ORGANIC CARBON AND CARBON STOCK: RELATIONS WITH PHYSICAL INDICATORS AND SOIL AGGREGATION IN AREAS CULTIVATED WITH SUGAR CANE[1]

[CARBONO ORGÁNICO Y DEPÓSITO DE CARBONO: RELACIONES CON INDICADORES FÍSICOS Y AGREGACIÓN DEL SUELO EN ZONAS CULTIVADAS CON CAÑA DE AZÚCAR]

Diego Tolentino de Lima[1], Alyne Dantas Mendes de Paula[1],
Ernane Miranda Lemes[1], Gabrielly Isaac Rodrigues[1],
José Luiz Rodrigues Torres[2*] and Dinamar Márcia da Silva Vieira[1]

[1]Agronomist, student of the Graduate Program in Agronomy, Institute of Agricultural Sciences at the Federal University of Uberlândia. Av. Amazonas n/nº, Umuarama. Uberlândia-MG, Brazil, Zip code: 38400-902.
Email: diegotolentino10@hotmail.com
[2] Ph.D. Plant production, Federal Institute of Mining Triangle (IFTM). St. João Batista Ribeiro, 4.000. Uberaba-MG, Brazil. Zip code: 38064-790.
Email: jlrtorres@iftm.edu.br
**Corresponding author*

SUMMARY

Soil organic carbon and carbon stock influence, directly or indirectly, most of soil aggregate stability indicators. The objective of this study was to quantify the production of dry biomass (DB), total organic carbon (TOC) and carbon stock (CStk) in soil, and to evaluate their influence on some indicators of aggregation in an Oxisol at a Cerrado biome in Uberaba-MG, Brazil. The design was completely randomized blocks, in two evaluation periods: three and six cuts, at six depths (0-0.1, 0.1-0.2, 0.2-0.3, 0.3-0.4, 0.4-0.5 and 0.5-0.6 m). It was evaluated: soil density (SD), volumetric humidity (VH), aggregate stability index (AEI), weighted mean diameter (WDA), mean diameter (GDA), index of aggregates with diameter greater than 2 mm (AI) and sensitivity index (SI), replicated by 4. The best AEI of the soil and the highest TOC contents were found in the most superficial layers, 0 to 0.2 m, for both cuttings. The greater values of TOC and CStk, occurred at the sixth cut area, where there was a higher amount of DB on soil surface. The higher levels of organic matter did not provide higher AEI in the area of sixth cut, when compared to that of the third cut. The TOC and CStk levels in both areas generally had a positive influence on soil aggregation indicators for both cuts.

Keywords: soil physical attributes; soil organic matter; soil aggregate stability.

RESUMEN

La producción de biomasa, el contenido de carbono orgánico total y del almacén de carbono, influyen, directa o indirectamente, los indicadores relacionados con la estabilidad de los agregados del suelo. El objetivo de este estudio fue cuantificar la producción de biomasa seca (BS), el carbono orgánico total (COT) y el stock de carbono (CSTK) en el suelo, y evaluar su influencia en algunos indicadores de agregación en un Oxisol en el bioma de El Cerrado, en Uberaba MG, Brazil. El diseño fue de bloques al azar, en dos períodos de evaluación: tres y seis cortes; en seis profundidades (0.00-0.10; 0.10-0.20; 0.20-0.30; 0.30-0.40; 0.40-0.50 y 0.50-0.60 m). Se evaluó la producción de biomasa seca (BS), la resistencia del suelo a la penetración (SMR), densidad aparente (BD), humedad volumétrica (UV), el índice de estabilidad de los agregados (ESI) diámetro medio ponderado (SMD), diámetro medio geométrico (DMG), índice de agregados de diámetro superior a 2 mm (AGRI) y el índice de sensibilidad (SI); cada uno con cuatro repeticiones. El contenido más grande de COT y de CSTK se encontraron en las capas superficiales 0,0 0,20 m, en ambos cortes. Los valores más altos de TOC y CSTK, se produjeron en la zona del sexto corte, donde había una mayor cantidad de BS en la superficie del suelo. Los niveles más altos de materia orgánica no contribuyeron a un mayor ESI en el área del sexto corte, en comparación con la sección del tercer corte. En general, los niveles de TOC y CSTK, en ambas áreas, influyeron positivamente en los indicadores de agregación del suelo, en ambos cortes.

Palabras clave: propiedades físicas del suelo; materia orgánica del suelo; estabilidad de agregados del suelo.

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INTRODUCTION

Brazil is the world's largest producer of sugar cane which can be used to produce alcohol. Brazil has planted around 10.4 million hectares of sugar cane, *Saccharum officinarum* L. (Poaceae) (CONAB, 2017), and the sugar cane area has consistently increased in the past years. The mechanized harvest system and the transshipment of the sugar cane production use heavy machineries, and lead to soil compaction and increase soil bulk density (SD) (Cavalieri *et al*., 2011). These soil modifications tend to worsen as the traffic in the crop area is repeated during different soil moisture conditions. This situation can modify the physical and chemical soil properties, and alter soil organic matter content (Oliveira Filho *et al*., 2015), leading to damages to the root development and the sugar cane productivity.

The cropping operations has caused the decrease of the soil macroporosity and size of the soil aggregates, reducing the rate of water infiltration, increasing the SD and the mechanical resistance to root penetration (RP), in addition to changing the soil organic carbon stocks (CStk) (Camargo *et al*., 2010; Severiano *et al*., 2011; Cavalieri *et al*., 2011; Torres *et al*., 2014). These attributes have been widely used as indicators of changes in soil quality, in order to assess the impacts caused by management systems (Torres *et al*., 2013; 2015).

However, the RP and the SD have been used to define levels of soil compaction. The RP is highly dependent on moisture, texture, mineralogy and organic matter, and due to that dependency, the DS has been more used as a reference to monitor this physical attribute (Moraes *et al*., 2012). The aggregate stability (AS) characterizes the resistance to rupture caused by external agents, i.e., mechanical action or action of water. The soil aggregation is of great importance to agricultural production because soils with stable aggregates are less subject to soil compaction and erosion (Maria *et al*., 2007).

The total organic carbon (TOC) is not considered a physical attribute, but influences directly or indirectly the majority of these attributes. The increase of the TOC content increases the soil resilience and the ability to support loads (traffic); while, its decline is directly linked to the physical degradation of the soil (Braida *et al*., 2010).

Studying the effect of the sugar cane mechanized harvest, over the levels of TOC and aggregation of an Oxisol, Souza *et al*. (2012) observed a positive and significant correlation between the levels of TOC and the values of weighted mean diameter (WMD) of the soil, being higher in the management involving sugar cane plant, compared to ratoon cane. The authors also claim that the management systems, without plowing or burning, favor the increase in TOC soil content in the superficial layers.

High organic matter content, and consequently of TOC, favors the increase of aggregate stability expressed by higher content of macroaggregates, and lower content of stable microaggregates in water (Luca *et al*., 2008). Salton *et al*. (2008) noted that the formation of microaggregates, smaller than 0.25 mm, are related to the interaction of mineral matter among themselves and with organic compounds; while, the growth of roots and fungal hyphae, in addition to residues of plants, insects and other organisms, favor the formation of macroaggregates more stable and larger than 0.25 mm.

The addition of crop residues is minimal in manual harvesting, while, in mechanical systems left a straw cover of estimated amounts above 10 Mg ha^{-1} year^{-1}, which adds approximately 4.5 Mg ha^{-1} of carbon in the soil (Resende *et al*., 2006). In this context, the objective of this study was to quantify the production of dry biomass, the level of total organic carbon and the carbon stocks in the soil and evaluate their influence on some indicators of the aggregation in a Dystrophic Oxisol, in the Cerrado biome, at Uberaba district, Minas Gerais state, Brazil.

MATERIAL AND METHODS

Experimental area

The study was conducted in the commercial area of a plant producing sugar and alcohol, in the city of Uberaba, Minas Gerais state, Brazil, located between the coordinates latitude 19º39'19' South and longitude 47° 57'27" West, at 795 m above sea level. Samples were taken in areas of third and sixth cuts, soon after the mechanized harvest held in December 2014. In the region, there is a Dystrophic Oxisol, medium texture, with 210 g kg^{-1} of clay, 710 g kg^{-1} of sand and 80 g kg^{-1} of silt, up to 0.20 m deep (Embrapa, 2013).

Climate

The climate of the region is classified as Aw, tropical, hot, according to the classification of Köppen, having hot and rainy summer, and cold and dry winter. In the region, the annual averages of rainfall, temperature and relative humidity of the air are 1,600 mm, 22.6 ºC and 68%, respectively (Uberaba, 2009).

Experimental design

The experimental design was in blocks completely randomized, where the dry biomass (DB) of the residues, the soil mechanical resistance to penetration

(PR), soil density (SD), volumetric humidity (VH), aggregate stability index (ASI), weighted diameter average (WDA), geometric diameter average (GDA) and aggregate index for above 2 mm diameter (AI) in six depths (0-0.1; 0.1-0.2; 0.2-0.3; 0.3-0,4; 0,4-0.5 and 0.5-0.6 m) were evaluated, in two seasons (third and sixth cut), all made with 4 replicates. Each plot consisted of 10 rows of sugar cane grown in spacing of 1.5 m between rows, with 50 meters of length (15 x 50 m), making a total of 750 m^2 per plot.

Plant Dry Biomass

The plant dry biomass (DB) production deposited on the soil surface, was assessed in four points at random per plot, using a template, 1 m^2 area, which was released at random and all the material contained in the defined area were then collected. The plant material was weighed before and after cleaning, and the results expressed in Mg ha^{-1}.

Soil mechanical (root) resistance to penetration soil density

The soil mechanical resistance to root penetration (PR) was determined with the use of an impact penetrometer model IAA/Planalsucar, with angle of Bevel tip of 30º. The field data were obtained by counting the number of impacts (impact m^{-1}); then, they were transformed in kgf cm^{-2}, through the equation R (kgf cm^{-2}) = 5.6 + 6.98 N (Sene *et al*., 1985). After, these values were multiplied by the constant 0.098 for processing in units MPa (Arshad *et al*., 1996).

For determination of the soil density (SD), two undisturbed soil samples were collected per plot in six soil layers. This method uses volumetric rings (48 mm diameter by 53 mm height) and an Uhland sampler type. The samples were saturated with water for 24 h, then evaluated using a suction unit equivalent to 0.6 m water column; after that the samples were dried at 105 °C for 24 h (Embrapa, 2011).

Soil water contend

For the evaluation of the content of water in soil (SWC), samples were taken on the same day and depths that were determined to PR and SD. Two samples per plot were collected and homogenized, to obtain the wet and dry mass. These samples were packed in aluminum cans, weighed and placed for drying in ovens of forced air at 105°C for 24 hours. After obtaining the gravimetric moisture, this was multiplied by the SD and the volumetric soil water content (VH) (Embrapa, 2011).

Aggregate stability index, weighted diameter average and geometric diameter average

Samples were collected from each plot, with the aid of a hoe, at depths of 0-0,1; 0.1-0.2; 0.2-0.3; 0.3-0.4; 0.4-0.5 and 0.5-0.6 m, for analysis of the contents of the stability of aggregates (ASI) (Kemper & Chepil, 1965) (Eq. 1), which represents a measure of the total aggregation of soil and does not consider the distribution by class of aggregates; therefore, the greater the amount of aggregate < 0.25 mm, the smaller the ASI.

$$ASI= \{(SW – wp < 0,25) / (P.A)\} *100 \text{ (Eq.1)}$$

Where *SW* is the weight of the sample; *wp* (grams) weight of soil aggregates lower than 0,25 mm (Demarchi *et al*., 2011).

From the values of mass of aggregates, it was calculated the weight diameter average (WDA) (Eq. 2), which depends on the percentage of large aggregates retained on the sieves with larger meshes, and the geometric diameter average (GDA) (Eq. 3), which represents an estimate of the size of the class of aggregates with the greatest occurrence.

$$WDA = \sum (xi \times wi) \text{ (Eq. 2)}$$

Where *xi* is the average diameter of the class (mm); and *wi*, is the proportion of each class in relation to the total (Wendling *et al*., 2005).

$$GDA = \exp \{\sum [(\ln [xi]*[pi])] / \sum [pi]\} \text{ (Eq. 3)}$$

Where *ln[xi]* is the natural logarithm of the average diameter of all class; and *PI*, the weight (g) retained in each sieve (Demarchi *et al*., 2011).

It was determined that the aggregate index for above 2 mm diameter (AI), which represents the proportion of aggregates larger than 2 mm (Eq. 4).

$$AGRI = wi>2 \times 100 \text{ (Eq. 4)}$$

Where *wi>2* represents the portion of aggregates > 2 mm (Wendling *et al*., 2005).

Sensibility index

To compare the values of ASI between the third and sixth cuts, it was used the sensitivity index (SI) which estimates the intensity of the changes in any soil attribute (Bolinder *et al*., 1999; Fontana *et al*., 2010; Pereira *et al*., 2010; Torres *et al*., 2015). This index was calculated as the equation 5.

$$SI = as / ac \text{ (Eq. 5)}$$

Where *SI* is the sensibility index, *as* is the variable (ASI) at the third cut, and *ac* is the variable (ASI) at the sixth cut. The closer to the SI unit, the less will be the change caused in the evaluated attributes.

Total organic carbon and soil organic stock

The soil retained in each sieve (2, 1, 0.5 and 0.25 mm) was used for evaluation of the stability of the soil aggregates (IEA). For total organic carbon (TOC) evaluation, 0.5 g of air dried soil were macerated and passed through the sieve of 0.25 mm. The material was placed in 250 mL Erlenmeyer flask and then, 5 mL of potassium dichromate ($K_2Cr_2O_7$ 0.167 mol L^{-1}) and 7.5 mL of sulfuric acid (H_2SO_4) were added. Later, warmed up in a block digester at 170 °C for 30 min. Then, it was added 80 mL of distilled water and 0.3 mL of fenantrolina indicator for titration with ammonium ferrous sulfate 0.2 mol L^{-1}solution (Yeomans and Bremner, 1988).

It was determined the organic carbon stock (CStk) in the soil, based on the method of soil layer equivalent (Luca *et al*., 2008), which, in addition to the contents of carbon, takes into account the thickness of the layer and the density of the soil. In this way, the stock of carbon was obtained by the product between organic carbon content (g kg^{-1}), the thickness of the layer (cm), and the soil bulk density (kg dm^{-3}) (Eq. 6).

$$CStk\ (Mg\ ha^{-1}) = (C \times SD \times e)/10 \quad (Eq.\ 6)$$

Where *CStk* is the value of the total organic carbon in the layer (g kg^{-1}); SD, soil bulk density (Mg m^{-3}); and *e* is the thickness of the layer in analysis, in cm.

Statistical analyses

The results were submitted to assumptions of the ANOVA model: analysis of normality of the residue (errors) distribution (Shapiro-Wilk test), homogeneity of the variances of the errors (Levene's test), and additivity of blocks (Tukey test). Given the assumptions of normality and homogeneity, the mean values were compared by the Tukey test at 5% probability ($p<0.05$). It was also performed Pearson’s correlation among the variables AI, GDA, WDA,and PR in the planting line, and PR between planting lines, SD, VH and CStk.

RESULTS AND DISCUSSION

Biomass production

The input of plant residues on the soil surface in the area of sixth cut (15.1 Mg ha^{-1}) was significantly ($p < 0.05$) greater than the quantity found in the area of third cut (10.2 Mg ha^{-1}), being about 50% higher after three slices, which evidences an average input of 1.63 Mg ha^{-1} $year^{-1}$ of dry biomass (DB) in the area of sixth court. The production of DB obtained in the area of third cut was similar to the results found by Garbiate *et al*. (2011) in studies conducted in the Cerrado (Brazilian savanna like biome) and lower than the DB reported by Souza *et al*. (2005) (12 Mg ha^{-1} $year^{-1}$), and by Schultz *et al*. (2010) (13.9 Mg ha^{-1}) in other climatic conditions.

In the sixth cut area the quantity obtained (15.11 Mg ha^{-1}) was superior to the data reported in the literature in other studies for the same period (Resende *et al*., 2006; Torres *et al*., 2015). Whereas the sugar cane plant is completely renovated, on average, after seven cuts, an well managed crop can prolong its commercial life providing more and constant residue inputs on soil surface after each sugar cane cut, justifying this greater volume of straw found in the oldest areas.

Resistance to penetration, density and soil humidity

By analyzing the values of soil resistance to penetration in the planting line (PRL), between lines (PRBL) and soil density (SD), it was observed that the areas presented a layer compressed between the depths of 0.1 to 0.3 m, where the values were higher in the depth of between 0.1 and 0.2 m, for the third (3.85 and 5.78 Mpa and 1.58 kg dm^{-3}) and sixth cut (5.86 and 7.07 Mpa and 1.77 kg dm^{-3}), followed by the values of the depth of 0.2 to 0.3 m for the third (3.80 and 4.56 Mpa and 1.54 kg dm^{-3}), and sixth cut (5.46 and 6.28 Mpa and 1.72 kg dm^{-3}), respectively (Table 1). These figures show that traffic of chopping and the transhipment of sugar cane production cause gradual soil compaction, increasing the values after each sugar cane harvest.

Even though, there is no consensus in the literature about what are the limits of compression that causes restriction in the development of plants, the values observed between the depths of 0.1 to 0.3 m are already causing restriction to root development, because all are above 3.5 MPa. Arshad *et al*. (1996) suggested that values of resistance to penetration (RP) between 2 and 4 MPa restricts the full growth of plant roots; while, Sene *et al*. (1985) reported values between 6 to 7 MPa as critical for sandy soils and 2.5 MPa for clay soils. However, it has been accepted by most scholars of the subject that values of PR around 2.5 MPa are considered low; while, values around 3.5 to 6.5 MPa are considered high and capable of causing problems to the development of legumes and grasses roots (Torres and Saraiva, 1999).

With respect to soil density (SD), the critical values are 1.65 Mg m^{-3} for sandy soils and 1.45 Mg m^{-3} for clay soils (Araújo *et al*., 2004); however, Reinert *et* *al*. (2001) propose the critical value of 1.55 kg dm^{-3}, characterizing the soil as compacted, when it has between 200 and 550 g kg^{-1} clay, pointing out that these values are the closest to the soil of this study, which has 210 g kg^{-1} clay, being classified as of medium texture (Embrapa, 2013).

In this study, practically all values of RPL, RPBL and SD are within the range that causes restriction on plant root development, and the effect of compression is more pronounced in RPBL, where the traffic of machinery is more frequent. Results by Roque *et al*. (2010), showed that the traffic of heavy machinery (20 to 30 tons, or greater) cause increase in SD, lower aggregation and porosity between planting lines, when compared to the planting line, causing the cumulative degradation of soil physical quality over the years of sugar cane cultivation. Souza *et al*. (2005), further highlighted that the traffic of heavy machinery in systems with low soil revolving promotes the soil compaction and increases it density at lower depths.

In a similar study Centurion *et al*. (2007), evaluated areas of planted cane, second and fourth cut, and observed that the time of sugar cane cultivation interfered in soil structure, causing the increase of SD and decrease in total porosity, due to the intense traffic of machineries. Severiano *et al*. (2011) pointed that low levels of soil compaction is beneficial for plant growth, due to the increased water retention caused by the increase of soil microporosity; this is desirable especially in dry years and in soils with low water holding capacity.

With respect to the content of water in soil, it was observed that the values were consistently higher in the sixth cut in all depths evaluated, when compared to third cut, which is easily justified by the greater amount of residue on the soil surface, which came to be 50% higher in this area, reducing the loss by water evaporation.

According to Almeida *et al*. (2008), the RP is strongly influenced by soil water content, since the greater is the water content in the soil, the lower are the values of PR; however, in this study this effect seems not to have been observed, since the volumetric (VH) was higher in the area with the greatest RP. Studying the soil cultivated traditionally mechanized harvest and mechanized cutting with traffic control, Roque *et al*. (2010) and Oliveira Filho *et al*. (2015) observed no variation in water content of the soil to a depth of 0.4 m for none treatment.

Table 1. Soil resistance to penetration in the planting line (RPL) and between lines (RPBL), soil bulk density (SD) and volumetric humidity (VH), in a sugar cane area. Uberaba-MG, Brazil.

Depth	RPL	RPBL	SD	VH
m	…………....Mpa.................		kg dm^{-3}	cm^3 cm^{-3}
		Third cut		
0.0 – 0.1	2.42 aB*	3.83 bC	1.61 bA	13.8 bA
0.1 – 0.2	3.85 bA	5.78 bA	1.58 bA	13.6 bA
0.2 – 0.3	3.80 bA	4.56 bB	1.54 bA	14.1 bA
0.3 – 0.4	2.90 bB	3.09 bD	1.47 bB	13.8 bA
0.4 – 0.5	2.37 bB	2.14 bE	1.45 bB	13.4 bA
0.5 – 0.6	1.78 bC	1.79 bE	1.40 bB	12.8 bA
		Sixth cut		
0.0 – 0.1	2.87 aD	4.72 aC	1.78 aA	21.8 aA
0.1 – 0.2	5.86 aA	7.07 aA	1.77 aA	21.4 aA
0.2 – 0.3	5.46 aA	6.28 aB	1.72 aA	22.8 aA
0.3 – 0.4	4.61 aB	4.72 aC	1.65 aB	21.5 aA
0.4 – 0.5	3.75 aB	3.96 aD	1.63 aB	21.2 aA
0.5 – 0.6	3.23 aD	3.46 aE	1.58 aB	22.5 aA
CV (%)	11.55	7.95	4.52	12.25

* Averages followed by the same minor letters do not differ among each other by the Scott-Knott test ($p<0.05$), comparing the same depth between third and sixth cuts; capital letters compare depths in the same treatment (same cut).

Aggregate stability index

Analyzing the indicators of soil aggregation, it was observed that the values of WDA, GDA, ASI and AI were superior in the area of sixth cut for all depths evaluated (Table 2), which proves that it is occurring a reorganization and stabilization of the soil particles that can be explained by the input of organic material (sugar cane crop residues) on the soil surface after each cut and the action of the hairy (fasciculated) root system on the soil aggregates, which proves that the time of sugar cane cultivation and the number of cuts interfere in the indices of soil aggregation.

In a similar study, Centurion *et al*. (2007) have compared areas of planted cane, cane of second and fourth cut, and observed that the time of sugarcane cultivation interfered in soil structure, reducing the aggregation, WDA and total porosity, as well as provide an increase of SD. Several factors can interfere with the soil aggregation and its stability. Studying the relationship between the aggregates and soil organic matter, Salton *et al*. (2008) identified that the mineral fraction, fauna, microorganisms, roots, inorganic agents, environmental variables, and management are the main factors involved in the formation and stability of soil aggregates. Pereira *et al*. (2010) noted that higher values of WDA and GDA highlights the contribution of management in the stabilization of soil aggregates (Table 2).

According to Ramos *et al*. (2010), the soils that are less disturbed maintain high quantity of roots, which has a positive influence on soil aggregation, because these roots act in the approximation of mineral particles due to the pressure exerted during its growth in the soil pore space and the release of organic exudates.

The AI index confirms the effect of structuring that occurs in soil over time, since the values obtained in this study were high and always above 50%. Caetano *et al*. (2013), assessing areas under no-tillage system with high deposition of residues, observed that there was an increase in some aggregates smaller than 2 mm, which caused the reduction of the WDA.

Comparing different management systems in an Oxisol, Demarchi *et al*. (2011) evaluated the WDA and GDA, ASI and AI and observed that the best aggregation index occurred in the pasture area of *Urochloa brizantha* cv Marandu, which presented the values of 4.12 and 2.96 mm, 92.9 and 79.7% for grazing, and 3.43 and 2.04 mm, 88.4 and 63.7% for native forest, respectively. The authors justify the results favoring the pasture area through the greater soil aggregation promoted by hairy roots of the Marandu grass, the soil protection from the organic matter provided, and the lower soil moisture and temperature fluctuations in the pasture area.

Table 2. Weighted diameter average (WDA), geometric diameter average (GDA), aggregate stability index (ASI), aggregate index for above 2 mm diameter (AI) and senssibility index (SI) in sugar cane area. Uberaba-MG, Brazil.

Depth	WDA	GDA	ASI	AI**	SI
m	…………..mm…………		………..%...........		
		Third cut			
0.0 – 0.1	0.35 bA*	0.23 bA	42.19 bA	1.69 bA	--
0.1 – 0.2	0.39 bA	0.24 bA	42.99 bA	2.16 bA	--
0.2 – 0.3	0.35 bA	0.23 bA	41.20 bA	1.78 bA	--
0.3 – 0.4	0.38 bA	0.24 bA	44.97 bA	1.86 bA	--
0.4 – 0.5	0.40 aA	0.25 aA	45.17 bA	1.80 aA	--
0.5 – 0.6	0.33 bA	0.22 bA	40.09 bA	1.73 bA	--
		Sixth cut			
0.0 – 0.1	0.67 aA	0.40 aA	70.09 aA	2.91 aA	1.7
0.1 – 0.2	0.77 aA	0.46 aA	74.40 aA	3.37 aA	1.7
0.2 – 0.3	0.63 aA	0.38 aA	67.52 aA	2.82 aA	1.6
0.3 – 0.4	0.81 aA	0.49 aA	72.10 aA	3.36 aA	1.6
0.4 – 0.5	0.59 aA	0.36 aA	66.01 aA	2.62 aA	1.5
0.5 – 0.6	0.68 aA	0.41 aA	70.44 aA	2.95 aA	1.8
CV (%)	25.06	22.94	11.86	27.77	--

* Averages followed by the same minor letters do not differ among each other by the Scott-Knott test ($p<0.05$), comparing the same depth between third and sixth cuts; capital letters compare depths in the same treatment (cut). ** The AI data was transformed by $(x+1)^{0,5}$ to meet the ANOVA presumption of residue normality and homogeneity of variance.

Sensibility index (SI)

By analyzing the sensitivity index (SI), which was calculated for the ASI, it was observed that the lowest value occurred in the depth of 0.4 - 0.5 m, and the ASI 50% higher in the sixth cut when compared to third cut, and in the other depths was even greater, ranging between 60 and 80% (Table 2). According to Bolinder *et al*. (1999) and Bertol *et al*. (2004), the SI has long been used to evaluate the influence of different types of vegetation cover and forms of management in the stability of aggregates; since the greater is the SI value, the closest to natural condition the soil will be.

The SI values indicate that the soil aggregation in sixth cut has improved when compared to the area of third cut, and shows that for this attribute, the cultivation of sugar cane for a longer period in the area favors the restructuring of the soil aggregates. This happen because after each cut, the sugar cane root system is renewed with the emergence of new roots, where 75% of the hairy root system concentrate up to 0.4 m depth; however, if there are no chemical and physical barriers, the sugar cane root system can exploit soil depth up to 2 m or more (Souza *et al*., 2014).

When comparing annual cropping soils with sugar cane and pasture, Fontana *et al*. (2010) observed that the values of the soils under pasture were higher than those under sugar cane. The authors also showed that the lowest SI values are found in the area of sugar cane, reflecting the harmful effect of hard tillage activities carried out in preparation of the area for the sugar cane planting. These activities break down the soil particles; however, planting the sugar cane hairy root system, promotes the approximation of soil particles and contributes to the restructuring of soil aggregates, and this fact was observed in this study, which presented higher SI value in the sixth cut, when compared to the third cut. Maia and Ribeiro (2004), studying the changes of physical attributes of an Ultisol submitted for different periods of cultivation of sugar cane (02 and 32 years), observed the same behavior, a positive influence of the sugar cane root system on the soil aggregation, after each cut.

Torres *et al*. (2015), using the aggregate stability index (ASI) and the sensitivity index (SI) to assess changes in physical attributes in areas after 12 years of no-till system, observed that for all SI calculated, the soil density, the macroporosity and microporosity, and total porosity were higher 12 years after the employment of the no-till system. According to the authors, this occurred due to the protection provided by plant residues, which protect the soil against rainfall erosion and fluctuations of humidity, the organic matter added to the soil, and microbial activity that produces substances responsible for the formation and stabilization of soil aggregates, in addition to the aggregator effect of the hairy root system.

Total organic carbon and soil carbon stock

It was found that the highest values of total organic carbon (TOC) occur in the superficial layers, with a significant difference only in the sugarcane sixth cut, and with values numerically higher in the 2 mm sieve for both periods assessed (Table 3). When there is a difference between years of cutting, it was found higher values in the area of sixth cut. This evidence justifies the best soil aggregation in this area, even knowing that this area was exposed to the intense use of machinery for harvesting and transfer for longer period.

According to Bertol *et al*. (2004), the TOC is one of the main factors of formation and stabilization of aggregates in areas without soil revolving, because the cycles of wetting and drying of the soil are improved and favors soil aggregation. Araújo *et al*. (2004) noted that the TOC content influences the physical properties of the soil, changing the form and the stability of the soil structure, which usually improve with the increase of soil organic matter content.

The increase of soil organic matter resulting from successive inputs of plant residues and roots can reduce the values of SD in the superficial layer (Guareschi *et al*., 2012). This situation was also observed in this study in two areas assessed (third and sixth cuts), even the SD above the critical level (1.55 kg dm^{-3}) up to 0.3 m depth in the area of sixth cut.

In their study, Souza *et al*. (2012) reported that the hairy root system of grasses have intense rhizospheric activity, which will contributes to the formation of soil organic matter, intensely favoring soil particles aggregation. Coutinho *et al*. (2010) noted that the greatest mass of aggregates in the 2 mm sieve may occur due to the larger volume of roots provided by the species of the Poaceae family and fungi hyphae associated, which benefit the formation and stability of larger size soil aggregates.

The correlations between the indicators of soil aggregation showed that the SD was the attribute that correlated significantly ($p<0.01$) with almost all other attributes, positively with PRL, PRBL, VH and CStk in third cut and with PRL, PRBL, VH, GDA, WDA, ASI and CStk in the sixth cut; while, the correlation was negative with GDA, WDA, ASI, and AI in the third cut (Table 4).

Table 3. Total organic carbon (TOC) in function of the soil aggregates and depth, and soil carbon stock (CStk), in sugar cane area. Uberaba-MG, Brazil.

Depth	Sieve				CStk
	(mm)				
	0.25	0.50	1.00	2.00	
	COT				
m	……………………...dag kg^{-1}……………………..				Mg ha^{-1}
Third cut					
0.0 – 0.1	1.44 aA*	1.59 bA	2.14 bA	2.30 bA	18.70 bA
0.1 – 0.2	1.31 aA	1.58 aA	1.93 bA	2.61 bA	18.57 bA
0.2 – 0.3	1.10 aA	1.49 aA	1.77 bA	1.79 bA	15.91 bA
0.3 – 0.4	1.24 aA	1.37 aA	1.62 bA	1.88 bA	15.29 bA
0.4 – 0.5	0.99 aA	1.42 aA	1.64 bA	1.87 bA	14.83 aA
0.5 – 0.6	0.95 aA	1.19 aA	1.66 aA	1.57 aA	13.97 aA
Sixth cut					
0.0 – 0.1	1.46 aA	2.64 aA	3.50 aA	3.88 aA	28.72 aA
0.1 – 0.2	1.15 aA	1.45 aC	3.46 aA	3.12 aB	22.97 aB
0.2 – 0.3	1.12 aA	1.60 aB	2.40 aB	3.76 aA	22.23 aB
0.3 – 0.4	1.26 aA	1.66 aB	2.21 aC	2.76 aC	19.73 aC
0.4 – 0.5	1.02 aA	1.52 aC	2.12 aC	2.35 aC	17.53 aC
0.5 – 0.6	1.08 aA	1.45 aC	1.72 aD	1.79 aD	14.58 aC
CV (%)	25.12				16.14

* Averages followed by the same minor letters do not differ among each other by the Scott-Knott test ($p<0.05$), comparing the same depth between third and sixth cuts; capital letters compare depths in the same treatment (cut).

Table 4. Pearson correlation coefficient among soil densit (SD), soil resistance to penetration in the planting line (PRL) and between planting lines (PRBL), volumetric humidity (VH), weighted diameter average (WDA) and geometric (GDA), aggregate stability index (ASI), aggregate index for above 2 mm diameter (AI), sensibility index (SI) and soil carbon stock (CStk) in sugar cane area. Uberaba-MG, Brazil.

Variables	PRL	PRBL	VH	GDA	WDA	ASI	AI	SI	CStk
Third cut									
SD	0.51*	0.71*	0.62*	-0.18*	-0.19*	-0.10*	-0.09*	-	0.37*
PRL		0.81*	0.32^{ns}	-0.07*	0.01*	-0.09*	-0.09*	-	0.29*
PRBL			0.38*	0.01*	0.07*	0.01*	0.28^{ns}	-	0.48*
VH				-0.23*	-0.34*	-0.05*	-0.43	-	0.04*
GDA					0.97*	0.94*	0.61*	-	-0.09*
WDA						0.86*	0.77*	-	0.01*
ASI							0.51*	-	-0.12*
AI								-	0.26^{ns}
SI									-
Sixth cut									
SD	0.20*	0.54**	0.29*	0.33^{ns}	0.33*	0.41*	0.31*	-0.44^{ns}	0.67*
PRL		0.78**	-0.01*	0.05*	0.12*	0.03*	0.10*	-0.30*	0.07*
PRBL			-0.02*	0.11*	0.12*	0.16*	0.16*	0.02*	0.40*
VH				0.07*	0.11*	-0.03*	0.18*	-0.48*	0.01*
GDA					0.98*	0.89*	0.93*	-0.24^{ns}	0.19*
WDA						0.83*	0,98*	-0.29^{ns}	0.17*
ASI							0.72^{ns}	-0.07*	0.21^{ns}
AI								-0.29*	0.16^{ns}
SI									-0.27*

^{ns} = non significative; * and ** = significative $p<0.01$ and $p<0.05$, respectively.

According to Ramos *et al*. (2010), the SD is one of the most important attributes and used as an indicator of soil quality, because it is a sensitive component to changes caused by management, this fact also demonstrated in this study, because as the SD has increased, at the same time occurred the elevation of the PRL and PRBL in both cuts, with the decrease in the third cut and increase sixth cut of the GDA, WDA, ASI and AI.

In a similar study, comparing areas cultivated with sugarcane of third and fifth cuts, Torres *et al*. (2015) showed that the soil compaction caused by the system of collection and shipment of sugar cane, after successive cuts alters the soil physical properties, affecting almost all other indicators used (PRBL, SD, ASI, WDA, GDA and AI).

In both evaluated areas, it was evident the influence of organic matter in the stability of aggregates; since almost all indexes were positive and significantly correlated with the CStk in soil (Table 4), which proves that the organic matter is one of the main aggregant agent of soil particles, also influencing on the variation of size and shape of the soil aggregates (WDA and GDA) and the aggregation index (ASI and AI).

Similar results were observed by Wendling *et al.* (2005), in their study, they investigated soils submitted to different managements, and verified positive correlations among indices SD, WDA, Gda, AI, and ASI.

CONCLUSIONS

In both places, in the planting line and between them, it was found a layer of compacted soil between 0.1 and 0.3 m, and for both cut periods (third and sixth) evaluated;
The highest levels of organic carbon and carbon stocks in soil occurred at the sixth cut, where there was a greater amount of dry biomass on soil surface, which also contributed to moisture retention and increased soil density;
High levels of organic matter in the area of sixth cut provided the best indices of soil aggregate stability, when compared to the third cut;
Soil organic carbon and the carbon stocks increases in the superficial layers, they were only observed for the sixth cut, where there was a greater supply of dry biomass.

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REFERENCES

Almeida, C.X.; Centurion, J.F.; Freddi, O.S.; Jorge, R.F.; Barbosa, J.C. 2008. Funções de pedotransferência para a curva de resistência do solo à penetração. Revista Brasileira de Ciência do Solo, 32: 2235-2243. http://dx.doi.org/10.1590/S0100-06832008000600003.

Araújo, M.A.; Tormena, C.A.; Inoue, T. T.; Costa, A.C.S. 2004. Efeitos da escarificação na qualidade física de um Latossolo Vermelho distroférrico após trezes anos de semeadura direta. Revista Brasileira de Ciência do Solo, 28, 459-504. http://dx.doi.org/10.1590/S0100-06832004000300011.

Arshad, M.A.; Lowery, B.; Grossman, B. 1996. Physical Tests For Monitoring Soil Quality. In: Doran, J.W.; Jones, A.J., eds. Methods for assessing soil quality. Soil Science Society of America, p.123-141.

Bertol, I.; Albuquerque, J. A.; Leite, D.; Amaral, A.J.; Zoldan Junior, W.A. 2004. Propriedades físicas do solo sob preparo convencional e semeadura direta em rotação e sucessão de culturas, comparadas às do campo nativo. Revista Brasileira de Ciência do Solo, 28:155-65. http://dx.doi.org/10.1590/S0100-06832004000100015.

Bolinder M.A.; Angers, D.A.; Gregorich, E.G.; Carter, M.R. 1999. The response of soil quality indicators to conservation manage. Canadian Journal of Soil Science., 79, 37-45. http://dx.doi.org/10.4141/S97-099.

Braida, J.A.; Reichert, J.M.; Reinert, D.J.; Veiga, M. 2010. Teor de carbono orgânico e a susceptibilidade à compactação de um Nitossolo e um Argissolo. Revista Brasileira de Engenharia Agricola e Ambiental, 14, 131-139. http://dx.doi.org/10.1590/S1415-43662010000200003

Caetano, J.O.; Verginassi, A.; Assis, P.C.R.; Carneiro, M.A.C.; Paulino, H.B. 2013. Indicadores de qualidade de um Latossolo Vermelho sob diferentes sistemas de uso e manejo. Global Science and Technology, 6, 26- 39. http://dx.doi.org/10.14688/1984-3801.v06n01a03.

Camargo, L.A.; Marques Júnior, J.; Pereira, G.T. 2010. Spatial variability of physical attributes of alfisol under different hillslope curvatures. Revista Brasileira de Ciência do Solo, 34(3), 617-630. http://dx.doi.org/10.1590/S0100-06832010000300003.

Cavalieri, K.M.V.; Carvalho, L.A.; Silva, A.P.; Libardi, P.L.; Tormena, C.A. 2011. Qualidade física de três solos sob colheita mecanizada de cana-de-açúcar. Revista Brasileira de Ciência do Solo, 35, 1541-1549. http://dx.doi.org/10.1590/S0100-06832010000300003.

Centurion, J.F.; Freddi, O.S.; Aratani, R.G.; Metzner, A.F.M.; Beutler, A.N.; Andrioli, I. 2007. Influência do cultivo da cana-de-açúcar e da mineralogia da fração argila nas propriedades físicas de Latossolo Vermelho. Revista Brasileira de Ciência do Solo, 31(2), p.199-209. http://dx.doi.org/10.1590/S0100-06832007000200002.

Conab - Companhia Nacional de Abastecimento. Acompanhamento de safra brasileira: cana-de-açúcar, Terceiro Levantamento - Safra 2016/17. Brasília, 2017.

Coutinho, F.S.; Loss, A.; Pereira, M.G.; Rodrigues Júnior, D.J.; Torres, J.L.R. 2010. Estabilidade de agregados e distribuição do carbono em Latossolo sob sistema plantio direto, Uberaba, MG. Comunicata Scientiae, 1(2), 100 - 105.

Demarchi, J.C.; Perusi, M.C.; Piroli, E.D. 2011. Análise da estabilidade de agregados de solos da microbacia do Ribeirão São Domingos, Santa Cruz do Rio Pardo – SP, sob diferentes tipos de uso e ocupação. Revista Brasileira de Tecnologia Aplicada nas Ciências Agrárias, 4(2)2, 07–29, 2011.

Embrapa - Empresa Brasileira De Pesquisa Agropecuária. Centro Nacional de Pesquisa de Solos. Manual de métodos de análise de solos. 3. Ed. Rio de Janeiro: Ministério da Agricultura e do Abastecimento, 2011, 230 p.

Embrapa - Empresa Brasileira de Pesquisa Agropecuária. 2013. Sistema brasileiro de classificação de solos. 3ª ed. Brasília, Embrapa, 353p.

Fontana, A.; Brito, R.J.; Pereira, M.G.; Loss, A. 2010. Índices de agregação e a relação com as substâncias húmicas em Latossolos e Argissolo de tabuleiros costeiros, Campos dos Goytacazes, RJ. Revista Brasileira de Ciências Agronômicas, 5, 291-297.

Garbiate, M.V.; Vitorino, A.C.T.; Tomasini, B.A.; Bergamin, A.C.; Panachuki, E. 2011. Erosão em entre sulcos em área cultivada com cana crua e queimada sob colheita manual e mecanizada. Revista Brasileira de Ciência do Solo, 35, 2145-2155. http://dx.doi.org/10.1590/S0100-06832011000600029.

Guareschi R.F; Pereira, M.G; Perin, A. 2012. Deposição de resíduos vegetais, matéria orgânica leve, estoques de carbono e nitrogênio e fósforo remanescente sob diferentes sistemas de manejo no Cerrado goiano. Revista Brasileira de Ciência do Solo, 36, 909-920. http://dx.doi.org/10.1590/S0100-06832012000300021.

Kemper, W.D.; Chepil, W.S. Size distribution of aggregation. In: BLACK, C.A. ed. Methods of Soils Analysis. Madison, American Society of Agronomy, 1965, pt.1, n.39, p. 499-510 (Agronomy, 9).

Luca, E.F.; Feller, C.; Cerri, C.C.; Barthès, B.; Chaplot, V.; Campos, D.C.; Manechini, C. 2008. Avaliação de atributos físicos e estoques de carbono e nitrogênio em solos com queima e sem queima de canavial. Revista Brasileira de Ciência do Solo, 32, 789-800, http://dx.doi.org/10.1590/S0100-06832008000200033.

Maia, J.L.T.; Ribeiro, M.R. Propriedade de um Argissolo Amarelo fragipânico de Alagoas sob cultivo contínuo de cana-de-açúcar. Pesquisa Agropecuária Brasileira, 39(1), 79-87, 2004.

Maria, I.C.; Kocssi, M.A.; Dechen, S.C.F. 2007. Agregação do solo em área que recebeu lodo de esgoto. Bragantia, 66, 291-298. http://dx.doi.org/10.1590/S0006-87052007000200013.

Moraes, M.T.; Debiasi, H.; Franchini, J.C.; Silva, V.R. 2012. Correction of resistance to penetration by pedofunctions and a reference soil water contente. Revista Brasileira de Ciência do Solo. 36(6), 1704-1713. http://dx.doi.org/10.1590/S0100-06832012000600004.

Oliveira Filho, F.X.; Miranda, N.O.; Medeiros, J.F.; Silva, P.C.M.; Mesquita, F.O.; Costa, T.K.G. 2015. Zona de manejo para o preparo do solo na cultura da cana-de-açúcar. Revista Brasileira de Engenharia Agrícola e Ambiental, 19:186-193. http://dx.doi.org/10.1590/1807-1929/agriambi.v19n2p186-193

Pereira, M.G.; Loss, A.; Beutler, S.J; Torres, J.L.R. 2010. Carbono, matéria orgânica leve e P remanescente emdiferentes sistemas de manejo do solo. Pesquisa Agropecuária Brasileira, 45, 508-14. http://dx.doi.org/10.1590/S0100-204X2010000500010.

Ramos, F.T.; Monari, Y.C.; Nunes, M.CcM.; Campos, D.T.S.; Ramos, D.T. 2010. Indicadores de qualidade em um Latossolo Vermelho-Amarelo sob pastagem extensiva no pantanal matogrossense. Caatinga. 23, 12-20.

Reinert, D.J.; Reichert, J.M.; Silva, V.R. 2001. Propriedades físicas de solos em sistema de plantio direto irrigado. In: Carlesso, R.; Petry, M.T.; Rosa, G.M.; Ceretta, C. A. (Ed.). Irrigação por aspersão no Rio Grande do Sul. Santa Maria: UFSM, 165p.

Resende, A.S.; Xavier, R.P.; Oliveira, O.C.; Urquiaga, S, Alves, B.J.R.; Boddey, R.M. 2006. Long-term effects of preharvest burning and nitrogen and vinasse applications on yield of sugar cane and soil carbon and nitrogen stocks on a plantation in Pernambuco, N.E. Brazil. Plant and Soil, 281, 339-351. http://dx.doi.org/10.1007/s11104-005-4640-y.

Roque, A.A.O.; Souza, Z.M.; Barbosa, R.S.; Souza, G.S. 2010. Controle de tráfego agrícola e atributos físicos do solo em área cultivada com cana-de-açúcar. Pesquisa Agropecuária Brasileira, 45, 744-750. http://dx.doi.org/10.1590/S0100-204X2010000700016.

Salton, J.C.; Mielniczuk, J.; Bayer, C.; Boeni, M.; Conceição, P.C.; Fabrício, A.C.; Macedo, M.C.M.; Broch, D.L. 2008. Agregação e estabilidade de agregados do solo em sistemas agropecuários em Mato Grosso do Sul. Revista Brasileira de Ciência do Solo, 32, 11-21, http://dx.doi.org/10.1590/S0100-06832008000100002.

Schultz, N.; Lima, E.; Pereira, M.G.; Zonta, E. 2010. Efeito residual da adubação na cana-planta e da adubação nitrogenada e potássica na cana-soca colhidas com e sem a queima da palhada. Revista Brasileira de Ciência do Solo, 34, 811-820. http://dx.doi.org/10.1590/S0100-06832010000300023.

Sene, M.; Vepraskas, M.J.; Naderman, G.C.; Denton, H.P. 1985. Relationsships of soil texture and structure to corn yield response to subsoiling. Society Soil Science Society of America Journal, 49, 422-427.

Severiano, E.C.; Oliveira, G.C.; Dias Júnior, M.S.; Costa, K.A.P.; Silva, F.G.; Ferreira Filho, S.M. 2011. Structural changes in Latosols of the cerrado region: I Relationships between soil physical properties and least limiting water range. Revista Brasileira de Ciência do Solo, 35(1), 773-782. http://dx.doi.org/10.1590/S0100-06832011000300013.

Souza, G.S.; Souza, Z.M.; Silva, R.B.; Araújo, F.S.; Barbosa, R.S.; Araújo, F.S. 2014. Effects of traffic control on the soil physical quality and the cultivation of sugarcane. Revista Brasileira de Ciência do Solo, 38, 135-146. doi: http://dx.doi.org/10.1590/S0100-06832014000100013.

Souza, H.A.; Marcelo, A.V.; Centurion, J.F. 2012. Carbono orgânico e agregação de um Latossolo Vermelho com colheita mecanizada de cana-de-açúcar. Revista Ciências Agronômicas, 43, 658-663, http://dx.doi.org/10.1590/S1806-66902012000400006.

Souza, Z. M.; Prado, R.M.; Paixão, A.C.S.; Cesarin, L.G. 2005. Sistemas de colheita e manejo da palhada de cana-açúcar. Pesquisa Agropecuária Brasileira, 40, 271-278, http://dx.doi.org/10.1590/S0100-204X2005000300011.

Torres, E.; Saraiva, O.F. 1999. Camadas de impedimento do solo em sistemas agrícolas com a soja. Londrina, Empresa Brasileira de Pesquisa Agropecuária, 1999. 58p. (Circular Técnica, 23).

Torres, J.L.R.; Pereira, M.G.; Cunha, M.A. Martins, M.E.; Vieira, D.M.S. 2013. Physicochemical properties of soil and biomass in sugarcane harvesting systems. Revista Ciências Agrárias, 56: 311-318. doi: http://dx.doi.org/10.4322/rca.2013.047

Torres, J.L.R.; Pereira, M.G; Moraes, A.G.L.; Beutler, S.J. 2014. Frações granulométricas e oxidáveis da matéria orgânica em sistemas de colheita de cana-de-açúcar. Revista Caatinga, Mossoró, 27(4), 16-23.

Torres, J.L.R.; Pereira, M.G.; Assis, R.L.; Souza, Z.M. 2015. Atributos físicos de um Latossolo Vermelho cultivado com plantas de cobertura, em semeadura direta. Revista Brasileira de Ciência do Solo, 39, 428-437. http://dx.doi.org/10.1590/01000683rbcs20140597.

Uberaba.MG. Prefeitura Municipal. Uberaba em dados. Edição 2009. Acesso em 21 nov 2011. Disponível em: http://www.uberaba.mg.gov.br/portal/acervo/desenvolvimento/arquivos/uberaba_em_dados/Edicao_2009/Capitulo01.pdf.

Wendling, B.; Jucksch, I.; Mendonça, E.S.; Neves, J.c.l. 2005. Carbono orgânico e estabilidade de agregados de um Latossolo Vermelho sob diferentes manejos. Pesquisa Agropecuária Brasileira, v.40, p.487-94. http://dx.doi.org/10.1590/S0100-204X2005000500010.

Yeomans, J.C.; Bremmer, J.M. 1988. A rapid an precise method for routine determination of organic carbon in soil. Communications in Soil Science and Plant Analysis, 19: 1467-1476. http://dx.doi.org/10.1080/00103628809368027.