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Edaphic attributes in pedoforms of gullies, in the Southeast region of Brazil

Atributos edáficos em pedoformas de voçorocas, na região Sudeste do Brasil

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ABSTRACT: Water erosion acts as the main form of soil degradation, promoting the release of particles that associated with factors such as climate, relief, soil vegetation and use and occupation favor this process. This study aimed to evaluate whether gullies are more likely to be present in a specific type of landform and how physical and chemical soil characteristics vary between the internal and external environments of concave and convex gullies. The study was performed in the Cachimbal River sub-basin, Pinheiral (RJ). Gullies were mapped and the quantitative and qualitative evaluations (occurrence in concave or convex surface). For each type of landform, one gully was selected. Soil samples (disturbed and undisturbed) were collected from the internal and external surfaces of each gully at a depth of 0-10 cm and soil chemical and physical characteristics were determined. More gullies were present in convex landforms and differences in soil characteristics were observed between the internal and external gully surfaces, but not between different landforms. Ca^{+2}, S value, H+Al, T value, Mg^{+2}, TOC and K^{+} were associated with the external surface, and P, Al^{+3}, aluminum saturation, V%, and pH with the internal surface. Natural and total clay content, and soil and particle density were the physical characteristics associated with the external surface, and total and fine sand content, porosity, degree of flocculation, and silt content with the internal surface.

Keywords: Erosive process. Indicators. Soil attributes.

RESUMO: A erosão hídrica atua como principal forma de degradação do solo, promovendo o desprendimento de partículas que associadas a fatores como clima, relevo, solo, vegetação, uso e ocupação favorecem a esse processo. Este estudo teve como objetivo avaliar se as voçorocas ocorrem em um tipo específico de relevo e como as características físicas e químicas do solo variam entre os ambientes interno e externo de voçorocas côncavas e convexas. O estudo foi realizado na sub-bacia do rio Cachimbal, Pinheiral (RJ). As voçorocas foram mapeadas e analisadas quantitativamente e qualitativamente (superfície côncava ou convexa). Para cada tipo de relevo, uma voçoroca foi selecionada. As amostras de solo (deformadas e indeformadas) foram coletadas nas superfícies interna e externa de cada voçoroca a uma profundidade de 0-10 cm e as características químicas e físicas do solo foram avaliadas. Mais voçorocas foram identificadas na forma de relevo convexa e diferenças nos atributos do solo verificadas entre as superfícies interna e externa, mas não entre as formas de relevo. Os teores de Ca^{+2}, Valor S, H+Al, Valor T, Mg, C e K associaram-se à superfície externa, e P, Al^{+3}, saturação por alumínio, V% e pH com a interna. O conteúdo de argila natural e total, densidade do solo e de partículas associaram-se à superfície externa, já o teor de areia total e fina, porosidade, grau de floculação e conteúdo de silte com a interna.

Palavras-chave: Atributos do solo. Indicadores. Processo erosivo.

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INTRODUCTION

In Brazil, water erosion is one of the main agents of agricultural soil degradation (DECHEN *et al.,* 2015), resulting in decreased crop productivity, decreased soil C, nutrient and water storage capacity,soil acidification, etc. (GONZALEZ, 2019).

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A large area of Pinheiral county, Rio de Janeiro is part of the Cachimbal River sub-basin, RJ, and is part of the "Mar de Morros" region, which is characterized by hilly terrain, a predominance ofdifferenttopographical features (concave and convex), and a history of land use and occupation. The first use of land in this area was extractive agriculture, later replaced by coffee cultivation during the colonial period. Coffee plantations were gradually replaced by dairy and meat cattle farms, especially the latter, which are characterized by large areas of natural or planted pasturesand alimited workforce. Due to thedifferentland uses in this municipality, large areas of land are at different stages of degradation (MENEZES *et al*., 2010; GAIA-GOMES *et al*., 2018).

The demand for information regarding the physical and chemical attributes in gullies is great since few studies are addressing this theme (SANCHEZ *et al*., 2009; MACHADO *et al*., 2010; GOMIDE *et al*., 2011; TEDESCO *et al*., 2014; GAIA-GOMES *et al*., 2020). This information aims to support programs for the recovery of degraded areas, contributing positively to the management and conservation of the soil.

Different agents of soil degradation exist along the sub-basin; however, erosion is the most apparent, occurring inseveraldifferent forms. Many gullies, the most advanced stage of erosion, are in the study area. Few studies have evaluated the effects of physical and chemical soil characteristics on environments degraded by water erosion, while considering the type of landform (SANCHEZ *et al*., 2009; MACHADO *et al*., 2010; GOMIDE *et al*., 2011). Evaluating the influence of soil characteristic son changes in soil quality in these environments is essential (GOMIDE et al., 2011), and may generate information that can be used to establish management systems, assisting the maintenance of sustainable ecosystems (CARNEIRO *et al*., 2009).

The assessment of physical and chemical attributes in areas where the action of erosive processes is verified is of fundamental importance to identify the degree of soil degradation (GOMIDE et al., 2011). Studying gullies in the Ribeirão Cachimbal Sub-basin, GAIA-GOMES *et al*. (2020) found that the soil chemical and physical attributes present different patterns in gullies with different evolutionary stages when the surfaces (internal and external) of these are evaluated. The authors observed that through the analysis of chemical and physical attributes it is possible to identify that gullies contribute to a greater reduction in soil fertility, mainly due to the decrease in the values of Ca^{+2}, Mg^{+2}, K^{+}, total cation exchange capacity (CEC (T)), and the decrease in the soil organic matter stock.The present study had as hypothesis that gullies, as well as their physical and chemical attributes occur in a differentiated way according to the surfaces and relief of the region. The objective of this study was to study the quantitative and qualitative characterization of the gullies present in the Cambimbal subbasin, to evaluate the physical and chemical characteristics of soils on different gullies (internal and external) and relief surfaces (concave and convex), and its influence on the formation of these advanced erosive processes.

2 MATERIAL AND METHODS

2.1 STUDY AREA

The study was conducted in the Cachimbal river sub-basin (CRSB), located in the municipality of Pinheiral, Rio de Janeiro (RJ) (Figure 1). The CRSB is part of the hydrographic basin of the Paraíba do Sul river, and is located in the Médio Paraíba Fluminense region, between the latitudes of 22°29'03'' S and 22°35'27'' S, and longitudes of 43°54'49" W and 44°04'05" W. The climate in the study area is classified as a C wa temperate climate with dry winters and rainy summers and Am rainy tropical climate with dry winters, according to the Koppen climate classification (ALVARES *et al*., 2014).

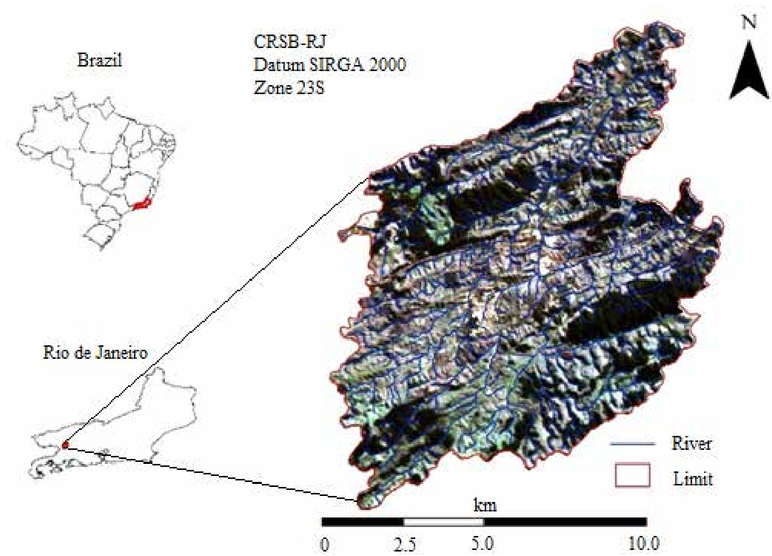

Figure 1. Cachimbal River sub-basin, Pinheiral – RJ
Source: Adapted of GAIA-GOMES *et al*. (2018)

During the colonial period, because of its intense use and occupation, the region that once contained Floresta Estacional Semidecidual Submontana as its original vegetation underwent changes and was replaced with coffee plantations, cattle raising and clay extraction. This associated with factors such as topography, geology, geomorphology and rainfall of the region contributed to the formation of gullies. Currently, the farm is not representative as it was in the past, being observed along the sub-basin a vegetation cover is comprised of implanted, spontaneous, and unmanaged pastures, which are degraded (MENEZES *et al*., 2010).

The soils in this region are predominantly Argissolos Vermelho-Amarelos (Ultisol) and Cambissolos Háplicos (Inceptisol) in the back solpe and Latossolo Vermelho-Amarelo (Oxisol) at the shoulder and summit (SANTOS *et al*., 2017). Thebasinaltitude varies from 360 mat the mouth of the Cachimbal creek, to 720 mat the Arrozal mountain (SANTOS *et al*., 2016).

Gullies were mapped on an image taken in 2016, retrieved from Google Earth, with a 2.34 m spatial resolution. All gullies in the study area were georeferenced from the image, andquantitatively and qualitatively classified. Quantification consisted of counting the number of gulliesin theimage.

Qualitative classification was performed using a digital elevation model of the surface curvature (SCDM) (Figure 2), generated using topographic maps of the Volta Redonda (Map SF-23-Z-A-V-2) and Piraí (Map SF- 23-Z-VI-1) municipalities, at a scale of 1:50,000, with a spatial resolution of 10 m at a scale 1:100,000, which were obtained from the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatistica - IBGE), and using ArcGIS 10.5.1. The coordinates for each identified gully were plotted in the DEMSC, and whether they were a concave or convex l and form was subsequently verified in the field. One gully was then selected for each landform (concave or convex) based on their similar size and slope orientation.

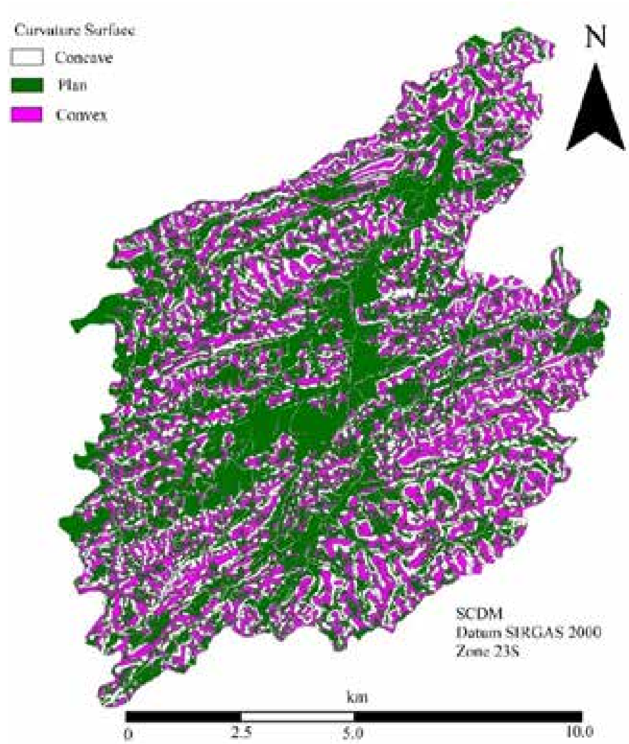

Figure 2. DMSC of Sub-basin of Cachimbal river, Pinheiral - RJ
Source: Adapted of GAIA-GOMES *et al*. (2018)

Disturbed and undisturbed soil samples were collected from the internal and external gully surfaces, at a depth of 0-10 cm (Figure 3A e 3B). Disturbed samples were collected from 59 points in the covex gully, and from 59 points in the concave gully. Undisturbed samples were collected using anUhland samplerfrom20 sampling points in the internal surface, and 20 points in theexternal surface of eachgully.Followingtheir collection, the disturbed samples were dried, de-clumped, and sieved through a 2mm mesh, to obtain air-dried fine earth. The undformed samples were used to determine bulk density (Bd), particle density (Pd) and calculate total porosity (TEIXEIRA *et al*., 2017).

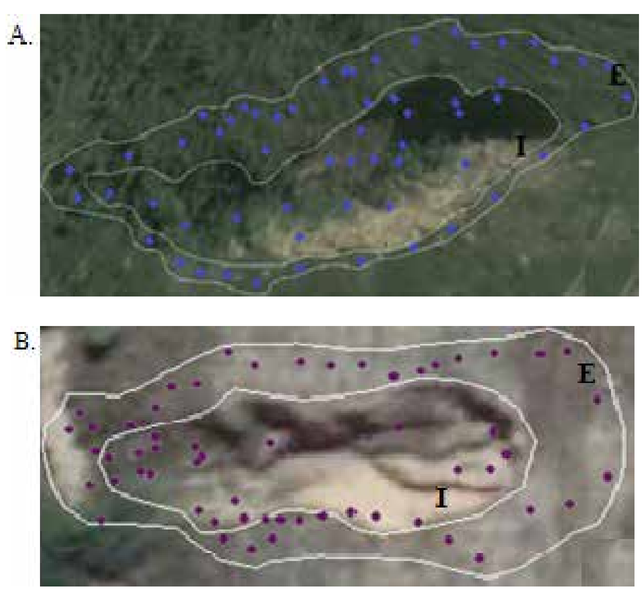

Figure 3. Fragmentation of the gullies (A.) concave and (B.) convex in internal (I) and (E) external surface with a random distribution of collection points.

Water pH and concentrations of Ca^{+2}, Mg^{+2}, Al^{+3}, K^{+}, Na^{+}, P, and H+ Al were determined from the disturbed samplesfollowingTEIXEIRA *et al*. (2017). Total organic carbon (TOC) was quantified following Yeomans and Bremner (1988). The values obtained were used to calculate the sum of bases, base saturation (V value), cation exchange capacity of soil (T value), and Al saturation. The following physical characteristics were quantified: sand, silt, total and natural clay contents. The grain-size analysis results were used to calculate the degree of flocculation (DF%).

Following gully identification and quantification, the gully distribution pattern was analyzed using a Chi-Square test, at $p < 0.05$, using the chisq.test function from the MASS package included in the free R core team software.

Differences between gullieslocated inconcaveorconvexlandforms, and between theinternal and externalsurface ofgullies, were analyzed using a Kruskal-Wallis test, at $p \leq 0.05$. A principal component analysis (PCA) was also performed, using the free Past.exe software, to identify which chemical and physical variables could be used as indicators of similarity or dissimilarity between the different landforms (concave or convex) and gully surfaces(external or internal).

3 RESULTS AND DISCUSSION

The sub-basin has an altimetric range ranging from360 to744 meters, his wide range is characteristic of the terrain in this “Sea of Morros” region. This elevation, with slope, can contribute to the occurrence of erosive processes. The model of the slope and its configuration in the sub-basin ranged from 0% to 181.37% and showed a large number of slightly undular, undular, and strongly undular slope classes, he slope affects the surface and subsurface water flow velocity, and consequently the soil water level and erosive potential, intensifying in the higher occurrence of gullies (GAIA-GOMES *et al*., 2018).

A total thirty gullies were quantified, with a distribution frequency of 6 gullies for the concave and 24 for theconvex landform; the distribution frequencies were significantly different ($p \leq 0.05$). This could be due to the history of coffee cultivation in the area, which occurred more frequently in convex landforms during the colonial period, due to their better microclimaticconditions for coffee growth. Cultivation in these landforms led to greater degradation (MENEZES *et al*., 2010)

The chemical and physicalsoil characteristics are presented in Table 1.

Table 1. Chemical and physical soil characteristics for the studied gullies (G), located in concave (GCO) or convex landforms (GCX), and for the internal (I) and external (E) gully environment

G	Ca^{+2}		Mg^{+2}		K^{+}		Na^{+}		Al^{+3}	
	....($cmol_c$ kg^{-1})...									
	I	E	I	E	I	E	I	E	I	E
GCO	0.02a	0.09a	1.33a	1.32a	0.01a	0.02a	0.003a*	0.04a*	1.66a	1.41b*
GCX	0.00a	0.00a	1.23a	1.36a	0.02a	0.02a	0.002a	0.001a	1.58a	1.76a
	H+Al		S value		T value		V value		Al Sat.	
	................................($cmol_c$ kg^{-1})....................						..................(%).......................			
	I	E	I	E	I	E	I	E	I	E
GCO	4.35b*	4.97a	1.36a	1.43a	4.48b	5.02a*	32.0a*	29.6a*	54.9a	48.3b*
GCX	3.48b	5.35a	1.26a	1.38a	4.74b	6.73a	27.1a	20.6b	55.3a	56.1a
	TOC		pH		P		Natural clay		Total clay	
	(g/kg)				(mg kg^{-1})		................(g kg^{-1}).................			
	I	E	I	E	I	E	I	E	I	E
GCO	31.1a*	16.9b	4.58a	4.63a*	5.8b*	6.4a*	5.8b	21.2a*	25.8a	30.1a*
GCX	7.2b	12.9a	4.55a	4.23b	11.3a	11.4a	5.4b	25.6a	27.5b	36.4a
	Total sand		Fine sand		CS		Silt		DF	
	....(g kg^{-1})...								(%)	
	I	E	I	E	I	E	I	E	I	E
GCO	488a	557a*	145a*	150a*	362a	404a	254a	145b	70.2a	29b
GCX	515a	455a	102a	98a	418a	353a	209a	182a	78.2a	29b
	Bd		Pd				Total porosity			
	....................(Mg m^{-3}).........................						(%)			
	I	E	I		E		I		E	
GCO	1.05a	1.04a	2.52a*		2.44b		58.5a		57.6a	
GCX	1.05a	1.07a	2.45a		2.47a		56.9a		56.7a	

Values followed by the same letter within the same line are not significantly different according to the Kruskal-Wallis test, at $p \leq 0.05$. * Indicates significant differences between different values within the same column, according to the Kruskal-Wallis test, at $p \leq 0.05$. I: Internal gully environment; E: External gully environment; Sat.: Saturation; DF: Degree of flocculation; CS: Coarse sand; Bs: Bulk density; Pd: Particle density; TOC: Total organic carbon

No differences in Bd and total porosity were observed between landforms (concave or convex), or gullysurfaces (internal or external). Pd was significantly higher in the internal surface soils of concave landforms than convex. This higher Pd could be due to the higher fine sand content, which was also observed for the internal surface. Pd was highestin the soils of the internal surface of the concave gully.

From the particle size analysis, a higher degree of flocculation (DF%) and lower natural clay content were identified in samples from the internal environment of both gullies. DF is inversely proportional to natural clay content, and soils with lower DF are more vulnerable to water erosion.This pattern could be associated with the removal of clay particles, which are dispersed naturally and progressively removed by erosion, whilst flocculated particles remain, increasing the degree of flocculation.

In areas subjected to erosion, individual particles are removed (naturally dispersed clay- NC), resulting in changes toDF, which was higher in internal than in external gully surfaces. DF is an indicator of the erosion process, and a low DF may be the result of inadequate management, erosion processes, and absence of conservation practices, which could favor the destruction of soil aggregates and decrease soil permeability (AYER *et al*., 2015), contributing Totals and content to water erosion.

Was higher in the external surface of the concave gully. Fine sand content was highest in the concave gully in soils from both the external and internal surface. Significant differences in silt content were only observed in the concave gully, but it was higher in the internal surface.

From the chemicalsoil characteristic analysis, no differences in Ca^{+2}, Mg^{+2}, and K^{+} concentrations were observed between concave or convex gullies, or internal and external gully surfaces. Although low concentrations of Na were observed, the highest Na concentrations were identified in the concave gully. The S value followed the same pattern that was observed for the exchangeable bases, except for Na, with no significant differences being observed between different landforms or surfaces.

In the concave gully, exchangeable $Al^{+3}$was higher for the internal surface than the external surface. Al concentrations were higher in the external surface of the convex than the external surface of the concave gully. Al^{+3} saturation and pH also followed this pattern, being highest in the convex gully. pH was also lower in the internal surface of the convex gully. H+Al was highest in the external surface of both gullies, but differences were only observed between the internal surfaces of the two gullies, with the highest H+Al observed in the concave gully.

Base saturation (V value) was higher for the concave gully, in both the internal and external surfaces, than the convex gully. Comparing the internal and external surfaces of each gully, base saturation was higher in the internal surface of the convex gully. P concentrations were higher in the convex gully, with no differences observed between the internal and external surfaces. In the concave gully, P concentrations were higher in the external surface.

Different patterns were observed for TOC in the concave gully, TOC was higher in the internal surface than the external surface, where as in the convex gully, it was higherin the external surface. The T value was higher in the external surface of both gullies. Differences between landforms were only observed in the external surface, with a higher T value in the convex gulley than the concave gully.

Gomide *et al*. (2011) studied gullies in the Lavras municipality, MG, and found a similar pattern to this study. The authors related decreased soil fertility in gully environments to decreases in organic matter content in soils from vegetation removal, resulting in decreased leaching and low nutrient cycling.Soil attributes in the concave pedoform have greater spatial variability, demonstrating that the shape of the relief conditions different patterns variability. The magnitude of the variability of soil attributes is most influenced by the shape of the relief than by erosion (SANCHES *et al*., 2009).

The PCA analysis for the chemical characteristics of soil presented a separation between the two gullies (concave – GCO and convex - GCX), and gully environments (internal – i and external – e), byPCA axes 1 and 2.The different gullies and gully environments were denoted as GCOi, GCOe, GCXi and GCXe. The variable correlations with axes 1 and 2 in Table 2, and the PCA results are presented in Figure 4A. The sum of the two axes could explain 80.52% of variance, as axis 1 explained 46.24%, and axis 2explained 34.28% of variance.

For GCOi, pH ($r = -0.96$) and V% ($r = -0.91$) were the most closely associated variables, which were negatively correlated with axis 1. For GCXi, P and Al (positively correlated), and Al saturation (negatively correlated) were the most closely associated variables.

The results presented differences between the internal and external gully environments. When conducting a case study to assess the role of vegetation in stabilizing of erosion processes by gullies in a degraded landscape in critical areas of Calhoun, BASTOLA *et al*. (2018) found that environments with pre-established vegetation were more stable. Such a pattern may be associated with the identification of vegetation in the external gully. Small variations in relief shape have been found to determine variations in chemical soil characteristics (CAMPOS *et al.*, 2012; ARTUR *et al*., 2014; JORDÃO, 2019).

Concavelandformsresult in higher water convergence, which may result in higher chemical soil characteristic variability (RESENDE *et al*., 1997). Santos *et al.* (2016) reported higher spatial variability of chemical characteristicsof soilsinconvexlandforms than concave, and ARTUR *et al*. (2014) also reported differences in chemical soil characteristics between concave and convex landforms.

ThePCA for physical soil characteristics presented a separation between the two gullies (concave and convex), and gully environments (internal and external) (GCOi, GCOe, GCXi and GCXe), by axes 1 and 2. The PCA results are presented in Figure4B, and the variable correlations withaxes 1 and 2 are presented in Table 2. The sum of the twoaxesexplained 87.54% of variance, with axis 1 explaining 55.45%, and axis 2 explaining 32.09% of variance.

Table 2. Correlations between chemical soil characteristics and PCA axes

	Chemical Characteristics					
Axis	pH	Ca^{+2}	Mg^{+2}	Al^{+3}	H+Al	K^{+}
1	-0.96	-0.72	0.16	0.64	0.15	0.41
2	0.57	0.75	0.71	-046	0.90	0.27
Axis	P	S value	T value	V%	Al saturation	TOC
1	0.91	-0.28	0.86	-0.91	0.60	0.68
2	-0.17	0.88	0.49	-0.20	-0.70	0.58
	Physical Characteristics					
Axis	FS	CS	TS	NC	TC	Silt
1	-0.28	-0.74	-0.58	0.86	0.93	-0.23
2	0.40	0.57	0.81	0.49	0.05	-0.92
Axis	DF	Bd	Pd	Porosity		
1	-0,77	0.94	0.93	-0.90		
2	-0,62	0.13	-0.36	0.06		

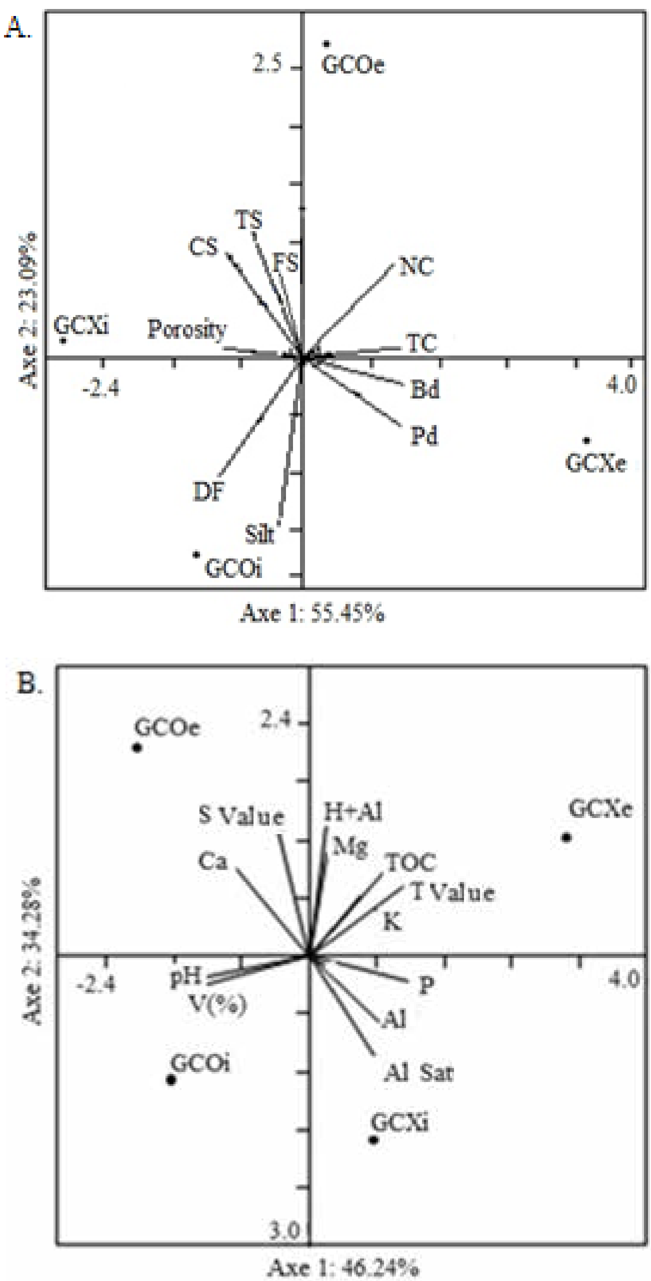

Figure 4. PCA for chemical (A) and physical (B) characteristics of soil in concave (GCO) and convex (GCX) landforms, and internal (i) and external (e) gully environments. GCOe: External environment of concave gully; GCOi: Internal area of concave gully; GCXe: External area of convex gully; GCXi: Internal area of convex gully; pH: aqueous pH; Ca: Calcium; Mg: Magnesium; Al: Aluminum; H+Al: Hydrogen +Aluminum; P: Phosphorus; Na: Sodium; K: Potassium; S value: Ca+Mg+Na+K; T value: Cation exchange capacity; V (%): Base saturation. TS: Total sand; CS: Coarse sand; Porosity: Porosity; Ds: Soil density; Dp: Particle density; TC: Total clay; FS: Fine sand; NC: Natural clay; DF: Degree flocculation

Axis 2 separated the externaland internal environments (Figure 4B). Overall, TS, CS, FS, porosity, DF, and silt contents, were more associated with the internal environment, and natural clay content, TC, Bd and Pd with the external environment.

GCOe was correlated with TS (r = 0.81), and GCXe with TC (r = 0.93), Ds (r = 0.94) and Dp (r = 0.93). TSwas best and positively correlated withaxis 2. The variables associated with GCXe were positively correlated withaxis 1.

The internal gully environmentis a modified environmentwhere a land slide has occurred, so alteredsoil characteristics tend to occur more herein comparison to the external environment. This was verified by some variables explaining the separation between different landforms and gully environments (Figure 4B).

The relationship between PCA axes 1 and 2 showed that GCXe and GCOe differed from GCXi and GCOi, and that most of the variables contributed to this separation. A similar pattern was observed by GOMIDE *et al*. (2011), who studied gullies in Lavras (MG) and detected a separation between the gully environments byaxes 1 and 2.

The PCA for chemical (Ca^{+2}, Mg^{+2}, Al^{+3}, K^{+}, P, H+Al, TOC,S value, V value, T value, and Al saturation; Figure4A) and physical soil characteristics (sand, silt, total and natural clay content, particle density, and bulk density; Figure4B) in the two gullies (concave – GCO and convex - GCX) and gully environments (internal surface– i and externa surface– e), showed that the two principal components (axes 1 and 2) explained 80.52 and 87.54% of the total variance (chemical and physical characteristics, respectively) (Figure4A and 4B).

The PCA for chemical soil characteristics also showed separations, particularly between the gully environments (internal surface– i; external surface– e; Figure 4A). Axis 2, which explained 34.28% of the total variance, separated the internal and external surfaces. This separation was best explained by the Ca^{+2}, Mg^{+2}, H+Al, S value, and Al saturation variables, which were correlated with axis 2, with positive and negative correlations values higher than of 0.70 were observed.

The values of Ca^{+2}, Mg^{+2}, H+Al and S value, were more strongly associated with the external surface, and the saturation by Al with the internal one. The observed patterns showed differences between the gullies' environments. The chemical characteristics of the soil have changed more noticeably with the erosion processes that occur in relief form. When characterizing areas of gullies as the objective of developing strategies for soil recovery in the municipality of Lavras - MG, Gomide *et al*. (2014) found that physical and chemical attributes were good parameters to reflect the damage caused by water erosion. The PCA for the physical soil variablesalso showed a separation between the two gullies by axes 1 and 2, particularly between the two environments (internal and external; Figure4B). The internal and external surfaces were separated by axis 2 (32.09% of data variance) for theconcave gully, and by axis 1 (55.45% of variance) forthe convex gully (Figure 4B). The variables that best explained the separation between the surfaces in the concave gully were TS and silt, which were correlated with axis 2 withpositive and negative correlations values higher than of 0.70.TS was more closely associated with the external surface, and siltwas more closely associated with the internal.

The variables that best explained the differences between the surfacesin the convex gully (positive and negative correlations values higher than 0.70) were CS, NC, TC, DF, Bd, Pd, and porosity. NC, TC, Bd, and Pd were more closely associated with the external surface, and CS and DFwith the internalsurface. Therefore, the gully environments (internal and external surface) for both landforms (concave and convex) differed, and most of the physical soil characteristicscould explain this separation. The internal gully surface is a modified environment, where landslides occur, so altered physical soil characteristics tend to be observed here more often than the external surface.

4 CONCLUSIONS

In the studied region, gullies predominantly occur inconvex landforms.

Differences inchemical and physical soil characteristics were observed between different environments (internal and external gully surfaces), but not between different landforms.

The attributes, Ca^{+2}, Mg^{+2}, H+Al, and S value were the chemical characteristics best correlated with the external surface, and aluminum saturation with the internal surface.

Natural and total clay content, bulk density, and particle density were the physical characteristics best correlated with the external surface, and total sand, fine sand and silt content, porosity, and degree of flocculation within the internal surface.

The type of topographical feature (landform) does not seem to affect erosion processesat the studied erosion stage.

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