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Natural fertility and intrinsic fragility of soils in the Brazilian Cerrado

Fertilidade natural e fragilidade intrínseca de solos do cerrado brasileiro

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ABSTRACT: This study aimed to evaluate the attributes of natural fertility and intrinsic fragility of the soils of Ivinhema River Basin (BHI), to subsidize agricultural development projects and environmental control and monitoring bodies. For this purpose, 62 soil samples were collected, at a depth of 0 to 20 cm, in areas of native vegetation belonging to the state of Mato Grosso do Sul – Brazil. The characteristic climate of the study area is of the humid mesothermal subtype (Cfa) without drought. The predominant vegetation is of the Cerrado type and the geological substrate is predominantly composed of the Serra Geral and Caiuá Formation. The samples were air-dried and the physical attributes (sand, silt, and clay) and chemical variables (pH H_2O, $CaCl_2$, KCl, ΔpH, Al^{3+}, m%, H + Al, Ca^{2+}, Mg^{2+}, K^+, CEC, SB, V%, OC, P, Cu, Fe, Mn, and Zn) were determined according to methodologies in Embrapa's soil analysis methods manual. The data obtained were evaluated by descriptive statistics and principal component analysis. The results showed a great variety of soils inside the basin, whose natural fertility was high for the Leptsol, Regosol, and Nitisol soils, and low for the Argiluvic Plinthosol, Petroplinthic Plinthosol, and Planosol soils. The sandy soils showed lower levels of organic carbon and negative surface loads, which shows less capacity to retain cations essential to plant nutrition and less retention of environmental contaminants if any. Regarding the textural fragility of the soils of BHI, it was possible to verify the high sensitivity of the soil to erosion and susceptibility to the contamination of groundwater or infiltrated water. The data shown in research can fill the gaps of knowledge and/or for adapting conservation practices of agricultural soils that are more susceptible to erosive processes, as well as for environmental control and monitoring bodies and/or studies of area recovery and maintenance of soil fertility.

Keywords: Tropical soils. Soil quality. Ivinhema hydrographic basin. Soil conservation. Principal component analysis.

RESUMO: Objetivou-se com este estudo de avaliar os atributos de fertilidade natural e fragilidade intrínseca dos solos na Bacia Hidrográfica do Rio Ivinhema, para subsidiar projetos de desenvolvimento agrícola e órgãos de controle e monitoramento ambiental. Para tanto, foram coletadas 62 amostras de solo, na profundidade de 0 a 20 cm, em áreas de vegetação nativa pertencentes ao estado de Mato Grosso do Sul – Brasil. O clima característico da área de estudo é do subtipo mesotérmico úmido (Cfa) sem estação seca definida. A vegetação predominante é do tipo Cerrado e o substrato geológico é composto predominantemente pela Formação Serra Geral e Caiuá. As amostras foram secas ao ar e os atributos físicos: areia, silte e argila, e variáveis químicas: pH (H_2O; $CaCl_2$ e KCl), ΔpH, Al^{3+}, m%, H+Al, Ca^{2+}, Mg^{2+}, K^+, CEC, SB, V%, C.O, P, Cu, Fe, Mn e Zn foram determinadas conforme o manual de métodos de análise de solo da Embrapa. Os dados obtidos foram avaliados por estatística descritiva e análise de componentes principais. Os resultados mostraram uma grande variedade de solos no interior da bacia, cuja fertilidade natural foi alta para os solos Neossolo Litólico, Neossolo Regolítico e Nitossolo, e baixa para os solos Plintossolo Argilúvico, Plintossolo Petroplíntico e Planossolo. Os solos arenosos apresentaram menores teores de carbono orgânico e cargas superficiais negativas, mostrando menor capacidade de retenção de cátions essenciais às plantas e de retenção de contaminantes ambientais, se houver. Com relação à fragilidade textural dos solos da Bacia Hidrográfica do Rio Ivinhema, pôde-se constatar alta sensibilidade do solo a erosão e suscetibilidade à contaminação das águas subterrâneas ou infiltradas. Os dados mostrados na pesquisa podem suprir as lacunas de conhecimento e/ou informações de referência para os solos da Bacia Hidrográfica do Rio Ivinhema, e do seu entorno. Estas informações são úteis, tanto para adequar práticas de conservação dos solos agrícolas mais suscetíveis a processos erosivos, quanto para os órgãos de controle e monitoramento ambiental e/ou estudos de recuperação de áreas e manutenção da fertilidade do solo.

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Palavras chave: Solos tropicais. Qualidade do solo. Bacia Hidrogáfica Ivinhema. Conservação do solo. Análise de componentes principais.

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INTRODUCTION

The world population growth is estimated to be 2 billion people over the next 30 years. This is an increase from the current 7.7 billion individuals to 9.7 billion in 2050 (ONU, 2019). This population increase implies constant and accelerated changes in the environment that will be influenced by economic factors, production activities, and the impacts of population dynamics. Projected population growth obviously generates prospects for higher food consumption in addition to the aspects and impacts from the occupation and use of these soils.

Brazil presents itself as an essential world food producer and has great potential to expand its supply (SAATH; FACHINELLO, 2018). In the 2019/20 harvest, it assumed global leadership in the production and export of soy, one of the main international commodities (VIANA *et al.*, 2021). In the Cerrado Biome alone, more than 27 million hectares of land under native vegetation were converted into large-scale food-oriented agriculture between 2001 and 2018 (MMA, 2018). The accelerated advance of the country's last agricultural frontier, i.e., in the Cerrado, generates high environmental concern, due to the growing pressure to open new areas (FERREIRA; LINO, 2021).

In the Ivinhema River Basin (BHI), the second-largest basin in the State of Mato Grosso do Sul (South of the Cerrado Biome), diverse crops predominate with emphasis on soy, corn, sugar cane, wheat, rice, cassava, beans, sorghum, coffee, pineapple, and pastures. In general, more than 80% of BHI's area is composed only of agriculture and pasture with an average of 10% of the native vegetation remaining, which is mostly found east of BHI in the Paraná River valley (WATER RESOURCES PLAN, 2015).

The few forest remnants in the Ivinhema hydrographic basin are of fundamental importance for studies aiming to analyze areas with minimal or no anthropic interference, since most of the native forest was suppressed in the last century (CARVALHO *et al.*, 2019). Studies that seek to analyze the natural dynamics of the soil to establish quality guiding values for potentially toxic elements depend on areas with characteristics as close to the natural as possible for reference (RIBEIRO *et al.*, 2019).

Soil studies in preserved areas are of double relevance. On the one hand, they help us to understand the natural dynamics of soil fertility.On the other hand, they allow the establishment of environmental quality criteria by the control and monitoring bodies (ALOVISI *et al*., 2021).

Despite the relevance, there are still insufficient records of studies at the hydrographic basin level on the attributes of natural fertility and intrinsic fragility of BHI soils, a fact that limits the little information from this BH to comparisons with other regions, which is not adequate due to the diversity of soils in a continental country like Brazil (CACHADA *et al*., 2018; RIBEIRO *et al*., 2019).

Thus, this study aimed to evaluate the attributes of natural fertility and intrinsic fragility of the soils of BHI, to subsidize agricultural development projects and environmental control and monitoring bodies.

2 METHODOLOGY

2.1 STUDY AREA

The study area is located in the Southern portion of the State of Mato Grosso do Sul, between coordinates 20º51' and 23º14' S and 52º21' and 55º57' W. The sampling points are distributed within the hydrographic of the Ivinhema River Basin (Figure 1).

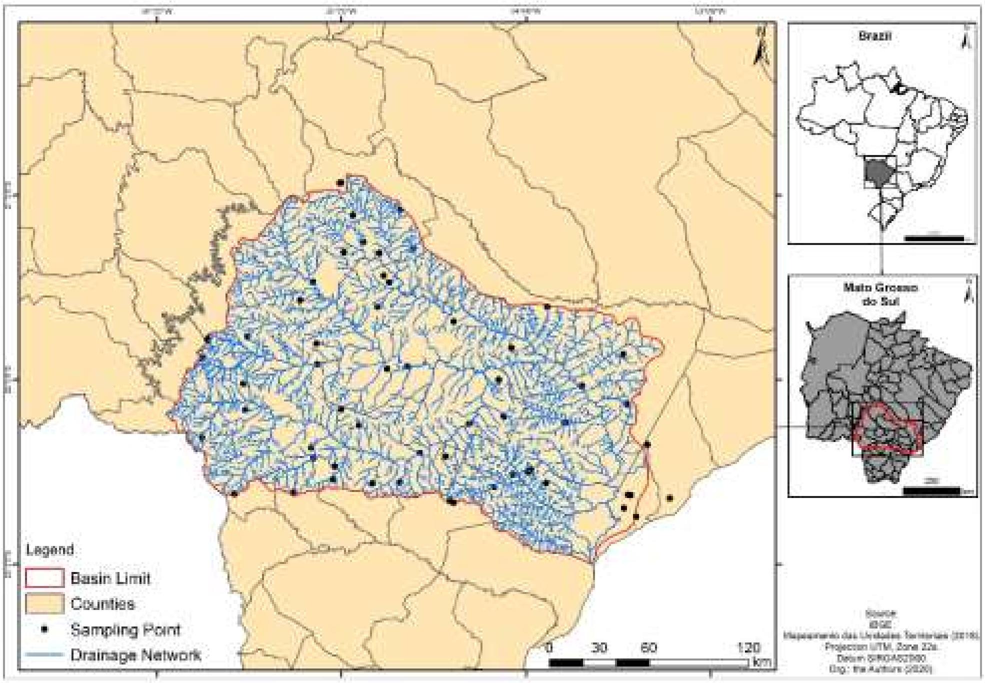

Figure 1. Sample points inside the BHI.
Source: Adapted from IBGE (2018).

The characteristic climate of the study area is of the humid mesothermal subtype (Cfa) without drought (WATER RESOURCES PLAN, 2015).

The vegetation of the BHI, from Northeast to Southeast is in the transition Cerrado/ Seasonal Semideciduous Forest, or Atlantic Forest. To the North of the Ivinhema River, Cerrado predominates and to the South, Semideciduous Seasonal Forest (IVASKO JÚNIOR *et al.*, 2020).

The samples covered soils developed on four geological substrates: Alluvial Deposits, in the Southeast of the basin, Caiuá Formation, from the central strip to the basin's outlet, in the extreme East, Serra Geral Formation, from the central strip to the topographical divide, in the extreme West and Ponta Porã Formation, in the Southwest of the basin, on the border with Paraguay (CPRM, 2006). The occurrence of places with high declivity is not very expressive in BHI, a condition explained by the geomorphology of the terrain formed predominantly by plateaus and other formations with also flat features (WATER RESOURCES PLAN, 2015).

The geological, geomorphological and climatic diversity conditioned the formation of several soil classes within the BHI. The soils found were: Argiluvic Plinthosol, Petroplinthic Plinthosol, Gleysol, Ferralsol, Nitisol, Acrisol, Arenosol, Leptsol, Regosol and Planosol. Soils were classified (Taxonomy) according to Brazilian soil classification standards (SANTOS *et al.*, 2018), and partial equivalence made to the universal system recognized by the international soil science union (IUSS) e FAO (WRB, 2015).

Sixty-two sample points representing the geological and pedological units of BHI were defined in remnants of native vegetation. For each sample collection point, composite samples were obtained (five simple homogenized samples) of approximately 2 kg of soil. Samples were removed at a depth of 0-20 cm.

2.2 CHEMICAL AND GRANULOMETRIC ANALYSIS

The soil samples were air-dried, protected from sunlight, manually removed, and passed through a 2 mm stainless steel sieve to obtain the air-dried fine earth (TFSA) for chemical and granulometric measurements.

All chemical and granulometric variables were determined according to the methodologies described by Teixeira *et al.* (2017).

The granulometric variables (sand, silt, and clay) were determined according to the pipette method, which is based on the physical law of particle sedimentation.

The pH was determined in water, $CaCl_2$ 10^{-2} mol L^{-1}, and KCl 10^{-2} mol L^{-1} in the proportion 1: 2.5 (m/v). The readings were performed by a bench pot. Potential acidity was estimated by using the pH of the SMP solution (a mixture of neutral salts with several buffers).

Exchangeable Ca^{2+} and Mg^{2+} were extracted by 1 mol L^{-1} KCl together with exchangeable Al. In a fraction of the extract, aluminum was titrated with NaOH in the presence of bromothymol blue indicator. In another fraction, Ca^{2+} and Mg^{2+} were determined by flame atomic absorption spectrometry (FAAS).

The available K^+, P, Fe, Mn, Cu, and Zn were extracted by a double-acid solution composed of a mixture of 0.05 mol L^{-1} H_2SO_4 and 0.025 mol L^{-1} HCl, which is known as Mehlich-1 solution. The K^+ levels were determined by flame atomic absorption spectrometry (FAAS). The determination of available P was made by UV/vis spectroscopy by reading the color intensity (660 nm) of the phosphomolybdic complex produced by the reduction of molybdate with ascorbic acid.

The organic carbon content (OC) was determined by oxidation with $K_2Cr_2O_7$ in a sulfuric acid medium using a heat source, H_2SO_4, and heating — a method known as Walkley-Black. The excess dichromate after oxidation was titrated with a standard solution of ammoniacal ferrous sulfate, and the amount of reduced $Cr_2O_7^{-2}$ was calculated to obtain the OC content.

To obtain the results, some calculations were performed to obtain the sum of bases (SB), the cation exchange capacity at pH 7 (CEC), base saturation (V%), aluminum saturation (m%), and delta pH (ΔpH). SB was obtained by adding Ca^{2+}, Mg^{2+}, and K^+ cations. For CEC, SB + H + Al^{3+} was added. The values of V% and m% were obtained by the equations: 100.SB/CEC, and 100.Al^{3+} / SB + Al^{3+}, respectively. Finally, the ΔpH values were calculated using the equation: pH H_2O - pH KCl.

2.3 STATISTICAL ANALYSIS

Results obtained were evaluated by descriptive statistical. In order to verify similarities and diferences between variables and soil classes, the Principal Component Analysis (PCA) was applied (JOLLIFFE; CADIMA, 2016). All statistical analysis were performed using the Statistica 10.0 software.

3 RESULTS AND DISCUSSION

The granulometric variables (sand, silt, and clay) made it possible to fit the soils into several textural classes. The soils Argiluvic Plinthosol, Acrisol, Arenosol, and Planosol had a sandy texture; Petroplinthic Plinthosol, Gleysol, Leptsol and Regosol had a medium texture;

and Ferralsol and Nitisol had a clay texture (SANTOS *et al.*, 2018). The contents of sand, silt, and clay varied widely in the classes of soils analyzed (Table 1).

On average 60% of the soil classes showed a predominance of sand in their granulometric composition, a feature that requires conservationist measures as a way to contribute to agricultural zoning and to estimate the productive potential of these soils which are characterized as light soils. One of the alternatives is to adopt integrated systems of production such as crop-livestock integration and crop-livestock-forest integration (DONAGEMMA *et al.*, 2016).

Among the several benefits of conservation systems, it is possible to highlight the soil's cover with vegetation and the permanence of adequate levels of organic matter (OM) for the system. With this, the levels of nutrients in the soil are increased, favoring soil fertility. On the other hand, the densities of negative charges generated on the surface of organic colloids favor the retention of possible environmental contaminants by load interactions.

Table 1. Average values and standard deviations of chemical and granulometric variables for the soils studied

Soil	Argiluvic Plinthosol (n = 4)	Petroplinthic Plinthosol (n = 1)	Gleysol (n = 6)	Ferralsol (n = 13)	Nitisol (n = 4)	Acrisol (n = 21)	Arenosol (n = 5)	Leptsol (n = 3)	Regosol (n = 3)	Planosol (n = 2)
Variables					0-20 cm					
Sand (g kg^{-1})	795,9 ± 111	621	564 ± 306	283,7 ± 296	296,8 ± 119	779,8 ± 99	875 ± 73	342,4 ± 135	356,4 ± 28	819,2 ± 69
Silt (g kg^{-1})	84,8 ± 66	114,0	179 ± 104	230,3 ± 69	227,9 ± 42	68,5 ± 50	65,5 ± 52	395,3 ± 99	331,8 ± 25	94,6 ± 32
Clay (g kg^{-1})	119,3 ± 51	265,0	257 ± 259	486 ± 129	475,3 ± 83	151,7 ± 74	59,5 ± 38	262,3 ± 65	311,8 ± 40	86,2 ± 37
pH (H_2O)	4,48 ± 0,1	4,50	5,08 ± 0,5	5,47 ± 0,7	5,79 ± 0,4	5,09 ± 0,7	5,62 ± 0,9	6,47 ± 0,2	6,42 ± 0,1	5,12 ± 0,9
pH ($CaCl_2$)	3,88 ± 0,1	3,90	4,48 ± 0,5	4,87 ± 0,7	5,19 ± 0,4	4,49 ± 0,7	5,02 ± 0,9	5,87 ± 0,3	5,82 ± 0,1	4,5 ± 0,9
pH (KCl)	3,88 ± 0,1	3,72	4,26 ± 0,3	4,49 ± 0,8	5,0 ± 0,4	4,41 ± 0,7	4,97 ± 0,9	5,44 ± 0,5	5,62 ± 0,2	4,5 ± 0,9
ΔpH	-0,59 ± 0,04	-0,78	-0,82 ± 0,13	-0,99 ± 0,26	-0,78 ± 0,1	-0,68 ± 0,13	-0,65 ± 0,03	-1,03 ± 0,29	-0,80 ± 0,07	-0,62± 0,04
Al^{3+} (cmol$_c$ dm^{-3})	1,13 ± 0,4	2,50	0,74 ± 0,8	0,76 ± 0,4	0,2 ± 0,1	0,92 ± 0,4	0,41 ± 0,2	0,00	0,00	0,45 ± 0,4
m (%)	68 ± 3,4	78,2	19,5 ± 2,1	7,2 ± 5,7	1 ± 0,3	38,3 ± 33	21,7 ± 18,3	0,00	0,00	45,8 ± 35,2
H+Al (cmol$_c$ dm^{-3})	1,9 ± 0,5	2,73	1,80 ± 0,6	1,84 ± 0,6	1,52 ± 0,4	1,46 ± 0,5	0,67 ± 0,3	1,08 ± 0,1	1,15 ± 0,3	1,17 ± 0,2
Ca^{2+} (cmol$_c$ dm^{-3})	0,18 ± 0,1	0,27	4,57 ± 4,1	7 ± 4,2	10,4 ± 3,2	2,77 ± 3,5	2,8 ± 2,6	15,4 ± 0,7	15 ± 0,2	1,1 ± 1,5
Mg^{2+} (cmol$_c$ dm^{-3})	0,10 ± 0,06	0,11	1,42 ± 1,4	2,56 ± 1,1	2,89 ± 0,8	0,92 ± 1	0,83 ± 1	3,96 ± 0,6	4,41 ± 0,3	0,26 ± 0,3
K^{+} (cmol$_c$ dm^{-3})	0,24 ± 0,03	0,31	0,14 ± 0,1	0,42 ± 0,4	0,46 ± 0,3	0,18 ± 0,1	0,18 ± 0,1	0,83 ± 0,2	0,96 ± 0,5	0,06 ± 0,03
CEC (cmol$_c$ dm^{-3})	2,46 ± 0,7	3,42	7,94 ± 5,2	11,8 ± 5,1	15,3 ± 3,7	5,40 ± 4,4	4,50 ± 3,6	21,3 ± 1,4	21,5 ± 1,1	2,63 ± 1,6
SB (cmol$_c$ dm^{-3})	0,53 ± 0,2	0,69	6,1 ± 5,6	10 ± 5,3	13,8 ± 3,8	3,8 ± 4,5	3,8 ± 3,6	20,2 ± 1,4	20,3 ± 0,9	1,46 ± 1,9
V (%)	21,4 ± 3,8	20,2	66,3 ± 28	79,4 ± 15	89,2 ± 5	51,1 ± 31	68,1 ± 32	94,8 ± 0,6	94,6 ± 1,3	40,7 ± 47
O.C (g kg^{-1})	15,7 ± 2,9	19,8	24,4 ± 14	25,1 ± 9	31,3 ± 17	15,5 ± 6	10,6 ± 6,3	55,2 ± 10	49,4 ± 11	18,4 ± 10
P (mg dm^{-3})	3,1 ± 0,7	1,40	6,2 ± 3,9	5,8 ± 6	6,5 ± 4	4,7 ± 4	9,3 ± 5	22,4 ± 17	5,7 ± 5	2,3 ± 0,5
Fe (mg dm^{-3})	167 ± 29	216,4	1088 ± 206	32,8 ± 28	29,6 ± 20	85,3 ± 64	28,2 ± 24	10,9 ± 0,5	44,6 ± 34	1033 ± 163
Mn (mg dm^{-3})	7,2 ± 6,4	6,4	89,6 ± 67	148 ± 99	172 ± 85	69,5 ± 61	107,5 ± 67	246,7 ± 102	256,4 ± 93	36,6 ± 31
Cu (mg dm^{-3})	0,65 ± 0,24	1,1	5,4 ± 1,9	4,7 ± 4	6,9 ± 6	1,7 ± 1	0,41 ± 0,1	1,1 ± 0,3	4,2 ± 2	2 ± 0,6
Zn (mg dm^{-3})	0,07 ± 0,05	0,17	2,1 ± 1,8	3,1 ± 2	1,5 ± 1	1,9 ± 1	1,3 ± 1	2,8 ±1,9	2,5 ± 1,3	0,6 ± 0,3

n = Number of samples; ± = standard deviation; ΔpH = pH KCl - pH H_2O; H+Al = Potential acidity; CEC = cation exchange capacity (SB + H + Al); SB = sum of bases (Ca^{2+}, Mg^{2+}, K^{+}); V = base saturation (SB/CEC) × 100; m (%) = aluminum saturation (100.Al^{3+}/SB + Al^{3+}); OC = organic carbon

The concern with environmental contamination, especially groundwater, in sandy soils is reported in the literature (heavy metals and pesticides). In sandy soils of northeastern Brazil, with annual applications of 510 kg ha^{-1} of nitrogen, movement of nitrate up to about 7 m in depth and the presence of the same ion in groundwater was observed in values higher than those allowed for human consumption (ANDRADE *et al.* 2009). Donagemma *et al.* (2016), reported available potassium contents above 50 mg dm^{-3} at depths more than 1.8 m in sandstone soils in western state of Bahia.

The susceptibility to groundwater contamination can be considered high in BHI's interior, since, in its most significant portion, the Caiuá outcropping aquifer has its direct recharge from precipitation (WATER RESOURCES PLAN, 2015).

All soils analyzed showed acidic pH characteristics. Regarding the average pH values (H_2O), the soils presented the following sequence of pH values: 4.48, 4.50, 5.08, 5.47, 5.79, 5.09, 5.62, 6.47, 6.42, and 5.12 for the soils Argiluvic Plinthosol, Petroplinthic Plinthosol, Gleysol, Ferralsol, Nitisol, Acrisol, Arenosol Leptsol, Regosol, and Planosol, respectively. According to the interpretation limits developed by Sousa and Lobato (2004) for samples of Cerrado soils in the 0 to 20 cm layer, the pH of the Petroplinthic Plinthosol, Argiluvic Plinthosol, Gleysol, Acrisol, and Planosol soils is low; while it is medium for Ferralsol and Nitisol, suitable for Arenosol soils, and high for Leptsol and Regosol soils.

The acidity of soils under native forests is considered a natural process due to the leaching of basic cations caused by precipitation and nutrient absorption by the plant root system. In tropical conditions, this process is intensified due to high temperatures and high precipitation (POLESSO *et al.*, 2021).

Low pH conditions as found for 50% of the analyzed soil classes are considered a serious problem in cropping systems. This is justified by the presence of elements such as Al^{3+} and Mn^{2+} in concentrations considered toxic. Not least, it should be noted that just as acidity is a limiting point for the development of species, high pH values are also considered harmful. For example, pH values above 6.5 can affect micronutrient availability by decreasing the solubilization and absorption of Cu, Zn, Fe and Mn, and increasing the availability of Mo (DECHEN *et al.*, 2018; POLESSO *et al.*, 2021).

Around 75% of the Gleysol and Acrisol soil samples, more than 25% of the Ferralsol, Nitisol, and Arenosol samples, and all of the Argiluvic Plinthosol and Petroplinthic Plinthosol samples had pH values below 5.6, a condition that indicates the presence of Al^{3+} in the soil solution. According to Kochian *et al.* (2015), acidity may be associated with Al^{3+} in soils where the pH (pH H_2O) is below 5.6. This is due to the increase in its solubility in this soil. However, in about 25% of Ferralsol and Nitisol soil samples, 50% of Arenosol samples, and all samples of Leptsol and Regosol, the soils showed pH values above 6.0. This is a favorable condition for soil fertility and retention of possible contaminants, due to the increase in negative charges generated on the surfaces of clay minerals and organic matter (COSTA *et al.*, 2019).

The ΔpH values showed that electronegative charges predominate in BHI soils. Adsorbing more cations than anions in colloids is an essential feature in the retention of heavy metals and micro- and macro-nutrients. The lowest value for ΔpH was found in the Leptsol soil. This indicates a possible contribution of organic matter in the generation of negative charges (Coringa; Weber, 2008) because this soil gave the highest organic carbon content compared to the other analyzed soils. This charge effect indicates that the preservation and increase of organic carbon stocks are fundamental for the generation of negative electrical charges in the soil, and consequently it can increase the CEC of the soil and reduce the toxic activity of Al^{3+} and improve the natural fertility of soils (BALDOTTO; VELLOSO, 2014).

In general, Argiluvic Plinthosol, Acrisol, Arenosol, and Planosol soils are less electronegative than the other classes analyzed. This can be justified by the high sand quartz content of these soils, poor in loads, where the soil organic matter (SOM) is the primary source of negative soil loads.

The predominance of negative loads on the soil is an essential parameter of fertility and an excellent environmental and soil quality indicator.

In general, the most electronegative soils in this study had higher CEC and less acidity. This indicates that the load sources of these soils are mostly variable and pH-dependent.

On average, the highest levels of Al^{3+} were found in soils Petroplinthic Plinthosol and Argiluvic Plinthosol, with 2.50 and 1.13 $cmol_c\ dm^{-3}$. To interpret Al^{3+} values, saturation by Al^{3+} (m%) must be calculated, since a high value of aluminum content in sandy soil can be negligible in a clayey soil. That is, the toxicity of Al^{3+} depends on the values CEC which vary from one soil to another. Thus, according to the aluminum saturation classes (m%) adopted by Sousa and Lobato (2004), there is a very high saturation for Petroplinthic Plinthosol and Argiluvic Plinthosol soils, high for Acrisol, Arenosol and Planosol soils, and low for soils Gleysol, Nitisol, Ferralsol, Leptsol, and Regosol.

In all analyzed samples of Leptsol and Regosol soils, Al^{3+} was not found. This condition is justified by the high base saturation found in these soils, and this results in low acidity. The only Petroplinthic Plinthosol soil sample, about 50% of the Argiluvic Plinthosol and Acrisol samples, and 25% of the Ferralsol samples expressed Al^{3+} contents higher than 1.0 $cmol_c\ dm^{-3}$. Consequently, these samples showed low values of base saturation, CEC, and high acidity, which indicate low natural soil fertility.

The highest H + Al levels were found in the soils Petroplinthic Plinthosol and Argiluvic Plinthosol, corroborating the high saturation of these soils by Al^{3+}. The relationship between H + Al and Al^{3+} results from the decomposition of clay minerals in which Al^{3+} is released from the octahedral layers. The Al^{+3} thus produced can remain on the surface in the exchangeable form (displacing H^{+} from the soil adsorption sites) or pass to the soil solution (RONQUIM, 2010).

According to Sousa and Lobato (2004), the levels of Ca^{2+} and Mg^{2+} are considered high for the soils Leptsol, Regosol, Nitisol, and Ferralsol, suitable for the soils Gleysol, Acrisol and Arenosol, and low for the soils Argiluvic Plinthosol, Petroplinthic Plinthosol, and Planosol. Except in Argiluvic Plinthosol and Petroplinthic Plinthosol soils, Ca^{2+} and Mg^{2+} were the elements that most contributed to the constitution of the CEC of the soil. The maintenance of Ca^{2+} and Mg^{2+} in the soil depends on the source material (rock) being influenced by its texture, organic matter content, and the removal of plants. In soils with a high content of Ca^{2+} and Mg^{2+}, the levels of OM are also high, which points to the importance of SOM in maintaining these nutrients.

Except for Argiluvic Plinthosol, Petroplinthic Plinthosol, and Planosol soils, K^{+} contents showed a similar trend to Ca^{2+} and Mg^{2+} for the other soil classes. It is important to note that K^{+} was the cation that most contributed to CEC in Argiluvic Plinthosol and Petroplinthic Plinthosol soils. However, when observing the SB values, it appears that only 21.5% of CEC is made up of basic cations, corroborating with high levels of saturation by Al^{3+} (m%).

Mean SB values ranged from 0.53 to 20.3 $cmol_c\ dm^{-3}$ for Planosol and Regosol soils, respectively. The variation of this parameter directly influences the constitution of CEC and V%. Thus, there is a wide range between these variables as well. In general, SB was higher in soils whose OC and clay content were also higher (Leptsol, Regosol, Nitisol, Ferralsol). On the other hand, the lower SB averages found in the Petroplinthic Plinthosol, Argiluvic Plinthosol, and Planosol soils are justified by the high acidity and the presence of H^{+} and Al^{3+} replacing basic cations (Ca^{2+} Mg^{2+} K^{+}) (RAMPIM *et al.*, 2013).

According to the classification adopted by Sousa and Lobato (2004), the average CEC of the soils of BHI are presented in the following order: high for the soils Leptsol, Regosol and Nitisol; suitable for Ferralsol, Gleysol, Acrisol, and Arenosol; medium for Argiluvic Plinthosol; and low for Planosol. CEC soil is an essential parameter of fertility. However, it can be an excellent environmental indicator due to its ability to retain heavy metals (KASEMODEL; RODRIGUES, 2015). In general, soils with a high CEC are seen as positive environmental indicators; while those with low CEC are contrary indicators. This condition is due to the matrix of negative soil loads, clay minerals, and especially SOM.

The average levels of OC varied from 10.6 to 55.2 g kg^{-1} for the Arenosol and Leptsol, respectively. In decreasing order, the average levels of OC in the soils of BHI presented the following sequence: Leptsol > Regosol > Nitisol > Ferralsol > Gleysol > Petroplinthic Plinthosol > Planosol > Argiluvic Plinthosol > Acrisol > Arenosol. Regarding the classification adopted by Sousa and Lobato (2004), the other soils are classified with high levels of OC, except for Ferralsol which is suitable.

All Leptsol and Regosol soil samples had OC content above 40 g kg^{-1}, values considered high (SOUSA; LOBATO, 2004). However, no sample exceeded the established limit of 80 g kg^{-1} of OC in the TFSA fraction to be considered organic soil; therefore, all of the sampled soils are mineral soils (SANTOS *et al.*, 2018).

The highest levels of OC are associated with the abundant deposition of plant material on the soil, a thick layer of litter, especially in soils from the Midwest region of BHI, under denser vegetation types, Submontane Semideciduous Seasonal Forest, Montana, and Semideciduous Seasonal Forest Cerradão. In the extreme West and Center to the East of the BHI, there are Cerrado phytophysiognomies in a restricted sense (Cerrado Denso, Typical Cerrado, Cerrado Ralo, and Cerrado Rupestre) and soils with lower levels of OC.

In addition to vegetation diversity, the lithology and climate present in BHI also influence OC levels in the soil (YANG *et al.*, 2020). Regarding lithology, it was found that the soils of igneous origin had the highest levels of OC compared to sedimentary soils. This can be attributed to the higher levels of clay present in these soils, as this favors the aggregation and stabilization of OC in the soil.

In sedimentary soils that are almost always sandy, the leaching processes are more intense than in clay soils. Also, high acidity can reduce microbial activity and consequently affect the decomposition of SOM (NOGUEIRA *et al.*, 2019). These conditions favor less OC content and consequently less SOM-dependent nutrients (especially P) in the natural system.

In general, there was a predominance of a shallow concentration of P in the soils of BHI. On average, the lowest levels of P were found in the soils Petroplinthic Plinthosol, Planosol, and Argiluvic Plinthosol, which can be justified by the high levels of Fe and Al and low pH values found in these soils. The relationship between these and other variables involved in the fixation of P in the soil matrix is widely reported in studies that analyze the maximum P adsorption capacity in the soil. In this sense, several studies have demonstrated a relationship between the adsorption of P in the soil matrix and the content of clay, pH, OM, aluminum oxide, and iron oxide (BENÍCIO *et al.*, 2017; MALUF *et al.*, 2018; ALOVISI *et al.*, 2020). Corrêa *et al.* (2011) reported higher P adsorption in more acidic soils with higher exchangeable aluminum values, potential acidity, and clay concentration.

In general, the more acidic soils with higher ΔpH values showed lower P content. This is consistent with the chemical behavior of this element which is immobilized because of precipitation as insoluble aluminum phosphate or in aluminum and mineral oxide clays at pH <5 (NDUWUMUREMYI, 2013). On the other hand, higher values of ΔpH mean more positive charges on the soil and, therefore, higher adsorption of anions such as phosphate, corroborating with the lower levels of P in the less electronegative soils.

The original contents of elements essential to plants, such as Fe, Mn, Cu, and Zn, depend on the composition of the source material on the pedogenetic processes and the degree of development of the soils (BIONDI *et al.*, 2011). These are highly evolved soils such as Oxisols and Argisols and also low weathering soils such as Leptsol and Regosol (SANTOS *et al.*, 2018). Thus, the levels of micronutrients found in these soils vary widely.

According to the classification adopted by Sousa and Lobato (2004), the average levels of Fe in BHI soils are presented in the following order: high for Argiluvic Plinthosol, Petroplinthic Plinthosol, Gleysol, Ferralsol, Acrisol, Regosol, and Planosol soils, medium for Nitisol and Arenosol, and low to Leptsol. In terms of average values, the Gleysol and Planosol soils showed the highest concentrations with 1088 and 1033 mg dm^3, respectively. The highest levels of Fe in these soils, among other factors, are associated with the occurrence of chemical redox reactions which are favored by the hydromorphism conditions characteristic of these soils (BIONDI *et al.*, 2011). Another justification is the low pH value found in these soils, which increases the availability of Fe for soil solution (PAYE *et al.*, 2010).

The average levels of Mn varied from 6.4 to 256.4 mg dm^3 for Petroplinthic Plinthosol and Regosol, respectively. According to the classification adopted by Sousa and Lobato (2004), the average Mn levels are high for all soil classes. In decreasing order, the Mn contents in the BHI soils presented the following sequence: Regosol > Leptsol > Nitisol > Ferralsol > Arenosol > Gleysol > Acrisol > Planosol > Argiluvic Plinthosol > Petroplinthic Plinthosol. The highest levels of Mn, especially in Regosol, Leptsol, Nitisol and Ferralsol soils, are associated with the presence of mafic rocks in the lithology of the region and with the presence of basaltic rocks (CPRM, 2006) rich in ferromagnesian minerals, a condition that allows greater concentration and maintenance of Mn in the soil system (BIONDI *et al.*, 2011). Althaus *et al.* (2018) and Gonçalves *et al.* (2013) reported higher levels of Mn in soils of basaltic origin when compared to other lithologies.

Except for Argiluvic Plinthosol and Arenosol soils, all the others presented high levels of Cu (SOUSA; LOBATO, 2004). On average, the highest Cu content was found in Nitisol (6.9 mg dm^3). This is a typical result for soils originating from underlying rocks, especially mafic rocks, which are naturally more abundant in microelements (PAYE *et al.*, 2010). The lower Cu content (0.41 mg dm^3) in the Arenosol soil of the present study corroborates the study by Hugen *et al.* (2013) who found lower levels of Cu in sedimentary lithologies compared to basaltic.

Among micronutrients, Zn is reported to be one of the most limiting factors for plant development as it expresses low levels in the natural soils of the Cerrado (FAQUIN, 2005; OLIVEIRA *et al.*, 2017). However, not all soils under Cerrado have low Zn levels. For example, of the ten soil classes sampled in BHI, on average, five had levels considered to be high, i.e., Gleysol, Ferralsol, Acrisol, Leptsol, and Regosol (SOUSA and LOBATO, 2004). On the other hand, Argiluvic Plinthosol, Petroplinthic Plinthosol, and Planosol soils showed shallow levels with an average of 0.07, 0.17, and 0.6 mg dm^3, respectively.

3.1 PRINCIPAL COMPONENT ANALYSIS (PCA)

The first two principal components showed high eigenvalues (12.91 PC1 and 2.53 PC2) which explained 81.34% of the data variance, 67.99% PC1 and 13.35% PC2 (Figure 2).

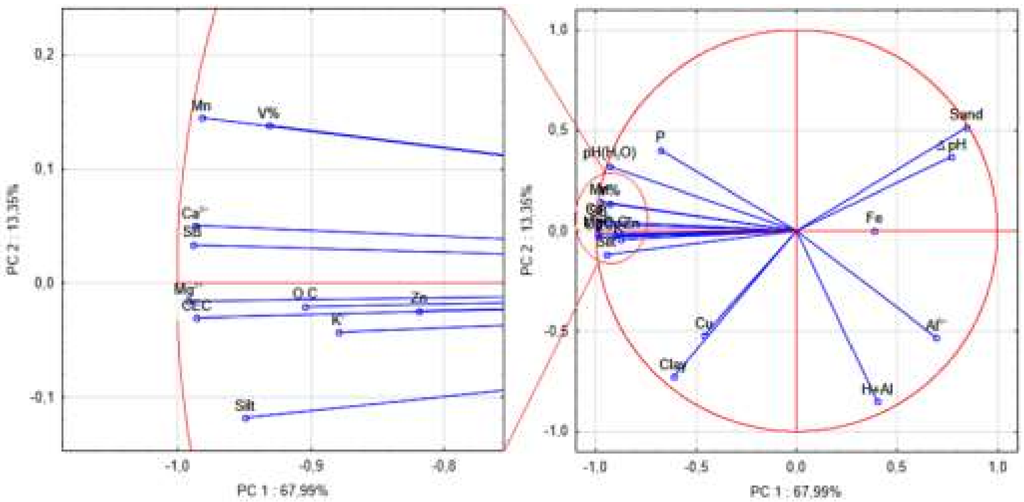

Figure 2. Ordering diagram obtained by PCA showing Projection of the variables on the factor-plane PC1 × PC2. H+Al = Potential acidity; CEC = cation exchange capacity (SB + H + Al^{3+}); SB = sum of bases (Ca^{2+}, g^{2+}, K^+); V% = base saturation (SB/CEC) × 100; OC = organic carbon; PC = Principal Component.

Based on the correlations of the variables with the PCs, it was possible to show the most significant variables for each factor. Thus, the PC1 positive X-axis highlights the variables: sand, ΔpH, and Al^{3+}. Still on PC1, however, the negative X-axis highlights the variables Mg^{2+}, Ca^{2+}, K^+, CEC, SB, V%, OC, silt, pH (H_2O), Mn, Zn, and P. For PC2 there were high negative factor loads for the variables H + Al^{3+} and clay, highlighting these variables as the most explanatory of PC2.

The cloud of variables superimposed on the negative X-axis shows strong positive correlations between these variables (Figure 2). The smaller the angles formed about the abscissa axis, for vectors of similar lengths, the higher the correlations between the variables are (NEISSE; HONGYU, 2016). On the other hand, vectors in the opposite direction in the plane of the variables indicate an inverse relationship.

The variables Mg^{2+}, Ca^{2+}, K^{+}, CEC, SB, V%, OC, silt, pH (H_2O), Mn, Zn, and P showed similar contributions to the negative axis of PC1, and they are highly correlated with each other. This was verified by variables that have a more extended vector and were closer to the negative axis of PC1. This component can be denominated high fertility and is represented by the soils Leptsol and Regosol. Despite the chemical fertility, these soils have some physical limitations, such as a small depth that prevents excellent water retention and infiltration, that do not allow conditions for proper root development; this mainly limits the soils to perennial crops (GONÇALVES *et al.*, 2013).

The lithology added to the low acidity and high OC contents favored the discrimination of the Leptsol and Regosol soils from the other analyzed soils. Concerning the source material, the high levels of silt compared to the other analyzed soils shows low pedogenetic development and the possible presence of primary minerals abundant in basic cations, as found in these soils (SANTOS *et al.*, 2018). As a result, there is an absence of exchangeable acidity, and the pH values are close to neutral. The OC eigenvector associated with the bases and fertility indices indicates that the OC content is an essential nutrient for these soils. Associations between OC and soil fertility variables are widely reported in the literature (BOCARDI *et al.*, 2018; COSTA *et al.*, 2019; CASSOL *et al.*, 2020).

The correlation of the micronutrients Mn and Zn to the negative X-axis is associated with a higher contents of Mn and OC in the Leptsol and Regosol soils. Similar associations were observed in soils of the same origin in western Paraná (CASSOL *et al.*, 2020). It should be noted that Zn is more strongly associated with OC, vectors with more acute angles, compared to Mn. This fact can be justified by the high degree of selectivity of humic substances for specific metals. This is one of the reasons why some micronutrients have a greater affinity with OC compared to others. This affinity also reflects the correlations between micronutrients and OC (KYZIOL *et al.*, 2006).

The association between Mn and Zn may be associated with the geochemical affinity of these elements in the soil. For example, the physical characteristics of Mn oxides and hydroxides, such as small crystals and consequently large surface areas, have important geochemical implications, especially in the retention of other metallic elements, including Zn (MINEROPAR, 2005).

In the third quadrant, the clay variable showed a positive correlation with Cu, vectors in the same direction as the plane. The association of clay with Cu can be explained by the strong adsorption of Cu on the surface of the colloids of the clay fraction, indicating that a large part of this element is concentrated in clay minerals and Fe oxides that make up this fraction (BIONDI *et al.*, 2011).

The clay fraction (and silt, to a lesser extent) contains the main mineral adsorbents in the soil, such as Fe and Al oxides, and therefore has a considerable influence on the distribution of metallic elements such as Cu in the soil profile (KABATA-PENDIAS, 2011; ALTHAUS *et al.*, 2018). Vendrame *et al.* (2007) reported that the oxides of Fe and the pH explain the availability of Cu in Ferralsols in the Cerrado. However, in soil samples from BHI, the pH effect was less evident than in clay. Associations between clay and Cu have been reported in other studies (ALTHAUS *et al.*, 2018; CASSOL *et al.*, 2020).

The fourth quadrant retained the variables associated with soil acidity, Al^{3+} and H + Al^{3+}. These variables are correlated with each other and inversely correlated with soil fertility and pH indices. The low pH condition (pH H_2O <5.6) found in most samples favors the appearance of free Al forms in the soil solution (KOCHIAN *et al.*, 2015). Once in the soil solution, Al^{3+} has a preference in the soil exchange complex. Due to its higher valence and smaller hydrated ionic radius, it occurs linked to the negative charges on the surfaces of clay minerals and soil organic matter (SPARKS, 2003; COSTA *et al.*, 2019). Consequently, the relative concentration Al^{3+} tends to increase due to the leaching of other bases, since the environment where it is found is characterized by high rainfall.

The sand vector associated with ΔpH in the first quadrant shows a positive correlation between these variables, indicating that in BHI soils, negative charges decrease with increasing sand content. A low amount of negative charges is unfavorable for soil fertility because it causes less retention of essential cations and, therefore, less CEC. Consequently, the capacity to retain possible contaminants, especially heavy metals, tends to be low (COSTA, 2015). Increasing OM levels is an excellent alternative to increase negative soil loads (BALDOTTO; VELLOSO, 2014).

The ten soil classes found in BHI formed four small groups in the projection diagram of the soil classes, which were named A, B, C, and D (Figure 3). In the first quadrant, soil classes Arenosol, Planosol, Acrisol, and Argiluvic Plinthosol are observed. These soils were distinguished from the others, especially in terms of sand and ΔpH contents. This is consistent with the sedimentary lithology that is responsible for the sandy texture and less electronegative soils.

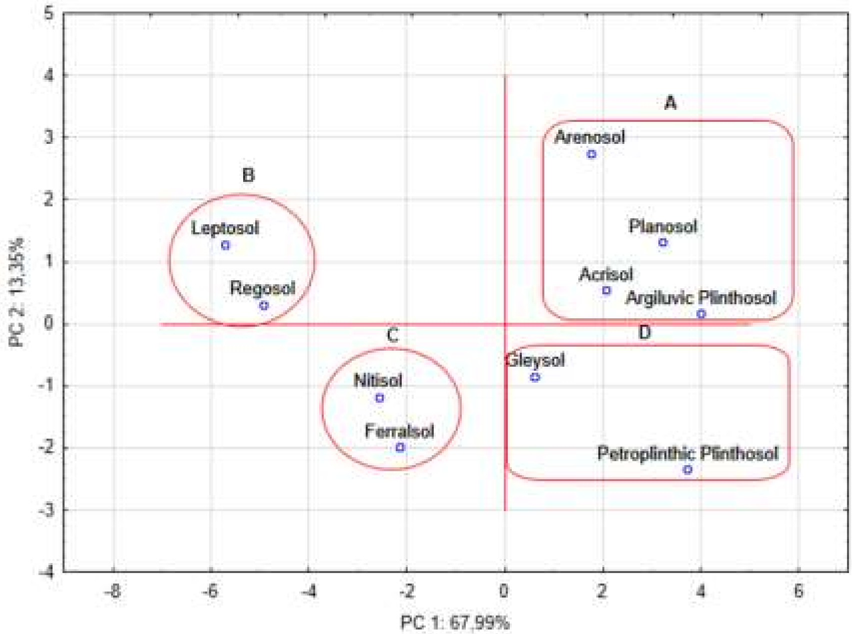

Figure 3. Projection diagram of the soil classes as a function of their variables on the factor-plane PC1 × PC2. PC = Principal Component.

Although natural ecosystems present harmonious integrations between vegetation cover and soil attributes, resulting from essential processes of nutrient cycling and accumulation and decomposition of SOM Cardoso *et al.* (2011), the discriminating characteristics of the soils in the first quadrant reveal that they are in environments that are sensitive to the degradation of their natural quality. Therefore, they must be preserved whenever possible or managed with mechanical and vegetative practices that aim to improve soil quality and control erosion (DONAGEMMA *et al.*, 2016).

For environments with these characteristics, the evolution of Brazilian agriculture has shown new production models by incorporating the principles of conservationist agriculture, such as the no-tillage system, livestock crop integration, forest livestock crop integration, and agroforestry systems, which enable the sustainable use of land and allow efficient use of available local resources (BALBINO *et al.*, 2011; DONAGEMMA *et al.*, 2016; FERNANDES *et al.*, 2019).

The soils present in group B were distinguished from the others by their high natural fertility which is evidenced by the high saturation by bases, OC, and silt. The proximity between these two classes of soils is coherent and can be justified by the similarity of the source material and low pedogenetic evolution (SANTOS *et al.*, 2018).

In the third quadrant, the proximity between the soil classes Ferralsol and Nitisol occurred due to the clay content. Thus, it is assumed that the clay content is the primary variable responsible for discriminating Ferralsol and Nitisol soils from the others. This finding is consistent with the aphanitic granulometry of the source material of these soils

(CPRM, 2006). Other factors, such as the advanced weathering stage of Ferralsol soils and to a lesser extent of Nitisol Santos *et al.* (2018), contributed to the separation of these soils from the Neossolos group which is also under basaltic lithology.

The variables Al^{3+} and $H + Al^{3+}$ were responsible for the discrimination of the Petroplinthic Plinthosol and Gleysol soils from the others. However, the Gleysol soil is positioned close to the origin which suggests the influence of the Fe variable, as this soil presented Fe content five times higher than the Petroplinthic Plinthosol soil. The Fe levels in Planosol soils are similar to those found in Gleysol soils. However, the texture of these soils is different and this is the primary justification for separating these two classes of soils.

The application of ACP proved effective in reducing the size of the data since it reduced the 19 variables to two main components and grouped the ten soil classes into four small groups with dominant characteristics. In general, the soils of group D can be called soils of low natural fertility, in contrast to the soils of group B which showed high natural fertility. The soils present in group C showed desirable characteristics for agricultural exploitation, while the soils in group A were sensitive to degradation of their natural quality due to the high levels of sand and the low amount of negative loads; these need attention and care with proper land-use practices.

4 CONCLUSIONS

The parameters of soil fertility, expressed by the values of V%, SB, and CEC, demonstrated the high natural fertility of the soils Leptsol, Regosol, and Nitisol, and low natural fertility of the soils Argiluvic Plinthosol, Petroplinthic Plinthosol, and Planosol.

The sandy soils showed lower levels of OC and negative surface loads, which shows less capacity to retain cations essential to plant nutrition and less retention of environmental contaminants if any.

Regarding the textural fragility of the soils of BHI, it was possible to verify the high sensitivity of the soil to erosion and susceptibility to the contamination of groundwater or infiltrated water.

The data shown in research can fill the gaps of knowledge and/or reference information for the soils of BHI and its surroundings.

This information is useful, both for adapting conservation practices of agricultural soils that are more susceptible to erosive processes, as well as for environmental control and monitoring bodies and/or studies of area recovery and maintenance of soil fertility.

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