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SOIL DENSITY AND OPTIMUM MOISTURE FOR SOIL COMPACTION IN FIVE SOIL CLASSES IN WESTERN BAHIA STATE

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ABSTRACT

The transformation of natural ecosystems into agricultural environments modifies the soil structure and it may result in its compaction. Therefore, the objective of this work was to determine the optimum moisture for soil compaction (wot) and maximum soil compaction density (Ds_{max}) in different soil classes in western Bahia State. The samples were collected in five sites covering different soil classes: Orthic Quartzarenic Neosol (RQ), Orthic Ebanic Vertisol (VEo), Haplic Cambisol (CX) and two Red-Yellow Latosol, one already cropped (LVA) and another with native forest (LVA1). Wot and Ds_{max} were determined according to ABNT NBR 7182 (1986) standards. Data were submitted to a regression analysis and also to the analysis of the principal components (PCA). Wot presented a decreasing order: VEo> LVA> LVA1> CX> RQo, ranging between 8.20 and 15.00% and Ds_{max} showed the following order RQo> LVA> LVA1> CX> VE, ranging between 1.34 and 1,92 $Mg.m^{-3}$. The wot was directly proportional to the clay content and the organic carbon and inversely proportional to the soil sand content. For Ds_{max}, the influence of the clay was inversely proportional whereas in wot, this variable promoted the growth.

Palavras-chave:
manejo do solo
atributos do solo
porosidade do solo
ensaio de Proctor

DENSIDADE DO SOLO E UMIDADE ÓTIMA DE COMPACTAÇÃO EM CINCO CLASSES DE SOLO NO OESTE DA BAHIA

RESUMO

A transformação dos ecossistemas naturais em ambientes agrícolas modifica a estrutura do solo podendo compacta-lo. Sendo assim objetivou-se com esse trabalho, determinar a umidade ótima de compactação (wot) e densidade máxima de compactação do solo (Ds_{max}) em diferentes classes de solos no oeste da Bahia. As amostras foram coletadas em cinco locais abrangendo classes de solos diferentes: Neossolo Quartzarênico órtico (RQ), Vertissolo Ebanico ortico (VEo), Cambissolo Háplico (CX) e dois Latossos Vermelo-Amarelo, sendo um já cultivado (LVA) e outro com mata nativa (LVA1). A wot e a Ds_{max} foram determinadas conforme as normas da ABNT NBR 7182 (1986). Os dados foram submetidos a uma análise de regressão e de componentes principais (ACP). As wot apresentaram uma ordem decrescente: VEo>LVA>LVA1>CX>RQo, com variação entre 8,20 e 15,00% e a Ds_{max}: RQo>LVA>LVA1>CX>VEo, variando entre 1,34 e 1,92$Mg.m^{-3}$. A wot foi diretamente proporcional ao conteúdo de argila e do carbono orgânico e inversamente proporcional ao teor de areia do solo. Para a Ds_{max} a argila influenciou de forma inversamente proporciona enquanto que na wot essa variável proporcionou crescimento.

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INTRODUCTION

Humans interfere in the natural ecosystems, where the soil is the component which was most modified by converting the natural environment into an agricultural one, requiring the frequent intervention of machines, implements and tools. These, in turn, change the structure of the soil in a beneficial or deleterious way, a determining property of the productive capacity of an agricultural area (MEDEIROS *et al*., 2015).

Compaction is one of the biggest problems related to the soil structure. It may occur due to the cultural treatments applied in the production process, mainly in "conventional" farming systems and annual crops, where the soil is inverted before each beginning of the crop. Compaction is usually caused by the traffic of agricultural machinery or by trampling of the animals during grazing. This process is aggravated when the soil has optimum water levels for compaction, also known as optimum soil compaction moisture (wot). Compaction rearranges the primary soil particles as well as their aggregates, therefore reducing the porous space and increasing its density (HAMZA; ANDERSON, 2005). The increase in the density resulting from the reduction of this porous space and the consequent reorganization of the aggregates impairs the adequate diffusion of gases (JESUS *et al*., 2017), resulting from the respiration process of the roots and soil microbiota (SILVA *et al*., 2015 ; TONIAZZO *et al*., 2018).While there is an attempt in farming to perform activities when the water content in the soil is beyond the wot range, this situation is almost always sought in civil engineering in an attempt to have the constructions that are as much steady as possible, including alternative methods to obtain the desired humidity when compacting land for construction of buildings or roads (MALTSEV *et al.*, 2017). Thus, the determination of wot becomes important for both agricultural sciences and civil engineering.

For the agricultural area, the degradation of soil structure resulting from compaction has caused negative effects on its physical, chemical and biological properties, impairing the development of plants and, consequently, the production of food and fibers (CAMARGO; ALLEONI, 1997; BOER *et al*., 2018).

The reduction in crop yield is reported in the forage used for grazing. There are also reports on productivity and nutrient absorption in soybeans. This reduction in crop yield may be related to the reduction in the root system of the plants, as it was reported for corn (BONELLI *et al*., 2011; CABRAL *et al*., 2012; VALADÃO *et al*., 2015; VALADÃO *et al*., 2017).

The factors that influence the most the soil ability to compact are the organic matter, quantity and quality of clays, soil management and water content (FREITAS *et al*., 2017; RIBELATTO *et al*., 2017). Other factors that may influence soil compaction are the amount of straw on its surface and the compaction energy applied to it (OLIVEIRA; SOARES NETO, 2011). Dias *et al*. (2012) also found that the type of land use significantly affects the liquidity limit, plasticity limit, plasticity index and optimum soil compaction humidity.

Thus, the objective of this work was to determine the optimum compaction moisture and maximum soil density in five classes of soils in Western Bahia, as well as the influence of the particle size and organic carbon (OC) content on the compaction of those soils.

MATERIAL AND METHODS

The soil samples were collected at a depth of 0.00-0.20 m, in the municipalities of Barreiras and Angical, both located in Western Bahia. The soils in the collection areas were classified according to the Brazilian Soil Classification System (SBCS) (EMBRAPA, 2018) as: Ortic Quartzarenic Neosol (RQ), Ortic Ebanic Vertisol (VEo), Haplic Cambisol (CX) and two Red-Yellow latosols, one was lain fallow (LVA) and one with natural vegetation (LVA1). Table 1 shows the geographical coordinates that locate the sampled areas.

Characterization of the particle size with the respective amounts of clay, silt and sand, as well as the organic carbon are shown in Table 2;

Table 1. Current use and geographic location of sample sites. Barreiras, BA. 2019.

Soil	Current use	Geographical coordinate	
		Latitude	Longitude
RQo	Pasture	12°00’43.7” S	44°42’58.2” W
VEo	Pasture	11°58’50.3” S	44°49’04.6” W
CX	Fallow after pasture degradation	12°08’40.2” S	44°57’49.2” W
LVA	Fallow after pasture degradation	12°05’29.6” S	45°02’42.1” W
LVA1	Native forest	11°53’39.8” S	45°36’01.5” W

*RQo- Ortic Quartzarenic Neosol, VEo- Ortic Ebanic Vertisol, CX- Haplic Cambisol, LVA- Red-yellow latosol.

Table 2. Clay, silt, sand and organic carbon (OC) of the soil in the experiment. Barreiras, BA. 2019.

Soil	Clay	Silt	Sand	OC
	.... g kg^{-1}………………...........................			
RQ	80	60	860	9.0
VEo	620	340	40	18.0
CX	180	200	620	18.0
LVA	180	70	750	10.0
LVA1	160	90	750	9.0

*RQo- Ortic Quartzarenic Neosol, VEo- Ortic Ebanic Vertisol, CX- Haplic Cambisol, LVA- Red-yellow latosol.

According to the classification of Köppen, the climate in the region is the Aw Dry Tropical, *i.e.*, a tropical savanna climate, with dry winter and rainy summer (OMETTO, 1981).

The tests were performed at the Soil Physics Laboratory of the University of Bahia State-UNEB, IX campus, Barreiras, Bahia State. Approximately 15 kg of soil from each class were used in the tests to determine each compaction curve. The soils were previously air-dried, afterwards they were removed and passed through a 4-mm mesh sieve, and the material retained in the sieve was disposed together with the non-decomposed organic material such as leaves, stems and small roots.

The particle size was determined through the pipette method by total dispersion, using sodium hydroxide (NaOH) as dispersing agent according to the methodology of (EMBRAPA, 2011) and organic carbon (CO), by hot oxidation with potassium dichromate in sulfuric medium (EMBRAPA, 2011).

The maximum density of each soil was determined using a normal Proctor-test gadget, without reusing the material according to ABNT NBR 7182 (1986). The soil was compacted in six specimens with increasing water content, with intervals of 2% of gravimetric humidity, with two repetitions. After compaction in each specimen, two samples were taken to determine the soil water content (w).

Soil densities were determined using the following equation 1:

$$Ds = (Dsw * 100) * (100 + w)^{-1} \quad (1)$$

Where,
Ds = Soil density ($g.cm^{-3}$);
Dsw = specific wet weight ($g.cm^{-3}$); and
w = average water content (%).

Following the determination of the soil densities, the points were plotted on graphs and adjusted in a second-degree polynomial ($Ds = aw^2 + bw + c$). Next, the optimal compaction water content (wot) and maximum soil density (Ds_{max}) were found with the aid of the first derivative of each function ($dDs / dw = 0$).

The density of the particles was determined according to the Volumetric Flask methodology (EMBRAPA, 2011). In this method, readings of the sample mass, flask volume and volume of total anhydrous alcohol were taken. The particle density was calculated using the equation 2:

$$Dr = \frac{M}{(Vb - Vaa)} \quad (2)$$

Where,
Dr = Real density of the particles ($g.cm^{-3}$);
M = sample mass (g);
Vb = volume of the flask; and
Vaa = total volume of the anhydrous alcohol.

The total porosity (Pt) was calculated using the samples of the specimen of each compaction test to determine the maximum density of the soil (Ds_{max}). By determining the volume of pores in the sample, according to Embrapa (2011), equation 3:

$$Pt\ (\%) = \frac{(Dr - Ds)}{Dr} \quad (3)$$

Where,
Pt = total porosity ($m^3.m^{-3}$); and
Dr = real density ($g.cm^{-3}$) Ds = soil density ($g.cm^{-3}$).

The void index (*e*), which is the relationship between the void volume and the volume of the solids was determined through the equation 4:

$$e = \frac{Pt}{(1 - Pt)} \quad (4)$$

Where,
e = void index (dimensionless); and
Pt = total porosity ($m^3.m^{-3}$).

Data were submitted to a regression analysis using the statistical program SigmaPlot 14, where the coefficients were tested by the "t" test with $p < 0.01$. These data were also submitted to analysis of the principal component (APC) in order to verify which of parameters in the study could be used to differentiate or to indicate similarities between the soils evaluated. This analysis was processed using PAST software version 2.17c (HAMMER *et al*., 2001).

RESULTS AND DISCUSSION

The analysis of the compaction curves (Figure 1) showed that regardless of the soil class, the soil density increased with the raise in the gravimetric humidity up to a maximum point, reflecting in this branch of the curve, the increase in soil susceptibility to compaction as the water content was incremented. The moisture corresponding to this maximum point is denominated "optimum compaction moisture". Once this level is reached, the increase in water content promoted a reduction in the soil density. This is due to the increase in the thickness of the water film among the soil particles, causing a dilution effect on its concentration per volume unit causing a decrease in the density on the wet branch of the curve.

Other physical properties of the soil that can influence Ds_{max} are the plasticity and liquidity threshold. When studying the influence of physical soil attributes on maximum density and optimum moisture, among the properties studied, Santos *et al*. (2015) found that these were the only ones that were significant. This explains the variation in the curves found in this work.

Also, it can be seen that the shapes of the compaction curves were different, particularly for VEo, indicating that the soil compaction develops differently, mainly influenced by the clay content with the contribution of organic matter and, probably due to soil management. Ribelatto *et al*. (2017) also observed a reduction in maximum soil density due to the accumulation of organic matter. In the construction of a compaction curve in Red-Yellow Latosol, with different managements, Soares Neto (2005) also found distinct compaction curves, which was attributed to the greater or lesser traffic of agricultural machines. This author also states that the soils submitted to the management with the use of a heavy harrow, with a cut depth of 0.20 m was the one that presented the greatest susceptibility to compaction and, the layer from 0.20 to 0.30-m, the one that was most compressed. Araujo-Junior *et al*. (2008) studying the resistance to compaction in a Red-Yellow Latosol with a clay texture showed that the 0.25-0.28-m layer showed to be the most favorable for compaction.

All equations had R^2 considered high, explaining more than 88% of the variation of the pairs of values of soil density versus gravimetric humidity. The three coefficients of the equations were significant by the "t" test with $p < 0.01$ of probability of error, with no intersection between the standard errors of

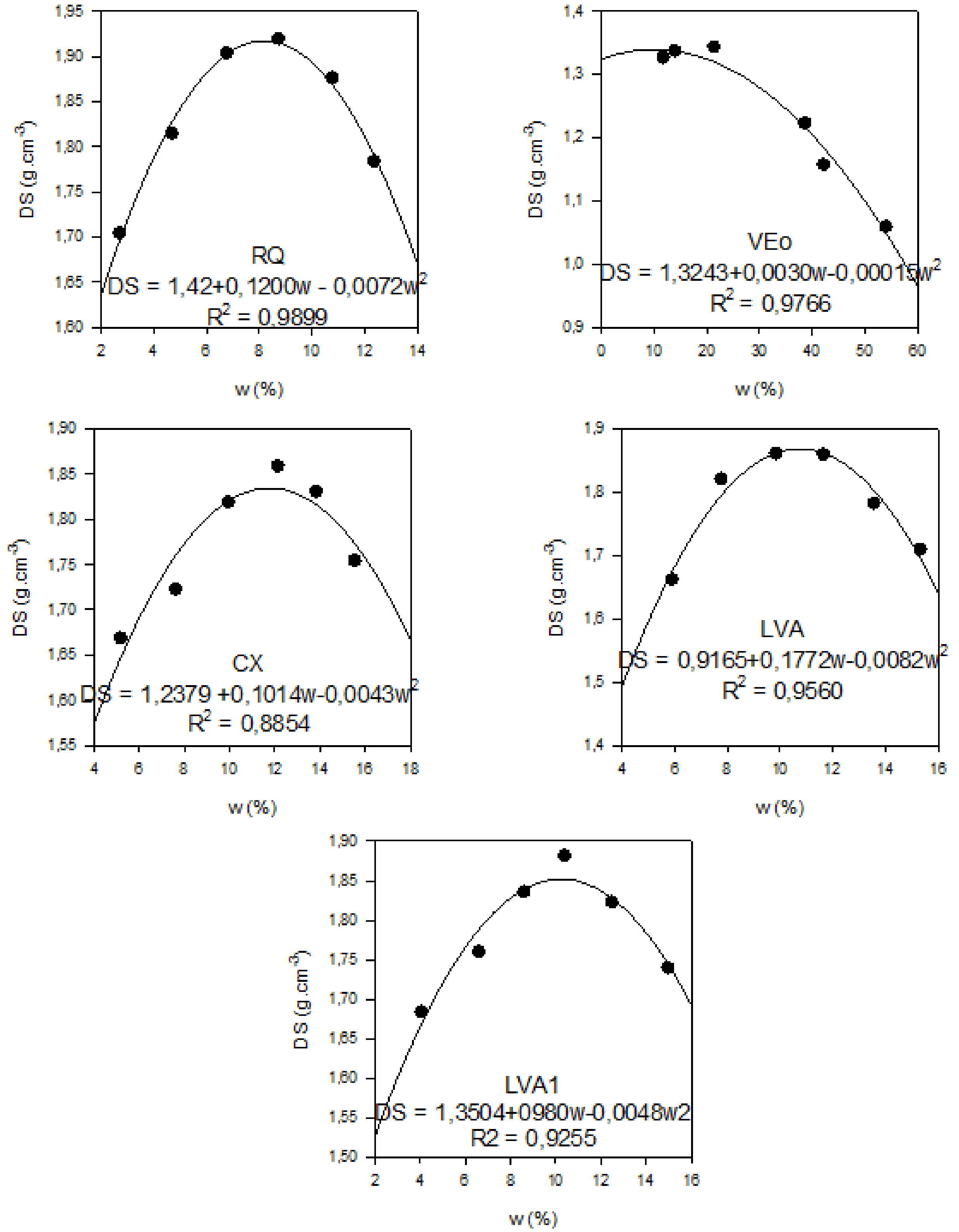

Figure 1. Compaction curves of the five soils in the experiment. Ortic Quartzarenic Neosol (RQo), Ortic Ebanic Vertisol (VEo), Haplic Cambisol (CX) Red-Yellow Latosol (LVA). Barreiras, BA. 2019.

the estimated coefficients, regardless of the studied soils. In a study with a Red-Yellow Latosol, Ramos *et al*. (2013) also found significant coefficients for regression equations with an explanation over 90%.

The optimum compaction moisture (wot) and maximum soil densities (Ds_{max}) can be seen in Table 3. It can be observed that compaction wot varied between 8.20 and 15.00%, with the maximum soil density varying between 1.34 and 1.92 g.cm^{-3}. The wot decreased in the following order: VEo > LVA > LVA1 > CX > RQo, and Ds_{max} as it follows: RQ > LVA1 > CX > LVA >VEo.

Luciano *et al*. (2012) stated that the high amplitude in the Ds_{max} and wot, shows the importance of studying different types of soil occurring in a region in order to establish reference values for these physical attributes. It is observed that each type of soil has a specific wot and Ds_{max} and the use of these values for other soil classes can lead to major errors in the definition of the ideal management moisture or in the assessment of the current status of compaction in a specific area. It is known that the soil tillage must be carried out when its water content is in the friability zone, defined as the interval between the water content at the contraction limit and the plasticity limit. This indicates that soils with a higher clay content and greater clay activity can increase the friability interval.

To better understand the values found for wot and Ds_{max}, a regression analysis was carried out, among them, the particle size fractions and organic carbon content. It can be seen in Figure 2 (A and C) that the wot values describe an upward curve due to the increment in the clay and total organic carbon, *i.e.*, , for the same compaction energy, soils with higher contents of clay and carbon organic can be worked in a wider range of humidity before reaching maximum compaction, however this does not reflect in the increase of the friability range, which depends on other variables. On the other hand, the wot decreases as the contents of sand are incremented (Figure 2 B).

The maximum soil density tends to decrease with the increment in the contents of clay and organic carbon. Conversely, Ds_{max} grows with the increase in the soil sand fraction (Figure 3A, B and C). This indicates that clayey soils with a high organic matter content reach Ds_{max} at lower values. It is believed that organic matter reduced the performance of water as a lubricant between mineral particles, which may diminish the Ds_{max}.

The comparison between the Latosol with the Vertisol revealed that the former reached a wot of 11.79 and 10.80% and Ds_{max} of 1.84 and 1.87 g.cm^{-3}, while the Vertisol reached a wot of 15 % and Ds_{max} of 1.34 g.cm^{-3}. This result may be related to the influence of organic matter and clay on the values of Ds_{max}. Other authors have also found equivalent values in similar soil conditions (FIGUEIREDO *et al*., 2000; LUCIANO *et al*., 2012). For medium-textured Red Latosols in mechanized operations carried out in the humidity range 0.14 to 0.20 kg.kg^{-1}, no physical degradation of the soil was observed (ROSSETTI *et al*., 2015).

The void indices (e) as a function of soil density (Ds) are shown in Figure 4. This relationship described a downward curve, *i.e.*, the void index has an opposite behavior to that of Ds. The VEo was the one with the highest angular coefficient of the equation that represents the relation e = f (Ds), indicating that the void index decreases more rapidly in this soil than in the others, with the increase in Ds. It can be stated that, for each increase of 1 Mg.m^{-3} in soil density, the void index is decreased by 1.8304.

Table 3. Optimum compaction moisture (wot) and maximum soil density (Ds_{max}) for the soils in the experiment. Barreiras, BA. 2019.

Soil	wot (%)	Ds_{max} (g.cm^{-3})
RQ	8.22	1.92
VEo	15.00	1.34
CX	11.79	1.84
LVA	10.80	1.87
LVA1	10.25	1.85

*RQo- Ortic Quartzarenic Neosol, VEo- Ortic Ebanic Vertisol, CX- Haplic Cambisol, LVA- Red-yellow latosol.

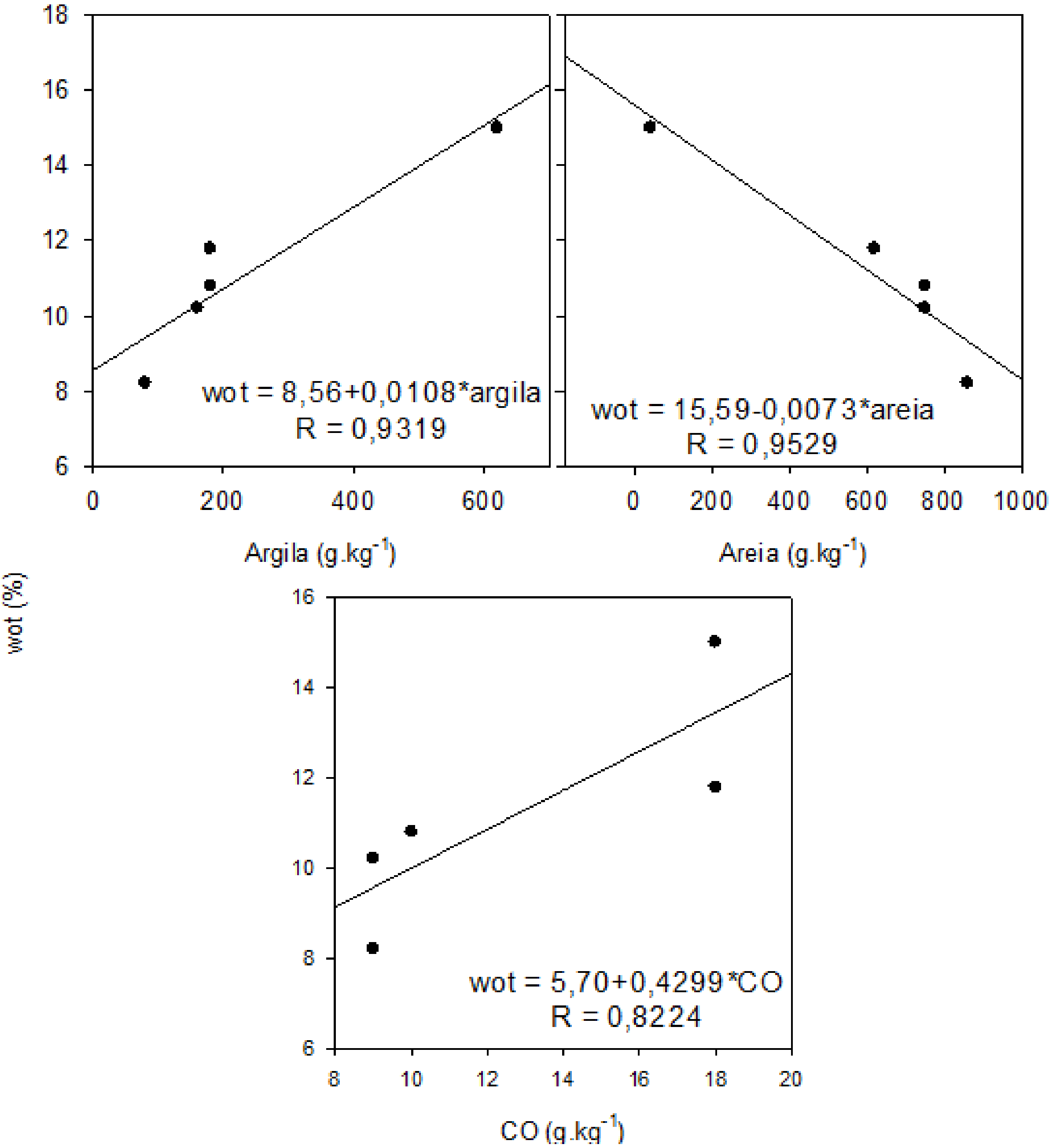

Figure 2. Optimum compaction moisture (wot) as a function of the quantity of clay, sand and organic carbon. Barreiras, BA. 2019.

It is observed in the RQ, CX, LVA and LVA1 soils that the regression lines almost overlapped each other (parallel), with angular coefficient ranging from 0.7810 to 0. 9991 and the linear coefficient varying between 1.8328 and 2.3645, although CX has twice as much organic carbon as the others. This is probably related to the Sandy-loam texture of the other soil classes (high sand content), when compared to CX. It is known that sand confers less binding between the organic components and the mineral colloidal constituents, thus providing less physical protection, therefore promoting the microbial decomposition of the organic matter (OLIVEIRA *et al.*, 2008; HICKMANN; COSTA, 2012; KUNDE *et al.*, 2016).

The results of the soil attributes, under the different environments, obtained in the first and second principal components 91.43 and 7.44% of

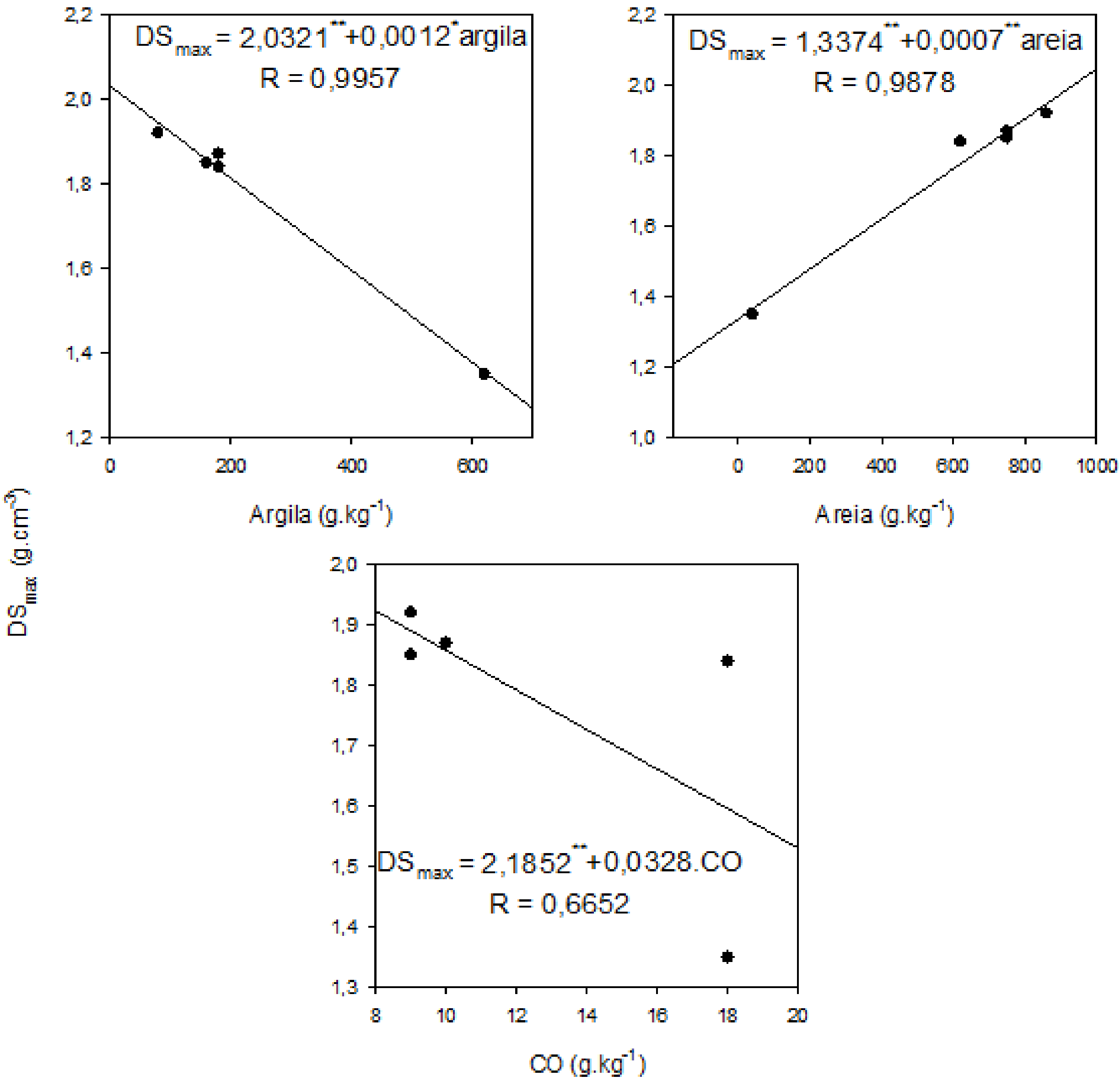

Figure 3. Maximum soil density (Ds_{max}) as a function of the quantity of clay, sand and organic carbon (OC). Barreiras, BA. 2019.

the variation, respectively. This represents 98.87% of the total variability of the data, which according to Cruz and Regazzi (1994) and Rencher (2002) is satisfactory for the evaluation through the graph dispersion of the scores in relation to the first and second canonical variables.

The scores for the principal component 1 (PC 1) were highly and positively correlated with clay (0.9895), OC (0.7740), wot (0.9580) and Pt (0.9860) and void index (0.9812), and negatively and highly correlated with sand (-0.9998) and Ds_{max} (-0.9854). In relation to the principal component 2 (PC 2), both correlations, positive and negative, were low. The correlation was positive with sand (0.0101), OC (0.6253), wot (0.1630), DS_{max} (0.1644), and the negative with clay (-0.1430), Pt (-0.1500)) and void index (-0.1778).

Figure 5 shows that the formation of three groups was evidenced: two made up by a single soil class (one made up by CX and another by VEo) and a third group formed by soils RQo, LVA and LVA1, therefore, demonstrating that these soils presented similar behavior regarding compaction, when considering the set of variables under study.

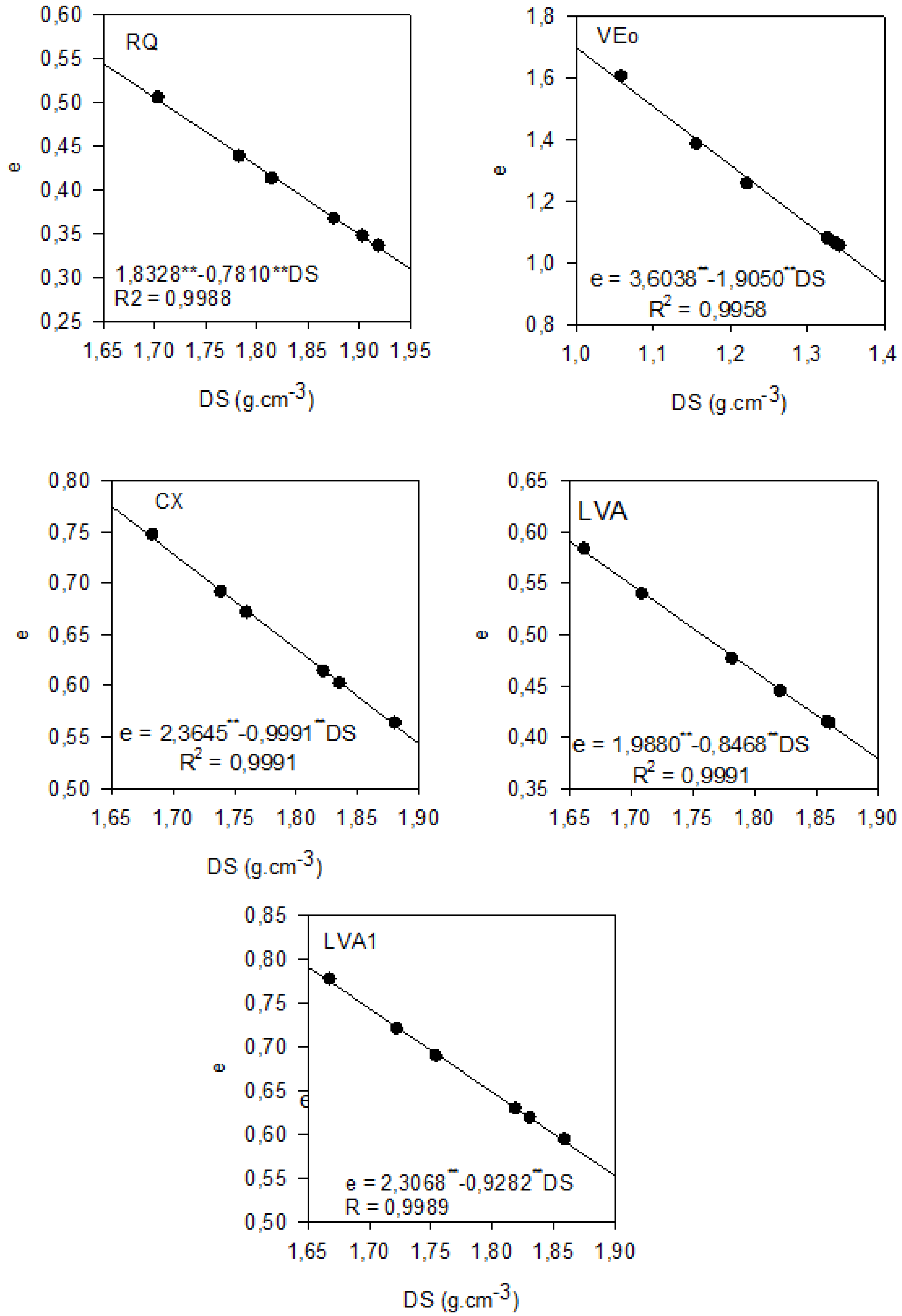

Figure 4. Void index (e) of soils evaluated as a function of soil density (Ds). Ortic Quartzarenic Neosol (RQ), Ortic Ebanic Vertisol (VEo), Haplic Cambisol (CX) Red-Yellow Latosol (LVA). Barreiras, BA. 2019.

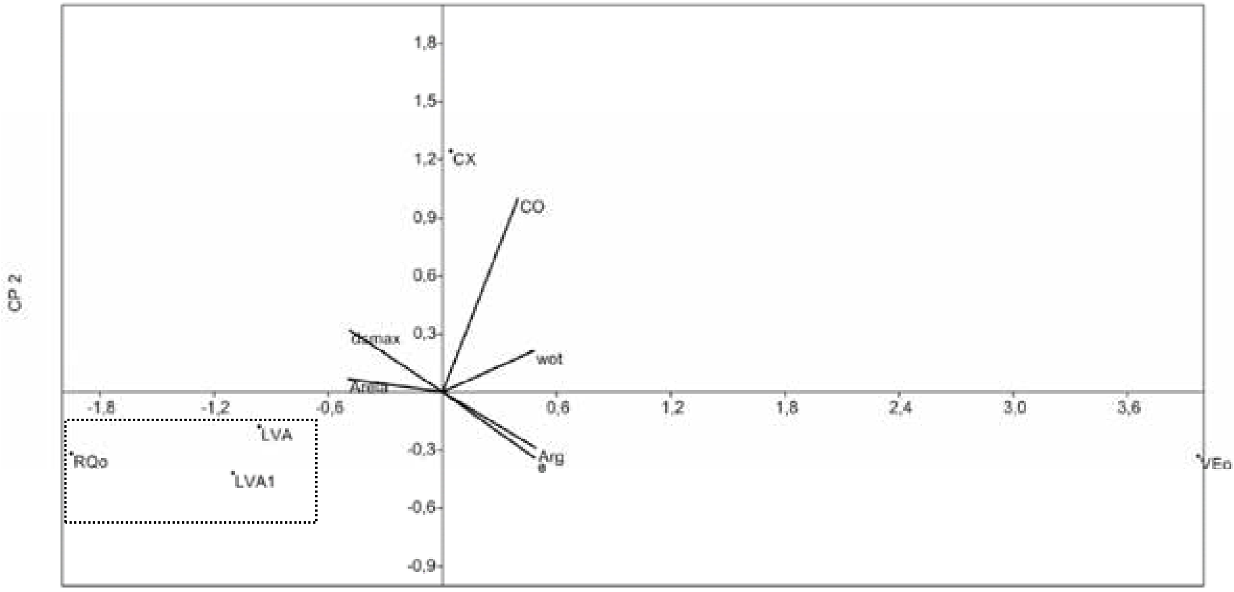

Figure 5. Soil dispersion and clustering of the first two canonical variables. Ortic Quartzarenic Neosol (RQ), Ortic Ebanic Vertisol (VEo), Haplic Cambisol (CX) Red-Yellow Latosols (LVA). Barreiras, BA. 2019.

The graphical representation and the correlation of the variables in the principal components (Figure 5) allowed to characterize the variables that most discriminated the formation of the groups. The soil attributes, sand and DS_{max} were responsible for the discrimination of the group formed by the soils RQ, LVA and LVA1, located on the left of the PC1 (negative correlations), while the variables CO and wot were active in the discrimination of the group formed by the soil CX (positive correlations) and the clay and void index discriminated VEo (positive correlations). Thus, the group made up by RQ, LVA and LVA1 is characterized by having higher sand content and lower organic carbon content, while CX is characterized by the high content of total organic carbon while VEo is characterized by the clay content.

From the perspective of the soil tillage, it is observed that each group of soil requires different management, the group of sandy soils had lower wotted and higher DS_{max}, while VEo, with higher clay content and higher wot, therefore indicating a greater humidity interval for operations using machine.

CONCLUSIONS

- The soil with the highest optimum compaction moisture and the lowest maximum density was the VEo and the RQ was that with the lowest optimum moisture and the highest maximum density.
- The optimum moisture was directly proportional to the content of clay and organic carbon and inversely proportional to the content of the sand in the soil. In relation to the maximum soil density, clay had an inverse influence on it, whereas for sand, the influence was directly proportional.
- The void index in VEo decreases more rapidly as soil density increases than in other soils.
- Principal component analysis indicated that the soils Neosol Quartzarenic Ortic, and both Red-Yellow Latosols made up one single group.

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