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RESEARCH ARTICLE

Monitoring desertification in semiarid Brazil: Using the Desertification Degree Index (DDI)

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Abstract
Desertification is a phenomenon that takes place in the arid, semiarid and dry subhumid areas of the Planet. Although its causes and consequences are well known, data and robust information are often insufficient to provide indicators that allow desertification effects to be measured precisely and efficiently. Accordingly, the objective of this study was to introduce a methodology for the drafting of a monitoring index for desertification, with indicators of vegetal coverage, taking the semiarid area of Paraiba State, Brazil, as the test example. For this purpose, we analyzed conserved and desertified areas (22 pairs), in which we evaluated the following parameters: woody species richness, woody plant density, canopy height, mean basal circumference, mean circumference at breast height and total absolute dominance. First, we selected the indicators, calculated the areas of coverage and measured the reference values. Subsequently, we obtained masses for the indicators, and developed and tested the desertification degree index (DDI). The DDI showed 99% accuracy and 95% efficiency, respectively, and was able to select indicators and evaluate the level of desertification in the test areas. The methodology is simple, inexpensive and replicable in other regions of the world as a means of monitoring and planning strategies to counter desertification.

KEYWORDS
caatinga, environmental degradation, environmental quality, reference values

1 | INTRODUCTION

Drylands cover about 41% of the Earth's surface and affect 38% of the global population (Reynolds et al., 2007). They form the region most susceptible to the land degradation process known as desertification, both when derived from climatic variations and from human activities (UNCCD, 1994). Given this scenario and the risks of degradation of productive land in different regions of the Earth, several studies (Khanamani, Fathizad, Karimi, & Shojaei, 2017; Tavares et al., 2015; Vasu et al., 2016) have been carried out to identify appropriate indicators and formulate desertification indices, greatly contributing to information related to the desertification process. However, it is necessary to develop methodologies that include the environmental variability of the regions, so as to monitor and plan efficient strategies to combat desertification in large areas, over appropriate time-scales and at low cost.

The total area susceptible to desertification in Brazil amounts to 1,340,863 km^2, including 1,488 municipalities in the nine States of the Northeast region (Perez-Marin, Cavalcante, Medeiros, Tinôco, & Salcedo, 2012). In the Brazilian Semiarid region the desertification process starts with the suppression of the native vegetation by anthropic activities, almost always via firewood production, clay deposit exploitation (Ferreira et al., 2018) and/or the improper implementation of agricultural systems (Costa, Oliveira, Accioly, & Silva, 2009), including overgrazing (Menezes, Sampaio, Giongo, & Perez-Marin, 2012). Herbaceous grasslands or short-cycle crops replace the native woody shrub and tree vegetation, which decrease the protection of the soil against climatic impacts (Galindo, Ribeiro, Santos, Lima, & Ferreira, 2008). Soil exposure, associated with agricultural cultivation without fertilization, fosters the decline of soil fertility, due to the loss of nutrients to by erosion and loss due to export of produced agricultural biomass (Perez-Marin, Menezes, Silva, & Sampaio, 2006). Therefore, the native vegetation suffers a gradual reduction in resilience and cannot recover in such areas.

The characteristics of soil, water and native vegetation cover are environmental indicators frequently used to monitor desertification (Tongway & Hindley, 2000; Almeida, Aguiar, Silva, & Damaseceno, 2014; Souza, Artigas, & Lima, 2015). Native vegetation cover, mainly of woody species, can be considered as a key indicator because it is directly influenced by modifications of soil fertility and water availability. Additionally, it has parameters that are measured in the field both easily and cheaply (i.e., height and circumference).

Evaluation of woody vegetation cover, based on pair-wise comparisons between the conserved and desertified areas, combined with statistical analysis and geoprocessing techniques, allows us to select suitable indicators to construct desertification indices that are specific to each region of interest. It allows us, therefore, to analyze the desertification index, making it possible to select the most suitable management strategies for the preservation of conserved areas and the recovery of the areas already desertified or in the process of desertification.

In the light of this, the objective of this study was to construct a methodology to select the indicators of the vegetation woody cover and to develop an index to evaluate the desertification level, taking the semiarid region of Paraiba State as an example.

2 | MATERIALS AND METHODS

2.1 | Study area location and general characteristics

We collected 22 paired data-sets from desertified areas and those with conserved native vegetation in the semi-arid region of Paraíba State, Brazil (Figure 1). This region covers 48,656.61 km^2, comprising 170 municipalities (Attachment 1), with 2,092,400 inhabitants (Medeiros et al., 2012). The climate is hot semiarid (Nimer, 1979), with annual precipitation below 800 mm (Sousa, Silva, Campos, & Oliveira, 2012). The area is considered to be at high risk of desertification (MMA, 2007).

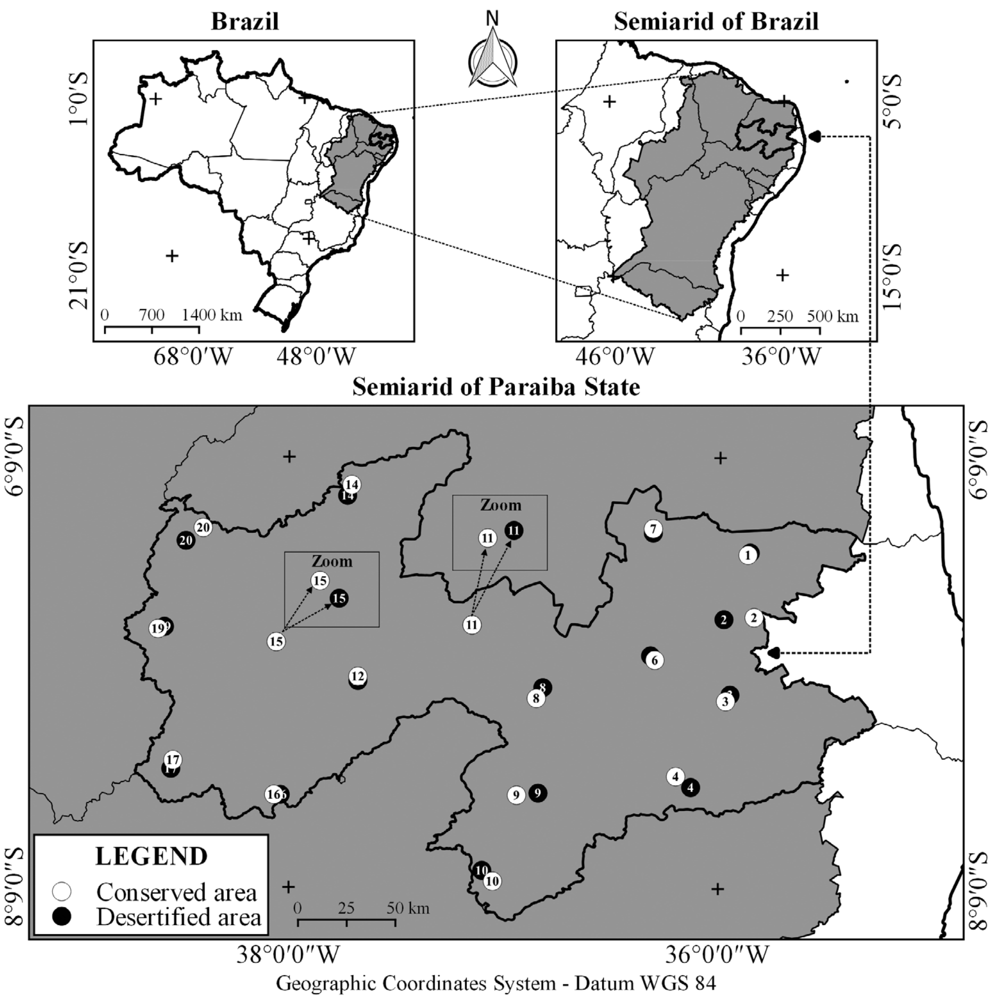

FIGURE 1 Conserved and desertified areas in the semiarid region of Paraíba State, Brazil

ATTACHMENT 1 Municipalities of the semiarid region of Paraíba State, Brazil

N°	Municipality	N°	Municipality	N°	Municipality	N°	Municipality
1	Água Branca	44	Conceição	87	Monte Horebe	130	Santo André
2	Aguiar	45	Condado	88	Monteiro	131	São Bentinho
3	Alcantil	46	Congo	89	Natuba	132	São Bento
4	Algodão de Jandaíra	47	Coremas	90	Nazarezinho	133	São Domingos
5	Amparo	48	Coxixola	91	Nova Floresta	134	São Domingos do Cariri
6	Aparecida	49	Cubatí	92	Nova Olinda	135	São Francisco
7	Arara	50	Cuité	93	Nova Palmeira	136	São João do Cariri
8	Araruna	51	Curral Velho	94	Olho D'Água	137	São João do Rio do Peixe
9	Areia de Baraúnas	52	Damião	95	Olivedos	138	São João do Tigre
10	Areial	53	Desterro	96	Ouro Velho	139	São José de Lagoa Tapada
11	Aroeiras	54	Diamante	97	Parari	140	São José de Caiana
12	Assunção	55	Dona Inês	98	Passagem	141	São José de Espinharas
13	Bananeiras	56	Emas	99	Patos	142	São José de Piranhas
14	Baraúna	57	Esperança	100	Paulista	143	São José de Princesa
15	Barra de Santa Rosa	58	Fagundes	101	Pedra Branca	144	São José do Bonfim
16	Barra de Santana	59	Frei Martinho	102	Pedra Lavrada	145	São José do Brejo do Cruz
17	Barra de São Miguel	60	Gado Bravo	103	Piancó	146	São José do Sabugi
18	Belém do Brejo do Cruz	61	Gurjão	104	Picuí	147	São José dos Cordeiros
19	Bernardino Batista	62	Ibiara	105	Pocinhos	148	São Mamede
20	Boa Ventura	63	Igaracy	106	Poço Dantas	149	São Sebastião de Lagoa de Roça
21	Boa Vista	64	Imaculada	107	Poço de José de Moura	150	São Sebastião do Umbuzeiro
22	Bom Jesus	65	Ingá	108	Pombal	151	São Vicente do Seridó
23	Bom Sucesso	66	Itabaiana	109	Prata	152	Serra Branca
24	Bonito de Santa Fé	67	Itaporanga	110	Princesa Isabel	153	Serra Grande
25	Boqueirão	68	Itatuba	111	Puxinana	154	Solânea
26	Brejo do Cruz	69	Jericó	112	Queimadas	155	Soledade
27	Brejo dos Santos	70	Juazeirinho	113	Quixaba	156	Sôssego
28	Cabaceiras	71	Junco do Seridó	114	Remígio	157	Sousa
29	Cachoeira dos Índios	72	Jurú	115	Riachão	158	Sumé
30	Cacimba de Areia	73	Lagoa	116	Riachão do Bacamarte	159	Tácima
31	Cacimba de Dentro	74	Lagoa Seca	117	Riacho de Santo Antônio	160	Taperoá
32	Cacimbas	75	Lastro	118	Riacho dos Cavalos	161	Tavares
33	Caiçara	76	Livramento	119	Salgadinho	162	Teixeira
34	Cajazeiras	77	Logradouro	120	Salgado de São Félix	163	Tenório
35	Cajazeirinhas	78	Mãe D'Água	121	Santa Cecília	164	Triunfo
36	Camalaú	79	Malta	122	Santa Cruz	165	Uiraúna
37	Campina Grande	80	Manaíra	123	Santa Helena	166	Umbuzeiro
38	Caraúbas	81	Marizópolis	124	Santa Inês	167	Várzea
39	Carrapateira	82	Massaranduba	125	Santa Luzia	168	Vieirópolis
40	Casserengue	83	Mato Grosso	126	Santa Teresinha	169	Vista Serrana
41	Catingueira	84	Maturéia	127	Santana de Mangueira	170	Zabelê
42	Catolé do Rocha	85	Mogeiro	128	Santana dos Garrotes		
43	Caturité	86	Montadas	129	Santarém		

2.2 | Steps in the development and testing of the Desertification Degree Index (DDI)

The methodology involved seven steps: (a) Selection of the conserved and desertified areas; (b) Sampling and measurement of woody vegetation parameters; (c) Selection of indicators scope and subsequent measurement; (d) Measurement of reference values; (e) Measurement of indicator masses; (f) Construction of the Desertification Degree Index (DDI); (g) Testing the DDI. In steps 3 to 6 we used the plots 1, 2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 17, 19 and 20, located in the conserved and desertified areas (pairs). For step 7 (testing) we used the plots 5, 13, 18, 21 and 22 (pairs).

2.2.1 | Step 1—Characteristics and selection of conserved and desertified areas

Conserved areas

The native vegetation used formed part of the *caatinga* biome. In this biome, trees with small and thorny leaves, and twisted trunks (mainly deciduous), succulent plants and thermophilic herbs, efficient in water usage, prevail (de Queiroz, Cardoso, Fernandes, & Moro, 2017). The conserved areas are not fenced (consequently, access of domestic animals is limited by the thorns of the native vegetation), with no clear-cutting since 1984 (≥31 years).

Desertified areas

The soils of the desertified areas of the semiarid region of Paraiba State have low fertility, and a surface crust of anthropic origin, which further accentuates aridity, and (Souza, Artigas, & Lima, 2015). In such areas, extraction of material for civil construction, roads and dams has resulted in the removal of the upper layer of the soil. As a result, it has been difficult to restore the woody vegetation in the desertified areas, with poor progress in regeneration since 2000 (>15 years).

Selection of study areas

Selection of conserved and desertified areas had three stages: (a) we used LANDSAT 5 (1984–2011) and LANDSAT 8 (2012–2015) satellites images, with spatial resolution of 30 m. (b) We used Google Earth images (high spatial resolution), which enabled us to identify the canopy heterogeneity, and characteristic of the conserved areas, due to the presence of several species. (c) We located the areas in the field using a GPS navigation device (Garmin 60CSx) (Figure 2).

2.2.2 | Step 2—Sampling and measuring woody vegetation parameters

In each area, we delimited a 100 m^2 (10 × 10 m) parcel, in which we performed the census of all species of plants present. We identified the plant species with the help of a specialist and by consulting specific literature (INSA, 2010; Lorenzi, 1992; Lorenzi, 1998; Lorenzi, 2009;

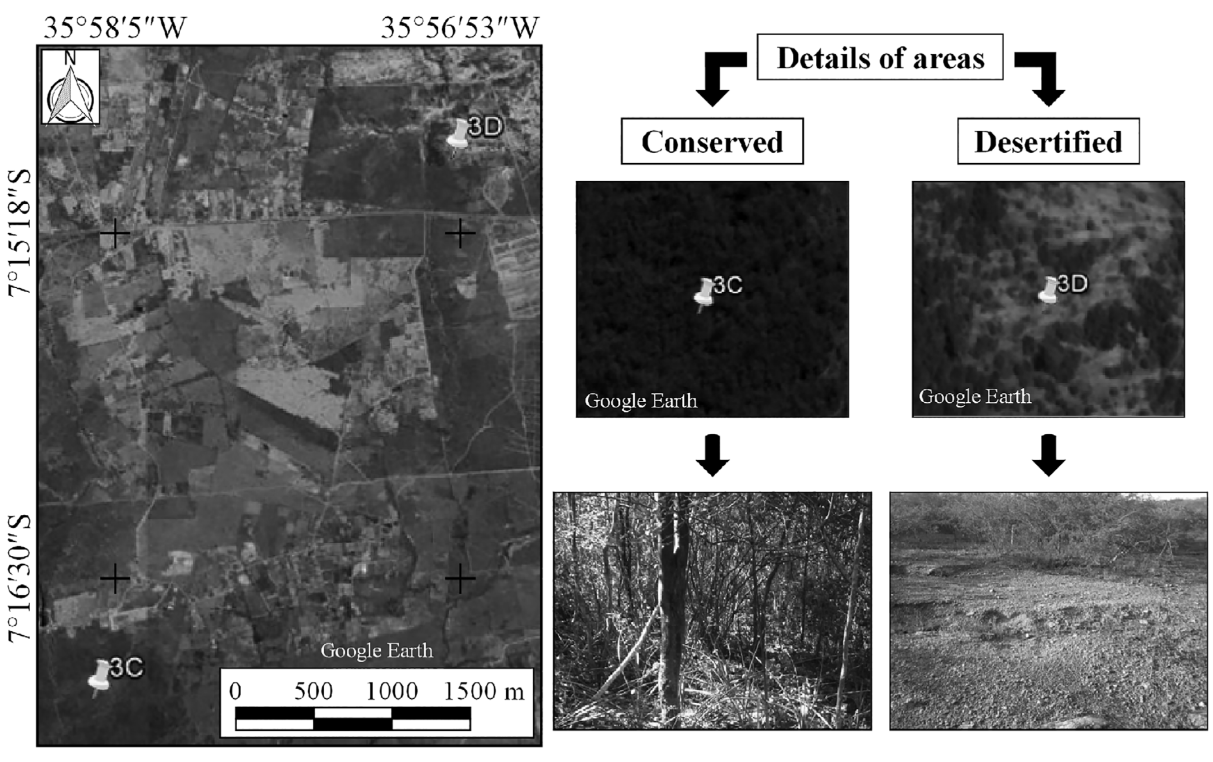

FIGURE 2 Details of the conserved and desertified areas (paired plots), by Google Earth and in the field, in the semiarid region of Paraíba State, Brazil

Maia-Silva, Silva, Hrncir, Queiroz, & Imperatriz-Fonseca, 2012; NUPEEA, 2010; Siqueira Filho, Santos, Nascimento, & Espírito Santo, 2009).

Vegetation structure was characterized with all woody individuals of the plot, regardless of diameter, using the following parameters: woody species richness, woody plant density, canopy height, mean basal circumference (CB-A), mean circumference at breast height (CBH-A), and total absolute dominance (AD-T) (Table 1).

Woody plant density corresponds to the number of individuals per area unit, measured with the Equation (1).

$$\mathrm{WPD} = \frac{NI}{A} \tag{1}$$

Where: WPD = woody plant density (I ha^{-1}); NI = number of individuals; A = area (ha).

The height of the canopy is the arithmetic mean considering all woody plants. The plant height was measured with a tape-measure, when the height was ≤7.0 m or with a clinometer (angle when the height was >7.0 m) (Equation (2), as a function of the morphologic characteristics of the vegetation.

$$H = (\mathrm{HD} \times \mathrm{Tangent\,X}) + \mathrm{HC} \tag{2}$$

where: H = woody plant height (m); HD = horizontal distance (m); tangent X = tangent of the angle; HC = clinometer height (m).

Mean basal circumference and the mean circumference at breast height, were calculated using Equations (3) and (4), respectively.

$$\mathrm{CB-A} = \frac{\sum \mathrm{CB}i}{\mathrm{NF}} \tag{3}$$

where: CB-A = mean basal circumference (cm); CB*i* = basal circumference (cm), measured at 0.30 cm from the ground, NS = number of stems.

$$\mathrm{CBH-A} = \frac{\sum \mathrm{CBH}i}{\mathrm{NF}} \tag{4}$$

where: CBH-A = mean circumference at breast height (cm); CBH*i* = circumference at breast height (cm), measured at 1.30 m from the ground, NS = number of stems.

Total absolute dominance was calculated using Equation ((5).

TABLE 1 Values of woody vegetation parameters in the semiarid region of Paraíba State, Brazil

	WSR*		Woody plant density		Canopy height		CB-A		CBH-A		AD-T	
			CA		CA		CA				CA	
Pair	CA	DA	—I ha^{-1}—	DA	—m—	DA	—cm—	DA	CA	DA	$\mathrm{m}^2\ \mathrm{ha}^{-1}$	DA
1	8	2	4,100	900	4.99	1.03	21.29	3.56	16.65	0.76	17.65	0.12
2	9	3	2,600	2,800	4.99	1.32	28.23	4.83	19.46	4.04	35.51	0.87
3	17	1	6,500	2,900	4.52	207	12.90	6.38	10.35	3.67	16.58	0.97
4	8	3	4,800	1,300	3.95	1.70	12.31	6.27	9.41	3.72	8.25	0.56
5	7	3	4,900	1,200	3.87	2.01	11.79	8.85	9.21	6.44	8.85	2.41
6	9	2	4,500	400	3.93	1.84	11.97	18.73	9.19	11.67	16.44	0.63
7	13	4	7,100	1,000	2.69	1.91	7.80	8.80	6.00	4.19	12.05	1.06
8	9	2	3,300	400	3.93	1.53	15.35	9.45	12.43	21.00	14.86	2.53
9	12	4	4,500	1,100	4.32	2.23	13.27	13.76	10.76	8.65	19.13	2.34
10	13	0	3,100	200	4.75	0.00	15.10	0.00	11.36	0.00	14.79	0.00
11	5	1	5,200	100	2.92	3.28	10.02	22.90	7.26	10.95	9.45	0.45
12	6	1	3,800	600	4.88	1.51	14.43	3.86	11.03	2.04	15.28	0.12
13	5	1	5,300	800	2.87	2.50	7.97	12.45	6.08	8.12	9.99	1.72
14	10	1	7,100	200	3.35	269	8.88	10.98	7.36	5.79	24.44	0.50
15	10	2	6,300	500	3.59	0.90	8.53	6.12	7.47	0.50	13.02	0.17
16	12	2	4,300	200	4.89	2.16	13.29	7.67	11.01	3.51	22.46	0.11
17	9	2	4,900	500	4.14	1.79	10.10	5.40	8.08	2.85	11.78	0.13
18	13	3	7,300	1,000	4.01	3.38	9.78	12.43	7.83	7.88	16.63	3.83
19	10	1	5,800	1,000	4.17	1.63	13.69	5.12	12.05	5.13	36.98	0.44
20	11	2	4,900	400	3.55	2.06	11.06	7.12	8.44	6.01	11.31	0.49
21	8	1	3,200	700	4.56	1.40	12.84	5.06	10.54	3.87	10.96	0.20
22	12	3	2,500	1,000	5.12	1.47	25.80	5.41	25.29	3.41	56.99	0.47

Note: CA, conserved area; DA, desertified area; WSR, woody species richness; *plot (100 m^2); I, individual; CB-A, mean basal circumference; CBH-A, mean circumference at breast height; AD-T, total absolute dominance.

$$\text{AD}-\text{T} = \sum\left(\frac{\text{BA}i}{A}\right) \quad (5)$$

where: AD-T = total absolute dominance (m^2 ha^{-1}); BA_i = individual basal area of the species *i* (m^2), based on the stem diameter at 1.30 m from the ground; *A* = the total sampled area (ha).

2.2.3 | Step 3—Selection and coverage of desertification indicators

We used a paired *t* test ($p \leq .05$) (Sokal & Rohlf, 1995), on software R (R Core Team, 2017) to evaluate the parameters from the conserved and desertified areas. Subsequently, we selected the parameters with significant difference ($p \leq .05$) as indicators.

Scope of the semiarid area indicators of the was calculated and mapped with the QGIS 2.10.1 (Pisa version) software. QGIS is a free Geographic Information System (GIS)-based software, which enables vector analysis, sampling, geoprocessing, geometric and database management system (QGIS User Guide Version 2.14, 2017)

Scope mapping had three steps: 1st) we created the layers for the conserved 'Cx' and the desertified 'Dx' areas, interpolating data from each selected attribute as an indicator. Data interpolation enables the assessment of values for the nonsampled areas. We used the Inverse Distance Weighted method (IDW); 2nd) we calculated the difference of values between the layers 'Cx' and 'Dx', creating the layer 'CD'; 3rd) we classified the 'CD' layer into recommended (CD ≥ SDD) or not recommended (CD < SDD or results opposed to the average result). The Smallest Detectable Difference (SDD) was achieved by the *t* test with paired data, enabling us to detect which is the smallest difference necessary to recommend an indicator for each pair of areas (conserved and desertified).

2.2.4 | Step 4—Measuring the reference values

Obtained reference values indicated six levels of desertification (0 to 5). Level 0 indicates an absence of desertification, measured by the mean value of the indicator of the conserved areas, and represents environments with stable conditions (Tótola & Chaer, 2002). Level 5 defines a very high level of desertification, measured by the mean value of the indicator of desertified areas, and represents highly degraded environments. Levels 1 to 4 are the intermediate conditions (very low, low, medium and high level of desertification, respectively); with their reference values defined by ranges from Equations (6) and (7).

$$\text{IVR} = \text{FVRp} - 0.01 \quad (6)$$

$$\text{FVR} = \left(\text{IVR} - \frac{\text{AVCA}-\text{AVDA}}{4}\right) + 0.01 \quad (7)$$

where: IVR = initial value of the range; FVRp = final value of the previous range; FVR = final value of the range; AVCA = mean value of the conserved area indicator; AVDA = mean value of the desertified area indicator.

2.2.5 | Step 5—Measuring the weights of the indicators

The importance of each indicator on the environmental quality index is termed 'weight' (Melo Filho, Souza, & Souza, 2007). Weights (Equation (8)) were measured by principal component analysis using R software (R Core Team, 2017), considering the eigenvector values on the principal components selected with the Broken Stick model (Jackson, 1993).

$$Wn = \frac{(x^1 \times y^1) + (x^2 \times y^2) + \ldots + (x^n \times y^n)}{y^1 + y^2 + \ldots + y^n} \quad (8)$$

Where: Wn = weight of the indicator (W1, W2, W3...); x^1 = value of the eigenvector on PC1 (Principal Component 1); y^1 = value of the proportion of variance of PC1; x^2 = value of the eigenvector on PC2; y^2 = value of the proportion of variance of PC2.

2.2.6 | Step 6—Drafting the Desertification Degree Index (DDI)

The Desertification Degree Index (DDI) is based on the desertification degrees of the indicators and their respective weights [Equation (9)]. There are six grades to evaluate the environmental conditions of the landscape. The grades run from 0 to 5 (0 = the absence of desertification, 1 = very low, 2 = low, 3 = medium, 4 = high and 5 = very high level of desertification).

$$\text{DDI} = \sum(\text{DDIn} \times \text{SW}i) \quad (9)$$

where: DDI = Desertification Degree Index (0 to 5); DDIn = desertification degree of the indicator (0 to 5), obtained by the classification of the indicator value in the area of interest, based on the reference values; SW_i = standardized weight for the indicator (0 to 1).

2.2.7 | Step 7—Testing the Desertification Degree Index (DDI)

We tested the DDI in three stages: (a) Classification of the desertification level present at plots 5, 13, 18, 21 and 22, located in the conserved and desertified areas (pairs). (b) The level of conservation in the 44 studied areas were sorting out using a dendrogram constructed using the selected indicators for the Paraíba State semiarid region. The similarity matrix between the areas was constructed using Gower distances (Gower, 1971), and the dendrogram using Unweighted Pair-Group Method using arithmetic means—UPGMA (Legendre & Legendre, 2012). (c) Comparison of stage 1 and 2 results, analyzing the clusters of the conserved and desertified areas. To do this, the classification order accuracy was assessed using the Willmott agreement index (Willmott et al., 1985) [Equation (10)], and the goodness-of-fit of the measure using modeling efficiency (Zacharias, Heatwole, & Coakley, 1996) [Equation (11)].

$$c = \left(1 - \frac{\sum_{i=1}^{n}(o_i - e_i)^2}{\sum_{i=1}^{n}(\bar{o}| + \bar{o}|)^2}\right) \times 100 \quad (10)$$

$$e = \frac{\sum_{i=1}^{n}(o_i - \bar{o})^2 - \sum_{i=1}^{n}(o_i - e_i)^2}{\sum_{i=1}^{n}(o_i - \bar{o})^2} \times 100 \quad (11)$$

where: c = concordance index (%); e = efficiency (%); e_i = ranking order assessed by DDI; o_i = reference ranking order as observed on the Gower similarities Index; $\bar{o}$ = mean of the reference ranking order, obtained by Gower similarities Index.

The Willmott Index relates the observed values to the assessed ones, varying from 0 to 100%, no concordance to perfect concordance, respectively (Cunha, Nascimento, Silveira, & Alves Júnior, 2013). A model is considered to be highly efficient when e exceeds 72% (Sentelhas & Folegatti, 2003).

3 | RESULTS

3.1 | Selection and scope of selected desertification indicators

Conserved areas have greater woody species richness, woody plant density, canopy height, mean basal circumference, mean circumference at breast height and total absolute dominance than the desertified areas (Table 2). These woody cover parameters may be used as indicators of desertification when the smallest detectable difference (SDD) varies from 0.50 to 673.

Woody species richness and the total absolute dominance (AD-T) showed a mean difference of 7.94 species and 7.45 m^2 ha^{-1} between conserved and desertified areas (Table 2). These indicators are recommended for the monitoring of the process of soil desertification across the entire semiarid region of Paraiba State (Figure 3).

The woody plant density in the conserved areas had a mean of 4,871 I ha^{-1}, far above the mean for desertified areas, which was, approximately 853 I ha^{-1} (Table 2). The use of indicator is recommended for 98.2% of the semiarid of Paraiba State (Figure 4).

Canopy height was 2.05 m greater in conserved areas than in desertified areas (Table 2). Height is recommended as an indicator in 92.4% of the studied areas (Figure 5).

Conserved and desertified areas differ from 4.35 and 5.34 cm for CB-A and CBH-A, respectively (Table 2). These indicators are recommended for 57.3 and 18.0% of the semiarid region, respectively (Figures 6 and 7).

3.2 | Reference values for the evaluation of desertification levels

Conserved areas showed the highest values for the indicators and the desertified areas showed the lowest values (Table 3).

3.3 | Weight of the desertification indicators

Analyzing the principal components, we selected the PC1 axis, which explains 70.22% of data variance. Weights of the indicators match the eigenvector values, following the sequence: Canopy height (0.4613), AD-T (0.4383), CBH-A (0.4320), woody species richness (0.4083), CB-A

TABLE 2 Parameters for woody vegetation on conserved and desertified areas, for the selection of the indicators of the desertification level in the semiarid region of Paraíba State, Brazil

Attribute	Area	Mean	*SD*	*t*	*p*	SDD
Woody species richness	Conserved	10.06	2.84	11.11	<.01**	1.25
	Desertified	2.12	1.05			
Woody plant density–I ha^{-1}	Conserved	4,870.60	1,339.67	10.42	<.01**	673.27
	Desertified	852.94	831.50			
Canopy height (m)	Conserved	4.09	0.71	7.13	<.01**	0.50
	Desertified	2.04	0.74			
Mean base circumference (cm)	Conserved	13.43	4.98	2.01	.06*	3.77
	Desertified	9.08	5.95			
Mean circumference at breast height (cm)	Conserved	10.49	3.43	4.06	<.01**	7.63
	Desertified	5.15	3.48			
Total absolute dominance (m^2 ha^{-1})	Conserved	17.65	8.18	8.53	<.01**	3.47
	Desertified	0.71	0.73			

Note: SD, smallest detectable difference; *t*, paired test; *p*, probability of significance; ** and *; significant at 1 and 10% probability, respectively, by paired *t* test; ^{ns}, no significance.

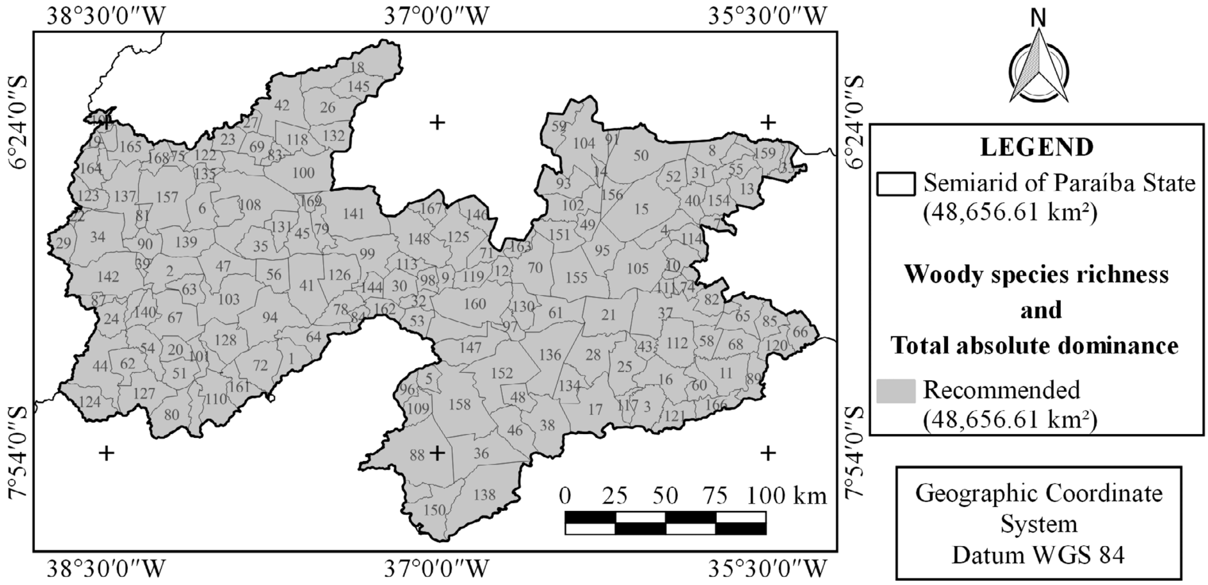

FIGURE 3 Recommended areas to use the woody species richness and total absolute dominance (AD-T) as indicators of the level of desertification in the semiarid region of Paraíba State, Brazil

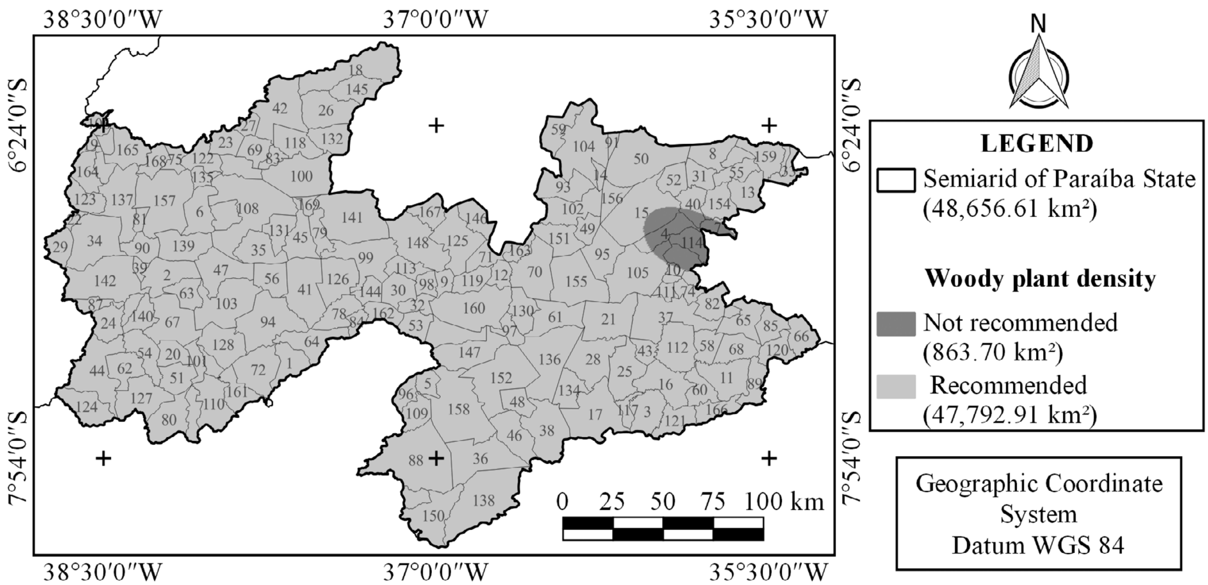

FIGURE 4 Recommended areas to use woody plant density as indicator of the level of desertification, in the semiarid region of Paraíba State, Brazil

(0.3491) and woody plant density (0.3464). According to the type and number of the recommended indicators for each region, there are five combinations of indicators, resulting in varied standardized weights (Table 4).

3.4 | Desertification Degree Index (DDI) in test areas

The areas of validation have different levels of desertification, following the order: 22C < 18C < 21C < 5C < 13C < 18D < 13D < 5D < 22D < 21D, with conserved areas distributed in levels 1 (60%), 2 (20%) and 3 (20%), and desertified areas in levels 3 (20%), 4 (40%) and 5 (40%) (Table 5).

The dendrogram shows the arrangement of two groups: conserved and desertified areas (Figure 8). Validation areas of were properly inserted in each group, in the following order, in relation to the level of desertification: 22C < 21C < 13C < 18C < 5C < 22D < 5D < 13D < 21D < 18D. The model (DDI) is 99.0% precise and 95.0% efficient.

The most limiting parameter for the maintenance of the conserved areas is related to woody species richness. In the

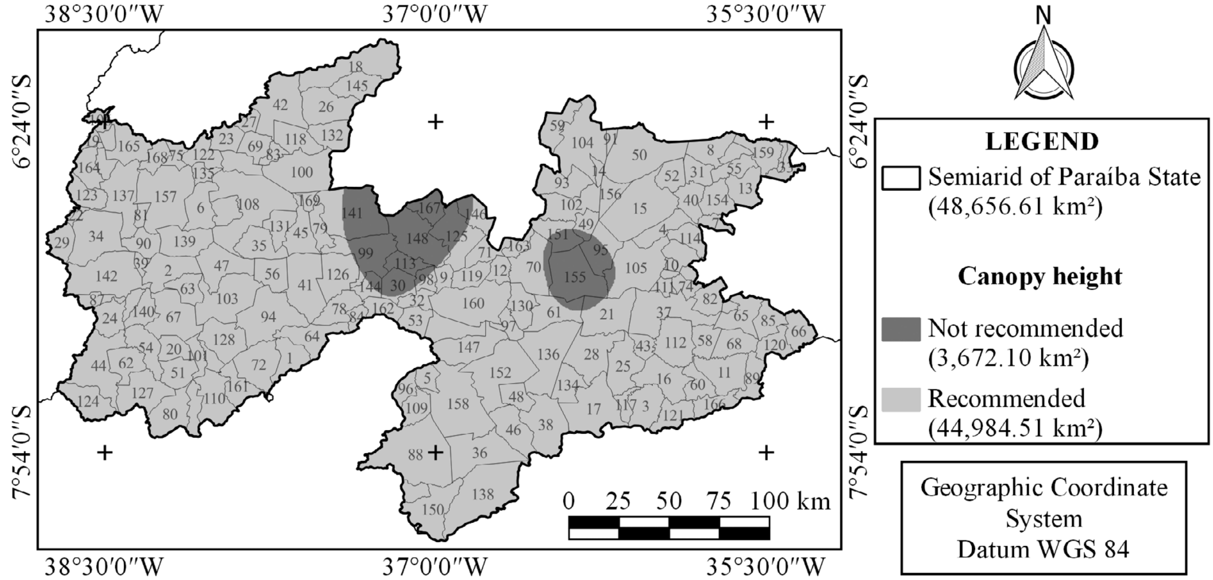

FIGURE 5 Recommended areas to use canopy height as indicator of the level of desertification, in the semiarid region of Paraíba State, Brazil

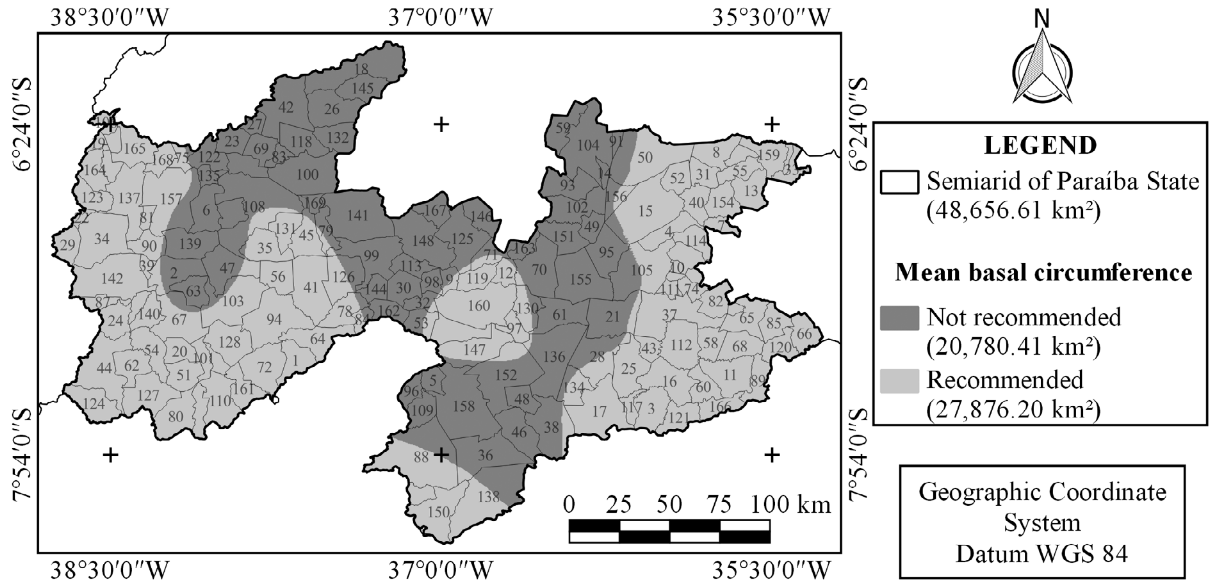

FIGURE 6 Recommended areas to use the mean basal circumference (CB-A) as indicator of the level of desertification, in the semi-arid region of Paraíba State, Brazil

desertified regions, the most limiting parameters for the recovery of woody vegetal cover were the richness and density of woody species.

4 | DISCUSSION

4.1 | Effects of desertification on forest cover

The desertification process reduces woody species richness. These results are similar to those found by Souza, Artigas, and Lima (2015), who identified 23 species of plants in the nondesertified areas (17 exclusive species) and nine species in desertified areas (2 exclusive species). The species present in desertified areas are adapted to the adverse conditions of this environment, primarily low water availability.

Among the exclusive species in the conserved areas are *Amburana cearensis* (Allemao) A. C. Sm., *Anadenanthera colubrina* (Vell) Brenan, *Sideroxylon obtusifolium* (H. ex. R. & S.), *Spondias tuberosa* L. and *Ziziphus joazeiro* Mart. These may be used as timber, food, medicine, forage and as raw material for industry (Francelino, Fernandes Filho, Resende, & Leite, 2003; NUPEEA, 2010). Therefore, the loss of

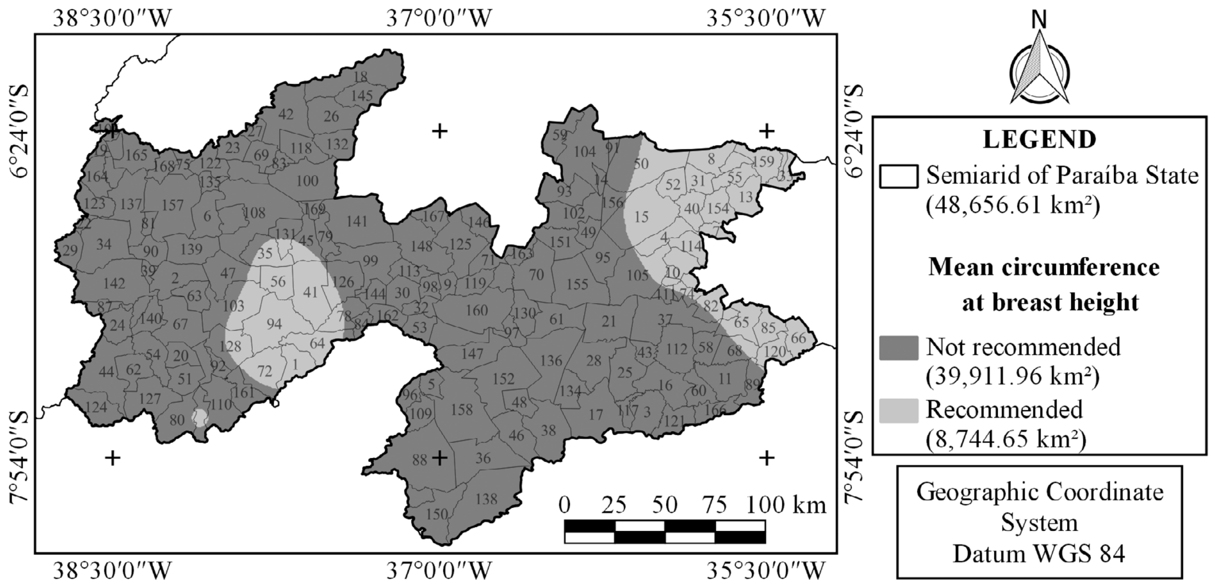

FIGURE 7 Recommended areas to use the mean circumference at breast height (CBH-A) as indicator of the level of desertification, in the semiarid region of Paraíba State, Brazil

TABLE 3 Reference values for the indicators of the woody vegetation, in the semiarid region of Paraíba State, Brazil

		Desertification levels					
Indicator	Unit.	Absent (0)	Very low (1)	Low (2)	Medium (3)	High (4)	Very high (5)
A		≥ 10.06	10.05–8.09	8.08–6.10	6.09–4.12	4.11–2.13	≤ 2.12
B	I ha^{-1}	≥ 4,870.60	4,870.59 -3,866.20	3,866.19 -2,861.78	2,861.77 -1,857.37	1,857.36–852.95	≤ 852.94
C	m	≥ 4.09	4.08–3.59	3.58–3.08	3.07–2.56	2.55–2.05	≤ 2.04
D	cm	≥ 13.43	13.42–12.33	12.32–11.23	11.22–10.12	10.11–9.09	≤ 9.08
E	cm	≥ 10.49	10.48–9.17	9.16–7.83	7.82–6.50	6.49–5.16	≤ 5.15
F	m^2 ha^{-1}	≥ 17.65	17.64–13.43	13.42–9.19	9.18–4.96	4.95–0.72	≤ 0.71

Note: A, woody species richness; B, woody plant density; C, canopy height; D, mean basal circumference; E, mean circumference at breast height; F, total absolute dominance.

TABLE 4 Standard weights for the indicators of the woody vegetation, in the semiarid region of Paraíba State, Brazil

		Standardized weight					
NI	Combinations of indicators	A	B	C	D	E	F
3	A, B and F	0.342	0.290	[a]	[a]	[a]	0.367
4	A, B, C and F	0.247	0.209	0.279	[a]	[a]	0.265
5	A, B, C, D and F	0.204	0.173	0.230	0.174	[a]	0.219
5	A, C, D, E and F	0.195	[a]	0.221	0.167	0.207	0.210
6	A, B, C, D, E and F	0.168	0.142	0.189	0.143	0.177	0.180

Note: NI, number of indicator; A, woody species richness; B, woody plant density; C, canopy height; D, mean basal circumference; E, mean circumference at breast height; F, total absolute dominance.
[a]not recommended.

biodiversity reduces the availability of natural resources used as raw material for income generation.

That the process of desertification changes the forest structure, is made apparent by reduction of woody plant density, canopy height, CB-A, CBH-A and AD-T. This change is attributed to the reduction of the number of large-sized woody species (such as *A. cearensis*, *A. colubrina* and *Z. joazeiro*) in the desertified areas (Galindo et al., 2008), which undermines the soil protection against the impact and erosional effects of pluviometric precipitation and incidence of sunlight. The vegetation protects the soil against

TABLE 5 Data from woody coverage and classification of the desertification level in the semiarid, by the Desertification Degree Index (DDI), in the semiarid region of Paraíba State, Brazil

	Conserved							Desertified						
Pared	A	B	C	D	E	F	DDI	A	B	C	D	E	F	DDI
5	2	0	1	[a]	[a]	3	1.57	4	4	5	[a]	[a]	4	4.28
13	3	0	3	5	4	2	2.86	5	5	4	1	2	4	3.53
18	0	0	1	[a]	[a]	1	0.54	4	4	2	[a]	[a]	4	3.44
21	2	2	0	1	[a]	2	1.37	5	5	5	5	[a]	5	5.00
22	0	3	0	0	[a]	0	0.52	4	4	5	5	[a]	5	4.62
DDL	0	1	2	3	4	5		0	1	2	3	4	5	
Area (%)	0	60	20	20	0	0		0	0	0	20	40	40	

Note: A, woody species richness; B, woody plant density; C, canopy height; D, mean basal circumference; E, mean circumference at breast height; F, total absolute dominance.
[a]not recommended.

precipitation intercepting the raindrops, allowing higher water infiltration in the system and the reduction of the surface runoff (Pinese Junior, Cruz, & Rodrigues, 2008). Areas with a less dense vegetation cover have a greater loss of soil, nutrients and organic matter (Lobato, Andrade, Meireles, Santos, & Lopes, 2009), all of which are essential to plant growth and development (Meurer, 2007). We emphasize that organic matter is a primary factor in the maintenance of the productive capacity of the soil (Silva & Mendonça, 2007) since it provides nutrients (Costa, Beltrão, Silva, Melo Filho, & Silva, 2010), retains cations (Ciotta, Bayer, Fontoura, Ernani, & Albuquerque, 2003), complex toxic elements and micronutrients (Pavinato & Rosolem, 2008; Pegoraro et al., 2006), stabilizes aggregates (Salton et al., 2008) and enhances aeration (Souza & Alves, 2003), infiltration, water retention (Sato, Figueiredo, Leão, Ramos, & Kato, 2012) and microbial activity (Capuani, Rigon, Beltrão, & Brito Neto, 2012).

In the a, where the woody vegetation is taller, the number of canopy strata is more abundant, functioning as reducing layers. First, they intercept and decrease the speed of the raindrops, and then guide them along the branches and stems to the soil (Albuquerque & Costa, 2012).

The diameter of the CB-A and CBH-A is highly important to protect the soil against the erosion process because they intercept and guide the raindrops, especially at the beginning of the rain season in the *caatinga* biome. In this season, the foliage is absent due to the prevalence of species with deciduous characteristics (Tabarelli, Leal, Scarano, & Silva, 2018).

The reduction of the structural quality of the woody component also elevates the soil temperature due to the direct sunray incidence on the soil surface, further compromising forest recovery. The optimum germination temperature for the bulk of the native *caatinga* species varies between 20 and 35°C (Oliveira, Matias, & Dantas, 2014), whereas the exposed soil temperature can reach more than 45°C (Silans, Silva, & Barbosa, 2006). When the temperature is above the considered optimum, it may denature proteins critical to the germination process, affecting the germination percentage and speed (Dousseau, Alvarenga, Arantes, Oliveira, & Nery, 2008).

4.2 | Measuring the weights of the indicators

Variation in parameter values is associated with the diverse phytophysiognomy of the native woody vegetation of the *caatinga* biome and the land-use conversion for economic purposes. The major phytophysiognomies of the region are afforested-steppe-savanna, woody-steppe-savanna and contact steppe-savanna/seasonal forest, although the replacement of the native vegetal species by pasture and agriculture can greatly modify them (IBGE, 2004).

The heterogeneous characteristics of the landscape in the study area explain why the majority of the indicators cannot be used for the entire region and underscores the importance of spatial analysis to enhance environmental monitoring accuracy. The most important indicators for the evaluation of the desertification degree in the semiarid region of Paraiba State are canopy height > total absolute dominance > mean basal circumference > woody species richness > mean basal circumference > woody plant density.

4.3 | Testing the Degree of Desertification Index (DDI)

The high level of accuracy and efficiency of the model explains the high similarity of the classification order among the results obtained by the DDI and the Gower Similarities Index. The model is highly sensitive for evaluating the desertification level in areas of the semi-arid region studied, since it aggregates the major indicators of the woody cover and considers the spatial characteristics of the landscape. If the indicators were used individually, it is likely that the model would lose sensitivity (Lima, Oliveira, Oliveira, Mendonça, & Lima, 2007).

The results, associated with the accuracy and efficiency of the DDI, show not only the reliability of the model to evaluate desertification, but also the reliability of the indicators to select management practices in accordance to the most limiting characteristics of the woody cover for woody vegetation protection, conservation and recovery.

It is important to highlight that the DDI can be incorporated into the remote sensing, which enables the correlation of the data

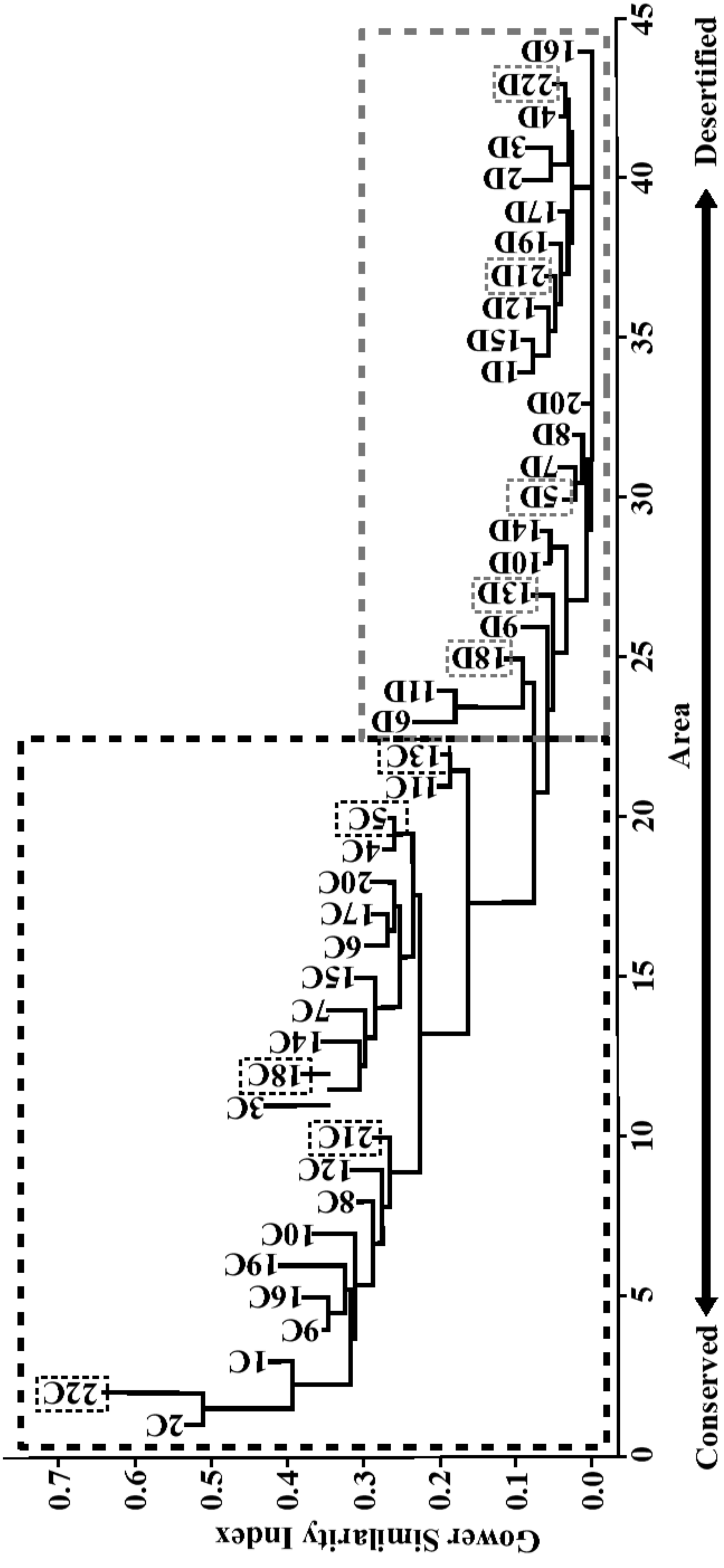

FIGURE 8 Classification of sampling sites by level of desertification in the semiarid region of Paraíba State, Brazil

obtained in the field with satellite images. It would, therefore, be possible to evaluate and monitor the desertification level in other regions of the earth, in real-time and at a low financial cost.

5 | CONCLUSIONS

The process of desertification causes modification to the woody structure of the *caatinga* biome. The integrated use of indicators can monitor the modification of such structure. The recommended indexes for 100, 100, 97.9, 87.9, 71.6 and 56.8% of the investigated region are woody species richness, total absolute dominance, woody plant density, canopy height, mean circumference at breast height and mean basal circumference.

The Desertification Degree Index is dynamic since it integrates indicators following the landscape characteristics. It allows assessments focused on regions of interest, analysis of desertification levels and the identification of the priority woody vegetation parameters for the recovery of native vegetation cover.

The methodology for the elaboration of the Desertification Degree Index is relatively simple and financially accessible to the population, to educational and research institutions and agencies, and it is replicable in other regions of the world, to monitor and plan strategies to effectively combat desertification.

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DATA AVAILABILITY STATEMENT

Research data are not shared.

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