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Research Article

Analysis of the impact of watershed management practices, vegetation, and land use on soil erosion using EPM-IntErO modelling in Ceará's semi-arid region

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Abstract

The semi-arid region of Ceará, located in Northeast Brazil, is typically characterized by low rainfall, high temperatures, and sparse vegetation – conditions generally associated with reduced soil erosion rates. However, the region's fragile soils, which are shallow, nutrient-poor, and particularly susceptible to degradation, exacerbate the erosion. This degradation poses a significant threat to soil fertility, agricultural productivity, and environmental sustainability in the area. The primary objective of this study was to quantify soil loss in Ceará and to challenge the prevailing assumption that semi-arid regions inherently experience minimal erosion due to limited rainfall. The Intensity of Erosion and Outflow (IntErO) model was used, in conjunction with remote sensing data and geographic information system (GIS) technologies. Through this approach, we estimated an average soil loss rate of 9.7 Mg ha^{-1} yr^{-1}. The results indicate that 38% of Ceará's land area experiences soil loss rates exceeding tolerance limits, particularly in regions lacking vegetation, as well as in agricultural lands and pastures. These elevated erosion rates are largely attributed to the area's poor soil properties, occasional intense rainfall events, and unsustainable land management practices. The findings underscore the urgent need for improved management of soil erosion processes to address these challenges. Implementing targeted soil conservation strategies and policies that promote sustainable land use is essential for mitigating water erosion, safeguarding long-term agricultural productivity, and enhancing environmental and socioeconomic sustainability in semi-arid regions.

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Keywords: IntErO model; land management; semi-arid regions; soil and water erosion; sustainability

Introduction

The state of Ceará, situated in Northeast Brazil, is characterized by a semi-arid climate with low rainfall, high temperatures, and sparse vegetation. The region's soils are by nature vulnerable to water erosion due to their low fertility, limited organic matter content, and fragile structural composition. These conditions, combined with the soils' restricted capacity for water and nutrient retention, exposure to intense seasonal rainfall, and unsustainable agricultural practices, induced soil erosion and lead to significant soil quality degradation and productivity loss (Lima *et al*., 2021).

Information about changes in land use and land cover is crucial for addressing issues related to soil management in semi-arid regions and supporting sustainable soil use (Guerra *et al*., 2014; Spalevic *et al*., 2024). Drylands are often impacted by accelerated soil erosion, land degradation, and desertification, primarily due to the loss of vegetation cover. Therefore, ongoing monitoring of land use and land cover changes is essential. Tomasella *et al*. (2018) investigated land degradation in Northeast Brazil using the Normalized Difference Vegetation Index (NDVI) from 2000 to 2016. Their findings revealed an increase in degraded areas, particularly within pastures and the Caatinga region. The authors also highlighted that land degradation has been intensified by the severe drought affecting the region since 2011. Furthermore, Vieira *et al*. (2020) emphasize that analyzing land degradation is highly complex due to its occurrence across various temporal and spatial scales and its influence by multiple factors.

Land use and land cover changes (LULC) are widely recognized as major drivers of soil erosion, as environmental degradation is often initiated by the removal of natural vegetation and further intensified by variability in precipitation patterns, rainfall intensity, and terrain characteristics. In this study, the authors analyzed LULC changes between 2000 and 2010 to assess susceptibility to degradation in Northeast Brazil. This assessment was achieved by integrating LULC trajectories with three downscaled climate change scenarios and projected population growth for the periods 2015-2025, 2025-2035, and 2035-2045, under Representative Concentration Pathways (RCP) emissions.

The results indicated that, under the RCP4.5 scenario, areas of moderate susceptibility to erosion decreased by 10.34%, while areas of high susceptibility increased by 12.28% between 2010 and the 2035–2045 period. Under the RCP8.5 scenario, moderate susceptibility areas declined by 16.85%, with a corresponding increase of 19.62% in high susceptibility areas. Additionally, De Sousa Barbosa *et al*. (2024) argues that accelerated soil erosion has become a critical environmental issue linked to land development for agriculture and forestry, and closely associated with population growth. Their study focused on a watershed downstream of the Parnaíba River in north-western Piauí State, located in north-eastern Brazil.

Using the Revised Universal Soil Loss Equation (RUSLE) to estimate erosion potential, the researchers observed that erosion risk ranged from very low to very high across the study area. The highest soil loss rates were associated with land uses involving pasture, exposed soil, and cultivated areas. In a related study, Guerra *et al*. (2014) presented a simplified map of soil erosion across Brazil, identifying medium to high erosion susceptibility in north-eastern regions. This highlights a substantial risk of water erosion, which can be further intensified by soil properties, rainfall erosivity, and land use and management practices. The study also emphasizes that, depending on specific soil classes, rainfall erosivity, and land management practices, there is a considerable probability of severe erosion occurring within this region.

Water erosion is a natural geomorphic process that is increasingly intensified by human activities, such as accelerated land use and land cover changes and unsustainable farming practices. This process represents a major global driver of soil degradation, resulting in increased sediment production, diminished agricultural productivity, and negative impacts on ecosystem services. Additionally, soil erosion has substantial social implications, contributing to rural migration, sedimentation, and pollution of water resources, reduced efficiency in hydroelectric power generation, and increased costs of water treatment (Polidoro *et al.*, 2021).

In semi-arid regions such as Ceará, the challenges of water erosion are intensified by specific morpho-structural and pedological characteristics, as well as a hydrological regime marked by water scarcity. This amplification of erosion significantly impacts socioeconomic activities, particularly agriculture (Sousa and Paula, 2019). Despite the critical nature of these challenges, research on soil loss rates due to water erosion in the Ceará region remains limited. Gaining a comprehensive understanding and accurate quantification of this process is essential for effective land management, promoting environmental sustainability, guiding soil conservation efforts, and identifying best practices to mitigate erosion (Lima *et al.*, 2021).

Direct assessment of water erosion in the field using experimental plots is often limited by high costs, long implementation times, and lengthy analysis periods (Alewell *et al.*, 2019). To address these limitations, soil loss estimation models have been developed, including the Erosion Potential Method – EPM (Gavrilovic, 1962, 1972) and its adaptation in the IntErO model (Spalevic, 2011). EPM, initially developed in the Balkans, has been widely adopted in various regions including Europe, the Middle East, Asia, North Africa, and South America, particularly in Brazil (Kostadinov *et al.*, 2014, 2018; Milanesi *et al.*, 2015; Manojlović *et al.*, 2018; Tošić *et al.*, 2019; Srejić *et al.*, 2023; Polovina *et al.*, 2024). This method is valued for its accuracy, cost-effectiveness, and integration with geographic information systems - GIS (Lense *et al.*, 2020; Bezak *et al.*, 2024).

The Erosion Potential Method (EPM) – IntErO model has been adapted to Brazilian soil and climatic conditions, proving effective in modelling large-scale soil losses. Applying the EPM-IntErO in soil loss estimation aids in understanding erosion dynamics and in identifying critical areas that require focused soil and water resource management interventions (Tavares *et al.*, 2019; Lense *et al.*, 2020; Sakuno *et al.*, 2020; Vujačić *et al.*, 2023; Aleksova *et al.*, 2023, 2024; Pavlova-Traykova and Dimitrov, 2023). Additionally, EPM method can be combined with the Soil Loss Tolerance (T) parameter, which indicates the maximum amount of soil that can be removed without adversely affecting soil fertility and productivity (Li *et al.*, 2009).

This study aims to model water erosion and estimate soil loss in the state of Ceará using the IntErO model, based on the Erosion Potential Method (EPM). The underlying hypothesis is that significant soil loss occurs in Ceará's semi-arid regions despite the area's low rainfall levels. By developing a comprehensive database of water erosion levels, this research seeks to inform planning initiatives and management strategies for effective erosion control in the region.

Materials and Methods

Study area

The study area comprises the Ceará state, which covers 148,826 km^2 and has the city of Fortaleza as its capital. According to the Instituto Brasileiro de Geografia e Estatística - IBGE (2020, 2023), the estimated population in 2023 was 8,791,688 inhabitants, with approximately 75% residing in urban areas. (Figure 1).

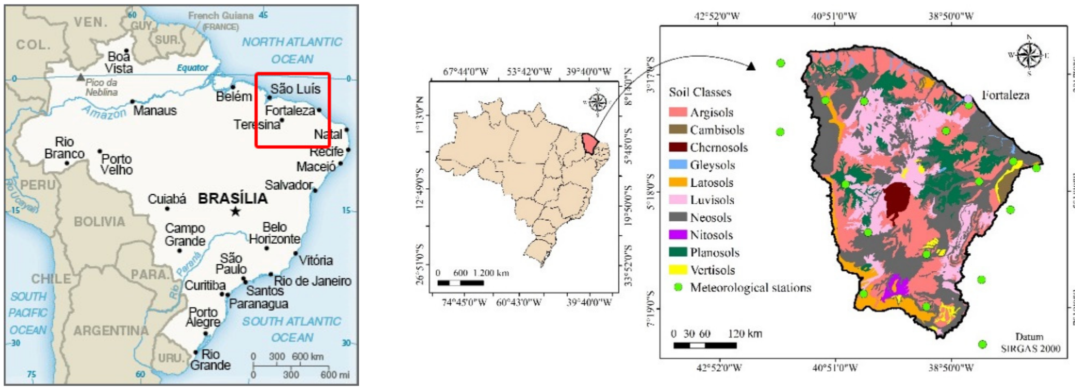

Figure 1. Study area and soil map of the Ceará, Brazil. Adapted from EMBRAPA (2017)

Table 1. Soil classes, values of soil resistance coefficient to water erosion (Y), soil density (Bd) and soil loss tolerance (T) in the Ceará state, Brazil

Soil classes	Area	Y	Bd	T
	%	dim.	kg dm^{-3}	Mg ha^{-1} yr^{-1}
Neosols	30.96	1.4	1.43	4.86
Argisols	28.75	0.9	1.46	5.70
Luvisols	17.98	0.9	1.35	5.90
Planosols	11.93	0.9	1.65	5.06
Latosols	4.83	0.8	1.45	8.41
Chernosols	1.75	0.6	1.27	4.45
Vertisols	1.09	1.2	1.31	8.23
Cambisols	1.02	1.0	1.35	7.56
Nitosols	0.87	0.8	1.29	6.80
Gleysols	0.82	0.5	1.28	7.17

Notes: dim. = dimensionless. Adapted from EMBRAPA (2017)

Soils in semi-arid are predominantly poor in organic matter content, stony, shallow, and have limited water retention capacity (Ribeiro Filho *et al*., 2017). The digital soil map (Figure 1) was derived from the Empresa Brasileira de Pesquisa Agropecuária - EMBRAPA (2017) at a scale of 1:6,000,000.

According to the Köppen classification, Ceará has two climatic types: the tropical savannah climate (Aw) with a dry winter, covering approximately 64% of the territory, which includes the coastal strip and a significant portion of the southern and eastern regions; and the hot semi-arid climate (Bsh), which occupies the remaining 36% of the territory, located in the central-western part (Alvares *et al*., 2013).

The spatial distribution of annual rainfall and average air temperature in Ceará (Figure 2) was obtained from meteorological stations operated by the Instituto Nacional de Meteorologia (Figure 1). Climatic data from 17 meteorological stations were interpolated using the ordinary kriging method, with adjustments made to the spherical model by the Geostatistical Wizard tool in ArcGIS 10.5 software (ESRI, 2016). The average total annual precipitation for the year 2020 in Ceará was 912 mm, with an average annual temperature of 26.5 °C.

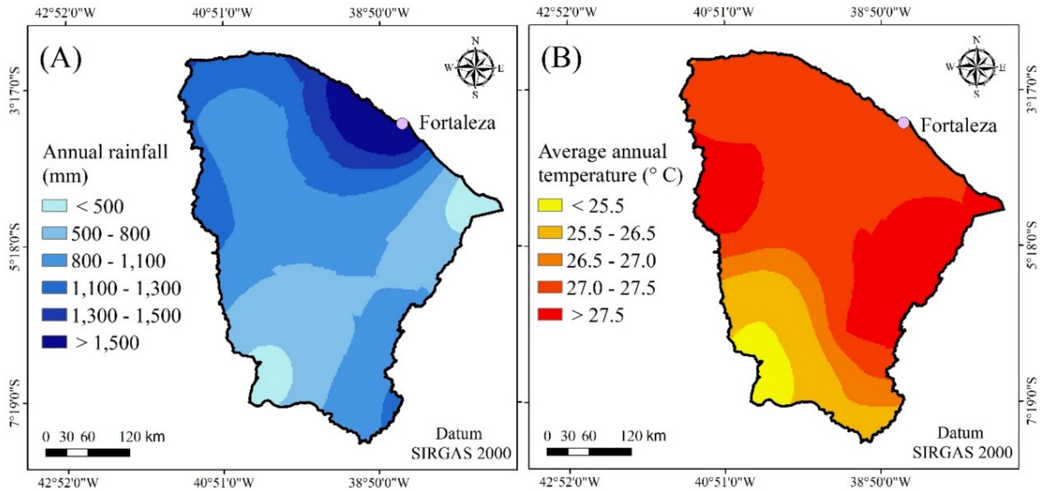

Figure 2. Maps of annual rainfall (A) and average annual temperature (B) in the Ceará state, Brazil

Despite the low rainfall in the interior of Ceará state, atmospheric phenomena such as the El Niño Southern Oscillation, the Atlantic Dipole, the sunspot cycle, and Decadal Oscillation can induce extreme rainfall events during specific short periods. For instance, heavy rainfall exceeding 100 mm in 24 hours occurred in March 2009, followed by severe drought conditions in subsequent years (Monteiro and Zanella, 2019).

Regarding land use, the predominant classes are Caatinga/Cerrado and temporary crops (Figure 3). The land use map was obtained from Collection 5 of the 2019 MapBiomas Project (2019). The Caatinga and Cerrado biomes were combined into a single class due to difficulties in distinguishing these biomes based on satellite images.

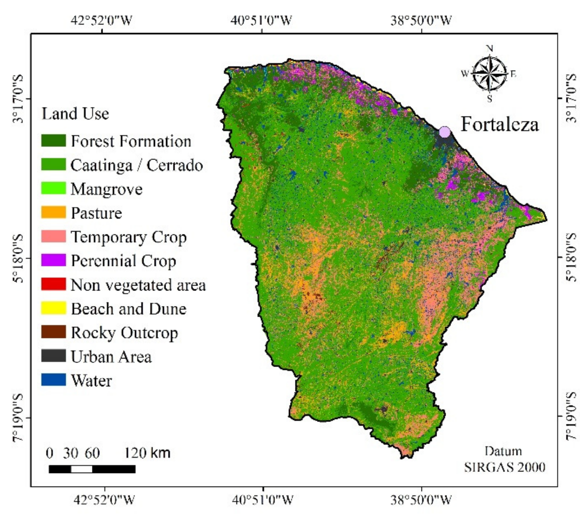

Figure 3. Land use map of the Ceará state, Brazil. Adapted from the MapBiomas Project (2019)

The altitude data (Figure 4A) were obtained from the digital elevation model (DEM) of Brazil, accessible through the "Brasil em Relevo" digital platform (Miranda, 2005). Using this data, the slope map was generated (Figure 4B) by the Slope tool in ArcGIS 10.5 (ESRI, 2016). The average elevation is 293 m, with the maximum elevation reaching 1,154 m at Pico da Serra Branca in the Municipality of Monsenhor Tabosa. In Ceará, flat (0 - 3%) and gently undulating (3 - 8%) terrain classes occur predominantly (Figure 4B).

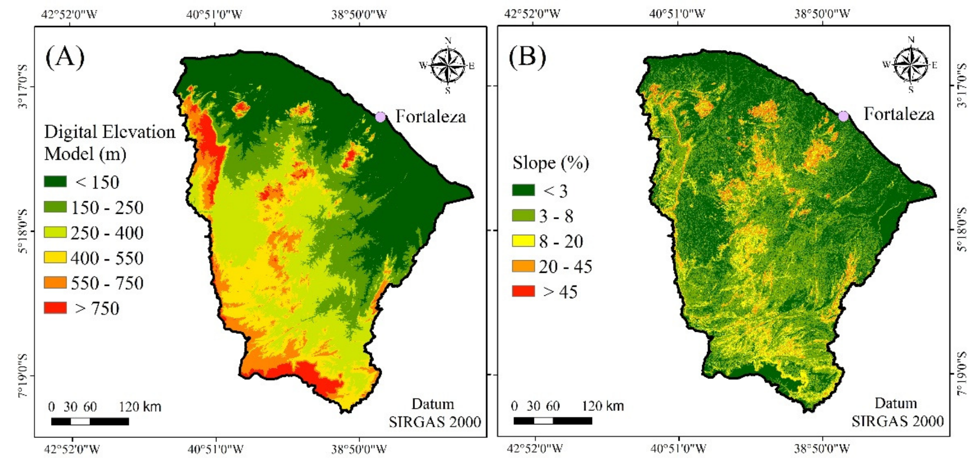

Figure 4. Digital Elevation Model (DEM) (A) and slope map (B) of the Ceará state, Brazil

Water erosion modelling

The model estimates soil losses according to Equation 1:

$$W_{yr} = \left(\sqrt[2]{\frac{t_0}{10}} + 0.1\right) \cdot H_{yr} \cdot \pi \cdot \sqrt[2]{\left[Y \cdot X_a \cdot \left(\varphi + \sqrt[2]{I_{sr}}\right)\right]^3} \cdot Bd \cdot F \quad \text{(Equation 1)}$$

where: Wyr = total soil loss, in Mg ha^{-1} yr^{-1}; t0 = average air temperature, in ° C yr^{-1}; Hyr = annual rainfall, in mm yr^{-1}; Y = soil resistance to water erosion, dimensionless; Xa = use and management coefficient, dimensionless; ϕ = coefficient of the degree of erosive features, dimensionless; Isr = average slope, in %, Bd = average soil bulk density, in kg dm^{-3}; and F = area, in ha. The climatic factors used to calculate were annual rainfall (Hyr) and average air temperature (t0), presented in Figure 2. The Y parameter demonstrates resistance to water erosion, depending on each type of soil, varying between 0.25 and 2.00, with areas with higher values showing lower resistance to erosion. The Y parameter was determined for each soil type (Table 1), according to Sakuno *et al*. (2020), ranging from 0.25 to 2.00.

The soil use and management coefficient (Xa) reflect the role of vegetation in protecting the surface against the impacts of rainfall and runoff. Values vary from 0.05 in areas with dense vegetation to 1.00 in areas with bared soils (Gavrilovic, 1962, 1972). The Xa parameter was determined for each land use class (Table 2) from values initially proposed by Gavrilovic (1962) and adapted to tropical soil and climate conditions by Sakuno *et al.* (2020).

Estimating soil losses in extensive areas such as Ceará state makes it difficult to identify erosive features in situ. Consequently, the ϕ factor was classified based on land use, utilizing values from specialized literature (Table 2). The ϕ factor signifies the predominant erosion characteristics in each area. Each erosive feature is assigned a value ranging from 0.10 for areas showing no signs of erosion to 1.00 for those exhibiting severe signs (Gavrilovic, 1972; Dragičević *et al*., 2016; Efthimiou *et al*., 2017).

The Isr factor represents the slope (Figure 4B) and the influence of relief on the erosion process. Soil densities in the Ceará state (Bd) are detailed in Table 1. This parameter was derived from soil surveys conducted in Ceará by the Fundação Cearense de Meteorologia e Recursos Hídricos (FUNCEME) in 2012.

Table 2. Land use and values of the soil use and management coefficient (Xa) and coefficient of the degree of erosive features (ϕ) in the Ceará state, Brazil

Land use	Area	Factor X_a	Factor ϕ**
	(%)	(dim.)	(dim.)
Forest formation	11.18	0.05	0.1
Cerrado/Caatinga	59.56	0.30	0.2
Pasture	10.68	0.50	0.5
Temporary crop	14.70	0.80	0.6
Perennial crop	1.83	0.60	0.5
Non vegetated area	0.01	1.00	0.7
Mangrove*	0.15	-	-
Rocky outcrop *	0.05	-	-
Beach and dune*	0.36	-	-
Urban area*	0.64	-	-
Water*	0.84	-	-

*Areas not considered in the calculation of soil losses. **Values adapted from Lense *et al*. (2020). Notes: dim. = dimensionless.

The soil loss estimate calculation and spatial representation of the results were conducted using map algebra in ArcGIS 10.5 (ESRI, 2016) by the Raster Calculator tool. Soil loss results were compared to soil loss tolerance limits (T) (Table 1). T represents the maximum intensity of soil erosion that still permits economically sustainable crop productivity, as defined by Wischmeier and Smith (1978).

The T values for soils in the Ceará state were determined using the methodology by Bertol and Almeida (2000). The data used is available in the Sistema de Informação de Solos Brasileiros (SISolos), a database containing various soil attributes from Brazilian regions (EMBRAPA, 2014). T values for soils are listed in Table 1. The IntErO model uses the Erosion Potential Method in its algorithm background (Spalevic, 2011, see also www.gasci.org/IntErO). The use of the IntErO, together with other models, allows a comprehensive understanding of the magnitude of erosion observed in watersheds with similar characteristics in different regions worldwide (Sestras *et al*., 2023). The IntErO model is an upgrading of the River Basins (Spalevic, 1999; Spalevic *et al*., 2000) and the Surface and Distance Measuring (Spalevic, 1999) programs. The model is described in Figure 5.

The IntErO model can be characterized as semi-quantitative because it is based on a combination of descriptive and quantitative procedures (Spalevic *et al*., 2020).

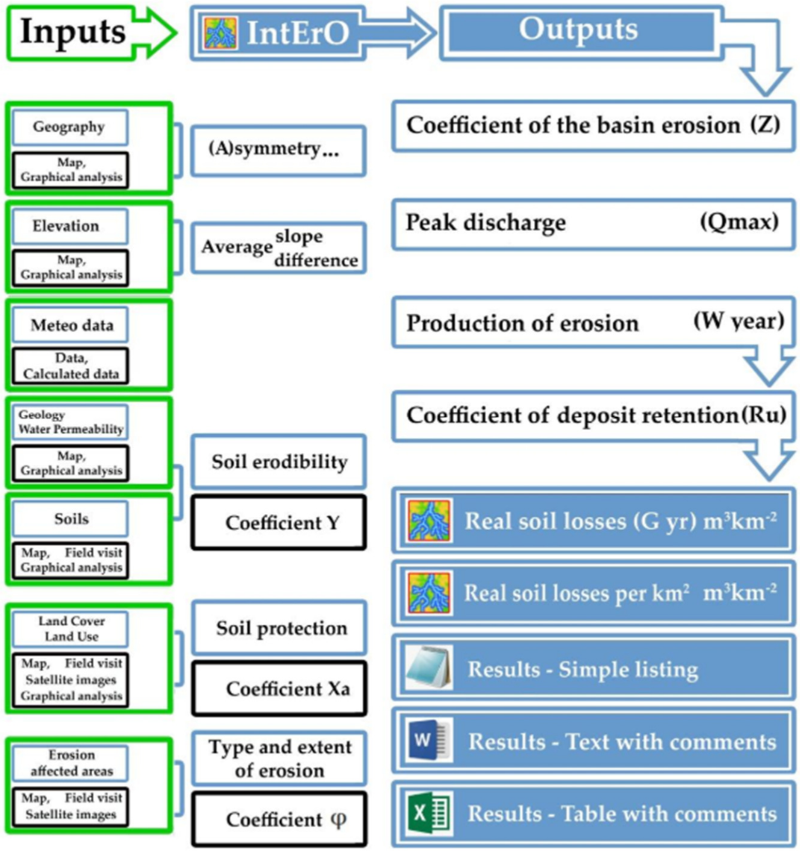

Figure 5. IntErO model Flow chart (based on Spalevic *et al.*, 2020)

Results and Discussion

The analysis reveals that Ceará experiences an average soil loss rate of 9.7 Mg ha^{-1} yr^{-1}, translating to a substantial total annual soil loss of 144 million tons. These average masks considerable variability across different land use classes. Non-vegetated areas exhibit the highest soil loss rates at 57.97 Mg ha^{-1} yr^{-1}, indicating that the absence of protective vegetation significantly intensifies erosion. Temporary crops follow with a soil loss rate of 30.57 Mg ha^{-1} yr^{-1}, while permanent crops and pastures show lower rates of 23.50 Mg ha^{-1} yr^{-1} and 14.46 Mg ha^{-1} yr^{-1}, respectively. Forested areas and Caatinga/Cerrado biomes have comparatively lower soil loss rates/degree of erosion, at 2.00 and 4.9 Mg ha^{-1} yr^{-1}, respectively according to Montanarella *et al*. (2015) and De Sousa Barbosa *et al*. (2024) (Figure 6).

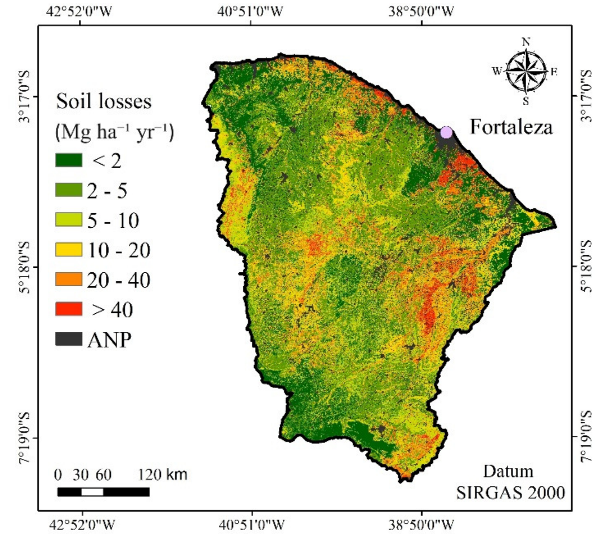

Figure 6. Map of the spatial distribution of soil losses in the Ceará state, Brazil
Notes: ANP = areas not considered in the calculation of soil losses

These findings underscore the essential role of vegetation in mitigating soil erosion. Even in areas with forest formations and Caatinga/Cerrado biomes, high erosion rates are still observed. This can be attributed to the sparse and uneven distribution of vegetation, which is insufficient for effective soil protection. The combination of shallow, nutrient-poor soils and limited vegetation cover increases erosion vulnerability, particularly in agricultural areas where soil management practices are unsustainable (Lima et al., 2021).

Comparing soil loss rates to Soil Loss Tolerance (T) values (Table 1), it is evident that 38% of Ceará's land area experiences soil losses exceeding T (Figure 7).

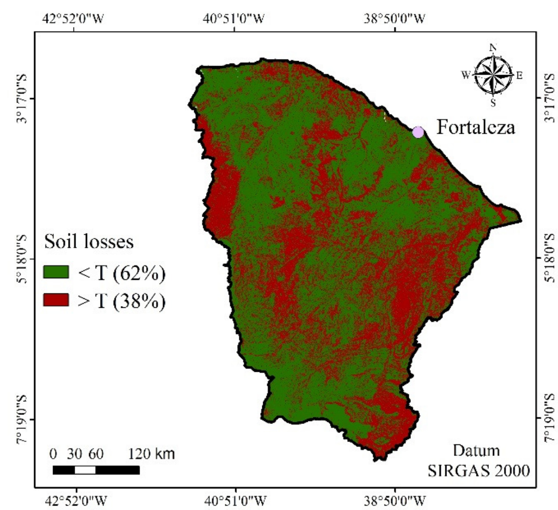

Figure 7. Map of areas in the Ceará state, Brazil, with soil losses below and above T

This widespread exceedance underscores the urgent need for comprehensive soil conservation strategies. The study by Tomasella *et al*. (2018) highlights that Caatinga regions in north-eastern Brazil, characterized by bare luvisols and argisols—covering 25% to 64% of the area—are generally susceptible to high rates of soil erosion. This erosion is primarily driven by climate variability and the practices associated with fallow farming systems. The spatial distribution of soil losses relative to T values demonstrates that areas of concern are dispersed throughout the state, emphasizing the need for targeted and region-specific erosion control measures.

The spatial distribution of annual rainfall (Figure 2A) reveals two distinct climatic regions within Ceará: the coastal area with annual rainfall exceeding 1,500 mm, and the semi-arid interior with less than 800 mm of rainfall. Both regions show elevated erosion rates in areas where soil losses exceed T.

This pattern is influenced by both inherent soil characteristics and land management practices. In the semi-arid interior, the low organic matter content and poor soil stability make the soils particularly prone to erosion (Ribeiro Filho *et al.*, 2017). The coastal region, despite higher rainfall, also exhibits high erosion rates due to suboptimal land management practices (Tomasella *et al.*, 2018; de Sousa Barbosa *et al.*, 2024). These results align with the contemporary study by Bezak *et al.* (2024), which conducted global soil erosion assessments using the EPM method and its modifications within a GIS environment.

Lima *et al.* (2021) indicates that around 40% of soils in Ceará are highly susceptible to water erosion. Tomasella *et al.* (2018) emphasizes the value of multi-temporal NDVI monitoring in identifying vegetation-free areas that are particularly vulnerable to land degradation and erosion in the Caatinga region. Their study revealed a rise in degraded areas from 2000 to 2016, with this increase being exacerbated by the severe drought that has affected the region since 2011. This trend underscores the intricate interplay between semi-arid conditions, rainfall variability and intensity, and land use practices associated with traditional agriculture.

Furthermore, this susceptibility is a critical factor to consider when evaluating the technical and economic viability of land use practices in the region. Using LULC modelling, Vieira *et al.* (2020) indicate an increased susceptibility to land degradation in north-eastern Brazil from 2010 to 2040. Their findings suggest the urgent need to introduce economically and environmentally sustainable alternatives to traditional low-income agricultural practices, which are contributing to land degradation.

Effective land use planning, informed by soil characteristics, is essential for mitigating erosion and promoting land sustainability. Medeiros *et al.* (2016) recommend that public policies prioritize the land's capacity or suitability for use, as this is a key factor in supporting sustainable agricultural practices and natural resource management.

In Ceará, agroecological practices supported by family farming present a promising approach to soil conservation. Family farming systems not only contribute to food production but also play a crucial role in landscape and biodiversity conservation, job creation, and erosion mitigation (Lima and Gamarra-Rojas, 2017; Lima *et al.*, 2019). These systems can be instrumental in promoting soil health and sustainability in semi-arid regions.

In conclusion, this study provides a detailed assessment of soil degradation in Ceará, highlighting the need for urgent adoption of conservation practices and land use policies. Addressing soil erosion is crucial for ensuring long-term soil health and productivity, given that soil is a finite resource on human time scales (Bertol *et al.*, 2019).

The results underscore the importance of targeted interventions and informed policy decisions to manage soil erosion and sustain the region's agricultural and environmental resources.

Conclusions

The study highlights that, contrary to the common belief that low rainfall results in minimal soil erosion, Ceará experiences significant soil erosion with an average rate of 9.7 Mg ha^{-1} yr^{-1}. This occurs even in the context of the semi-arid climate of Ceará, which has low annual rainfall.

Ceará's soils, inherently fragile, shallow, and nutrient-poor, contribute significantly to elevated erosion rates. These rates are further intensified by sporadic intense rainfall and unsustainable land management practices. Approximately 38% of Ceará's land area experiences soil loss rates that exceed the soil loss tolerance limits (T), with the problem being particularly acute in non-vegetated areas, agricultural lands, and pastures.

The Erosion Potential Method (EPM) and IntErO model are valuable tools for estimating and analyzing soil erosion dynamics in semi-arid regions. These models provide a comprehensive assessment of soil erosion, supporting land use planning and soil conservation strategies to mitigate erosion risks effectively.

There is an urgent need for targeted soil conservation strategies to mitigate the high erosion rates in Ceará. These strategies should include promoting sustainable land use practices and implementing erosion control measures, particularly in areas experiencing severe erosion.

Encouraging sustainable land management practices is essential to reduce soil erosion. This includes adopting agroecological methods, increasing soil organic matter, and enhancing vegetation cover to protect the soil surface.

Public policies should prioritize soil conservation by integrating soil characteristics and erosion risk assessments into land use planning. Policy initiatives should focus on areas where erosion rates exceed tolerance limits (T) and promote practices that effectively reduce soil loss.

Supporting family farming practices rooted in agroecology can play a vital role in soil conservation and sustainability. Agroecological practices not only enhance soil health but also contribute to biodiversity conservation and promote rural development.

Continuous monitoring of soil erosion and land use practices is essential. Adaptive management strategies should be implemented to address evolving erosion dynamics and land use challenges effectively.

Further research on soil erosion dynamics in semi-arid regions is necessary to deepen understanding and develop tailored solutions. Additionally, raising awareness about soil erosion and its environmental impacts can foster the adoption of effective conservation practices and inform policy-making.

Authors' Contributions

All authors contributed equally to all aspects of the research and preparation of this manuscript, including study design, data collection, analysis, and interpretation. All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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