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OROGRAPHY AND ITS INFLUENCE ON THE FORMATION OF THE DESERTIFIED CORE IN INHAMUNS

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Abstract

Analyzing the nucleus of desertification called Inhamuns, located in the state of Ceará - Brazil, it is observed that the relief represented by its orography, behaves as one of the influencing factors of such process. In this article, we seek to understand the role of the relief conditioning the desertification process, based on the analyzis between relief, climate and anthropic influence. For this, a detailed mapping of relief compartmentalization was carried out, the orography was related to the spatialization of centenary rainfall data and to the aridity index represented by 32 years of data, and the degradation levels were verified, between 1991 and 2017, in the main portions of interest. With the results it is verified that, the climate, when interacting with the relief, configures different characteristics on the windward and leeward sides, seen identifications of lower total rainfall and greater aridity in the desertified portion to leeward; anthropic action is present in areas inside and outside the desertification core, with growth in line shapes throughout the study area, given the priority use and occupation, in sectors close to water bodies and river plains; the relief compartments represented by sertaneja depressions 01 and 02 and residual massifs, showed an increase in environmental degradation; the primary factor in which there are fluctuations in your data, between desertified and non-desertified areas, given the presence of relief, it's the climatic. In view of this, it is understandable that, the configuration of the deserted core of Inhamuns, is the result of anthropic action on the effect of the semi-arid climate, downwind of a relief, over the years.

Keywords: DDesertification; Orography; Climate.

Resumo / Résumé

OROGRAFIA E SUA INFLUÊNCIA PARA FORMAÇÃO DO NÚCLEO DESERTIFICADO NOS INHAMUNS

Ao analisar o núcleo de desertificação denominado de Inhamuns, presente no estado do Ceará - Brasil, observa-se que o relevo representado por sua orografia, comporta-se como um dos fatores influenciadores de tal processo. Nesse artigo, busca-se compreender o papel do relevo no condicionamento do processo de desertificação, apoiando-se nas análises entre relevo, clima e ação antrópica. Para isso, realizou-se um mapeamento detalhado de compartimentação do relevo, relacionou-se a orografia com a espacialização de dados centenários pluviométricos e com o índice de aridez representado por 32 anos de dados, e verificou-se os níveis de degradação, entre 1991 e 2017, nas principais porções de interesse. Com os resultados constata-se que, o clima ao interagir com o relevo configura-se diferentes características a barlavento e a sotavento, visto identificações de menores totais pluviométricos e maior aridez na porção desertificada a sotavento; a ação antrópica está presente em áreas dentro e fora do núcleo de desertificação, com crescimento em formas de linhas em toda a área de estudo, dado o prioritário uso e ocupação, em setores próximos aos corpos hídricos e planícies fluviais; os compartimentos de relevos representados pelas depressões sertanejas 01 e 02 e maciços residuais, apresentaram-se com aumento na degradação ambiental; o primordial fator em que há oscilações nos seus dados, entre áreas desertificadas e não desertificadas, visto a presença do relevo, é o climático. Diante disso, compreende-se que, a configuração do núcleo desertificado dos Inhamuns, é resultado da ação antrópica sobre efeito do clima semiárido, a sotavento de um relevo, ao longo dos anos.

Palavras-chave: Desertificação; Orografia; Clima.

L'OROGRAPHIE ET SON INFLUENCE POUR FORMER LE NUCLEUS DÉSERIFIÉ DANS LE INHAMUNS

En analysant le noyau de désertification connu sous le nom d'Inhamuns, présent dans l'état de Ceará, on a observé que le relief représenté par son orographie se comporte comme l'un des importants facteurs qui influencent un tel processus. Dans cet article, nous cherchons à comprendre le rôle des secours dans le conditionnement du processus de désertification, en se basant sur l'analyse entre le relief, le climat et le action anthropique. Pour cela, une cartographie détaillée du compartimentage du relief a été réalisée, l'orographie était liée à la spatialisation des données pluviométriques centenaires et avec l'indice d'aridité représenté par 32 années de données, et les niveaux de dégradation ont été vérifiés, entre 1991 et 2017, dans les principales portions d'intérêt. Avec les résultats on trouve que, le climat, lorsqu'il interagit avec le relief, configure des caractéristiques différentes sur les côtés au vent et sous le vent, étant donné les identifications de précipitations totales plus faibles et d'une plus grande aridité dans la partie désertifiée sous le vent; l'action anthropique est présente dans les zones à l'intérieur et à l'extérieur du noyau de désertification, avec une croissance des formes de lignes dans toute la zone d'étude, compte tenu de l'utilisation et de l'occupation prioritaires, dans les secteurs proches des plans d'eau et des plaines fluviales; les compartiments de relief représentés par les dépressions sertaneja 01 et 02 et les massifs résiduels, a montré une augmentation de la dégradation de l'environnement; le facteur principal dans lequel il y a des fluctuations dans vos données, entre zones désertifiées et non désertifiées, compte tenu de la présence de relief, c'est le climatique. Compte tenu de cela, il est compréhensible que, la configuration du noyau désertification d'Inhamuns, est le résultat de l'action anthropique sur l'effet du climat semi-aride, sous le vent d'un relief, au cours des années.

Mots-clés: Désertification; Orographie; Climat.

INTRODUCTION

Desertification is considered one of the pressing environmental adversities curing humanity, as it decreases the availability of ecosystem services, increases food insecurity, and affects social well-being. Hence its recognition by the international community as an economic, social, and environmental problem (IRSHAD, 2007; CEARÁ, 2010; VIEIRA et al., 2020; RASTGOO and HASANFARD, 2022).

The overall genesis of desertification is related to the irrational use of natural resources in arid, semi-arid and dry subhumid areas, which predominate in the Northeast region of Brazil. Such practices include inadequate land management, overgrazing, slash-and-burn agriculture, deforestation, and overexploitation of woody resources as a source of fuel (VIEIRA et al., 2015; CCGE, 2016: TOMASELLA et al., 2018; LINS et al., 2023).

The relevance of desertification is evident, given that the risk of its occurrence affects approximately 4 billion hectares in more than 100 countries, directly impacting more than 250 million people (IRSHAD, 2007). In Latin America, it involves approximately 516 million hectares, with losses of billions of tons of arable land per year; in Brazil, it is responsible for annual economic losses of around 800 million dollars (BRASIL, 2004; CEARÁ, 2010).

Over time and in the various regions of the Planet, the concept of desertification is sometimes heterogeneous (ZONN, 2017). The United Nations - UN Convention's official definition, which advocates desertification as the process of land degradation in arid, semi-arid and sub-humid regions, resulting from several factors, including climatic variation and human activities, is somewhat imprecise regarding the factors attributed to the process, because of the phrase: "[...] resulting from several factors [...]" (UNCDD, 2018, p. 4).

Therefore, it is understood that the factors that cause or justify desertification are indicated from a specific analysis of the area studied. The natural and anthropogenic particularities vary in the different geographical positions where the process occurs.

To better understand the desertification in the study area, located in the sertão of Inhamuns, Ceará - Brazil, the discussion prioritizes the elements of relief, represented by hypsometric/orographic differentiation, and inserted in the context of depressions and residual masses; climate, represented by the rainfall and aridity index; and anthropic action, represented by quantification of uses and levels of degradation.

This article aims to understand the role of relief in conditioning the desertification process in the Inhamuns nucleus of Ceará through a detailed mapping of the relief compartmentalization, relating the rainfall spatialization and aridity index to the orography, and verifying degradation levels in the central portions of interest.

It is noteworthy that investigations on desertification, such as those carried out in this work, seek to contribute to a better understanding of the dynamics of this process and to creating strategies that aim to combat this problem. These are set out in objective 15 of the 2030 Agenda for Sustainable Development, which demonstrates the need for countries to "protect, restore and promote the sustainable use of terrestrial ecosystems; carry out sustainable forest management; combat desertification; halt and reverse land degradation; and reduce biodiversity loss" (UN, 2015).

STUDY AREA

When analyzing the Brazilian states, it is clear that Ceará has one of the most significant desertified areas. Fourteen of the state's 184 municipalities cover three distinct desertification nuclei: Inhamuns, Irauçuba and Jaguaribe. It is believed that the relief represented by orography is a determining factor in all three nuclei; however, this article summarizes the discussions and evidence for Inhamuns.

The search for an ideal spatialization and interaction between data is reflected in the study area's formation, which is composed of the junction of the municipalities with their surroundings and composes the Inhamuns desertification nucleus. Ceará (2010, p. 82) defined these as the municipalities surrounding and making up the residual massif of Pedra Branca, as follows: Tamboril, Monsenhor Tabosa, Boa Viagem, Madalena, Quixeramobim, Milhã, Senador Pompeu, Pedra Branca, Mombaça, Piquet Carneiro, Dep. Irapuã Pinheiro, Acopiara, Iguatu, Jucás, Saboeiro, Catarina, Arneiroz, Aiuaba, Parambu, Tauá, Quiterianópolis, Novo Oriente, Independência and Crateús (Figure 1).

In the central part of the study area, the orographic effect, windward to the east and leeward to the west, results from the combination of the altimetric oscillations and north-south arrangements of the residual massifs, with the predominant east-west/southeast-northwest wind directions and the rain-providing atmospheric systems (INMET, 2020). There are two principal altimetric changes. The higher levels in the central and extreme western sections are composed of residual massifs and plateaus, respectively. The low levels, located elsewhere in the area in question, are made up of the depressions and plains of the sertão (Figure 1). Briefly, the rains of the current climatic conditions are mainly due to the action of the Intertropical Convergence Zone – ITCZ. Annual totals vary from 300 mm to 1000 mm; three to four rainy months prevail, and there are nine to eight months with little rainfall or drought. In addition, the other active atmospheric systems are the Upper Tropospheric Cyclonic Vortices - UTCV, Easterly Wave Disturbances - EWD, Instability Lines - LI and Mesoscale Convective Complexes - MCC (MENDONÇA and DANNI-OLIVEIRA, 2007; ZANELLA, 2007; CAVALCANTI, 2009).

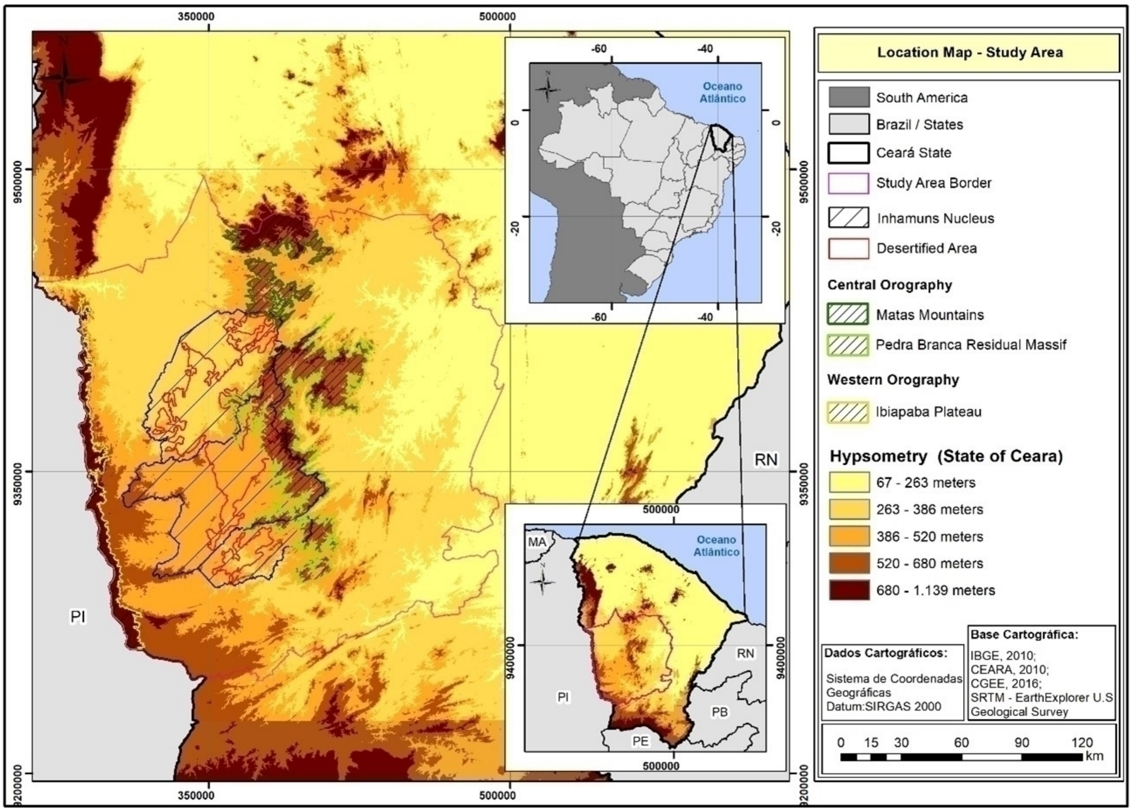

Figure 1 - Map showing the municipalities that make up the study area. Source: By the author

METHODOLOGY

SPATIALIZATION OF RELIEF COMPARTMENTS

The concept of landscape refers to the interactional understanding of current and past processes in a specific spatial segment in perpetual evolution, resulting from a dynamic combination of its constituent physical, biological and anthropic elements, forming a unique and inseparable set (BERTRAND, 2004). The term landscape enables the involvement of the various interdependent relationships of its constituent elements, which are changeable over time, and formers of a complex set with unique characteristics.

To create the landscape sectors in the study area, a division or compartmentalization is carried out based on topographic criteria and landforms with common traits regarding their physiognomic and genetic characteristics (SOUZA, 2000). Each landscape is called a relief compartment in this article based on these criteria.

Various actions were carried out to produce the relief compartmentalization map using ArcGIS software (ESRI). Fieldwork identified the relief features and geological maps by the Research and Mineral Resources Company - CPRM (CPRM, 2003) were studied. Shuttle Radar Topography Mission - SRTM images were analyzed, with a spatial resolution of 30 meters, taken from the Earth Explorer – US Geological Survey site, using the following coordinates: S05-W040-1ARCV3; S05-W041-1ARC-V3; S06-W040-1ARC-V3; S06-W041-1ARC-V3; S06-WP42-1ARC-V3; S07-W040-1ARC-V3; S07-W041-1ARC-V3. The resulting map with the compartment sections was on a mapping scale of 1:250,000 and a representation scale of 1:500,000.

PLUVIOMETRIC DATA

All the rainfall data used and spatialized were acquired on the website of the National Water Agency on the Hidroweb platform (ANA, 2020). Twelve rainfall series ranging from 1917 to 2016 were used for the database, which was able to correct any faults and identify feasible century-old historical series. The faults were remedied by replacing data from neighboring rain gauges (Table 1). Given the extent of the historical series and its essentially manual data collection, consistency in the respective database required the exclusion of 10% of the outliers in the rainfall totals, corresponding to the 05 totals with lower values and the 05 totals with higher values.

No.	Official Rain Gauge Long.Lat.	Rain gauge used – Filling Long.Lat.	Period	Distance between rain gauges
0	Crateus -40 40 00/ -05 12 00	Crateús Airport -40 42 00/ -05 12 00	1966-1975	4 Km
1	Monsenhor Tabosa – DNOCS -40 04 00/ -04 47 00	Monsignor Tabosa – FUNCEME -40 04 00/ -04 48 00	1976-2016	2 km.
2	Cacoci -40 30 00/-06 25 00	Parambu -40 42 00/-06 13 00	1976-2016	30 km
3	Saboeiro -39 54 00/ -06 32 00	Malhada -39 57 34/ -06 38 47	1993-2016	15 km
4	Independencia – DNOCS -40 20 00/ -05 23 00	Independencia – FUNCEME -40 18 46/ -05 23 37	1976-2016	2 km.
5	Mombasa - DNOCS -39 37 00/ - 05 45 00	Mombasa - FUNCEME -39 37 00/ - 05 45 00	1976-2016	same place.
6	Pedra Branca - DNOCS - 39 43 00/ -05 27 00	Pedra Branca - FUNCEME - 39 43 00/ -05 27 00	1976-2016	same place.
7	Tauá - FUNCEME -40 17 00/ -06 01 00	Perfect Data	Perfect Data	Perfect Data
8	Ibicuã -39 25 00/ -05 55 00	Piquet Carneiro -39 25 00/ -05 49 00	1986-2016	11 km
9	Senator Pompeu - ANA -39 20 54/ -05 34 42	Perfect Data	Perfect Data	Perfect Data
10	Quixeramobim – SUDENE -39 18 00/ -05 12 00	Quixeramobim - FUNCEME -39 17 00/ -05 12 00	1986-2016	2 km.
11	Iguatu - INMET 39 18 00/ -06 22 00	Iguatu - Airport 39 18 00/ -06 23 00	1966-1975	2 km.

Table 1 - Composition of the database from the official rain gauges and those used to fill faults. Source: By the author.

The averages of each rain gauge were used to spatialize the database results, corresponding to 01 rain gauge, 01 average for the respective 100 annual totals, or 12 rain gauges, and 12 averages for the respective 1200 annual rainfall totals. The spatialization of the resulting means was possible through the ArcGIS software (ESRI), using the Kriging method, which estimates the data, and fills in the voids (LANDIM and STURARO, 2002).

CALCULATION OF THE ARIDITY INDEX - AI.

The IA, elaborated by Thornthwaite (1948) and later adjusted by Penman (1953), is calculated:

$$IA = Pr / ET0$$

Where: (Pr) the total annual precipitation and (ET0) the total evapotranspiration.

The rainfall database above was also used to identify the total annual precipitation, corresponding to 100 years of data, with a single cut between 1974 and 2016.

To estimate total evapotranspiration, the Penman-Monteith method, currently considered standard and parameterized by the Food and Agriculture Organization of the United Nations - FAO (CONCEIÇÃO, 2006), was used. The calculation employed the SEVAP software, developed and made available free of charge by the Department of Atmospheric Sciences of the Federal University of Campina Grande - UFCG (SEVAP, 2020). This software estimates evapotranspiration, imputing the daily data of maximum and minimum temperature, wind speed, insolation, latitude–longitude, and height of the weather station in question.

Four meteorological stations – MS in the study area provided all the data necessary to calculate the AI in M.S. Crateús, MS Tauá, MS Quixeramobim, and M.S. Iguatu.

The temporal analysis of the AI covered the periods from 1974 to 1985 and 1994 to 2016. These dates were selected because they have less failure in the data required to calculate evapotranspiration, and their sum has data from 30 years. All four MS lack data from 1986 to 1994; thus, the period is excluded from the analysis to minimize errors.

For greater consistency in the data spatialization, the "inverse distance weighted average" technique was used to estimate the evapotranspiration data for eight rainfall stations, in this case by the distance of the two closest MS. With this application, it is possible to increase AI identification points by minimizing errors. This technique is used in applications to define AI by the Ceará Foundation of Meteorology and Water Resources - FUNCEME in Ceará state. All results are presented on maps applying the Kriging method.

CLASSIFICATION AND QUANTIFICATION OF DEGRADATION

The usage maps were produced from the supervised classification technique, in the Spring 5.5.2 software, applying the segmentation by the region growing method, the similarity in the value of 30, and the pixel area in the value of 30.

The classification was carried out for each satellite image; subsequently, all the classifications were combined to compose the study area. Landsat 5 TM images with bands from 1 to 6 were used to execute the 1991 usage map based on the dates 07.12.1991, 06.26.1991, 07.21.1991, and 07.05.1991. The 2017 usage map was created using Landsat 8 on 08.04.2017, 08.13.2017, and 09.30.2017. The criteria for choosing the years 1991 and 2017 were a multispectral resolution of 30 meters, the proximity of the monthly dates, and not belonging to outlier rainfall years.

Several types of equations analyze and quantify the rate of change in degradation (AL-AWADHI et al., 2005). Velazquez et al. (2003) are used herein to calculate land-use degradation rates as Equation 2 is accepted and applied in FAO studies.

$$X = \left[1 - \frac{S_2 - S_1}{S_1}\right]^{1/n} - 1$$

Where: X is the conversion rate of the environmental degradation process, S1 is the degraded area at time t1 (1991), S2 is the degraded area at time t2 (2017), and n is the difference in years between the two dates (i.e., 26).

This equation was applied to the quantitative data of the classifications identified in the relief compartments, referring to sertão depressions and residual massifs. Given their low representativity and lack of direct interaction with the discussions, it is not utilized in the other compartments.

RESULTS

RELIEF COMPARTMENTALIZATION

There is a prevalence of Shield and Crystalline Massif morphostructures in the study area. Additionally, Paleomesozoic Sedimentary Basins and Cenozoic Sedimentary Deposits and others are evident in smaller dimensions (Figure 2) (SOUZA, 2000; BRANDÃO, 2014; COSTA et al., 2020; SALES and MAIA, 2020).

A detailed analysis identified some relief compartments in the morphostructures, such as Residual Massifs - RM responsible for the orographic effect, Sertanejo Depression - SD, Ridges and Inselbergs, the Ibiapaba Plateau, and River and Inland Plains (Figure 2) (SOUZA, 2000; FUNCEME, 2009; BRANDÃO, 2014; COSTA et al., 2020; SALES and MAIA, 2020). The aim is to emphasize SD and RM, given the stronger presence of desertified areas and their correlation with the debates in this article.

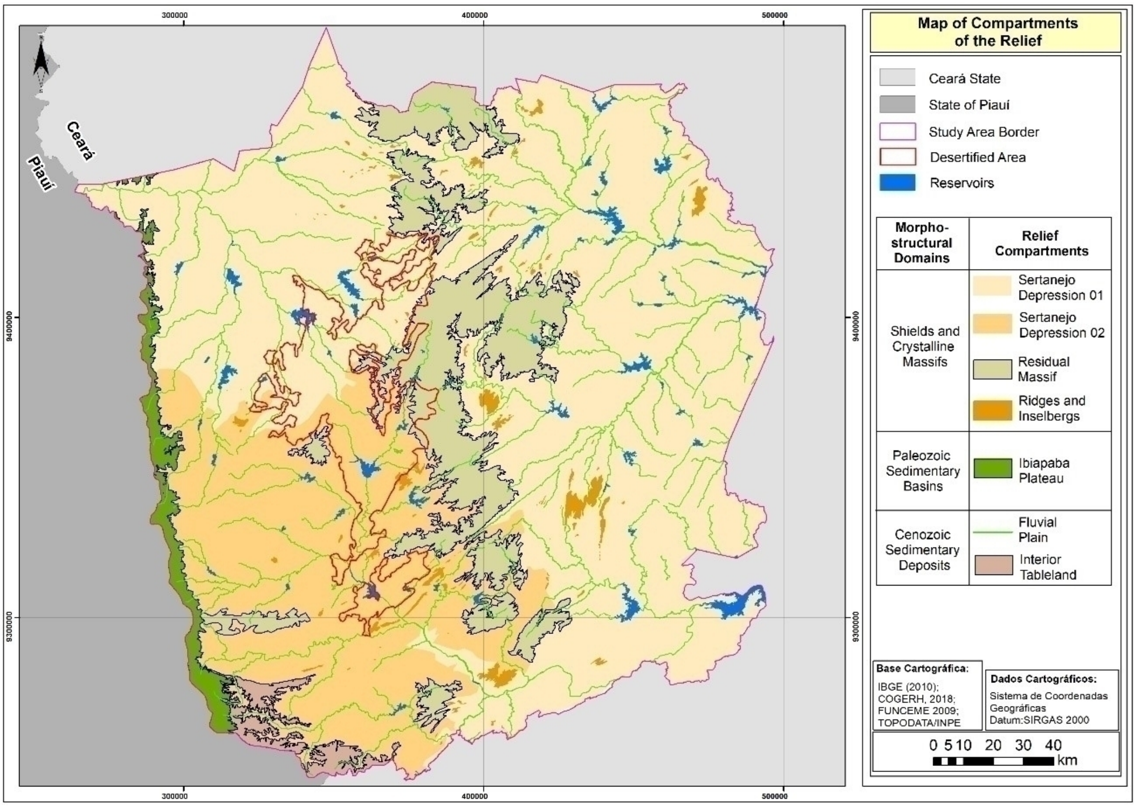

Figure 2 - Relief Compartment Map. Source: By the author.

Based on the methodology's SRTM images, the SD's pediplane surfaces are divided into two levels, called SD - 01, with altimetry ranging from 128 to 392 meters above sea level, and SD - 02, with altimetry ranging from 393 to 495 meters above sea level. This division was delimited from the study area's most significant disparity between SD levels (Figure 3). It is noteworthy that, depending on the research, there are different variations between the ranges of quotas in the SD on a state scale. Thus, Costa et al. (2020) divide the state into sectors with hypsometrics ranging from 50 to 250 meters and from 250 to 400 meters, whereas Brandão (2014) divides it into sectors with hypsometrics ranging from 40 to 350 meters and 250 to 550 meters.

Figure 3 - Contact area between SD 01 and 02, in the municipality of Independência and inserted in the desertification nucleus. Source: By the authors.

There are similarities in the physical factors of SD 01 and 02, including evidence of the predomination of dissection processes over those of deposition, leading to the exposure of the crystalline basement, composed of Precambrian igneous and metamorphic rocks, and formation of vast pediplanes dissected and embedded in the other compartments. Topographies with gentle slopes are observed based on erosion processes by diffuse surface runoff and concentrated in flood flow, seasonal, intermittent dendritic rivers, and shallow soils (BRANDÃO, 2014). During the year, the semi-arid climate, with high temperatures and a short rainy season, contributes to the variation of the floristic aspect of the caatinga vegetation.

There are two primary representations in the RM compartment, one by the Pedra Branca RM in the central section and another in the RM das Matas in the northern portion, both isolated and circumscribed by the SD in the study area.

RMs, made up of more resistant rocks than their lowered surroundings, result from the exhumation of plutonic intrusions in extension regions associated with tectonic structures (COSTA et al., 2020). On their steep slopes, dissection marks form amphitheaters, altimetric elevations ranging from 495 meters to 1138 meters, a predominance of shallow soils and less frequently deep, fertile, well-drained soils, such as Red-Yellow Eutrophic Argisols. These areas have springs that are the sources of important rivers in Ceará, such as the Banabuiú and Poti (COGERH, 2019). The altitude affects the semi-arid climate, and the densified vegetation varies from medium to high.

The Ridges are predominately elongated and rectilinear, whilst the Inselbergs have a preponderance of undulating and non-rectilinear shapes compared to RMs. They resemble each other because they are surrounded by SDs and have significant altimetric levels but differ in the greater dissection on their slopes, providing a sharp parallel retreat and consequently having smaller dimensions.

The River Plains, with slopes from 0 to 3 degrees, in constant cuts in the DPs, are forms of accumulation and deposition, retaining good soil conditions and water availability. They are considered distinctive areas (AB'SABER, 1999), given the higher humidity levels, lower temperatures caused by plant densification, and vegetation with a predominance of green foliage, even in the dry period.

The Ibiapaba Plateau to the east, represented by part of the Parnaíba sedimentary basin, is composed of the Siluro-Devonian Serra Grande formation, with cuestiform features, well-defined cornices, a front with a scalloped scarp developed by regressive erosion, slightly dissected or flat summit surface. Red-Yellow Latosols predominate, covered by arboreal caatinga vegetation and remnants of Atlantic Forest (SOUZA, 2000).

Composed of colluvium-eluvial coverings, the Inner Plateus to the southwest are evidenced by flat or slightly decayed areas to the south, interior accumulation ramps, tabular interfluves, carved foothills, a predominance of Argisol and Latosol, and plateau or caatinga vegetation (FUNCEME, 2009).

100 YEARS OF RAINFALL DATA AND ITS INTERACTIONS WITH OROGRAPHY

When seeking to understand the climatic conditions, it is apparent that the performance of the semi-arid climate in the study area is not homogeneous. Instead, there are distinct particularities sometimes due to interactions with other natural or anthropic elements.

When spatialized and compared to the east and west portions in the study area over 100 years of data, different mean rainfall totals are identified by a division marked by the RMs therein, clearly arising from orographic effects (Figure 4).

Given that total rainfalls are a determining factor in the desertification process (BRASIL, 2004) and the desertified areas in the Inhamuns core have low rainfall totals, resulting from the influence of its position leeward of the RMs, it is only possible to address the true causes of desertification if the relief factor is included in discussions and interactions (Figure 4).

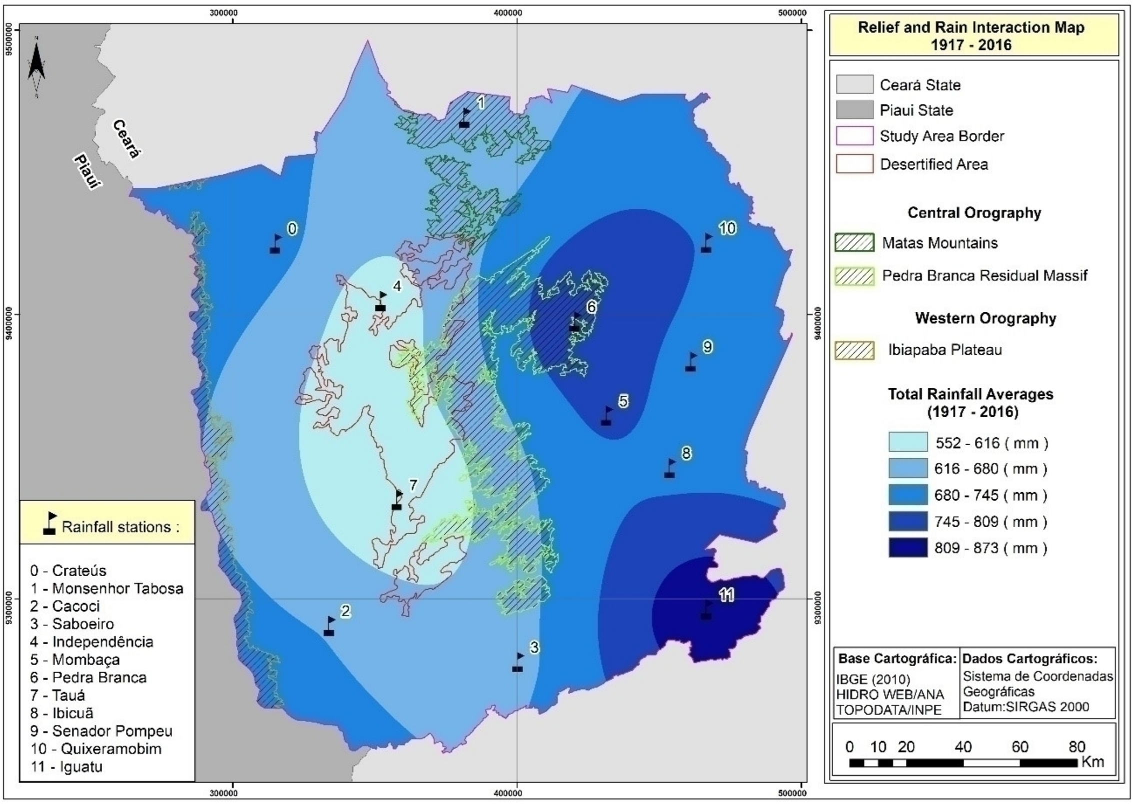

Figure 4 - Map of Relief and Rain Interaction between the years 1917 and 2016. Source: By the authors.

A synthesized analysis of the 100 years of rainfall data in Figure 4 shows:

•Average rainfall totals, responsible for the direct relationship with desertification, with results negatively or positively affected by the orography in the central section;

•Significant parts of the study area are in the process of desertification leeward of the central orographic features, with the lowest average annual rainfall totals.

•The windward portion of the central orographic landforms and the extreme southeast part, represented by the municipality of Iguatu, have the best rainfall averages in the study area.

•Areas leeward of central and desertified orography, with approximately 200 mm below the mean rainfall totals in many portions of the study area, including the predominance of windward RM possibilities.

Understanding the rainfall results, based on a climate and relief relationship, is related to desertification, as windward areas or areas with better rainfall inputs are predisposed to more densification of caatingas; better pedological protection from torrential effects; higher water fixation in the subsoil; higher prevalence of wildlife; and more significant superficial water accumulation. Leeward areas or areas with lower rainfall are predisposed to sparser caatingas; less soil protection from torrential effects; rocky outcrops; less or no water fixation in the subsoil; the exodus of wild fauna and less water accumulation (Figures 5 and 6).

Figure 5 - Aspect of the windward slope, present in the municipality of Pedra Branca-CE, evidenced on August 12, 2018. Source: Author's collection.

Figure 6 - Aspect of the leeward slope, present in the municipality of Independência-CE, evidenced on August 12, 2018. Source: Author's collection.

IDENTIFICATION OF THE ARIDITY INDEX

The calculation of the AI, composed of data from different climatic elements, is another component that reveals the expressiveness of the relief, represented by the orography, in the desertification process in the study area.

The AI is calculated by the ratio between the amount of water introduced into the system by rainfall and the amount of water leaving the system by evapotranspiration. The result shows the degree of aridity or dryness of a given area and can be associated with a climatic classification, with segments such as Hyper-arid, Arid, Semi-arid, Dry Subhumid, Wet, and Wet Subhumid (UNEP, 1992; MATALLO and SCHENZEL, 2003).

Identifying the AI and its correlation with desertification means that the greater the dryness in a given area, the easier agricultural losses, lack of water bodies, limited plant growth and dispersion of wildlife.

According to the 32 years of average AI data, all the municipalities in the study area are classified as semi-arid. Furthermore, the other climatic factors in its composition are related to the central orography; lower values prevail in the leeward and desertified portions. Other parts, such as windward and non-desertified areas, have a prevalence of higher values. These areas' variations in AI values may show differences above 0.5 mm (Figure 7). The extreme southeastern portion, not directly influenced by the orographic effects, has the lowest aridity.

The results of the AI calculation are related to the results obtained in the previous topic, strengthening the interactional role of orography in desertification (Figure 7).

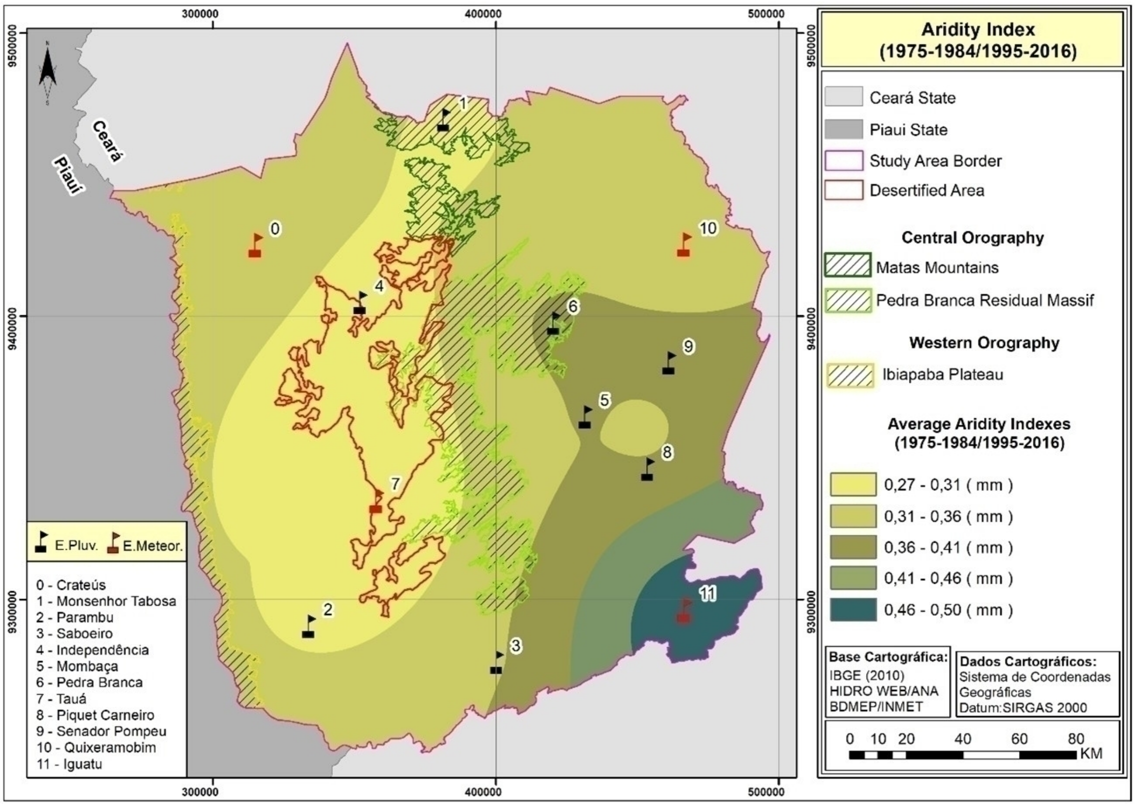

Figure 7 - Map with the spatialization of the averages of the Aridity Indices, between the years 1974 to 1985 and 1995 to 2016. Source: By the authors.

ANTHROPIC APPROACH

Degradation in the study area is evident in four principal factors, deforestation caused by the commercialization of wood, residential occupations, and crops and pastures; widespread grazing associated with inadequate soil management practices, resulting in compacted areas showing traces of erosion; rudimentary agricultural practices associated with the indiscriminate use of fire; and the domestic use of vegetation for firewood and charcoal production.

When comparing usage maps for 1991 and 2017, significant and calculable oscillations are identified between their classes, namely: Riparian Forest; Exposed Soil; Herbaceous-Shrub Vegetation; Arboreal-Shrub Vegetation; Waterbodies, such as lagoons, dams, rivers and dams; and Anthropic Areas, represented by crops, deforestation, population clusters, pastures, and possible natural pastures or areas under fallow (Figures 8 and 9).

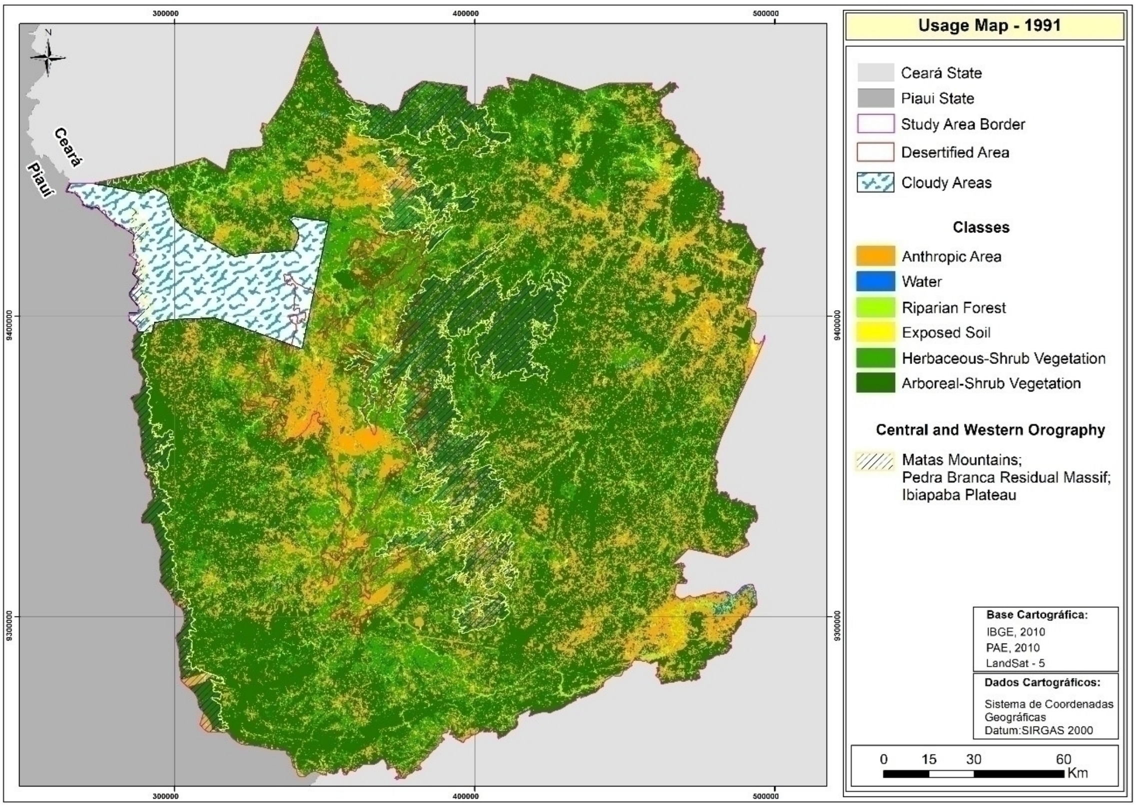

Figure 8 - Map of use for the year 1991. Source: By the authors.

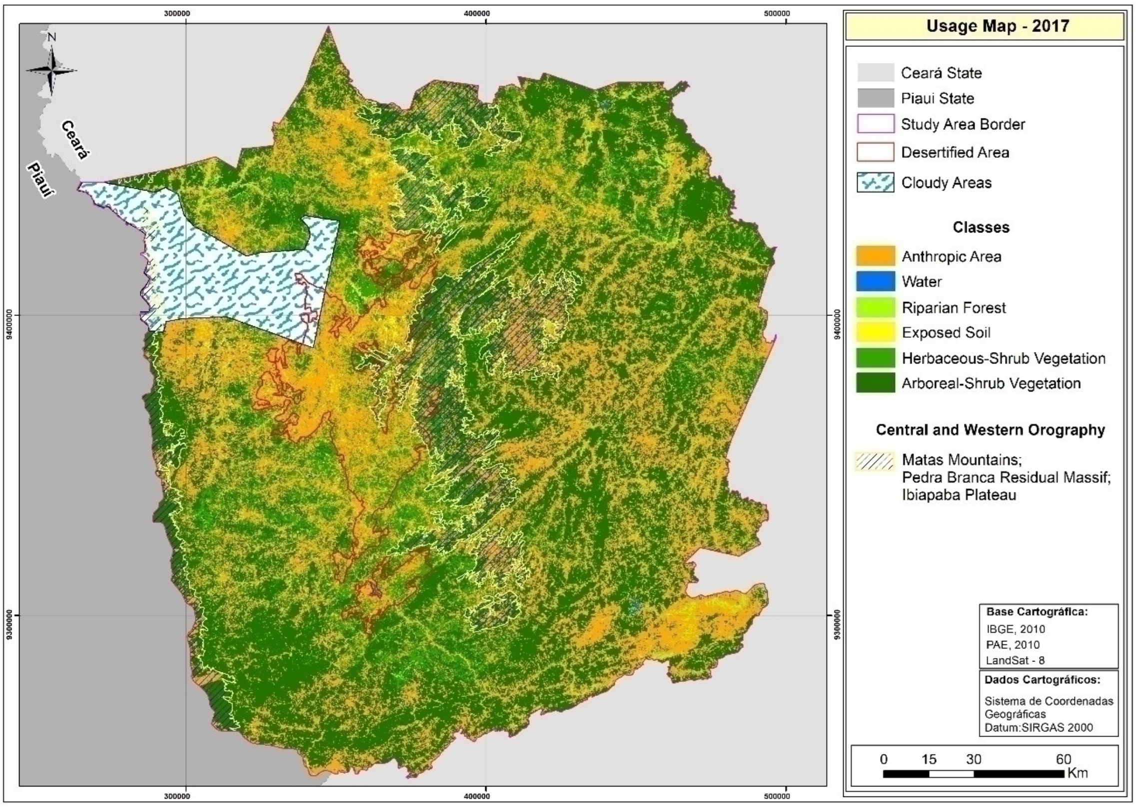

Figure 9 - Map of use for the year 2017. Source: By the authors.

Figures 8 and 9, for 1991 and 2017, respectively, indicate a perceptible increase of the anthropic area into the vegetation, both inside or outside the desertified polygon, assuming that the desertification factors are not just limited to the advance of anthropic areas. Much of the growth of anthropic areas is linear, as use and occupation predominate in areas close to water bodies and river plains, which have this format.

The analysis of other classes between the two years indicates that herbaceous-shrub vegetation predominates in areas within or near the desertified areas, whereas arboreal-shrub vegetation prevails in several fragments, such as over the uplands. The exposed soil had widened in plots inside and outside the desertified area. Riparian forests and water bodies had shrunk throughout the study area due to the continuous human quest for the best natural conditions in these landscapes, leading to their anthropization and degradation.

In summary, the oscillations between the classes in the usage maps show an increase in environmental degradation in the study area since there is a reduction in riparian forests, waterbodies, herbaceous-shrub vegetation, and tree-shrub vegetation, as well as an increase in exposed soil and anthropic areas (Table 2).

Given their greater interconnection with the evidenced desertification, below we focus on compartments SD 01 and 02 and RM to quantify their classes of use and their levels of degradation. In scenarios with higher degradations, the classes behave as follows: Water tends to -5; Exposed Soils tend to 5; Anthropized Area tends to 5; Riparian Forest tends to -5; Herbaceous-Shrub Vegetation tends to -5; and Arboreal-Shrub Vegetation tends to -5. Classes behave inversely in scenarios with lower degradations (FAO, 1996; VELAZQUEZ et al., 2003; AL-AWADHI et al., 2005).

Study area						
CLASSES	Area (km²)				Variation (km²)	Growth percentage
	1991	%	2017	%		
Exposed Soil	318	0,84	534	1,41	216	67,92
Anthropic Area	8834	23,27	13613	35,85	4779	54,10
Riparian Forest	1166	3,07	905	2,38	-261	-22,38
Water	327	0,86	134	0,35	-193	-59,02
Herbaceous-Shrub Vegetation	8376	22,06	5702	15,02	-2674	-31,92
Arboreal-Shrub Vegetation	18947	49,90	17080	44,99	-1867	-9,85

Table 2 - Quantification of the classes present in the use maps of the years 1991 and 2017. Source: By the author.

Comparing 1991 and 2017, the data for the RMs shows that, even with the advance of anthropic areas and the rise of degradation, areas with vegetation cover predominate. The increase in the anthropized areas and the exposed soils of 823 km² and 24 km², respectively, occurred mainly in arboreal-shrub vegetation, which reduced 614 km², and herbaceous-shrub vegetation, decreasing 222 km². All the classes show the advance of degradation, with the following values: 3.5 for exposed soil, 4.0 for the anthropized area, -0.9 for the riparian forest, -3.2 for waterbodies, -0.9 for herbaceous-shrub vegetation, and -0.8 for tree-shrub vegetation (Figure 10).

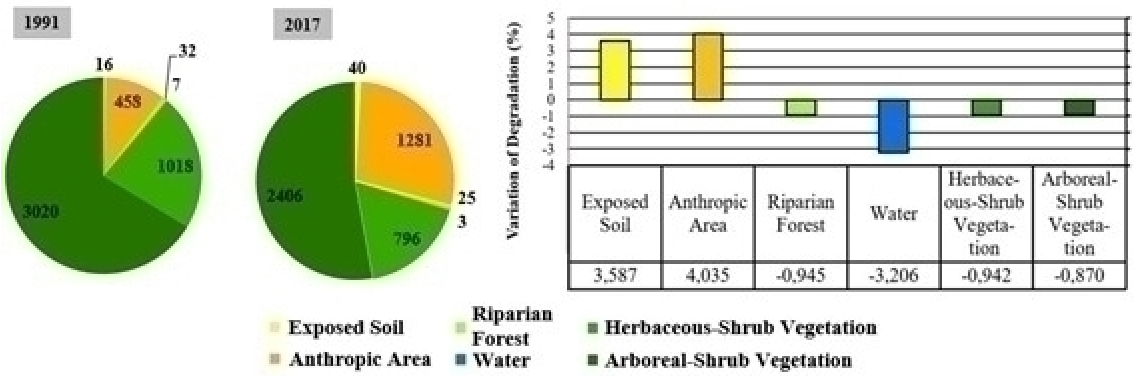

Figure 10 - Quantification in km² and degradation in classes present in the RM, in the years 1991 and 2017. Source: By the author.

In SD-01, the biggest relief compartment in the study area, a comparison of 1991 and 2017 shows the most considerable advance of anthropic areas on the vegetation cover among the compartments analyzed. The anthropic areas have grown 3005 km² over herbaceous-shrub and shrub-tree vegetations, reducing these by 1612 km² and 892 km², respectively. Moreover, due to these extensive anthropogenic areas, there has been an increase in exposed soils of 186 km². The wide variation between the classes reflected the increase in degradation, resulting in values of 1.4 and 2.5 for the anthropized areas and exposed soil, respectively, -0.3 for shrub tree vegetation, -1.7 for herbaceous-shrub vegetation, -3.3 for waterbodies, and -1.1 for riparian forest (Figure 11).

Also, comparing 1991 and 2017, we identified growth in anthropic areas of 1,094 km² on herbaceous-shrub and shrub tree vegetation in SD-02, providing a reduction in these of 796 km² and 256 km², respectively. This variation between classes reflected an increase in degradation, considering the following results: -1.2 for herbaceous-shrub vegetation, -0.2 for arboreal-shrub vegetation, -3.5 for water, -0.1 for riparian forest, 0.4 for exposed soils, and 1.5 for anthropic area (Figure 12).

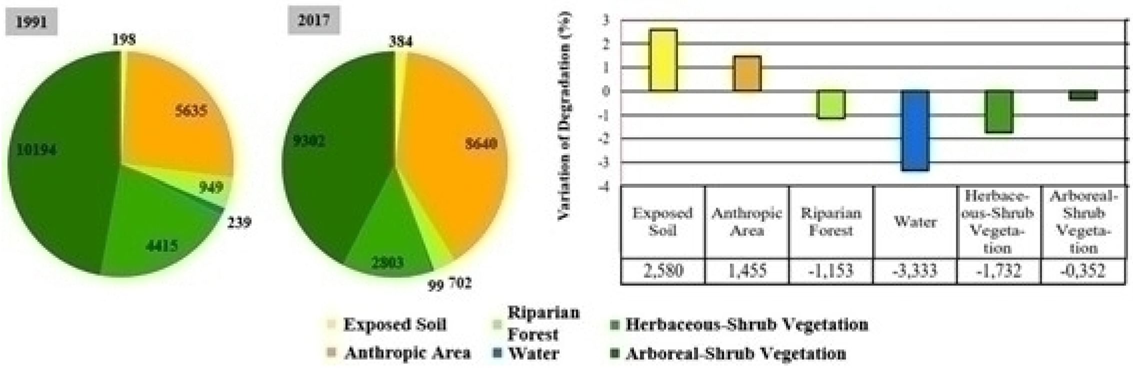

Figure 11 - Quantification in km² and degradation in classes present in SD-01, in the years 1991 and 2017. Source: By the author.

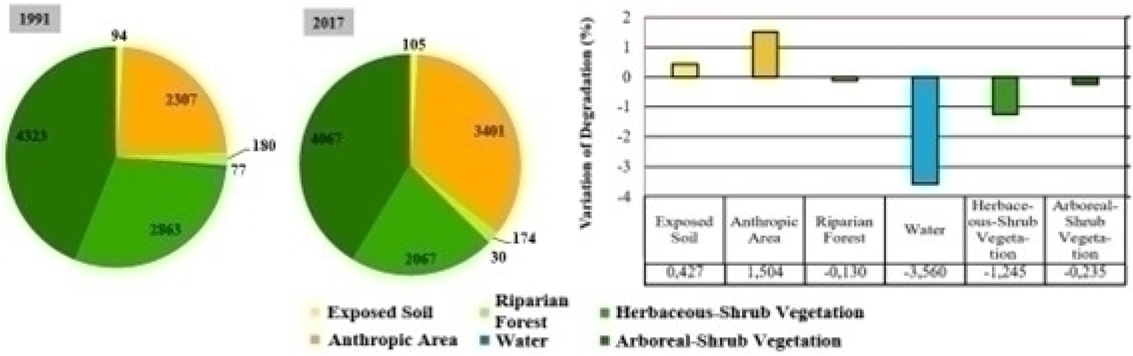

Figure 12 - Quantification in km² and degradation in classes present in SD-02, in the years 1991 and 2017. Source: By the author.

The detailed data verifies an expansion of uses and degradation in the investigated compartments, emphasizing the SD. It is evident that in the leeward areas of the residual massifs, where there is less water in the system when anthropic activities outstrip the support capacity, the recovery or vegetation flourishing is more complex compared to other areas with higher rainfall inputs. Over time this leads to a higher frequency of cycles composed of the abandonment of land, search for new non-degraded areas, and increased degradation (Figures 13 and 14).

Figure 13 - Area degraded by intense use in the desertified portion of Inhamuns, in Independência, leeward of the residual massif of Pedra Branca. Source: Author's collection.

Figure 14 - Area degraded by intense use in the desertified portion of Inhamuns, in Independência, leeward of the residual massif of Pedra Branca. Source: Author's collection.

DISCUSSION

DESERTIFICATION CRITERIA IN THE SERTÃO DOS INHAMUNS

Desertification occurs on different spatial and temporal scales, influenced by several factors, making it a complex evaluation process (VIEIRA et al., 2020; LINS et al., 2023). The concept of desertification factors offers potential criteria that lead to slightly degraded or even conserved areas falling into the process of desertification.

Thus, by understanding that the concept of desertification is linked to the existing factors and that the landscapes on the Planet where this problem is verified have dynamic dissimilarities, it is possible to state the relevance of this model, which can go beyond a general model and cover the specific factors that prevail in a given geographical surface.

The varied literature on the study area attributes desertification factors primarily to anthropic action and climate (VERDUM et al., 2002; NASCIMENTO, 2006; CEARÁ, 2010; CCGE, 2016). This article went beyond these two primary "genesis factors", inserting a new component, the relief, thus offering considerations that have been underexplored, even on a national scale.

Studies on desertification considering the factor of relief are already available in the international literature. For example, in Spain, a study entitled: "Programa de Acción Nacional Contra La Desertificación" was published in 2008. Despite using the official UN concept, it explains that Spanish desertification can be attributed to the intrinsic relationship between natural and human factors, in which the rugged relief in various parts of the country provides orographic effects, which affect bioclimatic and even socioeconomic conditions (ESPAÑA, 2008).

In the case of the Inhamuns nucleus, the orographic relief influences desertification, as it interacts actively with the climate. Over the years, in the respective windward and leeward portions, it has generated areas with distinct physical-natural characteristics and consequently greater or less susceptibility to the hegemony of this problem.

This perception is based on the results presented, which allowed us to verify the following statements, first, rainfall is an essential parameter to classify areas susceptible to desertification. Secondly, the relief has residual masses in the central portion, with higher altitudes, which provide windward and leeward situations for the sertanejo depressions on its eastern and western edges. When interacting with the relief, the climate has different windward and leeward characteristics, given the lower total rainfall and greater aridity identified in the desertified leeward segment. Thirdly, anthropic action has occurred in large areas inside and outside the desertification nucleus. Also, given the priority use and occupation, the anthropic areas' growth throughout the study area is linear in sectors close to water bodies and river plains, which predominantly have this format. The relief compartments represented by the sertanejo depressions 01 and 02 and residual massifs had an increase in environmental degradation. Finally, a comparison of the results of the climate (rainfall and aridity index) and anthropic action (quantification of uses and levels of degradation) indicates that the primary factor in data oscillations between desertified and non-desertified areas, given the presence of the relief, is the climate.

Given the above, together with the climate and human action, it is evident that the relief influences the desertification in the Inhamuns sertão. Consequently, it is possible to construct a concept adjusted to reality in situ involving these factors. Therefore, it is understood that the configuration of the desertified Inhamuns nucleus results from anthropic action affected by the semi-arid climate, leeward of a relief feature, over the years (Figure 15).

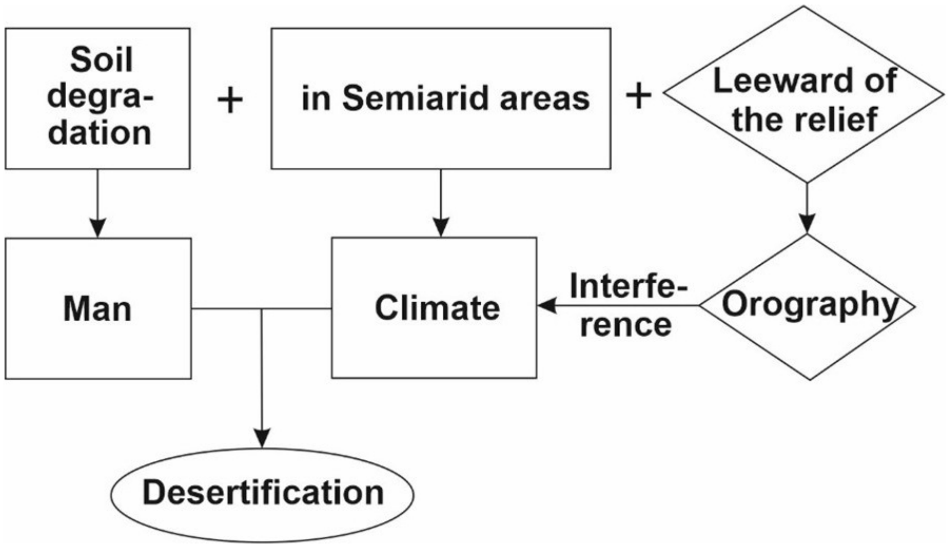

Figure 15 - Inclusion of the relief factor, as one of the criteria for desertification in the Inhamuns hinterland, Ceará.

CONCLUSION

The recovery of these currently desertified areas has become of paramount importance since the advance of current practices will increase the difficulty in reversing the problem. Vieira et al. (2020) explain that one possible global desertification scenario suggested an increase of around 53% of the area under high susceptibility to the process in question from 2010 to 2040, corresponding to 652,753 km² to 997,167km². The need to preserve waterbodies, soils, biodiversity, and harmony between use practices and nature reinforces the relevance of studies in this issue, which involve discussions about desertified areas. With the insights on the factors of desertification in the Inhamuns sertão, new research possibilities are emerging in other areas with similar characteristics, as evidenced in the other nuclei in the state of Ceará.

The analyses showed that the relief in the central portions of the study area, consisting of residual massifs, acts as one of the determining factors in the desertification process insofar as it provides distinct characteristics in windward and leeward slopes in the sertanejo pediplaned depression. Thus, its insertion in the concept of desertification of the Inhamuns nucleus is feasible. Furthermore, its insertion complements academic contributions that only consider the climate and anthropic action factors. This research enabled the creation of maps of the relief compartments, the quantification of one hundred years of rainfall in semi-arid areas, the identification of aridity indices, the production of usage maps between the years 1991 and 2017, the quantification of usage classes and environmental degradations, and the revelation of the relief factor as a driver of desertification in Inhamuns sertão. The authors believe that these objectives have been achieved throughout the discussions.

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