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RESEARCH ARTICLE OPEN ACCESS

INFLUENCE OF PRECIPITATION ON THE ENVIRONMENTAL VULNERABILITY TO EROSION OF SOILS: A CASE STUDY IN THE COASTAL REGION OF PARÁ

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ABSTRACT

Soil is a vital natural resource and is essential for sustainable socioeconomic development of a given region. The knowledge of the relationships between the elements of the physical environment is essential for formulating adequate proposals for preventing and controlling soil loss. It is important to identify the areas that are the most vulnerable to soil loss, such that best land use practices can be adequately and safely adopted. The present study aimed to determine the degree of environmental vulnerability to erosion of soils in the municipalities of Curuçá and Marapanim during high and low precipitation.These municipalities are located in the northeastern region of the state of Pará, Brazil. A selection of variables (climate, geology, geomorphology, slope, soil, vegetation, and land use), map algebra techniques, and multi-criteria analysis were used in this study to spatially analyze environmental vulnerability to erosion of soils in the study area. The results showed that the erosive processes are concentrated in the coastal zone in the municipality of Marapanim, occurring mainly during the period of the heaviest precipitation. The results of this study also identified areas that are moderately vulnerable and in need of attention in urban planning and management.

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INTRODUCTION

Erosive processes are natural phenomena that occur on the Earth's surface under geological denudation of the environment (Guerra e Cunha, 1980) wherein disintegration and removal of relief particles occurunder the combined action of gravity, water, wind, ice,and organisms (Guerra e Guerra, 2003). Among the erosive agents causing soil degradation, high precipitation is one of the major factors (Lepsch, 2002; Carvalho *et al*., 2009). The propensity of an area to experience soil loss depends on the fragility of the local environment and can be analyzed by mapping the environmental vulnerability of the area (Santos, 2014; Figueiredo 2010). According to Oliveira (2011), the mapping of environmental vulnerability indicates areas that are most susceptible to the effects of erosive processes, andtherefore, must be prioritized in the erosion recovery proposals. Crepani *et al*. (2001) proposed the use of variables, such as vegetation cover, soils, relief, land use and cover, and precipitation intensity, for erosion analysis. This methodology can been applied in hydrographical basins scale (Barbosae Lorandi, 2012) and in municipality scale (Rovani *et al*., 2015). The attribution of weights to each variable and the consideration of additional factors, such as socioeconomic factors, can be adapted based on thepeculiarities of each region (Limae Amaral, 2013; Esteves, 2011; Sporse Ross, 2004). In this context, geoprocessing techniques allow for speed and efficiency in the spatial analysis of variables and map algebra (Assis*et al*., 2017). The use of the Geographic Information System (GIS) in multi-criteria analysis helps integrate spatial and temporal data (Saini*et al*., 2015). Therefore, it is possible to spatialize, quantify, and qualify the degree of environmental vulnerability to erosion (Araújo e Cândido, 2014). The aim of this study was to map the environmental vulnerability to erosion of soils in the municipalities of Curuçá and Marapanim in the state of Pará, during periods with high and low precipitation.

METHODOLOGY

Study Area: The study area includes the coastal municipalities of Curuçá and Marapanim. The region is located in the mesoregion of Salgado in northeastern Pará, with access via PA-316 and PA-318 (Figure 1). The municipality of Curuçá has a population of 41,093 inhabitants, population density of 50.98 inhabitants per km², and territorial extension of 672.61 km², while Marapanim has 28,563 inhabitants, a population density of 33.42 inhabitants per km², and an extension of 792 km² (IBGE, 2021). With regard to protected areas, Mãe Grande de Curuçá Extractive Reserve (RESEX) is located in the municipality of Curuçá (ICMBIO, 2016). The RESEX has a territorial extension of 370 km², occupies approximately 35% of the total area of the municipality and includes 52 communities (SOUSA, 2008).

The conservation unit protects the "igarapés", sandbanks, and mangroves and provide extractive activities including mussel harvesting, artisanal fishing, and traditional collection of natural products (SOUZA, 2013). The main hydrography corresponds to the rivers Mocajuba and Curuçá in the municipality of Curuçá and Paramaú, Maú, and Marapanim in Marapanim (IBGE, 2021). The predominant climate in the region is Am based on the Köppen classification, that is, hot and humid, with an average temperature of 29.6°C and an annual average precipitation of 2012 mm (ALVARES *et al*., 2014). The geomorphology of the study area is mainly characterized by coastal plateau, floodplains, and fluvial and coastal plains, while the geology is characterized by sediments of the Barreiras Formation in the continental portion and alluvial and littoral deposits (CPRM, 2013).

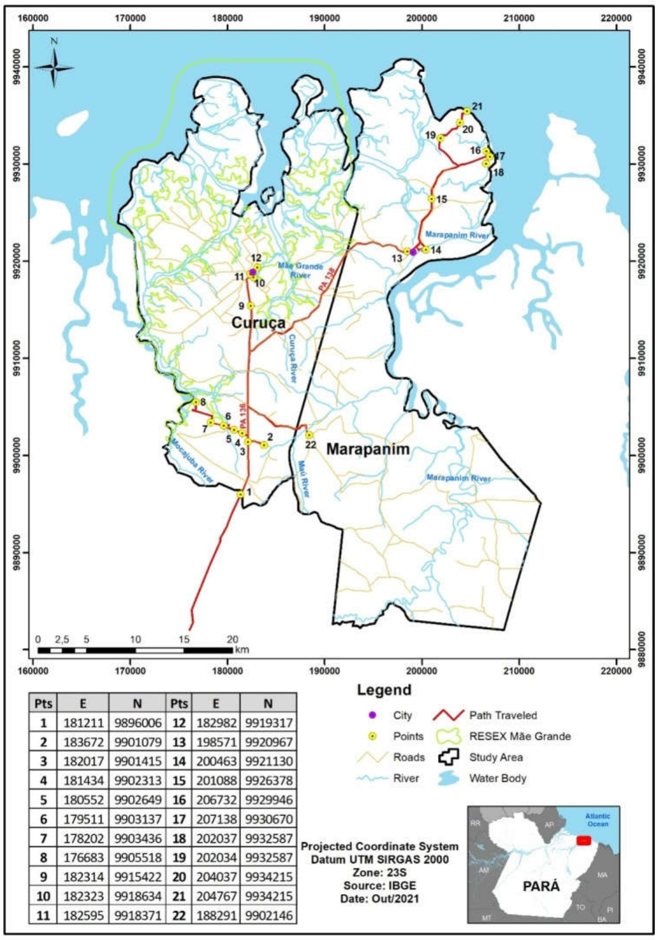

Figure 1. Location of the study area

MATERIAL AND METHODS

The following variables were considered for the analysis of the environmental vulnerability: climate, slope, geology, geomorphology, soil, vegetation, and land cover (Figure 2). The climate data for the study area were obtained from the database Global Precipitation Climatology Center (GPCC) and corresponded to the period from 1982 to 2020. GPCC has data from all over the globe and according to Limbergere Silva (2018) are the closest to the precipitation data collected in Agência Nacional de Águas (ANA) stations. Based on Bastos et al. (2002), the periods of high and low precipitation in the region, that is from December to May and from June to November, respectively, were identified. The spatialization of the precipitation data was performed by the Inverse Distance Weighted (IDW) method for the average precipitation of the six stations. This method is a simple and effective statistical technique, which uses a weighted linear combination, and is recommended when the points are evenly distributed (Shahid et al., 2017). Geological data were acquired from the Serviço Geológico do Brasil (CPRM) website, while information on soil, vegetation, and geomorphology was obtained from the Radar na Amazônia (RADAM project) available on the Instituto Brasileiro de Geografia e Estatística (IBGE) website. The slope was generated from the 30-m spatial resolution Shuttle Radar Topography Mission (SRTM) radar image acquired from the National Institute for Space Research (INPE). Ten images of the Planet satellite, that is, acquired on September 27, 202', with a spatial resolution of 4.7m, available on theNoreay´s International Climate and Forest Initiative (NICFI) website, were used for the analysis of land cover. The Planet satellite has a great contribution with better accuracy of land cover maps (Saraiva, et al 2019). In this study, six classes were established using the Ecognition Developer 64 software for processing: Urban Area, Anthropized Area, Waterbody, Vegetation, Others, and Paleodunes. The Ecognition software was used to process images with high spatial resolution (Bernadiet al., 2007). The identification and quantitative analysis of land cover data were performed using the segmentation technique. This method groups pixels with similar characteristics to determine the class type (Zhouet al., 2012). After data acquisition, the study area was selectedand all vector files of the variables were converted to raster format. Each variable was reclassified according to the weights applied to each class ranging from 1 to 3. The methodology used for the attribution of weights wasbased on Crepani et al. (2001). Each weight is related to a degree of vulnerability:values close to 3 indicate the dominance of erosion processes, values close to 2 reflect an equilibrium relationship between pedogenesis and morphogenesis, and values close to 1 mark the stability of the terrain due to predominance of pedogenesis processes (Tables 1 and 2).

Table 1. Degree of vulnerability

	Average		Degree of Vulnerability
↑Vulnerability	2.7–3.0	Stability↓	Vulnerable
	2.3–2.6		Moderately Vulnerable
	1.8–2.2		Stable on average/Vulnerable
	1.4–1.7		ModeratelyStable
	1–1.4		Stable

Source: Adapted from Crepani et al. (2001).

After the attribution of weights, maps of vulnerability and environmental erosion were generated based on map algebra and multi-criteria analysis using the arithmetic average of the variables according to Equation (1).

$$Environmental\ Vulnerability = \frac{(Soils + Geology + Vegetation + Climate + Slope + Land\ cover + Geomorphorlogy)}{7} \quad (1)$$

After the generation of the final maps, fieldwork was carried out in September 2017 to validate the results and photographic records. Control points were generated using a*GARMINEtrex 20x*GPS calibrated in the Universal Transverse Mercator coordinate system with WGS 84 datum and Zone 23S.

RESULTS AND DISCUSSION

The results are presented for each variable. The climate variable indicated that precipitation intensity ranged from 50 to 125 mm/month in the period of low precipitation, while it ranged from 275 to 300 mm/month during the rainy season (Figure 2). According to Santos et al. (2009), rainfall has a great potential to cause soil loss. Soil loss depends on rainfall intensity and the impact of the rain hitting the soil. The slope in the study are mainly low, varies from 0% to 28%, indicating predominantly flat and gently undulating areas. This indicates a stable degree of vulnerability in flat areas that together with areas with slope between 2 and 10% with stable on average covers more the half of both municipalities. The geology in the coastal region is characterized by alluvial deposits and the Barreiras Formation predominates in most of the continental area according to CPRM (2013).

Table 2.Variables used in the study and the assigned weights

Variable	Classes	Source	Weight
	Gleysol		3
Soil	Neosol	RADAM (2004)	3
	Latosol		1
	Alluvial deposits		3
Geology	Coastal Deposits	CPRM (2013)	3
	Barreiras Groups		1
	0–2		1
Slope	2–6	TOPODATA INPE	1.5
(%)	6–20	(2008)	2
	20–50		2.5
	Dense Alluvial Ombrophilous Forest		1
	Pioneer formations with fluvial and/or lacustrine		3
Vegetation	influence, her baceous without palms	RADAM (2004)	
	Pioneer formations with floodplain influence		3
Precipitation Intensity (MM/Month)	50–75		1.1
Low Precipitation	75–100	ANA (2017)	1.2
	100–125		1.3
Precipitation Intensity (MM/Month)	280–300		2
High Precipitation	300–325	ANA (2017)	2.1
	325–350		2.2
	350–375		2.3
	Anthropized Area		3
	Others	SENTINEL 2A	1
Land cover	Vegetation	(2017)	1
	Paleodunes		1
	Coastal Plains		3
Geomorphology	River plains	RADAM (2004)	2
	Coastal Plateau		3

Source: Adapted from Crepani et al. (2001).

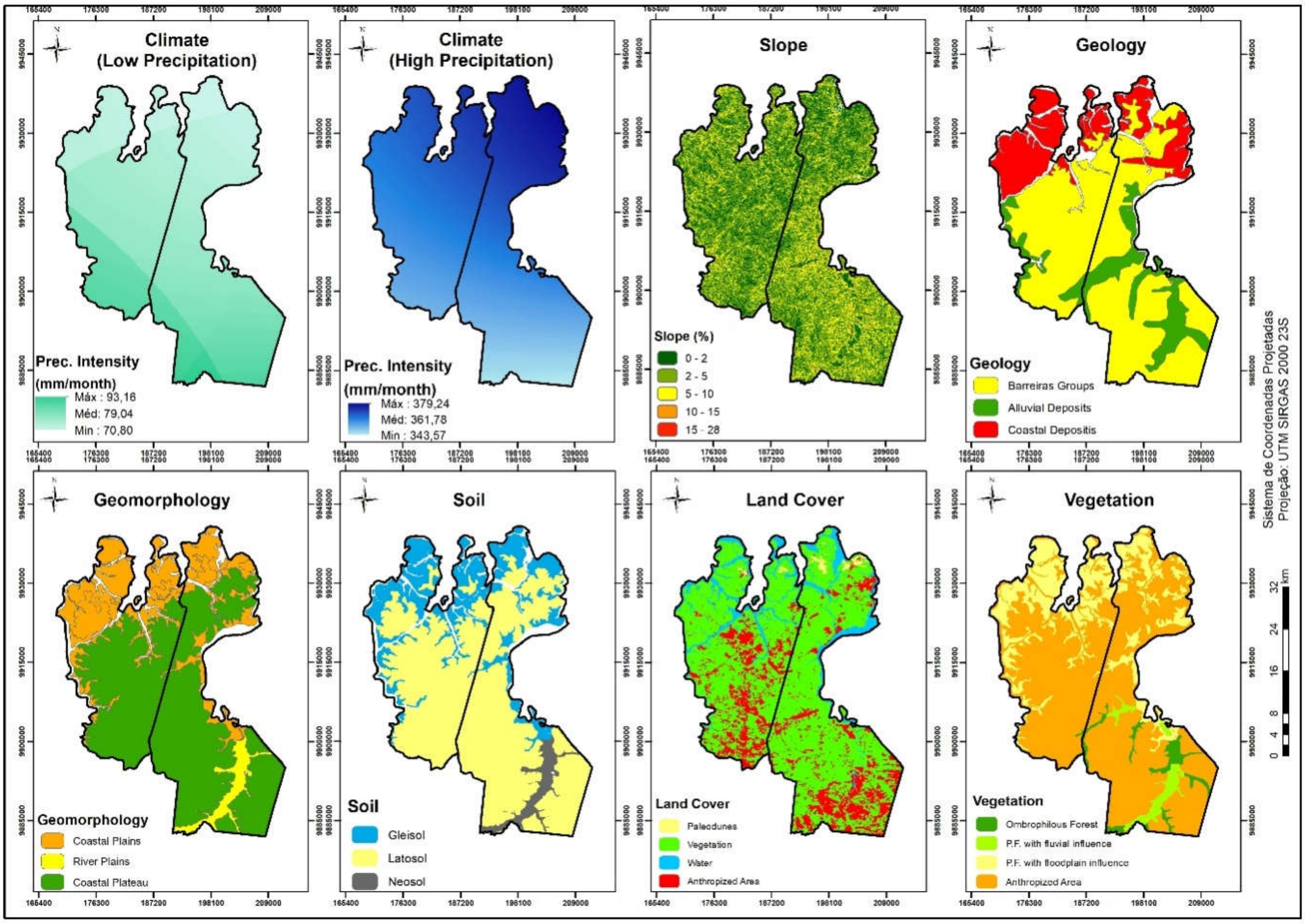

Figure 2. Variables used to map environmental vulnerability to erosion

The continental area has a stable degree of vulnerability corresponding to the sedimentary sequence of the geological formation. The alluvial and coastal deposits and considered vulnerable. The geomorphology include scoastalplains, alluvial plains, and coastal plateau according to RADAM (2004). The coastal plain and the coastal plateau area considered as vulnerable degree of vulnerability once this unit are more exposed to the morphogenetic process. The alluvial plains are stable on average once are accumulation landscape form. The soils corresponds to gleysols and neosols considered to have a vulnerable degree of vulnerability and the latosols the covers the mainly the continental area are stable. The vegetation are classified in dense alluvial ombrophilous forest considerable as stable and the pioneers formation with fluvial/lacustrine and floodplain influence have high degree of vulnerability.

gleisoil, coastal deposits and low relief area. In contrast, the same class corresponds to only 4.41% of the total area in the dry season. The urbanized area in close proximity to the Crispim beach in northeastern Marapanim stands out among the studied areas. This is a macro-tidal beach characterized by notable erosion, leading to the destruction of houses and retreat of the coastline. It is important to notice that this coastal erosion has also mainly influence of strong tidal and coastal dynamic (Rodrigues e Souza-Filho, 2012). According to Moura and Abreu Neto (2013), the coastal zones constitute an unstable natural environment with extreme sensitivity and complexity, characterized by soil loss and beach erosion. The moderate stable/vulnerable class accounted for an area of 118.33 km² during the dry season and is mainly located in the coastal region of the study area.

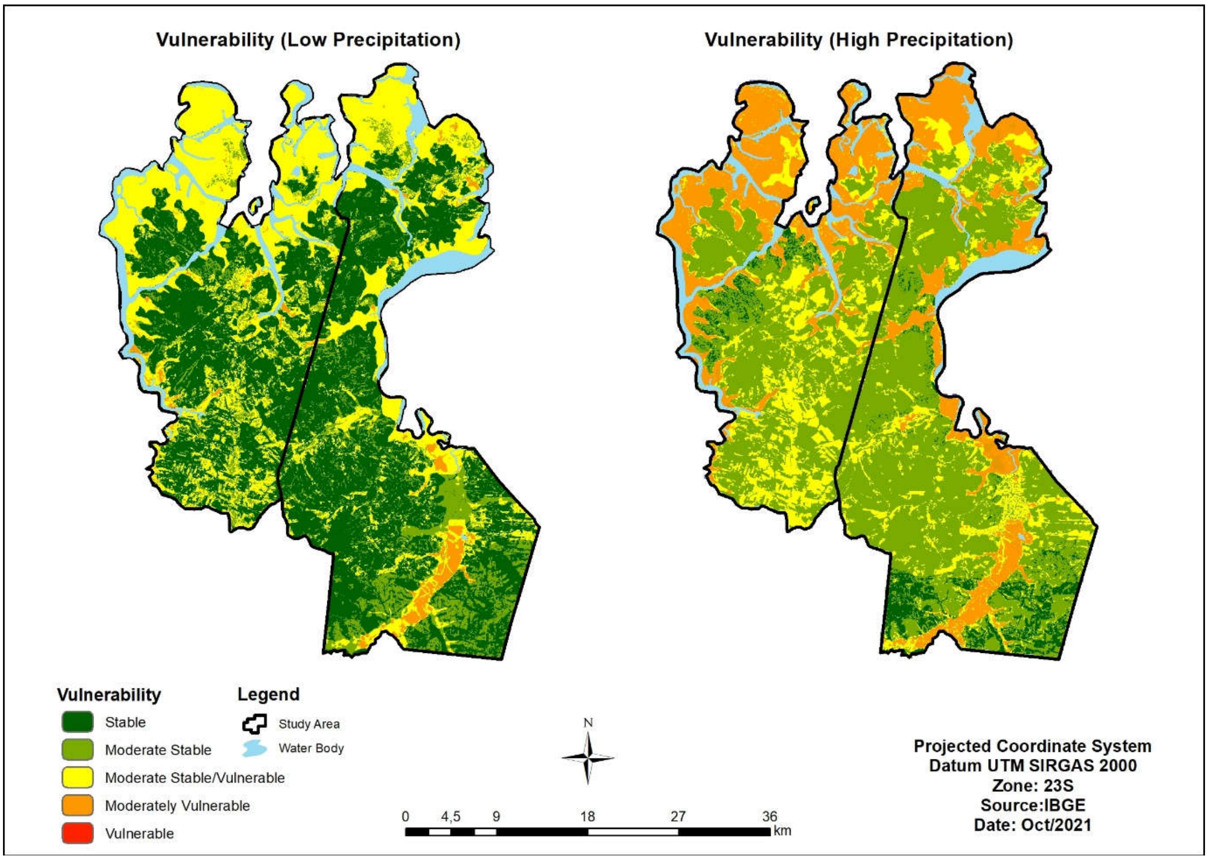

Figure 3. Map of the environmental vulnerability to soil loss between the periods of low and high precipitation

Table 3. Comparison of the area (km²) and environmental vulnerability (%) between the periods of low and high precipitation

Environmental Vulnerability	Area with Low Precipitation		Area with High Precipitation	
	km²	%	km²	%
Moderately Vulnerable	42.93	4.41	173.57	15.57
Moderate Stable/Vulnerable	118.33	12.17	107.96	9.68
Moderately Stable	350.35	36.04	731.51	65.62
Stable	460.32	47.36	101.70	9.12

The land cover was mostly characterized by the presence of vegetation cover and anthropized areas. This latter is considered vulnerable to loss soil.The north of the study area is characterized by in activedunes formations classified as paleodunes (Rodriguese Souza-Filho, 2012). Considering the overlay of the variables for the dry and rainy periods separately the areas of the erosion classes varies from moderately vulnerable to stable (Figure 3 and Figure 4). The main difference in the vulnerability maps is the increase in the area of the moderately vulnerable class during the rainy season (Table 1).The moderately vulnerable class corresponds to 15.57% of the total area in the rainy season and is located in coastal areas, coastal plain with mangroves.Also this moderately vulnerable is mainly covered by

In this class there are presence of permanent and vegetated inactive dunes with arboreal vegetation and grasses close to the Crispim beach in the municipality of Marapanim previous recognized as paleodunes from a supervised classification of coastal environments in the Paraense coastal zone (Rodrigues e Souza-Filho, 2012). The RESEX´s area is also mainly on moderate stable/vulnerable class. This conservation area allowing only self-sustaining exploitation by the native populations, created to shelter traditional populations, quilombolas, and artisanal fishermen (Sousa, 2008). Therefore, these areas experience little urban anthropogenic interference, leading to medium vulnerability. However, the same areas indicate a more vulnerable scenario during the rainy season, which is mainly because of increased precipitation as the land use remains the same. The moderately stable and stable classes are highly representative of the two analyzed periods and correspond to 83.4% and 74.74% of the area in the low- and high-precipitation periods, respectively. These areas are mostly located in the center of the study area and are characterized by latosol, which is not prone to soil loss by erosion.

CONCLUSIONS

The methodology used in this research allowed the integrated analysis of environmental data. Based on the use of geoprocessing techniques, it was possible to create vulnerability maps for the study area related to environmental aspects of soil loss in periods with high and low precipitation. During the rainy season, it was verified that the coastal zone has the highest degree of environmental vulnerability to soil loss. The moderately vulnerable class increase inside river plain and coastal plains. It has a greater susceptibility to soil loss owing to coastal erosion and pedogenetic processes. A decrease in the degree of vulnerability was observed during the period of low precipitation, indicating the great influence of rain on soil loss in the region. The vulnerable class was not discussed in this study because of its little representation in the study area. Therefore, the approach presented in this study may be used to inform public policy decisions in urban planning and management. It considers environmental vulnerability, and thus, identifies areas that need greater attention to reduce the degree of environmental vulnerability, and provide environmental conservation.

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