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Relationship between soil physical properties and cocoa yield in no-till renovated orchards in southern Bahia, Brazil

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ABSTRACT: In southern Bahia, Brazil, cocoa trees (*Theobroma cacao* L.) are grown in soils with varied physical properties. As many orchards in the region have surpassed their productive lifespan, renewal is crucial for increasing productivity. However, there is limited understanding of how soil physical properties affect the productivity of renovated cocoa orchards. This study aimed to assess the relationship between soil physical properties and cocoa productivity in no-till renovated orchards. The research was conducted across 15 field trials on cocoa farms in southern Bahia. Cocoa yield was monitored from 2019 to 2022 (4th to 7th year post-establishment), while soil physical properties—granulometry, porosity, bulk density, soil penetration resistance, and volumetric water content (at field capacity, permanent wilting point, and available water)—were measured in 2019 as baseline in three soil layers: 0.00–0.10, 0.10–0.20, and 0.20–0.40 m. Data were subjected to univariate and multivariate statistical analyses. In all layers, yield was significantly correlated ($p<0.05$) with silt content ($r = -0.29$ to -0.31), silt/clay ratio ($r = -0.23$ to -0.27), field capacity ($r = 0.24$ to 0.34), permanent wilting point ($r = 0.23$ to 0.26), and available water ($r = 0.22$ to 0.24). Principal Component Analysis showed that yield was positively associated with field capacity and permanent wilting point, and negatively related to soil resistance to penetration and bulk density in the surface layers. Hierarchical cluster analysis grouped the 90 plots into four productivity classes: G1 (74 %, 2,758 kg ha^{-1}), G2 (58 %, 1,878 kg ha^{-1}), G3 (37 %, 1,557 kg ha^{-1}), and G4 (17 %, 792 kg ha^{-1}). Tukey's HSD test ($p<0.05$) revealed that the higher-yielding groups (G1 and G2) had significantly lower silt content and silt/clay ratios compared to the lowest-yielding group (G4). Overall, cocoa yield was constrained by excessive soil penetration resistance in surface layers and by high silt content and silt/clay ratios across all layers, while balanced sandy-clay textures with improved aeration and water retention favored higher productivity. These results corroborate previous studies recommending cocoa cultivation in soils with lower silt content, due to its association with compaction, drainage limitations, and reduced water retention. The findings highlight the importance of considering soil physical properties, particularly granulometry, as a criterion for selecting priority areas for orchard renewal, thereby contributing to high-yielding and climate-resilient crops.

Keywords: soil texture, climate change, drought, flooding, cacao agroforestry system.

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INTRODUCTION

Globally, the cocoa supply chain faces the challenge of increasing bean supply through the renewal of aging orchards and the adoption of good agricultural practices. In southern Bahia, Brazil, as in West Africa (Wessel and Quist-Wessel, 2015; Saj et al., 2017; Asante et al., 2022), many cocoa crops are depleted and low-yielding, exposing the raw material supply to industry and farmers' incomes. This situation is primarily attributed to aging crops, inadequate management practices such as insufficient pruning, inadequate fertilization, and limited pest and disease control, as well as edaphic limitations and extreme weather events (Gateau-Rey et al., 2018; Somarriba et al., 2021; Orozco-Aguilar et al., 2024). Consequently, when renewing crops, priority should be given to areas with soil and climatic conditions conducive to higher productivity and enhanced cocoa resilience to climate change; for this, understanding the relationship between soil physical properties and crop productivity is crucial.

In southern Bahia, some soils exhibit physical limitations that hinder root growth, including poor aeration, inadequate drainage, low water retention capacity, and high resistance to root penetration (Paiva et al., 2018; Arévalo-Hernández et al., 2019). Cocoa tree root system is predominantly concentrated (60-90 %) in the 0.00–0.30 m soil layer (Cadima, 1970; Kummerow et al., 1982; Borden et al., 2020), although the taproot can reach depths of approximately 2.00 m (Toxopeus, 2001). Since the cocoa tree is extremely sensitive to water deficit (Carr and Lockwood, 2011; Gattward and Almeida, 2018), deep root development is crucial for water absorption, thereby enhancing productivity and crop longevity under rainfed conditions.

In recent decades, severe droughts in southern Bahia have reduced productivity and caused cocoa tree mortality (Gateau-Rey et al., 2018; Souza Júnior et al., 2023), particularly in soils with low water retention capacity and physical impediments to root development (Souza Júnior et al., 1999, 2023). These impediments arise from both water saturation in hydromorphic soils (e.g., *Gleissolo* - Entisols) and the presence of gravel and stones in young soils (e.g., Cambissolo - Inceptsols). Additionally, physical impediments are caused by cohesive layers in the subsurface horizons of certain soils (e.g., *Latossolo Amarelo* and *Argissolo Amarelo* - Oxisol and Ultisol), which naturally occur in the coastal tablelands of southern Bahia (Paiva et al., 2000).

Although some studies have addressed the influence of soil physical properties on cocoa cultivation (e.g., Paiva et al., 2018; Arévalo-Hernández et al., 2019), important knowledge gaps remain regarding their direct effects on the productivity of clonal cultivars in renewal areas under no-tillage, particularly concerning yield correlations with individual physical variables across soil layers. Field-based studies under diverse soil conditions are scarce yet essential for identifying soil physical indicators and supporting the selection of areas with greater productive potential on farms.

This study hypothesizes that specific soil physical properties—such as granulometry, porosity, bulk density, penetration resistance, and water retention—directly influence the productivity of cocoa clones in renewal areas under no-tillage. This study aimed to analyze the relationship between these properties and cocoa bean productivity within no-till systems, based on 15 field trials conducted on cocoa-producing farms in southern Bahia, Brazil.

MATERIALS AND METHODS

Study site and experimental design

The study was conducted from January 2019 to December 2022 across 15 field trials (FTs) on farms in 11 municipalities in southern Bahia, Brazil (latitudes 13° 11' 35'' S to 15° 26' 00" S; longitudes 39° 06' 36" W to 39° 35' 18'' W). The region is characterized by significant edaphic variability, as shown in figure 1a. The field trials were selected to capture this variability, ensuring a broad range of edaphic conditions for evaluating the influence of soil physical properties on cocoa productivity.

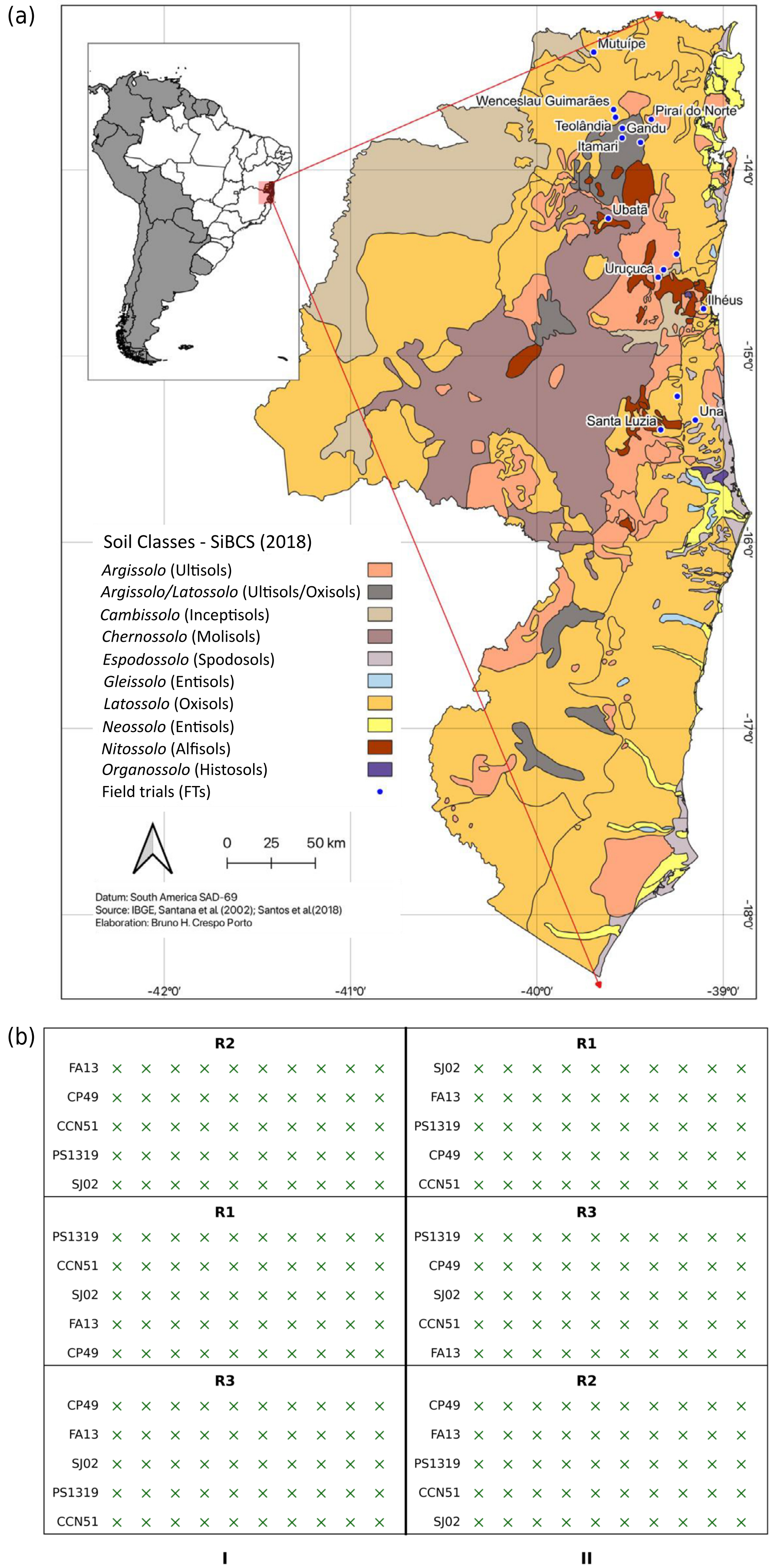

Figure 1. Location of the 15 field trials (FTs) and soil classes in southern Bahia, Brazil (a), classified under the Brazilian Soil Classification System (SiBCS) with their U.S. Soil Taxonomy equivalents; (b) experimental layout of one representative field trial (identical across all 15), comprising two blocks (I and II), three renovation methods (R1, R2, and R3), and five clonal cultivars (FA13, CCN51, CP49, PS1319, and SJ02), totaling 90 plots across the study (2 blocks × 3 methods × 15 trials). Source: Map based on Santana et al. (2002) and Santos (2018).

Three renovation methods were applied: R1, grafting onto basal shoots of old cocoa trees; R2, planting seedlings before removing old cocoa trees; and R3, planting seedlings after removing old cocoa trees. For R2 and R3, seedlings derived from open-pollinated seeds of clone TSH1188 were grafted in a nursery 60–90 days after sowing, using side grafting above the cotyledon and below the first pair of leaves. For all renovation methods, the plagiotropic branches of the five tested clonal cultivars were used as grafting material and reapplied in case of failure. In R1 and R2, old cocoa trees were gradually removed over 2 years through successive pruning until complete suppression, whereas in R3 they were removed before seedling planting. All renovation methods were conducted under no-till conditions.

As illustrated in figure 1b, each FT comprised six experimental units (three renovation methods × two replications) arranged within two blocks, totaling 90 plots arranged in a randomized block design. Each plot contained 50 cocoa trees, comprising 10 trees from each of the five clonal cultivars used (CCN51, CP49, FA13, PS1319, and SJ02). Cocoa bean yield was assessed using 25 productive cocoa trees, five from each clonal cultivar.

Soil tillage

In all treatments, soil was managed under no-tillage, with no disturbance from plowing or harrowing. Cocoa seedlings were planted in cylindrical pits, 0.60 m deep and 0.20 m in diameter, opened with a mechanical pit-drilling device (Stihl BT 121). To prevent root penetration problems caused by smoothed pit walls, grooves were made along the inner surfaces of the pits.

Fertilization was applied directly to each planting pit. During the first two years of orchard establishment, young cocoa trees received fertilization within the crown projection area. From the third year onward, production fertilization was carried out based on soil nutrient content and estimated nutrient extraction and export from the orchards (Souza Júnior et al., 2018).

Calculation of relative cocoa bean productivity

Relative cocoa bean productivity was determined by setting the highest annual cocoa bean yield (kg ha^{-1} yr^{-1}) for each clone, renovation method (R1, R2, R3), and analyzed year (4th, 5th, 6th, and 7th) as 100 %. The relative productivity of all other plots was then expressed as a percentage of this maximum. Subsequently, the average relative productivity across the five clones was calculated. Finally, the four-year average relative yield was calculated for each of the 90 plots.

Analysis of soil physical properties

Soil physical properties were determined from both undisturbed and disturbed samples collected from the 0.00–0.10, 0.10–0.20, and 0.20–0.40 m layers at the 90 plots. For each plot and soil layer, composite disturbed samples were created from 25 individual subsamples collected with a probe in the crown projection area of the cocoa trees, while undisturbed samples were collected in triplicate using cylinders (approx. 90 cm^3 volume). Soil granulometry (clay: <0.002 mm; silt: 0.002-0.05 mm; sand: 0.05-2.0 mm) was determined from disturbed soil samples, with sand fractions quantified by sieving, clay determined by the pipette method, and silt calculated by difference, following Donagemma et al. (2017).

Volumetric water content at field capacity (FC, –10 kPa for soils with ≤35 % clay and –33 kPa for soils with >35 % clay), permanent wilting point (PWP, –1,500 kPa), and available water (AW, calculated as the difference between FC and PWP) were determined from disturbed soil samples, following Klein (2018). Undisturbed soil samples were used to determine soil bulk density (BD) (Almeida et al., 2017a), and total porosity (TP) was obtained by the indirect method using BD and a fixed particle density (Almeida et al., 2017b).

Soil resistance to penetration (SRP) was measured in triplicate using a Planalsucar-Stolf impact penetrometer (Stolf et al., 1983; Stolf, 1991). To account for soil moisture, undisturbed samples from the three layers of each plot were collected in sealed aluminum containers to prevent moisture loss during transport, and subsequently oven-dried at 105 °C to constant mass for the determination of gravimetric water content (Viana et al., 2017). Because no soil tillage or tractor traffic occurred in the FTs, little change in soil physical quality was expected; thus, soil physical properties were collected only once in 2019 as a baseline.

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Analysis of soil chemical properties susceptible to redox reactions

Iron (Fe) and manganese (Mn) are prone to oxidation-reduction, with their availability strongly affected by soil aerobic or anaerobic conditions (Lindsay and Schwab, 1982). Under excess soil moisture, these elements become more available regardless of total soil content. Therefore, composite disturbed soil samples from the 0.00–0.10 and 0.10–0.20 m layers were chemically analyzed for Fe and Mn using the Mehlich-1 method (Campos and Teixeira, 2017).

Statistical analysis

All statistical analyses were performed using R software, version 4.0.5 (R Core Team, 2021). Both descriptive and inferential statistical analyses through univariate and multivariate procedures. Descriptive statistics were used to calculate measures of central tendency (mean, median) and dispersion (minimum, maximum, coefficient of variation) for the data.

Pearson linear correlation analysis was conducted between average relative yield and soil physical properties. Correlation coefficients were tested for significance at $p<0.05$ using a t-test and visualized with the ggcorrplot package (Kassambara, 2017). Data were also subjected to principal component analysis (PCA), considering soil physical properties by layer (0.00–0.10, 0.10–0.20, and 0.20–0.40 m). The analyses were performed with the FactoMineR package (Lê et al., 2008) and visualized with factoextra (Kassambara and Mundt, 2020).

The 90 plots were grouped based on productivity similarity using hierarchical cluster analysis. Euclidean Distance matrices were generated with the vegan package (Oksanen et al., 2020), and clusters were produced using Ward's linkage method as the agglomerative criterion. Group means of soil physical properties were compared using Tukey HSD test ($p<0.05$), performed with the agricolae package (Mendiburu, 2023).

RESULTS

Descriptive statistics for soil physical properties from the 90 plots are summarized in table 1. Across the three analyzed layers (0.00–0.10, 0.10–0.20, and 0.20–0.40 m), considerable variability was observed, particularly in soil granulometry. This variability is evidenced by high coefficients of variation (CV) and wide ranges (maximum - minimum values) for silt content and the silt/clay ratio. Coefficients of variation below 12 % indicate low variability, between 12 and 60 % indicate moderate variability, and values above 60 % indicate high variability (Warrick and Nielsen, 1980). Most other properties exhibited CVs within the moderate variability range. Generally, the means and medians of physical properties were similar, indicating that the mean was a suitable measure of central tendency.

In all three layers, average SRP exceeded 2.0 MPa, a threshold considered restrictive for root growth in most crops, with maximum values reaching 4.32, 5.14, and 7.25 MPa in the 0.00–0.10, 0.10–0.20, and 0.20–0.40 m layers, respectively. Average BD across the three layers ranged from 1.32 to 1.43 kg dm^{-3}. Total porosity averaged below 0.50 m^3 m^{-3} across the three analyzed layers. Average FC ranged from 0.35 to 0.42 cm^3 cm^{-3}, PWP from 0.21 to 0.26 cm^3 cm^{-3}, and AW from 0.14 to 0.16 cm^3 cm^{-3}.

Table 1. Descriptive statistics of soil physical properties across three soil layers (0.00–0.10, 0.10–0.20, and 0.20–0.40 m) in 90 experimental plots from renovated cocoa orchards in southern Bahia, Brazil

Soil layer	Physical properties	Unit	Minimum	Maximum	Mean	Median	CV
							%
0.00–0.10 m	Sand	g kg^{-1}	41.00	781.00	475.34	479.00	34.95
	Silt	g kg^{-1}	0.00	456.00	95,57	72.00	102.08
	Clay	g kg^{-1}	122.00	709.00	429.15	445.00	36.13
	Silt/Clay Ratio		0.00	1.77	0.29	0.16	117.12
	SRP	MPa	1.27	4.32	2.42	2.65	30.36
	BD	Mg m^{-3}	0.93	1.73	1.32	1.33	10.81
	TP	m^3 m^{-3}	0.36	0.62	0.48	0.48	10.74
	FC	cm^3 cm^{-3}	0.18	0.53	0.35	0.35	20.87
	PWP	cm^3 cm^{-3}	0.08	0.32	0.21	0.22	27.88
	AW	cm^3 cm^{-3}	0.07	0.23	0.14	0.13	27.21
0.10–0.20 m	Sand	g kg^{-1}	23.00	786.00	435.42	424.00	37.93
	Silt	g kg^{-1}	0.00	475.00	93.50	67.00	110.64
	Clay	g kg^{-1}	119.00	800.00	471.02	490.50	35.24
	Silt/Clay Ratio		0.00	1.55	0.28	0.13	130.60
	SRP	MPa	1.10	5.14	2.81	2.80	31.65
	BD	Mg m^{-3}	1.16	1.8	1.42	1.42	9.82
	TP	m^3 m^{-3}	0.33	0.55	0.45	0.45	11.11
	FC	cm^3 cm^{-3}	0.19	0.56	0.39	0.40	19.95
	PWP	cm^3 cm^{-3}	0.07	0.32	0.24	0.25	27.43
	AW	cm^3 cm^{-3}	0.09	0.25	0.15	0.14	26.17
0.20–0.40 m	Sand	g kg^{-1}	28.00	745.00	395.43	371.00	40.00
	Silt	g kg^{-1}	2.00	444.00	88.07	66.50	106.82
	Clay	g kg^{-1}	154.00	778.00	516.47	540.50	31.78
	Silt/Clay Ratio		0.00	1.44	0.23	0.12	126.72
	SRP	MPa	1.24	7.25	3.32	3.04	32.04
	BD	Mg m^{-3}	1.12	1.77	1.43	1.41	11.42
	TP	m^3 m^{-3}	0.32	0.56	0.44	0.44	13.18
	FC	cm^3 cm^{-3}	0.19	0.68	0.41	0.42	20.86
	PWP	cm^3 cm^{-3}	0.08	0.36	0.26	0.27	25.87
	AW	cm^3 cm^{-3}	0.08	0.33	0.16	0.15	29.75

SRP: soil Resistance to penetration; BD: bulk density; TP: total porosity; FP: field capacity; PWP: permanent wilting point; AW: available water; CV: coefficient of variation. n = 90 plots.

Pearson linear correlation results (Figure 2) indicated a significant correlation ($p<0.05$) between yield and both silt content ($r_{0.00\text{-}0.10m}$ = -0.29; $r_{0.10\text{-}0.20m}$ = -0.31; $r_{0.20\text{-}0.40m}$ = -0.31) and silt/clay ratio ($r_{0.00\text{-}0.10m}$ = -0.23; $r_{0.10\text{-}0.20m}$ = -0.27; $r_{0.20\text{-}0.40m}$ = -0.31). Conversely, yield was positive correlated ($p<0.05$) with FC ($r_{0.00\text{-}0.10m}$ = 0.24; $r_{0.10\text{-}0.20m}$ = 0.34; $r_{0.20\text{-}0.40m}$ = 0.29), PWP ($r_{0.00\text{-}0.10m}$ = 0.19; $r_{0.10\text{-}0.20m}$ = 0.26; $r_{0.20\text{-}0.40m}$ = 0.23), and AW ($r_{0.00\text{-}0.10m}$ = 0.17; $r_{0.10\text{-}0.20m}$ = 0.24). Additionally, Fe content in the 0.00-0.10 m layer showed a significant positive correlation with silt (r = 0.44).

The PCA (Figure 3) illustrated the variability of physical properties across the 90 plots. Regardless of soil layer, PCA vectors confirmed a positive correlation between FC and yield. Conversely, yield showed a negative correlation with sand content in all analyzed layers. The PCA also indicated a negative relationship between yield and SRP in the surface layers (0.00–0.10 and 0.10–0.20 m). In the 0.20–0.40 m layer, a positive relationship was observed between SRP, BD, and the silt/clay ratio, while these properties showed a negative correlation with TP.

Cluster analysis grouped the 90 plots into four productivity groups (Figure 4): Group 1 (G1, blue, high productivity), Group 2 (G2, green, medium-high productivity), Group 3 (G3, yellow, medium-low productivity), and Group 4 (G4, red, low productivity). The G1 comprised 12 plots (mean yield = 74 %, equivalent to 2,758 kg ha^{-1}), G2 included 26 plots (58 %, 1,878 kg ha^{-1}), G3 comprised 37 plots (37 %, 1,557 kg ha^{-1}), and G4 contained 15 plots (17 %, 792 kg ha^{-1}).

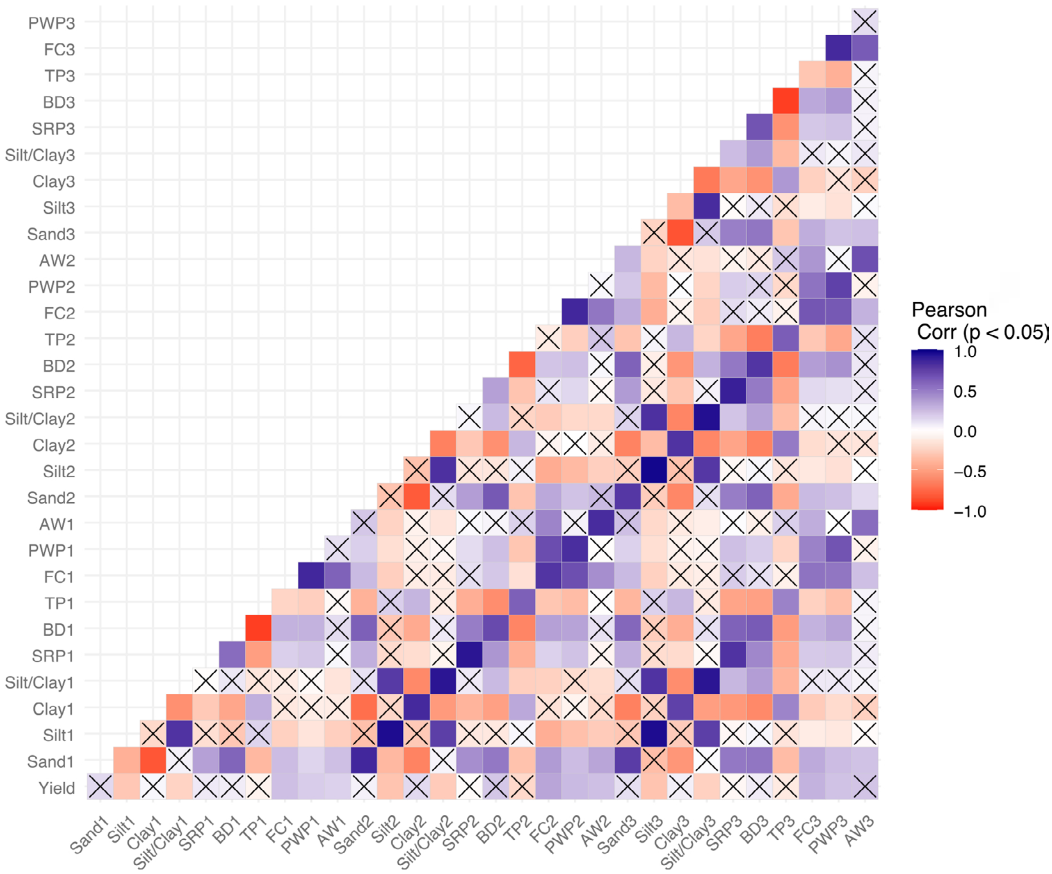

Figure 2. Simple linear correlations between soil physical properties (0.00–0.10, 0.10–0.20, and 0.20–0.40 m) and relative cocoa bean productivity (average from the 4th to 7th year post-establishment, 2019-2022) across 15 field trials (FTs) in renovated cocoa orchards in southern Bahia, Brazil. Color scale represents Pearson correlation coefficient (r), ranging from –1 (red, strong negative) to +1 (blue, strong positive). Absence of 'X' indicates significance by Pearson correlation ($p<0.05$). Average relative cocoa bean yield (Yield); Soil physical properties: Sand, Silt, Clay, Silt/Clay ratio, Soil Resistance to Penetration (SRP), Bulk Density (BD), Total Porosity (TP), Field Capacity (FC), Permanent Wilting Point (PWP), Available Water (AW). Subscripts: 1 = 0.00–0.10 m layer; 2 = 0.10–0.20 m layer; 3 = 0.20–0.40 m layer. n = 90 plots.

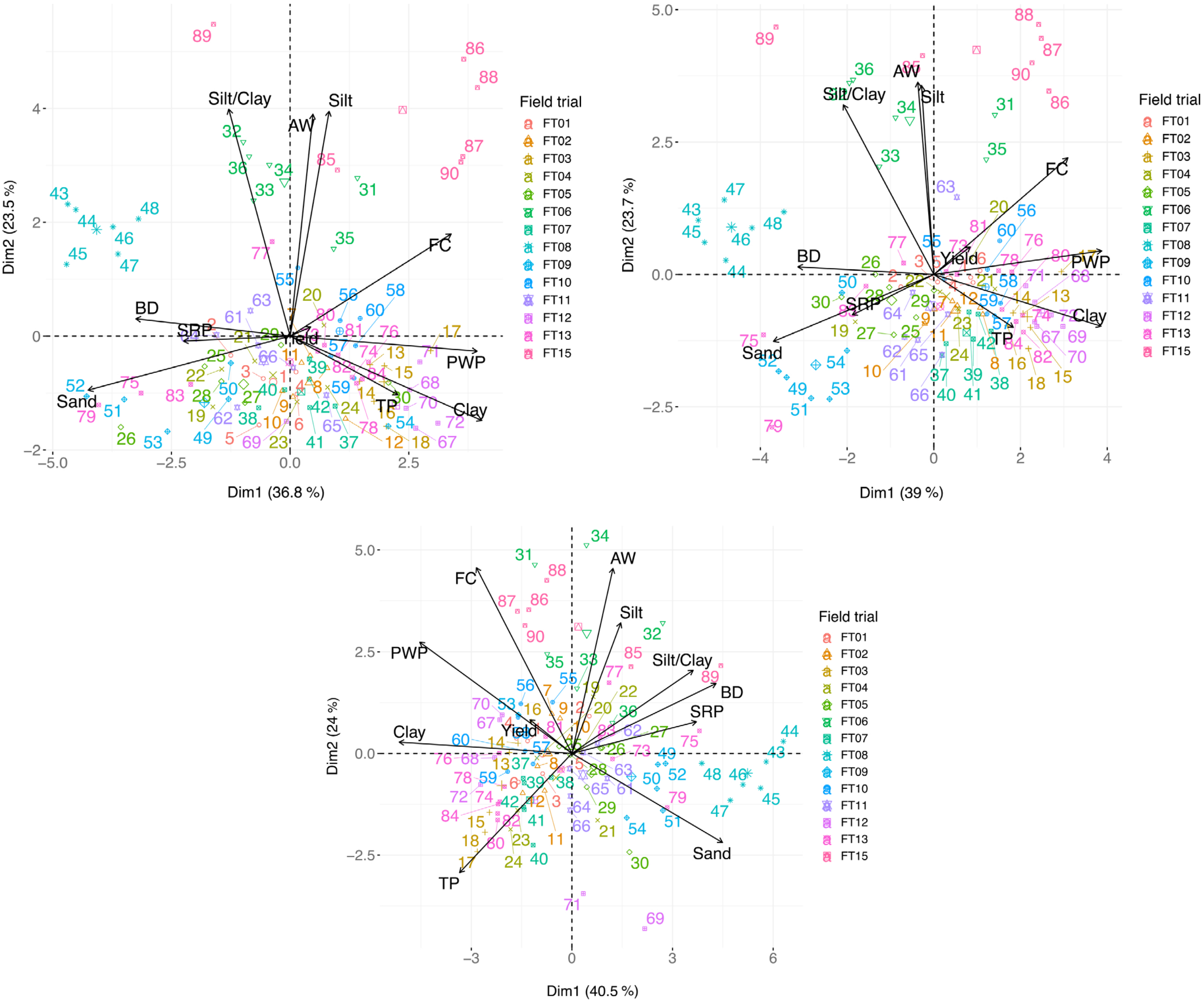

Figure 3. Principal component analysis (PCA) scatter plot of soil physical properties in (a) 0.00–0.10, (b) 0.10–0.20, and (c) 0.20–0.40 m layers and relative cocoa bean productivity (average from 4th to 7th year post-establishment, 2019-2022) across 15 field trials (FTs) in renovated cocoa orchards in southern Bahia, Brazil. Colors represent the different field trials (FT01 to FT15), while numbers and shapes correspond to the plots within each FT. Variables: Average relative cocoa bean yield (4th to 7th year, 2019-2022); Soil physical properties: Sand, Silt, Clay, Silt/Clay ratio, Soil Resistance to Penetration (SRP), Bulk Density (BD), Total Porosity (TP), Field Capacity (FC), Permanent Wilting Point (PWP), and Available Water (AW). n = 90 plots.

Tukey HSD test revealed significant differences ($p<0.05$) in soil granulometry among the productivity groups (G1, G2, G3, and G4) (Table 2). Across all layers, the higher-productivity groups (G1 and G2) had significantly lower silt content and silt/clay ratios ($p<0.05$) than the lowest-productivity group (G4). In the 0.00–0.10 m layer, the high-productivity group (G1) had significantly higher average sand content ($p<0.05$) and significantly lower average clay content ($p<0.05$) compared to G4. Furthermore, in the surface layer (0.00–0.10 m), group G1 had significantly lower ($p<0.05$) average TP, FC, and AW than group G4.

Overall, these results emphasize the agronomic importance of soil physical conditions for cocoa cultivation. Cocoa yield was primarily associated with soil granulometry, with high silt/clay ratios limiting productivity. The positive correlation between silt and Fe indicated poor aeration and reinforced the negative impact of high silt content on yield. Yield was also constrained by excessive penetration resistance.

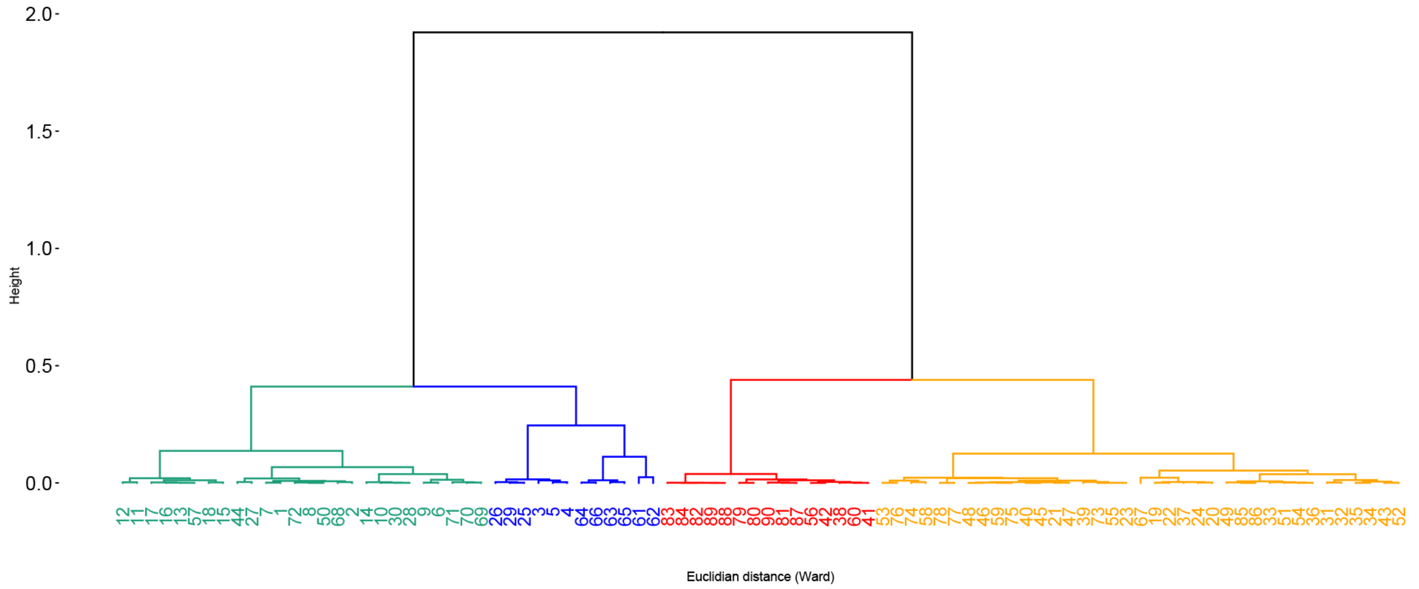

Figure 4. Dendrogram from hierarchical cluster analysis of relative cocoa bean productivity for 90 plots over four years (4th to 7th year post-establishment, 2019-2022) in renovated cocoa orchards in southern Bahia, Brazil, using Euclidean distance and Ward agglomerative method, showing four groups: G1 (blue, high productivity), G2 (green, medium-high productivity), G3 (yellow, medium-low productivity), and G4 (red, low productivity).

DISCUSSION

Cocoa productivity in the studied areas was directly related to soil physical properties influencing water retention, drainage, aeration, and deep rooting. Among the evaluated properties across the three soil layers (0.00–0.10, 0.10–0.20, and 0.20–0.40 m), soil granulometry was most strongly associated with cocoa productivity (Figures 2 and 3; Table 2). Soil granulometry is closely related to other physical properties, such as TP, BD, SRP, drainage, and water retention capacity (Arshad et al., 1996; Lal and Shukla, 2004). Thus, it serves as a key indicator of soil physical quality for cocoa cultivation.

The average soil granulometry of the four productivity groups (G1, G2, G3, and G4) ranged from sandy clay to clay textures (Santos et al., 2005; SSDS, 2018). Soil clay content showed a positive correlation with average relative yield; however, the high-productivity group (G1) had a sandy clay texture in all layers, while the low-productivity group (G4) had a clay texture. This apparent contradiction suggests that productivity depends not only on water retention but also on the balance between retention and drainage.

In general, sandy loam soils are recommended for cocoa in regions with well-distributed rainfall, while clayey to clay loam soils are preferred in regions with pronounced dry seasons (Paiva et al., 2018). Clay soils tend to have greater microporosity and higher water retention capacity, along with a lower proportion of macropores, which can potentially limit drainage and soil aeration. As a result, the cocoa tree biochemical, physiological, and nutritional processes may be compromised (Almeida et al., 2016; Branco et al., 2017; Gattward and Almeida, 2018), affecting root respiration, nutrient absorption, and the availability of nutrients susceptible to oxidation-reduction (e.g., N, Mn, Fe, and S).

Our results confirmed an inverse relationship between silt content and cocoa productivity (Souza Júnior et al., 1999). Both silt content and the silt/clay ratio were negatively correlated with yield. Silt, a variably shaped particle (0.002-0.05 mm diameter) composed predominantly of quartz and kaolinite, is often associated with soil compaction and reduced permeability (Lal and Shukla, 2004; Brady and Weil, 2017). Soils with high silt content tend to be less productive and exhibit higher cocoa tree mortality rates, as they are generally younger and present physical impediments to root penetration (Souza Júnior et al., 1999, 2023).

Table 2. Grouping of 90 plots by relative dry cocoa bean yield (4th to 7th year post-establishment, 2019–2022) in renovated cocoa orchards in southern Bahia, Brazil, and mean comparison (Tukey HSD, p<0.05) of soil physical properties across three layers (0.00–0.10, 0.10–0.20, and 0.20–0.40 m)

Soil layer	Physical properties	Unit	Groups			
			G1 - High productivity	G2 - Medium-high productivity	G3 - Medium-low productivity	G4 - Low productivity
0.00–0.10 m	Sand	g kg^{-1}	509.77a	387.83ab	471.71a	368.77b
	Clay	g kg^{-1}	433.25b	566.73a	412.67b	486.44a
	Silt	g kg^{-1}	56.86b	45.44b	115.64a	144.80a
	Silt/Clay		0.14b	0.12b	0.38a	0.35a
	SRP	MPa	2.78ab	2.78ab	3.08a	2.44b
	BD	Mg m^{-3}	1.39ab	1.39ab	1.41a	1.32b
	TP	m^3 m^{-3}	0.45b	0.46b	0.45b	0.48a
	FC	cm^3 cm^{-3}	0.31b	0.36ab	0.34ab	0.39a
	PWP	cm^3 cm^{-3}	0.19a	0.24a	0.20a	0.22a
	AW	cm^3 cm^{-3}	0.12b	0.13b	0.14ab	0.16a
0.10–0.20 m	Sand	g kg^{-1}	494.66a	377.50a	484.83a	366.53a
	Clay	g kg^{-1}	447.08b	579.31a	399.38b	479.20ab
	Silt	g kg^{-1}	57.92b	43.00b	115.78ab	154.53a
	Silt/Clay		0.14ab	0.11b	0.41a	0.38ab
	SRP	MPa	2.80a	2.67a	3.06a	2.41a
	BD	Mg m^{-3}	1.42a	1.44a	1.44a	1.33a
	TP	m^3 m^{-3}	0.45a	0.44a	0.44a	0.48a
	FC	cm^3 cm^{-3}	0.38ab	0.40ab	0.37b	0.44a
	PWP	cm^3 cm^{-3}	0.24a	0.26a	0.22a	0.26a
	AW	cm^3 cm^{-3}	0.15ab	0.14b	0.15ab	0.18a
0.20–0.40 m	Sand	g kg^{-1}	451.92a	369.31a	423.97a	325.13a
	Clay	g kg^{-1}	493.92a	588.31a	464.65a	537.87a
	Silt	g kg^{-1}	54.08b	42.38b	111.41ab	136.87a
	Silt/Clay		0.11a	0.12a	0.32a	0.32a
	SRP	MPa	3.12a	3.23a	3.60a	2.90a
	BD	Mg m^{-3}	1.44a	1.42a	1.46a	1.35a
	TP	m^3 m^{-3}	0.43a	0.44a	0.43a	0.47a
	FC	cm^3 cm^{-3}	0.41a	0.40a	0.42a	0.47a
	PWP	cm^3 cm^{-3}	0.26a	0.27a	0.25a	0.29a
	AW	cm^3 cm^{-3}	0.15ab	0.13b	0.17ab	0.18a

SRP: Soil Resistance to Penetration; BD: Bulk Density; TP: Total Porosity; FC: Field Capacity; PWP: Permanent Wilting Point; and AW: Available Water. Plot grouping by relative cocoa bean productivity (4th to 7th year post-establishment, 2019-2022), using Ward method and Euclidean distance: G1 (high productivity), G2 (medium-high productivity), G3 (medium-low productivity), G4 (low productivity). Different lowercase letters indicate significant differences between group means for each property, according to Tukey HSD test (p<0.05). n = 90 plots.

The literature presents divergent recommendations on optimal silt content and silt/clay ratios for cocoa cultivation (Wood, 2001; Chepote et al., 2012; Souza Júnior et al., 2023). Some studies recommend cultivating cocoa in soils with silt contents of 200-300 g kg^{-1} (Chepote et al., 2012), while others suggest 100-200 g kg^{-1} and a silt/clay ratio of 0.25-0.67 (Wood, 2001). Since soils with high silt content generally exhibit anaerobic conditions due to lower drainage capacity, Fe^{3+} is commonly reduced to the more soluble Fe^{2+} (Lal and Shukla, 2004), which can reach plant-toxic levels (Zahra et al., 2021; Li et al., 2024). Accordingly, the positive correlation between silt content and available Fe is expected, as observed in this study. Furthermore, given the lower water retention capacity of silty soils, a silt/clay ratio below 0.36 in the surface layer (0.00–0.20 m) and a maximum of 0.24 in the subsurface (0.30–0.50 m) is recommended for regions prone to drought (Souza Júnior et al., 2023).

The silt/clay ratio is also an indicator of the weathering stage of tropical soils, with values below 0.70 (medium texture) and 0.60 (clayey to very clayey texture) in most of the B horizon, indicating advanced weathering (Santos, 2018). In this study, the groups with the highest average yields (G1 and G2) exhibited average silt/clay ratios ranging from 0.11 to 0.14 for G1 and 0.11 to 0.12 for G2. In contrast, the least productive groups (G3 and G4) showed values ranging from 0.38 to 0.41 for G3 and 0.35 to 0.38 for G4. Maximum silt/clay ratio values in G1 remained below 0.30 across all layers, indicating highly weathered soils, whereas G3 and G4 exceeded 1.00, indicating the presence of younger soils. Although these results indicate a clear association between the silt/clay ratio and cocoa productivity, further validation in different soil and climatic conditions is required before using this attribute as a stand-alone criterion for site selection.

The positive correlations ($p<0.05$) between yield and FC, PWP, and AW were expected, as these properties estimate soil water retention capacity (Silva et al., 2014). Moreover, numerous studies have reported a positive relationship between water supply and cocoa yield (Alvim, 1960, 1977; Wood, 2001; Carr and Lockwood, 2011; Gattward and Almeida, 2018). For cocoa trees, maintaining soil moisture above 60 % of AW is recommended (Alvim, 1960). However, although individual correlations supported this trend, Tukey test showed higher FC and AW in G4. This suggests that finer-textured soils, despite retaining more water, may restrict aeration and rooting, thereby limiting yield.

Total Porosity was inversely related to BD and SRP (Santos and Reichert, 2022). This relationship was confirmed in the Pearson correlations (Figure 2), where TP showed significant negative correlation with BD ($r_{0.00\text{-}0.10m}$ = -0.90; $r_{0.10\text{-}0.20m}$ = -0.76; $r_{0.20\text{-}0.40m}$ = -0.90) and SRP ($r_{0.00\text{-}0.10m}$ = -0.50; $r_{0.10\text{-}0.20m}$ = -0.31; $r_{0.20\text{-}0.40m}$ = -0.56). Because TP is calculated from BD and particle density, the strong TP–BD correlation is algebraically expected and should not be interpreted as an independent effect. Although SRP is simultaneously related to several factors and, in some cases, does not show a significant correlation with soil physical variables (Arévalo-Hernández et al., 2019), our results indicated a significant positive correlation between BD and SRP across all three layers ($r_{0.00\text{-}0.10m}$ = 0.56; $r_{0.10\text{-}0.20m}$ = 0.35; $r_{0.20\text{-}0.40m}$ = 0.67).

The PCA showed that SRP was positively correlated with sand content in the surface layers (0.00–0.10 and 0.10–0.20 m), whereas in the 0.20–0.40 m layer (Figure 3c) it was positively associated with the silt/clay ratio. Although PCA indicated a negative relationship between sand content and yield, this contrasted with group comparisons, in which the highest-yielding plots (G1) were characterized by sandy clay-textures. This apparent inconsistency reflects the multivariate nature of PCA, which integrates the joint effects of soil properties. The positive association between SRP and sand likely reflects sand's greater frictional strength and faster drying relative to finer-textured soils (Souza et al., 2021; Kumi et al., 2023). Conversely, coarser textures tend to enhance drainage and aeration. Thus, excessively fine-textured soils with high silt/clay ratios constrain yield, whereas balanced sandy-clay textures can support higher productivity under adequate water supply.

Accordingly, recent research on sugarcane cultivation has suggested considering soil granulometry when defining SRP thresholds, recommending values of 1.5 MPa for sandy soils and 2.5 MPa for clayey soils (Barbosa et al., 2018). The mean SRP values across the three soil layers (Table 1) exceeded the 2.0 MPa threshold generally regarded as restrictive for root growth in most agricultural crops, including cocoa (Arshad et al., 1996; Imhoff et al., 2000; Paiva et al., 2018). According to Canarache (1990), SRP values up to 2.5 MPa are considered non-limiting, values between 2.6 and 10.0 MPa indicate moderate restriction, and values above 10.1 MPa prevent root growth. However, root system architecture and sensitivity to mechanical impedance differ among crops; thus, these thresholds should be interpreted with caution when applied to cocoa.

In this study, most plots exhibited SRP within the 2.6–10.0 MPa range, which likely restricted root growth and, by reducing the volume of soil explored by the root system, limited access to water and nutrients, thereby decreasing cocoa yield. Consistent with this interpretation, PCA (Figure 3) revealed a negative relationship between SRP and productivity in the 0.00–0.10 and 0.10–0.20 m layers. Early studies by Cadima and Alvim (1973) identified SRP as the edaphic property most closely associated with cocoa productivity. More recent evaluations of cocoa farms in southern Bahia have also reported high average SRP values, despite generally favorable soil physical conditions, corroborating our findings (Arévalo-Hernández et al., 2019).

Therefore, although cocoa can adapt to a range of soil physical conditions, excessive penetration resistance remains a critical constraint on yield. In the current climate change scenario, promoting deeper rooting could enhance subsurface water uptake and help buffer yield variability, although direct testing of this mechanism was beyond the scope of this study. A limitation is that soil physical data were measured only once in 2019; however, little variation is expected throughout the study period in non-mechanized cocoa orchards under no-tillage management.

CONCLUSION

Cocoa productivity is strongly related to soil granulometry, an intrinsic property that directly influences water retention and availability, drainage, aeration, and resistance to penetration. Soils with a sandy clay texture and a low silt/clay ratio exhibited the highest cocoa bean yields, attributed to their superior physical quality, greater aeration, and enhanced water-supply capacity for cocoa trees. Conversely, more clayey soils with high silt content and high resistance to root penetration exhibited physical limitations and reduced chemical conditions, thereby compromising cocoa productivity. This study is limited to a single assessment of soil physical properties, and the results should be interpreted in the context of southern Bahia agroecological conditions. Analyzing soil physical properties, particularly soil granulometry, is essential for identifying production areas more suitable for crop renewal, cocoa farming expansion, and enhancing productivity and resilience to climate change. Future studies should assess how different renovation methods influence soil physical quality and cocoa yield.

DATA AVAILABILITY

The data will be provided upon request.

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