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Temporal dynamics of soil susceptibility to erosion in semiarid watersheds

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ABSTRACT. The intensification of anthropogenic activities on soils contributes to soil loss through erosion. Moreover, the pattern of soil loss in the Cobra River watershed, located in the semiarid region of Rio Grande do Norte, is related to the history of land use and occupation, mainly from agriculture and the red ceramic industry, as well as the climatic seasonality of the region. Thus, the objective of this work was to identify the pattern of soil loss from the Cobra River microbasin in the state of Rio Grande do Norte. For this, the following analyses were performed: a survey of land use class areas for the years 1987, 1997, 2007 and 2017 as part of the Mapbiomas project; estimation of basin soil loss for these years; and quantification of areas of erosion vulnerability classes for this period. QGIS software was used to treat georeferenced data. According to the results, the land cover classes in the rich Cobra River microbasin fluctuated over time. Potential soil loss from the watershed increased from 1987 to 2017, with an increase of approximately 20 million megagrams of potentially erodible soil. The study of soil loss in a microbasin located in the Brazilian semiarid region should consider the variation in land cover over time, climatic seasonality and anthropic activity. To this end, it is important to use geotechnology and geoprocessing techniques to conduct a more robust spatiotemporal analysis.

Keywords: soil loss; seasonality; geotechnologies.

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Introduction

Erosion is the most extensive and worrisome of the eight categories of anthropogenic soil degradation established (Hudson, 1995) because the removal of the soil by the action of erosion can infinitely exceed the rates (natural and artificial) of renovation and the surface replacement of the soil (Rabelo & Araújo, 2019). Approximately 33% of the world's soils are considered degraded, and in Latin America, 50% show signs of degradation (Baldassarini & Nunes, 2018). Erosion is responsible for the loss of 25 to 40 billion tons of soil per year, promoting the reduction in agricultural productivity and negatively impacting food security and the storage capacity of water and soil nutrients (Food and Agriculture Organization of the United Nations [FAO], 2015). The intensification of human activities in natural resources, mainly in semiarid regions, affects the physical properties of soil and the hydrological and sedimentological processes of river basins, such as water retention, runoff and sediment production (Prasannakumar, Vijith, Abinod, & Geetha, 2012; Ribeiro Filho, Palácio, Andrade, Santos, & Brasil, 2017).

Understanding small-scale hydrological processes and the impact of different land uses is crucial to reducing runoff and sediment losses in semiarid regions (Lopes et al., 2019). Accelerated forms of soil erosion have become a widespread phenomenon, representing a major challenge for achieving the United Nations Sustainable Development Goals (Keesstra et al., 2016) and climate and food security (Amundson et al., 2015). The river basin is a basic unit of environmental planning and water resource management. Understanding the pattern of soil loss in a basin from land cover analysis is an important strategy for the management of natural resources by decision makers. In the context of the Brazilian semiarid region, the dynamics of watershed use and land cover are influenced not only by human action but also by the climatic seasonality of this region (Maia, Lopes, & Andrade, 2018).

In the context of the Cobra River microbasin, located in the semiarid region of Rio Grande do Norte, an understanding of soil loss should consider the history of land use and occupation, mainly from agriculture and the red ceramic industry, as well as the climatic seasonality of the region. Thus, the objective was to identify the pattern of the soil loss from the Cobra River microbasin through the analysis of land cover factors and to identify and analyse the influence that the climatic seasonality of the region exerts on the land cover.

Material and methods

The Cobra River microbasin is in the Piranhas-Açu River basin and at the Seridó Desertification Center (Figure 1). The basin area consists of part of the territory of the following municipalities: Parelhas, Jardim do Seridó and Carnaúba dos Dantas in the state of Rio Grande do Norte, Brazil.

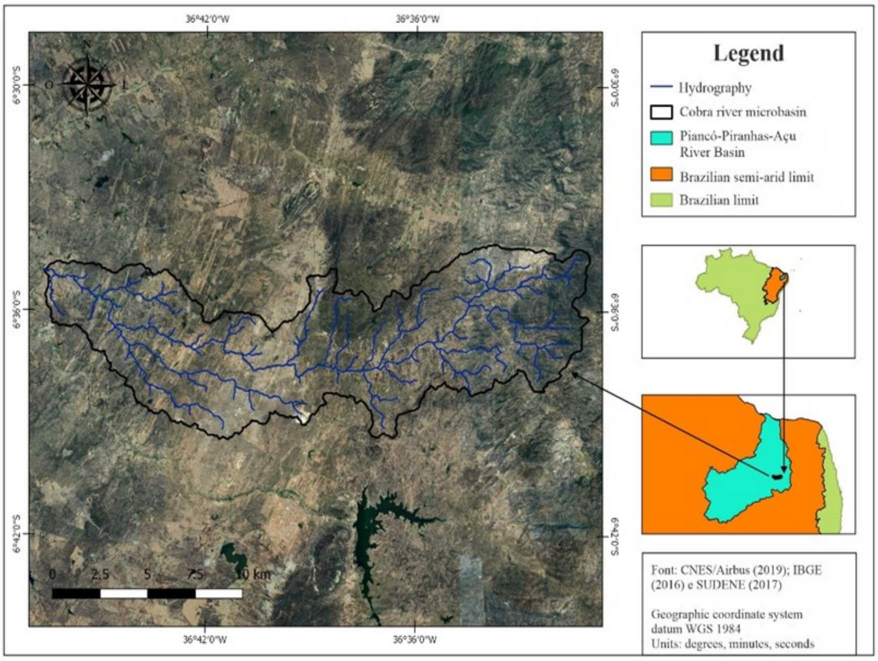

Figure 1. Location map of the Cobra River microbasin.

The municipalities of Carnaúba dos Dantas and Parelhas are within the Seridó Desertification Center, along with Acari, Cruzeta, Currais Novos, and Equador (Rio Grande do Norte, 2010), and constitute, with the exception of Ecuador, the Seridó Ceramic Pole. The socioeconomic structure of the municipalities that are part of the Cobra River microbasin was based, generally, on activities related to livestock, cotton and mineral extraction, but with the decline in the exploitation of cotton in the 1980s and 1990s, there was an expansion of the ceramic industry in the region as an alternative productive activity (Rio Grande do Norte, 2005). The red ceramic industry that depends on clay, water and wood exploration (Agência de Desenvolvimento Sustentável do Seridó [ADESE], 2008), coupled with the inappropriate use and management of agriculture, livestock and cotton cultivation, cooperated in a land degradation framework in these locations over recent decades (Araújo & Souza, 2017), contributing to the intensification of the desertification process.

The climate of the region is similar to BSw'h' (semiarid hot) according to the Köppen climate classification, with an average monthly temperature above 18°C in the coldest month and an annual average air temperature between 21.2°C and 33°C (Empresa de Pesquisa Agropecuária do Rio Grande do Norte [EMPARN], 2009). To better understand the rainfall of the study area, an analysis of the historical series for the years 1984-2017 for the Cobra River microbasin was performed. The average annual rainfall is 557 mm (Figure 2), and the potential evapotranspiration is 1,552.4 mm year^{-1}, based on the Penman-Monteith/FAO 56 methodology (EMPARN, 2009). The aridity index elaborated by Thornthwaite is 0.33 and is classified as semiarid.

Cobra River microbasin hypsometry has a maximum basin altitude of 575.28 m and a minimum altitude of 234.14 m with predominantly smooth and wavy relief (Silva, Ribeiro Filho, Silva, Lemos Filho, & Brasil, 2017). The predominant soil classes in the study area are Neossols (EMPARN, 2009). The vegetation cover is predominantly tree-shrub caatinga with exposed and urbanized land areas (Silva et al., 2017). For the delimitation of the Cobra River microbasin, the digital elevation model (DEM) collected in the Brazil Geomorphometric Database - TOPODATA, from the National Institute for Space Research - INPE, was used. After the acquisition of scene 06S375, referring to altitude data, the processing steps were performed using free QGIS software version 2.18.18. For this purpose, TauDEM 5.0 (Terrain Analysis Using Digital Elevation Models) was used as follows: 1 – eliminate depressions; 2 – define flow direction by the D-8 method; 3 – define accumulated flow; and 4 – delimit the extent of the basin. The morphometric parameters of the microbasin are shown in Table 1.

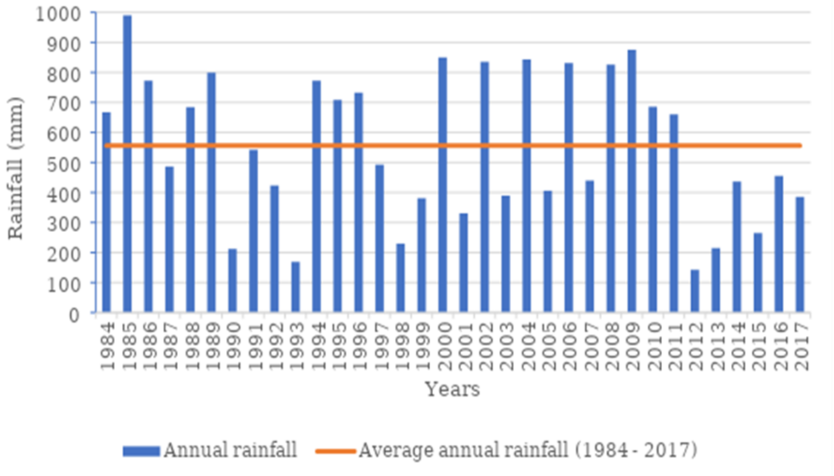

Figure 2. Historical rainfall series for the Cobra River microbasin from 1984 to 2017.

Source: Adapted from EMPARN (2019).

Table 1. Measurements and values of morphometric parameters of the Cobra River microbasin.

Morphometric characterization of Cobra River microbasin	Results
Geometric features	
Total area (km²)	162.73
Total perimeter (km)	116.24
Compactness coefficient (Kc)	2.55
Form factor (F)	0.11
Circularity index (Ic)	0.15
Drainage pattern	Dendritic
Relief features	
Maximum altitude (m)	575.29
Average altitude (m)	404.72
Minimum altitude (m)	234.14
Drainage network characterization	
Order	5
Total river length (km)	337.16
Length of main river (km)	38.75
Drainage density (km km^{-2})	2.07
Average slope of main river (%)	0.88
Main river winding	1.30
Sinuosity index (%)	26.81
Concentration time (h) (Kirpich)	9.18

Source: Adapted from Silva et al. (2017).

RUSLE Application

To estimate the basin soil loss by RUSLE (*Revised Soil Loss Equation*), secondary data were used to estimate the factors of this equation. The equation is expressed by:

$$EL = R \times \mathrm{K} \times \mathrm{LS} \times \mathrm{C} \times \mathrm{P}$$

where: EL is localized erosion (t ha^{-1} ano^{-1}); R is the rainfall erosive factor (MJ mm ha^{-1} ano^{-1}); K is the soil erodibility factor (t ha^{-1} MJ mm); LS is the topographic factor, which is dimensionless (Figure 3); C represents land use and management and agricultural practices (dimensionless); and P represents the adoption of conservationist practices, whose value is dimensionless.

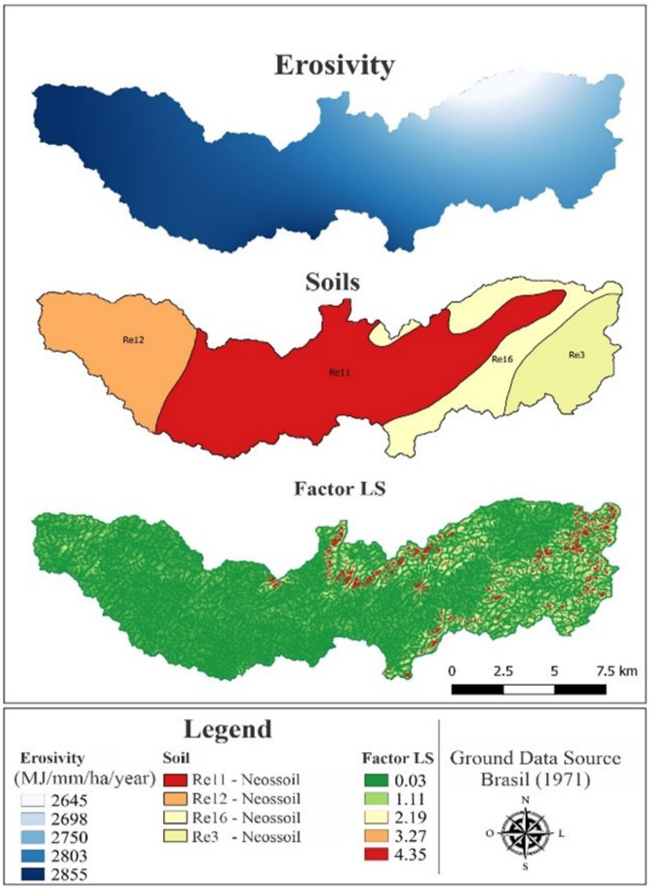

Figure 3. RUSLE factor map of the Cobra River microbasin.

The erosivity index EI30 was estimated from daily rainfall data (1962-2013) obtained from EMPARN (Empresa de Pesquisa Agropecuária do Rio Grande do Norte), using the daily rainfall disaggregation methodology. For erodibility, the soil class vector file according to Brasil (1971) was used on the scale of 1:500,000. The soil erodibility factor attributed to the basin was K = 0.046 for the Neossols class according to Silva, Paiva, and Santos (2009). To define the LS factor, the *r.watershed* algorithm from the Grass provider in QGIS was used.

Regarding land cover, the satellite image classification products from the Mapbiomas project were used for the years 1987, 1997, 2007, and 2017 (Mapbiomas, 2019), with values assigned to each class and nomenclatures inherent in factor C (uses and management), as defined by Pruski (2009) by reclassification of the images. Conservation practices were assigned the value of P = 1 because no practices are implemented in the study area.

In the Mapbiomas project, mapping of land cover change was carried out for all biomes that cover the national territory, applying the technique of machine learning. For this purpose, Landsat satellite images were used, with a spatial resolution of 30 metres. To produce a mosaic, all available scenes were collected within one year and the normalized difference fraction index (NDFI), the normalized difference vegetation index (NDVI), and non-synthetically active vegetation (NPV) were calculated from THE spectral fractions of Band 1 to Band 7 of the satellite (Mapbiomas, 2019). From the image mosaics, maps of each land cover and land use were produced through an image classification process using the automatic classifier "*random forest*" (Projeto Mapbiomas, 2019).

After the preprocessing step, the data were post-processed using the map algebra mechanism. The basin soil loss was calculated using the Raster Calculator function in QGIS by multiplying the maps obtained. Then, the erosion susceptibility classes were defined according to FAO (1980), as shown in Table 2, through the reclassification procedure using the *r.reclass* function in QGIS.

To understand the dynamics of the erosion vulnerability classes of the Cobra River basin for thirty years, as well as its relation with the total annual precipitation, the following analyses were conducted: survey of land use class areas for the years 1987, 1997, 2007, and 2017; estimation of basin soil loss for these years; and quantification of areas of the erosion vulnerability classes for this period. For this, the statistical tools for vectors in QGIS were used.

Table 2. Soil susceptibility to erosion.

Soil loss (t ha^{-1} $year^{-1}$)	Degree of erosion
< 10	Low
10 – 50	Moderate
50 – 200	High
> 200	Very high

Source: FAO (1980).

Results and discussion

Land cover classes

The land cover map included the following classes: water bodies, dense caatinga, open caatinga, exposed soil, and rural urbanization centres and urban areas. Through image processing of the land cover, it was possible to quantify the dynamics of each of the classes over the years 1987, 1997, 2007, and 2017 and determine the percentage of each class, as shown in Figures 4 and 5. It is possible to observe a greater growth (%) of the exposed soil area, increasing the vulnerability of the river basin to water erosion, representing a great challenge to reach the United Nations Sustainable Development Goals (Keesstra et al., 2016).

The extent of the land cover classes in the Cobra River microbasin varied as a function of time, and the percentage values fluctuated over the years studied (Figure 5). These landscape dynamics can be attributed to seasonality because the classes “water”, “open caatinga”, “dense caatinga” and “exposed soil” have patterns directly related to the rainfall regime. The region is characterized by high temporal variability in precipitation (Figure 2), where the annual total may range from < 200 mm to approximately 1,000 mm. From the years that make up the historical series, 18 years presented total annual precipitation below the annual average, with records of up to five consecutive years of drought.

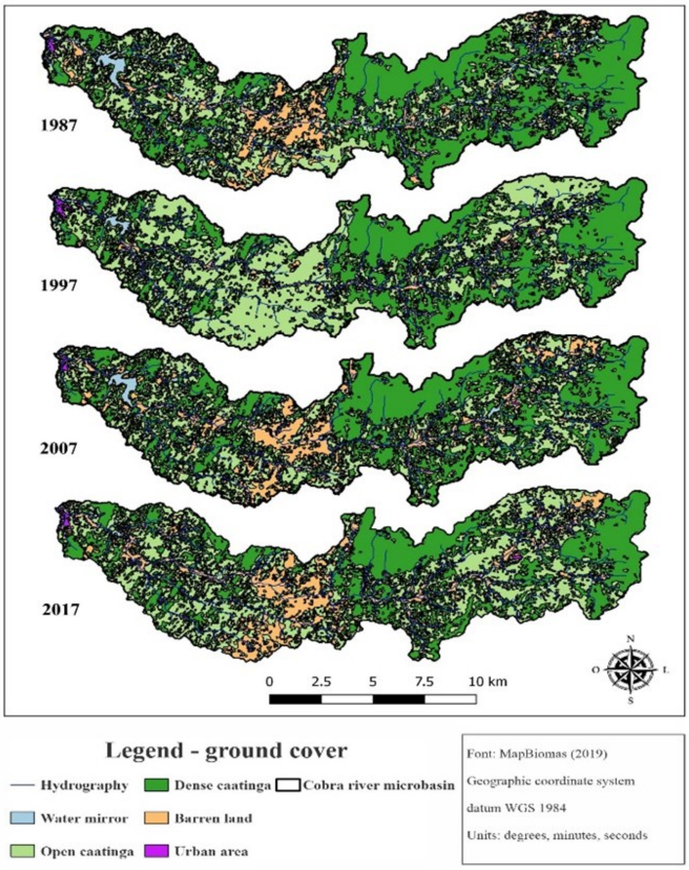

Figure 4. Map of the land cover factor (C) in the Cobra River microbasin.

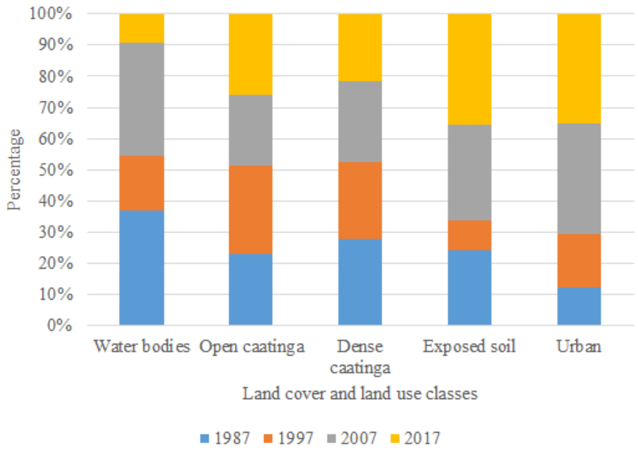

Figure 5. Percentage of the land cover classes in the Cobra River microbasin.

The semiarid regions of the globe are characterized by their high spatiotemporal rainfall variability. (Guerreiro, Andrade, Abreu, & Lajinha, 2013; Andrade, Aquino, Chaves, & Lopes, 2017). In the images for 1987 and 2007 (Figure 4), it is possible to see that the area covered by water mirrors is larger than that during the other two years (1997 and 2017). In terms of absolute area values, that class occupied a total of 207.7 ha in 1987 and 206.4 ha in 2007, i.e., 1.28 and 1.26% of the watershed area, respectively. This behaviour of the water bodies is attributed to the precipitation that occurred in the region, especially in the year before each image (Figure 6), since in the years of images, the total annual precipitation was always lower than the average annual precipitation (Figure 2).

The drastic reduction in the water class area in 2017 is explained by the occurrence of five consecutive dry years (Figure 2), expressing a high water deficit. After the beginning of historical records, researchers such as Andrade (2017) reported the total absence of runoff or only superficial runoff of less than 7 mm in the northeastern semiarid microbasins since 2012, when this period of prolonged drought began in the semiarid region of northeastern Brazil.

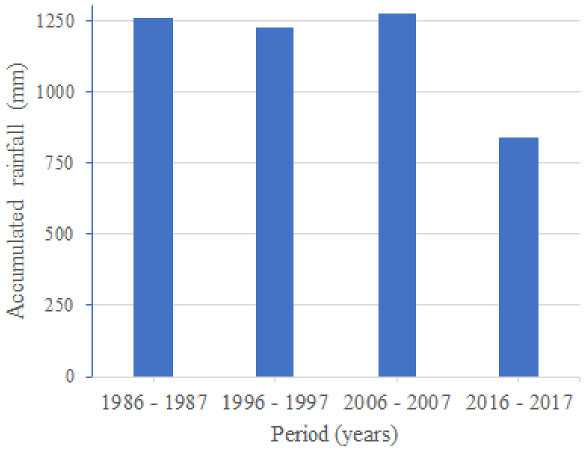

Figure 6. Accumulated rainfall over the two consecutive years prior to 1987, 1997, 2007, and 2017.

In relation to the classes "open caatinga", "dense caatinga" and "exposed soil", oscillations are also observed as a function of rainfall for the period. Between 1987 and 1997, there was a reduction of 947 ha (60%) in exposed soil areas and an increase of 1,752 ha (25.5%) in open caatinga areas, representing approximately 53% of the watershed area. Such variation may be partly related to the precipitated blade accumulated in the years prior to 1987 and 1997 (Figure 6) because of the values above the average of the region. According to Maia et al. (2018), where there is higher rainfall, there are also increased areas with vegetation, and the opposite is observed in anthropized areas. However, the 1997 image (Figure 4) shows distortions compared to those of 1987 and 2007, mainly in relation to the 'open caatinga' and "exposed soil" areas, since the cumulative values of precipitation for the first three images (Figure 6) are close, which may not be entirely related to seasonality.

In the periods 1997 and 2007, there was a reduction of 1,758 ha, totalling 20.4%, of the area of the “open caatinga” class and an increase of 272 ha, making a total of 4% of the “dense caatinga” area (Figure 5) under conditions of cumulative precipitation greater than the regional average (Figure 6). Although there is a close relationship between vegetation development and precipitated blades, in the area of the microbasin, there was an increase of 1,387 ha of exposed soil area, an increase of 218%, which may be related in part to anthropic actions. The results obtained by Zhou et al. (2016) and Ribeiro Filho et al. (2017) in studies conducted in semiarid regions showed that a significant increase in exposed soil area occurs after the vegetation cover has been removed. However, such variation may also be related to distortion evidenced in the areas of “open caatinga” and “exposed soil” (Figure 4), as previously reported.

The change in land cover of the area can be explained by seasonality and by the anthropic component; however, the evidence of distortions or inconsistencies in the 1997 image (Figure 4) concerning the areas of “open caatinga” and “exposed soil” suggests that such distortions are also associated with image classification procedures for the construction of land cover mosaics under the Mapbiomas project. To this end, the following points can be considered.

The first point is related to the spatial filter applied, which aims to increase the spatial consistency of data, eliminating isolated or border pixels (Projeto Mapbiomas, 2019). Neighbourhood rules are defined that can lead to a change in the pixel classification, with the possibility of reclassification from a certain class to the predominant class in the neighbourhood (Projeto Mapbiomas, 2019). The second process is a digital classification of the images for the caatinga biome, where certain classes were incorporated into the others where it was not possible to distinguish between the two classes. In this sense, it is important to consider in the analysis of land cover images both the natural components (seasonality) and the anthropic components, as well as the computational techniques and processes applied to the treatment of data from remote sensing products, in this case, the data from the Mapbiomas project.

Regarding anthropic action, the study area has been affected by the red ceramic industry, mainly in the rural area of Parelhas and especially in the communities of Cachoeira, Juazeiro and Santo Antônio da Cobra (Table 3), which are within the microbasin. The increase in the area of exposed soil may be related to the red ceramic industry activity. It is noteworthy that the removal of native vegetation to meet the energy demand of the sector and the extraction of clay in lowland areas and alluvial soils have caused adverse impacts on the environment in the Cobra River microbasin region (Araújo & Souza, 2017). From 1981 onward, there was a significant increase in these enterprises in the municipalities that are part of the microbasin, going from 4 industries in 1981 to 59 in 2013, predominantly from 2001 (Table 3). In 2010, there were 30 industries in the region, an increase of 3,000% compared to 1981. Within this period, an increase of 218% in exposed soil areas was accounted for.

Table 3. Quantity of red ceramic industries in the municipalities that are part of the Cobra River microbasin in different periods.

	Years				
Municipality	1981	1989	2001	2010	2013
Carnaúba dos Dantas	-	-	14	19	20
Jardim do Seridó	3	-	8	6	6
Parelhas	1	3	26	30	33

Source: Adapted from Araújo and Souza (2017).

It is important to emphasize that there are other anthropic actions to take into consideration regarding the use of natural resources in the region that promote the expansion of the exposed soil area. The worsening of the situation by overgrazing has already been discussed by authors in different regions of the world (Prasannakumar et al., 2012; Amundson et al., 2015; Lopes, Montenegro, & Lima, 2019).

Among the land cover classes, only the effect of climate seasonality on landscape dynamics is not applied to the evolution of areas with consolidated urbanization, whether cities or districts (Figure 4). In absolute values of the area, from 1987 to 2017, the "urbanization" class increased from 44.4 to 127.3 ha, an increase of 286%, which can be attributed to the growth of cities as a function of population increase (Table 4).

Brazil is currently an urban country, where the percentage of the population residing in urban areas has surpassed the population living in rural areas, having a direct impact on the increase in urban centres. In the context of the semiarid region of Rio Grande do Norte, from the 1970s and especially in the first decade of the 21st century, urban centres assumed the condition of urbanized space because of the concentration of population in these areas (Gomes, 2017). The resident population of the municipalities that make up the

Cobra River microbasin has increased over the last three decades (Table 4), especially the urban population, which comprised 81% of the population in the municipalities of Carnaúba dos Dantas and Jardim do Seridó and 84% of the population in Parelhas in 2010 (Instituto Brasileiro de Geografia e Estatística [IBGE], 2019).

Table 4. Resident population of the municipalities where the Cobra River microbasin is located.

	Municipality		
	Carnaúba dos Dantas	Jardim do Seridó	Parelhas
Years	Population		
1987	5,527	11,302	16,456
1997	6,325	11,900	18,378
2007	7,407	12,216	20,808
2010	7,429	12,113	20,354
2019	8,180	12,396	21,477

Souce: IBGE (2019) and Ministério da Saúde (2019).

Soil loss in the Cobra River microbasin

The estimate of the potential loss of soil in the microbasin in the GIS environment for the years 1987, 1997, 2007 and 2017 enabled the preparation of a map (Figure 7), where the information obtained served as a basis for the study of the pattern of soil loss in the microbasin on screen, allowing the diagnosis of its trends. The potential loss of soil estimated for the Cobra River microbasin is variable as a function of time, determined by changing the pattern of areas with potential for the occurrence of erosion (Figure 7). These changes reflect the dynamics of the area fostered by natural (Hudson, 1995) and anthropic (Zhou et al., 2016) processes that act as a function of time. In terms of natural processes, we highlight the climatic seasonality evidenced in the patterns of precipitation over time (Figure 2), which contributes to the promotion of changes in the landscape, especially in the use classes related to vegetation, water bodies, and exposed soil. With respect to anthropic actions, we observe the growing expansion of the red ceramic industry, the intensive use of agriculture and livestock and the growing urbanization in thestudy area.

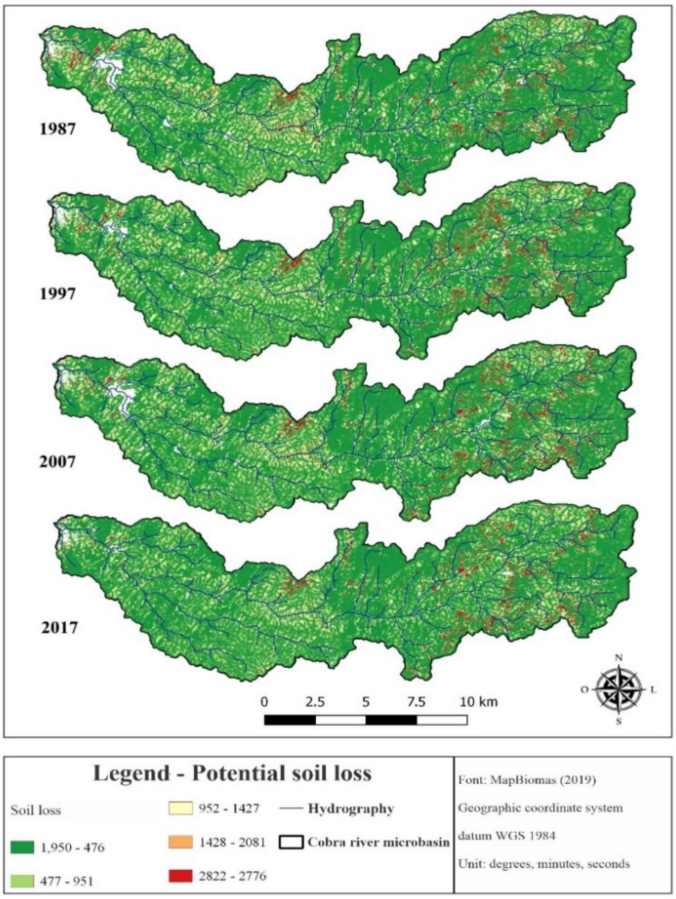

Figure 7. Map of potential soil loss in the Cobra River microbasin.

Although the changes in land cover over the years have experienced oscillations, except for urban use, the extent of potential soil loss in the microbasin increased from 1987 to 2017 (Table 5), with an increase of approximately 20 million megagrams of potentially erodible soils.

Table 5. Estimation of soil loss in the microbasin.

Year	Potential soil loss from basin (Mg year^{-1})
1987	55,406,100.00
1997	59,655,306.00
2007	64,903,279.00
2017	75,390,488.00

Regardless of the soil losses that occur naturally (natural erosion), land use without adequate management accelerates the process of soil loss in agricultural or urban areas. According to Rabelo and Araújo (2019), who sought to estimate the gross erosion of the Seridó River basin from 1992 to 2015, the areas with the greatest gross erosion were those with steeper slopes and exposed soils and near water reservoirs. One of the possible explanations would be the intensive use of soil due to the proximity of water use and its degradation to agricultural practices and vegetable extractions.

Such conditions are similar to those in the Cobra River microbasin, where we can observe that the areas with higher values of soil loss are located in regions with greater slopes or that follow the configuration of the drainage network (Figure 7), also indicating the pressure exerted by the use and management of the soil, especially the red ceramic industry, ranching, vegetable cultivation and mineral extraction (Araújo & Souza, 2017).

To understand the extent of potential soil loss in the microbasin, it was also necessary to define the areas and classes of soil susceptible to erosion, according to the classification established by FAO (1980) (Figure 8), given that the representation of the estimate of soil loss expressed in Figure 7 is up to date and not covering or associating the areas most susceptible to erosion.

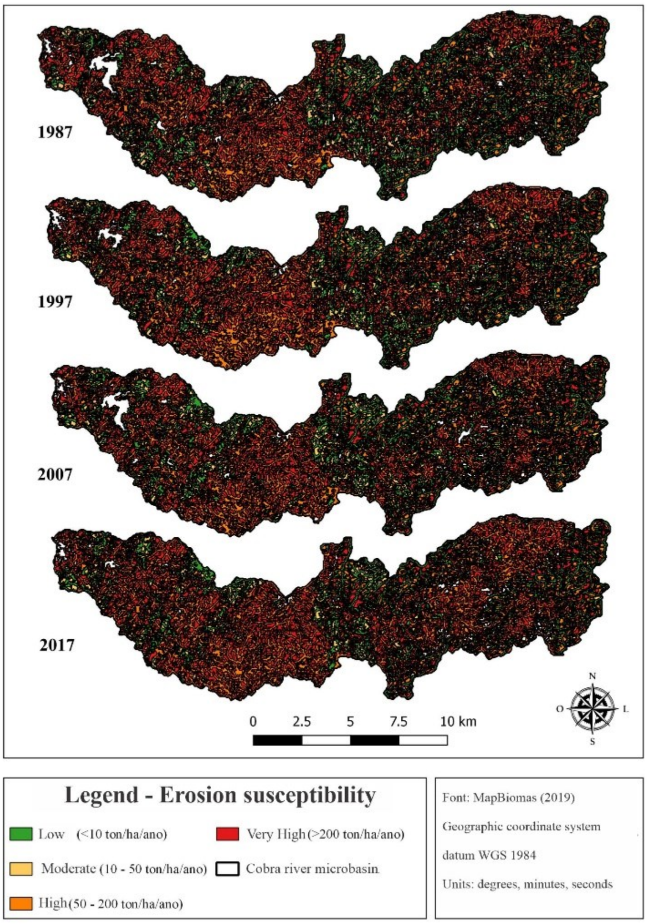

Figure 8. Map of soil susceptibility to erosion in the Cobra River microbasin.

Comparatively, the classes of soils susceptible to erosion are similar to those of land cover in terms of location in the microbasin (Figure 4). It can be seen that the "high" and "very high" classes are located in regions where there is a predominance of "exposed soil" and "open caatinga", and the "low" class is arranged in the areas of "dense caatinga". Such conditions express the influence of land cover on soil loss in a basin.

The percentage of erosion susceptibility classes (Figure 9) in 1987, 1997, 2007, and 2017 maintained a lower oscillation than the land cover classes (Figure 5). This condition can be explained by the homogeneity of the areas produced by grouping the potential values of the soil loss of different use classes.

The changes in the behaviour and spatial structure of the classes of soil susceptibility to erosion are related more to the coverage of "open caatinga", "exposed soil" and "water". These classes presented greater variability as a function of climate seasonality and anthropic activity. The changes in land cover over time provided an increase in the "high" and "very high" susceptibility classes and a reduction in the "low" and "moderate" susceptibility classes.

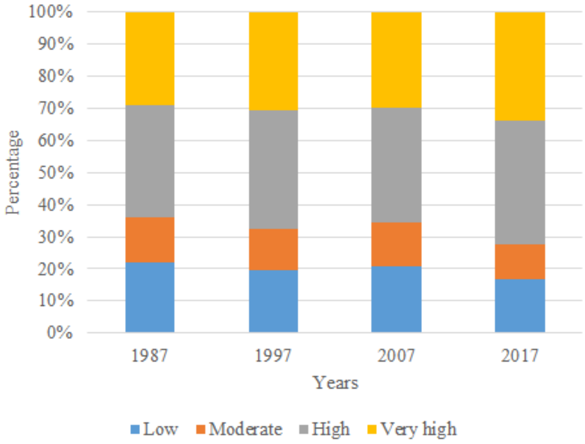

Figure 9. Percentage of areas susceptible to erosion, according to FAO (1980) classification.

According to Ramalho and Guerra (2018), both climatic and anthropic factors are grounds for the environmental risk for the region, considering the oscillation of dry periods with those of torrential rainfall, the expansion of crop areas and the misuse of natural resources. In this sense, Oliveira and Selva (2019) showed that the fragility of the natural environment of the Seridó region can condition and enhance the erosion process. This situation becomes more severe due to the use and occupation of local soil without adequate planning and management of natural resources, especially through the practice of mineral exploration.

For the context of the Cobra River microbasin, the climatic and anthropogenic components should be considered in an integrated manner for the purpose of analysing potential soil losses and vulnerability to erosion. The fluctuations of areas with potential soil loss (Figure 7), the increase in potential soil loss as a function of time, and especially the predominance of high and very high soil erosion risks in the watershed (Figure 9) are factors that should be observed and are related to land cover and climatic conditions.

Conclusion

The changes in cover were reflected in soil loss, which increased between 1987 and 2017. In addition, the changes in land cover that occurred during the period increased the susceptibility of the soil to erosion, with an increase in the most vulnerable areas and a decrease in the least vulnerable areas.

Finally, studies of soil loss in a microbasin located in the Brazilian semiarid region should observe the changes in land cover over time considering the climatic seasonality and anthropic activity as factors that influence the dynamics of the area.

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