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Main water characteristics and climatic types of environments undergoing degradation and/or desertification in northeastern Brazil

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R E S U M O

A desertificação é uma das maiores preocupações socioambientais do planeta, haja vista a redução da capacidade produtiva da terra, especialmente, nas áreas com clima do tipo Semiárido. A maioria das áreas em processo de degradação ambiental é dita de desertificação, embora haja controvérsia conceitual e de causas: climática, antrópica e/ou uma interação entre si. Diante disto, procurou-se comparar, as diferenças conceituais e as condições pluviais e hídricas dos núcleos de desertificação do Estado da Paraíba, em relação aos núcleos de outros estados nordestinos, sendo essas determinações os objetivos principais. Para efetivar este estudo, utilizaram-se os índices de aridez (Ia) da UNEP, adotado pela FAO, e o Ia, oriundo do balanço hídrico climatológico cíclico e sequencial (BHC), além de estabelecer a climatologia pluvial. Os principais resultados indicaram que, os processos de degradação, requerem estudos detalhados dos regimes pluviais e hídricos e não somente o índice de aridez. O critério da anomalia da chuva revelou num excelente indicador ambiental, por contemplar o valor da chuva esperada. O Ia, oriundo do BHC, difere do Ia da UNEP, além de possibilitar análise mais ampla da disponibilidade hídrica e das categorias de aridez. A desertificação é um processo de degradação ambiental dinâmico e complexo e, portanto, requer a inclusão de outros indicadores hídricos e não somente o índice de aridez.
Palavras-chave: Semiárido, climatologia da chuva, índice de aridez, susceptibilidade à desertificação.

Principais características hídricas e tipos climáticos de ambientes em processo de degradação e/ou desertificação no nordeste brasileiro

A B S T R A C T

Desertification is one of the biggest socio-environmental concerns on the planet, given the reduction in the land's productive capacity, especially in areas with a semi-arid climate. Most areas in the process of environmental degradation are said to be desertification, although there is conceptual controversy and causes: climatic, anthropogenic and/or an interaction between them. In view of this, we sought to compare the conceptual differences and the rainfall and water conditions of the desertification centers in the State of Paraiba, in relation to the centers of other northeastern states, with these determinations being the main objectives. To carry out this study, the aridity indexes (Ai) of the UNEP, adopted by the FAO, and the Ai, derived from the climatologically water balance (BHC), were used, in addition to establishing the pluvial climatology. The degradation processes require detailed studies of the rainfall and water regimes and not just the aridity index. The rainfall anomaly criterion proved to be an excellent environmental indicator, as it contemplates the value of expected rainfall. The Ai, from the BHC, differs from the Ia from the UNEP, in addition to enabling a broader analysis of water availability and aridity categories. Desertification is a dynamic and complex environmental degradation process and, therefore, requires the inclusion of other water indicators and not just the aridity index.
Key-words: Semiarid, rainfall climatology, aridity index, susceptibility to desertification

Introduction

The environment encompasses several biotic and abiotic factors, which have complex and multifunctional relationships with different elements of the landscape. Therefore, human actions on the environment have been one of the biggest concerns worldwide, given that human actions are the main causes of environmental degradation, with social and economic damage.

The idea of the term desertification was pioneered by Aubréville (1949), when associated with human actions in areas of tropical Africa, due to the intense use and degradation of natural resources and the lack of understanding the importance of environmental dynamics.

This African ecological degradation led to the progressive transformation of tropical forests into savannas or even drier ecosystems. Since then, the aforementioned term has received a series of other meanings, some of them contradictory and most of them ambiguous (Verstraete, 1986)

Fullen and Catt (2004) mention that the process of environmental degradation has different forms, although the best known is soil erosion, which removes a large part of the surface layer, causing mass movement. The wear and transport processes that soil and/or rocks undergo are not the only forms of environmental degradation, because human actions cause damage to the environment (Lima and Roncaglio, 2001; Nogueira de Souza, 2003).

Most concepts about desertification are discordant, ambiguous and generalist and the only convergence is related to the removal of vegetation cover and inadequate management techniques as factors that contribute to degrading the environment, being expanded in areas with arid, semi-arid and dry subhumid.

Desertification is, without a doubt, a terminology used most of the time to describe soil degradation and the formation of erosive juices, but there is a scientific consensus: environmental degradation, caused by anthropic actions, especially with the removal and The burning of native vegetation, in areas with irregular rainfall in quantity and distribution, with semi-arid climates, can initiate or intensify the desertification process (Almeida and Galvani, 2022).

Cunha and Guerra (2012) reported that, in some areas, the impacts caused by anthropogenic pressure on natural resources intensify desertification processes in the long or short term, depending on the impact and frequency.

When questions about environmental issues, it is common to define them as desertification. Matallo Júnior (2001) expresses that this uncertainty may be associated with theoretical and methodological weaknesses, such as: conceptual breadth; lack of universally accepted study methods to identify desertification processes and methodologies for economic assessment of desertification.

The lack of consensus, both with regard to the influence of natural processes and possible human interventions, capable of inducing an environmental transformation, Mainguet (1994) sought to define conceptual variations associated with the perception of the process at different spatial and temporal scales, establishing them five phases: 1) awareness, 2) exaggerated perception of the process, 3) doubt about the process, 4) the myth of desert growth and 5) the new realism

The awareness phase emerged in the 1940s, when Aubréville (1949) reported that soil and vegetation deterioration was caused at least in part by human activities, which were considered the main promoters, called desertification.

In this context, desertification is a global phenomenon and more than 33 thousand hectares are degraded daily. China is one of the countries most seriously affected by desertification in the world, with a percentage of desertified areas of 27.20% in relation to the total land area (Li et al., 2023).

The pioneering nature of studies on the subject of desertification in Brazil was developed by Vasconcelos Sobrinho (1978a; 1978b), when he introduced the so-called desertification centers in the semi-arid region of northeastern Brazil, an environmental issue that was contributed by Ab'Saber (1977) in studies of desertification and savannization in Inter tropical Brazil and sandization, proposed by Suertegaray et al., (2008), as being a phenomenon equivalent to desertification.

For Conti (2008), desertification is the deterioration of the natural environment, with a progressive reduction in biomass and environmental drying out, with an increase in temperature and intensification of erosion processes. The origin can be attributed to natural causes and/or triggered by human actions. It is a dynamic process, generally associated with relatively long dry periods and high climate variability, conditions that are predominant in places with arid and semi-arid climates (Conti, 2005).

In this process of environmental degradation, progressive losses in ecosystem productivity are more significant in sub-humid and semi-arid areas, where pressure on biomass, through the removal of shrub vegetation, overgrazing and mining activities, triggers environmental stress, which results in accelerated erosion and, ultimately, desertification (Conti, 2002).

Although the phenomenon of desertification is not new, science recognizes that it is a serious problem at a global level and attributes climate variability and human activities as the main causes. However, the scientific formulations that most contribute to desertification alarmism are attributed to human actions, especially the removal of native vegetation and overgrazing (Souto, 1985).

In the conception of Rodrigues (1987), desertification is a phenomenon that integrates economic, social and natural processes that destroy the soil, vegetation and environment, as well as the quality of life of the population, in areas subject to soil aridity and/ or climate.

It is noteworthy, however, that there are a lack of methodological procedures that make it impossible to indicate whether the process of environmental degradation is desertification or not. However, climate indicators (rainfall, air temperature, evapotranspiration, among others) are necessary to establish risk areas and must be monitored. In this context, the aridity index appears, for example, as a reliable indicator of desertification (Matallo Júnior, 2001).

In integrated studies of environmental conditions to characterize the desertification process in Portugal (Pimenta et al., 1998) they proposed three indices: a) the relationship between average annual precipitation and potential evapotranspiration; b) the loss of soil resulting from the erosion process (rain erosivity) and c) the rates of meteorological droughts.

The methodology based on the aridity index IA (ratio between precipitation and evapotranspiration (Thornthwaite, 1941), proposed by UNEP (UNEP, 1991), indicates the northeastern semi-arid region is susceptible to desertification, although human actions are more frequent.

The climatologically water balance of (Thornthwaite and Mather, 1955) is a technology that fills the gap left by IA, by accounting for the entry and exit of water and, consequently, estimating the real evapotranspiration, surplus and water deficiency, in addition to the variation time of water storage in the soil.

The criterion established for delimiting these areas was the aridity index (Thornthwaite, 1941), calculated by the ratio between rainfall and potential evapotranspiration (ETP). The values of this index are indicative of the types of climate: between 0.05 and 0.20, the climate is arid; in the range between 0.21 and 0.50, semiarid; from 0.51 to 0.65; sub humid dry and above this value, sub humid wet or humid.

Using trends in time series of potential evapotranspiration and rainfall in northern China as indicators of climate change, and relationships with desertification, for different periods of time, the reversal in desertification in the northeast and northwest regions of China, between 1975 and 1990, it was mainly influenced by human actions (Zhang et al., 2020).

Most published works, nationally and internationally, limit themselves to listing the annual aridity index, proposed by UNEP, as the only criterion to indicate land susceptibility to desertification.

In this context, we sought to analyze and compare the aforementioned index with the aridity, water, effective humidity and drought indices resulting from the climatologically cycle (average) and sequential (year by year) water balance, in addition to establishing the rainfall regime, this broad study being the main objectives.

Material and methods

The case study included the desertification nuclei of Cariri and Seridó in the State of Paraiba, in addition to comparing them with those in the Northeastern States of Ceará (Irauçuba- 03º44'S; 39º47'W; +153 m), Rio Grande do Norte (Caicó- 06º27'S; 37º05' W; +153 m), Pernambuco (Cabrobó- 08º29'S; 39º18' W; +312 m) and Piauí (Gilbués- 09º49'S; 45º20'W; +458 m).

For the desertification nuclei in Paraiba, the climatologically series of air temperature and rainfall from two locations were used: Cabaceiras (07º29'S; 36º17'W; +382m) and Santa Luzia (06º52'S; 36º55'W; +302m), located, respectively, in the aforementioned centers and in the intermediate geographic regions of Campina Grande and Patos.

For other locations in the Northeastern States, monthly and/or annual rainfall and air temperature data were extracted directly from the National Institute of Meteorology portal (https://portal.inmet.gov.br/)

Monthly and annual data of the above-mentioned meteorological elements have been provided by the Executive Water Agency of the State of Paraiba (AESA), Campina Grande, PB, for the period from 01/01/1970 to 12/31/2020. Rainfall data, on temporal scales, from each location, were analyzed, using the basic criteria of climatologically and descriptive statistics.

Due to the asymmetry of monthly and annual rainfall models, when comparing averages with medians, the median was adopted instead of the average, as it is the most likely value (statistically) to occur. Therefore, the rainy and dry (climatologically) times (seasons) were established by counting, respectively, the chronological sequences of the months with the highest and lowest median values and not the average, due to the asymmetry of the model.

To complement the study of rainfall climatology, in the desertification centers of Seridó and Cariri in the State of Paraiba, the criterion of the annual rainfall anomaly (AC) is included, accounting, annually, for the positive (above) and negative deviations (below), in relation to the expected median.

Potential (ETP) or reference (ETo) evapotranspiration was estimated, on daily and monthly scales, using the method of Hargreaves and Samani (1985), calculated using the expression:

$$ETo = 0{,}0023 \times Qo \times (t\max - t\min)^2 \times (tned + 17{,}8)$$

Being: Qo=extraterrestrial solar irradiance, in mm of equivalent evaporation (mm.d^{-1});

tmax= maximum daily temperature, in ^{o}C;
tmin= minimum daily temperature, in ^{o}C
tmed= average daily temperature, in ^{o}C

To determine the cyclical and sequential climatologically water balance (BHC), the methodologies recommended by Thornthwaite and Mather (1955) were used, adopting a maximum water depth stored in the soil of 20 mm.

This accounting between water input (rain) and output (ETo) resulted in water deficiency related to the susceptibility of land to desertification, estimated using the expressions.

Aridity Index

$$Ai\,(BHC) = \frac{\text{water deficiency } (mm)}{ETo(mm)}$$

Aridity Index

$$Ai\,(UNEP) = \frac{Rain\,(mm)}{ETo(mm)}$$

UNEP Ai values (1991) were grouped into classes with respective classifications as shown in Table 1. With the AI in hand, the levels of susceptibility to desertification were established according to the criteria proposed by Schenkel and Matallo Júnior (2003) according to Table 2.

Table 1. Class ranges of UNEP aridity indices (AI) and respective aridity classifications.

Aridity Index	Aridity classification
$Ai < 20$	Arid
$20 \leq Ai < 50$	Semi-arid
$50 \leq Ai < 65$	Sub humid Dry
$65 \leq Ai < 100$	Sub humid Humid
$Ai \geq 100$	Moist

Table 2. Categorias de susceptibilidade à desertificação, com base no índice de Aridez, proposta por Schenkel e Matallo Júnior (2003).

Level of susceptibility to desertification	Aridity Index
Very High (Ma)	0,05 < Ai ≤ 0,20
High (Al)	0,21 < Ai ≤ 0,50
Moderate (Md)	0,51< Ai ≤ 0,65
Low* (Bx)	Ai ≥ 0,66

(*) proposed by the author

The simple linear regression model between the aridity index, estimated by the water balance method, and annual rainfall was established by the equation: Y= a+bX and the choice of the coefficient of determination (R^2). The calculations, statistical analyze and creations of graphs were carried out using the Excel spreadsheet.

Results and discussion

Rain climatology in the desertification nuclei of Paraiba

In discussions regarding the northeastern semi-arid region, one issue immediately emerges: water, rain and drought. It is common to say that it doesn't rain and the lack of water is the biggest problem. This is a relative truth, given that there is a marked difference in quantity and temporal distribution when comparing one geographic area with another.

Figures 1 and 2 summarize the monthly rainfall distribution models for the locations of Cabaceiras and Santa Luzia, with indicators of central tendency measures (mean, median) and dispersion (standard deviation).

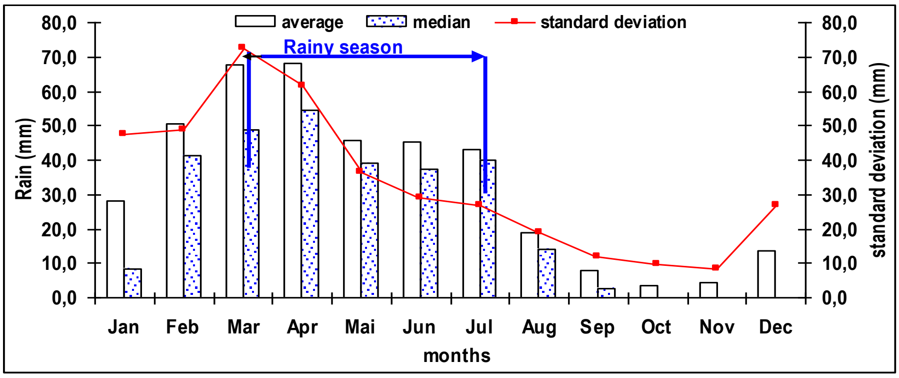

Figure 1. Monthly averages of the means, medians and standard deviation of rainfall. Cabaceiras, PB, period averages: 1970/2020.

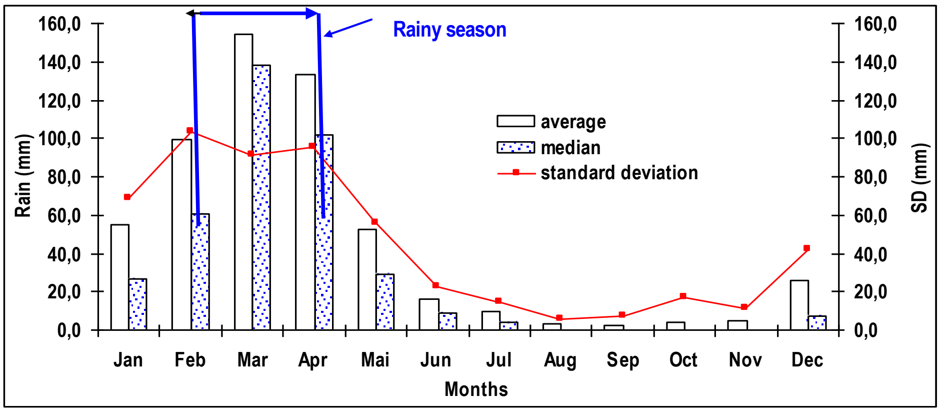

Figure 2. Monthly averages of the means, medians and standard deviation of rainfall. Santa Luzia, PB, period averages: 1970/2020

Degradation processes in semi-arid environments have always prioritized using annual rainfall averages. However, every average is associated with a standard deviation (SD), whose value is added or subtracted from the observed value (±).

These oscillations quantify trends, cycles and variability. Thus, the rainfall regime models for the two locations begin to be "designed", using the criteria of climatologically statistics.

The monthly rainfall distribution models for the two locations (Figures 1 and 2) show that the average values differ from those of the medians, that is, they are asymmetrical. For this condition, the use of the average is not recommended but the median, which agrees with the recommendations made for other locations by (Oliveira, Nóbrega and Almeida; 2012; Almeida and Brito, 2020; Almeida and Galvani, 2021).

Regarding monthly dispersions, it is also observed that there is a high dispersion, measured by the standard deviation of the mean (SD), when comparing, monthly, the arithmetic means with the SDs. These indicators, in most months, exceed the average values themselves, in which the variation coefficients were 58.6% for Cabaceiras and 49.0% for Santa Luzia.

It is noteworthy, however, that the monthly rainfall distribution models in the two locations are different in quantity and distribution. The expected annual medians, in Cabaceiras (320.0 mm) against 540 mm, in Santa Luzia. Although the desertification nucleus of Cariri in Paraiba is less rainy (59.3%) than Seridó, the type of climate, according to Koppen's classification, is the same; Hot semiarid (BSh).

This assertion seems to be subjective and, in most cases, it is made only considering the total rainfall accumulated in the year or the expected average, which ends up generating clashes of opinions.

A more appropriate scientific criterion is to establish the main characteristics of the rainfall regime in the rainy season.

Due to the asymmetry in the monthly rainfall distribution models, the rainy season, for each location, was established by the sequence of rainiest months, adopting the expected medians and not the arithmetic means.

Accounting for the accumulated rainfall (medians) in the months of the rainy season, for the two locations, as shown in Figures 1 and 2.

The choice of this period is justified by the partial concentration of rainfall equivalent to more than 50% of the annual total. It can be seen that in Cabaceiras (Figure 1), it rains in five months (March to July), corresponding to 50.5% of the annual amount. In Santa Luzia, this period is much shorter (three months), from February to April, but it rains 60.5% of what is expected during the year.

These rainfall distribution models, in the rainy season, reveal, very clearly, that rainfall regimes are extremely irregular. This irregularity occurs in other places in Paraiba, corroborating the results of Almeida and Brito (2020), when they report that rain is the climate element with the greatest spatial and temporal variability, regardless of the geographic region.

Another important characteristic in the rainfall regime, in the two locations analyzed, refers to the comparisons of monthly dispersions and those accumulated in the rainy season and in the year, in relation to the respective medians. These indicators were, respectively, 162.0; 99.0 and 59.0% for Cabaceiras against 170.4; 78.4 and 49.0%

This inequality shows, for example, that in the rainy season, both the amount of rain and its distribution are different. Furthermore, there are chances of it not raining, which corroborates the results of Almeida and Brito (2020) for other locations in Paraiba and those of Ferreira et al., (2018) and Dias and Panner (2021) for other locations.

It is customary to attribute these irregularities (in quantity and distribution), especially in the short rainy season, to droughts, rather than droughts, or natural variability of the aforementioned regime.

To complement the study of rainfall climatology, for the desertification centers of Seridó and Cariri in the State of Paraiba, the rain anomaly (RA) criterion is included in the rainy season, whose graphic representations are presented in 3 and 4.

Figures 3 and 4 show, respectively, the rainfall anomalies (accumulated), in the rainy season, of the two locations in the desertification centers of Seridó and Cariri in the State of Paraiba, associated with the means +SD and mean +2* SD.

Positive and negative deviations in relation to the expected median indicate, respectively, rainfall above and below the expected median. This criterion allows us to state not the accumulated rainfall in the respective period, but what should rain in relation to what was expected.

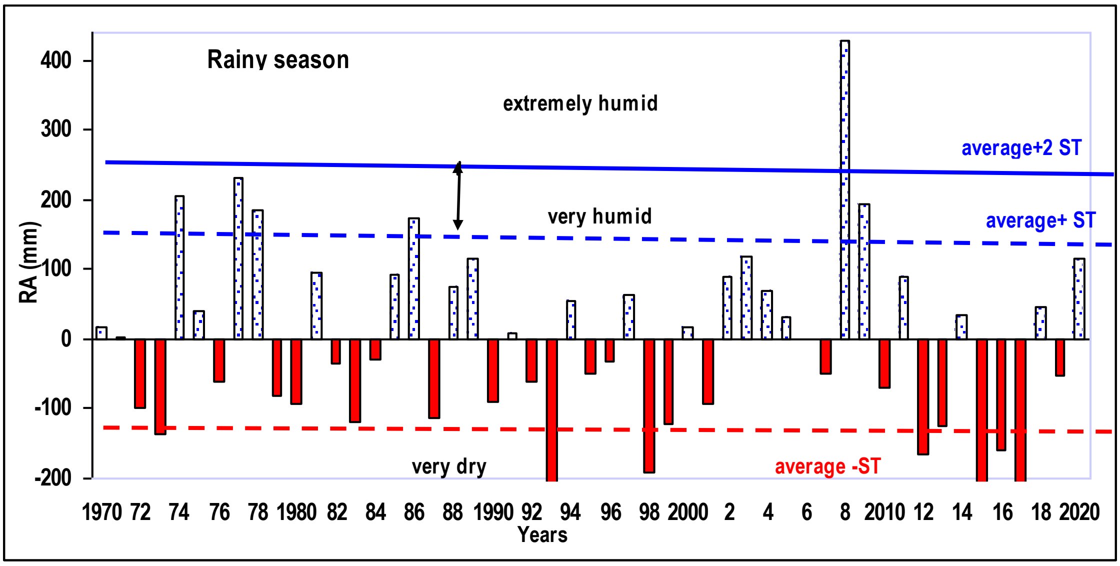

Figure 3. Rain anomalies observed in the rainy season associated with the mean ± standard deviation, in Cabaceiras, PB.

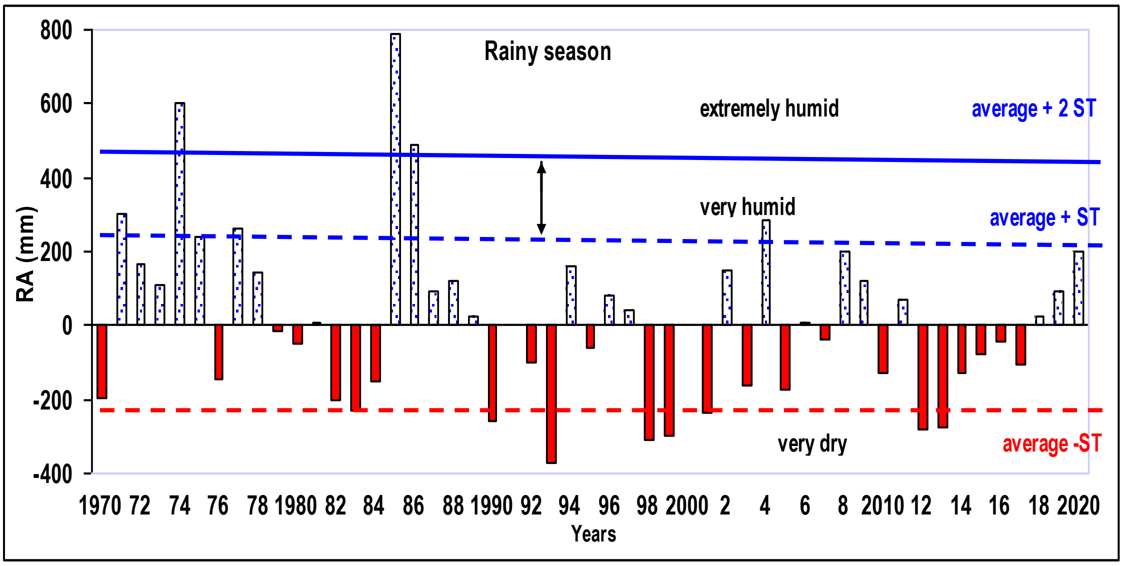

Figure 4. Rain anomalies observed in the rainy season associated with the mean ± standard deviation, in Santa Luzia, PB.

In a simple analysis, it is observed that of the 51 years analyzed, in Cabaceiras, 78.4% rained between the average and ST, 11.8% were very dry and 7.8% very humid or extremely humid, while, in Santa Luzia, this same sequence was 76.5%; 11.8% and 5.9%.

When characterizing the environment, the anomaly criterion is a better indicator than the total rainfall. Even though Cabaceiras is less rainy than Santa Luzia, it can be seen (Figures 3 and 4) that the RA magnitudes are equivalent to half that of Santa Luzia. This indicates, therefore, that a lower rainfall observed in a location is not an indication of it being drier, given that the RA explains the characteristics of the location.

The relationship between rainfall and potential evapotranspiration, called aridity index (AI), is the main indicator proposed by FAO to measure the degree of susceptibility to desertification, here called UNEP AI.

However, the climatologically water balance (BH), in addition to being an important tool to characterize the environment, makes it possible to carry out a broader analysis of local water availability, whose accounting also results in the aridity index

Aridity indices of desertification centers in Paraiba and others in the NE.

The UNEP aridity index has been used as the sole or main indicator of land susceptibility to desertification. To complement this understanding, Figure 5 presents the monthly relationships between rainfall and AI UNEP for the two desertification centers in Paraiba.

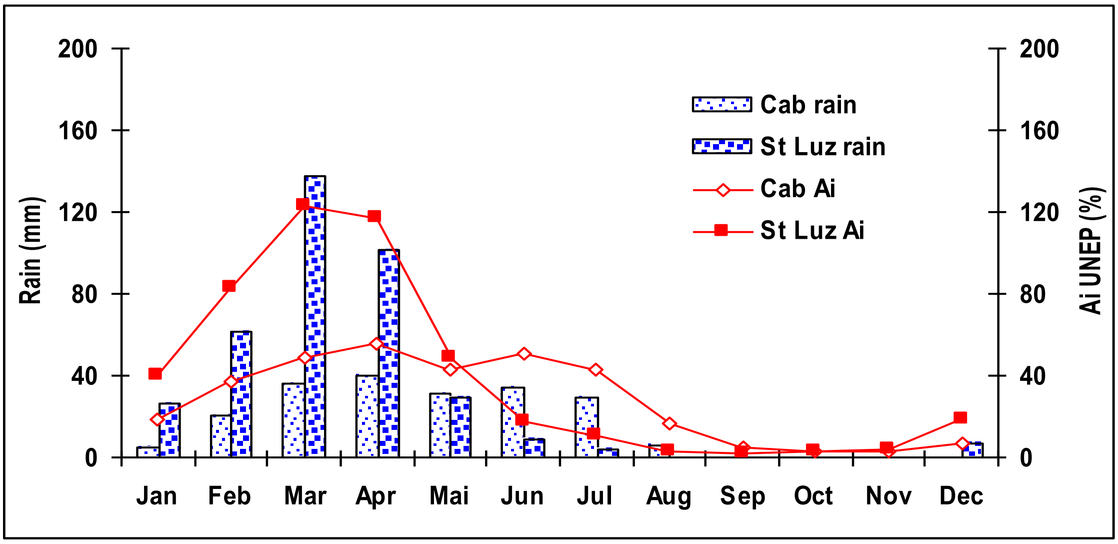

Figure 5. Monthly medians of rainfall (ch) and the relationship between ch and the UNEP aridity index (Ai).

As UNEP Ai results from a ratio between rainfall and potential evapotranspiration, the Ai indicators are higher in the rainiest months and lowest in the least rainy months (Figure 5). This proportional ratio explains why the UNEP Ais are lower than 20% between August and January, in both locations, the aridity classes are from Semi-arid to arid, corroborating Schenkel and Matallo Júnior (2003), which has a level of high to very high susceptibility to desertification.

Although these two locations' climate types have the same classification, BSh, according to Koppen's classification, Santa Luzia rains around 69.0% more than Cabaceiras.

It is also added that the months of the rainy season are sub-humid to humid versus semi-arid to dry sub-humid, respectively. These differences, for the same type of climate, therefore indicate that environmental conditions are not necessarily the same

Desertification centers in Cariri (Cabaceiras- Cab) and Seridó (Santa Luzia- St Luz) in the State of Paraiba.The long dry season, lasting seven to nine months, as it coincides with the hottest time of the year (spring and summer), contributes to greater drying out and soil degradation.

The land already degrades, to a large extent, due to nature itself, human actions, removing the little native vegetation and burning firewood, leave the soil uncovered, increasingly contributing to degrading the soil.

These conditions converge, in part, with the idea of the term desertification, proposed by Aubréville (1949), when associating it with human actions in areas of tropical Africa, due to the intense use and degradation of natural resources and the lack of understanding the importance of the dynamics environmental.

It is agreed with Fullen and Catt (2004) that the process of environmental degradation has different forms and human actions cause damage to the environment (Nogueira de Souza, 2003), although it disagrees with most concepts of desertification and the only convergence is that environmental degradation could be increased in areas with arid, semi-arid and dry sub-humid climates.

Due to the lack of consensus, I subscribe to what Mainguet (1994) described, who sought to define conceptual variations associated with the perception of the process at different spatial and temporal scales, in five phases: 1) awareness, 2) exaggerated perception of the process, 3) of doubt about the process, 4) of the myth of desert growth and 5) of the new realism.

This is corroborated by Matallo Júnior (2009): “desertification results from the inadequate management of natural resources in semi-arid and arid zones and the formation of deserts, from climate evolution", therefore, they are absolutely different concepts.

In the case of the northeastern semi-arid region, the results of Rodrigues (1987) are confirmed, in which soil degradation processes cause loss of productive capacity and involve the economic, social and natural sectors.

To check whether the desertification centers in Paraiba have differences in the monthly rainfall distribution models and the UNEP aridity index, Figures 6 and 7 show, respectively, the relationships between them and compare them with those of the centers in Piauí (Gilbués), Ceará (Irauçuba), Pernambuco (Cabrobó) and Rio Grande do Norte (Caicó).

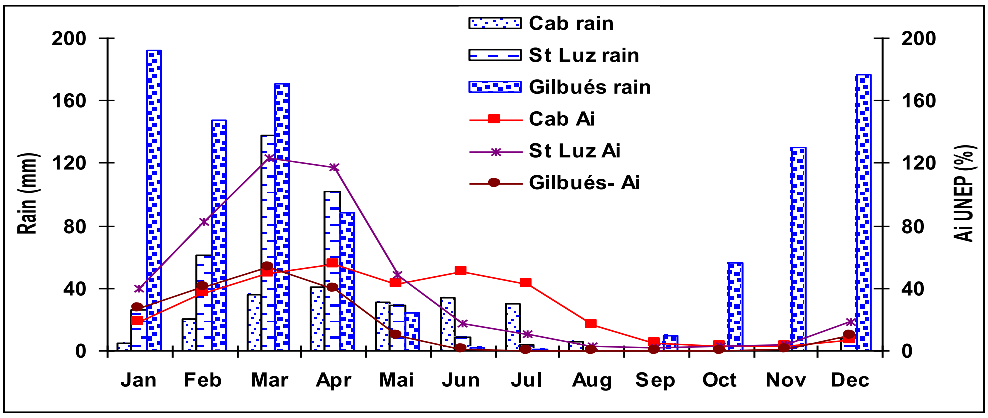

Figure 6. Monthly comparative analyzes of the relationships between rainfall (ch) and the UNEP aridity index (Ai), of the desertification centers of Paraiba (Cariri- Cabaceiras (Cab) and Seridó- Santa Luzia- St Luz), with the from Piaui (Gilbués)

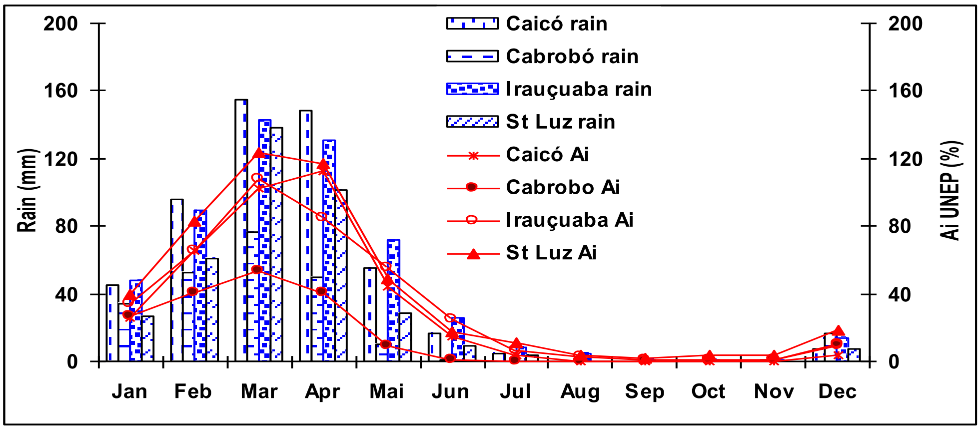

Figure 7. Monthly comparative analyzes of the relationships between rainfall (ch) and the UNEP aridity index (Ai), of the desertification nucleus of Seridó in PB, with that of Seridó in Rio Grande do Norte, Ceará and Pernambuco.

Comparing the monthly rainfall distribution models, it is observed (Figure 6) that the one in Gilbués is very different, when compared to those in the desertification centers in Paraíba, both in quantity and in distribution, raining three times more than Cabaceiras and almost twice as much as Santa Luzia.

The type of climate, according to Köppen's climate classification (1948), is hot and humid tropical (Awh), with rain in the summer and drought in the winter. The official concept of desertification, by the United Nations, is the "degradation of land in arid, semi-arid and dry sub-humid regions, resulting from various factors, including climate variations and human activities.

The criteria established by Vasconcelos Sobrinho (1978b) when framing Gilbués as a desertification nucleus seems confusing and/or contradictory. It is observed (Figure 6) that most months are humid, that is, outside the range adopted by the United Nations Convention, which classifies lands susceptible to desertification

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It is agreed with Sales's (1997) challenge to the term desertification core, adopted by the aforementioned author, and ratifies the concept of arenization, proposed by Silva (2014), by redirecting his interpretations, because desertification does not occur in areas with exposure of sand or in places with annual rainfall averages above those in arid and semi-arid climates (Suertegaray el al., 2008).

Similar comparisons were made using indicators of rainfall and aridity index from the desertification nucleus of Seridó in PB with the desertification nuclei of Seridó in Rio Grande do Norte, West of Ceará and Sertão de Pernambuco (Figure 7).

When viewing Figure 7, one can see the existence of a long dry season (seven months), from June to December, when the average accumulated rainfall is less than 30.0 mm, which results in UNEP aridity indices lower than 20%, classified as arid and very high levels of susceptibility to desertification.

The climatology of the rainfall regime - monthly and annual- of the four locations (Figure 7) shows irregularities in the quantity and distribution, both spatially and temporally. Comparing the annual accumulation, it appears that Caicó, RN, as the rainiest, and Cabrobó, PE, the driest, with a percentage of 70.0% higher and around 20.0% in relation to Santa Luzia and Irauçuba.

It is noteworthy, however, that the main characteristic of the desertification nucleus of Irauçuba, which does not differ much from that of Cabrobó, is the great occurrence of laminar erosion, favored by the exposure of the soil in addition to erroneous practices, overgrazing, intensive monoculture cultivation, among others. The long period without rain makes it difficult for vegetation to regenerate and therefore worsens the process of environmental degradation.

It is agreed with Almeida et al., (2014), that the use of only the UNEP aridity index, based only on average annual values of P and ETP, seems to be insufficient to delimit/characterize the phenomenon of desertification.

Potential evapotranspiration refers to the loss of water from an extensive vegetated surface without water restrictions, a condition that is not even found in humid regions.

To expand the analysis of the water conditions of the desertification centers in Paraiba, the aridity, humidity and drought indices estimated by the cyclical and sequential climatologically water balance method are included.

Water indices for desertification centers in the State of Paraiba

The sequential climatologically water balance (BHC) is an important technological tool, as it allows the oscillation of water storage to be established at the effective depth of the soil, computing water gains and losses. This accounting results in the components of the BHC, of which the aridity, humidity and drought indices stand out. Figure 8 presents a relationship between the aridity indices (UNEP and BHC)

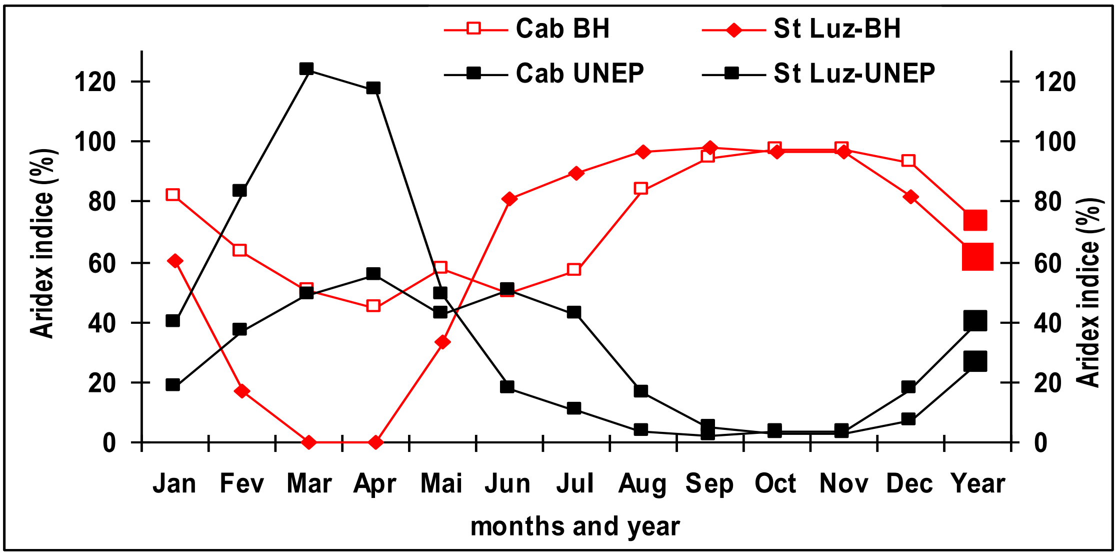

Figure 8. Relationship between the aridity index, using the average climatologically water balance (BH) methods and that of UNEP, for Cabaceiras (Cab) and Santa Luzia (St Luz), PB

Comparing the aridity index curves using the UNEP method, it can be seen that the aridity index of Santa Luzia is greater than that of Cabaceiras, only during the rainy season (from January to April), justified, in almost its entirety, by due to it raining 62% more than Cabaceiras.

However, some characteristics stand out that differentiate the aridity index estimated by the UNEP method from that of the climatologically water balance.

The first is the ratio (P/ETP) itself, as an indicator of aridity, justified because potential evapotranspiration is the necessary rain, although ETP, by definition, refers to water losses through evapotranspiration of a low-growing crop in full development and without any water restrictions, conditions very different from those that occur in the Semiarid.

The United Nations Environment Program (UNEP, 1991) adopted a conceptualization of climate classification associated with the value of the aridity index, although there is none that includes its historical study.

The aridity index, estimated by the climatologically water balance, differs from AI UNEP, as it results from water accounting (input-output) in a volume of soil occupied by at least 80% of the root system.

The inversions in the two AIs curves (BHC and UNEP) in Santa Luzia and, in particular, in the months of the rainy season, but also their continuity in the other months, show semi-aridity according to the UNEP method and humid sub-humid according to the BHC.

It is also noteworthy that even in the rainy season of both locations, which corresponds to the months of February to July, the UNEP AIs, for Cabaceiras, ranged from sub-humid to semi-arid while, in Santa Luzia, they varied from humid, subhumid, semiarid and arid.

The tendency to desertification is always seen through various methodologies and classifications, from the most complete to the simplest, agreeing with Matallo Júnior and Schenkel and Matallo Júnior (2003) that the most simplified is based on the AI ranges.

Due to the importance and relationship of rainfall with the aridity index, regardless of the estimation method, the respective linear regression models are shown in Figures 9, 10, 11 and 12.

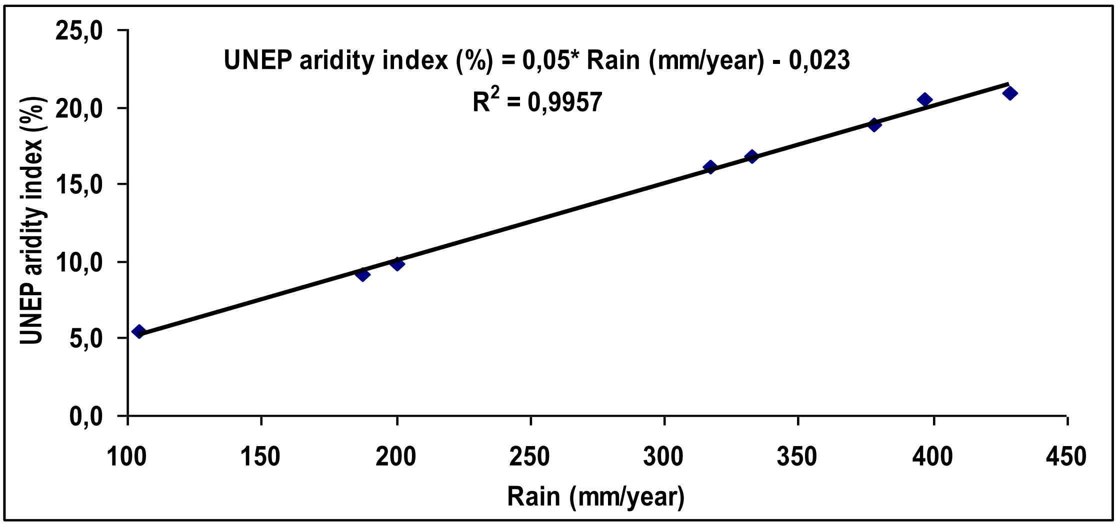

Figure 9. Linear regression model between the UNEP aridity index and year rain, in Cabaceiras, PB.

It can be seen in Figures 9 and 10 that the regression line of the aridity index, estimated by the UNEP method, increases with the total annual rainfall.

However, when AI is determined using the climatologically water balance method (Figures 11 and 12), an opposite trend is observed, that is, the greater the rainfall, the lower the aridity index However, when AI is determined using the climatologically water balance method (Figures 11 and 12), an opposite trend is observed, that is, the greater the rainfall, the lower the aridity index.

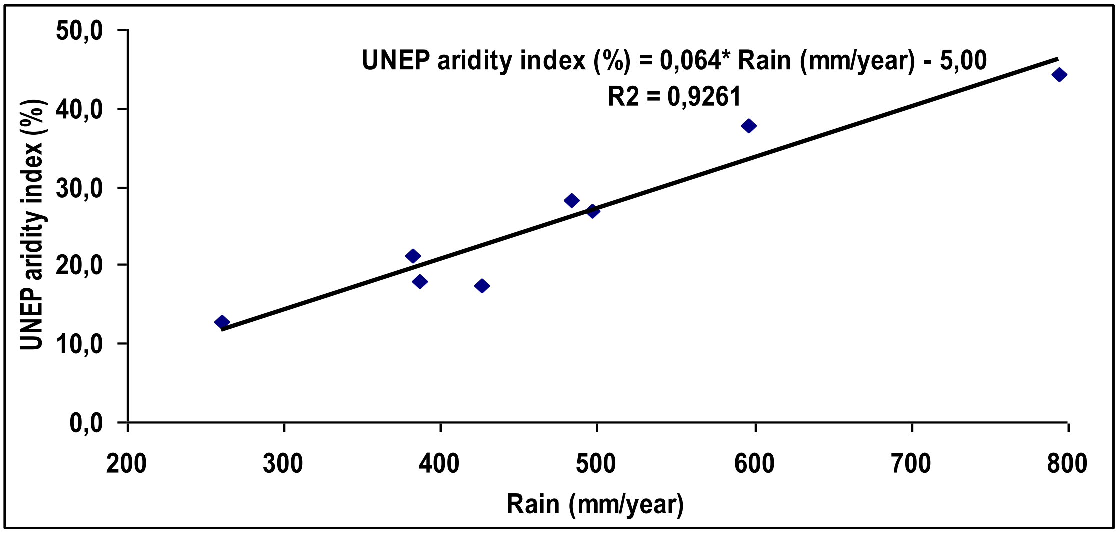

Figure 10. Linear regression model between the UNEP aridity index and annual rainfall, in Santa Luzia, PB.

The differences between them are due to the direct relationship between rainfall, in the UNEP AI calculation, and the water deficit, in the Ai resulting from the climatologically water balance.

The comparison of the aridity index, estimated by the two methods, shows that Ai by the water balance method results in a more coherent value than Ai by UNEP.

The high statistical precision indices (R^2), in all regression models, show high precision in the annual estimates of the aridity index, by the two methods tested, using only the annual rainfall accumulations.

When comparing the regression models of aridity indices, estimated by the UNEP method (Figures 9 and 10) with those of the water balance (Figures 11 and 12), it can be seen that the respective indicators increase and decrease with the accumulated annual rainfall

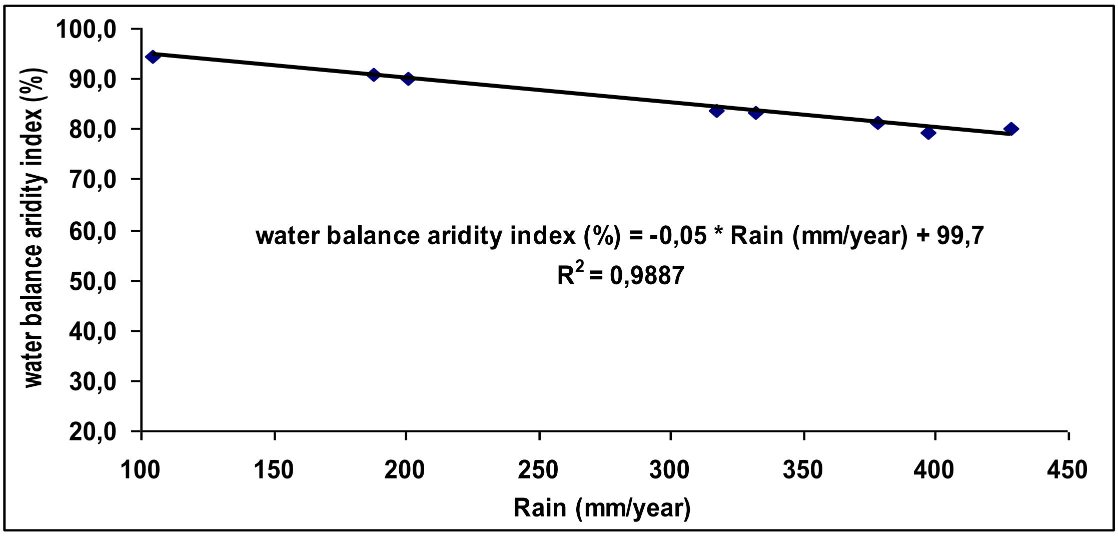

Figure 11. Linear regression model between the aridity index of the climatologically water balance and annual rainfall, in Cabaceiras, PB

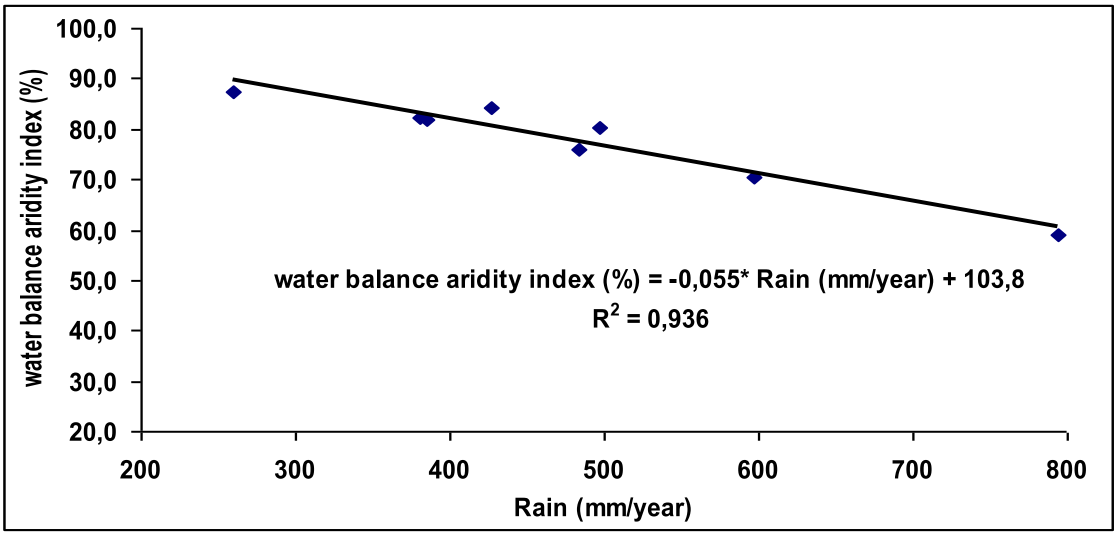

Figure 12. Linear regression model between the aridity index of the climatologically water balance and annual rainfall, in Santa Luzia, PB.

The tendency to increase in the UNEP aridity index, with the increase in rainfall, shown in Figures 9 and 10, is a condition that, at least a priori, can infer doubt when adopting it as the main or only indicator for map lands susceptible to desertification.

On the contrary, the aridity index, estimated by the water balance method, which results from a relationship between soil water deficiency and reference evapotranspiration, increases with the decrease in rainfall and vice versa.

To complement the climatologically study, the last driest years (2013 to 2020) were chosen, for which the Ia were estimated using the UNEP methods and the sequential annual climatologically water balance, whose indicators are presented in Figure 13.

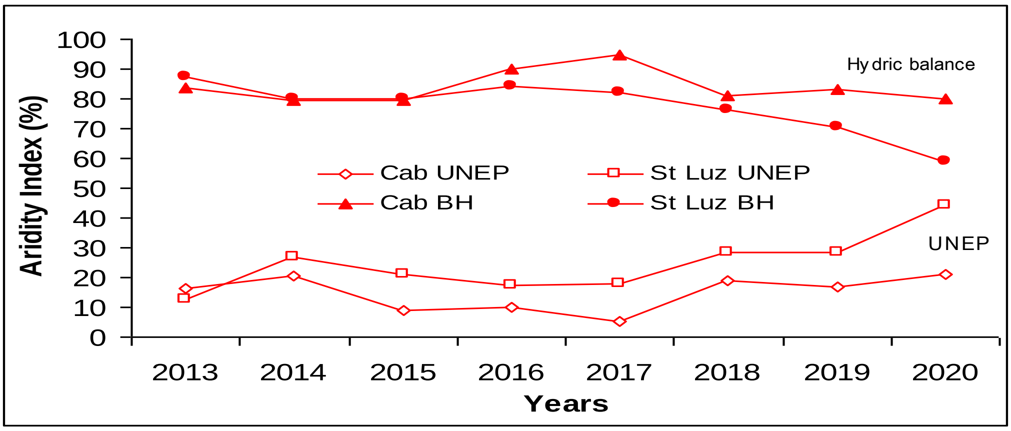

Figure 13. Annual relationship between the aridity index (AI), using the annual sequential water balance (BH) methods and that of UNEP, for Cabaceiras (Cab) and Santa Luzia (St Luz), PB.

Comparing the curves of the aridity indices, using the UNEP method, in relation to the sequential climatologically water balance, on an annual scale, the differences in the values of this indicator are clear.

It is observed (Figure 13) that the UNEP Ais were lower, in the years studied, in Santa Luzia than in Cabaceiras. However, the AIs using the sequential water balance method were inverse, higher in Cabaceiras and lower in Santa Luzia.

It is noteworthy, however, that differences in the values of aridity indicators indicate different climatic classes, which may vary depending on the method or the Ai of one method with the Ai of the other.

According to the UNEP method, Cabaceiras has a climate class that ranges from hyper-arid to semi-arid while Santa Luzia varies from semi-arid to arid. According to the annual sequential climatologically water balance, the climatic classes are classified, respectively, by humid subhumid and humid subhumid to dry subhumid.

The differences in aridity indices, obtained by the two methods, corroborate the reports of Pachêco, Freire and Borges (2006), that there is no scientific consensus on the size and scope of the problem, due to the differences of interpretation in the text of the Convention about Desertification, by the media, justified by Sampaio and Sampaio (2002), because the concept is not applied by use, but by diplomatic understanding. This doubt also seems to exist regarding the irreversibility or not of desertification.

The importance of the relationship between the water balance sequential climatology, in particular, and the susceptibility of land to desertification, is justified by considering aspects related to the soil, the effective depth of the root system and the water dynamics in the soil during the evaluated period

Droughts can be a “catalyst” for desertification in arid climate conditions and under the influence of climate change. However, they can be diagnosed, based on historical series of meteorological data, and quantified using indices. The most effective understanding to investigate drought and its impacts, monitoring, beginning and end can be done using meteorological drought indices (Fernandes et al., 2009).

Conclusions

The characterization of degradation processes in semi-arid environments requires detailed studies of rainfall and water regimes and not just the aridity index. The temporal distribution models of rainfall in the desertification centers of the State of Paraiba are irregular and asymmetrical; more than half of the total annual rainfall is concentrated in the short rainy season (three to five months), and with a chance of being dry.

The rain anomaly criterion (RA) proves to be an excellent environmental indicator, as it includes not only the accumulated rainfall observed, but what should rain, establishing the rainy (RA+) and dry (RA-) periods and explaining them It is clear that rainfall characteristics are inherent to each location

The UNEP aridity index (AI), although it is the main indicator proposed by the FAO, to measure the degree of susceptibility to desertification, the AI, derived from the climatologically water balance and the association of the AI versus rainfall relationship, enable broader analyzes of the local water availability and categories of susceptibility to desertification.

Long dry seasons, lasting seven to nine months, which occur in most desertification centers in the northeast, coincide with the hottest time of the year (spring and summer). This condition naturally contributes to drying out and degrading soils, whose human actions increasingly accelerate environmental degradation, increasing it in areas with arid, semi-arid and dry sub-humid climates.

The desertification nuclei of Gilbués, PI, has a different rainfall model from the other centers, with rain in the hottest time of the year (spring-summer), hot and humid tropical climate, UNEP aridity index, with predominance humid, and occurs in areas exposed to sand, therefore, they diverge from the official concept of desertification, established by the UNEP.

The rainfall and water regimes of the desertification centers in the State of Paraíba are different from the desertification centers of Seridó do Rio Grande do Norte, Oeste do Ceará and Sertão de Pernambuco. Anthropogenic actions are responsible, in general, for the increase in land degradation, in addition to affecting biodiversity and accelerating desertification.

The climatologically water balance (BHC) is an important technological tool, as it allows quantifying the availability of water, at the effective depth of the soil, computing water gains and losses, whose accounting results in the different components, of which the aridity indices, of humidity and drought.

The UNEP annual aridity indices, compared with the Ai of the sequential climatologically water balance, in the desertification centers of Cariri and Seridó of the Paraiba, are clearly different and inverse and, consequently, the aridity classification and the levels of susceptibility to desertification, depend on the method.

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