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Variability and correlation of physical attributes of soils cultivated with cacao trees in two climate zones in Southern Bahia, Brazil

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Abstract Cacao (*Theobroma cacao*) is a very important crop in Southern Bahia, Brazil, which needs good climate and soil conditions and management for great productivity. In this region, cacao is grown on a large number of soil types, and soil properties have great effects on its sustainability and production potentials. The aim of this study was to evaluate the variability of physical attributes of soils cultivated with cacao in two climate zones in Southern Bahia, Brazil, as well as to evaluate the correlation between these physical attributes. Eighty soil samples were evaluated from 20 cacao farms with cacao agroforestry systems, from the 0–0.1 and 0.1–0.3 m soil layers. The soil analyses comprised granulometry, soil bulk density, particle density, porosity (total, macro, and micro), gravimetric moisture, and soil resistance to penetration. The data were submitted to descriptive statistical analysis and correlation between variables. Most variables had normal distribution ($p > 0.05$) and high variability. In general, these soils had good physical conditions for the production of cacao, except for the high resistance to root penetration which can be limiting factor. The greatest differences in physical attributes of the soils were: gravimetric moisture, resistance to penetration, macroporosity, and sand content. The correlations between physical attributes of the soils varied according to the sampled layer and the climate zone. The resistance to penetration was not correlated with any of the determined physical attribute.

Keywords Agroforestry system · Cacao-cabruca · Soil physical properties · Descriptive analysis

Introduction

Cacao (*Theobroma cacao* L.) has been cultivated for centuries in the Americas, and there are reports that confirm its cultivation long before the European settlers came to the Americas (Lobão et al. 2012). In Southern Bahia, the first plantings started more than 200 years ago, and the cacao trees were planted in the primary forest, this agricultural system was later called the Cacao-cabruca system (Lobão et al. 2012).

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Southern Bahia region is considered the “cacao belt” in Brazil and the soils are highly variable, composed of 31 pedologic units, mainly related to their geological and mineralogical diversity (Santana 1985; Santana et al. 2002; Chepote et al. 2012). Among the characteristics of the soils, the physical attributes are important for crops development, due to the influence of soil water retention capacity, infiltration rate, depth of root system and, hence, productivity, especially in less rainy years (Braudeau 1970; Souza Júnior et al. 1999; Sanchez 1976; Chepote et al. 2012).

In general, soil texture (granulometric composition) alone is considered one of the most important soil physical attributes, since it influences soil bulk density (BD), porosity, soil structure and water retention (Ferreira 2010). After the granulometric composition, the soil structure is considered the next most important property, since it affects gas exchange, porosity, soil bulk density and water retention (Koorevaar et al. 1999). Soil bulk density is an important attribute used to estimate the structure and porosity of the soil (Letey 1985), and it is influenced by soil management practices (Becher 1995). The porosity of the soil has an impact on gas exchange, water dynamics, resistance to penetration and, therefore, the spreading of roots in the soil and the absorption of the available water and nutrients (Tognon 1991). The porosity has different size of pores, which can be classified as macropores and micropores; the first ones are important for the drainage of water and gas exchange of the soil, while the micropores are important for water retention in the soil.

Briefly, the physical attributes of a soil affect its capacity for drainage, storage, and availability of water in the soil (Tognon 1991; Koorevaar et al. 1999; Ferreira 2010), which is essential in the production process of plants. The effects may be direct, considering their participation in the metabolism and turgidity of cells, or indirect, considering their role as agents in the movement of solutes and metabolic products (Zevallos 1977; Kramer and Boyer 1995).

Cacao is considered highly susceptible to water deficit, and the oscillations of rainfall are the main cause of variations in crop productivity (Alvim 1959; Almeida et al. 1987; Souza Júnior 1997); however, in drier years, the physical attributes of the soils related to water dynamics better explain the differences in productivity between stands of cacao (Souza Júnior et al. 1999). With the more worrying effects of climate change and consequently drier years, it is crucial to carry out research on soil physical attributes due to their high influence in production with varying climate. Therefore, this study aimed to evaluate the variability of physical attributes of soils cultivated with cacao in two climate zones in Southern Bahia, as well as to evaluate the correlations between these physical attributes.

Materials and methods

The study was carried out in Southern Bahia, Brazil between January and February of 2012 on 20 farms that had cacao in an agroforestry system (Cacao-cabruca). Mature cacao trees up to 30 years old were being replaced through grafting of basal shoots with clones that are tolerant to witches’ broom diseases. Since the plants were in the process of renovation no production data were obtained from the selected fields. In each farm four areas were selected in different topographical and edaphic situations, making a total of 80 areas (80 soils) cultivated with cacao. Selected areas had different clones in each plot with cultural practices that included liming, fertilizer, pruning, shading management and disease control, without mechanized practices or irrigation.

Among the selected farms, ten were located in the humid zone with mean annual precipitation ranging from 600 to 1200 mm, fitting in seven climate types according to Thornthwaite: B4r A’, B3r A’, B2r A’, B2r B’, B1r A’, B1r’ A’, and B1w A’; and ten farms were selected in the humid to sub-humid zone, hereafter referred to only as sub-humid, which has mean annual water surplus ranging from 50 to 600 mm, fitting in four climate types: C2d A’, C2d’ A’, C2d B’, and C2w A’ (SEI 2014). Table 1 presents the municipalities according to climate zone and the selected farms in each of the climatic zone.

In each farm, four areas situated in different edaphic and topographic conditions were selected, and one plant was selected in each area as a reference to carry out the sampling of the soils.

Soil sampling

Within a radius of 1.5–2.0 m from the stem of the reference plant, disturbed and undisturbed samples were collected in the layers 0–0.1 and 0.1–0.3 m. To

Table 1 List of municipalities in Southern Bahia, Brazil, where the farms selected for the descriptive analysis study of soil properties are located

Zones	Municipalities	Farms
Humid	Camacã	Nossa Senhora de Fátima
	Piraí do Norte	Deus que me deu
	Igrapiúna	Santo Antônio
	Nova Ibiá	São Rafael
	Ibirapitanga	São Domingos 2
	Maraú	Moeda
	Santa Luzia	Bom Retiro
	Itabuna	Nova Vida
	Arataca	Ubirajara
	Uruçuca	Leolinda
Sub-humid	Barra do Rocha	Bela Floresta
	Ibirataia	Lajedo do Ouro
	Itagibá	São Domingos 1
	Jequié	São Domingos 4
	Itagi	Jacarandá
	Ibirataia	Bom futuro
	Ipiaú	Sucuriú
	Ibirataia	São José
	Ibirataia	Canaã
	Itagibá	Oceania

obtain the disturbed composite samples, 12 simple samples of soil were collected with the aid of a 2 cm soil probe; these samples were air dried and sieved through a 2 mm mesh, obtaining the air-dried fine soil (ADFS). The undisturbed samples were collected with the use of volumetric rings, with five replications per area.

Physical analyses of the soil

The physical analyses were determined according to EMBRAPA (2011). The granulometric analysis was carried out on samples of ADFS through the Hydrometer method, in which 50 g of soil was added to 100 mL of distilled water and 25 mL of NaOH (1 mol L^{-1}) and stirred in shakers at 12,000 rpm for 5 min when the soil was sandy or 15 min when clayey.

The particle density (PD) was determined through the volumetric flask method, using ethyl alcohol as penetrant liquid. The soil bulk density (BD) and the porosities (micro, macro, and total) were determined in the undisturbed samples. The BD was calculated through the following formula: BD = m/v, in which m = sample mass dried at 105 °C (kg), v = ring volume (dm^3); and total porosity (TP) was determined through the formula TP = (PD − BD)/PD (m^3 m^{-3}). For microporosity (Mi), the samples were saturated for 24 h and, thereafter, placed on a suction table and submitted to a tension of 60 cm of water column until drainage ceased; then, they were weighed and placed in an air circulation oven at 105 °C for 48 h, and then weighed again. To calculate microporosity, the following formula was used: Mi = (a − b)/c, in which a = sample mass after being submitted to a tension of 60 cm of water column (kg), b = sample mass dried at 105 °C (kg), and c = cylinder volume (dm^{-3}). Macroporosity (Ma) was determined through the difference between TP and Mi.

In order to determine the current gravimetric moisture (GM), undisturbed soil samples were oven-dried at 105 °C for 24 h. The calculation was: GM = (a − b)/b, in which a = moist sample mass (kg) and b = dry sample mass (kg).

To determine the soil resistance to penetration, an impact penetrometer (Model IAA/Planalsucar/Stolf) (Stolf et al. 1983) was used, in the layers 0–0.1 and 0.1–0.3 m, with five replications. Subsequently, the values were transformed into MPa and adjusted based on the current gravimetric moisture and the BD, according to Vaz et al. (2011).

Statistical analysis

Descriptive analysis (minimum, maximum, mean, median, and, coefficient of variation) was performed for the two climate zones, together and separately, as well as Shapiro–Wilk normality test, F test for climatic zones and Pearson correlation analysis, both at the 5% level of significance, using the statistical software R (R Development Core Team 2008).

Results and discussion

The descriptive analyses of the physical attributes of the 80 soils from the 20 farms studied in Southern Bahia, Brazil (humid and sub-humid zones), in both soil layers, are presented in Table 2 and, according to climate zone, Table 3.

Table 2 Descriptive analysis of the physical attributes of 80 soils cultivated with cacao trees, in 20 farms in Southern Bahia, located in two climate zones (humid and sub-humid zones)

Variable	Unit	Minimum	Maximum	Mean	Median	CV %	Normality
0–0.1 m layer							
Sand	g kg^{-1}	36	869	509	508	34.1	0.96*
Silt	g kg^{-1}	55	474	168	145	52.5	0.84**
Clay	g kg^{-1}	60	590	322	330	44.0	0.96*
BD	kg dm^{-3}	0.92	1.78	1.35	1.38	12.4	0.98^{ns}
PD	kg dm^{-3}	2.35	2.84	2.60	2.60	3.4	0.99^{ns}
TP	m^3 m^{-3}	0.33	0.63	0.48	0.47	12.5	0.98^{ns}
Mi	m^3 m^{-3}	0.04	0.58	0.33	0.36	34.8	0.97^{ns}
Ma	m^3 m^{-3}	0.02	0.33	0.15	0.13	53.2	0.95**
PR	Mpa	0.66	4.60	2.03	1.80	39.6	0.87**
GM	kg kg^{-1}	0.06	0.64	0.28	0.27	44.9	0.96*
0.1–0.3 m layer							
Sand	g kg^{-1}	38	813	428	416.3	40.8	0.99^{ns}
Silt	g kg^{-1}	55	459	134	109.6	59.8	0.74**
Clay	g kg^{-1}	40	755	438	467.5	39.7	0.97*
BD	kg dm^{-3}	1.07	1.87	1.44	1.43	12.1	0.99^{ns}
PD	kg dm^{-3}	2.55	2.91	2.69	2.69	2.7	0.97^{ns}
TP	m^3 m^{-3}	0.30	0.62	0.46	0.47	14.5	0.99^{ns}
Mi	m^3 m^{-3}	0.05	0.51	0.33	0.37	32.9	0.93**
Ma	m^3 m^{-3}	0.02	0.39	0.13	0.12	62.3	0.93**
PR	MPa	0.07	6.90	3.00	2.85	50.2	0.96**
GM	kg kg^{-1}	0.06	0.41	0.25	0.25	36.2	0.97*

BD soil bulk density, *PD* particle density, *TP* total porosity, *Mi* microporosity, *Ma* macroporosity, *PR* soil resistance to penetration, *GM* soil gravimetric moisture

*, ** Non-normal distribution according to the Shapiro–Wilk test at 5 and 1% significance

^{ns}Normal distribution according to the Shapiro–Wilk normality test at 5% significance

Regardless of the climate zone and the sampled layer, there were high values of coefficient of variation (CV) and high amplitudes (differences between the minimum and maximum values) for most physical attributes of the analyzed soils (Tables 2, 3), indicating high spatial variability of the cultivated soils with cacao in both climate zones in Southern Bahia, Brazil, which is an understandable fact, given the great pedologic and mineralogic diversity of the region (Santana 1985; Santana et al. 2002; Chepote et al. 2012). An exception was observed for PD, which had little variability, and BD and TP, which had moderate CVs, despite the differences between the minimum and maximum values of the 80 soils being greater than 75% (Table 2).

When the data from the 20 variables analyzed (10 physical attributes of two layers of soil) were pooled, only eight had normal distribution (Table 2); however, when analyzed by climate zone, it was observed that 15 and 14 variables had normal distribution in the sub-humid and humid zones, respectively (Table 3), indicating that, when analyzed separately by climate zone, more than 70% of the variables had symmetric distribution around the mean.

For most of the variables, regardless of the sampled layer and climatic zone, the observed mean values were similar to their respective median, indicating that the mean would be a good reference of the central value of the sample. In general, this proximity between the mean and median values was greater for the sub-humid zone, compared to the humid zone (Table 3). When the 80 soils were analyzed together, considering all the physical attributes, the greatest differences between mean and median were detected for silt and PR, which were higher than 16%, regardless of the soil layer (Table 2); and these differences were greater than 21% for the humid zone alone, except for PR in the layer 0–0.1 m (Table 3).

The total data set (Table 2) demonstrates that the soils had mean sand contents of 509 and 428 g kg^{-1}; silt of 168 and 134 g kg^{-1}; clay of 322 and 438 g kg^{-1} at depths of 0.0–0.1 and 0.1–0.3 m, respectively, indicating that on average the soils should have a fast infiltration rate, good aeration, and good water retention (Brady and Weil 2013).

Table 3 Descriptive analysis of the physical attributes of 80 soils cultivated with cocoa trees, in 20 farms in Southern Bahia, according to climate zone

Variable	0–0.1 m layer										0.1–0.3 m layer									
	Sand	Silt	Clay	BD	PD	TP	Mi	Ma	GM	PR	Sand	Silt	Clay	BD	PD	TP	Mi	Ma	GM	PR
Unit	g kg^{-1}			kg dm^{-3}		m^3 m^{-3}			kg kg^{-1}	Mpa	g kg^{-1}			kg dm^{-3}		m^3 m^{-3}			kg kg^{-1}	MPa
Humid zone (40 soils in 10 farms)																				
Minimum	36	55	64	0.92	2.42	0.33	0.04	0.00	0.06	1.10	38	54	105	1.07	2.55	0.30	0.05	0.00	0.10	1.25
Maximum	865	474	590	1.78	2.84	0.63	0.58	0.33	0.64	4.19	771	459	755	1.87	2.89	0.62	0.51	0.39	0.41	5.99
Mean	474	189	337	1.34	2.60	0.48	0.32	**0.17**	**0.34**	**1.68**	**385**	157	458	1.43	2.69	0.47	0.31	**0.16**	**0.30**	**2.44**
Median	479	155	338	1.40	2.59	0.47	0.32	0.15	0.33	1.52	382	129	488	1.43	2.69	0.47	0.32	0.14	0.33	1.96
CV %	42.6	55.5	44.5	15.1	3.6	15.1	46.5	51.8	40.4	36.5	49.3	63.2	37.5	14.1	3.0	16.2	44.2	63.5	29.0	46.9
Normality	0.96^{ns}	0.84**	0.95^{ns}	0.97^{ns}	0.96^{ns}	0.96^{ns}	0.96^{ns}	0.95^{ns}	0.98^{ns}	0.61**	0.98^{ns}	0.78**	0.95^{ns}	0.98^{ns}	0.97^{ns}	0.99^{ns}	0.90**	0.96^{ns}	0.90**	0.78**
Sub-humid zone (40 soils in 10 farms)																				
Minimum	283	69	60	1.12	2.35	0.40	0.15	0.02	0.06	0.66	200	59	40	1.17	2.57	0.33	0.15	0.03	0.06	0.07
Maximum	869	335	545	1.60	2.79	0.55	0.46	0.28	0.33	4.60	813	24	735	1.74	2.91	0.56	0.45	0.27	0.33	6.90
Mean	545	147	308	1.36	2.60	0.48	0.35	**0.13**	**0.22**	**2.38**	**472**	111	417	1.45	2.69	0.46	0.36	**0.11**	**0.20**	**3.56**
Median	544	134	325	1.36	2.61	0.48	0.37	0.12	0.21	2.22	450	101	443	1.42	2.69	0.47	0.37	0.11	0.21	3.69
CV %	24.5	42.1	43.5	9.2	3.3	9.4	20.4	49.8	31.4	34.7	31.4	40.8	42.1	9.8	2.5	12.8	18.7	45.2	31.0	45.8
Normality	0.96^{ns}	0.92**	0.96^{ns}	0.96^{ns}	0.98^{ns}	0.95^{ns}	0.87**	0.95^{ns}	0.97^{ns}	0.94^{ns}	0.97^{ns}	0.84**	0.97^{ns}	0.97^{ns}	0.95^{ns}	0.96^{ns}	0.94*	0.92**	0.98^{ns}	0.94^{ns}
Pv^a	0.28	0.09	0.35	0.63	0.94	0.59	0.18	**0.02**	**< 0.01**	**< 0.01**	**0.02**	0.09	0.30	0.67	0.59	0.78	0.15	**< 0.01**	**< 0.01**	**< 0.01**

BD soil bulk density, *PD* particle density, *TP* total porosity, *Mi* microporosity, *Ma* macroporosity, *PR* soil resistance to penetration, *GM* soil gravimetric moisture

*, ** Non-normal distribution according to the Shapiro–Wilk test at 5 and 1% significance, respectively

^{ns}Normal distribution according to the Shapiro–Wilk normality test at 5% significance

^{a}Significative differences between variables in the humid and sub-humid zone, values $Pv < 0.05$ show significative differences according to test F

Bold represents the significant correlations

However, due to the mean clay contents present in the subsurface layer, they may have slower drainage rates, which could affect cacao development due to its high susceptibility to long periods of flooding (Alvim 1959). The mean contents of the granulometric fractions, in the assessed areas are close to those recommended for cacao cultivation by Wood and Lass (1985), which are of 500 g kg^{-1} of sand, 100–200 g kg^{-1} of silt, and 300–400 g kg^{-1} of clay; however, there are farms with cacao in Southern Bahia with highly variable soil texture conditions; from loamy sand (864 g kg^{-1} of sand and 80 g kg^{-1} of clay) to clayey (318 g kg^{-1} of sand and 590 g kg^{-1} of clay), in the layer 0–0.1 m, and from sandy loam (771 g kg^{-1} of sand and 105 g kg^{-1} of clay) to highly clayey (175 g kg^{-1} of sand and 755 g kg^{-1} of clay) in the layer 0.1–0.3 m. Farms with higher contents of silt and sandy soils, that have low water retention capacity and, consequently, high leaching potential may compromise, especially in drier years, not only the cocoa productivity (Souza Júnior et al. 1999) but also the survival of the plants (Souza Júnior and Menezes 2000); while the highly clayey ones may favor conditions of flooding and anaerobiosis (Baver et al. 1972; Brady and Weil 2013), compromising the productivity of the cocoa trees as well.

Comparison of the data by climate zone (Table 3), reveals that cacao cultivation in the humid zone is conducted in soils with higher contents of sand, since the mean sand content in the subsurface layer is 22.7% higher in relation to the sub-humid zone, however no significant differences were observed. These results are an understandable fact, because the sub-humid zone has a higher frequency of years with water stress, which caused death of cocoa trees, especially in soils with lower water retention capacity (Souza Júnior and Menezes 2000), i.e., the remaining cultivation fields in this region tend to occur in soils having higher water retention capacity and consequently higher available water in periods of water stress.

The coefficients of correlation between the physical attributes of the soils are presented in Tables 4, 5, and 6. For the 0–0.1 m layer, the correlations for the two climate zones together and separately were similar, therefore it was decided to present only the correlations of the set of the two climate zones (Table 4); for the second layer, 0.1–0.3 m, the correlations are presented by climate zone (Tables 5, 6). In all the situations, the sand content of the soils correlated negatively and significantly with clay and GM, and these two variables had positive and significant correlations with each other (Tables 4, 5, 6), a fact that is directly related to the specific surface of the particles, the clay fraction has greater specific surface and, consequently, higher water retention capacity (Hillel 1998).

In the 0–0.1 m layer, no other correlation between the granulometric fractions and the other physical attributes was significant (Table 4). However, in the two climate zones and in the layer 0.1–0.3 m, there were significant positive correlations between clay and TP, and negative correlations between clay and BD (Tables 5, 6). These results were expected due to the inverse relationship between BD and clay and between BD and TP (Baver et al. 1972; Brady and Weil 2013), because the minerals of the clay fraction are important for keeping the soil particles flocculated and stabile in the soil aggregates (Ghidin et al. 2006).

In the sub-humid zone, at 0.1–0.3 m depth, significant correlations were observed between granulometric fractions and other physical attributes of the soils; positive correlations between sand and BD, and between clay and Mi; and negative correlations between sand and TP, between sand and Mi, and between clay and silt (Table 5), which can be understood by the fact that sandy soils tend to have higher density and clayey soils have higher microporosity (Baver et al. 1972; Brady and Weil 2013).

In general, soils had mean values of BD of 1.35 and 1.44 kg dm^{-3} at 0–0.1 and 0.1–0.3 m depth, respectively (Table 2) and no significative differences were observed between climatic zones. USDA (1998) considers optimal values for BD: < 1.6 kg dm^{-3} for sandy soils; < 1.4 kg dm^{-3} for loamy and silty soils; and < 1.1 kg dm^{-3} for clayey soils. With these references, it can be asserted that most of the soils cultivated with cacao trees in Southern Bahia have no restriction in root growth, as a consequence of a good soil structure, which reflects the effect of the cacao agroforestry system on the soils (Severiano et al. 2010; Paiva and Araujo 2012). However, there are soils with higher density, with BD of up to 1.87 kg dm^{-3}, which may cause a decrease in root growth and result in anaerobiosis conditions due to the decrease of MA, flow of water, and gas exchange (Lal and Shukla 2004).

There were significant negative correlations between BD and TP and between BD and Mi, and

Table 4 Coefficients of simple linear correlation (r) between physical attributes of the layer 0–0.1 m, of 80 soils cultivated with cocoa trees, in 20 farms in Southern Bahia, located in two climate zones (humid and sub-humid zones)

	Silt	Clay	BD	PD	TP	Mi	Ma	GM	PR
Sand	− 0.58	**− 0.86****	0.47	0.17	− 0.46	− 0.55	0.46	**− 0.80****	0.25
Silt		0.09	− 0.11	− 0.16	0.07	0.20	− 0.24	0.51	− 0.23
Clay			− 0.51	− 0.11	0.52	0.55	− 0.41	**0.67***	− 0.17
BD				0.39	**− 0.96****	**− 0.78****	0.41	− 0.45	0.07
PD					− 0.12	− 0.17	0.16	− 0.17	0.12
TP						**0.79****	− 0.39	0.44	− 0.04
Mi							**− 0.88****	0.38	0.07
Ma								− 0.22	− 0.14
GM									− 0.48

BD soil bulk density, *PD* particle density, *TP* total porosity, *Mi* microporosity, *Ma* macroporosity, *PR* soil resistance to penetration, *GM* soil gravimetric moisture

*, ** Significance at 5 and 1%, respectively, according to the t test

Bold represents the significant correlations

Table 5 Coefficients of simple linear correlation (r) between physical attributes of the layer 0.1–0.3 m, of 40 soils cultivated with cocoa trees, in 10 farms in Southern Bahia, located in the sub-humid zone

	Silt	Clay	BD	PD	TP	Mi	Ma	GM	PR
Sand	0.51	**− 0.98****	**0.69***	− 0.28	**− 0.68***	**− 0.87****	0.37	**− 0.86****	− 0.04
Silt		**− 0.68***	0.57	− 0.18	− 0.57	− 0.57	0.10	− 0.61	− 0.18
Clay			**− 0.73****	0.29	**0.72****	**0.88****	− 0.34	**0.88****	0.08
BD				− 0.33	**− 0.98****	**− 0.72****	− 0.20	**− 0.65***	0.03
PD					0.52	0.28	0.25	0.22	− 0.02
TP						**0.72****	0.24	**0.63***	− 0.03
Mi							− 0.51	**0.84****	0.19
Ma								− 0.39	− 0.30
GM									0.05

BD soil bulk density, *PD* particle density, *TP* total porosity, *Mi* microporosity, *Ma* macroporosity, *PR* soil resistance to penetration, *GM* soil gravimetric moisture

*, ** Significance at 5 and 1%, respectively, according to the t test

Bold represents the significant correlations

positive correlations between TP and Mi, for both climate zones and soil layers that were assessed (Tables 4, 5, 6). This is due to the great mathematical interdependence between TP and BD, an inverse relationship, in which the variations of both attributes are related to the genesis and management of the soil (Silva et al. 2000). There were significant negative correlations between Ma and Mi for the layer 0–0.1 m, in both climate zones (Table 4), a fact observed only in the subsurface layer for the humid zone (Table 6).

The mean values for TP, regardless of the layer and the climate zone, ranged from 0.46 to 0.48 $m^3\ m^{-3}$, which are similar to the value of 0.50 $m^3\ m^{-3}$ proposed by Brady and Weil (2013) for an ideal soil of average texture; therefore, these soils have good aeration and proper conditions for the growth of plants. However, there were soils with minimum TP values of 0.30 $m^3\ m^{-3}$, indicating possible problems with aeration of the soil (Tables 2, 3). The mean values for Mi ranged from 0.32 to 0.35 $m^3\ m^{-3}$; however, in the humid zone, regardless of the sampled

Table 6 Coefficients of simple linear correlation (r) between physical attributes of the layer 0.1–0.3 m, of 40 soils cultivated with cocoa trees, in 10 farms in Southern Bahia, located in the humid zone

	Silt	Clay	BD	PD	TP	Mi	Ma	GM	PR
Sand	− 0.43	− **0.85****	0.56	− 0.05	− 0.57	− 0.60	0.39	− **0.70***	− 0.01
Silt		− 0.10	0.21	0.16	− 0.18	0.18	− 0.39	0.14	− 0.18
Clay			− **0.74****	− 0.03	**0.73****	0.56	− 0.20	**0.69***	0.12
BD				0.09	− **0.98****	− **0.67***	0.17	− 0.60	− 0.08
PD					0.11	0.16	− 0.14	− 0.27	− 0.11
TP						**0.71***	− 0.20	0.55	0.06
Mi							− **0.84****	0.32	0.15
Ma								− 0.02	− 0.17
GM									− 0.09

BD soil bulk density, *PD* particle density, *TP* total porosity, *Mi* microporosity, *Ma* macroporosity, *PR* soil resistance to penetration, *GM* soil gravimetric moisture

*,** Significance at 5 and 1%, respectively, according to the t test

Bold represents the significant correlations

layer, extreme values for Mi (< 0.04 m^3 m^{-3} and > 0.58 m^3 m^{-3}) were observed, which compromises the satisfactory dynamics of the water in the soil, either by low retention or low percolation of water in the soil, respectively, and can affect the root growth and production of plants. On the other hand, the mean values for Ma ranged from 0.13 to 0.17 m^3 m^{-3} (Tables 2, 3), i.e., above the minimum of 0.10 m^3 m^{-3} for aeration porosity proposed by Tormena et al. (1998), so there should be no limitation to the full development of the plants root system. The Ma values for the humid zone were significantly higher ($Pv < 0.05$) than those for the sub-humid region, on average, 31 and 45% for the layers 0–0.1 and 0.1–0.3 m, respectively (Table 3).

There was a great variation in the soil gravimetric moisture of the soil samples between the climate zones, presenting significant differences ($Pv < 0.01$) and the means for the GM in the humid zone were 55 and 50% higher than the means of the sub-humid zone, in the layers 0–0.1 and 0.1–0.3 m, respectively (Table 3), a fact that reflects the water regime of each zone. In the humid zone, the mean GM contents were 0.34 and 0.30 kg kg^{-1} in the layers 0–0.1 and 0.1–0.3 m (Table 3), respectively, which are higher than the reference value of 0.25 kg kg^{-1} suggested by Kiehl (1979), indicating good water reserve at the time the samples were collected. In the less humid region, there was significant positive correlation between GM and TP and between GM and Mi and negative between GM and BD, evidencing the importance of porosity, especially with Mi, for the storage of water in soils (Baver et al. 1972; Kiehl 1979; Brady and Weil 2013).

Another physical attribute that differed significantly ($Pv < 0.01$) between the two regions was the soil resistance to root penetration, the mean values for PR in the sub-humid zone were 42 and 46% higher than the means for the humid zone, in the layers 0–0.1 and 0.1–0.3 m, respectively (Table 3). In the sub-humid zone, the mean PR values were 2.38 and 3.56 MPa in the layers 0–0.1 and 0.1–0.3 m, respectively, indicating high values, considering the reference value of 2.0 MPa as the limit above which there is limitation for root growth of agricultural crops (SSDS 1990; Imhoff et al. 2000; Tormena 2002). Furthermore, high PR values decrease the air space and water storage in the soil (Holshouser 2001), with negative effects on plant growth due to reduced availability of water and absorption of nutrients (Cueto et al. 2009; Giarola et al. 2009). For the humid zone, it was observed that only for the surface layer the mean value of PR is considered adequate (Table 3). Although soil moisture is considered a factor controlling compactness (Dias Junior and Pierce 1996) and consequently PR, this fact should not be attributed to the higher water content in the soil in the humid zone, since the PR data were adjusted based on moisture and BD according to Vaz et al. (2011). The PR had no significant correlation with any other physical variable of the soil individually (Tables 4, 5, 6), suggesting that it depends simultaneously on various physical attributes of the soil.

Conclusion

The soils cultivated with cacao in Southern Bahia, Brazil had high variability in their physical attributes; however, on average, they have good physical attributes, except for the high resistance to penetration. In general the cacao trees cultivated in the sub-humid zone have major physical constraints and could even show some reduction of yield due to low macroporosity and humidity and high penetration resistance. The correlations between the physical attributes of the soils varied according to the sampled layer and the climate zone, and the resistance to penetration alone was not correlated with any other physical attribute.

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