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ORIGINAL ARTICLE

Toposequences of soils developed on basaltic rocks: physicochemical attributes

Topossequências de solos desenvolvidos sobre rochas basálticas: atributos físicos e químicos

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ABSTRACT: Soils are formed in a structural continuity of layers along a toposequence. The objective of this study was to characterize the chemical and physical properties of soils in two topossequences derived from basaltic rocks in the state of Parana, with different slopes, aiming to identify the relationships between their attributes, relief, and parent material. We studied two toposequences, with differentiated reliefs, developed on parent material consisting of vesicular and aphanitic basaltic rocks. The following physical properties were evaluated: texture, bulk density, particle density, macroporosity, microporosity, aggregate stability in water, degree of dispersion, and degree of flocculation. Chemical analyses were carried out for determination of Ca, Mg, K, P, Al, H+Al, C, and ΔpH. The results were submitted to principal component analysis (PCA) to obtain the correlation circles. In the circle of eigenvectors, in the slope with soft undulating relief, most vectors are located in the negative sector, both for physical and chemical properties with the latter being closer together. Also, the relationships between Ca, Mg, K and aluminum are evident. This way, chemical and physical properties are listed in the two slopes, and the level of correlation depends on the existing interactions. In addition, young soils with different characteristics and behavior were different from the others. Effective depth and structure were limiting attributes, but other favorable attributes were observed. The relationships among the attributes are differentiated along the slopes, and are influenced by the physicochemical nature of the geological substrate.

RESUMO: *Os solos são formados em uma continuidade estrutural das camadas ao longo da topossequência. Assim, o objetivo deste trabalho foi caracterizar atributos químicos e físicos de solos em duas topossequências, originados de rochas basálticas, no Estado do Paraná, com declividades distintas, buscando identificar as relações entre seus atributos, o relevo e o material de origem. Foram estudadas duas topossequências, desenvolvidas sobre material de origem composto por basalto vesicular e basalto afanítico, sendo o relevo de ambas diferenciado. Foram avaliados os seguintes parâmetros: a textura; a densidade do solo e de partículas; a porosidade total; a macroporosidade; a microporosidade; a estabilidade de agregados em água; o grau de dispersão e o grau de floculação, além de análises químicas para determinação de Ca, Mg, K, P, Al, H+Al, C e ΔpH. Os resultados foram submetidos à análise de componentes principais (ACP) para obtenção dos círculos de correlações. No círculo de autovetores, na vertente com relevo suave ondulado, a maioria dos vetores se encontra no setor negativo, evidenciando-se tanto as relações físicas quanto as químicas, porém as últimas estão próximas entre si. Também as relações entre Ca, Mg, K e alumínio se apresentam evidentes. Assim, os atributos químicos e físicos estão relacionados nas duas vertentes, sendo o nível de correlação dependente das interações existentes. Também os solos jovens e com características diferenciadas apresentaram comportamento diferente dos demais. Profundidade efetiva e estrutura foram os atributos limitantes, apesar de serem observados outros atributos favoráveis. As relações entre os atributos são diferenciadas ao longo das vertentes, sendo influenciadas pela natureza química e física do substrato geológico.*

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1 Introduction

Soils are formed as associated units in a structural continuity of layers along a toposequence. Superficial soils contribute with water, solutes and colluvial materials to the formation of lower soil layers (LAVELLE; SPAIN, 2001). Therefore, from the crest to the watercourse of a hillslope, the conditions of soil formation are differentiated. Specific local conditions such as temperature, altitude, and water availability may restrict the development of profile (RASMUSSEN; DAHLGREN; SOUTHARD, 2010).

Because of the influence of processes of addition, alteration, loss, and translocation which act in the soil, profile becomes vertically differentiated in horizons or layers, reflecting the dominance of one process over the others. Horizons or layers may differ in color, structure, consistency, texture, mineralogy, and amount of organic matter and nutrients. Although there is predominance of highly weathered soils in tropical environments, less developed soils with moderate morphological, chemical and mineralogical evolution can occur, as in temperate environments (VIDAL-TORRADO et al., 2006).

The variability of mineralogical, chemical and physical soil attributes in specific layers or in a horizon is also influenced by the chemical and physical nature of the geological substrate (TERAMOTO; LEPSCH; VIDAL-TORRADO, 2001). Drainage is another important aspect to be noted in the study of soil attributes. In higher and flat areas, drainage is usually good and occurs in one way (vertically), originating deeper soils with simpler morphology and mineralogy; in lower areas, drainage is smaller and saturation spots may occur, leading to formation of more heterogeneous soils with altered organic matter dynamics (LAVELLE; SPAIN, 2001).

According to Balieiro et al. (2008), relief has a strong influence on soil chemical properties. Carbon stocks along a toposequence are associated with landscape position, clay content, and particle density. Moreover, small variations in relief forms condition differentiated variability in chemical properties (SOUZA et al., 2004). For the use of soil and fertilization, recognition of the spatial variability of fertility provides important information for the rationalization of agricultural inputs (MONTEZANO; CORAZZA; MURAOKA, 2006); thereby, knowing the chemical and physical characteristics of a toposequence is extremely important for the use and management of soils.

Among the physical properties of soil, aggregation plays an important role because it ensures good resistance to erosion, preventing dispersal in soil and consequent surface erosion (MARSHLL; HOLMES, 1979). Soil flocculation is associated with aggregation, because soil reaction to its content of charges is associated with dispersion, and these are physicochemical factors. Soil dispersion is also dependent on its mineralogy and electrochemical potential (ALBUQUERQUE et al., 2002; TAVARES FILHO; BARBOSA; RIBON, 2010). To understand this type of alteration, parameters such as ΔpH (pH KCl – pH H_2O) and the point of zero charge (PZC) are used in these studies, which show the importance of these interactions of charges in soil flocculation, and consequently in its structure.

Non-cultivated soils present better aggregation conditions compared with cultivated soils (BARRETO et al., 2009). Soil tillage and the traffic of machines and agricultural implements modify the size of aggregates and the macropore/micropore ratio, with an increase in the proportion of small pores compared with large pores (SOARES; ESPINDOLA; CASTRO, 2005; ALBUQUERQUE et al., 2005; MACHADO et al., 2010) and implications in water infiltration into the soil and greater water retention by the soil and therefore, greater difficulty in release of water to plants, decreased gas exchange, and greater difficulty for root development. The objective of this study was to characterize the chemical and physical properties of soils in two topossequences derived from basaltic rocks in the state of Parana, with different slopes, aiming to identify the relationships between their attributes, relief, and parent material.

2 Materials and Methods

The study was carried out in an area of 1,055 ha located between the municipalities of Bela Vista do Paraiso and Alvorada do Sul in the state of Parana, Brazil (22°55'S; 51°13'O) (Figure 1). Geologically, the area is located in the Serra Geral Formation, in a sandstone-basalt transition. In the higher parts, it is possible to observe, along with the predominant material of tholeiitic basalt in its aphanitic form, traces of sedimentary material of overlying sandstone rocks from the Caiua Group. In the lower parts, vesicular and massive basaltic rocks are predominant (Table 1). The climate is Cfa, according to Köppen classification, with a trend of rainfall concentration in the summer months, but with no clearly defined dry season. Average annual precipitation is 1,588 mm.

Two toposequences were described with transects 2,000 m apart from each other. The two topossequences present the same direction (northeast-southwest), but with variation in the parent material along the lythosequence (Table 1). They were named undulating relief slope (URS) and soft undulating relief slope (SRS) (Figure 1).

The transect used for the study of the URS is 1,800 m long; it presents average elevation of 505 m with undulating relief in the lower segment (the first 700 m) and soft undulating relief in the upper segment (the next 1100 m). The current use of soil consists of intermediate stand forest regeneration in the lower segment and pasture and annual crops in the rest of the area. The transect used for the study of the SRS is 2,000 m long; it presents average elevation of 497 m with average declivity of 6% and soft undulating relief throughout. The current use of soil consists of pasture and annual crops (Table 1, Figure 1).

Initially, soil sampling was conducted along the two toposequences in order to identify and demarcate the main variations regarding soil classes. Observations aiming to identify the topography and parent material of the study areas were also performed. After that, a trench was opened in each relief segment or each representative site of the soil unit in the previously identified geomorphological unit.

The profiles, 1.0 x 0.8 x 2.0 m (length, width and depth, respectively), were opened and described according to Santos et al. (2005). Deformed and undeformed samples were

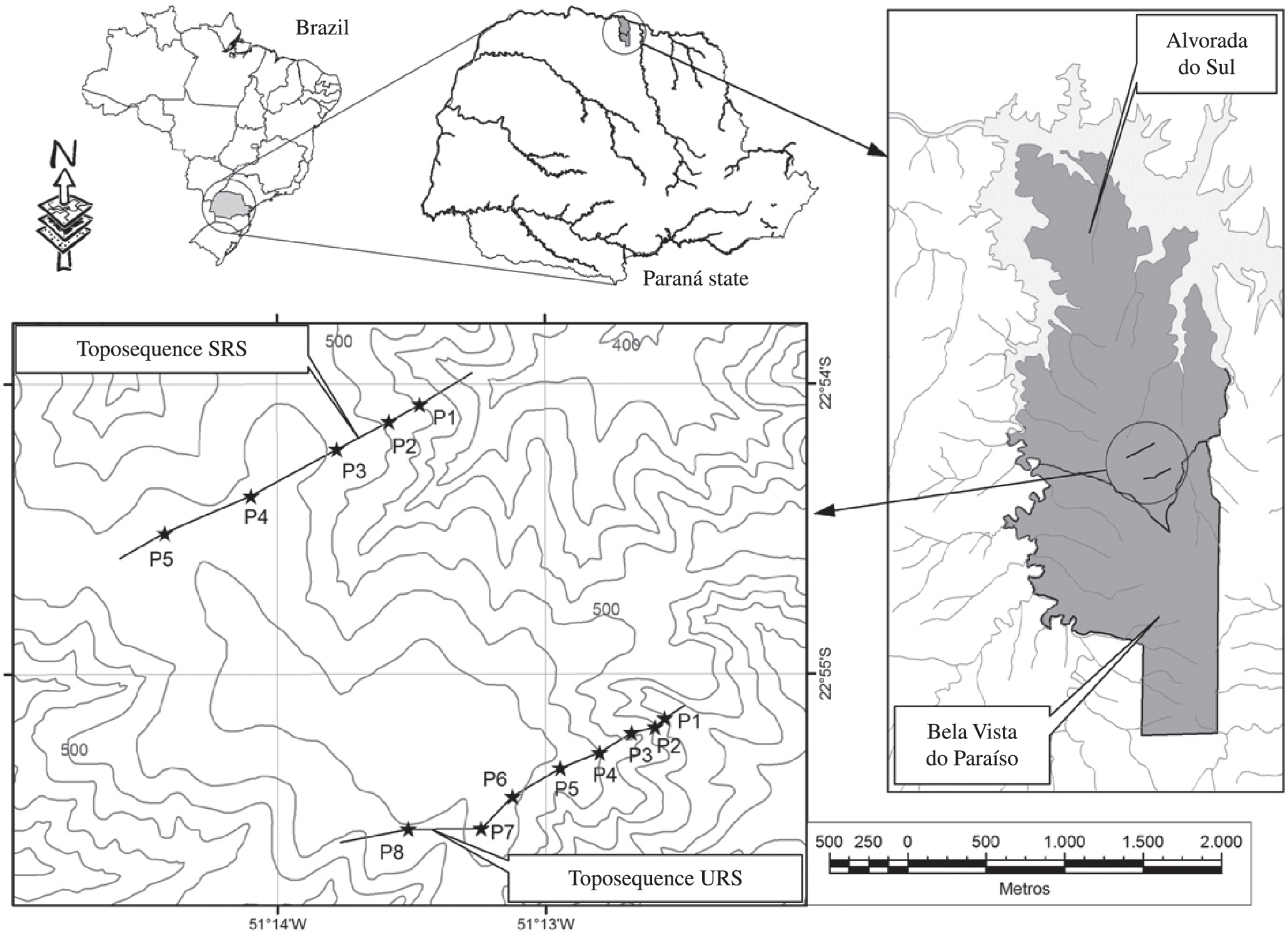

Figure 1. Maps of Brazil and the state of Parana, highlighting the location of the study area, local topography, topossequences, and positions of the profiles.

Table 1. Declivity, elevation, use, vegetation, and parent material of the profiles analyzed in the toposequences: undulating relief slope (URS) and soft undulating relief slope (SRS).

Profile	Declivity (%)	Elevation (m)	Use	Vegetation	Parent material
			URS		
P1[(1)]	2	463	permanent preservation	intermediate stand forest	vesicular basalt and colluvial material
P2	20	470	permanent preservation	intermediate stand forest	vesicular basalt
P3	4	492	agriculture	annual crops	vesicular basalt
P4	15	513	agriculture	annual crops	vesicular basalt
P5	4	532	agriculture	annual crops	aphanitic basalt
P6	5	542	agriculture	annual crops	aphanitic basalt and sandstone
P7	2	548	agriculture	annual crops	aphanitic basalt and sandstone
P8	5	538	agriculture	annual crops	aphanitic basalt and sandstone
			SRS		
P1	10	472	livestock	sown pasture	aphanitic basalt
P2	8	488	agriculture	annual crops	aphanitic basalt
P3	6	513	agriculture	annual crops	aphanitic basalt
P4	5	525	agriculture	annual crops	aphanitic basalt and sandstone
P5	2	530	agriculture	annual crops	aphanitic basalt and sandstone

(1)Sequence direction from the lower segment to the upper segment.

collected on all horizons and sub-horizons for performance of physicochemical analyses.

The following physical properties were determined: soil porosity (total pore volume – TPV) determined by the expression: TPV = 1-(Db/Dp); macroporosity (Ma); microporosity (Mi); bulk density (Db); particle density (Dp); and texture. Aggregate stability was carried out according to Kemper and Chepil (1965) with a set of 8, 2, 1, 0.5 and 0.25 mm sieves, with determination of weighted mean diameter (WMD), geometric mean diameter (GMD), and aggregate stability index (ASI) according to Castro Filho, Muzilli and Podanosch (1998). Physical properties and their determination methods were as follows: Ma - tension table method at 0.6 Mpa; Db - volumetric ring method; Dp - volumetric flask method; and texture - pipette method with slow agitation (CLASSEN, 1997).

Also, clay dispersed in water (CDW) was quantified by the pipette method, but without chemical dispersant, and subsequently the degree of dispersion (DD) and flocculation (DF) were calculated. No samples of the Gley and CA horizons were analyzed in the determination of aggregate stability and bulk density, because of the massive structure and the high moisture content of the Gley horizon and the large amount of coarse material in the CA horizon.

Chemical characterization was performed according to the methods described by Classen (1997): pH in H_2O, $CaCl_2$ and KCl 1 mol L^{-1}; Ca^{2+}; Mg^{2+}; K^+; Al^{3+}; P; organic carbon; and H+Al. Based on these analyses, the sum of bases (SB), base saturation (V%), cation exchange capacity ($CEC_{pH7.0}$), and ΔpH (the difference between pH in KCl 1 mol L^{-1} and pH in water) were calculated.

Principal component analysis (PCA) was carried out with the use of the ADE-4 program (THIOULOUSE et al., 1997), aiming to correlate the physicochemical attributes of the soil with the parent material and relief of the toposequences. PCA reduces data dimensions and, according to Gomes et al. (2004), it is a suitable tool for the comparison and understanding of differences and similarities in several pedological environments.

3 Results and Discussion

According to the Brazilian System of Soil Classification - – SiBCS (SANTOS et al., 2006), the profiles studied in the URS toposequence were classified as Haplic Gleysol, Regolithic Neosol, and Red Nitosol. In the SRS toposequence, all profiles were classified as Red Nitosol, with profile number one (P1) classified as Eutroferric Red Nitosol and the others as Latossolic Eutroferric Red Nitosol (Figure 2).

The concept of diagnostic horizon, for instance, B-latossolic, is used for taxonomy construction, adopted to create, identify and distinguish classes (taxa) of soils; while the concept of pedogenic horizons, for example, Bw, is more genetic in nature and the wording of definitions is ordinarily more qualitative. Therefore, pedogenic horizons are not always diagnostic of soil classes. In this study, with the purpose of characterizing chemical and physical properties of soils in two topossequences, we chose to use diagnostic horizons according to Santos et al. (2006). To facilitate representation in the figures and tables, B-latossolic horizons were designated as Bw, B-nitic horizons as Bt, B-incipient as Bi, and Gley as Bg.

The morphological description of diagnostic horizons identified the presence of B-latossolic horizons in the area, always under the B-nitic ones, and this way the soils were classified in the first category level of the SiBCS as Nitosols. Although the presence of B-latossolic horizons is observed, there is predominance of B-nitic horizons, which can be explained by the landscape position, type of elevation, length, and ramp forms of the evaluated profiles, as also noted by Bognola et al. (2011). Latossolic eutroferric or latossolic dystroferric Red Nitosols are commonly found in soils of basalt origin and, in most cases, are located downstream to Red Latosols in the landscape, in the lower third of the slope with soft-undulating to undulating relief, similar to the toposequences assessed in this study.

The other diagnostic horizons found in the area of undulating relief were Gley and B-incipient, with the consequent occurrence of Gleysols and Cambisols, respectively. P2 and P3 profiles presented only the A horizon inferior to 20 cm, with regolith layer followed by rock in the first 80 cm in P2, and greater depth in P3, with regolith depth greater than 100 cm. These soils were classified as Regolithic Neosols.

In the SRS toposequence and in the upper profiles of the URS toposequence, Nitosols with a few variations can be observed, but in the lower segment of the URS, there is variability on the pedological cover, which indicates differentiated environments for the formation of these soils.

Except for the A horizons of profiles 6 and 7 in the URS toposequence, all horizons assessed presented clay contents greater than 600 g kg^{-1}, and are therefore classified as clayey to very clayey (SANTOS et al., 2006). The lower concentration of clay in the surface horizons of profiles 6 and 7 may be explained by the influence of sandstone in the upper segment of the toposequence, which provides sandier material to the surface horizons of the profiles located in that area.

All soils presented increased clay in depth, except Gleysol. However, the increases observed are not sufficient to classify B-typical textural or argiluvic character (Table 1). No trend of increase or decrease of clay was observed between the B-latossolic and B-nitic horizons (Table 2).

It was possible to verify that the B-latossolic horizons presented low dispersion indices (Table 1). This occurs mainly owing to the physicochemical condition of these horizons, which can be proven by the values of ΔpH, always close to zero, differently from the horizons with higher degrees of dispersion, where ΔpHs were more negative. There is a strongly marked microstructure, characteristic of B-latossolic horizons, formed by the physicochemical and mineralogical condition of these soils, and when these soils are physically disperse, they quickly return to their flocculated state. As a rule, most B-nitic horizons present high degrees of flocculation. In profile 1 of the SRS toposequence, the B-nitic horizons showed high degrees of dispersion, probably because this site is located in transition zones of the toposequence between different types of soils, and also in areas of alterations, therefore presenting quite complex physicochemical behavior (COOPER; VIDAL-TORRADO; GRIMALDI, 2010).

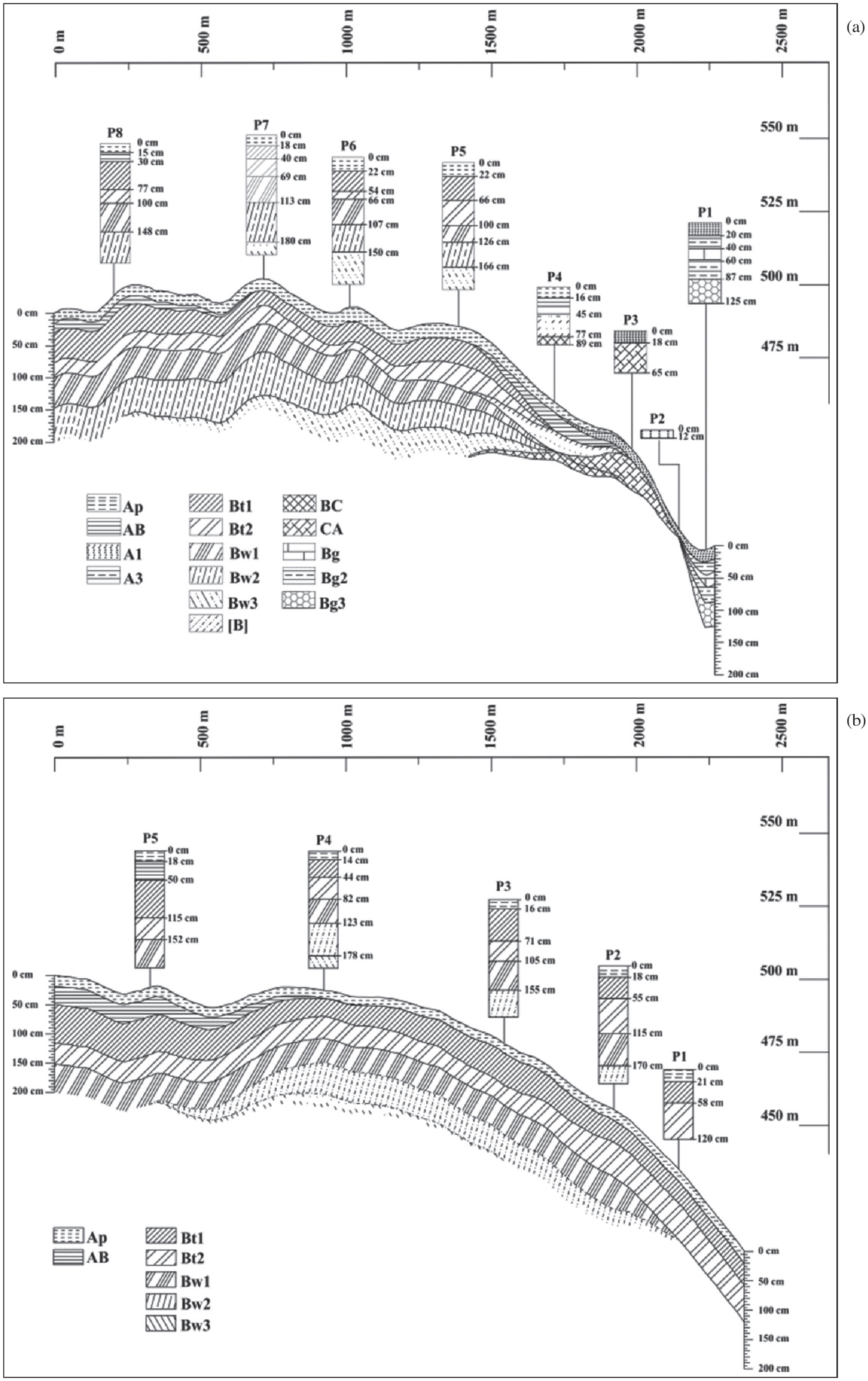

Figure 2. Schematic design of URS toposequence (A) and SRS toposequence (B) showing the location of profiles and the lateral distribution of horizons. [B] represents the incipient B horizon.

Table 2. Physical properties of soil horizons in the URS and SRS topossequences.

Profile	Soil	Horizon	Clay	Silt	Sand	DD	DF	Db	Dp	Δ pH	WMD	GMD	ASI	Ma	Mi	TPV
				g kg^{-1}		%								%		
URS																
P1	Haplic Gleysol	A1	830	120	50	86.75	13.25	1.18	2.56	–1.00	–	–	–	19.63	36.15	55.78
		A3	870	100	30	96.5	3.5	1.04	2.58	–1.28	–	–	–	16.72	41.28	58.01
		Bg1	740	130	130	100	0	1.18	2.47	–1.94	–	–	–	7.45	41.43	48.88
		Bg2	705	100	195	100	0	1.11	2.56	–1.63	–	–	–	10.78	46.26	57.04
		Bg3	800	110	90	98.75	1.25	1.19	2.6	–1.75	–	–	–	9.44	49.40	58.84
P2	Regolithic Neosol Regolithic Neosol	A1	600	170	230	83	17	–	–	–1.05	3.44	1.39	76.68	–	–	–
P3	Regolithic Neosol	Ap	600	145	255	100	0	–	–	–1.26	2.8	7.71	83.07	–	–	–
		CA[(1)]	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P4	Haplic Cambisol	Ap	700	120	180	87.85	12.15	1.11	2.77	–0.93	1.74	2.9	78.27	22.43	36.58	59.01
		A3	765	190	45	89.54	10.46	1.43	2.74	–0.59	5.15	6.96	91.77	20.05	38.28	58.33
		Bi	810	80	110	88.5	11.5	1.57	2.66	–0.82	3.59	2.26	92.33	24.67	32.60	57.27
		BC	885	80	35	84.18	15.82	1.49	2.74	–0.9	3.3	8.12	90.82	22.15	31.86	54.01
P5	Red Nitosol	Ap	720	165	115	87.5	13.5	1.39	2.77	–0.8	3.28	5.47	72.98	24.53	30.80	55.33
		Bt1	820	65	115	0	100	1.45	2.77	–0.61	2.5	1.15	81.8	18.45	29.87	48.32
		Bt2	790	75	135	0	100	1.42	2.89	–0.64	3.74	2.87	85.7	12.39	32.67	45.05
		Bw1	875	60	65	3	97	1.35	2.81	–0.8	3.41	5.9	75.88	14.45	36.72	51.17
		Bw2	795	135	70	0	100	1.16	2.81	–0.29	3.96	1.13	69.01	27.60	22.06	49.66
		Bw3	800	45	155	0	100	1.19	2.7	–0.24	3.25	3.41	66.5	29.84	21.13	50.97
P6	Red Nitosol	Ap	520	125	355	93	7	–	2.82	–0.54	1.57	7.05	46.48	–	–	–
		Bt1	660	110	230	92	8	1.48	2.7	–0.47	3.8	9.59	87.55	14.77	31.53	46.29
		Bt2	810	60	130	2	98	1.45	2.74	–0.75	3.43	3.1	86.76	17.03	33.97	51.00
		Bt3	760	55	160	0	100	1.21	2.78	–0.81	2.77	7.66	73.33	21.26	25.44	46.70
		Bw1	755	60	185	0	100	1.17	2.9	–0.27	3.25	1.45	42.35	33.37	25.59	58.96
		Bw2	705	125	170	1.42	98.58	1.12	2.81	–0.47	1.96	1.39	55.84	31.15	22.99	54.13
P7	Red Nitosol	Ap	555	50	395	97.30	2.7	1.35	2.81	–0.51	2.53	1.21	67.77	13.28	30.80	44.08
		Bt1	670	100	230	92.54	7.46	1.43	2.94	–0.47	3.55	1.45	88.69	13.68	38.84	52.52
		Bt2	765	85	150	3.27	96.73	1.38	2.85	–0.46	3.20	2.85	75.30	16.14	36.98	53.12
		Bw1	710	90	200	0	100	1.31	2.89	–0.27	3.05	1.42	65.53	17.01	32.59	49.60
		Bw2	695	75	230	0.5	95.5	1.29	2.94	–0.24	0.97	1.53	42.41	25.07	31.00	56.08
		Bw3	690	75	235	0	100	1.26	3.12	–0.17	1.11	7.93	41.21	30.45	27.05	57.50
P8	Red Nitosol	Ap	730	30	240	89.04	10.96	1.19	3.07	–0.87	5.88	2.41	84.03	28.13	24.11	52.24
		Ba	685	85	230	97.81	2.19	1.53	3.07	–0.86	7.18	5.34	89.9	15.30	31.29	46.59
		Bt1	775	135	90	0	100	1.55	2.98	–0.23	5.42	3.02	89.31	9.01	42.11	51.12
		Bt2	795	70	135	0	100	1.47	2.98	–0.24	2.85	4.6	76.01	11.84	38.98	50.82
		Bw1	710	60	230	0	100	1.22	3.17	–0.29	0.63	1.78	44.43	15.33	39.92	55.25
		Bw2	795	40	165	0	100	1.12	2.94	–0.24	0.75	4.75	39.07	20.22	41.92	62.15
SRS																
P1	Red Nitosol	Ap	805	120	75	91.92	8.08	1.28	3.12	–0.49	7.77	3.95	92.22	18.45	37.67	56.12
		Bt1	910	60	30	91.21	8.79	1.46	3.39	–0.77	4.27	4.18	94.08	22.12	30.22	52.34
		Bt2	905	50	45	44.2	55.8	1.50	2.98	–0.83	3.02	1.98	89.95	18.72	40.16	58.88
P2	Red Nitosol	Ap	820	120	60	94.51	5.49	1.26	3.27	–0.53	3.47	5.09	66.36	16.05	36.93	52.98
		Bt1	915	50	35	0	100	1.34	3.17	–0.35	4.63	5.86	87.15	9.52	44.68	54.20
		Bt2	910	50	40	0.55	99.45	1.28	3.03	–0.71	4.71	4.31	77.2	10.29	39.35	49.64
		Bw1	925	40	35	0	100	1.27	3.22	–0.25	4.27	7.9	60.76	27.57	34.65	62.22
		Bw2	915	50	35	0	100	1.31	3.33	–0.1	1.73	1.62	47.33	25.12	28.87	53.99
P3	Red Nitosol	Ap	790	110	100	99.4	0.6	1.35	2.98	–0.77	3.17	6.29	77.42	22.05	36.15	58.20
		Bt1	870	80	50	0	100	1.47	2.98	0.53	6.01	1.59	92.14	10.07	45.57	55.64
		Bt2	865	110	25	0	100	1.29	3.03	–0.36	3.61	6.91	76.63	13.58	40.85	54.43
		Bw1	860	85	55	0	100	1.31	3.03	–0.66	1.03	0.21	46.48	23.66	31.98	55.65
		Bw2	865	110	25	0	100	1.10	3.12	–0.69	1.01	0.68	45.31	25.08	37.16	62.24

[(1)] Not analyzed.

Table 2. Continued...

Profile	Soil	Horizon	Clay	Silt	Sand	DD	DF	Db	Dp	Δ pH	WMD	GMD	ASI	Ma	Mi	TPV
			g kg^{-1}			%							%			
P4	Red Nitosol	Ap	755	120	125	96	4	1.15	3.03	–0.61	5.01	1.25	83.96	28.46	28.36	56.82
		Bt1	840	65	95	1.2	98.8	1.40	2.81	–0.45	4.62	6.09	89.39	8.81	42.41	51.23
		Bt2	890	70	40	0	100	1.31	2.94	–0.22	5.36	2.55	83.4	9.66	42.42	52.08
		Bw1	890	75	35	0	100	1.21	2.7	–0.07	7.43	2.02	83.43	15.22	38.91	54.14
		Bw2	880	85	35	0	100	1.11	2.98	0.02	2.02	3.08	54.82	22.71	35.72	58.43
		Bw3	880	70	50	0	100	1.11	3.03	0.07	2.61	2.38	56.64	23.22	34.55	57.77
P5	Red Nitosol	Ap	810	50	140	9.4	90.6	1.35	2.89	–0.5	6.24	7.14	87.42	13.28	30.80	44.08
		Ab	795	55	150	100	0	1.16	2.98	–0.98	3.66	4.22	83.2	25.48	28.13	53.61
		Bt1	800	50	150	6.8	93.2	1.41	2.81	–0.32	8.06	2.33	94.98	13.99	30.87	44.87
		Bt2	790	35	175	0	100	1.44	3.07	–0.22	4.81	1.61	84.73	11.70	34.88	46.58
		Bw1	880	35	85	0	100	1.19	3.07	–0.1	1.84	2.64	58.42	16.07	33.88	49.95

(1) Not analyzed.

In the B-latossolic horizons, it was possible to observe that most ΔpH values were higher than -0.5. The low values of ΔpH found in the Bw horizons may be attributed to the advanced stage of weathering of these horizons compared with the other diagnostic horizons described in the area, because they usually present simpler mineralogy formed by great amounts of clay (1:1) and oxides of Fe and Al (GHIDIN et al., 2006). Centurion et al. (1995) found values of ΔpH between –0.3 and –0.4 with 100% flocculation in B-latossolic horizons.

The B-latossolic horizons presented lower ASI than the other horizons of the same profile and showed a small amount of aggregates larger than 2 mm (Table 2). Predominance of smaller size aggregates is expected for B-latossolic horizons, because it is one of the morphologic characteristics used in their classification (SANTOS et al., 2006). According to Ferreira, Fernandes and Curi (1999), gibbsite and hematite present in large quantities in B-latossolic horizons derived from basalt, interfere in the face-to-face adjustment of phyllosilicate minerals such as kaolinite, which favors the formation of smaller structures with spherical shape. Although these horizons presented lower ASI, some smaller-than-0.25 mm aggregates pass through the last sieve and are not considered in the index calculation. This way, the B-latossolic horizons, despite presenting relatively low ASI, are highly structured, which can be confirmed by the high values of degree of flocculation (Table 2).

Regarding the B-nitic horizons, it was possible to verify predominance of 2-8 mm-class aggregates and high ASI, because these soils are structured and present much larger aggregates than the B-latossolic horizons. Also, the structures present waxiness caused by the filling of porosity by illuviation coatings (COOPER; VIDAL TORRADO, 2005).

In the A horizons, we observed predominance of 2-8 mm-size aggregates, with high values of geometric mean diameter (GMD) and clay dispersed in water (CDW). On the other hand, the B horizon showed higher values of weighted mean diameter (WMD) and degree of flocculation (DF). For Pedrotti et al. (2003), within the same soil profile, the A horizon presented higher values of GMD and CDW. According to the authors, the differences between horizons A and B are associated with the contents of organic matter, as noted. The contents of basic elements (Ca, Mg and K) and, consequently, of SB and V% verified in the URS toposequence were higher for Gleysol, Neosol and Cambisol – less developed soils (Table 3). This fact can be associated with the wealth of parent material, as it is observed that these soils are slightly weathered, with less intense processes of soil loss. Furthermore, the parent material observed at these sites is distinct from the others, and it is a form of vesicular basalt (Table 2). Such vesicles, filled with Ca carbonate and Mg carbonate, provide large amounts of these elements when weathered, increasing their levels in the soil formed. Although minerals which are typical of basaltic rocks contribute with bases when they are weathered, as mentioned by Escosteguy and Klamt (1998), the basalt formation found in these sites provides more effective contribution. Such fact explains the differentiation in the indices of bases between the profiles.

In the lower segment of the URS toposequence, of more undulating relief, it is possible to observe less developed soils, with physicochemical properties different from those of soils in its upper segment and from the soils of the SRS toposequence. Therefore, a correlation between the soil positions in the toposequence can be verified, as well as the influence of variations of parent material. Chemically, the soils developed at the lower segment of the URS toposequence showed high levels of macronutrients P, Ca, Mg and K, and low levels of Al. In addition, they were susceptible to erosion at the points of steep slope. Conversely, the soil in the upper segment of the toposequence (Red Nitosols), presented smaller CEC and contents of bases and higher levels of Al, but lower susceptibility to erosion due to the softer declivity.

The soils located in the flatter areas (the upper segments of the URS and SRS toposequences) are deeper and better developed. Besides the type of rock, with smaller concentration of Ca and Mg and the greater weathering and leaching, these soils are also undergoing a process of loss of cations and residual increase of Al contents. In some profiles (P3, P4 and P5; SRS), such fact can moderately reflect on soil fertility.

Principal components analysis (PCA), performed on the data of physicochemical attributes of the soils in the URS toposequence, showed that the two first axes explained 57% of the total variability of data: 40% (A1) and 17% (A2) (Figure 3).

Table 3. Chemical properties of soil horizons in the URS and SRS topossequences.

Profile	Horizon	pH	C	P	Al	Al+H	Ca	Mg	K	$CEC_{pH7..0}$	SB	V
		$CaCl_2$	g dm^{-3}	mgdm^{-3}			$cmol_c dm^{-3}$					%
URS												
P1	A1	4.91	37.63	2.82	0.04	5.76	26.0	9.5	1.19	42.45	36.69	86.43
	A3	4.02	13.94	1.76	0.09	9.00	19.7	11.2	0.21	40.11	31.11	77.56
	Bg1	4.18	16.73	0.96	0.75	4.28	27.5	18.6	0.31	50.69	46.41	91.56
	Bg2	5.02	6.97	2.20	0.04	4.61	21.6	13.5	0.21	39.92	35.31	88.45
	Bg3	5.75	9.76	2.07	0.03	3.68	28.9	13.6	0.19	46.37	42.69	92.06
P2	A1	5.83	87.81	37.52	0.00	3.42	24.6	8.7	1.43	38.15	34.73	91.04
P3	Ap	5.68	51.57	53.03	0.00	3.68	38.4	9.9	0.78	52.76	49.08	93.02
	CA	5.75	12.54	87.59	0.02	2.95	43.4	8.8	0.12	55.27	52.32	94.66
P4	Ap	5.69	64.11	33.30	0.00	3.97	21.9	2.9	0.57	29.34	25.37	86.47
	A3	5.85	25.09	2.20	0.00	3.18	19.6	2.2	0.43	25.41	22.23	87.48
	Bi	6.01	18.12	2.01	0.00	2.74	17.3	2.7	0.37	23.11	20.37	88.14
	BC	6.31	13.94	3.68	0.00	2.54	16.5	2.1	0.31	21.45	18.91	88.16
P5	Ap	4.81	27.88	5.98	0.07	5.35	7.9	3.1	0.19	16.54	11.19	67.66
	*Bt1	5.15	2.79	2.07	0.03	3.18	8.0	1.9	0.01	13.09	9.91	75.70
	Bt2	5.18	5.58	2.69	0.00	3.42	8.3	1.2	0.00	12.92	9.50	73.53
	Bw1	5.17	29.27	3.37	0.03	2.95	6.6	1.5	0.03	11.08	8.13	73.37
	Bw2	4.99	2.79	2.57	0.09	3.42	6.4	1.7	0.05	11.57	8.15	70.44
	Bw3	5.40	16.73	2.94	0.00	2.95	6.2	1.9	0.05	11.10	8.15	73.42
P6	Ap	5.85	26.48	12.06	0.01	2.95	7.9	10.7	0.72	22.28	19.33	86.76
	Bt1	5.76	11.70	1.01	0.28	3.68	6.9	1.3	0.39	12.27	8.59	70.00
	Bt2	6.04	8.36	3.31	0.04	2.95	6.6	1.3	0.03	10.88	7.93	72.88
	Bt3	6.18	13.94	4.24	0.08	2.36	6.6	1.1	0.02	10.08	7.72	76.58
	Bw1	6.18	8.36	3.31	0.01	2.19	6.2	0.7	0.02	9.11	6.92	75.96
	Bw2	6.23	5.58	2.51	0.00	2.19	4.4	1.9	0.00	8.49	6.30	74.20
P7	Ap	5.14	29.27	8.09	0.06	3.97	5.9	2.7	0.36	12.93	8.96	69.29
	Bt1	5.70	9.76	2.20	0.05	2.74	6.9	1.8	0.05	11.49	8.75	76.15
	Bt2	5.70	6.97	2.63	0.03	2.74	5.7	1.5	0.00	9.95	7.21	72.46
	Bw1	5.20	8.36	2.38	0.02	2.95	5.5	1.0	0.00	9.45	6.50	68.78
	Bw2	5.48	5.58	1.70	0.02	2.74	4.4	1.2	0.05	8.39	5.65	67.34
	Bw3	5.17	2.79	3.25	0.03	2.74	2.9	2.0	0.01	7.65	4.91	64.17
P8	Ap	5.58	27.88	4.62	0.04	3.42	7.2	2.1	0.75	13.47	10.05	74.60
	BA	5.4	19.51	2.94	0.00	3.18	7.2	1.0	0.56	11.94	8.76	73.37
	Bt1	5.66	8.36	2.88	0.00	2.74	6.0	1.5	0.26	10.50	7.76	73.92
	Bt2	5.40	2.79	2.51	0.00	3.18	4.6	2.7	0.19	10.67	7.49	70.20
	Bw1	4.50	4.18	1.82	0.13	3.42	4.0	0.1	0.11	7.63	4.21	55.18
	Bw2	4.55	4.18	2.07	0.25	3.42	1.5	1.6	0.08	6.60	3.18	48.18
SRS												
P1	Ap	5.72	36.24	7.10	0.00	3.68	20.1	3.6	0.93	28.31	24.63	87.00
	Bt1	5.68	16.73	3.37	0.00	2.95	12.9	2.8	0.50	19.15	16.20	84.60
	Bt2	5.54	8.36	5.55	0.06	2.95	9.5	2.4	0.52	15.37	12.42	80.81
P2	Ap	5.08	33.45	8.59	0.17	4.96	8.4	4.4	0.26	18.03	13.07	72.50
	Bt1	5.13	12.54	3.62	0.14	3.97	9.0	1.5	0.04	14.51	10.54	72.64
	Bt2	5.44	8.36	3.62	0.00	3.18	8.1	1.7	0.03	13.01	9.83	75.55
	Bw1	5.15	4.18	2.26	0.07	3.42	6.2	1.5	0.01	11.13	7.71	69.27
	Bw2	4.46	2.79	1.64	0.34	4.28	2.8	2.6	0.01	9.69	5.41	55.82

Table 3. Continued...

Profile	Horizon	pH	C	P	Al	Al+H	Ca	Mg	K	$CEC_{pH7..0}$	SB	V
		$CaCl_2$	g dm^{-3}	mgdm^{-3}			$cmol_c dm^{-3}$					%
P3	Ap	4.95	27.30	11.57	0.24	6.21	5.1	2.5	0.68	14.50	8.29	57.16
	Bt1	4.26	9.10	0.82	1.39	8.36	3.3	1.8	0.11	13.57	5.21	38.40
	Bt2	4.85	6.50	1.32	0.17	4.96	4.6	1.3	0.02	10.88	5.92	54.41
	Bw1	4.35	5.20	0.39	0.97	6.69	2.4	1.5	0.02	10.61	3.92	36.94
	Bw2	4.25	5.20	0.45	1.24	7.20	1.1	0.8	0.04	9.15	1.95	21.30
P4	Ap	4.48	27.30	11.39	0.18	6.69	6.0	2.8	0.72	16.21	9.52	58.72
	Bt1	4.98	13.00	0.26	0.12	5.35	5.5	1.5	0.34	12.69	7.34	57.83
	Bt2	4.87	6.50	1.63	0.25	4.61	4.2	1.8	0.03	10.64	6.03	56.67
	Bw1	4.92	5.20	1.75	0.11	4.28	3.9	2.1	0.08	10.36	6.08	58.69
	Bw2	5.01	3.90	0.32	0.05	3.97	2.9	2.0	0.02	8.89	4.92	55.34
	Bw3	5.08	2.60	0.01	0.45	3.97	1.9	2.7	0.00	8.57	4.60	53.66
P5	Ap	5.25	14.30	18.28	0.21	4.61	4.3	1.6	0.72	11.23	6.62	58.93
	AB	5.01	18.20	5.98	0.15	4.96	3.4	1.5	0.61	10.47	5.51	52.64
	Bt1	4.63	16.90	1.07	0.55	5.76	2.6	1.5	0.25	10.11	4.35	43.05
	Bt2	4.62	13.00	1.44	0.38	5.76	2.6	1.0	0.26	9.62	3.86	40.15
	Bw1	4.51	9.10	0.32	0.33	4.96	1.4	0.9	0.34	7.60	2.64	34.71

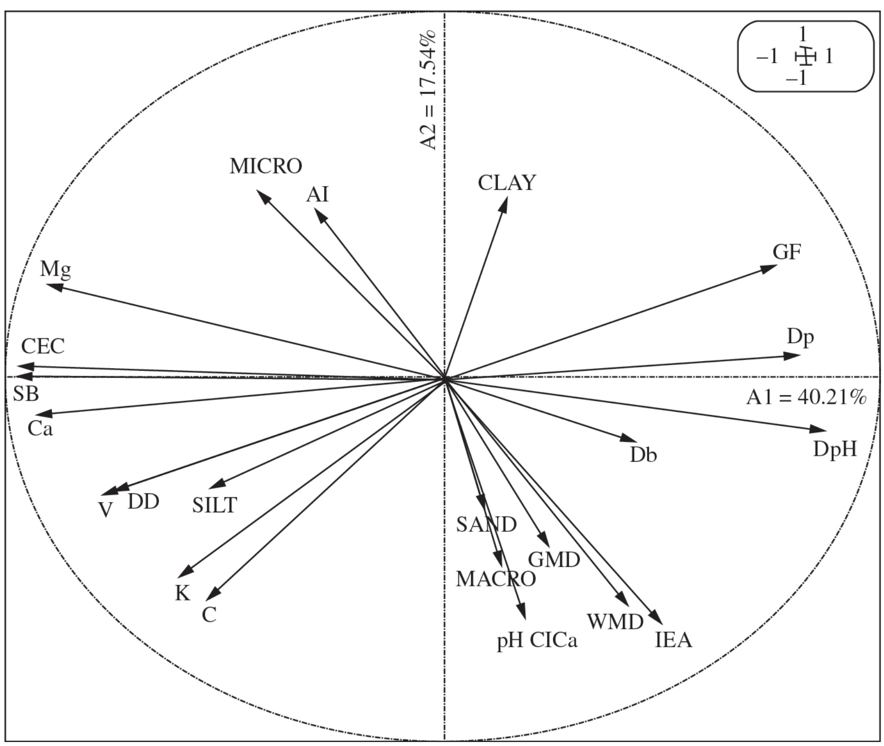

Figure 3. Circle of correlations among physicochemical attributes evaluated in the URS toposequence in the municipality of Alvorada do Sul, Paraná state.

Except for Al and pH $CaCl_2$, all chemical properties evaluated influenced the construction of axis 1 (A1), making quadrants negative. No clear trend was verified concerning the physical properties, because DD, DF, Db, and Dp influenced the construction of A1, while sand, clay, GMD, WMD, ASI, Ma, and Mi influenced axis 2 (A2). The eigenvectors of sand and Ma, on axis 2, are negative, while the eigenvectors of clay and Mi are positive. Therefore, a strong correlation between the texture of soils and the size of pores can be established, that is - texture and porosity are positively correlated.

The attributes related to aggregate stability (WMD, GMD and ASI) presented eigenvectors very close to each other, which indicates that these three parameters are reflecting the stability of soil aggregation in a single direction, with no inconsistency among them.

Some attributes presented known correlations, such as DD opposite to DF and Al opposite to pH $CaCl_2$. The eigenvectors of DF and ΔpH are close to each other and in the same direction; therefore, it can be inferred that the higher the ΔpH, the higher the degree of flocculation, following the principle

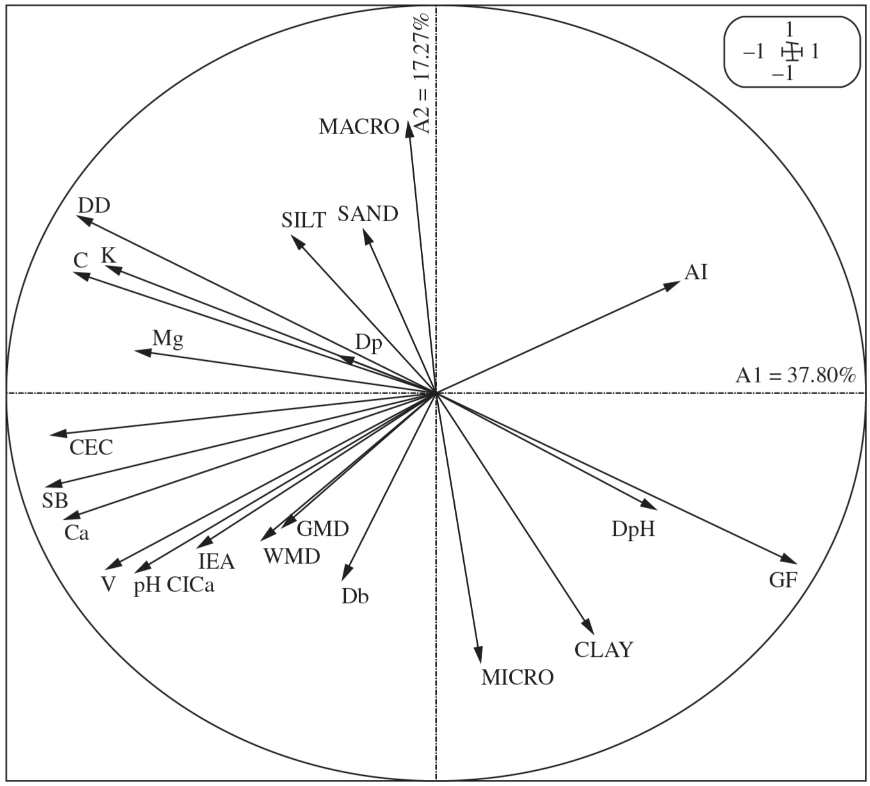

Figure 4. Circle of correlations among physicochemical attributes evaluated in the URS toposequence.

that clay tends to flocculate when pH approaches the PZC. In the soils of the URS toposequence, ΔpH, influenced by the results of profiles of less developed soils (P1-P4), was not representative in the understanding of soil aggregation and flocculation.

The eigenvectors with variables related to soil aggregation are not in the same axis, which also corroborates the condition of the relationships of aggregation in the soils of this toposequence be distinct, especially in its lower segment.

In the variables derived from the chemical analysis of the soil, separation between basic and acid elements was observed in the graph; however, not as clearly as noted by Eberhardt et al. (2008), who assessed correlations among chemical and mineralogical attributes of soils of the Cerrado region. The bases (Ca^{2+}, Mg^{2+} and K^{+}), V%, and SB influenced the construction of axis 1, while Al and pH $CaCl_2$ influence the formation of axis 2. The eigenvectors of DD and V% follow the same direction; therefore, it can be inferred that the higher the base saturation in the soil, the higher the degree of dispersion of clay. This fact can be explained by the greater relative presence of bases in the CEC to the detriment of aluminum and, as bases have smaller radius of hydration than Al, colloids are deviated favoring dispersion.

In the URS toposequence, different soils were observed regarding characteristics and evolution (Figure 3). This may have influenced the relationships between attributes or the representativeness among them. In the circle of correlations with the values of the URS toposequence (Figure 4), it was possible to note that most eigenvectors were concentrated in the negative sector of axis 2, with only the Al vector remaining in the first quadrant.

In the variables derived from the chemical analysis of the soil, as expected, a separation between basic and acid elements was observed in the graph, as described by Eberhardt et al., (2008).

Regarding the physical properties, there is similarity between soil flocculation and ΔpH, and opposition to DD; such relations were also observed by Albuquerque et al. (2000) in a study of soil reaction and dispersion.

The attributes related to soil aggregation participate in the construction of axis 2, which confirms the relationship between all parameters assessed and aggregation. The properties related to aggregate stability (WMD, GMD and ASI) presented eigenvectors very close to each other, which indicates that these three parameters are reflecting the stability of soil aggregation in a single direction, with no inconsistency among them. This fact was also observed in the URS toposequence; the eigenvectors of clay and Mi follow the same direction, as well as the eigenvectors of sand and Ma.

It is possible to observe that the eigenvector of Al is close to and in the same direction of the eigenvector of DF, as expected, because this element is involved in soil aggregation. Nevertheless, the eigenvector of K^{+} follows the opposite direction of the eigenvector of DF, because monovalent ions tend to disperse the soil.

As the profiles of the SRS toposequence are more developed and belong to the same class (Red Nitosol), the behavior of their attributes presented clearer correlations, unlike the profiles of the URS toposequence.

4 Conclusions

Parent material and position of profile in the toposequences influenced the physicochemical attributes of the soil as well as the correlations among them.

The mineralogical differentiations in the basalt influenced the physicochemical attributes of the soil, especially regarding aggregation and supply of mineral elements.

Interactions between the physicochemical attributes of the soil are more easily observed with PCA in the more developed and uniform soils.

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