the best explanation of the desertification processes.

The weight factors assigned to each indicator are described in Tables 3, 4, 5 and 6.

Analyses from 11 indicators stress that areas with predominantly humid and sub-humid climate are potentially susceptible to desertification due to inadequate soil management, which is a key factor for adaptation and mitigation of climate change (IPCC, 2007).

On the MEDALUS methodology, variables like HDI and conservation units were not included. However, these two indicators were considered important in the semi-arid region Brazil based on the fact that the region has relatively low development indexes and several inadequate land uses practices, and previous studies in other regions of Brazil (Trancoso et al., 2010) have shown that conservation enforcement in protected areas is crucial for avoiding degradation.

4.1 Physical land quality index

In terms of soil types, the northeast and southern portions of the region are largely covered by Podzolic soils (23 %) that are more prone to erosion due to the low permeability of the B clayey horizon. Lithosols (21 % of the area) occur in the semi-arid region, associated with rock outcrops. Lastly, the Latosols (18 %) dominate the northwest region, associated with Savanna vegetation, where the relief is plain and favors the mechanized agriculture increasing soil compaction (Cavaliere et al., 2006; Araújo et al., 2007).

The eastern part of the study area is dominated by crystalline rocks. However, there is a predominance of sedimentary basins located in coastal regions and in the western part of the study area. To the south of the region, extensive karst formations can be found. Most of the study area consists of flat and undulating relief, but the occurrence of steep formations and the presence of inselbergs have also been noted.

According to the spatial distribution of the physical land quality index (Fig. 3a), 52 % of the study area has a moderate susceptibility. The areas with high susceptibility are on soil types that are more vulnerable to erosion processes, such as podzols (23 %) and lithosols (21 %).

4.2 Management quality index

The analyses showed an increase of 3 % of the area with high susceptibility for a period of 11 years between 2000 and 2010 (Table 7). Areas with high susceptibility reached 87 % (1 571 033 km^2) of the studied area in 2000, while in 2010 the percentage increased to 90 % (1 622 716 km^2). Among the factors that might be contributing to the increase in area are shrimp farming, agriculture, livestock and fire hot spots. Analyzing the results of use land and land cover, it is possible to observe that the natural vegetation is being replaced by pastures and agriculture. According to the land use/cover map developed by Vieira et al. (2013), the typical vegetation of the semi-arid of Brazil, known as *caatinga*, has been replaced by pasture and agricultural activities. Approximately 40 % of the *caatinga* has been converted to these uses, and the remaining area is being transformed at a rate of 0.3 % per year (IBAMA/MMA, 2010).

Table 6. Classes and weights of the parameters used for social quality assessment.

Susceptibility class	Human development index Per municipality	Susceptibility weight
Low	0.70 to 1.00	1.00
Moderate	0.60 to 0.70	1.50
High	0 to 0.60	2.00
	Rural population density	
Low	0 to 25	1.00
Moderate	25 to 50	1.50
High	above 50	2.00

In recent years, agribusiness has become one of the most dynamic segments in the northeastern states with the production of fruits, such as papayas, melons, grapes, watermelons, pineapples and mangos. The activities related to shrimp farming covered an area of 69.7 km^2 in 2000, which increased to 136.7 km^2 in 2010. Northeastern Brazil is responsible for 94 % of all shrimp production in Brazil (Ferreira, 2008).

Even though areas located in sub-humid and humid areas are less vulnerable from a climatic point of view, they are susceptible to land degradation and desertification due to inadequate land use and management. In the northwestern portion of study area, for example, the deforestation is one of main causes to land degradation. The natural vegetation is being replaced by pasture and agriculture, increasing from 106 568 in 2000 to 143 323 km^2 in 2010 and from 10 425 in 2000 to 20 100 km^2 in year 2010. In livestock areas of the region, fire is routinely used as a method for clearing land from bushes and for the re-establishment of pasture (Miranda, 2010). In the present work, the number of fire hot spot increased from 26 181 in 2000 to 73 429 in 2010.

4.3 Climate quality index

According to the climate quality index (Fig. 3c, Table 7), 42 % of the area is a highly susceptible semi-arid climate, while 38 % is classified as moderate susceptible dry sub-humid. Finally, 20 % of the area, where the climate is sub-humid to humid, is considered as having a low susceptibil-

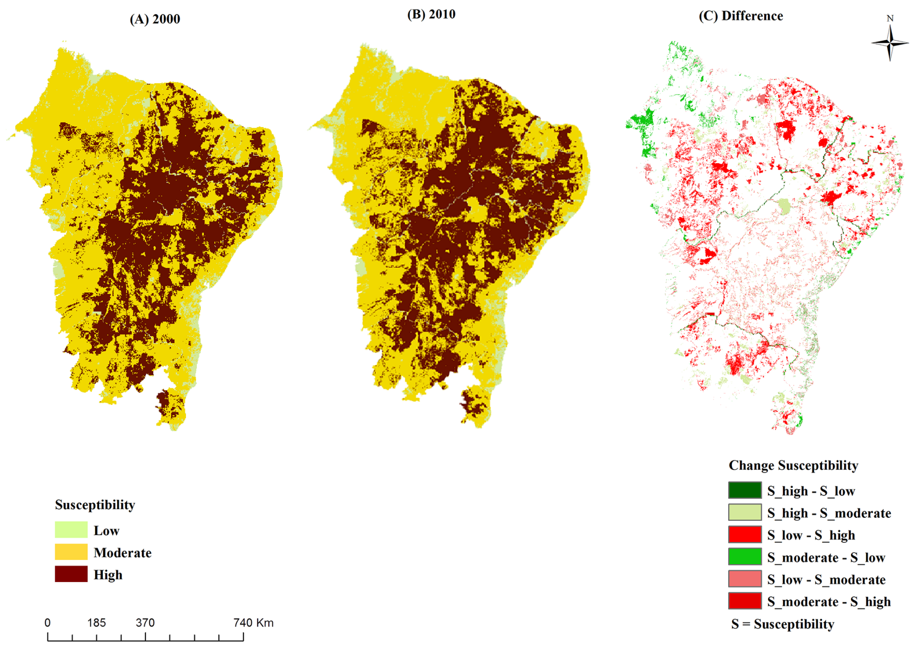

Figure 4. Environmental susceptibility area for **(a)** 2000 and **(b)** 2010. **(c)** Difference between 2000 and 2010.

Table 7. Percentage of the land area covered by each susceptibility class of the four quality indices in 2000 and 2010.

Index	Susceptibility class	2000 (%)	2010 (%)
Physical land quality index (PLQI)	Low	24.5	24.5
	Moderate	52.7	52.7
	High	22.9	22.9
Management quality index (MQI)	Low	1.0	0.8
	Moderate	11.6	8.9
	High	87.4	90.3
Climate quality index (CQI)	Low	19.5	19.5
	Moderate	38.2	38.2
	High	42.3	42.3
Social quality index (SQI)	Low	42.4	48.1
	Moderate	34.8	32.9
	High	22.8	19.0

ity. From a climatic point of view, rainfall exceeds 1250 mm in the coastal region annual. To the west, annual rainfall is around 1500 mm, while in the semi-arid interior annual rainfall is less than 1000 mm, ranging from 350 to 750 mm (IBGE, 1996).

4.4 Social quality index

The social quality index showed that 42 % of the region had low susceptibility in 2000, while the value increased to 48 % in 2010 (Table 7). According to IBGE (2010), the HDI improved in this period in response to the country's economic growth. The region is marked by socioeconomic inequality; the highest HDI is in the northern (0.682) and eastern (0.684) regions and the lowest is in the northeast (0.631).

4.5 Susceptibility areas to desertification

The areas susceptible to desertification in the Brazilian semi-arid region for both 2000 and 2010, as well as the changes that occurred between these periods, are presented in Fig. 4. The results showed that 94 % of the semi-arid region is moderately (59.4 %) or highly (35 %) environmentally sensitive for both periods: 2000 (94.4 %) and 2010 (94 %). High-sensitivity areas increased from 35 to 39.6 %, which corresponds to 83 348 km^2. Moderate regions decreased almost 5 % (89 856 km^2), while low-sensitivity areas increased from

5.6 % (2000) to 6 % (2010). The most susceptible areas were mapped, both in 2000 and 2010, in the central-eastern regions that include the four desertification hot spots officially recognized by the Brazilian Ministry of the Environment: Gilbués (PI), Irauçuba (CE), Cabrobó (PE) and Seridó (RN) (MMA, 2007).

The results also showed several areas with high susceptibility, specifically in the south of the study area. According to the field survey, desertification in this area is increasing due to inadequate soil management and indiscriminate deforestation (MMA, 2005). The human activities are the dominant factor for desertification expansion. However, in the northwest of the study area, several spots showed low susceptibility. Government incentives in the last decades have turned this region into a tropical fruit producer (Araujo and Silva, 2013).

From these results, it is clear that the management quality index is the main driver of desertification in the study region (Fig. 3b). Therefore, mitigation actions for reducing the susceptibility to degradation in the region depend heavily on changes in management practices towards more sustainable land use.

Finally, it is important to note that the validation results indicated that the environment susceptibility map has an accuracy of 85 %, which is considered acceptable due to the extent and complexity of the study area.

5 Final considerations

The environmentally sensitive area index calculated in the present study allowed a better understanding of the degradation/desertification process in the Brazilian semi-arid region. The study showed that desertification susceptibility ranges from moderate to high in the Brazilian semi-arid region.

From a climatic point of view, the humid and sub-humid areas have low vulnerability. However, when management issues associated with land use are taken into consideration, these areas become potentially susceptible to degradation.

The northwestern part of the study area is highly susceptible to land degradation due to inadequate soil management associated with intensive agricultural land expansion. In the last 50 years, the area received millions of migrants looking for better opportunities created by agriculture expansion.

This study is the first effort to produce a comprehensive diagnosis of the desertification processes for the entire region and combines the existing experience from previous studies in the region with a consolidated methodology. Additionally, new indicators were included in the methodology of this study, such as HDI (social indicator) and conservation units (management indicator), because previous knowledge indicated that they would be relevant in the study area.

In addition, it was possible to obtain a database with biophysical and social information on the same scale and resolution, which allowed the integrated analysis of the desertification indicators.

One of the major issues facing humanity today is the development of knowledge in regards to the occupation of land in regions affected by desertification in a sustainable way. Then it becomes critical to define adaptation alternatives for living in semi-arid regions. Furthermore, it can be applied in multi-scale studies, showing the magnitude of the risk in different areas and the factors that may contribute to triggering the process. The approach was based on the use of indicators that are routinely surveyed in the area, allowing for continuous monitoring of the desertification processes. The proposed methodology proved to be a useful, timely and cost-effective tool to identify areas that are susceptible to degradation/desertification.

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