

Division - Soil in Space and Time | Commission - Soil Genesis and Morphology

# Relief Position and Soil Properties under Continuous Banana Cropping in Subhumid Climate in Northeast Brazil

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**ABSTRACT:** Sequences of thick and eroded soils in hills surfaces are cultivated with banana since the beginning of the last century in the Northeast of Pernambuco (PE), Brazil. Measurements of soil properties depending on soil slope under intensive agricultural cultivation are limited mostly as the pedogenetic approach. This study aimed to identify the dominant soil types, to evaluate morphological, physical, chemical, and mineralogical properties of soil profiles, and link them to the relief position under continuous banana cropping, in the transition Mata-Agrete of PE. Three slope classes and soil profiles were considered: Profile 1 (P1), upper third of the elevation slope; Profile 2 (P2), middle third of the slope; and Profile 3 (P3) lower third. They were opened, described, and soil samples collected from all horizons at a typical slope of the region. Independent of relief position and land use, all soils are deep (>1.50 m) and present the argic horizons (Bt) developed in all steeply sloping surfaces (15-33 %). The Bt horizon presented the highest values of soil bulk density and microporosity. Despite the presence of illite, all the soil profiles showed remarkable degree weathering, are mostly kaolinitic, besides presenting goethite and quartz in the soil clay fraction, and predominance of quartz in the silt and sand fraction. Water-stable aggregates >2 mm were dominant in all the relief positions. Acidity, low cation exchange capacity, and in general, nutrient poverty were observed in the soil profiles, as opposed accumulation of exchangeable cations on the lower third of the slope (P3). However, the soil properties were affected by land use and water erosion. The Ap horizons showed the highest values of pH, exchangeable bases, phosphorus available, and organic carbon due to agricultural practices, while the steepest slope (P2) had the lowest content of clay, phosphorus and mean weight diameter of aggregates, and higher organic carbon content, in the superficial horizon, due to removal and deposition by water erosion. From the upper third to the lower third of the slope, Nitic Acrisol, Haplic Acrisol, and Nitic Lixisol were formed.

**Keywords:** pedogenesis, argic horizon, cultivated hillslopes, illite, Vale do Siriji.

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## INTRODUCTION

Cultivated hillslopes in the coastal area of Pernambuco (PE), “*Zona da Mata*”, are one of the most altered ecogeomorphological systems in northeast Brazil. The areas of hills in the northeast of PE were especially affected by deforestation of the Atlantic Forest, which has been reduced to less than 8 % of its original size (Myers et al., 2000), and replaced by sugarcane cultivation still in the 16th century. More recently, since the beginning of the last century, the banana farming has become the second agricultural activity of importance for this region, in addition to medium-sized properties, banana cultivation supports family farming. Several studies have been conducted to evaluate controlling factors of soil properties on the landscape, with bears visual evidence of various linkages between surface processes, as well as surface disturbances (Brubaker et al., 1993; Pawlik et al., 2013; Comino et al., 2016). Thus, understanding the soil formation and distribution of the soil properties as influenced by landscape features is critical for assessing the effect of future land use changes on soil use and management (Kosmas et al., 2000).

Along of the topographic gradient in the “*Vale do Siriji*”, transition area between the *Zona da Mata* and *Agreste* of PE, the dissected scarps structured in faults constitute elevated areas that underwent the action of weathering and denudational events, suggesting that erosive and geochemical processes, as well as possible tectonic reactivations, contributed to the present forms that cover the slopes of the region (Bigarella et al., 1994; Bezerra et al., 2008; Silva et al., 2012). This relief, with altitudes between 100 and 600 m, influences the climate and the economic occupation of the region (Andrade, 2001).

Many studies have determined the topography as the dominant factor influencing soil property variation due to its influence on microclimate, drainage, runoff and soil erosion, and on soil formation (Park and Burt, 2002; Clemens et al., 2010; Dessalegn et al., 2014; Silva et al., 2017). For instance, Anjos et al. (1998) observed that pedogenic intensity is strongly dependent on characteristics of the major geomorphic surfaces in the Caetes basin. Similarly, Moniz and Buol (1982) advocate that the steep slope favors the flow of water within the solum, as proposed by the double-water flow model, which accelerate the formation of an argic horizon by creating a compressed layer of a blocky structure. The desilication on the upper-slope soils over the granite gneiss saprolite should be recovered by resilication of lower-slope soils (Moniz and Buol, 1982).

In this sense, the IUSS Working Group WRB (2015) considers that the soils with argic horizons often have a specific set of morphological, physicochemical, and mineralogical properties other than a mere clay increase, which allow various types of argic horizons to be distinguished and their pathways of development to be traced (Sombroek, 1986). Soils with argic horizons predominate in the *Vale do Siriji*, mainly *Argissolos Vermelhos* and *Vermelho-Amarelos* (Acrisols) and *Luvissolos* (Luvisols). The technological level of most producers in the region is low, and soil conservation practices on systems subject to land-use change are uncommon (Araújo Filho et al., 2000).

The influence of land use systems on the soil properties, the advance in chemical weathering and erosion processes is a research subject of great interest, that can contribute to the understanding of pedogenesis (Courchensne, 2006), pedodiversity, and the risk of soil degradation. The continuous cultivation has altered the content of potassium exchangeable on the soil surface (Sharpley and Buol, 1987; Strawn et al., 2015). Similarly, changes in land use influences on the quantity and quality of soil organic matter (Purton et al., 2015; Baddeley et al., 2017). Tree roots influence the creation and stabilization of soil aggregates, and protection of the soil surface against erosion also is indicated by Courchensne (2006).

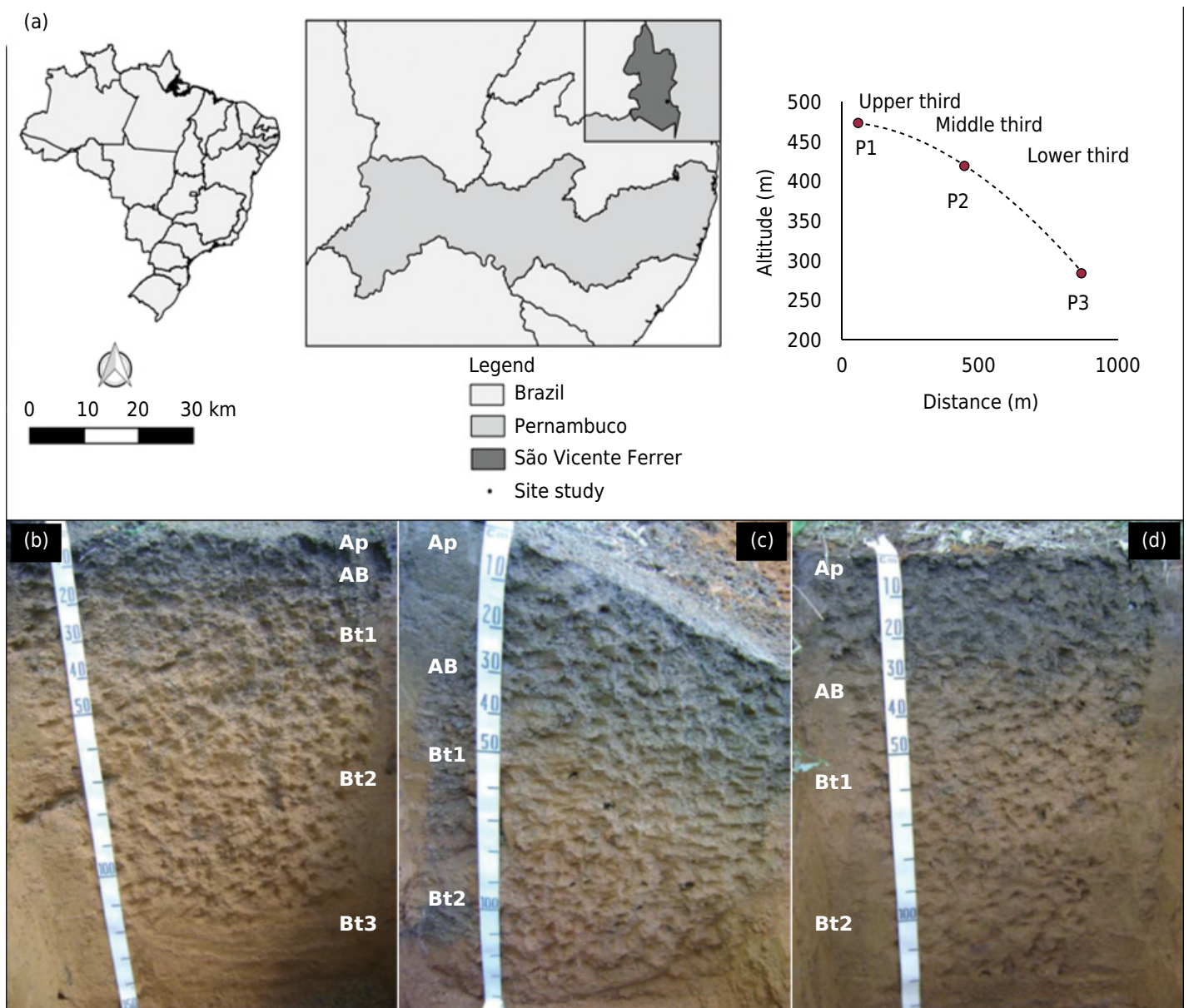
The hypothesis is that the slope position influenced the soil properties and genesis. Also, that cultivated hillslopes can result in different levels of degradation of soil physical

conditions, such as soil aggregate degradation and compaction. Thus, the objectives of the present study were to identify the dominant soil types, to evaluate morphological, physical, chemical, and mineralogical properties of soil profiles, and link them to the relief position under continuous banana cropping, in the transition Mata-Agreste of PE.

## MATERIALS AND METHODS

### Description of the area and sample collection

The study was carried out in private property, in the municipality of São Vicente Férrer, state of Pernambuco, located at coordinates 07° 35' 28" S and 35° 29' 29" W (Figure 1). Geology is characterized by orthogneisses of granitic to tonalitic composition, with the presence of monzonites, monzodiorites, and diorites. The relief is bustling, strong wavy and hilly, with deep and narrow valleys. The climate of the region is classified, according



**Figure 1.** Location of the study area, with the relief positions, altitudes, and distance between the profiles in the municipality of São Vicente Férrer, Pernambuco, Brazil (a). Image of the profiles: Profile 1 (b): *Argissolo Vermelho-Amarelo Distrófico nitossólico* (Nitic Acrisol); Profile 2 (c): *Argissolo Vermelho-Amarelo Distrófico típico* (Haplic Acrisol); Profile 3 (d): *Argissolo Vermelho-Amarelo Eutrófico nitossólico* (Nitic Lixisol).

to the Köppen classification system, as As', hot and humid with autumn-winter rains (Beltrão and Macêdo, 1994). The average annual rainfall is 1,103 mm, the average annual temperature of 24.1 °C, presenting from five to six months with precipitation over 100 mm and a dry period of three to four months. The rainy season begins in January/February with the end in September, but it may advance until October.

In the farm where the study was carried out, banana is cultivated for approximately 40 years, chicken manure is used as organic fertilizer, and NPK (05-07-32) is applied twice a year, at a dosage of 100 g per plant, reaching producing 8.4 t ha<sup>-1</sup> (Almeida, 2009).

A typical slope of the region was selected, apparently uniform in terms of parent material. On this slope three trenches were opened, in the upper third (15 % slope), the middle third (33 % slope), and the lower third near the slope (20 % slope), the extension of approximately 800 m (Figure 1). All horizons were described morphologically according to norms established by Santos et al. (2005), and deformed samples were collected for the analyses carried out except the soil density, which was used for undisturbed samples. Undisturbed soil samples were also collected at all layers to evaluate aggregate stability.

Soils were classified according to Santos et al. (2018) and the samples sent to the laboratory in which the physical, chemical, and mineralogical analyses were performed.

### Physical and chemical analyses

The physical and chemical analyses were performed on the air-dried fine earth (ADFE). The physical analyses comprised the particle size distribution by the pipette method, soil bulk density by the volumetric ring method, particle density by the volumetric balloon method, and the total porosity was calculated from the values of soil and particle density, according to Claessen (1997). Microporosity was determined in samples with preserved structure and a tension table (0.60 m column of water). Macroporosity was obtained by difference between total porosity and microporosity (Claessen, 1997).

The specific surface was determined according to Quirk (1955) and for stability of aggregates in water the methodology adopted was that recommended by Angulo et al. (1984), with some modifications, using 100 g of soil and sieves of 3.35, 2.00, 1.00, 0.50, and 0.25 mm of opening. We calculated the mean weight diameter (MWD).

The chemical analyses followed the methods described by Claessen (1997): pH(H<sub>2</sub>O) and pH(KCl) in at a ratio of 1:2.5; Ca<sup>2+</sup>, Mg<sup>2+</sup>, and Al<sup>3+</sup> extracted with KCl 1 mol L<sup>-1</sup> - Ca<sup>2+</sup> and Mg<sup>2+</sup> were measured by atomic absorption spectrophotometry, and Al<sup>3+</sup> by volumetry; Na<sup>+</sup> and K<sup>+</sup> extracted with Mehlich-1 and dosed by flame photometry; H+Al extracted with calcium acetate 1 mol L<sup>-1</sup> at pH 7.0 and determined volumetrically with NaOH solution. The organic carbon (C) determined by oxidation using potassium dichromate in sulfuric medium and the available phosphorus (P) by Mehlich-1 extraction and colorimetric determination, following the method of Braga and Defelipo (1974).

### Mineralogical analysis

The ADFE was separated by wet sieving (sand) and decantation (silt and clay) to identify its components and qualitative analysis by X-ray diffraction (XRD), with specific treatments inherent to each fraction, as recommended by Jackson (1975) and Whitting and Allardice (1986).

The diffractograms were obtained using a Shimadzu diffractometer, operating at a voltage of 40 kv, with a current of 20 mA, CuK $\alpha$  radiation, with graphite monochromator. The scanning range was 5 to 70° (2 $\theta$ ), with a recording speed of 3°  $\theta$  min<sup>-1</sup> for total sand and silt, and amplitude of 3 to 70° (2 $\theta$ ) and the same velocity for clay dust. For samples saturated with K at ambient temperature and heated to 550 °C, the scanning range was 3 to 35° (2 $\theta$ ) and the recording speed of 2° 2 $\theta$  min<sup>-1</sup>.



## RESULTS

### Morphological and physical properties

Independent of relief position, all soils are deep (>1.50 m) (Table 1) and well developed. Morphologically, the root system of the crop was deeper in the upper and lower third of the hillside, while in the middle third, with less favorable physical conditions, a good amount of roots up to 1.00 m depth was observed. In the aggregates predominate moderate to abundant clay coatings and the increase clay contents in the subsurface horizons (Table 1).

The profiles exhibit Ap-AB-Bt1-Bt2-Bt3 (P1) and Ap-AB-Bt1-Bt2 (P2 and P3) pedogenic horizon sequences (Table 1). They have predominantly blackish colors on the A horizon, and yellowish-red in the subsurface horizons (7.5YR and 5YR, moist color, respectively). In subsurface, values from 4 to 5 and chromas  $\geq 6$  in all profiles. All horizons were firm, friable, plastic, and sticky (except P1), which was also very firm. The structure is well developed, moderate, very small and small in subangular, and angular blocks.

According to the criteria established by SiBCS (Santos et al., 2018) and World Reference Base of Soil Resources (IUSS Working Group WRB, 2015), the distribution of the soil classes from the upper third to the lower third of the slope is in the following order: P1 - *Argissolo Vermelho-Amarelo Distrófico nitossólico* (Nitric Acrisol) (Figure 1b); P2 - *Argissolo Vermelho-Amarelo Distrófico típico* (Haplic Acrisol) (Figure 1c); and P3 - *Argissolo Vermelho-Amarelo Eutrófico nitossólico* (Nitric Lixisol) (Figure 1d).

The profiles ranged from sandy clay loam to very clayey (Table 2). The clay content ranged from 270 to 497 g kg<sup>-1</sup> in the A horizon, and increased towards the subsurface horizons, allowing the characterization of the argic horizon (Bt). The profile of the middle third (P2) is more sandy at the surface (Table 2), consistent with the high silt/clay ratio (>1.0). While this ratio was lower than 0.7 in P1 and P3. The fine sand/coarse

**Table 1.** Morphological properties of soils in a topographic sequence, São Vicente Férrer, Pernambuco, Brazil

Horizon	Layer	Color		Structure	Clay coating	Consistency		Transition
		Wet	Dry			Humid	Wet	
m								
P1 - <i>Argissolo Vermelho-Amarelo Distrófico nitossólico</i> (Nitric Acrisol)								
Ap	0.00-0.15	7.5YR 4/3	10YR 4/4	mod vsma sma sub		fi	pl v sti	c f
AB	0.15-0.35	7.5YR 4/6		mod vsma med sub	mod abu	vfi	pl v sti	g f
Bt1	0.35-0.78	5YR 5/6		mod vsma sma sub	mod abu	fi	pl v sti	d f
Bt2	0.78-1.20	5YR 5/6		mod vsma sma sub	mod com	fri	pl sti	d f
Bt3	1.20-1.60 <sup>+</sup>	5YR 5/6		wea vsma sma sub	wea com	fri	pl sti	
P2 - <i>Argissolo Vermelho-Amarelo Distrófico típico</i> (Haplic Acrisol)								
Ap	0.00-0.27	7.5YR 4/3	10YR 5/4	mod vsma sub		fi	v pl v sti	g f
AB	0.27-0.50	7.5YR 4/6		mod str vsma sma angb	str abu	fi	v pl v sti	g f
Bt1	0.50-1.00	5YR 4/6		mod vsma sma angb	mod abu	fi	pl v sti	d f
Bt2	1.00-1.60 <sup>+</sup>	5YR 5/8		mod vsma sma sub	mod com	fri	pl sti	
P3 - <i>Argissolo Vermelho-Amarelo Eutrófico nitossólico</i> (Nitric Lixisol)								
Ap	0.00-0.24	7.5YR 3/2	10YR 4/3	mod vsma sma sub		fi	pl v sti	c f
AB	0.24-0.50	7.5YR 4/3		mod vsma sma sub angb	mod abu	Fi	pl v sti	g f
Bt1	0.50-0.90	5YR 4/6		mod vsma sma sub angb	mod abu	Fri	pl v sti	d f
Bt2	0.90-1.40 <sup>+</sup>	5YR 4/6		mod vsma sma sub angb	mod com	Fri	pl sti	

Abu: abundant; angb: angular blocks; com: common; c: clear; d: diffuse; f: flat; fi: firm; fri: friable; g: gradual; med: medium; mod: moderate; pl: plastic; sma: small; sti: sticky; str: strong; sub: subangular blocks; v: very; vfi: very firm; vsma: very small; wea: weak.

**Table 2.** Physical properties of soils in a topographic sequence, São Vicente Férrer, Pernambuco, Brazil

Horizon	Layer	Sand	Coarse sand	Fine sand	FS/CS	Silt	Clay	S/C	DF	Bd	Ps	SS
	m	g kg <sup>-1</sup>				g kg <sup>-1</sup>			%	Mg m <sup>-3</sup>		m <sup>2</sup> g <sup>-1</sup>
<i>P1 - Argissolo Vermelho-Amarelo Distrófico nitossólico (Nitric Acrisol)</i>												
Ap	0.00-0.15	378.7	214.3	164.4	0.77	127.8	492.1	0.26	54.20	1.46	2.58	24.30
AB	0.15-0.35	328.0	191.6	136.4	0.71	174.0	497.0	0.35	31.47	1.47	2.61	36.18
Bt1	0.35-0.78	258.1	147.6	110.5	0.75	117.9	622.2	0.19	100.00	1.47	2.61	35.46
Bt2	0.78-1.20	247.1	137.4	109.7	0.80	112.5	640.3	0.18	99.28	1.41	2.63	27.72
Bt3	1.20-1.60 <sup>+</sup>	247.0	137.9	109.1	0.79	247.6	502.6	0.49	99.79	1.25	2.62	37.44
<i>P2 - Argissolo Vermelho-Amarelo Distrófico típico (Haplic Acrisol)</i>												
Ap	0.00-0.27	433.2	262.5	170.7	0.65	295.4	270.4	1.09	44.13	1.56	2.60	36.36
AB	0.27-0.50	398.5	248.5	150.0	0.60	121.8	477.9	0.25	100.00	1.55	2.62	58.68
Bt1	0.50-1.00	318.8	196.7	122.4	0.62	131.4	543.1	0.24	98.55	1.57	2.64	74.52
Bt2	1.00-1.60 <sup>+</sup>	256.5	164.0	92.5	0.56	128.1	614.1	0.21	97.13	1.37	2.69	40.14
<i>P3 - Argissolo Vermelho-Amarelo Eutrófico nitossólico (Nitric Lixisol)</i>												
Ap	0.00-0.24	452.7	278.9	173.8	0.62	222.0	326.8	0.68	24.71	1.56	2.57	43.02
AB	0.24-0.50	373.8	224.8	149.0	0.66	185.3	438.4	0.42	58.01	1.55	2.59	30.42
Bt1	0.50-0.90	306.4	180.7	125.7	0.70	201.2	491.5	0.41	100.00	1.57	2.63	40.50
Bt2	0.90-1.40 <sup>+</sup>	313.7	179.8	133.9	0.74	195.8	490.7	0.40	100.00	1.37	2.60	37.62

FS/CS: fine sand/coarse sand; S/C: silt/clay; DF: degree of flocculation; Bd: soil bulk density; Ps: particle density, all analyzes performed according to the method described in Claessen (1997); SS: specific surface (Quirk, 1955).

sand ratio exhibits a small variation in depth in all profiles. Soil bulk density ranged from 1.27 to 1.47 Mg m<sup>-3</sup> in the upper third (P1), and from 1.37 to 1.57 Mg m<sup>-3</sup> in the middle third (P2) and lower third (P3). Particle density was between 2.57 and 2.9 Mg m<sup>-3</sup> (Table 2).

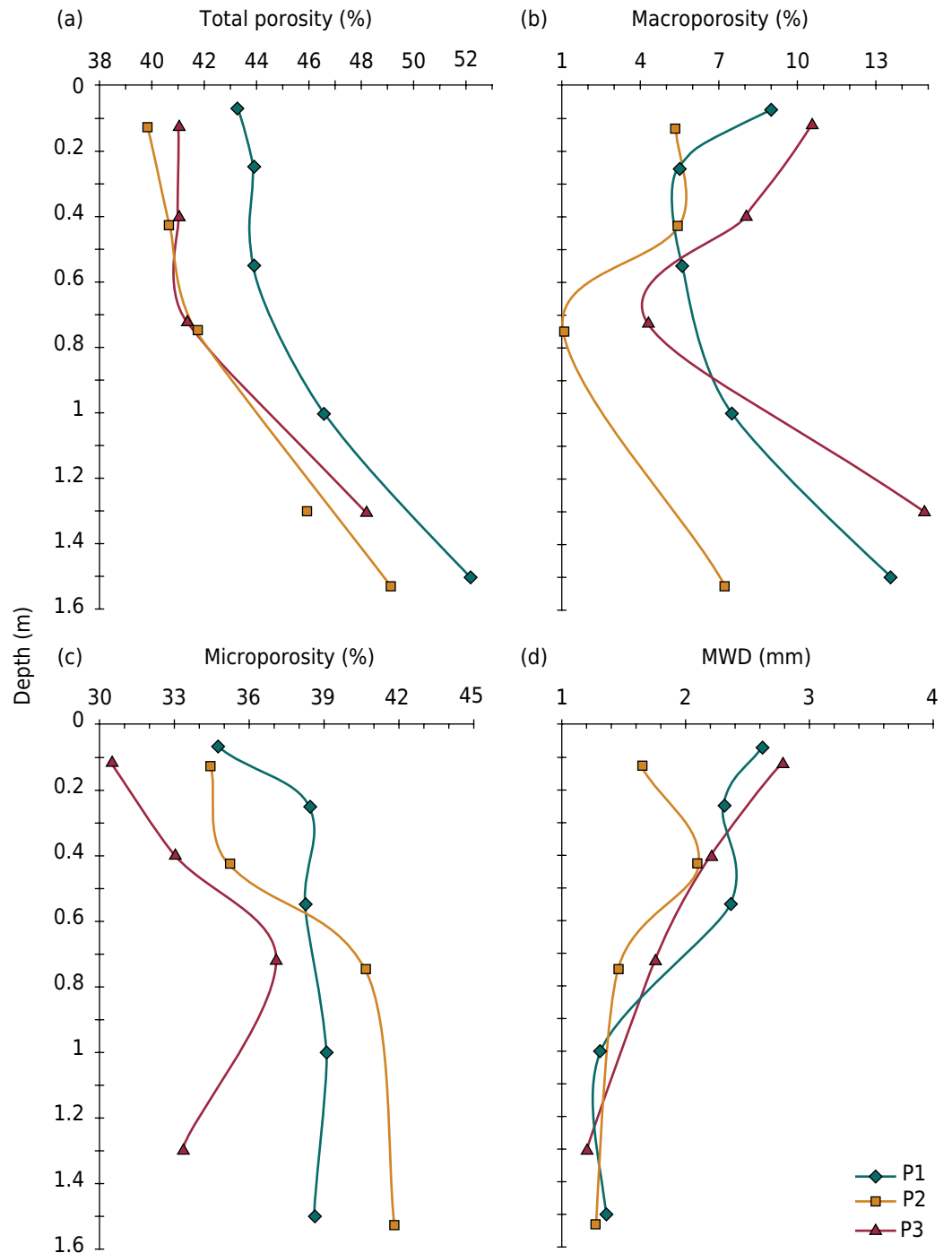
The degree of flocculation of the clays presents values of 100 % in most of the Bt horizons, being observed a greater dispersion in the superficial layers (Table 2). The distribution of the total pore quantity ranged from about 40 to 52 % in the soil sequence, the microporosity increased in the Bt horizons of all profiles, to the detriment of the reduction of macroporosity (Figure 2b). The SS referring to the upper, middle, and lower thirds of the slope presented mean values of 32, 52, and 38 m<sup>2</sup> g<sup>-1</sup> of clay, respectively.

The predominance of aggregates >2.0 mm in the soil profiles (except at the A horizon of P2) demonstrates the good physical condition of the soil (Figure 2d). This was indicated by aggregation index MWD, which is an estimate of the relative amount of soil in each class of aggregates and increases with a higher percentage of large aggregates (Castro Filho et al., 2002). The MWD of water-stable aggregates decreased in depth in all profiles, was 2.47 mm on average in the horizons A of P1 and P2, and 1.87 mm in P2 (on average) in the superficial horizon, influence of land use.

### Chemical composition

The soils of the topographic sequence are classified as dystrophic (P1 and P2), but with high base saturation in the horizons Ap, while the P3 (lower third) was eutrophic (Table 3). The soils were characterized by low acidity pH or neutral, except for the P3 which had pH > 7. All profiles still presented negative ΔpH values [pH(KCl) - pH(H<sub>2</sub>O)] (Table 3).

The K<sup>+</sup> values ranged from 0.03 to 0.17 cmol<sub>c</sub> kg<sup>-1</sup>, with decreases in the subsurface horizons in all profiles, while P3 had the highest values (0.14 to 0.32 cmol<sub>c</sub> kg<sup>-1</sup>)



**Figure 2.** Values of total porosity (a), macroporosity (b), microporosity (c), and mean weight diameter (MWD) at depth in all soil profiles (d).

compared to other profiles (Table 3). The  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  contents ranged from 1.30 to 3.04  $\text{cmol}_c \text{kg}^{-1}$  and 0.07 to 0.56  $\text{cmol}_c \text{kg}^{-1}$ , respectively, in the A horizons, with decreases of  $\text{Ca}^{2+}$  in the subsurface horizons. The  $\text{Mg}^{2+}$  values increased in the subsurface in all profiles (Table 3).

The available P contents were high at an average of 47.7  $\text{mg kg}^{-1}$  in the superficial horizons with an emphasis at the P2 Ap horizon that had 2.57  $\text{mg kg}^{-1}$ . The T presents the average values of 4.86, 4.15, and 3.03  $\text{cmol}_c \text{kg}^{-1}$  in the profiles P1, P2, and P3, respectively, reflecting the kaolinite mineralogy of the soils, consistent with XRD (Figure 3). The Ap horizons showed 9.87, 12.31, and 9.63 g of organic C per kilogram of soil in the upper, middle, and lower third, respectively, with values decreasing in depth. In the other

**Table 3.** Chemical properties of soils in a topographic sequence, São Vicente Férrer, Pernambuco, Brazil

Horizon	Layer	pH		C	P	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Na <sup>+</sup>	K <sup>+</sup>	Al <sup>3+</sup>	H+Al	S	T	V	m
		H <sub>2</sub> O	KCl												
m		g kg <sup>-1</sup>			mg dm <sup>-3</sup>			cmol <sub>c</sub> dm <sup>-3</sup>			%				
P1 - <i>Argissolo Vermelho-Amarelo Distrófico nitossólico</i> (Nitric Acrisol)															
Ap	0.00-0.15	6.91	6.17	9.87	56.87	3.04	0.17	0.01	0.17	0.05	3.33	3.51	6.84	51.33	0.73
AB	0.15-0.35	5.91	5.20	9.13	28.65	1.65	0.07	0.07	0.06	0.05	3.52	1.86	5.38	34.58	0.94
Bt1	0.35-0.78	5.74	5.57	5.21	3.62	1.19	0.60	0.05	0.05	0.10	2.93	1.85	4.78	38.79	2.09
Bt2	0.78-1.20	5.67	5.64	2.99	0.82	1.04	0.50	0.04	0.03	0.05	2.04	1.66	3.70	44.90	1.35
Bt3	1.20-1.60 <sup>+</sup>	5.98	5.96	2.69	1.37	1.13	0.60	0.04	0.03	0.05	1.82	1.81	3.63	49.32	1.38
P2 - <i>Argissolo Vermelho-Amarelo Distrófico típico</i> (Haplic Acrisol)															
Ap	0.00-0.27	7.14	6.31	12.31	2.57	2.48	0.09	0.07	0.14	0.05	1.79	2.77	4.57	60.73	1.09
AB	0.27-0.50	5.69	5.17	6.26	0.33	1.30	0.56	0.05	0.07	0.15	2.92	1.98	4.90	40.40	3.06
Bt1	0.50-1.00	5.74	5.57	3.88	0.00	1.18	0.39	0.05	0.05	0.05	1.93	1.68	3.62	46.50	1.38
Bt2	1.00-1.60 <sup>+</sup>	4.96	4.93	3.15	0.00	1.02	0.28	0.04	0.04	0.15	2.12	1.38	3.51	39.46	4.28
P3 - <i>Argissolo Vermelho-Amarelo Eutrófico nitossólico</i> (Nitric Lixisol)															
Ap	0.00-0.24	7.49	6.78	9.63	38.48	1.51	0.07	0.09	0.32	0.05	1.77	1.99	3.76	53.04	1.33
AB	0.24-0.50	7.19	6.43	6.20	2.38	1.33	0.33	0.05	0.13	0.05	1.02	1.84	2.86	64.23	1.75
Bt1	0.50-0.90	6.97	6.48	3.69	2.68	1.08	0.20	0.04	0.14	0.05	1.22	1.46	2.68	54.59	1.87
Bt2	0.90-1.40 <sup>+</sup>	6.90	6.61	2.36	6.65	1.43	0.29	0.04	0.14	0.05	0.91	1.90	2.82	67.59	1.77

S: sum of exchangeable bases (Ca<sup>2+</sup> + Mg<sup>2+</sup> + Na<sup>+</sup> + K<sup>+</sup>); T: sum of exchangeable bases and extractable acidity (H+Al); V = 100 × S/CEC; m = [100 × Al<sup>3+</sup>/(S + Al<sup>3+</sup>)]. All analyzed and calculated according to the methods described in Claessen (1997). P: available phosphorus (Braga and Defelipo, 1974).

horizons, these values were not conditioned to the landscape position, were relatively uniform (Table 3).

### Bulk mineralogical composition

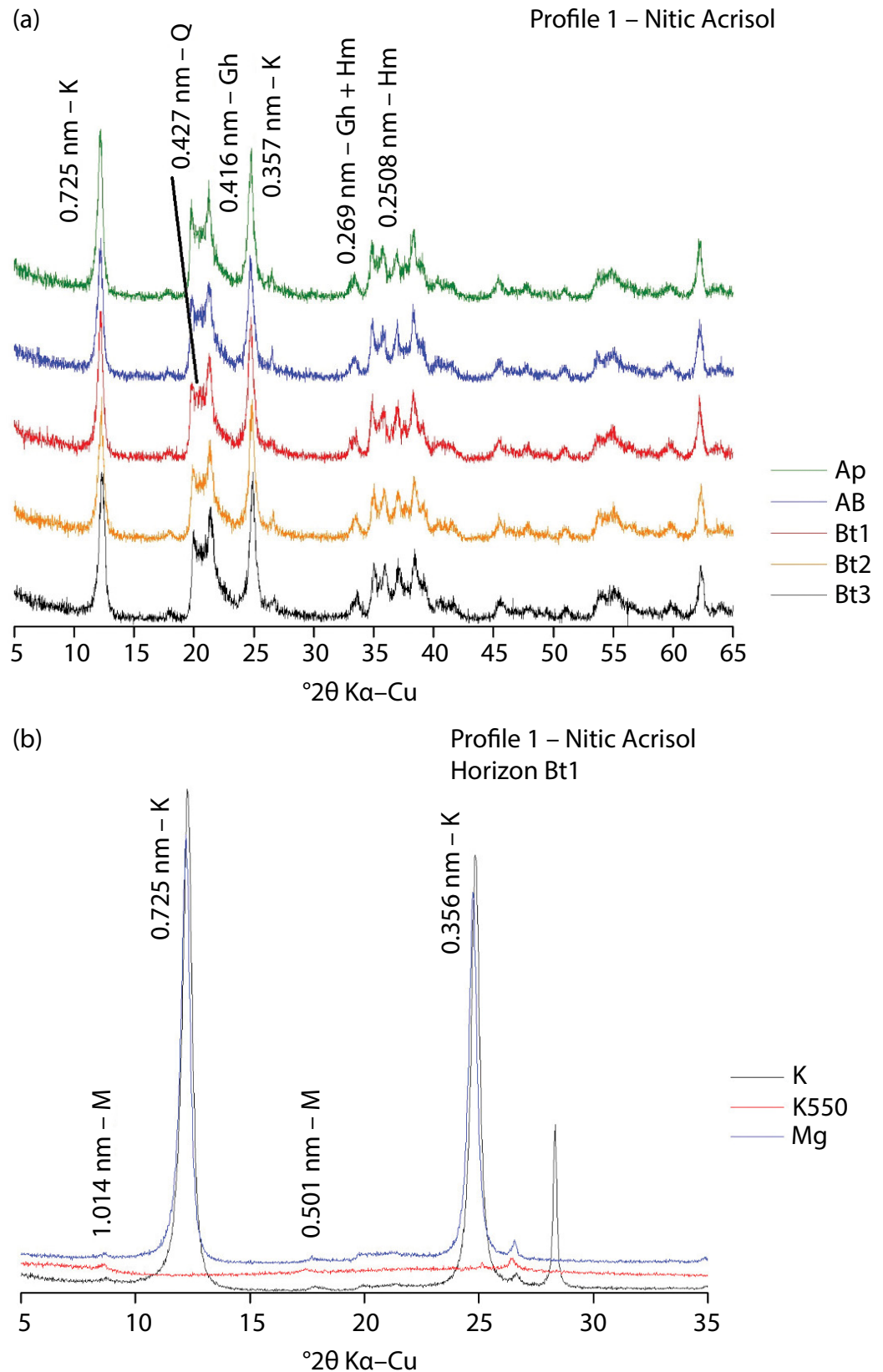
The mineralogy is identical in all profiles studied. Thus P1 was chosen to represent the toposequence, since the XRD of all horizons and profiles were similar. The mineralogical assemblage of the clay fraction of the studied soils is constituted mainly by kaolinite, goethite, and hematite in addition to quartz (Figure 3a). The presence of mica (illite) in all profiles was also detected (Figure 3b).

## DISCUSSION

The soils distribution does not follow a catenary differentiation, as a sequential change in soils along the slope, common in models of soil genesis in the tropics, as Milne's catena concept. Although with variations in soil location in the landscape and steeply sloping surfaces (15-33 %), no change was observed in the soil class along the slope, but a sequence of *Argissolos Vermelho-Amarelos* (Acrisols and Lixisol) well developed (>1.50 m). Nevertheless, differences between the profiles of soils studied can be attributed to the relief, supposedly reflect erosive processes and the participation of lateral water flow (superficial and basal) (Moniz and Buol, 1982).

The argic horizon in the studied sequence was developed on a convex slope, which did not favor its development. Thus, the development of argic horizon of profiles may be related to desiccation-induced compression as described by Moniz and Buol (1982). These authors suggest that a steeper relief increases the lateral flow of the soil solution and the cycles of wetting and drying, favoring the dispersion and clay illuviation (Castro, 1989; Vidal-Torrado and Lepsch, 1993), as observed by the textural gradient and clay coatings in all profiles (Tables 1 and 2).





**Figure 3.** X-ray diffraction (XRD) of the natural clay fraction in the form of oriented aggregates from all horizons of P1 (a), and of the clay fraction from Bt1 horizon of P1 (b). The XRD of P1 represents all the profiles studied since the XRD of all horizons and profiles were similar.

Bulk density values were high in the surface horizons ( $1.52 \text{ Mg m}^{-3}$ , on average) and subsurface (average of  $1.67 \text{ Mg m}^{-3}$ ) of the studied profiles, especially larger on the surface of the Bt horizon. This may be related to the formation of a compressed layer

by desiccation of horizon, and the plastic deformations induced by soil water behavior (Costa and Libardi, 1999). The depth of occurrence does not indicate compaction due to agricultural practices.

The higher clay content and soil bulk density of the Bt horizons determined a higher microporosity (Figure 2c), especially in the P2 and P3 profiles. According to Moniz and Buol (1982), on steeper slopes with anisotropic hydraulic conductivity values can favor the conditions for the formation of the Bt horizon. This occurs because to the concentration of water in a lateral flow zone, since favors the dispersion of clay minerals, deposited in the pores of the soil, increasing the clay content and microporosity (Moniz et al., 1982; Moniz, 1996; Costa and Libardi, 1999).

A moderate, strong, very small, and small angular blocky structure of the compressed layer (Bt) was observed in P2 and P3. Moniz and Buol (1982) also suggest that subangular blocky structure of the compressed layer occurs due to a plastic deformation induced by different conditions of alternate wetting and drying, which are induced probably by sloping surfaces. The aggregates have a large amount of flat surfaces, on the contrary of the subangular blocky structure of P1.

Desilication and leaching are the major processes in the well-drained soils, indicating a high degree of weathering of these soils, as reflected by the low values of silt/clay ratio (Table 2). The studied profiles were obtained of surfaces with a relief of dissected escarpments, constituting a testimony of the erosive retreat between the upper compartments of the Borborema Plateau and the recessed areas (Bigarella et al., 1994; Bezerra et al., 2008). The fine sand/coarse sand ratio, with small variation in depth, indicates that on this slope there is apparently no lithological discontinuity.

Despite the absence of mechanization and the permanent character of the banana crop, the rugged relief favored laminar erosion along the whole slope. The profiles of the upper and lower third are more clayey from the surface, while the profile (P2) of the middle third is more sandy on the surface (Table 2). The P2 show a silt/clay ratio higher than the other profiles, above 1.0 and a textural relationship that influences its classification, which can be attributed to a loss of clay in the A horizon by differential erosion at this relief position.

The topography, texture, and lower flocculation degree in the surface layers, probably due to increased negative charges after application of corrective and higher organic matter content, could favor the loss of suspended clay under heavy rainfall or cultivation practices, which could determine the widespread occurrence of erosion. Nunes et al. (2001) observed soils highly susceptible to erosion with argic/nitic B horizons in the hilly landscape of Minas Gerais. However, the low disintegration of aggregates during wet sieving, as indicated by high MWD values (predominantly >2.0 mm) due to small soil movement, reflects high stability and contributes to the maintenance of the great thickness of the studied soil profiles, even in steep slopes (P2). Although the reduction of MWD values was evident on the surface of P2.

The aggregates observed in the present study are larger than those found by Palmeira et al. (1999) and Soares (2005), who describe sizes of the concentrated aggregates in the median range inferior to 1.00 mm in the conventional management area. Water-stable aggregates contribute to improved porosity, increased water infiltration, and erosion resistance (Tisdall and Oades, 1982; Pinheiro et al., 2004).

Despite the presence of illite, the levels of  $K^+$  were low in all soils (Figure 3 and Table 3). This indicates that under continued cultivation this element is rapidly depleted, which can be attributed to the export by the fruits, since the banana is a very demanding crop of this nutrient (Delvaux, 1995), besides the leaching, requiring supply by fertilizer application, at a high economic cost. The higher and more uniform K content in P3 (lower

third) in relation to the other profiles is attributed to its great mobility in the soil, which facilitates its displacement to the lower part of the relief.

The most of the chemical analyses showed that the studied soils presented characteristics (movement of elements and especially in cations) that are common features of the location soil (i.e., erosion or accumulation position) of tropical and sub-tropical areas (Clemens et al., 2010; Dessalegn et al., 2014). The highest SS in the middle and lower third of the slope is probably related to materials deposited by soil erosion from the higher portions of the relief, such as clay and oxides (Grohmann, 1972). *Argissolos* (Acrisols) from gneiss change in moist climates show low chemical fertility (Lima et al., 2007).

This is consistent with the presence of minerals such as kaolinite, goethite, illite, and quartz in the clay fraction of all soils profiles (Figure 3) and low values T (Table 3), indicating the neof ormation was an important process. This soil mineralogy demonstrates the influence of the humid tropical climate for the genesis of soils with a high degree of weathering, which generally uniformizes the mineralogy of the clay fraction along the slope, as described by Neves et al. (2018) and Brilhante et al. (2017) on the south coast of Pernambuco. This also highlights the importance of management that increases the contribution of the organic matter to the exchange complex of these soils (Stevenson, 1994).

Kaolinite formed during the mineralogical evolution of the soils can be attributed to the alterations of the feldspars, common in the parent material. Costa et al. (2018) described pathways of alteration followed by feldspars, mainly, resulted in kaolinite when studying soil developed from the conglomerate of the Cabo Basin in a similar environment, on the south coast of Pernambuco (Litoral/Mata physiographic unit).

Most studies describing illite formation in soils have concluded that the source of illite particles is mica, usually muscovite (Meunier and Velde, 2004). Only a few studies have indicated considerable illite formation in leached soils of the temperate or tropical regimes (Juang and Uehara, 1968; Torrent and Cabedo, 1986; He et al., 2008). In the present study, the inexpressive occurrence of other 2:1 minerals that could be a source of illite suggests that illite may be a product of muscovite alteration in these soils, already present among the primary minerals more resistant to weathering of the parent rock.

The fact that illite have easy relative weathering at the local climate, hot and humid, implies that the weathering solutions suggesting that the activity of potassium is high. Although the available K content is low (Table 3), the amount of exchangeable K extracted from the soil may be less than the K absorbed by the crop, indicating the importance of non-exchangeable forms of K for plant nutrition (Martins et al., 2004). The presence of these minerals in the clay fraction of the profiles as a source of K for plants may have contributed to the banana farming has become the second most important agricultural activity in this region (Barros et al., 2008).

The formation of goethite in these soils would be product of the alteration of ferromagnesian minerals (Buol and Weed, 1991), such as amphiboles and biotite present in granite, which exhibit strong alteration in tropical climate (Buol and Weed, 1991). Brilhante et al. (2017) demonstrated that the formation of goethite in rhyolite-derived soils under similar climatic conditions was derived of mafic minerals and primary oxides, associated with changes in the pedogenetic environment, more favorable to the maintenance of moisture in the soils.

In the lower third of the slope, the pH(H<sub>2</sub>O) is higher throughout the profile (~7.0), which may have a negative effect on the availability of micronutrients such as boron, zinc, iron, and manganese (Miller and Donahuer, 1990) and, also, the availability of phosphorus. In the upper and middle third the pH is higher only on the surface, reflecting the productive

system due to the application of limestone to the superficial layer. These changes in pH reflect a movement of bases along the slope. For the banana crop, which does not have many restrictions on pH, its highest yields are in soils with pH between 6.0 and 6.5. This is confirmed by the eutrophic V in P3 (lower third), possibly due to the mobilization of the nutrients towards the lower part of the toposequence, and in the superficial horizon of the other profiles, attributed to fertilization and soil organic matter. While the highest value of S ( $3.51 \text{ cmol}_c \text{ dm}^{-3}$ ) was observed in the A horizon of P1 (upper third), due to the lower slope and erosion.

High available P values (Table 3) in the surface may be due to the NPK fertilization carried out in the area. Higher levels of P in the superficial layers were also observed by Azevedo et al. (2007) in the chemical characterization of an Oxisol, in the layers of 0.00-0.05, 0.05-0.10, 0.10-0.20, 0.20-0.40 m, under tillage systems in eastern Maranhão. Besides the release of P during the decomposition of residues and the lower P fixation by inorganic soil constituents (Sidiras and Pavan, 1985), since the studied soils undergo little or no incorporation of plant residues into the soil. The low mobility of P can be seen by its low distribution in depth (Table 3). In P2 (middle third) did not observe high available P content at the surface, which may be related to the precipitation of insoluble calcium phosphates at high values of pH and  $\text{Ca}^{2+}$  (Haynes, 1982) in the Ap horizon, demonstrating that soil erosion is not the only loss factor of P (Table 3).

The higher C content observed in P2 (middle third) is considered atypical for slope position, probably resulting from erosive processes and the characteristics of banana crop, with high incorporation of cultural remains on the soil surface. Or it may be related to its greater slope, making it a position of lesser movement due to its position, resulting in a decrease in the rates of losses of organic matter by decreasing the decomposition (Bayer et al., 2000), due to the smaller fractionation and incorporation of the vegetal residues.

Despite the accumulation of clay in the subsurface in all studied profiles, only the P2 (middle third) has textural gradient to be classified as *Argissolo* (Acrisol). The polychromy and dystrophy in P2 allowed for the classification as *Argissolo Vermelho-Amarelo Distrófico típico* (Haplic Acrisol). The other profiles, P1 (upper third of the slope) and P3 (lower third), do not exhibit typical textural gradient of *Argissolo*; however, the presence of polychromy prevents their classification as *Nitossolo* (Nitisol), so they were therefore classified as intermediate soils between these two orders. In addition, the basic difference between the profiles (P1 and P3) is the base saturation, higher in the lower third (P3), classified as *Argissolo Vermelho-Amarelo Eutrófico nitossólico* (Nitic Lixisol), while the P1 was classified as *Argissolo Vermelho-Amarelo Distrófico nitossólico* (Nitic Acrisol).

Whereas the studies of soil as part of an inventory of soil and landform systems in the northeast of PE are scarce, where *Argissolos Vermelho-Amarelos* and *Vermelhos* represent the most extensive soil type of this region (Araújo Filho et al., 2000; Embrapa, 2012). Our results show the development of highly weathered soils with presence of 2:1 minerals (illite), even under humid tropical climate and continuous cultivation of banana. This highlights the existence of a pedodiversity still little known in the region, which probably differentiated the agricultural potential of these soils, allowing the cultivation of banana with low technology management systems, in contrast to the cultivation of sugarcane extensively practiced in the region. The formation of illite, although not investigated in this study, in an environmental setting that, within the framework of the wider survey, seems confined to the dry areas of the landscape (transition Mata-Agreste), relative to the coast of Pernambuco, Litoral/Mata physiographic unit (wetter).

## CONCLUSIONS

The soils are highly weathered, essentially kaolinitic, with goethite, quartz, and illite in the soil clay fraction, low nutrient retention, good internal drainage and subject to leaching.

Although the soils show a decrease in total porosity and increase soil density in the sequence from the highest to the lower third, and present small variations in physical properties in the position of the middle third (P2), they are well structured and allow good development of the root system.

The steepest slope (P2) had the lowest content of clay, phosphorus and the mean weight diameter of aggregates, and higher organic carbon content, in the Ap horizon, due to removal and deposition by water erosion.

The soils were classified as: P1 - *Argissolo Vermelho-Amarelo Distrófico nitossólico* (Nitric Acrisol); P2 - *Argissolo Vermelho-Amarelo Distrófico típico* (Haplic Acrisol); and P3 - *Argissolo Vermelho-Amarelo Eutrófico nitossólico* (Nitric Lixisol), as a function of the position in the relief. The profile of the lower third (P3) was enriched by the exchangeable bases removed from the higher parts.

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