Ciência e Agrotecnologia
SCIENCE AND AGROTECHNOLOGY

Ciência e Agrotecnologia, 47:e015022, 2023
http://dx.doi.org/10.1590/1413-7054202347015022

Agricultural Sciences
eISSN 1981-1829

Compactibility of cohesive soils from tablelands as influenced by cassava wastewater

Compactabilidade de solos coesos dos tabuleiros costeiros do nordeste sob influência de água residuária de mandioca

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Received in October 18, 2022 and approved in April 27, 2023

ABSTRACT

Consolidation tests give important insights into soil compactibility. However, it requires equipment that is not always available. The costal tablelands in Northeastern Brazil have extensive areas of cohesive soils where compaction is an expressive problem. This region is a prominent producer of food and fibers with cassava as one of the leading products. Part of the cassava is used for flour production, generating wastewater, which is often applied as organic fertilizer to the soil. This can affect the compaction properties of soil due to its dispersing-flocculating characteristics. Uniaxial-compression tests and mathematical models are the primary methods to measure or estimate soil compaction. This study measured soil compression with a centrifuge, seeking a simple-quick method. We used specific loads (stainless-steel cylinders: mass) and increasing G-force (weight) to simulate the pressure on the samples used in most consolidation apparatus. Soils, sampling layers, and the presence of cassava wastewater (manipueira) were also compared since they may affect compactibility-related attributes. Samples of a Gray Cohesive Argisol and Dystrocohesive Yellow Latosol (depths of 0-0.20 m and 0.20-0.40 m) from the Tablelands of the state of Bahia, Brazil, were used. Wastewater affected water-dispersible clay, aggregate stability, pH, ΔpH, flocculation, and organic carbon, thus influencing compactibility but not the moisture and maximum density measured by the Proctor test. Centrifugation caused lower density than the Proctor test. The results were close to those estimated by the mathematical models, thus considered a promising alternative to estimating consolidation. This method also provides insight into the root growth-limiting density and the moisture content that leads to it.

Index terms: Preconsolidation pressure; soil density; moisture content; G-force; centrifugation.

RESUMO

Os testes de consolidação fornecem informações importantes sobre a compactabilidade do solo. No entanto, eles requerem equipamentos especiais, disponíveis em poucos laboratórios no Brasil. Esta região é uma proeminente produtora de alimentos e fibras em solos coesos. Esses solos apresentam problemas frequentes de compactação. Como a mandioca é um dos principais produtos, suas águas residuais (manipueira) são frequentemente utilizadas para adubação. Esse uso pode afetar a compactação devido à sua influência na dispersão-floculação de partículas. A compressão uniaxial e modelos matemáticos são as principais formas de medir ou estimar a compactação do solo. Aqui, a compressão foi medida com um teste alternativo de centrifugação usando amostras deformadas, buscando um método alternativo simples e rápido. Foram usadas cargas específicas (cilindros de aço inoxidável: massa) e força G crescente (peso) em centrífuga, para simular a pressão nas amostras usadas na maioria dos aparelhos de consolidação. Os solos, as camadas de amostragem e a presença de água residuária (manipueira) também foram comparados, pois podem afetar os atributos relacionados à compactabilidade. Foram utilizadas amostras de Argissolo Cinzento Coeso e Latossolo Amarelo Distrocoeso (profundidades de 0-0,20 m e 0,20-0,40 m), ambos provenientes dos Tabuleiros costeiros do estado da Bahia, Brasil. A água residual afetou o teor de argila dispersa em água, a estabilidade dos agregados, o pH, o ΔpH, a floculação e o teor de carbono orgânico, influenciando a compactabilidade, mas não a umidade e a densidade máxima medidas pelo teste de Proctor. Embora a centrifugação tenha proporcionado menor densidade do que o teste de Proctor, os resultados foram comparáveis àqueles estimados pelos modelos matemáticos. Este método também forneceu informações sobre a densidade, próxima aos valores que limitam o crescimento da raiz, e o teor de umidade que leva a essa densidade limitante.

Termos para indexação: Pressão de pré-consolidação; densidade do solo; teor de umidade; força G; centrifugação.

INTRODUCTION

Soil compaction is one of the most significant consequences of excessive machinery use and can be worse in cohesive soils such as those in the costal Tablelands of Brazil. Compaction reduces porosity, water availability to plants, aggregation, and nutrient uptake by plant roots (Shah et al., 2017; Rabot et al., 2018). On the other hand, it increases load support capacity where necessary (Ajayi et al., 2009).

Cassava production is one of the most popular uses of soils the costal tablelands of Brazil, mainly by small flour producers. However, flour production generates large quantities of residual wastewater, called “manipueira”; farmers apply this wastewater as fertilizers (Kuczman et al., 2017; Cruz et al., 2021). In this case, it can change not only the chemistry but some soil attributes related to soil compactibility.

Different soils respond differently to loads (Ajayi et al., 2009; Andrade et al., 2017; Dias Junior; Martins, 2017; Martins et al., 2018; Kamimura et al., 2020). Such loads, when not controlled, lead to situations where bulk density limits root growth. The change in soil bulk density is one of the most studied indexes to quantify soil deformation and its relationship to intensive mechanization and its impact on plant production. Bulk density is naturally higher in sandy soils than in clayey soils, and it is the main physical factor impacted by crop activities (Reichert et al., 2009; Cavalcante et al., 2021). The Proctor compaction test (Proctor, 1933), described for use in Brazil (Associação Brasileira de Normas Técnicas - ABNT, 2016), has been used to help understand how soil moisture and loads produce compaction, thus impacting agricultural soils or increasing suitability for engineering purposes in construction sites. This method plots soil density against increasing moisture content for a given load over the sample in a standard cylinder.

Soil compactibility is also accessed by uniaxial compression or consolidation tests (Ajayi et al., 2013), by which soil compression curves are plotted and the compression index (m) and preconsolidation pressure (σp) of the soil samples are determined. The preconsolodation pressure outlines the two segments of soil compression: the secondary or elastic segment, when compaction may be reversed (Horn; Lebert, 1994, Dias Junior; Pierce,1995), and the virgin (plastic) compression curve, when compaction is no longer reversible. Dias Junior and Pierce (1995) developed a spreadsheet to determine preconsolidation pressure from the soil compression curve using a numerical method rather than the sometimes-subjective curve fitting method. Furthermore, correlation studies that allow estimating preconsolidation pressure based on soil moisture and bulk density, among other parameters, have been proposed for tropical soils in Brazil (Ajayi et al., 2009; Martins et al., 2018).

Some organic and inorganic chemicals can affect aggregate stability and compactibility. In amending soil, fertilizers, some organic material, and other agroindustry byproducts have been used to improve fertility (Ribeiro et al., 2019; Chavadej et al., 2019; Peres et al., 2019). In this regard, “manipueira” has been applied to soil (Kuczman et al., 2017; Cruz et al., 2021). “Manipueira” is rich in starch, sugars, linamarin, glycose proteins, cyanogenic glycosides, nitrogen, phosphate, and potassium, among other substances (Souza et al., 2021). However, manipueira affects not only chemical but physical properties, such as water retention, bulk density, and aggregate stability, causing soils to respond differently to applied loads. This impact remains to be adequately understood.

Since both the Proctor test and the compression curve (uniaxial pressure) methods use pressure as a function of the soil-moisture content to determine soil compactibility, an alternative method that applies increasing loads on a given soil sample with increasing moisture contents using centrifuge G-force should also be feasible to fit curves and estimate soil compatibility. This study investigated this possibility by comparing the results with those estimated using mathematical models, based on uniaxial consolidation and adjusted for tropical soils by Ajayi et al. (2009) and Martins et al. (2018). Samples of most representative soils of the Northeastern Brazil Tablelands with “manipueira”, or distilled water treatments were compared.

MATERIAL AND METHODS

Soil sampling sites

The soils were sampled from the Costal Tablelands of Northeastern Brazil. According to the Köppen’s classification, the climate of the area is defined as Af: tropical rain forest, with an average temperature of 24.2 °C, average annual rainfall of 1500 mm, 82% relative humidity, with no defined drought season. A Dystrocohesive Yellow Latosol (Oxisol) – DYL – under native rain forest with *Anadenanthera macrocarpa*, *Astronium fraxinifolium, Mimosa caesalpinifolia*, and pasture (*Urochloa decumbens*), 12° 39’ 22” S 39° 04’ 56” W, and a Gray Cohesive Argisol (Ultisol) – GCA – under pasture and exotic species (bushes), 12°39’39” S

39°05’37” W were sampled from the 0–0.2 m and 0.2–0.4 m layers, which represent the A and AB horizon in the DYL and the A and BA horizons in the GCA.

Three replicates of each sample were shade-dried and sieved to 2 mm. These samples were fractionated into three different subsamples, and each subset was incubated with either manipueira (100 ml kg^{-1}) or deionized (distilled) water for 15 days. As described by Ribeiro et al. (2019), the manipueira used in this study was collected from a Cassava flour mill in the county of Cachoeira, Bahia, Brazil; its chemical properties are presented in Table 1.

After incubating the soil samples under the conditions described above, samples and replicates were collected from each treatment (soils with cassava-flower-factories wastewater-manipueira-WW and with distilled water-DW) for chemical and physical characterization. The parameters measured were the degree of flocculation (DF), particle density (PD), aggregate stability (AS), weighted mean diameter (WMD) of aggregates, pH in water and a 1 M KCl solution, remaining phosphate (Prem), and organic carbon (TOC). Meanwhile, undisturbed samples were also collected to measure the soil density (BD) and porosity (TP). The methods for each measurement are shown in Table 2.

Standard Proctor Test

The variously treated samples considered in this study were sieved to 4.8 mm. Each sieved sample (30 kg per treatment) was further portioned into (6 subsamples of 3 kg) packs and moistened with water (100 mL, 150 mL, 200 mL, 250 mL, 300 mL, and 350 mL of distilled water for each 3 kg of soil sample). These moistened samples were used to determine the relationship between the moisture content and density of soils compacted in

Table 1: Chemical characterization of manipueira (cassava wastewater) produced in Northeastern Brazil.

Parameter	Mean ± standard deviation
pH	5.98 ± 0.03
Free cyanide (mg L^{-1})	61.27 ± 5.94
Reducing sugars (g L^{-1})	40.60 ± 1.74
Nonreducing sugars (g L^{-1})	17.51 ± 1.74
Total carbohydrates (g L^{-1})	58.11 ± 2.13
Total nitrogen (g L^{-1})	1.94 ± 0.08
Ca mg (L^{-1})	241.62 ± 5.56
Mg mg (L^{-1})	370.59 ± 4.35
P mg (L^{-1})	220.35 ± 3.28
Na mg (L^{-1})	147.55 ± 1.31
K mg (L^{-1})	1247.92 ± 7.36
Zn mg (L^{-1})	1.83 ± 0.16
Fe mg (L^{-1})	15.37 ± 1.75
Cu mg (L^{-1})	1.51 ± 0.02

Source: Ribeiro et al. (2019) Data are expressed as the means of three replicates ± standard deviation.

Table 2: Chemical and physical parameters of a Gray Cohesive Argisol and a Dystrocohesive Yellow Latosol at 0–0.2 m and 0.2–0.4 m from the Coastal Tableland areas of the state of Bahia, Brazil.

Parameter	Symbol	Unit	Method
Soil texture	–	g kg^{-1}	Day (1965)
Water-dispersible clay	Wdc	g kg^{-1}	Day (1965)
Degree of flocculation	DF	%	Df = 100(Total Clay-Wdc)/Total Clay
Particle density	PD	Mg m^{-3}	Blake and Hartge (1986)
Density	Ds	Mg m^{-3}	Blake and Hartge (1986)
Aggregate size fraction	AS	mm	Yoder (1936)/Grohmann (1960)
Total porosity	TP	%	Tp =100 [1- (Bd/Pd)]
Weighted mean diameter	WMD	mm	Kemper and Rosenau (1986)
1:2.5 water pH	pH_{H2O}	–	–
1M KCl pH	pH_{KCl}	–	–
Delta pH	ΔpH	–	$\Delta pH = pH_{KCl} - pH_{H2O}$
Remaining P	P_{rem}	mg L^{-1}	Alvarez et al. (2000)
Total organic matter	OM	g kg^{-1}	Walkley and Black (1934) Yeomans and Bremner (1988)

a mold of 1 dm^{-3} with a 2.5 kg (5.5 lb) rammer dropped from a height of 305 mm (12 in), representing a load of 5.9 kg.cm cm^{-3} (Proctor, 1933; ABNT, 2016; *American Society for Testing and Materials* - ASTM D698-12, 2021). Subsequently, the compacted samples were oven dried at 105 ºC to a constant weight to determine the moisture content and density. These data were plotted and fitted to a quadratic equation. The optimal moisture content for maximum density under each treatment was then obtained.

Alternative centrifugation load test

To simulate compaction using a centrifuge, dry soil samples previously treated (incubated) with either *manipueira* or distilled water were poured into centrifuge cylinders (31 mm in diameter and 64 mm in height) with a draining bottom, saturated with distilled water, and submitted to centrifugation. To ensure an increasing load, 268.72 ± 0.2 g stainless steel weights were used over the samples under increasing G-forces. The centrifuge parts used in this work are shown in Figure 1.

During each centrifugation test, four centrifuge cylinders, representing four replicates, were submitted to 17 G, 30 G, 47 G, 68 G, and 93 G, corresponding to 300, 400, 500, 600, and 700 revolutions per minute (rpm), for thirty minutes. Increasing pressures acted over the samples since weight is M × G. The samples were weighed and their heights were measured to calculate their moisture and volume at each load stage. After the last load, each sample-cylinder set was oven dried for 24 h at 105 ºC to measure the water content and density. The total porosity was calculated using particle density and the density under each load condition.

The data from this centrifuge method was compared to soil consolidation estimated by the mathematical models used by Martins et al. (2018), $\sigma p = 10^{(2.70 - 1.77\theta)}$ ($R^2 = 0.92^{**}$), and Ajayi et al. (2009), $\sigma p = 10^{(2.87 - 3.96\theta)}$ ($R^2 = 0.88^{**}$).

Statistics

A factorial design (2x2x2) with two soils (Gray Cohesive Argisol and Dystrocohesive Yellow Latosol), two depths (0-0.20 and 0.20-0.40 m), and two treatments (distilled water-control-DW or manipueira-WW) was used, and the data were submitted to three-way analyses of variance (ANOVA) using SISVAR 5.6 (Ferreira, 2019). When significant differences were found, the Scott-Knott test ($P < 0.05$) was used to compare the means. Graphs were plotted with Sigma Plot 11, Demo version. Error bars represent the standard error of means.

RESULTS AND DISCUSSION

Physical and chemical parameters of soil samples incubated with manipueira and distilled water

All parameters except for the particle density differed between the soils. The differences are further compared in Figures 2, 3, and 4.

Changes in WMD, TOC, and ΔpH ($p < 0.001$) differed between soil types. Only the bulk density ($p < 0.05$) and pH ($p < 0.001$) were different in both studied layers. The incubation material (manipueira, or distilled water) ($p < 0.05$) and ΔpH ($p < 0.001$) affected the degree of flocculation. The two-way interactions (soil*incubation material and soil*layer) showed no differences for any of the studied attributes. Only the interaction of layer*incubation material differed significantly for degree of flocculation, WMD, and ΔpH ($p < 0.01$). The three-way interaction (soil*layer*incubation material) was also significant for those parameters. Soil type did not affect the P_{rem} value for any of the layers or incubation materials.

Figure 1: a: Stainless steel cylinders with draining bottoms; b: Stainless steel weights; b: Centrifuge tube holders with the cylinder, soil sample, and weights.

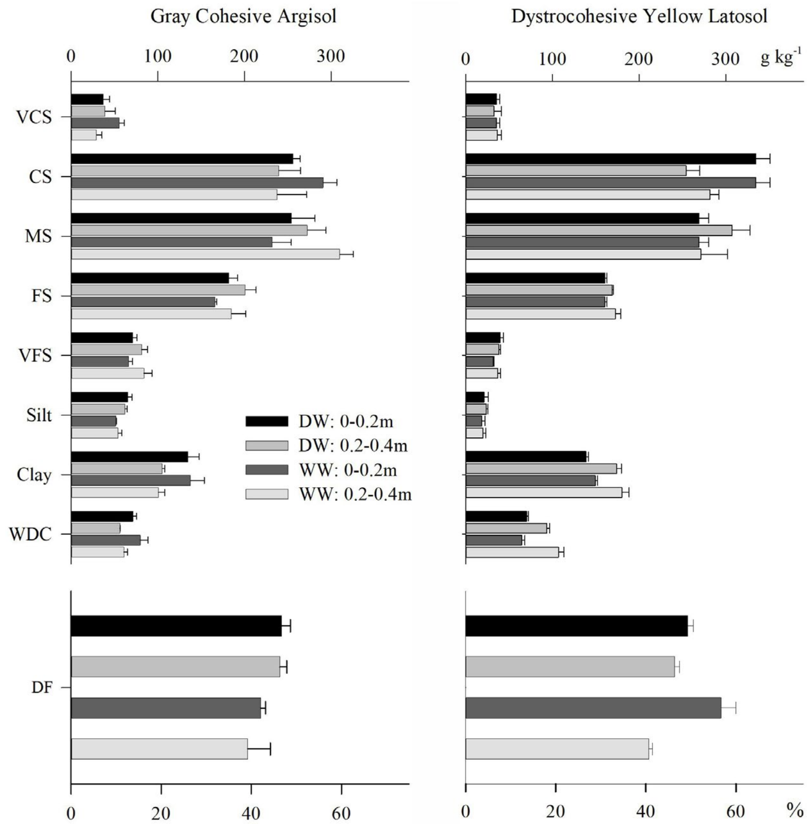

Figure 2: Particle size, water-dispersible clay, and degree of flocculation of samples of a Gray Cohesive Argisol and a Dystrocohesive Yellow Latosol collected at depths of 0–0.2 m and 0.2–0.4 m from the Coastal Tableland areas of Bahia, Brazil, incubated with distilled water (DW) and wastewater-manipueira (WW). Above: Particle size (g kg^{-1}) – VCS-very coarse sand, CS-coarse sand, MS-medium sand, FS-fine sand, VFS-very fine sand, silt, and clay. Bellow: WDC-water-dispersible clay (g kg^{-1}) and DF-degree of flocculation (%), (n = 3). Error bars represent the standard error of the mean.

Particle size distribution, water-dispersible clay, and degree of flocculation are presented in Figure 2. The soil textures were classified as loamy sand (Gray Cohesive Argisol) and sandy loam (Dystrocohesive Yellow Latosol).

Amending the soil samples with manipueira or distilled water had no effect between the layers in each soil. The water-dispersible clay and degree of flocculation were higher for Dystrocohesive Yellow Latosol. There was a less negative charge when manipueira was present in the samples, as seen in Figure 4, where ΔpH was drastically reduced towards a neutral charge balance. The presence of calcium, magnesium, and potassium in the manipueira favors particle flocculation, as also found by Ferreira et al. (2010) and Duarte et al. (2013).

The results for pH_{H2O}, pH_{KCl}, ΔpH, remaining P, and organic matter are shown in Figure 4. In both soils, the samples incubated with manipueira had reduced pH_{H2O}. However, incubation with manipueira did not affect the pH_{KCl}, which caused the ΔpH to decrease, when compared to the distilled water.

The aggregate stability values, expressed as size-class diameters, are shown in Figure 3. The Latosol had a higher amount of aggregates > 2 mm; therefore, presenting a higher WMD than the Argisol, regardless of the treatments. The incubation affected the aggregate sizes in the Argisol depending on the treatment. The 0.2–0.4 m Argisol samples presented larger amounts of aggregates > 2 mm when treated with manipueira compared to the samples from the 0–0.2 m layer and incubated with distilled water. As mentioned earlier, the Ca, Mg, and K in manipueira favors aggregate stability or prevents particle dispersion during the test. This cations concentration effect, observed during WDC determination, is due to cation bridges affected by higher valence and concentration that compress the electrical double layer and allow particles to get closer enough for flocculation to occur (Essington, 2003). This happens due to the decrease of the diffuse layer surrounding the particles.

Standard Proctor results

The densities of the samples at different moisture contents obtained in the standard Proctor test were plotted, and the curve was fitted to a quadratic equation, from which the maximum compaction density (Dmax) and the soil compaction optimum moisture content (OMC) were derived (Table 3).

The optimal moisture content (OMC) and maximum compaction density (Dmax) for the various treatments were compared using ANOVA. The OMC values for the Dmax differed significantly between the soil types ($p < 0.001$), and the soil*layer (depth) interactions were significant ($p < 0.05$), suggesting that the OMC changes with the soil type and sampling depth. Only the soil type affected the results regarding Dmax ($p < 0.05$).

The coefficients of variation of the ANOVA were 7.01% and 1.32% for the OMC and Dmax, respectively. According to Warrick and Nielsen (1980), these results are sufficiently homogeneous to be tested as they were in this study.

As shown in Figure 5, the Latosol samples were generally better compacted at higher moisture contents than the Argisol samples. There was no difference between the layers for either soil, although the Argisol samples can reach higher densities than the Latosol samples. Although both studied soils are sandy (loamy sand - Gray Cohesive Argisol and sandy loam - Dystrocohesive Yellow Latosol), with more negatively charged samples, as one may observe in Figure 4 (ΔpH for the samples treated with distilled water), the Argisol has finer and more negatively-charged particles that account for closer particle packing and, consequently, higher density by fitting into smaller pores, which does not seem to occur with the Latosol samples.

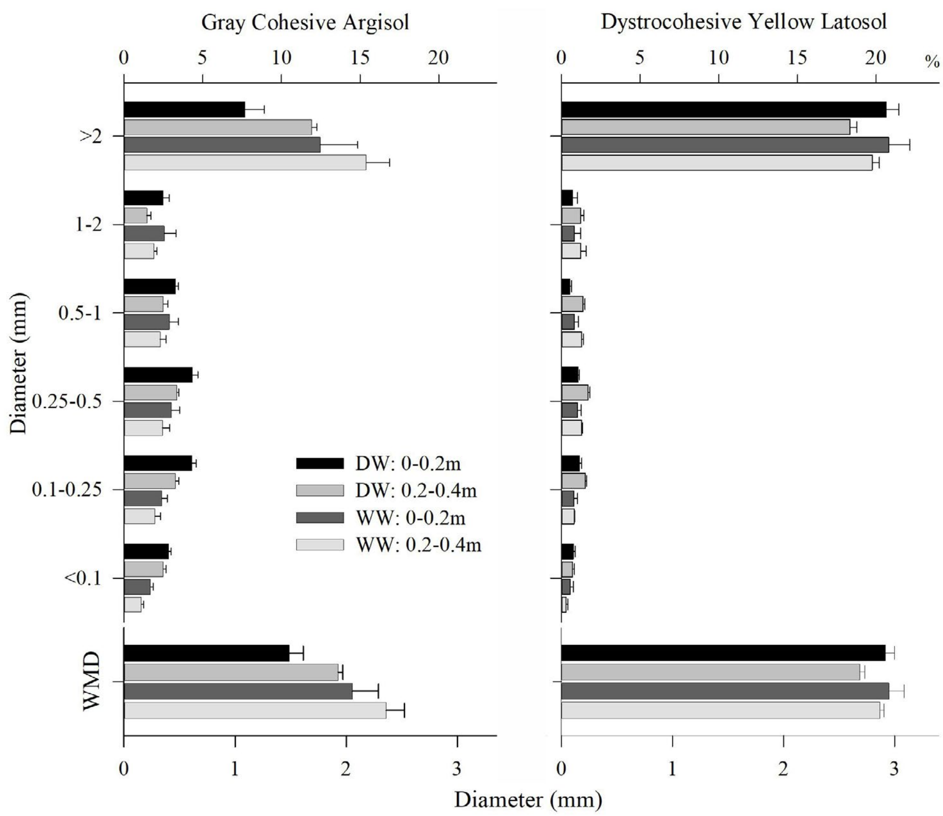

Figure 3: Aggregate size distribution and weighted mean diameter (WMD) of a Gray Cohesive Argisol and a Dystrocohesive Yellow Latosol from the Coastal Tableland areas of Bahia, Brazil. Soil samples incubated using distilled water (DW) or wastewater-manipueira (WW). Above: Classes of aggregate sizes (%). Bellow: WMD (mm), (n = 3). Error bars represent the standard error of the mean.

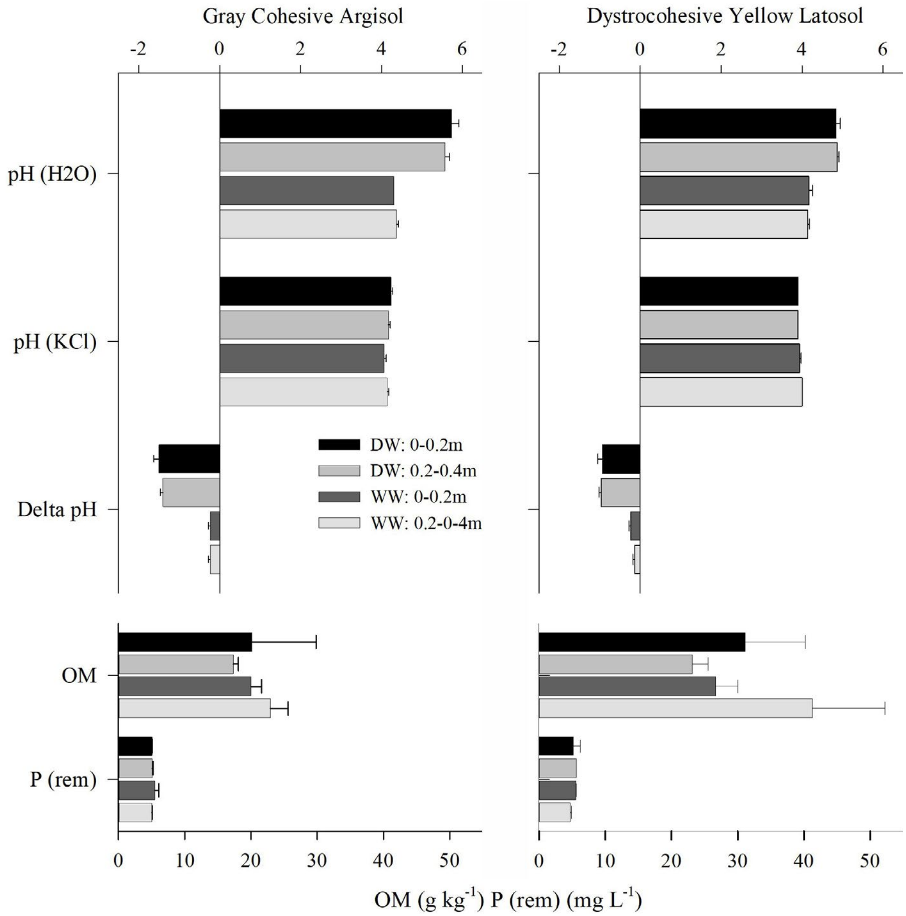

Figure 4: Chemical attributes of a Gray Cohesive Argisol and a Dystrocohesive Yellow Latosol sampled from depths of 0–0.2 m and 0.2–0.4 m in the Coastal Tableland areas of Bahia, Brazil. Samples incubated using distilled water (DW) or manipueira (WW). P_{rem}: remaining phosphate; OM: Total organic matter; (n = 3). Error bars represent the standard error of the mean.

Table 3: Comparison of the optimum moisture content (OMC) and maximum density (Dmax) from the Proctor test of samples of a Gray Cohesive Argisol (GCA) and a Dystrocohesive Yellow Latosol (DYL) collected at depths of 0–0.2 m and 0.2–0.4 m from the Coastal Tableland area of Bahia, Brazil.

Depth (m)	OMC			Dmax		
	GCA	DYL	1	GCA	DYL	1
	--------------------%------------------			-------------------- g cm^{-3} ---------------		
0 – 0.2	8.88 bA	9.71 aA	1	2.23 aA	2.19 bA	1
0.2 – 0.4	8.26 bA	10.22 aA	1	2.23 aA	2.20 bA	1
Mean*	8.57 B	9.97 A		2.23 A	2.20 B	

Sample depth: 0–0.2 m and 0.2–0.4 m; OMC: optimum moisture content for maximum density of samples; Dmax: maximum density of compaction. Means followed by the same lowercase letters in the column and the same uppercase letters in the rows do not differ according to the Scott-Knott test at a 5% probability. *: Harmonical mean calculated by the Sisvar software.

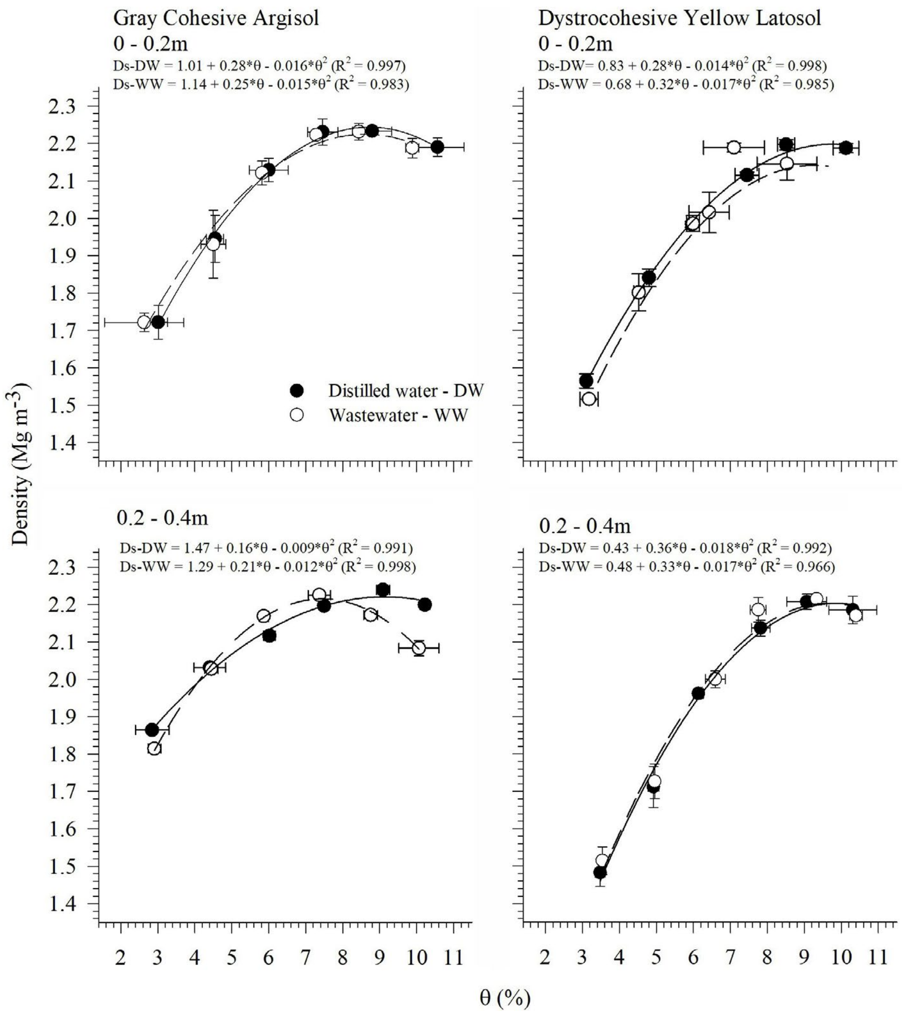

Figure 5: Results of the standard Proctor test comparing density as a function of moisture, as affected by distilled water and manipueira for samples from the 0–0.2 m and 0.2–0.4 m layers of a Gray Cohesive Argisol and a Dystrocohesive Yellow Latosol from the Coastal Tableland areas of Bahia, Brazil. Ds: Density; DW: Distilled water; WW: Wastewater. Error bars represent the standard error of the mean.

Higher Dmax values were found in the samples from both sampling layers of the Latosol when incubated with distilled water. The higher moisture content and lower Dmax in these samples are related to their higher organic matter content (Figure 4). In turn, the lowest Dmax value was found in the samples from the 0.2–0.4 m layer incubated with manipueira, which also shows that the samples require higher moisture contents to reach Dmax. Besides having a higher organic matter content, adding manipueira to the sample also helps it hold more water (Ribeiro et al., 2019; Chavadej et al., 2019; Peres et al., 2019). The lower-density organic carbon decreases the Dmax and retains more water but tends to decrease the compaction by reducing particle-to-particle attachment in soil, as shown for sandy soils by Braida et al. (2006).

Compared to the Latosol, the Dmax values of the Argisol were higher with lower OMC values, which means it is more compactable than the Latosol.

Centrifugation results

Figure 6 shows the density and porosity as functions of the load applied on the saturated samples from the 0–0.2 m and 0.2–0.4 m layers of a Gray Cohesive Argisol and a Dystrocohesive Yellow Latosol treated with manipueira or distilled water. The data from the alternative method proposed here were compared to the results estimated using two mathematical models fitted to the uniaxial data for soils with textures similar to that used in this study. The density values found here ranged from about 1.4 g cm^{-3} to 1.65 g cm^{-3} for all cases. The porosity ranged from about 0.37 cm cm^{-3} to 0.52 cm cm^{-3}. These densities bring some insight on the limiting density to root-growth of plants.

The density values (Figure 6) found by the centrifuge method were lower than those found in the standard Proctor test since the applied loads were about 0.47 kg.cm cm^{-3} to 2.6 kg.cm cm^{-3}, according to the G-force applied during centrifugation. The loads in the standard Proctor test were 5.9 kg.cm cm^{-3}. This difference shows that the load applied during the centrifuge test was not enough to promote higher densities in the samples, even at the highest G-force. Therefore, the centrifuge data cannot simulate the standard Proctor results in this case. During the centrifuge test, the load applied by the weight/G-force should be higher if a comparison with the standard Proctor test is to be made. Also, unlike in the standard Proctor test, the load applied during the centrifuge test is quite uniform over the sample, whereas the hammer causes the samples to be "shaken" and mixed throughout the standard Proctor test, allowing the particles to have a better particle-to-particle fitting, resulting in higher density (compaction). Therefore, even with higher loads/G-force, the centrifuge test will not reproduce the extent of sample compaction achieved in the standard Proctor test. However, the centrifuge test can give important results to simulate the limits after which the root system no longer grows in the soil. Thus, the standard Proctor test is important when the soil is to be used for engineering purposes, while the centrifuge test may be more suitable for understanding soil mechanics in agricultural soils.

The treatment of the samples with distilled water allowed a greater increase in the soil densities of the Argisol samples, from both layers, than in the Latosol samples. As expected, the total porosity followed the same pattern as the bulk density (Figure 6).

There were no differences in compactibility among the various treatments in the Latosol samples. In turn, the different treatments were reflected in the compactibility of the Argisol samples. For instance, the compaction was higher in the samples from the 0–0.2 m layer than in those from the 0.2–0.4 m layer. In this case, as the pressure increases, the total pore volume decreases more in the samples of the 0–0.2 m layer. The influences were in the following order: manipueira > distilled water. Soil tillage affects the total porosity; thus, our results suggest that the Argisol is at a more advanced degradation stage than the Latosol (Rocha et al., 2015; Enck et al., 2020). This is most likely due to the contribution of a thick layer of organic debris under the native forest condition from which the Latosol samples were collected.

Comparing mathematically - estimated pre-consolidation pressure data against centrifuge data

The results of centrifugation and its impact on the density and moisture content of the samples after being centrifuged with each G-force value were compared with the preconsolidation pressures estimated by mathematical models in soils whose texture classes are close to the ones used in this study (Figure 7). The mathematical models were those used by Martins et al. (2018), $\sigma p = 10^{(2.70 - 1.77\theta)}$ $(R^2 = 0.92^{**})$, and Ajayi et al. (2009), $\sigma p = 10^{(2.87 - 3.96\theta)}$ $(R^2 = 0.88^{**})$.

As expected, the moisture content of the samples decreased with the increasing G-force since the weight (load) and G-force value defined the entire mass pressure over the sample. The samples collected at the 0.2–0.4 m layer of the Argisol were most affected. In turn, the water retention improved at a lower matric potential in the Latosol amended by the manipueira treatment, regardless of the sampling layer.

The samples from the 0.2–0.4 m layer of the Argisol were more easily compacted than those from the 0–0.2 m layer. In addition, the preconsolidation pressure estimated using the equation by Ajayi et al. (2009) was closer to the pressure exerted by centrifugation for the 0–0.2 m layer samples. The pressure caused by centrifugation was closer to that estimated using the equation proposed by Martins et al. (2018), regardless of the treatments, soils, and layers.

The shape of the curves from the centrifuge data leads to two-segment curves (considering the average of all three treatments shown with a dashed line), resulting in different moisture contents and nearly the same pressure considering the sampling layers in both soils. There is a cross point in the curves for each soil and sampling layer at about 100 kPa, which is within the range of the preconsolidation pressure found by Oliveira et al. (2011). At these pressures, there were higher moisture contents in the upper layer (over 16% in the Latosol and 15% in the Argisol) due to the higher organic matter content, compared to about 13% in the 0.2–0.4 m layer of both soils. The pressures from these inflection points were used in the equations shown in Figure 7, resulting in soil densities (Table 4) close to the root growth-limiting densities presented by Reichert et al. (2009) for soils in the range of texture like the studied soils. The Argisol showed higher densities than the Latosol (Cavalcante et al., 2021).

Therefore, the centrifuge method gives some insight into the root growth-limiting density and the moisture content that leads to this density.

The centrifugation results are close to those estimated using the mathematical models. Martins et al. (2018) found higher compactibility in sandy-loam samples of Red Latosol compared to other clayey soils. The same was found by Andrade et al. (2017) in sandy-loam soils in other regions of Bahia. The results of centrifugation proved to be closer to those estimated using the equation proposed by Ajayi et al. (2009), who worked with soils from the Coastal Tableland areas that are even more similar to those in the present study, especially the Yellow Latosol. Such results indicate the possibility of using the centrifuge to estimate the pressure that may limit soil management; other studies are still necessary to verify the possibility of using this method for other fine-textured soils.

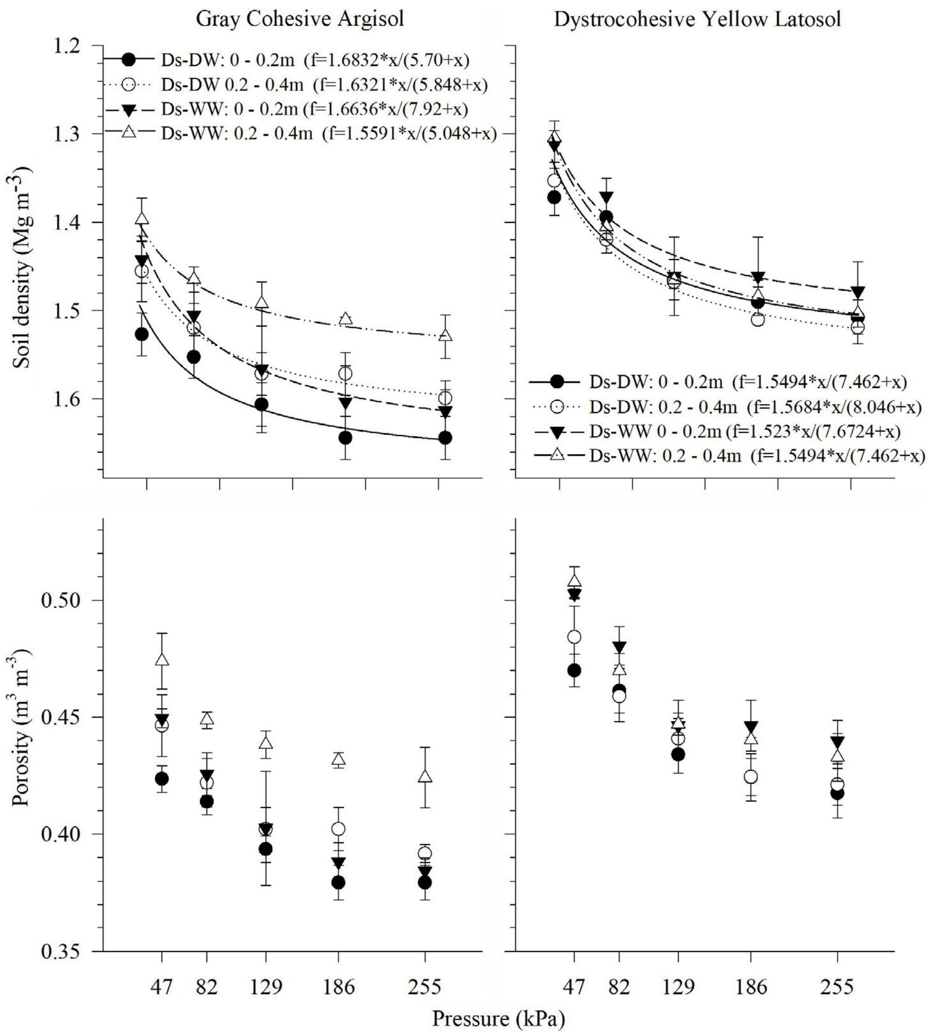

Figure 6: Density (above) and porosity (bellow) as functions of pressure during centrifugation in samples from the 0–0.2 m and 0.2–0.4 m layers of a Gray Cohesive Argisol and a Dystrocohesive Yellow Latosol from the Coastal Tableland areas of Bahia, Brazil, as affected by distilled water, distilled water with manipueira. Ds: Density; dw: Distilled water; ww: Wastewater. Error bars represent the standard error of the mean.

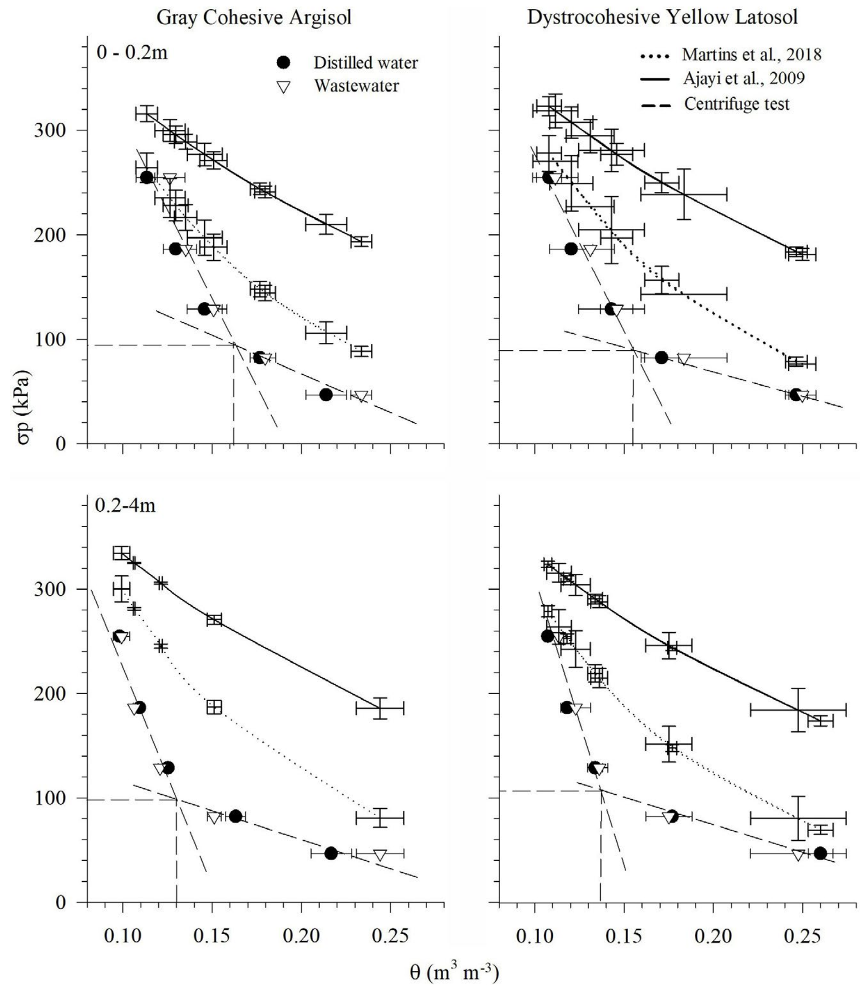

Figure 7: Preconsolidation pressure estimated by mathematical models and the pressure caused by centrifugation on samples of a Gray Cohesive Argisol and a Dystrocohesive Yellow Latosol collected in the 0–0.2 m and 0.2–0.4 m layers in the Coastal Tableland areas of Bahia, Brazil, and treated with distilled water or manipueira. Error bars represent the standard error of the mean.

Table 4: Estimated density for the inflection point of pressure as a function of the moisture content of the centrifuge results from samples of a Gray Cohesive Argisol (GCA) and a Dystrocohesive Yellow Latosol (DYL) collected at depths of 0–0.2 m and 0.2–0.4 m in the Coastal Tableland area of Bahia, Brazil, and treated (incubated) with distilled water (dw) or wastewater-manipueira (ww).

Layer (m)	Treat.	GCA		DYL	
		Pressure* (kPa)	Density (Mg m^{-3})	Pressure (kPa)	Density (Mg m^{-3})
	DW		1.59		1.43
0 – 0.2	WW	95	1.54	90 1.40	
	DW		1.54		1.46
0.2 – 0.4	WW	98	1.48	108 1.45	

*Pressure was taken graphically from Figure 7.

CONCLUSIONS

The centrifuge results were in the same range as those obtained by the mathematical models for coarse-texture soils, providing a reasonable estimate of the preconsolidation pressure. The compression caused by centrifugation is lower than the compression/compaction from the Proctor test and underestimates the maximum density of soil samples. The Gray Cohesive Argisol (Ultisol) was more susceptible to compaction. The centrifuge method provides insight into the root growth-limiting density and the moisture content that leads to this limiting density.

AUTHOR CONTRIBUTION

Conceptual idea: Lima, JM; Gonçalves. R.H.; Methodology design: Lima, JM; Gonçalves.R.H.; Data collection: Lima, JM; Gonçalves.R.H,; Santos, D.N.; Data analysis and interpretation: Lima, JM; Gonçalves.R.H,; Santos, D.N.; and Writing and editing: Lima, JM; Gonçalves.R.H,; Santos, D.N.; Nobrega, J.C.A.; Silva, R.B.; Ajayi, A.E.

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