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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 semiarid 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 eleven driving 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 (HDI), conservation units) which were model-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 result indicates 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 % (83.35 km^2) from 2000 to 2010. The implementation of the methodology provide the technical basis for decision making that involves mitigating actions, as well as the first comprehensive national assessment within the United Nations Convention to Combat Desertification framework.

1 Introduction

Drylands 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, 2007). In these regions the vegetation is composed by scrublands patches (high plant cover) interspersed with herbaceous patches (low plant cover) (Aguiar and Sala, 1999). This heterogeneity is induced by grazing which accompanied of the increased bare soil areas facilitate water and wind erosion and accelerates the desertification process (Kropfl et al., 2013; Cerdà and Lavee, 1999; Ziadat et al., 2013).

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In the case of wind erosion silt and clay content contribute to soil resistance (Buschiazzo et al., 1995), decreasing aeolian transport rates (Wang et al., 2013).

Land cover change, with potential soil degradation, threatens agricultural productivity (Cerdà et al., 2010) which can affect soil quality and modify water spatial variation (Gao et al., 2011), runoff and water infiltration (Kashaigili and Majaliwa, 2013). In addition, may cause land abandonment which increases erosion and runoff (Cerdà, 1997).

Forty four percent of global agricultural areas and almost 2 billion people are located over the drylands, and the majority (90 %) is from developing countries (D'Odorico et al., 2013). Overexploitation of natural resources in extremely vulnerable regions can accelerate land degradation and the desertification process, affect ecosystem functioning and decrease productivity, biodiversity and landscape heterogeneity with a serious threat to the environment, and human welfare (Mainguet, 1994; Reynolds and Stafford Smith, 2002b; Montanarella, 2007; Salvati and Zitti, 2008; Santini et al., 2010; 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 hotspots are located in the semiarid Northeast. In this region the climate is just one of the factors that control the desertification process. Soil type, geology, geomorphology, relief, 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 semiarid 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 km^{-2} (IBGE, 2010), and that global climate

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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 United Nations Conference to Combat Desertification (UNCCD) recognizes desertification as an environmental problem with huge human, social and economic costs (Hulme and Kelly, 1993).

The most accepted definition up to date states that desertification is land degradation at arid, semiarid and dry subumid areas resulting from various factors, including climatic variations and human activities (United Nations – 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, 2010).

Several methods have been successfully applied for desertification analysis based on indicators and indices (Kepner et al., 2006; Sommer et al., 2011). One of the most used method in the Mediterranean is based on the Environmentally Sensitive Area Index (ESAI) (Kosmas et al., 1999), due to its simplicity and flexibility (Parvari, 2011; Salvati et al., 2011; Javari and Bakhshandehmeh, 2013; Izzo, 2013). This methodology analyzes four main variables: climate, soil, vegetation and land management (Kosmas et al., 1999, 2006; Lavado Contador et al., 2009a); in order to identify areas potentially affected by land degradation. It has been validated on regional and local scales (Basso et al., 2000; Brandt, 2003; Salvati and Bajocco, 2011) and was applied to quantify the impact of mitigation policies against desertification (Basso et al., 2012).

Symeonakis (2014) estimated the environmental sensitivity areas on the island of Lesvos (Greece) through a modified Environmentally Sensitive Area Index (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 in the eastern side of the island mainly due to human-related factors, which was not previously identified.

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Although several studies have been conducted to detect desertification or to identify the drivers (indicators) of the process in critical hotspots in the Brazilian Northeast (Matallo Júnior, 2001; Lemos, 2001; Sampaio et al., 2003; Soares et al., 2011; Aquino and Oliveira, 2012) there have been no studies addressing the entire region.

Crepani (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, which can influence soil loss.

Therefore, this paper presents a novel approach which integrates the MEDALUS project and the methodology developed by Crepani (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 obtained results will be useful by providing the basic information for the diagnosis and prognosis of desertification in the region, as well as to provide subsidies for the technical support for mitigation and adaptation actions.

2 Materials and methods

2.1 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

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the southward movement of the Intertropical Convergence Zone (ITCZ), 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 nearby land (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 semiarid 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 lowers 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 occurs only during the rainy season (MMA, 2010).

In the Northeast region of Brazil, natural vegetation includes rainforests, riparian forests, savannas, montane forests, among others (Foury, 1972). However, the natural vegetation that dominates 62 % of Brazilian semiarid region is steppic savana also known as caatinga in Brazil. (MMA, 2007). Caatinga vegetation is composed of shrubs and small trees, usually thorny and deciduous that loses 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 semiarid area has already undergone a very high degree of environmental degradation, being susceptible to desertification (Oyama and Nobre, 2004).

2.2 Selection of the susceptibility indicators

To identify areas susceptible to desertification, we evaluated eleven indicators of susceptibility to desertification (Table 1), based on previous and extensive analysis of the studied area (Vasconcelos Sobrinho, 1978; Ferreira et al., 1994; Matallo Júnior, 2001; Lemos, 2001). They were grouped into three sets: physical, biological and socioeconomic quality indicators.

2.2.1 Topography data, geology, geomorphology and pedology maps

The basic topographic data used was a 30 m spatial resolution Digital Elevation Model (DEM), derived from TOPADATA (Valeriano, 2008) which was developed based on STRM (Shuttle Radar Topography Mission) data (Farr and Kobrick, 2000; van Zyl, 2001). The DEM was processed to derive altimetry and slope and used to identify surface break-lines (surface discontinuities where occur changes in the vertical curvature).

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 reinterpreted, to scale of 1 : 500 000, using the processed DEM, following the procedure suggested by Valeriano (2008) and Valeriano and Rossetti (2008).

Soil maps from the Brazilian Agricultural Research Corporation (EMBRAPA) (Jacomin et al., 2005) at a 1 : 5 000 000 scale were also reinterpreted, to scale of 1 : 500 000, using the topographic map.

2.2.2 Land use and land cover maps

Ninety 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 PROBIO (Project for Conservation and Sustainable Use of Biological Diversity) (MMA, 2007), 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.

2.2.3 Aridity index

The aridity index (AI) 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).

2.2.4 Rural population density

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

2.2.5 Livestock density

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

2.2.6 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

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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).

2.2.7 Human development index (HDI)

The HDI indicators for the years 2000 and 2010 were obtained from the João Pinheiro Foundation. Population data, as well as HDI, are essential to understand the territorial dynamics. The calculation of the HDI includes three kinds of data: longevity, education and income. HDI scale ranges from 0 to 1, where values from 0 to 0.49 represents low HDI, 0.5–0.59 medium, 0.7 to 0.79 high, and 0.8 to 1.0 very high. According to the Atlas of Human Development of Brazil in 2013, developed by a partnership between United Nations Development Program (UNPD), the Institute of Applied Economic Research ("IPEA") and the João Pinheiros Foundation, Brazil have reduced the inequalities between its subindices of Education, Income and Longevity (Table 3).

2.2.8 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). In the first one, any use of natural resources is strictly forbidden, and includes national parks, ecological stations, biological reserves and wildlife sanctuaries. The second includes national forests, extractive reserves and sustainable development reserves; where the sustainable use and the management of natural resources are allowed under certain regulations.

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2.3 Method

Each index was estimated from the combination of indicators of desertification, which depends on geology, pedology, land management, human occupation, conservation policies, etc. The quality indexes, as well as their indicators, were divided into classes of susceptibility to desertification by assigning weights ranging from 1 (no susceptibility) to 2 (susceptibility). Each class of each map, listed in Table 1 as an indicator of desertification, received a weight between 1 (low susceptibility) and 2 (high susceptibility), producing 11 susceptibility maps (SM). These maps were then grouped according to four quality indexes: Management Quality Index, Climate Quality Index, Soil Quality Index and Social Quality Index. Three susceptible classes were associated with each map: low, moderate and high.

2.3.1 Quality index

– Environmental Quality Index (EQI):

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

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):

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

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where I_a is the aridity index SM.

– Social Quality Index (SQI):

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

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).

2.3.2 Determination of the Environmentally Sensitive Area Index (ESAI)

To obtain an Environmentally Sensitive Area Index (ESAI), the geometric mean among the four indexes was determined through the following equation:

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

Based on these calculations, three types of ESAs were assigned: (a) high susceptibility areas (ESAI > 1.75), (b) moderate susceptibility areas (ESAI 1.25 ≥ 1.50), and (c) low susceptibility areas (ESAI 1.00 ≥ 1.25).

3 Results and discussion

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

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).

3.1 Environmental Quality Index

Maps of soil, geology, geomorphology and slope were combined to evaluate environmental fragility. 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 which favors the mechanized agriculture increasing soil compaction (Cavaliere et al., 2006; Araújo et al., 2007).

According to the spatial distribution of the environmental quality index (Fig. 2a), which synthesizes the conditions of characteristics of indicators (Table 4), 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 %). The areas with high susceptibility are concentrated mainly in the south portion of study area.

3.2 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 totaled 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, shrimp farming, agriculture, livestock and fire hot spots can be mentioned. 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 semiarid of Brazil, known as caatinga, has been replaced by agricultural activities and pasture area in only a few years. Approximately 40 % of the caatinga has been converted to these uses, and the remaining area is being transformed at a rate

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of 0.3 % yr^{-1} (IBAMA/MMA, 2010). 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 the shrimp farming covered an area of 69.7 km^2 in 2000, which was and has increased to 136.7 km^2 in 2010. Northeastern Brazil is responsible for 94 % of all shrimp production in Brazil, according to the Brazilian Association of Shrimp Creators-BASC (Ferreira, 2008). Burning practice increased 9 % from 2000 (133 855 km^2) to 2010 (295 176 km^2). In the region the livestock activities, use fire as a management agent (Miranda, 2010).

3.3 Climate Quality Index

According to the climate quality index (Fig. 2c, Table 8), 42 % of the area, under semi-arid climate is highly susceptible, while 38 %, classified as dry sub-humid, is considered to be of moderate susceptibility. Finally, 20 % of the area, where the climate is sub-humid to humid, presents low susceptibility. From a climatic point of view, in the coastal region annual rainfall exceeds 1250 mm. To the west, annual rainfall is around 1500 mm, while in the semiarid interior annual rainfall is less than 1000 mm, ranging from 350 to 750 mm in several areas (IBGE, 1996).

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 km^2 in 2000 to 143 323 km^2in 2010, and from 10 425 km^2 in 2000 to 20 100 km^2 in year 2010 respectively.

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3.4 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. 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, and the higher HDI are in the north (0.682) and east (0.684) region and the lower in the northeast (0.631).

3.5 Susceptibility areas to desertification

The susceptibility areas to desertification of the Brazilian semiarid region for both 2000 and 2010, as well as the changes that occurred between these periods, are presented in Fig. 3. The results showed that 94 % of the semiarid 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, as highly susceptible in the central-east regions, which include the four desertification hotspots 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. On the other hand, 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 pole producer (Araujo and Silva, 2013).

The 2010 map validation was based on the method proposed by Van Genderen et al. (1978). One hundred and ten random samples were selected and compared

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with high resolution images from Google Earth (Ginevan, 1979; Congalton and Green, 1999) and in-situ images. The result of this analysis indicated that our map has an accuracy of 85 %.

From this result, it is clear that the management quality index is the main driver of desertification in the study region (Fig. 2). Therefore, mitigation actions for reducing the susceptibility to degradation in the region depend heavily on changes in management practices towards more sustainable land use.

4 Conclusions

Desertification is the final state of the land degradation process and is recognized as one threat to the global environment, with direct impacts on human well-being. The lack of an adequate and integrated monitoring system has been identified as one of the major constraints for combating desertification and land degradation.

In this context, it was derived the Environmentally Sensitive Area Index (ESAI method), which allowed a better understanding of the degradation/desertification process in the Brazilian semiarid region. The study showed that the Brazilian semiarid region is moderately to highly susceptible to degradation/desertification processes. However, the areas under sub-humid and humid climates, with low susceptibility, are potentially susceptible to land 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, this 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 existent experience from previous studies in the region with a consolidated methodology. 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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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
Declivity	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 ClimateResearch.
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.

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Table 2. Land use and land cover classes.

Land use and 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.
Fluvio-marine	Mangrove.
Alluvial	Similar characteristics to the evergreen forest which differs because of it physiographical position (alluvial plain).
Campo Maior Complex	Herbaceous vegetation prevaling. Presence of carnaubais (coconut type) in floodplains.
Steppe Savanna (Caatinga)	Vegetation typically of the Brazilian semiarid characterized by xeric shrubland and thorn forest, primarily consisting in small, thorny trees that shed their leaves seasonally.
Shrimp farming	Shrimp producing.
Pasture	Pasture Area (both natural and planted).
Agriculture	Cultivated Areas (temporally and permanent crops).
Baixada Maranhense	Low Plain areas that is flooded in the rainy season creating large lagoons.
Bare soil	Bare soil areas, without the natural covering.
Dunes	Sand dunes along the coast
Rock outcrops	Rock surface or covered by coarse rock fragments
Salt fields	Sea salt production areas

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Table 3. List of Brazilian federative units according to Human Development Index and its subindices of education, income and longevity.

2010	HDI	0.660
	E	0.565
	I	0.653
	L	0.779
2000	HDI	0.512
	E	0.338
	I	0.583
	L	0.680
1991	HDI	0.394
	E	0.197
	I	0.528
	L	0.573

E – Education.
I – Income.
L – Longevity.

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Table 4. 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; 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; carstic relief.	1.75
Geology type		
Low	Quartzite, metaquartizite, banded iron formation, metagranodiorite, metatonalite.	1.00
	Rhyolite, granite, dacite, meta-syenogranite, monzongranite, syenogranite, magnetite, metadiorite, metagabbro.	1.05
	Granodiorite, quartz-diorite, granulite.	1.10
	Migmatite, gneiss, ortogneiss.	1.15
	Nepheline syenite, trachyte, quartz-monzonite, quartz-syenite.	1.20
	Andesite, basalt.	1.25
	Gabbro, anortosite	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), ortoquartzites	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
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	1.66
	Non-cohesive soils, immature soils, laterites, rocky outcrop	2.00
Slope (%)		
Low	2–6	1.00
Moderate	6 –18	1.50
High	> 18	2.00

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

Susceptibility class	Land Use Land Cover classes	Susceptibility weight
Low	Evergreen forest	1.00
	Water body	
	Beach	
	Urban area	
	Deciduos forest	1.40
	Restinga	1.45
Moderate	Savanna (Cerrado)	1.50
	Fluvio-marine pionner	
	Aluvial pionner	
	Complex of Campo Maior	1.55
	Baixada Maranhense	
	Caatinga	1.60
	Shrimp farming	1.80
	Pature	
	Agriculture	1.90
High	Bare soil	2.00
	Dunes	
	Rocky outcrop	
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

Table 6. 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	Semiarid (AI between 0.21 to 0.50)	2.00

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Table 7. Classes and weights of the parameters used for social quality assessment.

Susceptibility class	Human development index (HDI)	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

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Table 8. Percentage of the land area covered by each susceptibility class of the four quality indices in 2000 and 2010.

Index	Susceptibility Class	2000 (%)	2010 (%)
Environmental Quality Index (EQI)	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

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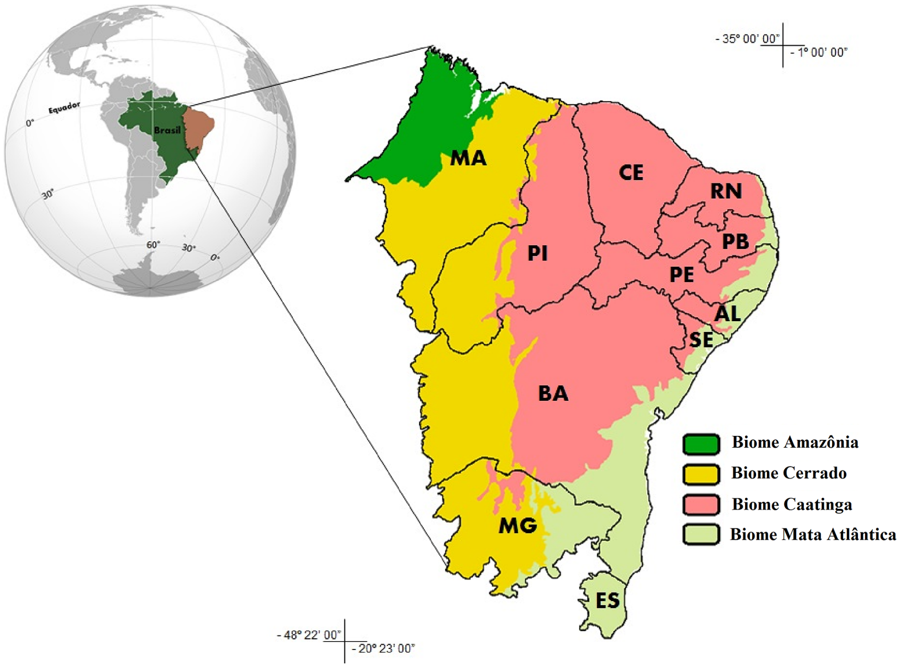

Figure 1. Study area location and its main biomes.

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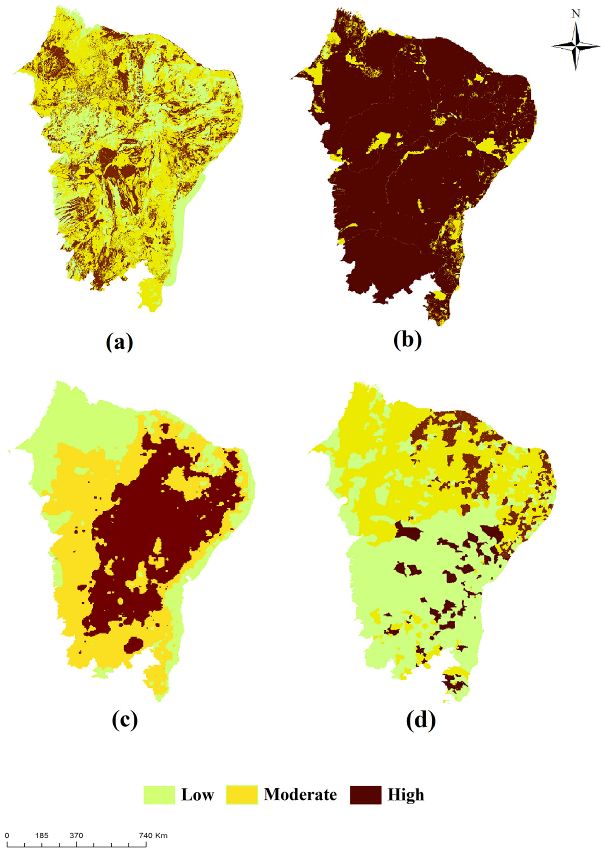

Figure 2. (a) Environmental Quality Index; **(b)** Management Quality Index; **(c)** Climate Quality Index; **(d)** Social Quality Index.

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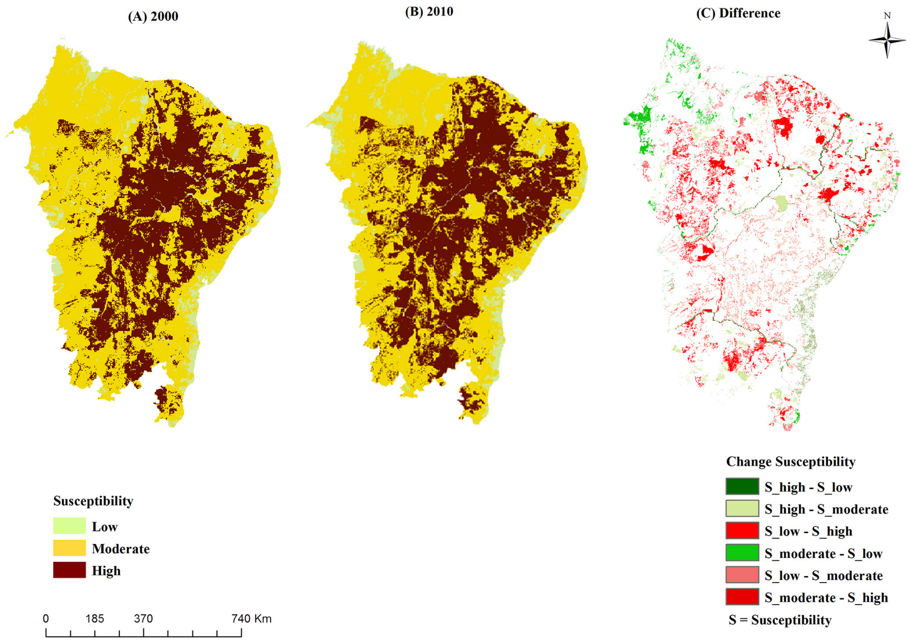

Figure 3. Environmental susceptibility area for **(a)** 2000 and **(b)** 2010. **(c)** Difference between 2000 and 2010.

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