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Physical and chemical indicators of soil quality in gully environments, State of Rio de Janeiro (Southeast Brazil)

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ABSTRACT

Water erosion is one of the primary causes of agricultural soil degradation in Brazil, leading to diminished crop productivity and soil acidification, thereby impairing its ability to store carbon, nutrients, and water. Identifying the intensity of erosion can be achieved by utilizing indicator attributes that are highly sensitive to changes in the edaphic environment. The study analyzed the physical and chemical attributes of soil in areas with gullies exhibiting varying degrees of degradation/stabilization. The study was conducted across four areas with varying degrees of gully formation: a) initial, intermediate, mature, and senile. Samples were collected from both the external and internal sides of each gully at the end of the dry season. Among the physical attributes assessed, soil density and total porosity were found to be the most significantly altered. Evaluation of microaggregates provided insights into soil quality through fractions including water-dispersible clay, water-reflocculable clay, and non-water-dispersible clay. Total carbon, total nitrogen, and the C/N ratio elucidated the dynamics of soil and nutrient loss across different stages of erosion formation and stabilization processes, with lower values observed on the internal side of the gullies compared to the exterior side. Vegetation was observed to influence the results of the physical and chemical attributes. Overall, the values tended towards equilibrium between the faces at the senile stage, indicating greater stabilization.

Keywords: agricultural sustainability, agroecosystem degradation, food security, soil attributes.

Indicadores de qualidade física e química do solo em ambientes de voçorocas, estado do Rio de Janeiro (Sudeste do Brasil)

RESUMO

A erosão hídrica é uma das principais causas da degradação das terras agricultáveis brasileiras, levando à diminuição da produtividade das culturas e à acidificação do solo, prejudicando sua capacidade de armazenar carbono, nutrientes e água. O manejo inadequado do solo é um dos principais responsáveis por esse tipo de degradação. A identificação da intensidade da erosão pode ser feita por meio da utilização de atributos indicadores que são altamente sensíveis as mudanças no ambiente edáfico. O estudo teve como objetivos: i) analisar os atributos físicos e químicos do solo em áreas de voçorocas com diferentes graus de degradação/estabilização; e ii) verificar a viabilidade de utilização desses atributos como indicadores de recuperação ambiental. O estudo foi realizado em quatro áreas com diferentes graus de formação de voçorocas: a) inicial, intermédia, madura e senil. As amostras foram coletadas nas faces externa e interna de cada voçoroca no final da estação seca. Entre os atributos físicos avaliados, a densidade do solo e a porosidade total foram os mais significativamente alterados. A avaliação dos microagregados permitiu conhecer a qualidade do solo através de frações como a argila dispersável em água, a argila refloculável em água e a argila não dispersível em água. O carbono total, o nitrogênio total e a relação C/N elucidaram a dinâmica da perda de solo e de nutrientes em diferentes fases dos processos de formação e estabilização da erosão, com valores mais baixos observados na face interna das voçorocas em comparação a externa. Observou-se que a vegetação influenciou os resultados dos atributos físicos e químicos. No geral, os valores tenderam ao equilíbrio entre as faces na voçoroca SE, indicando maior estabilização. Com base nesses resultados, os atributos avaliados podem servir como indicadores de qualidade do solo, pois são mais eficientes e sensíveis em expressar a recuperação da qualidade física e química do solo, fornecendo informações valiosas para o monitoramento de processos de degradação e para a prevenção, controle e recuperação de voçorocas no Bioma Mata Atlântica.

Palavras-chave: atributos do solo, degradação de agroecossitemas, segurança alimentar, sustentabilidade agrícola.

1. INTRODUCTION

Soil is an essential natural resource crucial for the survival of humans and all other species on the planet. Its degradation poses a significant environmental challenge, notably impacting agricultural production areas worldwide, particularly through processes like water erosion (Lal, 2003). Such processes affect the productive potential of soils and can be intensified by anthropogenic actions coupled with inadequate management practices (Silva *et al.*, 2005). While erosion is a natural process, removing vegetation cover accelerates soil erosion, reducing fertility and exacerbating land, water, and nutrient loss (Poesen *et al.*, 2003; Bertol *et al.*, 2004; Chen *et al.*, 2018). In addition, this phenomenon affects water quality through siltation and contamination of water bodies, consequently elevating water treatment costs (Pruski, 2009).

These impacts directly impact food security, employment, health and livelihoods (Gupta, 2019). Research conducted by the Food and Agriculture Organization of the United Nations (FAO) estimates that around 33% of the world's soils are moderately or highly degraded, resulting in an annual loss of 20–37 million tons of sediment (FAO, 2021). In tropical and subtropical areas of Brazil, this significant loss contributes to the intensification of erosion processes, leading to the formation of gullies in advanced stages. Gullies, characterized by significant soil mass loss, are erosive features found in various agricultural areas worldwide, including regions where no anthropogenic action is observed. Gullies originate from natural processes due to dynamic adjustments between energy and matter within hydrogeomorphological systems and occur in varying magnitudes and frequencies (Morgan, 2005; Vanwalleghem *et al.*, 2005). They are common in mountainous areas with steep slopes that facilitate high runoff velocities (Valentin *et al.*, 2005).

Gully formation is influenced by natural factors such as rainfall, relief, pedological, and geological characteristics, as well as those associated with anthropogenic action such as changes in land use and management, including the removal of the soil's primary vegetation cover (Guerra, 1995; Pimentel, 2006; Manstretta *et al.*, 2023; Zhao *et al.*, 2022). The progression of this type of erosive process reduces areas available for development and jeopardizes the sustainability of agricultural production activities. Therefore, controlling and restoring these areas is crucial for re-establishing the balance of the agro-ecosystem. However, recovering these areas can be costly, necessitating scientific research to understand the degradation process and develop proposals for preventing, controlling, and recovering eroded areas (Ferreira, 2015).

Observing soil formation processes in these areas and evaluating their attributes through physical, chemical and biological quality indicators (USDA, 1993; Araújo *et al.*, 2012) are fundamental for studying the impacts of environmental degradation. These indicators are directly linked to the critical functioning of the soil and can therefore provide insights into soil dynamics in these environments. However, there are limited studies addressing soil attributes in areas affected by gullies. These include: i) Gomide *et al.* (2011), who evaluated the physical, chemical, and biological attributes of different gully environments in southern Minas Gerais, Brazil; ii) Gaia-Gomes *et al.* (2020), who evaluated the physical and chemical attributes of soil in gullies in the Atlantic Forest biome; iii) Silva *et al.* (2021), who measured soil attributes as indicators of stabilization processes in gullies at different stages of formation in southeastern Brazil; and iv) Gomes *et al.* (2021), who assessed the variability of soil attributes in different gully environments in the Atlantic Forest biome.

In this context, assessing soil physical and chemical attributes in environments affected by advanced-stage water erosion processes is crucial. These attributes reflect changes in the physical and chemical quality of the soil and can provide valuable insights towards the establishment of rational management systems, thereby contributing to the maintenance of sustainable ecosystems (Carneiro *et al.*, 2009). Restoring these environments aligns with the United Nations' Sustainable Development Goals (SDGs), which represent a global call to action to reduce poverty (SDGs 1 and 2) and to protect the environment and climate (SDGs 13, 14 and 15), and contributes towards achieving the 2030 Agenda goals in Brazil. Therefore, the objectives of this study were: i) to analyze the physical and chemical attributes of the soil in areas with gullies at various degrees of degradation/stabilization; and ii) to verify the feasibility of using these attributes as indicators of environmental recovery.

2. MATERIALS AND METHODS

2.1. Study area

The study area is located in the Guandu River Basin, within the municipality of Seropédica, in the Baixada Fluminense region of the state of Rio de Janeiro (Figure 1) coordinates 22°40'46.78" S and 43°40'10.20" O. The climate is tropical subhumid, with little or no water deficit, and mesothermal with well-distributed heat throughout the year. It is classified as Aw (Álvares *et al.*, 2013), characterized by high temperatures and rainfall during the summer and average temperatures during the winter, with an annual average of 23.79°C (INMET, 2023). It has a history of occupation by agriculture and cattle breeding. The area is dominated by shallow, less weathered soils, classified as *Argissolo Vermelho-Amarelo Eutrófico*, *Argissolo Vermelho-Amarelo Distrófico,* and *Cambissolos Háplicos*, according to the Brazilian soil classification system (Santos *et al.*, 2018), which correspond respectively to Ultisols and Inceptisols according to the Soil Taxonomy of the USA (USDA, 2014). In general, the two soil classes in the area have limitations to their use due to the relief landscape-type of the area, and the associated high susceptibility to water erosion and obstacles to mechanization.

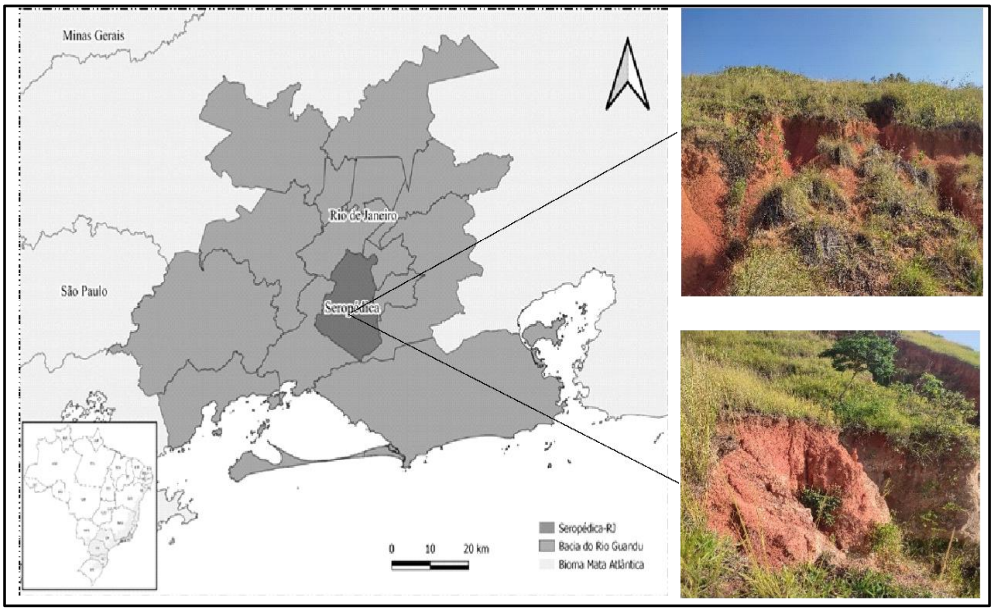

Figure 1. Study area in the municipality of Seropédica, Rio de Janeiro – southeast of Brazil.
Source: Created from the cartographic base of the Brazilian Institute of Geography and Statistics (IBGE, 2015).

In the study region, areas with gullies at different stages of formation were selected using the methodology proposed by Oka-Fiori and Soares (1976) and Dobeck (2011). The varying stages of gully formation were classified as: Initial (IN), Intermediate (INT), Mature (MA), and Senile (SE). The areas were identified and mapped using Google Earth software and validated through field trips. The four stages of formation are arranged irregularly on the slope, not necessarily following an ascending order, i.e., from the initial stage of formation to the most stabilized, and are spaced out as follows: IN - INT (27.2 m); IN - MA (61.1 m); IN - SE (927.2 m); INT - MA (69 m); INT - SE (44.9 m); MA - SE (117 m). The area was estimated for each stage as follows: N (42.8 m^{-2}); INT (134 m^{-2}); MA (1939 m^{-2}); and SE (1963 m^{-2}). The division into thirds was applied only to the MA and SE stages, due to their extent and to better express the variations within the intervals (upper, middle and lower thirds). The IN and INT formation stages, due to their smaller size, had their areas divided into two, namely: upper (top) and lower (bottom) according to Figure 2. Soil samples were collected from the external and internal faces of each stage, with the external face demarcated from the ravine wall up to 2 m from the ground and the internal face of the ravine wall. The soil samples were taken from the surface layer on the external (Ext) and internal (Inte) faces of the four gullies at different stages of formation (initial, intermediate, mature and senile).

The gullies exhibit varying vegetation characteristics depending on the stages of formation and stabilization of the erosion process, distinguishing between their external and internal faces. In the IN and INT stages, degraded pastures predominate the external face, while the internal face is devoid of vegetation. Conversely, the MA stage exhibits a fragment of secondary forest in the initial successional stage (capoeira), primarily composed of embaúba (*Cecropia pachystachya*), a pioneer species, with individuals presenting an average height of 4 m and an average diameter at breast height (DBH) of 8 cm, with no occurrence of canopy stratification.

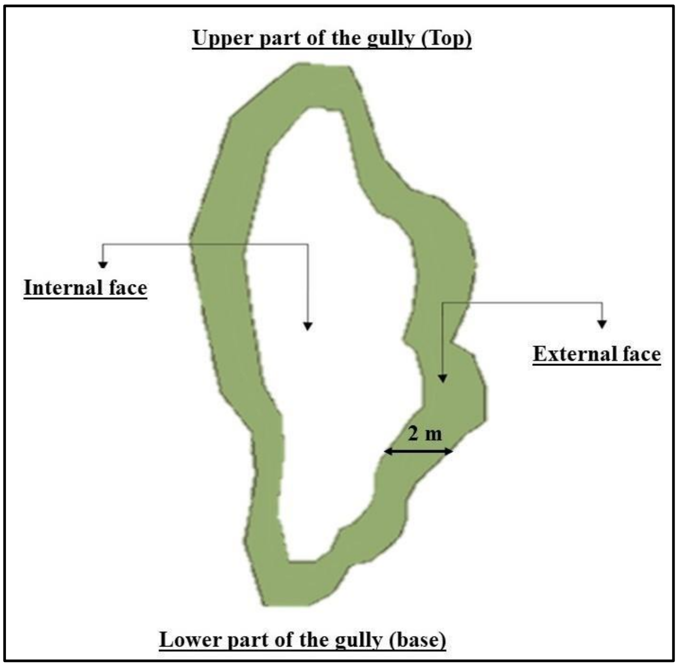

Figure 2. Sketch showing the outside and inside of the gullies.
Source: Authors, 2023.

In the fragment, individuals of leiteira (*Tabernaemontana hystrix*), tamanqueira (*Aegiphila integrifólia*), carrapeteira (*Guarea guidonia*), cambará (*Gochnatia polymorpha*), fruta-de-lobo (*Solanum lycocarpum*), borrachudo (*Machaerium hirtum*), araçá-do-mato (*Psidium araca*), and angico-da-mata (*Parapiptadenia rigida*) were found. In this stage, natural regeneration is scarce, with few herbaceous and shrubby plants, while colonião grass (*Panicum maximum*), sapê (*Imperata brasiliensis*), fat grass (*Melinis minutiflora*), and rabo de burro (*Sedum morganianum*) is abundant. Additionally, two species of lianas were found sporadically in the understory.

The most advanced stage of formation, SE, consists of a fragment of secondary forest in an early successional stage, primarily dominated by cambará (*Gochnatia polymorpha*) and nega-mina (*Siparuna guianensis*), both pioneer species with individuals averaging 4 m in height and 12 cm in DBH, with no occurrence of canopy stratification. The largest individuals recorded were the borrachudo (*Machaerium hirtum*) and the Ingá-branco (*Inga laurina*). Less frequently found in the fragment were carrapateira (*Guarea guidonia*), angico-da-mata (*Parapiptadenia rigida*), arco-de-pipa (*Erythroxylum pulchrum*), pau-pólvora (*Trema micrantha*), araçá-do-mato (*Psidium araca*), embaúba (*Cecropia pachystachya*), tamanqueira (*Aegiphila integrifólia*), fruta-de-lobo (*Solanum lycocarpum*), and macaúba (*Acrocomia aculeata*).

Among the tree species found in lesser numbers in the area, i.e. three or fewer individuals, we identified marianeira (*Acnistus arborescens*), araticum (*Annona cacans*), gonçalo-alves (*Astronium fraxinifolium*), pau-de-leite (*Sapium glandulosum*), and camboatá-vermelho (*Cupania vernalis*), all of which are species native to the Atlantic Forest. In this stage, considered to be the most advanced in the degradation process, natural regeneration is not very prevalent. This area primarily consists of herbaceous plants and shrubs, with stretches of fat grass (*Melinis minutiflora*), rabo de burro (*Sedum morganianum*) and brachiaria (*Brachiaria* sp.). Additionally, five species of lianas were found in some parts of the understory.

2.2. Collecting soil samples

The soil samples were collected in the 0–10 cm layer at the end of the dry season, from both the Ext and Inte faces of the gullies. In the IN and INT stage areas, four individual deformed samples were collected at random to make up one composite (pseudo repetition). This totaled eight composite samples: four from the Ext face and four from the Inte face of each gully.

The gullies in the MA and SE stages of formation were subdivided into thirds (upper, middle and lower), and four individual samples were taken from each third to create one composite (pseudo repetition). This resulted in eight composite samples per third: four from the Ext and four from the Intersection of each gully. From the 0–10 cm layer, the undeformed samples were collected using a Kopeck volumetric ring (Teixeira *et al.*, 2017), and the number of samples was the same as the deformed composite samples. After collection, the deformed soil samples were air-dried, crushed, and passed through a 2 mm mesh sieve (Teixeira *et al.*, 2017) for subsequent assessment of the soil's physical and chemical attributes.

2.3. Analysis of physical attributes

After collection, the deformed samples were air-dried, disintegrated, and passed through a 2 mm sieve to obtain air-dried fine soil, as outlined by Santos *et al.* (2018). The sand (fine, coarse, and total), silt, and clay (naturally dispersed and fully dispersed) contents were determined using the pipette method. Subsequently, the degree of flocculation (GF) was calculated. Particle density (PD) was determined using the volumetric flask method. In the undeformed samples, the soil density (SD) was quantified using the volumetric ring method (Kopeck ring). The total soil porosity (TP) was calculated from the SD and PD values. All the analyses were carried out according to Teixeira *et al.* (2017).

To assess the stability of microaggregates, three classes of clay were quantified according to the method proposed by Melo *et al.* (2019), with adaptations outlined in Melo *et al.* (2021). These classes include: a) water-dispersible clay (WDC), which is clay that mechanically disaggregates in water and does not flocculate in suspension; b) water-reflocculable clay (WRC), which is clay that mechanically disaggregates and flocculates in suspension; and c) non-water-dispersible clay (NDC), which is clay that does not mechanically disaggregate. The WDC, WRC, and NDC data were then relativized for the percentage of total clay in the aggregates.

2.4. Analysis of chemical attributes

The following analyses were conducted to characterize the chemical attributes of soil: a) pH in water at a ratio of 1:2.5 (soil:water); b) exchangeable Ca^{2+}, Mg^{2+}, Al^{3+} extracted with KCl 1 mol L^{-1}, analyzed by titration; c) P (mg kg^{-1}), K^{+},and Na^{+} extracted using the Mehlich-1 method and analyzed by colorimetry and flame photometry, respectively, d) H+Al evaluated using a 0.025 mol L-1 calcium acetate solution. From the contents of the chemical attributes, the values of the soil sorption complex were calculated: sum of bases (SB); cation exchange capacity at pH 7.0 (CEC); aluminum saturation (m); and base saturation (BS) (Teixeira *et al.*, 2017).

The total carbon (TC) and total nitrogen (TN) contents were determined using the dry combustion method in a Perkin Elmer 2400 CHN elemental analyzer at the Laboratory for Research on Biotransformations of Carbon and Nitrogen (LABCEN), Santa Maria (RS). The analyses were carried out using 1.0 (± 0.1) mg of soil sample macerated in a mortar and passed through a 100 mesh (149 μm) sieve (Nelson and Sommers, 1996; Sato *et al.*, 2014). Subsequently, the stoichiometric ratio of total carbon/total nitrogen (C/N) was calculated.

2.5. Statistical Analysis

The results obtained were analyzed for normality of error distribution (Lillifors test / SAEG 5.0) and homogeneity of variances (Cochran and Bartlett tests / SAEG 5.0). In cases where the data did not show a normal distribution, a log-transformation was applied, and subsequently, the mean values were compared using the Bonferroni T-test at a 5% significance level, using the Sisvar 4.6 statistical program (Ferreira, 2003). In cases where the data did not meet the assumptions, the Kruskall-Wallis nonparametric test followed by Fisher's minimum significant difference criterion was applied to evaluate the gullies at different stages of formation. Additionally, the Wilcoxon test was used to compare the variables between the faces. The non-parametric tests were analyzed at 5% significance using the R Core Team software (2020).

Multivariate principal component analysis (PCA) and dendrogram analysis were performed, which is a tree diagram that displays the groups formed by hierarchical clustering of observations at each step and their levels of dissimilarity. These analyses were performed using R Software (R Core Team, 2020) with the "Openxlsx" and "Ggplot2" packages.

3. RESULTS

Table 1 shows the results of the physical attributes related to soil texture. The greatest differences occurred between the faces, primarily for the natural clay (Clay-N), degree of flocculation (GF), and fine sand (Sand-F) attributes. Analysis of the clay fraction results revealed that the Clay-N content differed solely between the stages on the Inte face Inte; specifically, the IN stage differed from the MA and SE stages. When comparing the Clay-N content between the faces, differences were discerned only in the IN and INT formation stages, with the highest Clay-N content on the Ext face. Notably, there were no differences in total clay content (Clay-T) between the stages or their respective faces (Table 1).

Table 1. Physical attributes of the soil, at a depth of 0–10 cm, on the external (Ext) and internal (Inte) faces of gullies at different stages of formation, state of Rio de Janeiro (Southeast Brazil).

Stages	Clay-N		Clay-T		GF		Silt	
	(g kg^{-1})				(%)		(g kg^{-1})	
	Ext	Inte	Ext	Inte	Ext	Inte	Ext	Inte
IN	524.33 a*	113.66 c	744.67 a	565.00 a	29.98 a*	70.06 ab	31.33 a*	147.00 a
INT	319.33 a*	77.66 bc	535.67 a	456.67 a	39.03 a*	87.59 a	90.67 a	185.33 a
MA	475.17 a	343.58 ab	585.42 a	585.33 a	17.52 a	39.16 b	45.17 a	56.17 a
SE	362.42 a	373.50 a	519.67 a	499.17 a	28.74 a	24.71 b	64.08 a	59.58 a
CV%	31.05		28.88		25.31		41.15	

Stages	Sand-F		Sand-G		Sand-T		Texture	
	(g kg^{-1})							
	Ext	Inte	Ext	Inte	Ext	Inte	Ext	Inte
IN	119.00 a*	35.67 c	105.00 a	252.33 a	224.00 a	288.00 a	Clay	Clay
INT	106.33 a	58.00 bc	267.33 a	317.33 a	373.67 a	375.33 a	Clay	Clay
MA	105.92 a	131.42 ab	263.50 a	227.08 a	369.42 a	358.50 a	Clay	Clay
SE	107.83 a	149.25 a	312.67 a	292.00 a	420.50 a	441.25 a	Clay	Clay
CV%	41.15		34.03		15.04			

Averages followed by the same letter in the column do not differ by the Bonferroni T-test at 5%. *Indicates a significant difference between the external and internal faces of the gully by Bonferroni's T-test at 5%. IN: Initial; INT: Intermediate; MA: Mature; and SE: Senile. Clay-N: Natural clay; Clay-T: Total clay; GF: Degree of flocculation; Silt: Total silt; Sand-F: Fine sand; Sand-G: Coarse sand; and Sand-T: Total sand.

No differences were observed in the GF between the stages on the Ext face; however, on the Inte face, the GF values tended to vary between the stages, with the highest values being observed in INT and IN stages, and the lowest values in MA and SE stages. Between the faces, differences were observed solely in the stages with the lowest degree of evolution (IN and INT) in the erosion process, aligning with similar patterns observed in Clay-N. However, higher GF values were observed on the Inte face compared to the Ext face (Table 1).

For the sand fraction, the Sand-F contents varied only on the Inte faces of the erosion stages, with higher Sand-F contents observed in SE and MA, and lower Sand-F contents in IN and INT. Between the faces, differences were observed solely in the IN formation stage, where higher levels of Sand-F were quantified in the Ext face compared to the Inte face. For the Sand-G and Sand-T fractions, no difference was observed between the stages and their faces; however, analysis of the Sand-T fraction showed that the sand contents tended to balance out between the faces. For the silt fraction, differences were only discernible when comparing the faces at the IN formation stage (Table 1).

There was no significant variation in SD between the stages on the Ext face. On the Inte face, higher SD values were found in the gullies at the INT and MA stages. When comparing the faces, differences were observed in all stages, with the highest values being observed on the Ext face. The PD on the Ext face differed only between the IN and INT gullies. Whereas on the Inte face, there was no difference between the stages, mirroring the absence of disparities between the faces across the different stages of formation (Table 2). As for TP, no differences were observed between the stages of formation on both the Ext and Inte faces. However, when each stage and its respective faces were compared individually, a distinction was found between the faces of the IN and INT stages, with higher TP values on the Inte faces compared to the Ext faces (Table 2).

Table 2. Soil density, particle density, and total soil porosity, at a depth of 0–10 cm, of the external (Ext) and internal (Inte) faces of gullies at different stages of formation, state of Rio de Janeiro (Southeast Brazil).

Stages	**SD**		**PD**		**TP**	
	(Mg m^{-3})				**(%)**	
	Ext	**Inte**	**Ext**	**Inte**	**Ext**	**Inte**
IN	1.59 a*	0.94 b	2.21 b	2.04 a	27.74 a*	53.36 a
INT	1.84 a*	1.19 a	2.41 a	1.71 a	23.51 a*	40.17 a
MA	1.74 a*	0.99 a	2.28 a	2.23 a	23.37 a	55.68 a
SE	1.85 a*	0.93 b	2.37 a	2.23 a	22.11 a	57.95 a
CV%	29.10		151.57		30.0	

Averages followed by the same letter in the column do not differ by the Bonferroni T-test at 5%.
*Indicates a significant difference between the external and internal faces of the gully by Bonferroni's T-test at 5%. IN: Initial; INT: Intermediate; MA: Mature; and SE: Senile. SD: Soil density; PD: Particle density; and TP: Total porosity.

The soil microaggregation analysis showed that the values of the three clay classes (water-dispersible clay, water-reflocculable clay and non-dispersible clay) were influenced by the different stages of gully formation and stabilization only on the Inte side (Table 3). For the WDC class, there was an increasing pattern of values depending on the degree of gully formation and stabilization. The highest WDC values were observed in the SE and MA stages compared to the INT and IN stages. Comparing the faces, there were differences in all stages, with the exception of the SE stage, where the WDC values between the two faces tended to balance, which can be attributed to the stabilization of the erosion process. The highest WDC values were quantified on the Ext face of the IN, INT and MA stages compared to the Inte face (Table 3).

Table 3. Stability of soil microaggregates, at a depth of 0–10 cm, on the external (Ext) and internal (Inte) faces of gullies at different stages of formation, state of Rio de Janeiro (Southeast Brazil).

Stages	WDC		WRC		NDC	
	(%)					
	Ext	Inte	Ext	Inte	Ext	Inte
IN	36.23 a*	0.10 b	0.00 a*	0.64 b	63.77 a*	99.26 a
INT	47.26 a*	0.81 b	0.00 a*	4.93 a	52.74 a*	94.27 a
MA	45.86 a*	23.07 a	1.37 a	4.68 a	52.76 a*	72.25 b
SE	34.54 a	35.73 a	0.00 a	0.00 c	65.46 a	64.27 b
CV%	29.10		151.57		11.44	

Averages followed by equal lowercase letters do not differ between gullies by the Kruskal-Wallis test + Fisher's minimum significant difference. Averages followed by (*) differ between faces using the Wilcoxon test. IN: Initial; INT: Intermediate; MA: Mature; and SE: Senile. WDC: Water-dispersible clay; WRC: Water-reflocculable clay; and NDC: Non-water-dispersible clay.

The highest values of WRC were quantified in the INT and MA stages, followed by the IN stage on the Inte face (Table 3). Notably, the values of this clay class on both sides of the SE stage were equal to zero. Conversely, regarding the NDC class, an inverse pattern to the results for the WDC class was observed between the stages and between the faces. The highest values of this clay class were observed in the IN and INT stages. The Inte face of the IN, INT and MA gullies had the highest NDC values compared to the Ext face (Table 3).

Analysis of the chemical attributes associated with soil fertility revealed differences between the stages and their faces (Table 4). Specifically, the pH values exhibited variation solely between the stages on the Inte face, with the lowest value being observed for the INT stage, differing from the MA and SE stages. When comparing the faces, disparities were only evident in the MA stage, where the Ext face showed a lower pH value compared to the Inte face. For Ca^{2+} content, differences were observed solely between the faces in the MA stage, with higher Ca^{2+} content in the Ext face. Similarly, for Mg^{2+} content, differences were solely observed between the faces in the MA stage, with higher Mg^{2+} content in the Ext face compared to the Inte face. The K^+ contents separated the stages on the Inte face into two groups: IN and INT and MA and SE. The first group represents the initial stages of formation, while the second represents the greatest degree of formation and stabilization of the erosion process (Table 4).

For Al^{3+}, differences were observed between the stages on both sides. On the Ext side, the IN stage differed solely from the SE stage (Table 4). On the Inte side, the IN and INT stages differed from the MA stage, where the content of this element was zero. Notably, no differences were observed when comparing the faces. As for the potential acidity values (H+Al), differences were evident between the SE stage and the IN, INT, and MA stages on the Ext side.

On the Inte side, the initial formation stages IN and INT differed from the stages with a higher degree of formation and stabilization (MA and SE). Moreover, the comparison between the faces revealed differences in this attribute between the IN and MA stages. Analysis of the P content revealed differences between the SE stage and the IN, INT, and MA stages on the Inte face. Between the faces, the difference was observed only for the SE stage (Table 4).

Table 4. Chemical attributes associated with soil fertility, at a depth of 0–10 cm, on the external (Ext) and internal (Inte) faces of gullies at different stages of formation, state of Rio de Janeiro (Southeast Brazil).

Stages	pH***		Ca^{2+} ***		Mg^{2+} **		K^{+} **	
	(cmolc kg^{-1})							
	Ext	Inte	Ext	Inte	Ext	Inte	Ext	Inte
IN	4.51 a	4.60 ab	0.50 a	0.27 a	0.93 a	0.57 b	0.18 a*	0.07 b
INT	4.45 a	4.31 b	0.63 a	0.60 a	0.53 a	0.67 b	0.14 a	0.09 b
MA	4.53 a*	5.11 a	0.72 a*	0.45 a	1.17 a*	2.14 a	0.17 a	0.26 a
SE	4.89 a	5.34 a	0.91 a	1.97 a	1.04 a*	3.05 a	0.28 a	0.46 a
Stages	Al^{3+} ***		H+Al ***		P ***		Na^{+} ***	
	(cmolc kg^{-1})							
	Ext	Inte	Ext	Inte	Ext	Inte	Ext	Inte
IN	0.27 a	0.13 a	5.84 a*	5.01 a	0.13 a	0.14 b	1.13 a	2.83 a
INT	0.10 ab	0.13 a	5.46 a	5.07 a	0.14 a	0.13 b	0.49 a	0.64 a
MA	0.03 ab	0.00 b	5.10 a*	1.88 c	0.16 a	0.15 b	1.06 a	4.24 a
SE	0.01 b	0.05 ab	3.55 b	3.53 b	0.17 a*	0.22 a	1.00 a	1.25 a
Stages	SB **		CEC **		BS **			
	(cmolc kg^{-1})				(%)			
	Ext	Inte	Ext	Inte	Ext	Inte		
IN	1.74 ab *	1.04 c	7.58 a*	6.06 bc	22.94 bc*	17.12 b		
INT	1.44 b	1.49 c	6.91 ab	6.56 b	20.76 c	22.72 b		
MA	2.21 ab	3.00 b	7.31 ab*	4.89 c	30.51 ab*	62.23 a		
SE	2.40 a*	5.70 a	5.94 b*	9.24 a	40.92 a*	59.73 a		

Averages followed by the same letter in the column do not differ by the Bonferroni T-test at 5%.
*Indicates a significant difference between the external and internal faces of the gully by Bonferroni's T-test at 5%. IN: Initial; INT: Intermediate; MA: Mature; and SE: Senile. pH: Active acidity; Ca^{2+}: Exchangeable calcium; Mg^{2+}: Exchangeable magnesium; K^{+}: Exchangeable potassium; Al^{3+}: Exchangeable aluminum: H+Al: Potential acidity; P: Available phosphorus; Na^{+}: Sodium; SB: Sum of bases; CEC: Cation exchange capacity at pH 7.0; and BS: Base saturation.

The sum of bases (SB) differed between the INT and SE stages on the Ext side, and on the Inte side, this attribute separated the IN and INT stages from the others (Table 4). For the IN and SE stages, the SB separated the Int and Ext faces. Analysis of the cation exchange capacity (CEC) revealed differences between the stages and faces. For the IN and SE stages, differences were found on the Ext face. Stages INT, MA, and SE differed from IN in terms of the values quantified on the Inte face. The comparison between the faces revealed differences between the faces of the IN, INT, and SE stages. For base saturation (BS), differences were observed between the INT and SE stages on the Ext face. The IN and INT stages differed from the MA and SE stages when compared to the Inte face. Notably, differences were observed between the IN, MA, and SE stages on their respective faces (Table 4).

There were no differences in total carbon (TC) content between the gully formation stages on the Ext face. However, on the Inte face, higher levels were observed in the SE stage compared to the IN, INT, and MA stages (Table 5). Analysis of the faces across the stages revealed differences in the IN, INT, and MA stages. Interestingly, there was no difference between the faces in the SE stage, possibly due to the proximity and balance of the TC contents between the two faces. TN followed a similar pattern to that found for TC (Table 5). For the C/N ratio, no differences were observed between the stages on the Ext face of the gullies. However, on the Inte face, the highest values were observed in the SE gully n compared to the IN and INT stages. Notably, there was a higher C/N ratio on the Ext face compared to the Inte face across all stages of gully formation (Table 5).

Table 5. Total carbon (TC), total nitrogen (NT), and C/N ratio of the soil, at a depth of 0–10 cm, on the external (Ext) and internal (Inte) sides of gullies at different stages of formation, state of Rio de Janeiro (Southeast Brazil).

Stages	**CT**		**NT**		**C/N**	
	(g kg^{-1})					
	Ext	**Inte**	**Ext**	**Inte**	**Ext**	**Inte**
IN	17.65 a*	5.78 b	1.42 a*	0.71 b	12.36 a*	7.95 b
INT	18.37 a*	5.81 b	1.47 a*	0.72 b	12.42 a*	7.99 b
MA	18.49 a*	7.23 b	1.50 a*	0.84 b	12.27 a*	8.46 ab
SE	22.90 a	20.62 a	1.92 a	2.01 a	11.99 a*	10.24 a
CV%	17.40		18.23		7.62	

Averages followed by the same letter in the column do not differ by the Bonferroni T-test at 5%.
*Indicates a significant difference between the external and internal faces of the gully by Bonferroni's T-test at 5%. IN: Initial; INT: Intermediate; MA: Mature; and SE: Senile.

Table 6 shows the correlation values of each variable with the principal component (PC) axes. Variables with correlation values of $-0.70 \geq r \geq 0.70$ (high correlation) were selected for principal component analysis (PCA; Figure 3) and hierarchical cluster analysis (Figure 4). For the PCA study, only the first two principal components (PC1 and PC2) were considered, with values of 44.8% and 35.0%, respectively, with an accumulated variance of 79.8% (Figure 3). Using the PCA, a clear separation of the gullies in their different stages was evident, with the formation of four distinct groups: (1st) the SE-Ext and MA-Ext group, located in the upper right quadrant; (2nd) the SE-Inte and MA-Inte group, located in the lower right quadrant; (3rd) the IN-Ext and INT-Ext group, located in the upper left quadrant; and (4th) the IN-Inte and INT-Inte group, located in the lower left quadrant (Figure 3).

Table 6. Principal component analysis (PCA) matrix. The relative contribution corresponds to the Pearson correlation (r) between each principal component (PC, axis) and the variables.

Variables	PC1	PC2	Variables	PC1	PC2
pH	**0.72**	0.55	TP	−0.02	**0.87**
Ca	**0.73**	0.25	TC	**0.78**	−0.53
Mg	**0.70**	0.52	TN	**0.86**	−0.33
Al	−0.44	−0.36	C/N	0.49	**−0.83**
H+Al	−0.42	**−0.70**	Clay-T	−0.09	−0.37
K	**0.83**	0.35	WDC	**0.70**	−0.58
SB	**0.84**	0.46	WRC	−0.29	0.44
CEC	0.54	−0.13	NDC	**−0.70**	0.54
BS	**0.72**	0.59	Sand-T	0.34	0.28
P	−0.13	0.34	Sand-F	**0.70**	−0.04
SD	0.14	**−0.87**	Sand-G	0.08	0.33
PD	0.47	−0.43	Silt	−0.51	0.29

Values in bold: High correlation (−0.70 ≥ r ≥ 0.70). pH: Active acidity; Ca: Exchangeable calcium; Mg: Exchangeable magnesium; Al: Exchangeable aluminum; H+Al: Potential acidity; K: Exchangeable potassium; SB: Sum of bases; CEC: Cation exchange capacity at pH 7.0; BS: Base saturation; P: Available phosphorus; SD: Soil density; PD: Particle density; TP: Total porosity; TC: Total carbon; NT: Total nitrogen; C/N: Carbon/nitrogen stoichiometric ratio; Clay-T: Total clay; WDC: Water dispersible clay; WRC: Water reflocculable clay; NDC: Non-water dispersible clay; Sand-T: Total sand; Sand-F: Fine sand; and Sand-G: Coarse sand.

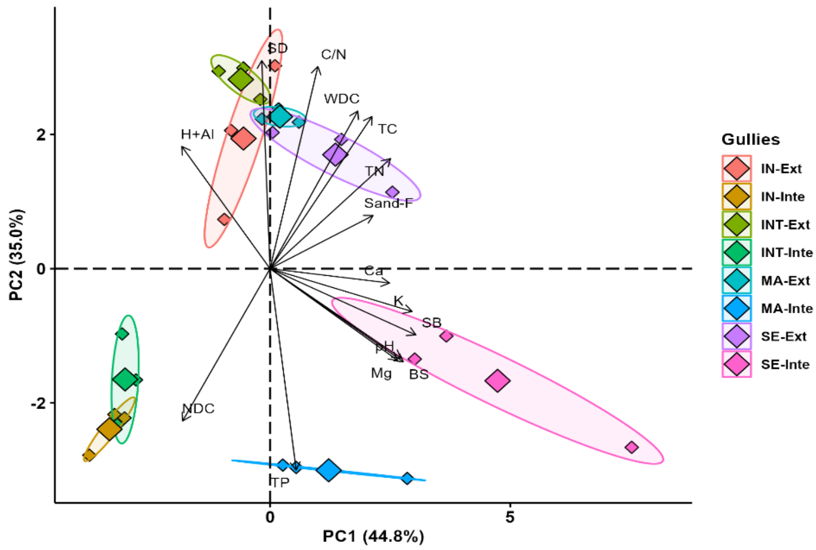

Figure 3. Principal component analysis integrating the physical and chemical attributes of the soil, at a depth of 0–10 cm, of the external (Ext) and internal (Inte) faces of gullies at different stages of formation, state of Rio de Janeiro (Southeast Brazil).
IN: Initial; INT: Intermediate; MA: Mature; and SE: Senile. pH: Active acidity; H+Al: Potential acidity; K: Exchangeable potassium; SB: Sum of bases; BS: Base saturation; SD: Soil density; TP: Total porosity; TC: Total carbon; TN: Total nitrogen; C/N: Carbon/nitrogen stoichiometric ratio; WDC: Water-dispersible clay; NDC: Non-water-dispersible clay; and Sand-F: Fine sand.

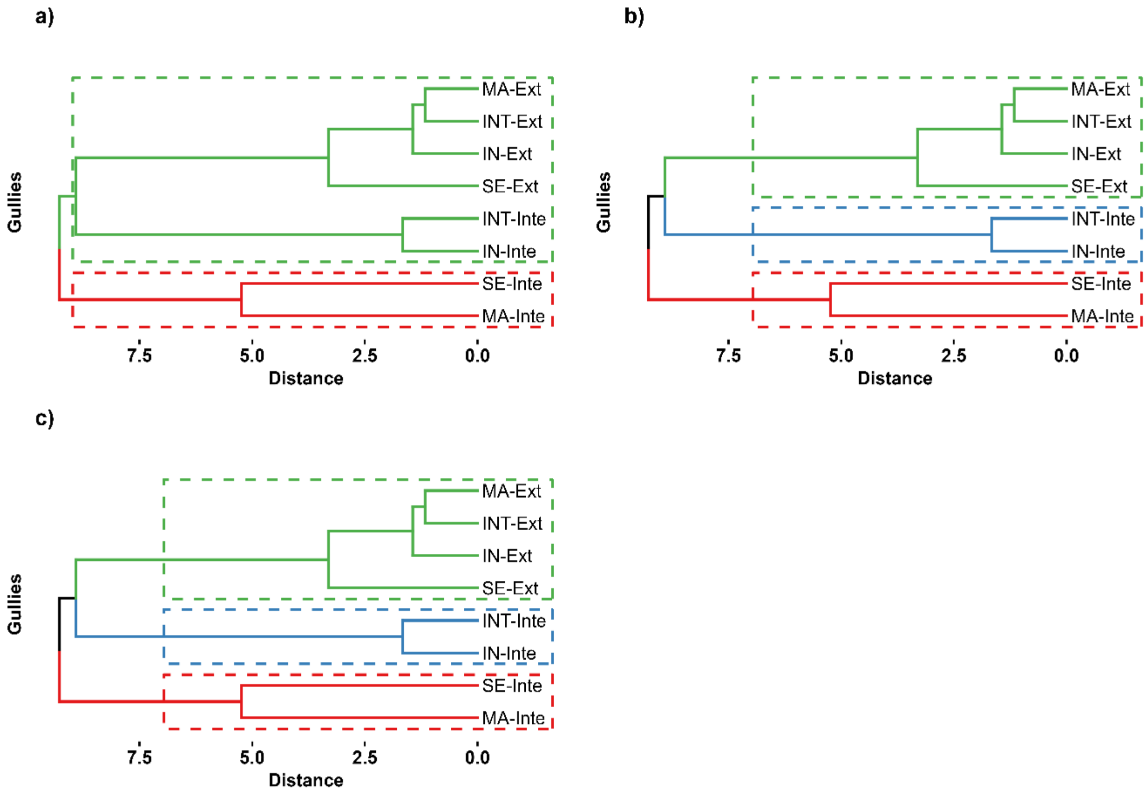

Figure 4. Hierarchical cluster analysis integrating the physical and chemical attributes of the soil, at a depth of 0–10 cm, of the external (Ext) and internal (Inte) faces of gullies at different stages of formation, state of Rio de Janeiro (Southeast Brazil).
IN: Initial; INT: Intermediate; MA: Mature; and SE: Senile. pH: Active acidity; H+Al: Potential acidity; K: Exchangeable potassium; SB: Sum of bases; BS: Base saturation; SD: Soil density; TP: Total porosity; TC: Total carbon; TN: Total nitrogen; C/N: Carbon/nitrogen stoichiometric ratio; WDC: Water-dispersible clay; NDC: Non-water-dispersible clay; and F: Fine sand.

The main axis (PC1: 44.8%), which represents the greatest variability in the data, individualized the most advanced stages from the initial stages of the gullies, with MA and SE on the left side, and IN and INT on the right side of the PCA (Figure 3). The variables that predominantly contributed to the formation of this axis were NT (0.86), SB (0.84), K (0.83), CT (0.78), Ca (0.73), BS (0.72), pH (0.72), Mg (0.70), WDC (0.70), Sand-F (0.70) and NDC (0.70) (Table 6). The secondary axis (PC2: 35.0%) separated the gully faces, with Ext at the top and Inte at the bottom of the PCA. The variables responsible for constructing this axis were TP (0.87), H+Al (−0.70), C/N (−0.83) and SD (−0.87).

The hierarchical cluster analysis (Figure 4) of the physical and chemical attributes with high correlation (Table 5) initially showed the formation of two primary clusters, with the SE-Inte and MA-Inte stages (the most heterogeneous group) separated from the other stages (the most homogeneous group), with approximately 75% dissimilarity (Figure 4a). The construction of three secondary clusters was also observed, primarily separating the IN-Int and INT-Inte stages from the stages on the Ext face, with approximately 55% dissimilarity (Figure 4b). Additionally, the hierarchical cluster analysis showed the formation of four tertiary clusters, specifically differentiating the SE-Inte stage from MA-Inte, with approximately 40% dissimilarity (Figure 4c).

4. DISCUSSION

The physical quality of soils represents a fundamental aspect of soil evaluation and warrants continual analysis (Lal, 2000; Reynolds *et al.*, 2002). Changes in the soil's physical and chemical attributes were observed throughout the stages of gully formation and stabilization of the erosion process. The differences seen in the clay fraction between the faces of the initial stages of the erosion process (IN and INT) and the transition/stabilization stages (MA and SE) suggest that the fractions of smaller granulometry, such as clay, are being eroded. This erosive process appears less intense in the gullies in the transition/stabilization phases, due to the lower intensity of surface runoff, attributed to the presence of vegetation cover and the colonization of plant species (Gaia-Gomes, 2021).

The GF values in the early stages show an inverse relationship with the Clay-N values, indicating that soils with lower GF values are more vulnerable to water erosion (Lima *et al.*, 2013). This pattern suggests the selective removal of naturally dispersed clay particles as a result of the erosion process, leaving behind predominantly flocculated particles, thereby increasing the overall degree of flocculation (Gaia-Gomes, 2021). According to Ayer *et al.* (2015), lower GF values result from the lack of soil conservation and inadequate management, facilitating aggregate destruction and preferential removal of clay particles that are naturally dispersed in water. For the sand fraction, the differences observed for the fine sand fraction between the faces of the IN stage may be attributed to surface runoff dynamics, since fractions of smaller diameter granulometry require less kinetic energy to be transported and deposited in the lower parts of the relief.

The SD is one of the primary soil physical properties, i.e., the easiest to measure in the soil (Huang *et al.*, 2021). It relates to soil porosity and directly affects the movement of soil water. The decrease in SD values in the Inte environments of the gullies correlates with the heightened erosive processes; however, as the erosive processes stabilize, the decline in SD values may be attributed to the organic material deposited to the soil by the vegetation established there, as well as by the roots, leaves and branches of the native vegetation (Bertol *et al.*, 2000). These organic inputs foster the formation of aggregates, contributing to an increase in porosity, and consequently a reduction in SD.

The SD results from this study align with those of Huang *et al.* (2021). In their analysis of the physical and chemical properties of the soil and the evolution of the fertility of a permanent ravine during ecological restoration in the southern granite mountain region of China, they observed that the SD decreased with increasing restoration. Generally, the higher the SD, the greater the soil compaction due to structural degradation, as evidenced by the analysis of the Ext face. The increase in SD consequently leads to a decrease in TP, implying greater restrictions both for the internal flow of water and for the growth of the root system and plant development, which are essential factors for stabilizing the erosion process.

In this study, the highest TP values were observed on the Inte faces of the gullies, because while the Ext area is in a uniform condition of degradation, the Inte area shows a greater intensity of the erosion process and soil loss. Subsequently, with the colonization of the vegetation, the transport of materials stabilized, and the erosion process decreased. This is similar to the pattern observed by Gaia Gomes *et al.* (2020) during their evaluation of the physical and chemical attributes of the soil in gullies in the Atlantic Forest Biome. The authors also attributed the increase in TP to the decrease in the intensity of the erosion process that occurs within these environments, due to colonization by vegetation.

In the early stages, mass runoff from the erosive process culminating in soil degradation is more intense, altering the distribution of porosity. However, structural reorganization, which enhances TP, initiates within the gully’s interior, particularly during the stabilization (SE stage) of the erosion process. This stabilization is attributed to colonization by vegetation, favoring aggregation through the addition of soil organic matter (SOM), which acts as a cementing agent, fostering aggregate formation. Additionally, vegetation provides protection against the direct impact of raindrops on the soil surface, thereby reducing the erosive intensity.

The different stages of gully formation and stabilization affect soil microaggregation differently, with these effects being particularly evident in areas most impacted by the erosion process. This phenomenon can be attributed, in part, to the dynamic dispersion of the clay fraction in the soil. This allows for the stability of aggregates to be used as an indicator of the soil's structural resistance to disruptive agents, such as raindrops or mechanical disturbance, under field conditions (Melo *et al.*, 2019; Pinto *et al.*, 2022).

The increasing trend in WDC values may be related to the intense removal of this clay in the initial formation stages (IN and INT), since it is more easily displaced. Conversely, in stages with greater stabilization of the erosion process, the increase in total clay content explains the increase in WDC class levels. The analysis of this class provides insights into how soil clay responds to mechanical forces and hydration; therefore, it serves as an indicator of the stability of microaggregates (Igwe and Obalum, 2013; Melo *et al.*, 2019; Pinto *et al.*, 2022). The difference found between the stages, with the exception of the SE stage, in which the WDC values between the two sides tend towards equilibrium, may be attributed to the stabilization of the erosion process, since clay and SOM have a direct influence on the aggregation process (Castro Filho *et al.*, 1998; Ribon and Tavares Filho, 2008).

The higher WRC values observed in the INT, MA, and IN stages may be related to the particle characteristics or chemical conditions of these areas (e.g. high concentration of cations). The WRC class is presumed to be more transportable than the NDC class, as WRC remains in suspension during mechanical disturbances experienced in the soil solution, such as rainfall. However, when mechanical disturbances are reduced, the WRC class has greater aggregation potential compared to WDC (Melo *et al.*, 2019; Pinto *et al.*, 2022). Yet, the WRC class is not indicative of resistance against mechanical forces, but only of the balance of charges on the surface of the particles, particularly in extremely oxidic soils, such as *Latossolos* (Melo *et al.*, 2019).

The results of the NDC class in the gully areas may be associated with the stabilization of the erosive process caused by the vegetation present in the areas and the incorporation of SOM, resulting from the contribution of organic waste in the form of leaf litter. This organic vegetative input promotes the bonding and cementing forces of the particles, and contributes to a reduction in the dispersion of the clay fraction. The NDC class serves as an indicator of a higher degree of aggregation, which can occur due to various processes involving organic and inorganic components that promote bonding of particles and/or when the dispersive net charge is estimated to be zero (Melo *et al.*, 2016; Melo *et al.*, 2019; Pinto *et al.*, 2022).

Notably, the effects of plants on the stability of aggregates can be both direct and indirect, mainly through the mechanisms such as the protective action of surface aggregates, the contribution of SOM surface or within the soil profile, and the activity of the root systems (Reichert *et al.*, 2003). During the mass loss process that occurs in gullies, nutrients as well as soil are transported and deposited in lower parts of the terrain. Soil fertility is a comprehensive reflection of all aspects of soil properties and is commonly used to assess soil quality (Huang *et al.*, 2021).

Regarding the chemical attributes associated with soil fertility, it is evident that their significant variations are largely influenced by the absence or presence of vegetation inside the gullies of study. The pH values observed in the MA stage are higher on the Inte side compared to the Ext side, suggesting a reduction in the base removal and the onset of the stabilization of the erosion process. This observation aligns with the presence of a fragment of forest in the initial successional stage within this erosion stage.

The higher levels of Ca^{2+} and Mg^{2+}, K^{+}, and P observed on the Inte face of the SE gully indicate an increase in fertility in these environments, due to a reduction in the removal of soil and nutrients, as well as the contribution of SOM. The H+Al values tending towards equilibrium in the SE stage reflect the action of stabilization processes occurring more intensely in this evolutionary stage. This may be related to the contribution of leaf litter, which increases the carbon content.The variation observed in the SB indicates a significant increase, particularly on the Inte face in the SE stage, corresponding to an increase of more than 50% in relation to the Ext face. For the CEC and BS, the difference observed in the SE stage for both faces stand out, with higher values on the Inte face of the stages, emphasizing the influence of the stabilization of the erosive process taking place in the SE gully.

The fertility results obtained can be attributed to the decomposition and mineralization processes that develop at different intensities due to the characteristics of each stage, primarily influenced by the vegetation, water dynamics, surface runoff, and availability of SOM (Gomide *et al.*, 2011; Gaia-Gomes *et al.*, 2020). The results reinforce the positive influence of plant regeneration on soil and water conservation by promoting improvements in aggregation, water circulation, gas exchange and greater protection of aggregates against the direct impact of raindrops.

The levels of C and N in the soil can be an effective predictor of mineralization. The addition of SOM, promoted by the leaf litter, can increase the amount of C in the soil, stabilizing the erosion process inside the gully, as evidenced in the SE gully. A similar trend is observed for the soil N content. The C/N ratio is an indicator of the degree of decomposition of the SOM, indicating the availability of these elements for use by soil organisms (Luchese *et al.*, 2002). In general, the values of C/N indicate that biological transformation of N is taking place within these areas. The lack of reference values for areas degraded by gullies necessitates the use of values obtained from areas subject to other types of degradation for the comparative analysis. The forests and agricultural crop areas typically tend to have C/N ratios between 9–14, with an average value of 12, whereas pasture areas tend to have higher values (Mullen, 2011; Bui and Henderson, 2013). In general, the C/N ratio is inversely proportional to the decomposition rate of organic material (Zhang *et al.*, 2019).

Notably, the study area is characterized by a predominance of degraded pastures, devoid of forest fragments or agricultural activities. As evidenced by the varying stages of gullies (IN, INTE, MA and SE), the erosion stabilization process becomes increasingly significant when the interior of the gullies is colonized by plant species (trees and/or shrubs), which is particularly noticeable in the SE stage. In this gully, there is a balance between the C/N ratio values on both sides, which confirms the stabilization process.

The multivariate techniques applied in the study elucidated the pattern of the results obtained for the physical and chemical attributes in association with the univariate statistical tests. According to the correlation matrix of the principal components, the first group of highly weighted variables indicates that PC1 is mainly associated with soil fertility, TC and TN contents, and microaggregation stability. In this context, the chemical attributes of fertility are more associated with the SE-Inte stage, reinforcing the hypothesis of the greater influence of the vegetation present inside the gully on the chemical indicator attributes of the soil. The TC, TN, Sand-F, and WDC contents are more closely related to the SE-Ext stage. Whereas the NDC values showed a negative correlation with PC1, being associated with the IN-Int and INT-Inte stages.

In PC2, the highly weighted variables indicate that the component is mainly related to the physical attributes SD and TP, and the chemical attributes H+Al and C/N ratio. These variables are associated with different stages: SD and H+Al for IN-Ext and INT-Ext; C/N ratio for MA-Ext; and TP for MA-Inte. Both principal components separate both the stages of formation and the gully faces. In this study, the indicator attributes selected by the PCA are considered to be the most critical, efficient, and sensitive for expressing the recovery of the soil's physical and chemical quality in areas with advanced-stage erosion processes within the Atlantic Forest biome.

5. CONCLUSION

The analysis of the soil physical and chemical quality in areas with gullies under different degrees of degradation elucidates the dynamics of the advanced stage erosion processes that occur in these areas. The assessment of soil structure using microaggregation revealed the dynamics of the clay fraction in erosion processes at different levels of gully formation and stabilization. Therefore, microaggregates can serve as an indicator of the soil's physical quality in degraded areas, especially when the use of macro aggregation is unfeasible. However, further research is warranted to comprehensively understand the dynamics of microaggregation, particularly in the subsurface layers.

The chemical attributes demonstrate a higher association with the SE stage on the Inte face, reinforcing the hypothesis that the vegetation present inside the gully has a greater influence on the soil's chemical indicator attributes. Soil density, water-dispersible clay, water-reflocculable clay, non-dispersible clay, exchangeable basic cations, potential acidity, total carbon and total nitrogen were the most efficient attributes for assessing of the soil physical and chemical quality. They are recommended as promising soil indicators for monitoring the degradation, prevention, control and recovery of gullies. We suggest the need for future studies using these indicators to monitor the soil quality of degraded areas in other environmental conditions.

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