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Souza Júnior, Valdomiro Severino; Bretas Bittar, Sheila Maria; Gomes dos Santos,
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Planosols Developed in Different Geoenvironmental Conditions in Northeastern Brazil

José Thales Pantaleão Ferreira⁽¹⁾, Mateus Rosas Ribeiro Filho⁽²⁾, Mateus Rosas Ribeiro^{†(3)}, Valdomiro Severino de Souza Júnior^{(2)*}, Sheila Maria Bretas Bittar⁽²⁾ and Robson Gomes dos Santos⁽²⁾

⁽¹⁾ Instituto Federal de Alagoas, *Campus* Piranhas, Piranhas, Alagoas, Brasil.

⁽²⁾ Universidade Federal Rural de Pernambuco, Departamento de Agronomia, Recife, Pernambuco, Brasil.

⁽³⁾ *In memoriam*. Universidade Federal Rural de Pernambuco, Departamento de Agronomia, Recife, Pernambuco, Brasil

ABSTRACT: The semiarid region of northeastern Brazil has a large area occupied by Planosols, where in the State of Pernambuco these soils are mainly used for livestock farming and subsistence crops. The knowledge on these soils is limited, which compromises the understanding on their behavior, potentialities and limitations. This study aimed to analyze morphological, chemical, physical and mineralogical attributes of Planosols developed under different geoenvironmental conditions. Morphological descriptions and chemical, physical and mineralogical analyses were performed in four profiles of Planosols along a rainfall gradient. An increase in rainfall allowed for an increase in the clay content in the Bt horizon and a reduction in ESP, EC, Na⁺, CEC, S, pH (water and KCl) and soil density. Horizons A and E were thicker in Planosols in more humid environments. The increase in ESP associated with the presence of expansive minerals (smectite and vermiculite) allowed the development of a prismatic structure in Haplic Planosols and a columnar structure in Natric Planosols. The mineralogical assembly is indicative of poorly weathered soils. The mineralogical assemblies of the silt and clay fractions were similar in the different geoenvironments, while higher contents of easily alterable minerals were observed in the composition of the sand fraction in environments with a drier climate.

Keywords: soil mineralogy, weathering, climate, semiarid.

*** Corresponding author:**

E-mail: valdomiro.souzajunior@ufrpe.br

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INTRODUCTION

Planosols occupy large areas in subtropical and temperate regions with alternating dry and humid seasons, for example in Latin America (Brazil, Paraguay and Argentina), Africa, Eastern United States, Southeast Asia (Bangladesh and Thailand) and Australia. Its total extent is estimated at about 130 million hectares, 40 % of which are found in Latin America (FAO, 2006). In Brazil, Planosols mainly occur in the state of Rio Grande do Sul, in approximately 27,763 km² (about 10 % of the State's surface) (Lemos et al., 1973) and in the northeast, where they are predominantly Natric and Haplic solodic (Northern Bahia to Ceará) (IBGE, 2007). In Pernambuco, Planosols encompass an area of 15,830 km² (16 % of the State's surface) (Araújo Filho et al., 2000).

These soils have been widely used in Pernambuco for extensive livestock farming, cotton, corn and bean in the regions of Agreste and Sertão, especially when they occur with thicker A and E horizons (Araújo Filho et al., 2000). The main limitations to the agricultural use of these soils are the lack of water in the dry period and a normally extremely hard and dense B horizon, which significantly limits crop development and water movement. The densification of the Bt horizon causes deficient drainage, higher mechanical resistance to root penetration and lower availability of water and nutrients to plants (Silva et al., 2002; Cunha et al., 2010). These aspects have direct implications on the agricultural management of these soils, because they increase the erosive potential with the possibility of surface runoff of the non-infiltrated water. Some studies have shown a reduction in hydraulic conductivity, macro and microporosity in Planosols with an increase in depth (Lima et al., 2006, 2008).

The large amount of 2:1 minerals in Planosols of semiarid regions, such as smectite and vermiculite, is associated with a dry climate, water deficiency and restricted drainage, which favor the process of bisialitization (Corrêa et al., 2003). Smectites are generally neoformed from solutions rich in Al, Si and bases, derived from the weathering of primary and secondary soil minerals, subjected to low to moderate leaching of silica (Borchardt, 1989).

The formation of the textural gradient in Planosols is still an issue to be elucidated. In general, it is attributed to the influence of transport and deposition of coarser material in surface, for having fragments of rocks and edgeless materials in the upper horizons. However, Parahyba et al. (2009, 2010), studying Planosols in the state of Pernambuco, concluded that these soils have an autochthonous origin, with little indication of reworking of materials at the surface, and that the remarkable textural contrast is formed by a combination of pedogenetic processes, such as clay eluviation-illuviation, in situ clay formation and selective clay loss in the surface horizon due to lateral movements through mechanical drag or dissolutions. Another widely cited hypothesis is the destruction of clay by ferrolysis in more superficial horizons (Brinkman, 1970), although van Ranst et al. (2011) question ferrolysis as the main process in the formation of Planosols.

Better management of soils, as well as the transfer of technology to different areas, is ensured when one has information on their genesis and classification, which require more detailed analyses of complete profiles. Since Planosols from semiarid regions have been little studied, it is necessary to search for information that provides a better understanding of their characteristics, differences and relationships, which can contribute to their sustainable use. Thus, this study aimed to analyze the morphological, chemical, physical and mineralogical attributes of Planosols developed under different geoenvironmental conditions in the state of Pernambuco, Brazil.

MATERIALS AND METHODS

Selection of soils and characterization of the studied areas

The study was conducted in the state of Pernambuco, Brazil, where four Planosol profiles were selected along a climatic gradient, in the municipalities of Timbaúba (Profile 1) (1,097.1 mm, 24.6 °C), Altinho (Profile 2) (633.2 mm, 23.1 °C), Arcoverde (Profile 3) (574.4 mm, 22.4 °C)

and Jataúba (Profile 4) (510 mm, 22.7 °C) (Costa et al., 2013; ITEP, 2015). The studied profiles have the following geographical coordinates: profile 1 – UTM 25M 0256193 mE and 9172982 mN; profile 2 – UTM 24L 0827309 mE and 9062144 mN; profile 3 – UTM 24L 0710092 mE and 9069986 mN and profile 4 – UTM 24M 0773102 mE and 9118436 mN. The studied locations were selected using soil maps of the state of Pernambuco (Jacomine et al., 1973; Araújo Filho et al., 2000; Embrapa, 2001) and soil maps of the Usina Central Olho d'Água, in the municipality of Timbaúba, by choosing various profiles in similar topographic conditions. At each site, a soil pit was dug for the description and collection of disturbed and undisturbed samples, following the method proposed by Santos et al. (2005). The soils were classified according to the Brazilian Soil Classification System – SiBCS (Santos et al., 2013).

Chemical and physical analyses

The chemical analyses of soil and saturation paste extracts were performed according to the methods of Claessen (1997) and consisted of: pH in water and in 1 mol L⁻¹ KCl, exchangeable Ca²⁺, Mg²⁺, K⁺, Na⁺, Al³⁺, potential acidity (H+Al), organic carbon (OC) and extractable P. Electrical conductivity (EC), pH, Na⁺ and K⁺ were determined in the saturation paste extracts. From these data, the following parameters were determined: cation exchange capacity (CEC), sum of bases (SB), base saturation (V), aluminum saturation (m) and exchangeable sodium percentage (ESP).

The physical analyses were performed according to the recommendations of Claessen (1997): granulometry of the fine earth fraction (coarse sand, fine sand, silt, total clay and clay dispersed in water), soil density, particle density and fractions larger than 2 mm, gravel (2-20 mm) and cobbles (20-200 mm). With the results, the degree of flocculation, total porosity and the silt/clay ratio were calculated. The textural differentiation index of the horizons (TDI_h) was obtained according to Baize (1988). In order to evaluate the occurrence of lithological discontinuity in the profile, the uniformity value (UV) was calculated according to Bortoluzzi et al. (2008), adapted from Schaetzl (1998).

Cluster analysis was performed using the program Statistica 7 (Statsoft, 2007) for the chemical attributes of the Bt horizon (pH in water, pH in KCl, Ca²⁺, Mg²⁺, Na⁺, K⁺, SB, Al³⁺, H+Al, CEC, OC and P) and of the saturation paste (pH, EC, Na⁺ and K⁺), and for physical attributes (total sand, coarse sand, fine sand, silt, clay, clay dispersed in water, degree of flocculation, silt/clay, fine sand/total sand, soil density, particle density, total porosity and gravel). Dendrograms of similarity were constructed by measuring the Euclidean distance and using the complete-linkage mode with standardized data.

Mineralogical analyses

Coarse and fine sand fractions were separated from silt and clay fractions through wet sieving. The silt and clay fractions were separated through sedimentation according to Stokes' Law.

The mineralogical composition of the clay fraction was determined through X ray diffractometry, after pre-treatment to remove carbonates, organic matter and Fe oxides using 1 mol L⁻¹ sodium acetate at pH 5.0, 30 % hydrogen peroxide and citrate-bicarbonate-dithionite, respectively (Jackson, 1975). Then, the clay powder was mounted on a metal support after light pressure was applied on the sample using rough paper, in such a way as to minimize the preferential orientation of the particles. The silt powder did not receive any treatment and followed the same mounting procedure.

Treatments with K, Mg and Mg-glycerol saturation and heating of K treatments at 350 and 550 °C were performed in order to identify and characterize minerals in the clay fraction, which were then analyzed through X ray diffractometry, in the form of oriented microaggregates (Jackson, 1975).

The diffractograms were obtained using a Shimadzu XRD-6000 diffractometer, operating at a tension of 40 kV and a current of 20 mA, with CuKα radiation and a graphite monochromator.

A scanning amplitude of 5-70° (2θ) and a recording speed of 2° 2θ min⁻¹ were used for clay and silt. For clay samples saturated with K at room temperature and heated at 350 and at 550 °C, the scanning amplitude was 3-35° (2θ) and the recording speed was 1.5° 2θ min⁻¹. In samples saturated with Mg and Mg-glycerol, the scanning amplitudes were 2-35° (2θ) and 2-15° (2θ), respectively, with a recording speed of 1° 2θ min⁻¹.

The criteria for the interpretation of diffractograms and the identification of minerals constituting silt and clay fractions were employed according to Grim (1968), Jackson (1975), Dixon and Weed (1977), Brown and Brindley (1980), Whitting and Allardice (1986) and Moore and Reynolds (1989).

The characterization of coarse and fine sand fractions was based on the usual methods described by Klein and Hurlbut Jr. (1999) and Leinz and Campos (1979), which involve homogenization and quartering of samples; utilization of physical (magnetism) and chemical (addition of 10 % HCl for carbonates determination and 10 % H₂O₂ for Mn oxide determination) microtests; and description and characterization of physical properties of minerals, such as luster, color, cleavage, habit, fracture etc., performed using a binocular loupe.

The semi-quantitative determination of the percentages of minerals constituting coarse and fine sand fractions was based on the method of visual estimation proposed by Terry and Chilingar (1955).

RESULTS AND DISCUSSION

Morphological attributes

The A horizon had a massive, moderately cohesive structure in all the studied Planosols, with sandy loam texture and color from brown to yellowish brown (Table 1). The E horizon had a texture ranging from loamy sand to sandy clay loam and lighter color, between brown and grayish brown.

In the A horizon, there was a reduction in the color value and chroma with an increase in rainfall rate; therefore, the soils become darker: profile 1 (10YR 3/3) > profile 2 (10YR 4/2) > profile 3 (10YR 4/3) > profile 4 (10YR 5/4) (Table 1). Barbosa et al. (2015), studying the effect of slope orientation on soil pedogenesis, observed that soils under drier conditions have higher value and chroma, and that the lower value and chroma in soils under humid conditions are related to the greater supply of organic matter to the soil and the more intense melanization process.

Profile 1, located in the Zona da Mata, in Northern Pernambuco state, a region with higher rainfall (1,097.1 mm), showed thicker A and E horizons, respectively 0.27 and 0.12 m (Figure 1). Profiles 2 and 3 were located in areas with higher water deficit, respectively, showing A horizons with similar thickness, around 0.20 m, and E horizons with only 0.06 m in P2 and 0.02 m in P3. Profile 4, in Jataúba, located in the most semiarid area compared with the others, had a poorly developed A horizon, only 0.15 m in thickness and an absent E horizon. These observations confirm the influence of rainfall on the development of soil profiles; as rainfall increases, there is better development of the A and E horizons in the studied soils (Figure 1).

Reduced development of the A and E horizons in areas with lower rainfall is explained by the lower rate of chemical weathering in the semiarid region, which is characterized by mean annual temperatures from 27 to 29 °C, rainfall between 800 and 400 mm yr⁻¹ and mean potential evapotranspiration of 2,000 mm yr⁻¹. In addition, rainfalls are irregular in time and space, concentrated in three to four months, with well-defined alternation of rainy periods with long, very dry periods (Ab'Saber, 1996; Silva et al., 2010). Additionally, there is lower supply of plant biomass to the soil in drier areas, which directly influences the melanization process, as observed by Barbosa et al. (2015) when studying the effect of slope orientation on the pedogenesis of soils in Ceará.

The absence of the E horizon in profile 4 may also be related to the presence of a sodic character and higher salinity compared with the other studied soils, which negatively influence the dispersion of clay particles (Tables 2 e 3), causing them to remain flocculated, which interferes with the process of lessivage.

Table 1. Description of morphological attributes studied in Planosols located in different geo-environmental conditions

Hor.	Depth	Color Munsell		Texture ⁽²⁾	Structure ⁽³⁾	Consistency ⁽⁴⁾	Transition ⁽⁵⁾
		Matriz	Freaked ⁽¹⁾				
m							
Perfil 1 - <i>Planossolo Háplico Eutrófico solódico</i> (Typic Albaqualf)							
Ap	0.00-0.27	10YR 3/3		FR-AR	Ma, MC	MD, F, LPL, LPE	CL and PL
E	0.27-0.39	10YR 5/3		FR-AR	Ma, MC	MD, F, LPL, LPe	ABR and OND
Btn	0.39-0.60	10YR 4/2	2,5YR 4/6 Ab, Peq, and Pro	ARG	Mo, Gr, Pr	ED, MFi, PL,Pe	ABR and OND
Perfil 2 - <i>Planossolo Háplico Eutrófico solódico</i> (Typic Albaqualf)							
A	0.00-0.19	10YR 4/2		FR-AR	Ma, MC	MD, ED, Fi, LPL, LPe	CL and PL
E	0.19-0.25	10YR 4/2		FR-ARG-AR	Fr, Pe, Me, BSub	MD, F, LPL, LPe	ABR and PL
Btn	0.25-0.55	10YR 4/3	7,5YR 4/4 Po, Peq, and Di	ARG	Mo, Me, MGr, Pr	ED, MFi, PL, Pe	GRA and PL
BCn	0.55-0.75	10YR 5/3		FR-ARG-AR	Ma, Co	ED, EFi, LPL, LPe	CL and OND
Perfil 3 - <i>Planossolo Nátrico Órtico típico</i> (Typic Natraqualf)							
A	0.00-0.20	10YR 4/3		FR-AR	Ma, MC,	LD, D, F, NP, LPe	ABR and PL
E	0.20-0.22	10YR 5/2		AR-FR	Ma, PCo, Du	NP, NPe	ABR and IR
Btn	0.22-0.48	10YR 5/3		FR-ARG-AR	Mo, Fo, Gr, MGr, Col	ED, EFi, PL, Pe	CL and PL
BCn	0.48-0.66	10YR 6/3		FR-ARG-AR	Ma, Co	ED, EFi, PL, Pe	GRA and PL
Perfil 4 - <i>Planossolo Nátrico Órtico salino</i> (Typic Natraqualf)							
Ap	0.00-0.15	10YR 5/4		FR-AR	Ma, MC	MD, Fi, LPL, LPe	ABR and OND
Btzn1	0.15-0.35	10YR 4/3		FR-ARG-AR	Fo, MGr, Col (Fr, Mo, Gr, MGr, BAng)	ED, EFi, LPL, LPe	CL and PL
Btzn2	0.35-0.55	10YR 6/3		FR-ARG-AR	Fo, MGr, Col (Mo, Gr, MGr, BAng)	ED, EFi, LPL, LPe	CL and PL

Hor.: horizon. ⁽¹⁾ Po: little; Di: diffuse; Ab: abundant; Peq: small; Pro: prominent; ⁽²⁾ AR-FR: loamy-sand; FR-AR: sandy-loam; FR-ARG-AR: sandy-clay-loam; ARG: clay; ⁽³⁾ Pe: small; Me: mean; Gr: big; MGr: very big; Fr: weak; Fo: strong; Du: hard; Ma: solid; Co: cohesive; PCo: little cohesive; Mo: moderate; MC: moderately cohesive; Pr: prismatic; BSub: subangular blocks; BAng: angular blocks; Col: columnar; ⁽⁴⁾ LD: lightly hard; D: hard; MD: very hard; ED: extremely hard; Fi: solid; MFi: very solid; EFi: extremely solid; F: friable; PL: plastic; LPL: slightly plastic; NP: aplastic; Pe: sticky; LPe: slightly tacky; NPe: not sticky; ⁽⁵⁾ CL: evident; PL: flat; ABR: abrupt; OND: corrugated; GRA: gradual; IR: not regular.

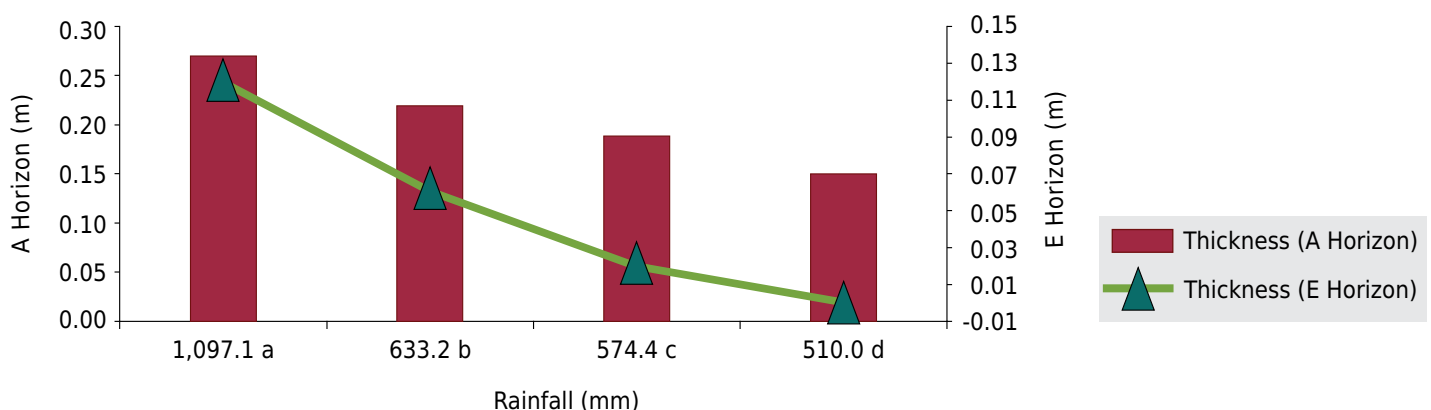


Figure 1. Relationship between rainfall and thickness of horizons A and E in the soils (a - profile 1; b - profile 2; c - profile 3; and d - profile 4).

Table 2. Physical analysis of four Planosols in different geo-environmental conditions in the State of Pernambuco

Hor.	Depth	Gravel	TFSA<2mm	TS	CS	FS	Silt	Clay	CDW	DF	Silt/clay	AF/AT	UV	TDIh	DP	Bd	TP
	m	%					g kg ⁻¹			%					Mg m ⁻³		%
<i>Planossolo Háplico Eutrófico solódico (Typic Albaqualf) (P1 – Timbaúba)</i>																	
Ap	0.00–0.27	1	99	608	225	383	203	189	110	42	1.08	0.63	0.12	1.12	2.70	1.53	43
E	0.27–0.39	1	99	619	250	369	212	169	90	47	1.26	0.60	0.27	1.00	2.77	1.77	36
Bt _n	0.39–0.60	4	96	298	152	146	133	569	270	53	0.23	0.49	–	3.37	2.60	1.98	24
<i>Planossolo Háplico Eutrófico solódico (Typic Albaqualf) (P2 – Altinho)</i>																	
A	0.00–0.19	6	94	638	344	294	174	189	130	31	0.92	0.46	0.21	1.00	2.89	1.78	38
E	0.19–0.25	7	93	645	360	285	119	236	130	45	0.50	0.44	0.08	1.25	2.71	–	–
Bt _n	0.25–0.55	2	98	392	260	132	139	469	410	13	0.30	0.34	0.24	2.48	2.59	1.81	30
BC _n	0.55–0.75	6	94	576	376	200	116	309	250	19	0.37	0.35	–	1.64	2.77	1.96	29
<i>Planossolo Nátrico Órtico típico (Typic Natraqualf) (P3 – Arcoverde)</i>																	
A	0.00–0.20	22	78	750	577	173	102	149	70	53	0.68	0.23	0.62	1.37	2.74	2.02	27
E	0.20–0.22	17	83	815	689	126	77	109	50	54	0.70	0.15	–0.50	1.00	2.66	1.73	35
Bt _n	0.22–0.48	6	94	525	423	101	147	329	270	18	0.45	0.19	–0.27	3.02	2.73	1.92	30
BC _n	0.48–0.66	18	82	491	361	130	160	349	290	17	0.46	0.26		3.21	2.65	1.92	27
<i>Planossolo Nátrico Sáfico típico (Typic Natraqualf) (P4 – Jataúba)</i>																	
Ap	0.00–0.15	12	88	648	198	451	203	149	90	40	1.36	0.70	2.26	1.00	2.77	1.92	31
Bt _n 1	0.15–0.35	4	96	557	343	214	134	309	250	19	0.44	0.38	–0.39	2.08	2.73	1.94	29
Bt _n 2	0.35–0.55	2	98	542	266	276	170	289	250	13	0.59	0.51	–	1.94	2.70	1.93	28

Hor.: horizon; TS: total sand; CS: coarse sand; FS: fine sand; CDW: clay dispersed in water; DF: degree of flocculation; Silt/clay: relation fine sand/total sand; UV: uniformity value; TDIh: the textural differentiation index of the horizon; Pd: soil particule density; Bd: soil bulk density; TP: total porosity.

Table 3. Chemical analysis of four Planosols in different geo-environmental conditions in the State of Pernambuco

Hor.	Depth	pH		Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	SB	Al ³⁺	H+Al	CEC	V	m	ESP	OC	P	Saturation paste			
		H ₂ O	KCl														pH	EC	Na ⁺	K ⁺
	m							cmol _c kg ⁻¹					%		dag kg ⁻¹	mg kg ⁻¹		dS m ⁻¹ 25 °C	– cmol _c kg ⁻¹ –	
<i>Planossolo Háplico Eutrófico solódico (Typic Albaqualf) (P1 – Timbaúba)</i>																				
Ap	0.00–0.27	5.9	4.6	3.5	2.6	0.2	0.3	6.6	0.1	3.0	9.6	68	2	2	1.0	0.8	6.9	0.5	0.1	0.0
E	0.27–0.39	5.6	4.1	1.8	2.1	0.1	0.1	4.1	0.4	2.0	6.0	67	9	2	0.8	0.5	7.1	0.4	0.1	0.0
Bt _n	0.39–0.60	5.6	4.0	5.6	8.1	1.2	0.1	15.0	0.6	2.9	17.9	84	4	7	0.4	0.0	6.9	0.4	0.2	0.0
<i>Planossolo Háplico Eutrófico solódico (Typic Albaqualf) (P2 – Altinho)</i>																				
A	0.00–0.19	5.9	4.6	3.6	3.3	0.2	0.2	7.3	0.3	2.6	9.8	73	4	2	1.2	0.1	5.9	0.4	0.2	0.0
E	0.19–0.25	6.1	4.2	3.2	4.7	0.8	0.1	8.8	0.5	2.9	11.6	75	5	7	0.7	0.0	7.5	0.3	0.3	0.0
Bt _n	0.25–0.55	6.2	4.1	6.8	15.2	2.3	0.1	24.4	0.4	2.1	26.5	92	2	9	0.7	0.0	7.1	0.5	0.4	0.0
BC _n	0.55–0.75	6.7	4.8	6.8	15.2	3.4	0.1	25.5	0.2	0.8	26.3	97	1	13	0.3	2.2	7.1	1.7	1.2	0.0
<i>Planossolo Nátrico Órtico típico (Typic Natraqualf) (P3 – Arcoverde)</i>																				
A	0.00–0.20	7.8	6.9	4.0	1.5	0.1	0.5	6.1	0.0	0.1	6.2	99	1	1	1.2	5.4	7.7	0.4	0.2	0.1
E	0.20–0.22	7.7	6.1	1.2	1.6	0.2	0.2	3.2	0.0	0.2	3.4	95	5	5	0.7	1.1	–	–	–	–
Bt _n	0.22–0.48	7.2	5.6	6.0	6.8	1.7	0.2	14.7	0.0	0.1	14.8	99	1	12	0.5	0.3	7.7	0.6	0.5	0.1
BC _n	0.48–0.66	7.1	5.5	7.1	8.8	2.9	0.1	18.9	0.0	0.1	19.0	99	1	16	0.4	4.0	7.5	1.3	1.2	0.1
<i>Planossolo Nátrico Sáfico típico (Typic Natraqualf) (P4 – Jataúba)</i>																				
Ap	0.00–0.15	5.6	4.3	2.6	1.8	0.8	0.1	5.3	0.1	0.5	5.8	91	9	14	0.6	0.7	6.8	0.8	0.7	0.1
Bt _n 1	0.15–0.35	5.8	4.2	6.5	5.9	4.9	0.0	17.3	0.1	0.9	18.2	95	5	27	0.5	0.1	7.3	9.3	7.8	0.0
Bt _n 2	0.35–0.55	7.0	6.7	6.6	8.3	6.6	0.1	21.6	0.0	0.2	21.8	99	1	30	0.3	0.8	7.5	10.1	10.1	0.0

Hor.: horizon; pH (soil:solution relation, 1:2.5 v/v); SB: sum of bases; CEC: cation exchangeable capacity; V: base saturation; m: aluminum saturation; ESP: exchangeable sodium percentage; OC: organic carbon; P: phosphorus.

The E horizon of profile 3 penetrated between the structural units of the Btn horizon and reached a depth of 0.26 m (Figure 2). Soil swelling and shrinking allows the structural units (prismatic and columnar) to move away from each other, creating fissures or channels between the structures, where material from the E horizon and roots can penetrate, forming the “tongues” observed in profile 3. The brown to grayish light brown color of the E horizon seems to result from a process of ferrolysis; however, according to van den Berg et al. (1987), for the confirmation of this process, complementary analyses are necessary, which would also be able to assess whether clay is currently being destroyed on the top of the B horizon.

These soils showed an abrupt transition and a clear interface between the A or E horizon and the Btn horizon, with a prismatic structure in Haplic Planosols (Profiles 1 and 2) and a very large columnar structure in Natric Planosols (Profiles 3 and 4) (Figure 2). The prismatic structure is usually related to the presence of high activity clays, which have more pronounced expansion and contraction due to soil wetting and drying cycles (Capeche, 2008), while the columnar structure reflects high values of Na saturation.

The influence of the variation in climatic conditions and the exchangeable Na content on the formation of the structure in the Btn horizon was clearly observed when all the profiles were compared with profile 4, with a sodic character and salinity (Tables 1, 2 and 3).

All the Planosols clearly had expansive minerals (smectite and vermiculite) in the clay fraction. However, at higher ESP values, a columnar structure developed in Natric Planosols (Profiles 3 and 4) and, with a reduction in ESP, a prismatic structure developed in Haplic Planosols (Profiles 1 and 2) (Figure 2) (Tables 1 and 3).

The Btn horizons of all the studied Planosols showed a substantial increase in clay contents, with an abrupt transition and textural change in relation to the overlying A or E horizon (Tables 1 and 2), responsible for the formation of a suspended water table during the rainy period, which can lead to the appearance of mottles, as observed in profiles 1 and 2 (Table 1). This drainage deficiency may also have favored the action of ferrolysis in the contact area between A or E horizons and the Btn, and can lead to the destruction of clay minerals, thus contributing to the formation of textural gradient in Planosols (van den Berg et al., 1987; Fanning and Fanning, 1989).

The structure of the Btn horizon in the studied profiles underwent clear changes with the alteration of climatic conditions and ESP. Profile 1, under a more humid climate condition, had a lower content of exchangeable Na (Table 3) and a Btn horizon with a moderate, large, prismatic structure (Table 1). In profile 2, the Btn horizon had a moderate, medium to very large, prismatic structure, with compression surfaces, i.e., a larger size and higher clay activity compared with profile 1, possibly due to the reduction in moisture and increase in exchangeable Na content. Profiles 3 and 4, in the Btn horizon, had a moderate to strong, large and very large, columnar structure, reflecting the increase of sodicity with a reduction in rainfall (Tables 1 and 3) (Figure 2).

The studied profiles have morphological features that indicate the influence of transported material in surface horizons, although from a short distance, because fragments of rocks, some times without edges (Profile 3), were observed in the transition between the horizons E and Btn in all the profiles. Some of these fragments penetrated cracks between the columnar structures of the Btn horizon, in profiles 3 and 4 (Table 1). Parahyba et al. (2009), studying Planosols, also in the state of Pernambuco, observed some indication of reworking of more superficial materials and concluded that the studied soils had an autochthonous origin. However, as pointed out by Michelon et al. (2010), it is difficult to confirm the transport of material, because the processes of weathering and pedogenesis tend to level the differences that allow for the recognition of different materials.

Physical attributes

The dendrogram of similarity (Figure 3a) initially allows for observing similarities between the physical attributes of the Bt horizons in the profiles. Two different groups were formed; one comprising profiles 1 (Timbaúba) and 2 (Altinho), both with the highest rainfalls (1,097.1 and 633.2 mm). However, despite having similar attributes, which placed them in the same group (Euclidean distance of 5.0), this similarity was even less than that of the second group. The second group comprises profiles 2 (Arcoverde) and 3 (Jataúba), which are very similar with respect to their physical attributes (Euclidean distance of 3.8).

The textural contrast observed in the field during soil morphological descriptions (Table 1) was confirmed by the granulometric analysis and the textural differentiation index (TDIh) (Table 2), evidencing the abrupt textural change between A or E horizons and the Btn.



Figure 2. Soil profiles studied (a) profile 1 – Planossolo Háplico Eutrófico solódico (Typic Albaqualf); (b) profile 2 – Planossolo Háplico Eutrófico solódico (Typic Albaqualf); (c) profile 3 – Planossolo Nátrico Órtico típico (Typic Natraqualf); (d) profile 4 – Planossolo Nátrico Órtico salino (Typic Natraqualf).

Profiles 1 and 2 had A and E horizons with medium texture and a Btn horizon with a clayey texture, with a lower amount of gravel in the Btn of profile 2, compared with the other Btn horizons (Table 2). The A horizon of profiles 3 and 4 and the E horizon of profile 3 had a sandy (light) texture, with less than 150 g kg^{-1} of clay, and a Btn horizon with medium texture and 300 g kg^{-1} of clay or more. Profiles 3 and 4 also showed higher amounts of gravel in the surface horizons, reinforcing the idea of lithological discontinuity between the A and E horizons, and the Btn horizon.

Water erosion is a concern in semiarid regions, because rainfalls are concentrated in a short period and due to the predominance of bushy, arboreal and herbaceous vegetation with a few or no leaves, which could reduce the impact of raindrops at the beginning of the rainy season (Sampaio et al., 2005; González-Botello and Bullock, 2012). These characteristics explain the increase in the gravel percentage in the A horizon of the Planosols with an increase in semiarid conditions (Table 2).

The high clay content in the Btn horizon of profile 1 may have resulted from rainfall in the region, which allowed for increased action of pedogenetic processes, such as lessivage, ferrolysis and leucinization and/or a higher clay content in the parent material. In general, profile 1 differs from the others by having the highest contents of clay in the Btn horizon and silt in the A and E horizons (Table 2).

The silt/clay ratio, in some situations, can indicate the weathering stage of soils in tropical regions (Anjos et al., 1998). In all the profiles, the silt/clay ratio values were higher in the surface horizons, probably due to the loss of clay from the surface through eluviation, according to Silva et al. (2002), or even through the selective removal of fine material by water from the surface runoff of rainfalls (Chaves et al., 1985; Oliveira et al., 2009). However, the percentage of the silt fraction can increase as a function of the deposition of silica, which is present in plants in the form of phytoliths. Costa et al. (2010), who studied phytoliths in many Brazilian ecosystems, pointed out that they mainly occur in the silt fraction of soils. Although it was not the objective of this study, the process of ferrolysis, which may occur in this environment, can corrode minerals from the fine sand fraction, transforming them into the silt fraction.

The degree of flocculation in the Btn horizon of profile 1 was higher compared with the Btn horizons of profiles 2, 3 and 4, with lower rainfalls (Table 2). Semiarid conditions can lead to higher Na contents in the exchange complex of the soils (Table 3), causing the dispersion of soil particles, similar to that observed by Galindo et al. (2008).

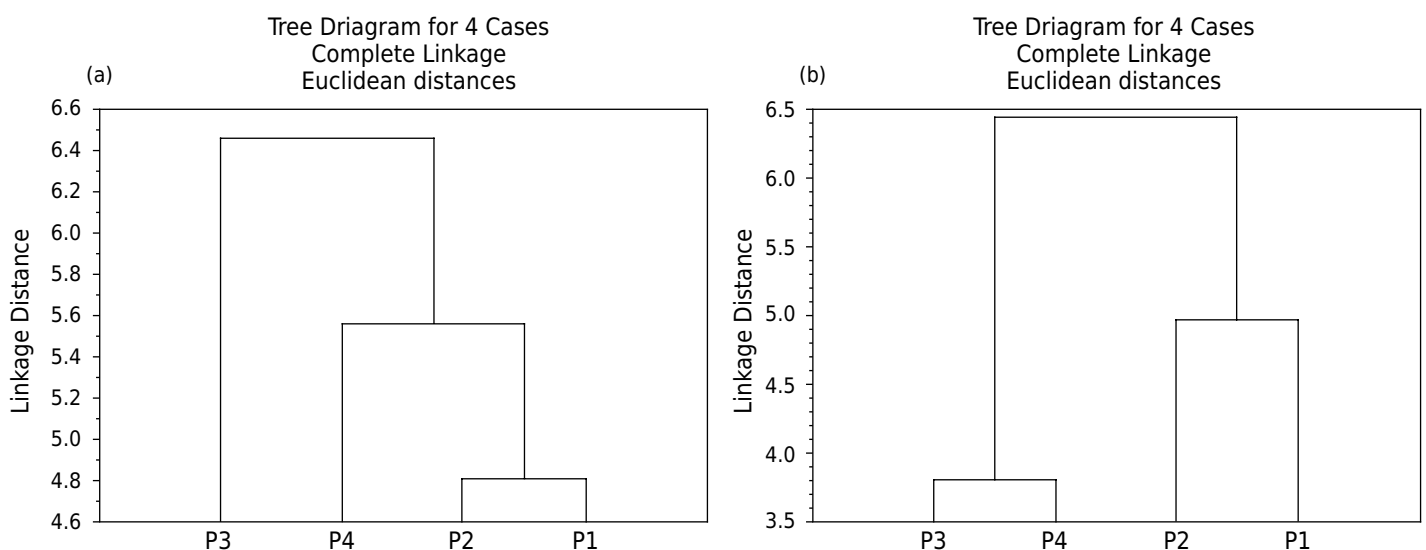


Figure 3. Dendrogram similarity based on physical attributes and saturated paste (a) and chemical (b) of the Bt horizon of soils (P1 - Profile 1; P2 - Profile 2; P3 - Profile 3; P4 - Profile 4).

High values of soil density were observed, from 1.53 to 2.02 Mg m⁻³, especially in the Btn horizons, confirming the higher densification of the planic B horizon compared with the others (Table 2). The Ap horizon of profile 3 had an extremely high density, possibly due to compaction caused by anthropic action.

The high soil density in the Bt horizon and lower total porosity (Table 2), associated with morphological characteristics (Table 1) (columnar and/or prismatic structures, ranging from medium to very large and with extremely hard consistency), promote an environment with deficient drainage, difficult aeration for plant roots and, consequently, poor root development. As a result, better root development is observed in the field between structures, possibly due to the densification of the Bt horizon of the soils (Reichardt and Timm, 2004; Galindo et al., 2008). Some studies have shown a reduction in electrical conductivity, macro and microporosity in Planosols with an increase in depth (Lima et al., 2006, 2008).

According to the uniformity values (UV) (Table 2), the possibility of lithological discontinuity is discarded for profiles 1 and 2, which showed UV below 0.30. Combined with that, the data on the fine sand/total sand (FS/TS) ratio between the horizons, with variation of only 0.14 and 0.12, respectively, confirmed the continuity of the same lithology, as also observed by Almeida et al. (1997), Mafra et al. (2001) and Bortoluzzi et al. (2008). Conversely, profiles 3 and 4, which had UV of 0.62 and 2.26, and FS/TS ratios with amplitudes of 0.04 and 0.32, respectively, show the possibility of having lithological discontinuity, especially in profile 4. However, more studies are necessary to confirm the presence of materials of allochthonous origin, because, according to Michelon et al. (2010), the transport of material similar to that from the basement rock can occur and the processes of weathering and pedogenesis can level the differences that allow for the recognition of different materials.

Studying Planosols in the state of Pernambuco, Parahyba et al. (2009, 2010) concluded that the studied soils had an allochthonous origin, with an expressive textural contrast formed by a combination of pedogenetic processes, such as clay eluviation-illuviation, in situ clay formation and selective clay loss in the horizon due to lateral movements through mechanical drag.

It is assumed that the studied soils have high erosive potential, due to the accumulation of clay in the Btn horizon and the presence of exchangeable Na dispersing clays, which makes water percolation difficult, as well as a gently undulating landscape and a high content of silt, coarse sand and fine sand in the surface horizons. The situation is more alarming in profiles 1 and 4, because they had much higher fine sand values than coarse sand values. Therefore, these are soils susceptible to erosion, which need conservational practices to avoid degradation. However, the erosive potential of profile 4 deserves more attention than the others, because its A horizon had the least depth, only 0.15 m, and can be easily eroded in case of inadequate soil use through the processes of laminar, rill and/or gully erosion.

Chemical attributes

For a better visualization of the behavior of soil chemical attributes, a dendrogram of similarity was constructed based on the chemical attributes of the Bt horizon of the profiles (pH(H₂O), pH(KCl), Ca²⁺, Mg²⁺, Na⁺, K⁺, Al³⁺, H+Al, OC, P, CEC and SB) (Figure 3b). Profiles 1 (Timbaúba) and 2 (Altinho) showed great similarity in their chemical attributes, with a Euclidean distance of only 4.8. Profiles 3 (Arcoverde) and 4 (Jataúba) had very different chemical characteristics; profile 4 was more similar to profiles 1 and 2, but with a Euclidean distance of only 5.6. This behavior, verified in the dendrogram of similarity, is similar to that observed in the relationship between rainfall and thickness of A and E horizons, which were thicker in profiles 1 and 2 (Figure 1).

The studied profiles are under different climate conditions; with an increase in rainfall, there was greater leaching of basic cations (Ca^{2+} , Mg^{2+} , Na^+ and K^+), thus concentrating Al^{3+} and H+Al (Table 3). Profile 1, with a more humid climate, had lower SB values and higher contents of acidic cations (Table 3). In addition, it had the highest percentages of quartz in the sand fraction, with only a small reserve of nutrients in the structure of minerals from the silt (feldspar and amphibole) and clay (feldspar, vermiculite and smectite) fractions, which justifies the low contents of exchangeable cations and the more obvious presence of Al^{3+} and H+Al.

All the studied soils were eutrophic, with a clear contribution of Ca^{2+} and Mg^{2+} in all the profiles, corroborating the results of Corrêa et al. (2003), Alves et al. (2005, 2007), Galindo et al. (2008) and Parahyba et al. (2010). Profile 1 had the lowest base saturation (V) among the studied profiles, possibly due to the high rainfall in this region.

The contents of Mg^{2+} in the deeper horizons in most of the profiles were higher than the Ca^{2+} contents. This can be explained by the alteration of minerals containing Mg^{2+} in their crystalline structure, such as smectite, vermiculite, mica and amphibole, which were observed in all of the studied Planosols (Table 4). Planosols with high Mg^{2+} contents are commonly found, as observed by Jacomine et al. (1973), Galindo et al. (2008), Oliveira et al. (2009) and Parahyba et al. (2010).

The horizons of profile 1 were acidic, with pH values below 6.0, due to the higher rainfall in this region (1,194 mm). Profile 2 was moderately acidic in the A horizon, with a pH of 5.9, tending to neutrality in deeper horizons. Profile 3 was alkaline. Profile 4 had a moderately acidic pH, which tended to increase (7.0) in the deepest horizon (Btnz2) (Table 3). These pH values are consistent with the values of other Planosols in semiarid regions (Oliveira et al., 2009; Parahyba et al., 2010).

The contents of organic C were low and were similar in the A horizon of profiles 1, 2 and 3, and slightly lower in profile 4. These results are similar to those observed by Galindo et al. (2008) and Oliveira et al. (2009), in Planosols under similar climatic conditions.

High Na^+ values were observed in the subsurface horizons, in relation to the surface horizons, in all the profiles. This is due to the higher leaching of the element in surface horizons with a more sandy texture and its accumulation in the more clayey Bt horizons, with higher CEC. The high Na^+ content in the profiles is possibly caused by the weathering of feldspars (Table 4), especially those of the series of calco-sodic plagioclases, which are frequently found in Planosols, according to the studies of Mota and Oliveira (1999), Galindo et al. (2008), Oliveira et al. (2008) and Parahyba et al. (2010). These contents, associated with semiarid conditions and poor drainage, favor the maintenance of high Na^+ contents, according to Mota and Oliveira (1999). The effect of Na^+ was more pronounced in profiles from more semiarid regions (profiles 3 and 4), which showed a sodic character (ESP equal to or higher than 15 %).

The electrical conductivity (EC) of the saturation paste extract and the content of soluble Na^+ in the studied profiles were low in the surface horizons (A and/or E), but always tended to increase in the subsurface, except in profile 1. The highest values were observed in profile 4, with EC of 9.3 and 10.1 dS m^{-1} in the horizons Btnz1 and Btnz2, respectively, which adds a salic character to the third categorical level of the Brazilian Soil Classification System (Santos et al., 2013).

Mineralogy of the silt and clay fractions

Most of the studied soils had a mineralogical assembly typical of poorly weathered soils, with the presence of feldspars, smectites, vermiculites, micas and amphiboles (Table 4). These minerals are easily altered in soils with good drainage, in a humid tropical climate (Kämpf et al., 2009). However, profiles 2, 3 and 4 were found in a currently semiarid environment, with low rainfalls that are irregular in time and space, and high temperatures

Table 4. Mineralogical composition of the fractions coarse sand, fine sand (qualitative and quantitative), silt and clay (qualitative) of soils studied

Horizont	Coarse sand	Fine sand	Silt	Clay
<i>Planossolo Háplico Eutrófico solódico</i> (Typic Albaqualf) (P1 – Timbaúba)				
Ap	Qz (96 %); Fr (1 %); Fo (1%); traces (2 %)	Qz (97 %); traces (3 %)	Anf; Fd; Qz	Es; Vm; Ct; Fd
Btn	Qz (99 %); traces (1 %)	Qz (99 %); traces (1 %)	Fd; Qz	Es; Vm; Ct; Fd
<i>Planossolo Háplico Eutrófico solódico</i> (Typic Albaqualf) (P2 – Altinho)				
A	Qz (94 %); Fd (1 %); Anf (1 %); Ag (1 %); Fr (1 %); Fo (1 %); traces (1 %)	Qz (93 %); Anf (3 %); Bi (1 %); Mo (1 %); traces (2 %)	Anf; Fd; Qz	Es; Vm; Mi; Ct; Fd
Btn	Qz (92 %); Fd (2 %); Fr (2 %); An (1 %); Ag (1 %); traces (2 %)	Qz (93 %); Bi (2 %); Anf (2 %); traces (3 %)	Anf; Fd; Qz	Es; Vm; Ct; Fd
Cr	Fr (40 %); Qz (23 %); Bi (18 %); Anf (12 %); Fd (5 %); traces (1 %)	Qz (47 %); Bi (28 %); Anf (16 %); Fd (6 %); traces (3 %)	Anf; Fd; Qz	Es; Vm; Ct; Fd
<i>Planossolo Nátrico Órtico típico</i> (Typic Natraqualf) (P3 – Arcoverde)				
A	Qz (94 %); Fr (2 %); Fd (1 %); Fo (1 %); traces (2 %)	Qz (94 %); Bi (2 %); Fo (1 %); traces (3 %)	Ct; Fd; Qz	Es; Vm; Mi; Ct
Btn	Qz (95 %); Fr (2 %); Fd (1 %); traces (2 %)	Qz (97 %); traces (3 %)	Ct; Fd; Qz	Es; Vm; Mi; Ct
Cr	Fr (52 %); Qz (20 %); Bi (19 %); Fd (8 %); traces (1 %)	Bi (48 %); Qz (40 %); Anf (8 %); Fd (3 %); traces (1 %)	Anf; Ct; Fd; Qz	Es; Mi; Ct
<i>Planossolo Nátrico Sáfico típico</i> (Typic Natraqualf) (P4 – Jataúba)				
Ap	Qz (95 %); Fo (2 %); Fr (1 %); traces (2 %)	Qz (98 %); traces (2 %)	Anf; Ct; Fd; Qz	Es; Mi; Ct
Btzn	Qz (97 %); traces (3 %)	Qz (97 %); traces (3 %)	Anf; Ct; Fd; Qz	Es; Vm; Mi; Ct
Cr	Fr (60 %); Qz (24 %); Anf (7 %); Bi (5 %); Fd (3 %); traces (1 %)	Qz (53 %); Bi (30 %); Anf (12 %); Fd (2 %); traces (3 %)	Anf; Ct; Mi; Fd; Qz	Es; Mi; Ct

Qz: quartz; Bi: biotite; Fd: feldspars; Anf: amphibole; Mi: mica; Es: smectite; Vm: vermiculite; Ct: kaolinite; Ag: aggregate of iron; aggregate of clay; aggregate of manganese; aggregate of clay-iron; aggregate of manganese -iron; Fr: fragment of rock; Fo: fragment of organic; traces: fractions individually totaled less than 1 %.

(Ab'Saber, 1996). Combined with the physical characteristics (imperfect drainage) of Planosols, these factors favor the process of bisialitization and neoformation of 2:1 clay minerals from solutions rich in Al, Si and bases, originating from the weathering of primary minerals in the soil under low to moderate leaching of silica (Borchardt, 1989; Corrêa et al., 2003; Melo and Wypych, 2009).

The mineralogy of the studied Planosols is consistent with the concepts of Oliveira (2007), who claims that the Order of Planosols includes dystrophic and eutrophic soils, formed from materials with various origins, and can have a mineralogy from essentially kaolinitic to predominantly smectitic, but always with low contents of free Fe oxides, due to the formation conditions and the more or less pronounced hydromorphism to which they are susceptible during some parts of the year.

The silt fraction of the studied profiles was basically formed by quartz, feldspars and amphiboles in all the horizons (Table 4). These minerals were predominant in the A and Bt horizons of all the profiles, and are more evident in the profiles from Timbaúba (P1) and Jataúba (P4). Many Planosols in the Mesoregion of the Agreste of Pernambuco have a mineralogical assembly in the silt fraction composed of quartz, feldspars and micas (Galindo et al., 2008).

Particles of feldspar, when found in the silt and clay fractions, are very susceptible to hydrolysis reactions and can undergo dissolution, with the release of silica, Al and K to the soil solution, and later recrystallization of 1:1 (kaolinite) and 2:1 (smectite and vermiculite) minerals, as observed in the studied Planosols (Melo and Wypych, 2009) (Table 4). However, the neoformation of kaolinite in this environment is not facilitated, because the virtual absence of Na, Ca, Mg, Fe and K would be necessary, which does not happen in these Planosols. These soils have minerals that are the source of these cations and imperfect drainage, which hampers the leaching process, attenuating the weathering in this environment.

Despite being from different geoenvironmental conditions, the studied Planosols did not show considerable modification in the mineralogical assembly in the silt and clay fractions. Possibly, the condition of imperfect drainage, typical of Planosols, disfavors the more efficient action of weathering, allowing an environment with solutions rich in basic cations, Al and silica, which can neoform clay minerals such as smectite, vermiculite and kaolinite, observed in the clay fraction of these soils (Table 4).

In the profiles from Altinho (P2), Arcoverde (P3) and Jataúba (P4), mica was found in the clay fraction (Table 4), which may undergo weathering and the formation vermiculite and smectite, resulting from the loss of K from the interlayers, Fe^{2+} oxidation and reorientation of hydroxyls, as pointed out by Douglas (1989) and Azevedo and Vidal-Torrado (2009).

The characteristics of deficient drainage and alternating cycles of oxidation and reduction, typical of Planosols, promote an environment favorable to lower solubilization and loss of silica from the system, allowing the genesis of 2:1 layer minerals. This allows not only the neoformation of 2:1 minerals in the studied sites, but also their stability (Borchardt, 1989; Corrêa et al., 2003; Melo and Wypych, 2009).

In the Cr horizon of profiles 2, 3 and 4 (Table 4), the presence of secondary minerals such as kaolinite and smectite in the clay fraction was common to all. This is due to the high contents of easily alterable primary minerals in the parent material of these soils, which can be altered to form the secondary minerals found in the clay fraction.

The kaolinite of the studied profiles can be being formed from the alteration of 2:1 clay minerals and directly from the alteration of micas and feldspars in some sites with better soil drainage.

Mineralogy of the coarse and fine sand fractions

The mineralogy of coarse and fine sand fractions was mainly formed by quartz (99 to 92 %) in A and Btn horizons (Table 4). Feldspar was the second most predominant mineral (1 to 2 %) in the coarse sand fraction of the horizons A and Btn of the profiles 2 (A – 1 %; Btn – 2 %) and 3 (A – 1 %; Btn – 1 %), which were the only ones with this mineral. In the Cr horizon, feldspar was found in all the profiles (P2 – 5 %; P3 – 8 % and P4 – 3 %), except in profile 1, in which the Cr horizon was not analyzed. In this horizon, feldspar dropped to the third position in terms of abundance and was surpassed by quartz (24 to 20 %) and biotite (5 to 19 %) (Table 4).

Unlike the coarse sand fraction, in the fine sand fraction feldspar was not present in the horizons A and Btn of the profiles, and was found only in the Cr horizon (6 to 2 %), where only quartz appeared as the most abundant mineral (Table 4). The absence of feldspar in the A and Btn horizons in the fine sand fraction is due to its lower stability with the reduction in particle size, which becomes more vulnerable to hydrolysis reactions and can suffer dissolution with release of silica, aluminum and potassium to the soil solution and later recrystallization of 1:1 (kaolinite) and 2:1 (smectite and vermiculite) minerals (Melo and Wypych, 2009).

Evaluating the reserve and availability of nutrients in some soils cultivated with eucalyptus, Castro et al. (2010) observed the presence of feldspar in the sand fraction of two Haplic Planosols and attributed to this element the high contents of total and exchangeable Ca and Mg in the subsurface horizons.

In the coarse sand fraction, biotite was observed in the Cr horizon of the profiles (P2 – 18 %; P3 – 19 % and P4 – 5 %). Possibly, this mineral underwent the action of physical weathering and was fragmented into smaller particles, which were observed in greater amount in the fine sand fraction (Table 4).

Biotite was found in the fine sand fraction of the A horizon of profiles 2 (1 %) and 3 (2 %) and only in the Btn horizon of profile 2 (2 %). However, in the Cr horizon, there was a large amount of biotite (P2 – 28 %; P3 – 48 % and P4 – 30 %) (Table 4). A reduction in the size of biotite particles favors the action of weathering and can lead to the formation of vermiculite in silt and clay fractions, resulting from the loss of K from the interlayers, Fe²⁺ oxidation and reorientation of hydroxyls, as pointed out by Douglas (1989) and Azevedo and Vidal-Torrado (2009). A large amount of biotite (52 %) in a Planosol from a semiarid region was also reported by Oliveira et al. (2008) and Parahyba et al. (2010), the latter of whom associated the in situ weathering of this element with the remarkable textural contrast frequently observed in Planosols.

The presence of partially altered mica in the coarse and fine sand fractions of surface horizons of various Planosols in the state of Pernambuco was pointed by Galindo et al. (2008).

Amphiboles were present in the coarse sand fraction, especially in the Cr horizon of the profiles 2 (12 %) and 4 (7 %). In the A and Btn horizons, only profile 2 had amphibole in the coarse sand fraction. The other profiles (1 and 3) did not have amphibole in the mineralogical assembly of the coarse sand fraction.

In the fine sand fraction, the presence of amphibole followed the distribution observed in the coarse sand fraction, where only profile 2 [A horizon (3 %) and Btn horizon (2 %)] had amphibole. In the other profiles, amphibole was only observed in the Cr horizon (except profile 1, where the Cr horizon was not analyzed), and was the third most abundant mineral in the mineralogical assembly (P2 – 16 %; P3 – 8 % and P4 – 12 %).

The lower percentage of amphiboles in the A and Btn horizons in the fine sand fraction, compared with coarse sand fraction, is due to the lower stability of this mineral when its size is reduced, because the specific area available to chemical weathering increases.

Amphiboles are double-chain inosilicates and can be a source of mainly Ca, Mg, Na, Fe, Si and Al, which can contribute to the neoformation of clay minerals in the soil. They are minerals with little mobility in the soil and are below the stability of albite in the Goldich series (Toledo et al., 2009). Nevertheless, amphiboles were observed in all the studied Planosols (Table 4), under the most varied climate conditions. This shows that the geochemical environment in these soils has favorable conditions for stabilization, since these minerals are easily alterable under the conditions of a humid tropical climate.

The mineralogical assembly of coarse and fine sand fractions was simplified with an increase in rainfall. However, possibly due to differences in the parent material, profile 4, located in the semiarid region of Pernambuco, with rainfall of only 510 mm, had a mineralogical assembly in the A and Btn horizons similar to that of profile 1, from a much more humid climate (1,097.1 mm).

Similar results were obtained by Parahyba et al. (2009), studying the quantitative evolution of Planosols. These authors observed the presence of quartz, micas and feldspars as the main minerals constituting the coarse fraction of the soil, which also showed lower amounts of amphiboles and traces of zircon, tourmaline, rutile, epidotes and pyroxenes.

CONCLUSIONS

With an increase in rainfall, there was an increase in the clay contents in the Bt horizon, a reduction in ESP, EC, Na⁺, CEC, SB and soil density, and thicker A and E horizons.

The increase in ESP, associated with the presence of expansive minerals (smectite and vermiculite), allowed for the development of a prismatic structure in Haplic Planosols and a columnar structure in Natric Planosols with higher ESP.

The mineralogical assemblies of the silt and clay fractions were similar in the different geoenvironments studied, while higher contents of easily alterable minerals were observed in the composition of the sand fraction in environments with a drier climate.

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