



Using statistical techniques to conduct the geo-environmental compartmentalization of Serra de Martins-RN, Brazil

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Abstract

The systemic approach has been widely disseminated, with significant acceptance and applicability in geographic science, especially in Physical Geography. The geosystemic approach often refers only to the simple grouping of thematic information on the natural elements, using map overlay and visual interpretation as the main techniques for individualization and spatialization of homogeneous units. Thus, this article aims to present the geoenvironmental compartmentalization of Serra de Martins-RN, performed with support in the systemic approach and using multivariate cluster analysis as a technique for identification and spatialisation of geoenvironmental units. The methodological procedures used were: data treatment and analysis, unit taxonomy, physical-geographical descriptions, tabulation, and cartography. For the application of statistical techniques, a set of data was used involving geological, geomorphological, pedological, phytogeographical and land cover variables, from which the most significant ones were selected applying the Principal Component Analysis technique from the minimum variance. The method allowed to identify and to spatialize six Classes of Facies. In the end, it was verified that, although it requires a more in depth knowledge in data manipulation and in the use of complex techniques, the application of statistical treatment was objective and effective for the geoenvironmental compartmentalization.

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INTRODUCTION

Environmental systems are defined as well-organized entities where spatiality is an inherent feature (CHRISTOFOLETTI, 1999). The envisioned organization is a synthesis of the structure and functioning presented by the constituent elements in an evolutionary process. Given the great diversity of constituent elements as well as the interactive flows between them, environmental systems are considered as complex spatial systems.

Christofoletti (1980) points out that the systems can be classified as isolated or uninsulated regarding their relations with the surrounding environment. Isolated systems are those that do not suffer loss or receipt of energy and / or materials from the environment; uninsulated systems, in contrast, refer to those that maintain relations with the other systems of the larger set. Isolated systems can be closed (with energy exchange only) or open (with constant exchange of matter and energy) (CHRISTOFOLETTI, 1980). There are several methodologies employed in the study of environmental systems, whose main objective is to understand their complexity, their constituent elements and their interactions, with views for environmental sustainability (ISACHENKO, 1973; SOTCHAVA, 1977; CHRISTOFOLETTI, 1999; PHILIPPS, 1999; RODRIGUES et al., 2010; RODRIGUES; SILVA, 2016).

Santos (2004) highlights Zoning as the subdivision of a region into territorial portions, obtained by evaluating the most relevant attributes and their dynamics. In turn, Geoenvironmental Zoning (ZGA), which identifies and spatializes geoenvironmental units, is a form of integrative analysis, which considers the compartmentalization of a system from the dynamic interaction of physical and anthropic elements. This systemic approach, as a management tool, is advocated in Brazil through various legal provisions (BRASIL, 2002; 2004) or instrumental (BRASIL, 2006).

The Brazilian Institute of Geography and Statistics (IBGE) (1997) is one of the pioneers in geoenvironmental zoning, specifically in the state of Maranhão. As a criterion, it was based on a morphostructural compartmentalization related to lithostructures and the relief and drainage network features, resulting in the identification of 28 natural systems.

In the state of Piauí, Barros and Castro (2006) carried out a geoenvironmental zoning in the Campo Maior region, an area of ecological stress, using the geopedomorphological method,

which allowed the stratification and identification of ecogeographic characteristics (mother rock, soil, relief and vegetation) and their geoenvironmental problems, based on Tricart and Keewitdejonge (1992).

Souza et al. (2009) conducted the geoenvironmental partitioning of the state of Ceará, based on the relief element, resulting in 13 geoenvironmental units. Also in the state of Ceará, Lima et al. (2010) developed a ZGA proposal for the Crato municipality, resulting in the integration of the geological map, geomorphological units, soils and drainage network using primarily the geological and geomorphological structure as a basis for the individualization of geoenvironmental systems and subsystems. Also in Ceará, Carvalho and Meireles (2008) propose the East Coast Zoning of Fortaleza, following a methodology based on environmental analysis and based on Geosystem Theory and Ecodynamics.

In this same perspective, Rossete and Santos (2012) conducted an environmental zoning in the municipality of Querência, Mato Grosso, supported by the mapping of environmental variables (planialtimetry, geology, geomorphology, pedology, agricultural suitability, vegetation and deforestation).

Sato and Cunha (2013), sought to analyze in an integrated way the municipality of Itanhaém (São Paulo), having the systemic approach as the theoretical basis of the research, based on the methodology of integrated landscape analysis proposed by Rodriguez et al. (2010), concluding that the municipality has two sectors with distinct natural characteristics: the mountainous sector, formed by the Atlantic plateau, the escarpments of the Serra do Mar and the isolated hills; and the lowland sector, formed by the sedimentary plain.

Cavalcanti (2017) presents the Curuçá, Bahia geosystems, defining the boundaries of facies groups, the types of models and variations in vegetation/land cover. The author identified 29 different facies groups, representing the main environmental groups of the municipality in question.

From a classification system for the natural units of the state of Rio Grande do Norte, aiming at a ZGA, Cestaro et al. (2007) defined 9 natural regions, 17 geosystems and 35 geofacies. These were defined by mapping the variables: geology, geomorphology, pedology, altimetry, climate and vegetation. In this Zoning proposal, the area corresponding to Serra de Martins houses the following natural regions: Country Depression, Residual Plateau, Chapada and Fluvio-Lacustrine Plain.

Based on the above, it is noticed that there are several techniques used to identify and delimit the environmental systems, especially the totalizing techniques, map overlay, multivariate grouping, digital image processing and the techniques that use controlling factors (BAILEY, 2009).

Sales (2004) establishes a critique of this aspect, elucidating that, in Brazil, most researches that use the geosystemic approach refer only to simple groupings of thematic information about natural elements, which consequently generates terminological complications. Cavalcanti (2013) points out that the Theory of Geosystems is not based purely on a criterion for nature analysis, but seeks to understand the relationships between the various elements and natural processes. This fact elucidates the need to consider the essence of the systemic methodology, conceived from the set of relationships that are established between the physical, biotic and anthropic elements.

Few works in Brazil use statistical techniques, especially Silva and Santos (2004). The complexity of employing quantitative techniques, which require elaborate and intensive, often costly, sampling and in-depth knowledge of statistical data processing and outcome analysis, is likely to be a hindrance to their more frequent use. Their use, however, considerably reduces subjectivity in the unit identification process and allows for more detailed recognition of individual characteristics, the environmental factors that control and/or exert greater influence, and the hierarchization of units.

Therefore, understanding that environmental systems are units of homogeneous organization, composed of several elements, with mutual relations and continuously subjected to the flows of matter and energy, this paper aims to present the geoenvironmental compartmentalization of Serra de Martins, in Rio Grande do Norte, supported by the systemic approach and using multivariate analysis with the clustering technique.

METHODS

Geographic location of the study area

Serra de Martins is located in the Western Mesorregion of the state of Rio Grande do Norte, more specifically in the Umarizal Microregion, and has altitudes that rise from 210 meters tall

to 720 meters tall above sea level. The study area comprises part of the municipalities of Martins, Serrinha dos Pintos, Umarizal, Frutuoso Gomes and Antonio Martins, totaling approximately 310km² (Map 1).

Data Acquisition

In the study area, the central coordinates of 105 square plots of 10 m x 10 m were randomly drawn (Map 2).

In each plot, a survey of environmental data was carried out, involving the identification of different characteristics of the lithology, the forms of relief, the soil and the land cover, which constituted the research variables.

The geological variables emphasized the type of rocks, from the collection of fragments of the basement, in the case of outcrops, as well as those from mass movements, the colluvium. The subsequent identification of the lithology was performed at the Laboratory of the Department of Geology, Federal University of Rio Grande do Norte (UFRN).

The variables related to geomorphology are in accordance with IBGE (2009) and focus on the position of the relief (top, upper slope, half slope, lower slope, base and canal), curvature (rectilinear, convex and concave), and hypsometry (less than 450 meters, between 451 to 690 meters and above 690 meters). The slope was determined according to the following classes: flat: 0° to 3°, smooth: 3° to 8°, inclined: 8° to 20°, steep: 20° to 45°, very steep: 45° to 75°, and steep: > 75°.

The soil variables observed were texture (sand percentage and clay percentage), pH and CTC (Cation Exchange Capacity).

The variables of land cover involved the size of the plant formation: high woody: 15 - 7m, medium woody: 7 - 2m, low woody: <2m and Herbaceous, and the use: extractivism, livestock, agriculture and no apparent use. In this sense, the research variables totaled 46 and can be evidenced in table 1.

Data organization and processing

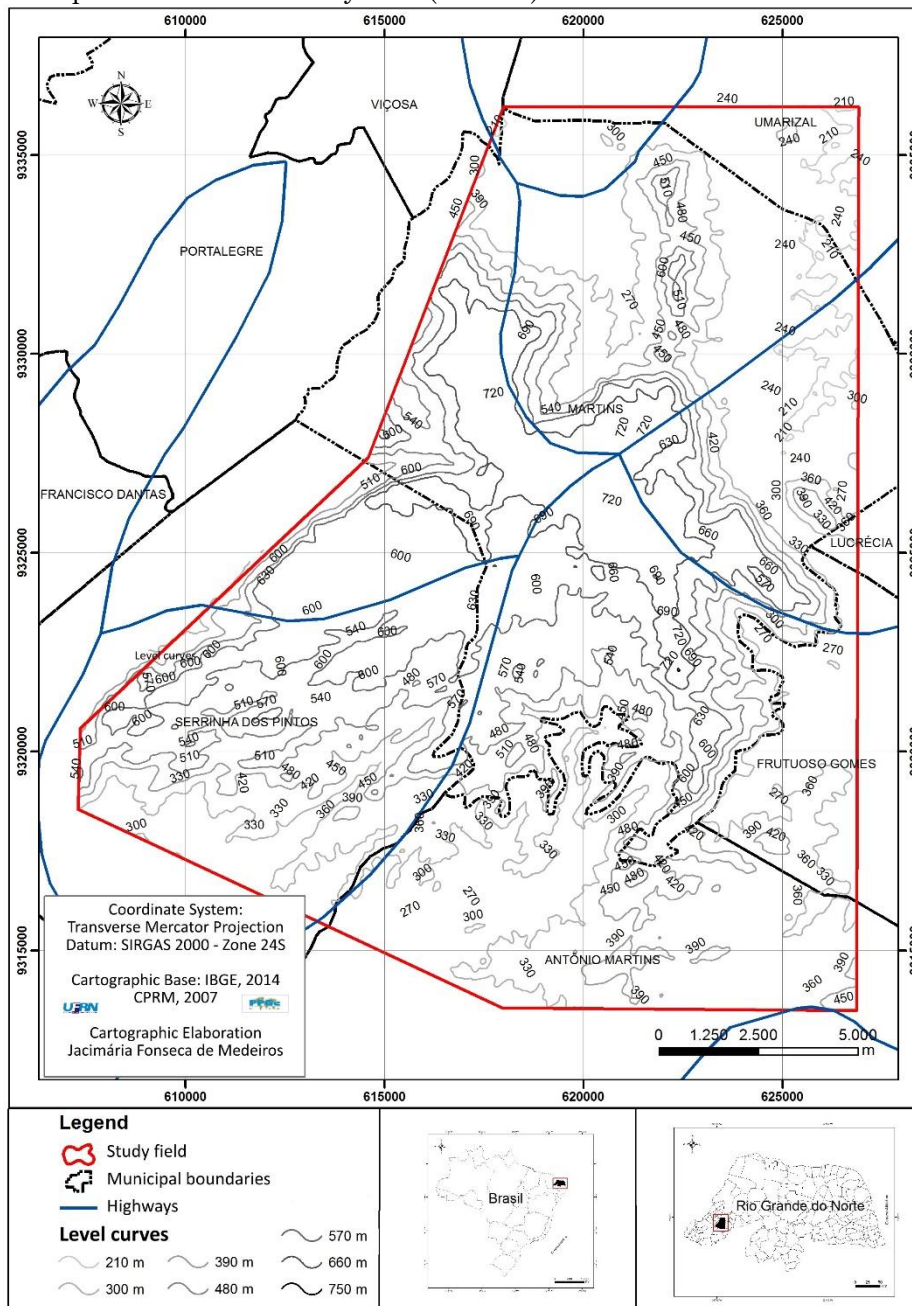
The data were organized in a table, with the variables in the columns and the sample plots in the rows. From the table, statistical procedures were performed to apply the multivariate cluster analysis technique. Cluster analysis is defined as a procedure used to divide a data set into

relatively homogeneous subsets based on the distance or similarity between the data (SANTOS, 2004).

Given that some variables have a nominal response, it was necessary to transform the raw data table into a Boolean or binary matrix, with entries from the Boolean domain $B = \{0, 1\}$, which represent absence and presence,

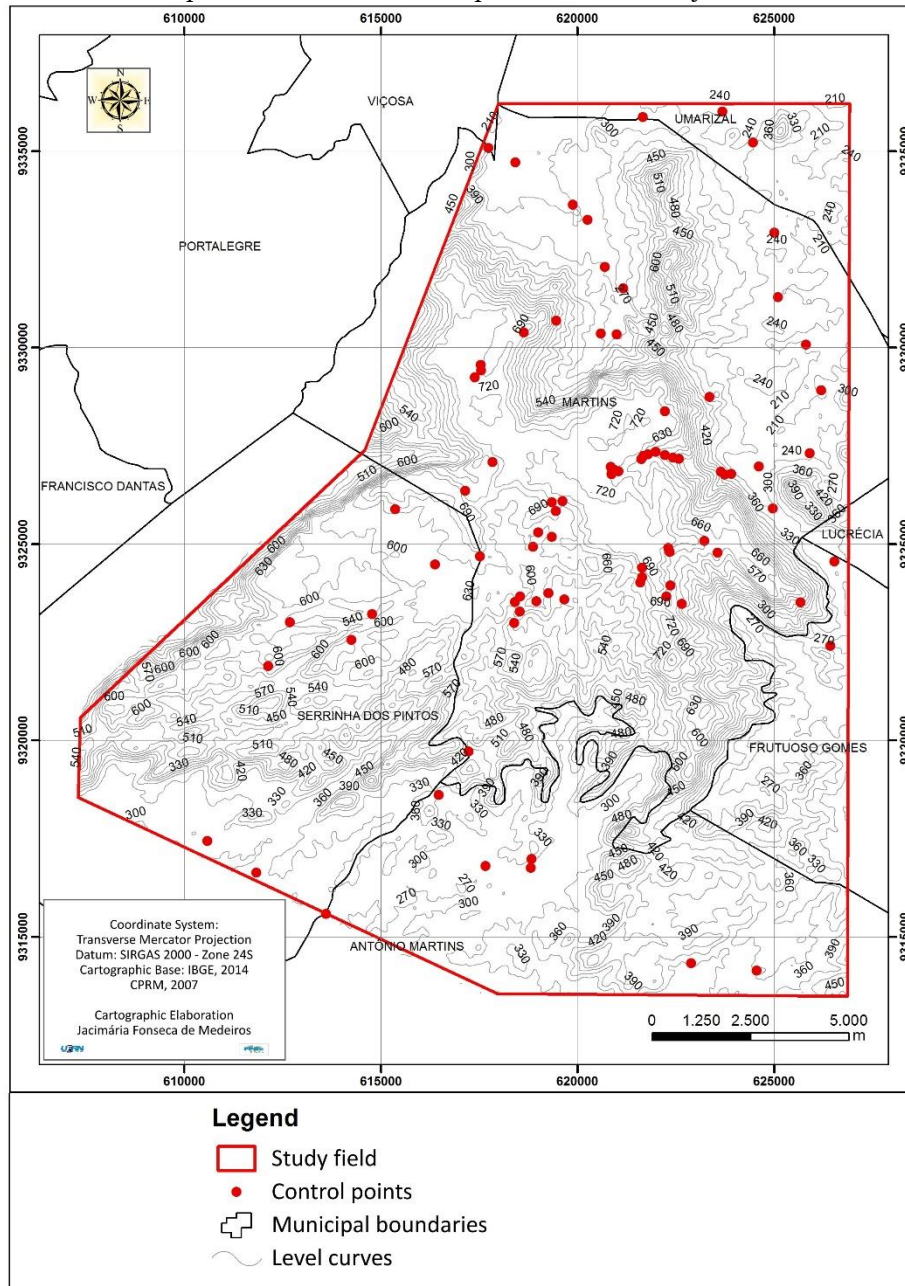
respectively. The original data were standardized to minimize the effects of different measurement scales. Santos (2004) points out that, for binary variables, the measure of the distance between data or groups of data is expressed by coincidence or disagreement between their states.

Map 1. Limits of the study area (red line) Serra de Martins-RN/Brazil.



Source: the authors, 2016.

Map 2. Location of control points in the study area.



Source: the authors, 2016.

Table 1. Variables used for geoenvironmental compartmentalization

Number	Variable
LITHOLOGY	
01	Crystalline Rocks
02	Sedimentary Rocks
03	Outcrops
04	Colluvium
GEOGRAPHICAL RELIEF	
05	Top
06	Upper slope
07	Half slope
08	Lower slope
09	Ground
10	Channel
11	Steep
12	Very steep
13	Steep
14	Sloping
15	Soft
16	Flat
17	Height > 690 meters
18	Height between 690 and meters
19	Height < 450 meters
20	Rectilinear
21	Convex
22	Concave
SOIL	
23	pH 4,5 to 5,2
24	pH 5,21 to 6,0
25	pH 6,01 to 6,8
26	pH 6,81 to 7,7
27	CTC 4,82 to 13,69
28	CTC 13,7 to 22,57
29	CTC 22,58 to 31,45
30	CTC 31,46 to 40,33
31	Sand 427 to 519
32	Sand 519,01 to 612
33	Sand 612,01 to 705
34	Sand 705,01 to 795
35	Clay 40 to 100
36	Clay 100,01 to 161
37	Clay 161, 01 to 222
38	Clay 222,01 to 280
LAND COVER	
39	Herbaceous vegetation
40	Low woody vegetation
41	Medium woody vegetation
42	High Woody Vegetation
43	No apparent use
44	Vegetal extractivism
45	Livestock
46	Agriculture

Org.: the authors, 2016.

The data set, with all observations and variables obtained in the field, was represented as a matrix, built in a spreadsheet. At this stage, it was decided to analyze the behavior of the set of previously selected variables, based on the statistical technique Principal Component Analysis (PCA), aiming to evaluate the set of original variables. A PCA can be used to evaluate the interrelationships between a large number of variables to condense information into a smaller set of statistical variables with minimal loss of information. This technique aims to minimize possible redundancies synthesizing data variability in a few components, and making information mapping simpler (ALENCAR, 2009).

The main components were obtained by the system solution:

$$\det (R - \lambda I) = 0$$

Where: R = correlation matrix between estimated means; λ = characteristic roots (or eigenvalues) of R; I = matrix identity of dimension p x p; and a = characteristic vector (or eigenvector) associated with eigenvalues (HOFFMANN, 1999).

Thus, the eigenvalues of R correspond to the variances of each component and the normalized eigenvectors to the weighting coefficients of the standardized characters.

The PCA was processed using PAST - Palaeontological Statistics, version 1.81 (HAMMER et al., 2008).

After determining the main components of the research, the phase of choice and testing of clustering methods began. Hierarchical clustering methods start from the set of all separate elements and, at each stage, bring together the “most subsets” next” to build a new subset, until the total set of individuals is obtained (ROGERSON, 2012). Hair et al. (2005) highlight that the characteristics of each variable are combined into a measure of similarity, which may be similarity or dissimilarity, calculated for all pairs of variables, allowing the comparison of any variable with another by the similarity measure and the association of the variables similar variables through cluster analysis. The distance measurements represent the similarity, which is represented by the proximity between the observations along the variables. In this case, the correlation coefficient was used as a measure of similarity.

Among the hierarchical agglomerative methods, the WARD minimum variance method was chosen, which,

“Assumes that one group will be joined to another if that meeting provides the smallest increase in intragroup variance. This variance will be calculated for all clustering alternatives, choosing the one with the smallest variance. The same procedure applies to all steps of the analysis. It is highly efficient in forming groups because it is based on the notion of intergroup variance.” (SANTOS, 2004)

Cluster Analysis was processed using the PAST - Palaeontological Statistics, version 1.81 software (HAMMER et al., 2008). After inserting the data array into the program, follow these commands: Multivar - Cluster Analysis. Next, in the Algorithm section, Ward's Method is chosen.

The grouping of variables led to the separation of groups with homogeneous characteristics, called geofacies. For spatialization purposes, a map of the geofacies present in the study area was generated.

Spatialization of geoenvironmental units

The preliminary stage of the map elaboration involved acquiring the SRTM image, downloaded directly from the electronic address of TOPODATA1 - Geomorphometric Database of Brazil, where the data is organized in 1:250.000 scale, in GeoTiff format. The original product is georeferenced in the WGS84 datum, but the SRTM data has been converted to the projected coordinates (Universal Transverse Mercator), SIRGAS 2000 UTM, Zone 24S, considering the greater ease concerning the location and better quality of the triangular grid processing (TIN).

To map the Serra de Martins geofacies, an SRTM radar image (SB-24-Z-A-Folha Souza) was used. Using ArcGIS 10 software (software licensed by the Center for Geoenvironmental and Cartographic Studies / Department of Geography / State University of Rio Grande do Norte / Pau dos Ferros Advanced Campus) the shapes of the area delimitation were inserted from the level curves and especially from the points corresponding to each cluster. Consequently, the polygons were generated for each group through the vectorization technique. The map was produced in 1:2,500 scale.

RESULTS AND DISCUSSION

Statistical treatment of data

The high number of variables raised and the large mass of data, many of them with little variation to influence the formation of the groups, required the reduction of data dimensionality, provided by the PCA, whose results are presented in table 2.

Table 2. PCA analysis of 46 variables

Main components (variables)	Eigenvalue	Variance (%)	Cumulative Ratio of Variance (%)
1	1,44	22,46	22,46
2	1,00	15,70	38,16
3	0,65	10,18	48,34
4	0,54	8,56	56,90
5	0,39	6,22	63,12
6	0,34	5,33	68,45
7	0,27	4,22	72,67
8	0,26	4,13	76,89
9	0,23	3,60	80,49
10	0,17	2,71	83,20
11	0,15	2,37	85,57
12	0,13	2,16	87,73
13	0,11	1,81	89,54
14	0,10	1,67	91,21
15	0,07	1,24	92,45
16	0,07	1,17	93,62
17	0,06	0,94	94,56
18	0,05	0,87	95,43
19	0,05	0,78	96,21
20	0,04	0,74	96,95
21	0,03	0,61	97,56
22	0,03	0,56	98,12
23	0,02	0,39	98,51
24	0,01	0,28	98,79
25	0,01	0,22	99,01
26	0,01	0,19	99,20
27	0,01	0,18	99,38
28	0,009	0,14	99,52
29	0,007	0,11	99,63
30	0,006	0,10	99,73
31	0,004	0,07	99,80
32	0,004	0,07	99,87
33	0,002	0,04	99,91
34	0,001	0,01	99,92
35	0,0004	0,008	100,00
36 to 46	0,00	0,00	100,00

Org.: by the authors, 2016.

When analyzing the data variation for each variable, it is noteworthy that the four initial variables, related to lithology, presented the highest eigenvalue, with an accumulated proportion of variance of 57%. It was also noted that the first 35 variables explained 100% of the variance, indicating that the remaining 11 are linear combinations of the first 35.

Thus, it was assumed that the variables related to lithology, landforms and soils presented 100% of the variance, that is, they are the most representative to differentiate the individualized geoenvironmental units.

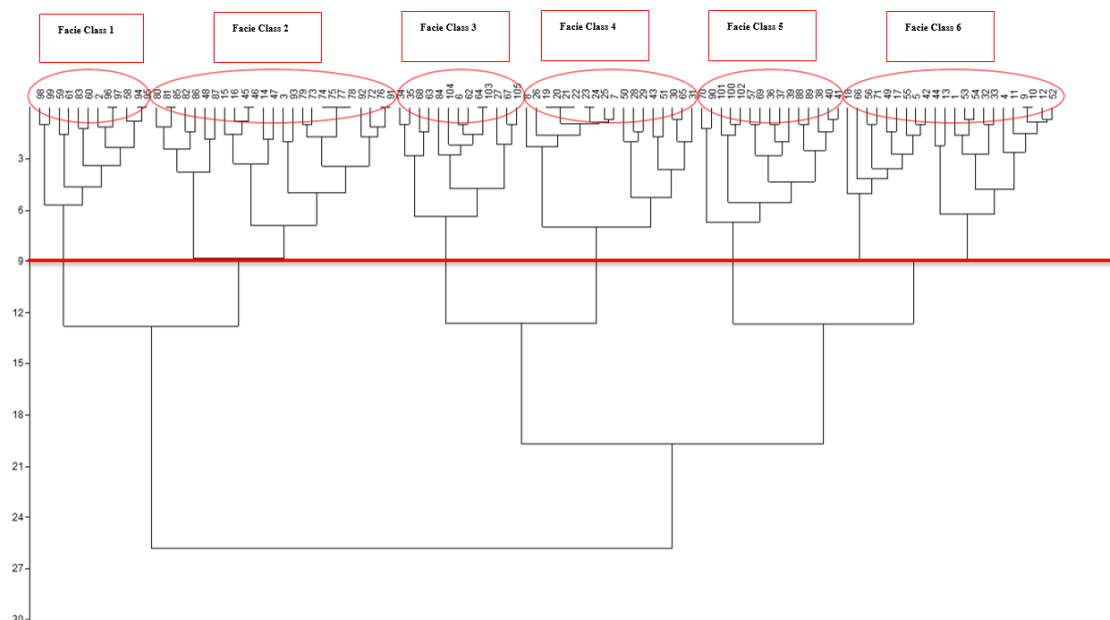
Geoenvironmental units identified

As seen above, the PCA allowed the understanding that the database could be truncated in a number of variables smaller than 46, however, it was decided to use all of them to apply the hierarchical cluster analysis, called variance method. WARD minimum. It is emphasized that this decision assumes that in the systemic analysis all the constituent elements need to be considered.

The generated dendrogram allowed to identify in the study area six clusters, considering the geofacies present in the study area (Dendrogram 1). Considering the absence of a theory that indicates when to perform the dendrogram cut (VICINI, 2005), we defined a cut in line 9 based on the characteristics of the area, resulting in six homogeneous groups would be obtained, which represent the very approximate context in the study area, in terms of its geofacies.

The correlation coefficient calculated for the dendrogram was 0.6723, which is considered satisfactory by the fact that in using the similarity measure, the higher the observed value, the more homogeneous the groups will be (HAIR et al., 2005), thus evidencing consistency in the grouping.

Dendrogram 1. Formation of six groups, considering the geofacies identified in the study area.



Source: The authors, 2016.

Thus, from the hierarchical cluster analysis it was possible to identify in the area six groups, which from the chosen taxonomic system (SOTCHAVA, 1978), were called Facie Classes, namely:

✓ Facie Class 1: Flat to Soft Undulating Relief Surfaces in Crystalline Basement with Wooded Steppe Savannah over Luvisols. Delimited from the grouping of control points 2, 58, 59, 60, 61, 83, 94, 95, 96, 97, 98 and 99, located in the South-Southwest portion of the study area. It has a territorial extension of 28.60 Km², which represents 9% of the studied area.

✓ Facie Class 2: Recessed Relief Surfaces Dissected in Crystalline Basement with Wooded

Steppe Savannah on Eutrophic Red-Yellow Argisols. This facie class was formed from the grouping of control points 3, 14, 15, 16, 45, 46, 47, 48, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 85, 86, 87, 91, 92 and 93, located in the South, Southeast, East, Northeast and North portions of the study area, extending over 71.68 km², which represents 23% of the sampled area.

✓ Facie Class 3: Mountain Relief Slabs Dissected in Crystalline Basement with Forested Steppe Savannah on Litholic Neossols. Defined by the grouping of control points 6, 27, 34, 35, 62, 63, 64, 67, 68, 84, 103, 104, 105, distributed in the North, South, East and West portions, with an extension of 122 Km², which corresponds to

approximately 40% of the study area, and is, therefore, the largest facies class.

✓ Facie Class 4: Flat Relief Tabular Surfaces in Sedimentary Basement with Seasonal Semideciduous Forest on Dystrophic Yellow Latosols. It was formed from the grouping of control points 7, 8, 19, 20, 21, 22, 23, 24, 25, 26, 28, 29, 30, 31, 43, 50, 51 and 65 in the central portion of the study area. It covers an area of 16 km², equivalent to 5% of the total.

✓ Facie Class 5: Mountaineering Slopes with Soft Wavy Relief in Crystalline Basement with Forested Steppe Savannah over Luvisols. Defined by grouping the following control points: 36, 37, 38, 39, 40, 41, 57, 69, 70, 88, 89, 90, 100, 101 and 102, located in the central portion, occupying an area of 49 Km², *i.e.* 16% of the study area.

✓ Facie Class 6: Erosive Relief Cliffs Dissected in Crystalline Basement and Sedimentary Capping with Forested Steppe Savannah on Litholic Neossols. This facie class was defined by grouping the control points 1, 4, 5, 9, 10, 11, 12, 13, 17, 18, 32, 33, 42, 44, 49, 52, 53, 54, 55, 56, 66 and 71, occupying an area of 25 km², which corresponds to 8% of the sample universe. It is located in the central portion of the study area, bordering Facie Class 4.

The diversity of units found in the study area was expected because it is an enclave saw, in its various natural and usage aspects, in a

relatively more homogeneous environment in which the regionally dominant Country Depression is constituted.

The main geoenvironmental features (lithology, landform, pedological characteristics and land cover) of the Facies Classes described above are summarized in Table 3. The cartography of the Facies Classes of the study area can be viewed at Map 3.

FINAL REMARKS

The systemic approach used in the selection process of the environmental variables considered and the use of statistical techniques allowed satisfactory geoenvironmental compartmentalization of Serra de Martins, based on groupings generated by the geological (crystalline basement, sedimentary capping, rocky outcrops, colluvium) geomorphological (relief position, curvature, hypsometry and slope), pedological (texture, CTC and pH) and land cover (plant formation and uses) variables.

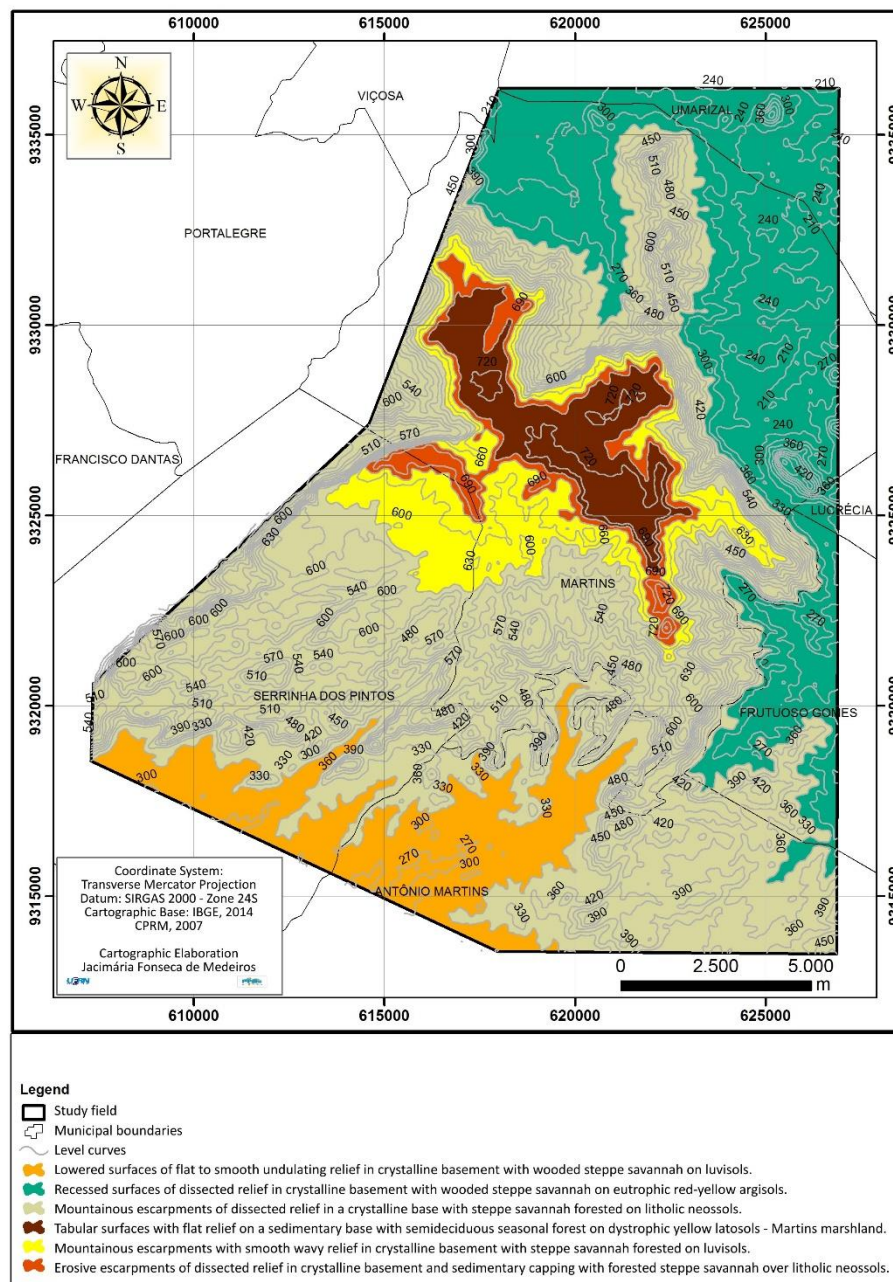
In this sense, the main contribution given by this article was that the use of independent environmental variables and quantitative techniques reduce subjectivity and increase the accuracy of the compartmentalization process.

Table 3. Characteristics of Facies Classes in the study area

Facie	Rocks	Relief	Soils	Vegetation	Use
Facie class 1	Crystalline Rocks	Concave Shapes	Luvisols	Wooded Savannah-Steppe	Temporary and permanent crops; Livestock
Facie Class 2	Crystalline Rocks	Rectilinear Shapes	Eutrophic Red-Yellow Argisols.	Wooded Savannah-Steppe	Temporary and permanent crops; Livestock
Facie Class 3	Crystalline Rocks	Convex Shapes	Litolic Neossols	Savannah-Steppe Forested	Temporary and permanent crops (incipient)
Facie Class 4	Sedimentary Rocks	Tabular Shapes	Dystrophic Yellow Latosols	Seasonal Semideciduous Forest	Temporary and permanent crops; urban core
Facie Class 5	Crystalline Rocks	Concave Shapes	Luvisols	Savannah-Steppe Forested	Temporary and permanent crops (incipient)
Facie Class 6	Sedimentary Rocks	Erosive Cliffs	Neossols Literals	Savannah-Steppe Forested	Temporary and permanent crops

Org.: the authors, 2016.

Map 3. Facie Class of the Serra de Martins-RN.



Source: the authors, 2016.

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