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Structural soil quality related to microbiological parameters in sugarcane

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Abstract: Sugarcane crop conventional tillage has been replaced by deep soil preparation with few studies about its effect on soil quality and sustainability. The aim of this study was to assess structural volumes ina dystrophic Red-Yellow Latosol subjected to conventional tillage (CT) and deep localized soil tillage (DLST) to verify how the microbiological parameters were affected. The study was conducted in a soil derived from the Caiuá Sandstone formation in Brazil. Four trenches were dug for each soil tillage system to describe the cultural profile and evaluate carbon microbial biomass (CMB) and nitrogen (NMB), basal respiration (BR), and metabolic quotient (qCO_2). CT profiles exhibited a predominance of cracked soil volumes, medium-sized and large compact clods with some porosity, and continuous volumes with no cracks and of intermediate porosity. DLST profiles were predominantly free-soil volume with no cohesion and porous in appearance, and compact, cohesive volumes with no porosity visible. The highest levels of CMB and NMB were in the cracked soil under CT. Higher microbial activity indicated by BR and qCO_2 were in the free powdery soil under DLST. Soil pulverization caused by DLST could cause serious consequences on soil functionality, boosting erosion, and metabolic stress in the microbiota.

Key words: Basal respiration, cultural profile, microbial biomass, soil tillage.

INTRODUCTION

The northwestern region of the Brazilian state of Paraná is the fifth largest producer of sugarcane in the country (CONAB 2015). Seventy percent of the soils in this region are derived from Caiuá Sandstone. They are generally medium-textured to sandy soils with low levels of clay and organic matter, impairing aggregate stability and water retention capacity (Viana et al. 2011, Zoline et al. 2011). Because of these characteristics, the soils in this region are considered extremely fragile and highly susceptible to erosion (Carvalho 1994, Fidalski 1997), and therefore the intensive use of agricultural machinery and implements could speed up the erosion process, resulting in environmental damage and impaired yield.

Recently, there has been a trend towards replacing conventional soil tillage (CT) for the sugarcane crop (subsoiling + heavy disking) with a new system known as deep localized soil tillage (DLST) with traffic control, the aim of which is to improve physical conditions for deep root growth. The implement used in DLST consists of a subsoiler with tines that can penetrate to a depth of 0.80 m, a hopper for applying correctives/fertilizer, a rotary hoe for breaking up clods and a furrower that folds residual straw from the harvest into the soil (Sousa et al. 2015).

Soil tillage operations are critical in agricultural management, and can structurally

alter the soil by forming compact layers and impairing aggregate stability, increasing its propensity to erode (Paredes Junior et al. 2014, Cherubin et al. 2016a, b), especially when cropped as a monoculture over lengthy periods of time. Research on cropping practices that have lower impacts on the soil environment has led researchers to look for indicators that provide early assessments of the production system, identifying those that could be useful for preserving and/or improving soil quality (Paredes Junior et al. 2014, Souza et al. 2015, Cherubin et al. 2016a).

Among possible indicators, the structure of the soil is one of the most important attributes for this assessment, since it provides information on the morphology of horizons affected by human activity, acting as a diagnostic tool for agricultural practices (Silva et al. 2015, Boizard et al. 2017). The cultural profile method (Gautronneau & Manichon 1987), originated in France and was modified by Tavares Filho et al. (1999) for tropical conditions. It provides results that can be interpreted immediately concerning the structure of the soil, and can also be combined with physical (Tavares Filho et al. 2014, Baquero et al. 2012), chemical (Fregonezi & Espindola 2008) and biological methods (Silva et al. 2014).

Changes in the structure of the soil affect the habitat of microorganisms, considered critical components in natural and/or anthropogenic ecosystems because they regulate the decomposition of organic matter and biogeochemical cycles, having a direct effect on soil fertility plant nutrition (Cui & Holden 2015, Heijboer et al. 2016). Microbiological parameters have been widely used as soil quality bioindicators because they are sensitive to the effects of land use.

The hypothesis of this study is that more intensive tilling of the soil can aggravate the erosion process and compromise the structural quality and sustainability of naturally fragile sandstone soils. Furthermore, the morphological alterations in soil structure can provide an indication of the activity and metabolic condition of microbiota. The aim of this study was to assess structural volumes of a Red-Yellow Latosol under conventional tillage (CT) and deep localized soil tillage (DLST), and to observe the effects of these practices on microbiological parameters.

MATERIALS AND METHODS

Characteristics of the experimental area

The study was conducted in the municipality of São Tomé (23°32'00.0"S 52°35'00.0"W) in the northwestern region of the state of Paraná, Brazil. The soil in the region is classified as a dystrophic Red-Yellow Latosol (Brazilian classification: LatossoloVermelho-Amarelo distrófico) (Santos et al. 2013), Typic Hapludox (Soil Taxonomy), with 820 g sand, 140 g clay and 40 g silt per kg^{-1}soil. The climate is humid subtropical mesothermal (Köppen classification Cfa), with an annual average temperature of 20 °C and average rainfall of 1340 mm (Alvares et al. 2013). The landscape is flat to slightly undulating, with long, slightly convex contours and a slope of approximately 6%.

Before planting the experimental sugarcane, coffee (*Coffea arabica* L.) had been grown on the land for 32 years and it had been used as pasture (*Brachiaria decumbens*) for 6 years. In 2000, to prepare the land for sugarcane, the soil was subjected to conventional tillage (CT) with one subsoiling operation (~0.35 m deep) and two heavy diskings (~0.25 m deep). Every five years, the sugar plantation was restored by carrying out CT. Until 2009, the sugarcane was burnt for manual harvesting. Subsequent to this date, green cane harvesting was mechanized. On the

third restoration of the crop in 2014, part of the area was subjected to deep localized soil tillage (DLST) [~0.70 m deep] in addition to CT. Traffic was controlled during DLST and the soil tilled only along the strip used for growing the plants, with alternating spacing of 0.90 m (tire space) x 1.50 m (growing strip). For both soil tillage (CT and DLST), cropping furrows were opened up using a furrower (~0.25 m deep).

The sugarcane plants were fertilized in accordance with the soil analysis (Table I), which generally involved respective annual respective applications of 60, 90 and 120 kg ha^{-1} N, P_2O_5 and K_2O, and the stumps were treated with 60 kg ha^{-1} P_2O_5 and 100 kg ha^{-1} K_2O. The soil was sampled and assessed 40 days after the soil tillage operations.

Cultural profile

Two cropping areas of 1.5 ha were delimited for each soil tillage system. Two trenches were dug in each area, separated by a distance 500 m. Two profiles were described in each trench, giving 4 field replications for each soil tillage method. The trenches were 3.50 m long x 2.50 m wide x 1.20 m deep, and the profiles were described on the faces perpendicular to the implement direction of travel. The assessments were carried out as described in Tavares Filho et al. (1999).

Volumes of soil were classified in two ways: (1) organization of clods in the profile (C- continuous; F- cracked; L- free; Z- laminar and NAM- not altered by soil use and management); and (2) internal state of clods, assessing porosity to the naked eye (μ- not compacte; Δ- compact and μΔ/Δμ-± compact). To describe the internal states of clods in greater detail, the following classification was used: μ- porous; μΔ- porous with indications of compression; μΔ/Δμ- medium porosity; Δμ- compact with some porosity; Δ- compact with no visible porosity to the naked eye.

Graphic representations of the profiles and computation of the areas of structures (m^2) were produced by ArcView 10.2 software, as described in Silva et al. (2014).

Soil sampling

For the microbiological analysis (CMB, NMB, basal respiration and qCO_2) in the structure of the culture profile, samples were collected in four equidistant points from the center, composing simple samples (~1.5 kg soil). Soil samples to evaluate microbial biomass (CMB and NMB) were also collected at three depths: 0.00-0.20, 0.20-0.40, and 0.40-0.60 m in two profiles of each trench, totalizing 12 simple samples (~1.5 kg soil) per depth for each soil tillage system. In the laboratory, the samples were homogenized, screened (< 4mm, 5 mesh) and stored in plastic vessels in a refrigerator at 4 °C. For microbiological analysis, soil samples were collected from the structures in the cultural profile (CMB, NMB, BR and qCO_2) and at depths of 0.00-0.20; 0.20-0.40 and 0.40-0.60 m (CMB and NMB). In the laboratory, the samples were

Table I. Soil chemical characterization.

Depth	pH($CaCl_2$)	Organic carbon	P	Ca^{2+}	Mg^{2+}	K^+	Al^{3+}
(m)		-----g dm^{-3}-----		---------- $cmol_c$ dm^{-3}----------			
0.00 – 0.20	5.3	1.71	0.02	1.76	0.45	0.28	0.00

Organic carbon extraction with $K_2Cr_2O_7$; P and K^+ extraction with Mehlich^{-1};Ca^{2+}, $Mg^{2+}$and Al^{3+}extraction with KCl (1 mol L^{-1}).

homogenized, screened (<4 mm, 5 mesh) and stored in plastic receptacles in a refrigerator at 4 °C.

Evaluation of microbial biomass, basal respiration (BR) and metabolic quotient (qCO_2)

The modified fumigation-extraction method described in Vance et al. (1987) was used to analyze microbial biomass carbon (CMB), and the method proposed by Brookes et al. (1985), modified as described in Babujia et al. (2010), to analyze microbial biomass nitrogen (NMB).

The BR was assessed by incubating 50 g soil from each sample containing 10 mL NaOH 0.5 N solution in a beaker to capture released CO_2 (Alef 1995). After 7 days, the remaining NaOH was quantified by titration with HCl at the same concentration, using a phenolphthalein indicator after addition of $BaCl_2$.The qCO_2 was obtained based on the ratio of BR to CMB ($C_{Resp.}$/ CMB), as described in Babujia et al. (2010).

Statistical analysis

The microbiological data was analyzed by R software (R development core team 2011). Detrended Correspondence Analysis (DCA) was used to analyze the cultural profiles and verify data linearity. Then principal component analysis (PCA) was analyzed to examine the relationships between the soil tillage systems and the structural characteristics of the profiles.

Normality of variables and homogeneity of variances were tested as a necessary prerequisite for analysis of variance. When a statistically significant *p*-value was confirmed, the *post hoc* test was run, and the Tukey test ($p \leq 0.05$) used to compare the means based on a fully randomized experimental design with four replications.

RESULTS

Cultural profile descriptions

Figures 1 and 2 are graphic representations of the cultural profiles under CT and DLST. In the morphological alterations produced in the structure of the soils, the degree of mechanical intervention was a decisive factor, i.e. more intensive tilling resulted in the appearance of free soil volume with no aggregation and

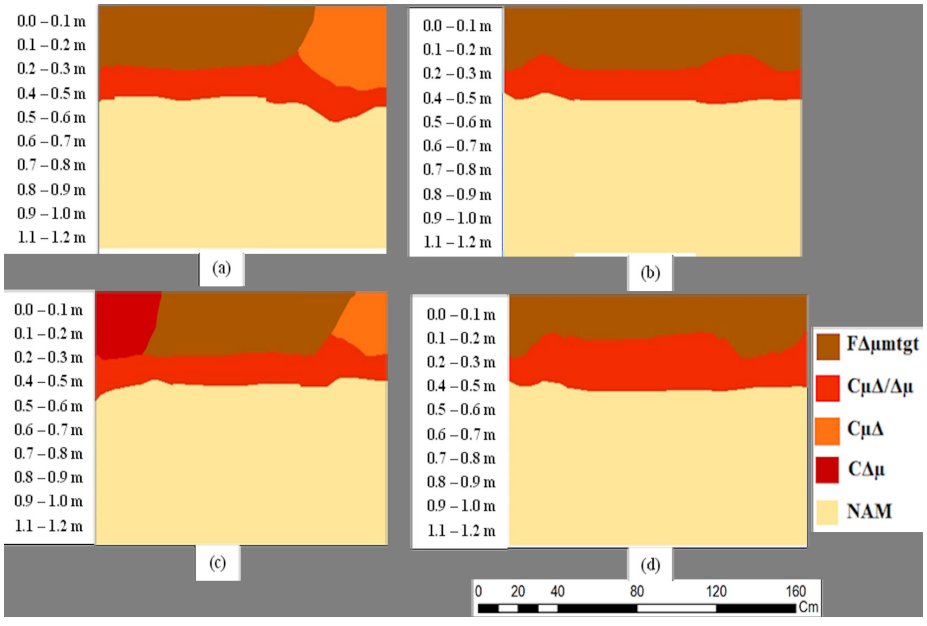

Figure 1. Cultural profiles of a dystrophic Red-Yellow Latosol under conventional tillage (CT). Field replications: a, b, c and d. Organization of clods: C = continuous soil volume, F = cracked soil volume, NAM = unaltered soil volume by soil use and management, mt = medium clods (7 cm ∅), gt = large clods (10 cm ∅). Internal state of clods: μΔ = porous with indications of compression, μΔ/Δμ = medium porosity, Δμ = compact with some porosity.

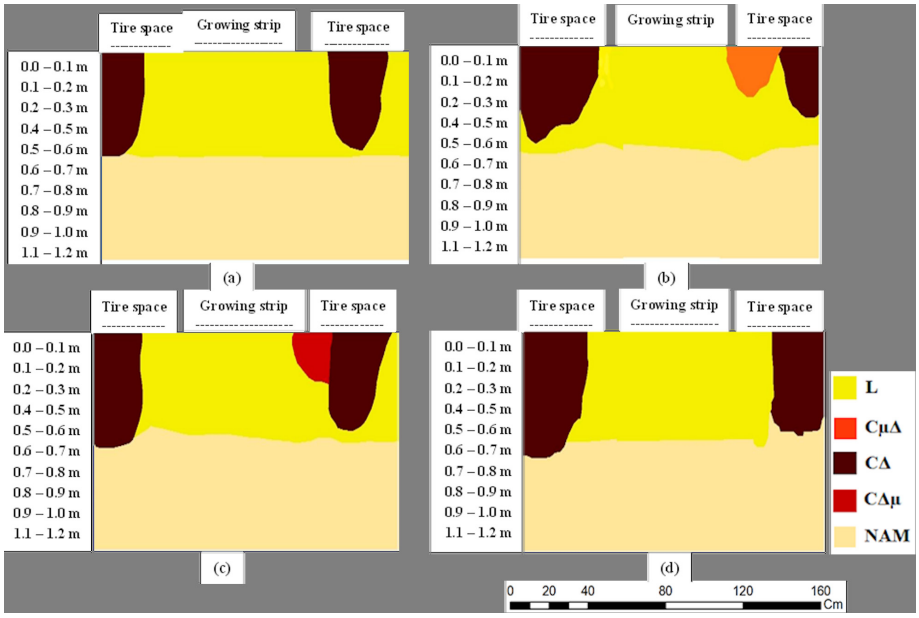

Figure 2. Cultural profiles of a dystrophic Red-Yellow Latosol under deep localized soil tillage (DLST). Field replications: a, b, c and d. Organization of clods: L = free soil volume, C = continuous soil volume, NAM = unaltered soil volume by use and management. Internal state of clods: μΔ = porous with indications of compression, Δμ = compact with some porosity, Δ = compact with no visible porosity to the naked eye.

compact volumes in the profile. In all profiles, the volumes of soil visually unchanged by soil tillage were represented by unaltered structure NAM (Figures 1 and 2). In general, this structure accounted for 62.43% (CT) and 50.39% (DLST) of the total area of the profiles.

The CT profiles exhibited a volume of cracked soil characterized by the presence of medium-sized (7 cm in ∅) and large (10 cm de ∅) compact clods, with some porosity visible to the naked eye and low visible roughness, corresponding to structure FΔμmtgt (Figure 1). This structure occupied an average area of 0.51 m^2, accounting for 45.42% of the area altered by the soil tillage in the profiles subjected to CT (Figure 3). Next to the FΔμmtgt structure, there were also homogeneous, continuous crack-free volumes of soil corresponding to structures CμΔ, with indications of compacting, and CΔμ, compact structures with some porosity. These structures occupied an area of 0.26 and 0.20 m^2 respectively, corresponding to 22.31 and 18.96%, of the area altered by soil use and management (Figure 3).

Below these structures, the profiles under CT exhibited a continuous, crack-free volume of soil of intermediate roughness and porosity, corresponding to structure CμΔ/Δμ (Figure 1). This structure occupied an average area of 0.43 m^2, or 38.66% of the altered area under CT (Figure 3).

The profiles under DLST exhibited free soil volume with no cohesion, pulverized in appearance, corresponding to structure L (Figure 2). This structure occupied an average area of 0.76 m^2, corresponding to 51.20% of the area altered by soil tillage (Figure 3). The CμΔ and CΔμ soil volumes were observed in the cropping strip in two profiles under DLST (B and C), with a morphological structure similar to that found under CT. These structures occupied respective areas of 0.13 and 0.10 m^2 corresponding to 8.96 and 6.78% of the altered areas in these profiles (Figure 3).

In the profiles under DLST, volumes of compact, cohesive soil with no visible porosity corresponding to structure CΔ (Figure 2) were also found. This structure occupied a significant area of the profiles under DLST, accounting for

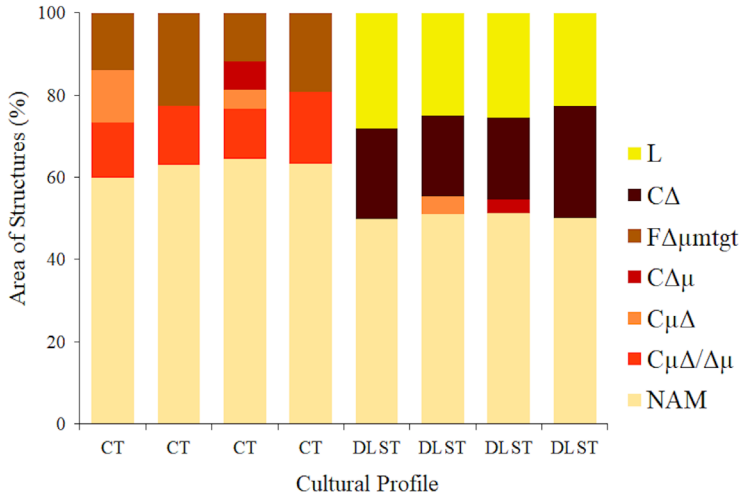

Figure 3. Percentage areas of structures in a dystrophic Red-Yellow Latosol under conventional tillage (CT) and deep localized soil tillage (DLST).Field replication. Organization of clods: L = free soil volume, C = continuous soil volume, F = cracked soil volume, NAM = unaltered soil volume by use and management, mt = medium clods (7 cm Ø), gt = large clods (10 cm Ø). Internal states of clods: μΔ = porous with indications of compression, μΔ/Δμ = medium porosity, Δμ = compact with some porosity, Δ = compact with no visible porosity to the naked eye.

an average 0.67 m^2, or 44.86% of the area altered by soil tillage (Figure 3).

PCA was used to reveal the relationships between the soil tillage systems (CT and DLST) and the structures in the profiles (Figure 4). The first axis of the principal component accounted for 70.95% of the variability of the data, but axis 2 accounted for only 14.96%. Note the separation between the two soil tillage systems in factorial terms, with the formation of groups including both CT and DLST. The areas under DLST are located in the positive part of axis 1, whereas the areas under CT are located at the other end, in the negative part of the axis. The volumes of soil corresponding to the CμΔ and CΔμ were notable in the lower negative part of axis 2. The volumes of soil corresponding to the L and CΔ structures are positively correlated with those of DLST and negatively correlated with those of CT, whereas the volumes of soil corresponding to the FΔμmtgt, CμΔ/Δμ and NAM structures are positively correlated with CT.

Microbiological parameters in the profile structures

Significantly higher levels of CMB (Figure 5) and NMB (Figure 6) were found in the FΔμmtgt structure under CT. The average respective levels of CMB and NMB in this structure were 344.11 and 27.15 mg kg^{-1} dry soil. The average increment of CMB in this structure ranged from 30.81 to 59.88% compared to the other structures found in the profiles under CT and DLST. For NMB, the FΔμmtgt structure exhibited an average increment ranging from 29.62 to 59.25% compared to the other structures.

Microbial activity, estimated in terms of BR (Figure 7) and qCO_2 (Figure 8), was greater in the L structure under DLST. The average values were 213.34 mg $C\text{-}CO_2$ kg^{-1} soil day^{-1} for BR and 1.56 mg $C\text{-}CO_2$ g^{-1} CMB h^{-1} for qCO_2. This structure exhibited increments of 44.60 (BR) and 66.66% (qCO_2) compared to the values found for the FΔμmtgt structure under CT.

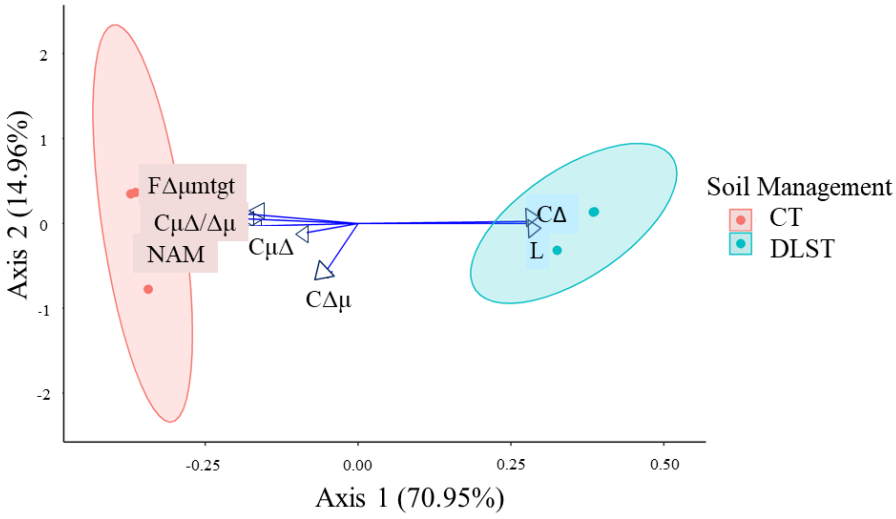

Figure 4. Principal component analysis (PCA) based on the areas of structures in a dystrophic Red-Yellow Latosol under conventional tillage (CT) and deep localized soil tillage (DLST). Organization of clods: L = free soil volume, C = continuous soil volume, F = cracked soil volume, NAM = unaltered soil volume by use and management, mt = medium clods (7 cm Ø), gt = large clods (10 cm Ø). Internal states of clods: μΔ = porous with indications of compression, μΔ/Δμ = medium porosity, Δμ = compact with some porosity, Δ = compact with no visible porosity to the naked eye.

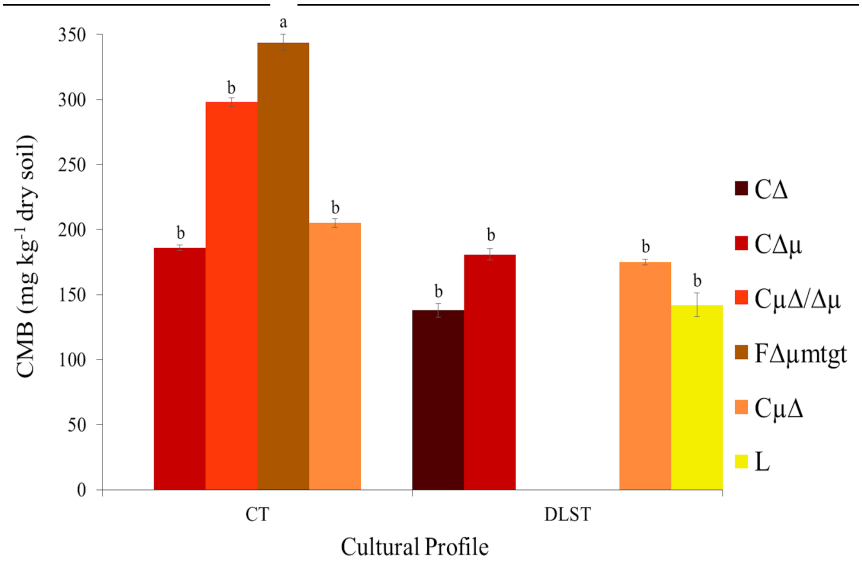

Figure 5. Carbon microbial biomass (CMB) in a dystrophic Red-Yellow Latosol under conventional tillage (CT) and deep localized soil tillage (DLST). Organization of clods: L = free soil volume, C = continuous soil volume, F = cracked soil volume, NAM = unaltered soil volume by use and management, mt = medium clods (7 cm Ø), gt = large clods (10 cm Ø). Internal states of clods: μΔ = porous with indications of compression, μΔ/Δμ = medium porosity, Δμ = compact with some porosity, Δ = compact with no visible porosity to the naked eye. Bars indicate the mean standard error. Volumes of soil with the same letter for different soil tillage systems did not differ statistically in Tukey test ($p \leq 0.05$).

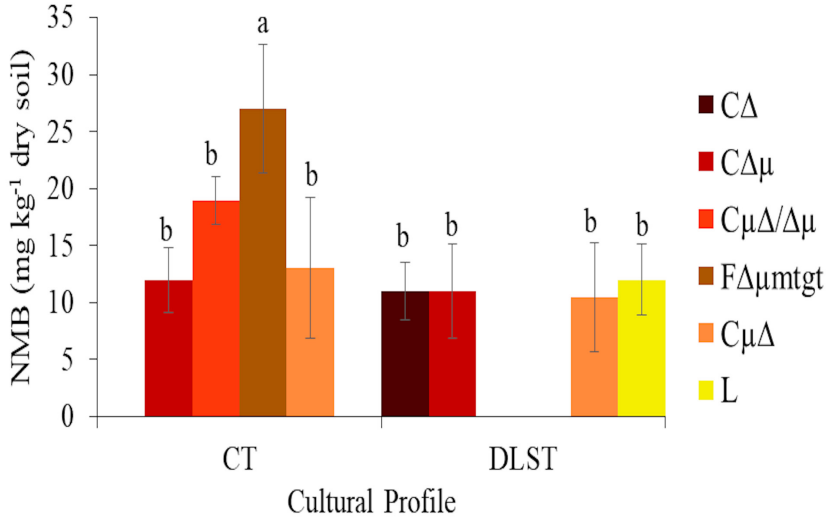

Figure 6. Nitrogen microbial biomass (NMB) in a dystrophic Red-Yellow Latosol under conventional tillage (CT) and deep localized soil tillage (DLST). Organization of clods: L = free soil volume, C = continuous soil volume, F = cracked soil volume, NAM = unaltered soil volume by use and management, mt = medium clods (7 cm Ø), gt = large clods (10 cm Ø). Internal states of clods: μΔ = porous with indications of compression, μΔ/Δμ = medium porosity, Δμ = compact with some porosity, Δ = compact with no visible porosity to the naked eye. Bars indicate the mean standard error. Volumes of soil with the same letter for different soil tillage systems did not differ statistically in Tukey's test ($p \leq 0.05$).

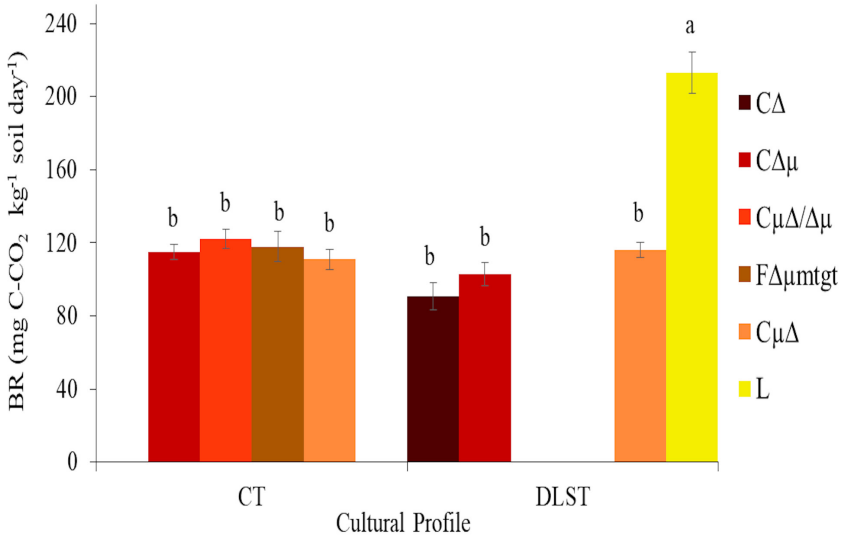

Figure 7. Basal respiration (BR) in a dystrophic Red-Yellow Latosol under conventional tillage (CT) and deep localized soil tillage (DLST). Organization of clods: L = free soil volume, C = continuous soil volume, F = cracked soil volume, NAM = unaltered soil volume by use and management, mt = medium clods (7 cm Ø), gt = large clods (10 cm Ø). Internal states of clods: μΔ = porous with indications of compression, μΔ/Δμ = medium porosity, Δμ = compact with some porosity, Δ = compact with no visible porosity to the naked eye. Bars indicate the mean standard error. Volumes of soil with the same letter for different soil tillage systems did not differ statistically in Tukey's test ($p \leq 0.05$).

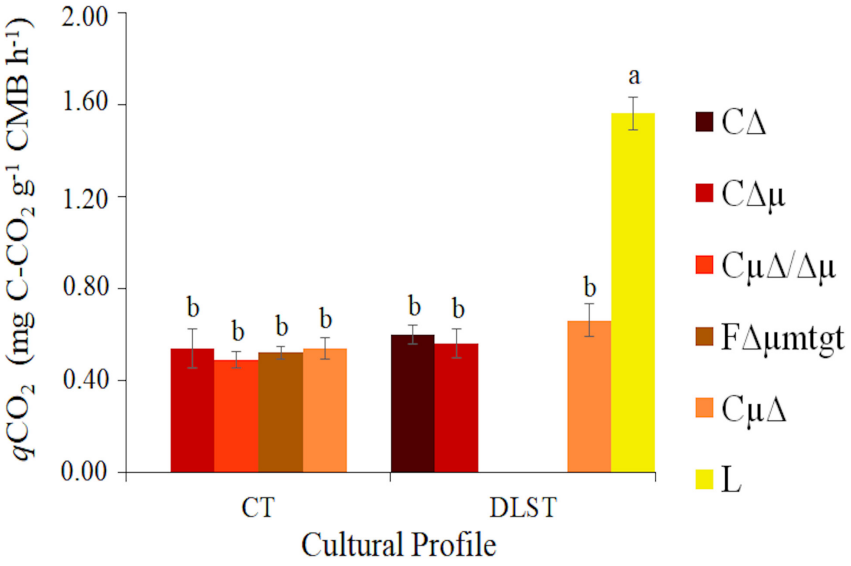

Figure 8. Metabolic quotient (qCO2) in a dystrophic Red-Yellow Latosol under conventional tillage (CT) and deep localized soil tillage (DLST). Organization of clods: L = free soil volume, C = continuous soil volume, F = cracked soil volume, NAM = unaltered soil volume by soil use and management, mt = medium clods (7 cm Ø), gt = large clods (10 cm Ø). Internal states of clods: μΔ = porous with indications of compression, μΔ/Δμ = medium porosity, Δμ = compact with some porosity, Δ = compact with no visible porosity to the naked eye. Bars indicate the mean standard error. Volumes of soil with the same letter for different soil tillage systems did not differ statistically in Tukey's test (p ≤ 0.05).

Microbial biomass at depth

Significantly higher content of CMB was found at depth of 0.00-0.20 m of CT (Table II), which presented an increase of 56.74% when compared with the same layer of DLST. There was no difference between the depths of 0.00-0.20 and 0.20-0.40 m for CMB in CT (Table II). However, the layer of 0.40-0.60m presented lower content of CMB (Table II), which did not differ among the soil tillage systems.

Regarding NMB, significantly higher content was also found in the layer of 0.00-0.20 m of CT (Table III), which showed an increase of ~45% compared to the same layer of DSLT. There were no differences between the layers of 0.20-0.40 and 0.40-0.60 m for the soil tillage systems and the depths.

DISCUSSION

Alterations in the soil structure

Intensely mechanized soil tillage causes changes in the soil's physical properties, affecting chemical and biological attributes (Baquero et al. 2012, Evangelista et al. 2013, Signor et al. 2014), due mainly to the changes brought about in the soil structure (Souza et al. 2015, Cherubin et al. 2016b, Mthimkhulu et al. 2016). In our study, PCA segregated the structures according to the intensity of tillage (Figure 4), showing that each implement used to work the soil brought about specific and different changes in the soil structure.

Morphological descriptions of the profiles were made in order to observe the FΔμmtgt structure, predominantly crack-induced porosity with medium and large clods (~0.00-0.30 m) in the profiles under CT (Figure 1). In general,

Table II. Carbon microbial biomass (CMB) in a dystrophic Red-Yellow Latosol under conventional tillage (CT) and deep localized soil tillage (DLST).

Depth (m)	CMB (mg kg^{-1}dry soil)	
	DLST	CT
0.00-0.20	134.97 A b[1]	237.86 A a
0.20-0.40	127.44 A a	181.32 A a
0.40-0.60	65.88 B a	82.04 B a
[2]CV (%)	Soiltillage = 9.78	Depht = 10.18

[1]**Means followed by different uppercase letters on the column indicate differences among depths and means followed by different lowercase letters on the row indicate differences between the soil tillage systems according to Tukey's test (p ≤ 0.05).**
[2]**Coefficient of variation.**

this structure occupied the largest altered area in the profiles (Figure 3) and was the result of subsoiling and heavy disking operations that ruptured the soil structure by inducing cracks. The presence of large clods forms empty spaces that can impair contact between the stems and the soil and impair shoot production and initial root development. In addition, the low internal porosity of these structures can also limit root growth inside the clods. When present in this volume of soil, the roots develop primarily at points of lower resistance, i.e. in the cracks, and can become deformed (flattened or twisted) as well as having few or poorly branched roots (Tavares Filho et al. 2014, Silva et al. 2014).

On the surface of the two profiles under CT (Figures 1a and 1c) and also under DLST (Figures 2b and 2c), there were continuous structures respectively denoted CμΔ (~0.00-0.30 m) and CΔμ (~0.00-0.30 m), with a lower or higher level of compaction. These structures were formed by machinery travelling across the cropping area, modifying the previously cracked structures in the profiles. The CμΔ and CΔμ structures occupied a larger area under CT where machinery traffic was not controlled (Figure 3). The results show how the structure of the soil can become severely compact, initiating total disaggregation of the soil and resulting in the formation of structures with low visible porosity, or none at all (L> CμΔ> CΔμ> CΔ). Disaggregation is the main factor responsible for increasing the compaction of farmland since machinery deployment soon after soil tillage, especially when the soil moisture content is disregarded (Saffih-Hdadi et al. 2009), can lead to the rearrangement of disaggregated particles to form a cohesive mass in the soil matrix (Souza et al. 2012b, 2015).

Immediately below these structures, there was a continuous structure CμΔ/Δμ (~0.30-0.45 m) of intermediate porosity, occupying the second largest area in the profiles under CT (Figure 3). The operations carried out during CT, remaining at the same depth, caused the formation of this layer by pressure from the subsoiler on the soil structure.

The more stringent requirements of farming sugarcane impact the soil subsurface, leading to deeper compact layers (Soares et al. 2005, Baquero et al. 2012, Cherubin et al. 2016a), a factor that is aggravated by the reduction of organic matter content (Viana et al. 2011, Signor et al. 2014). According to Soares et al. (2005), these changes can be observed at even greater depths than those covered by this study, and although this layer can limit deep root growth preventing the roots from spreading, it cannot totally impede root growth.

The NAM structure remained unaltered by soil tillage operations. It is characterized

Table III. Nitrogen microbial biomass (NMB) in a dystrophic Red-Yellow Latosol under conventional tillage (CT) and deep localized soil tillage (DLST).

Depth (m)	NMB (mg kg^{-1}dry soil)	
	DLST	CT
0.00-0.20	13.24 A b[1]	30.15 A a
0.20-0.40	12.48 A a	18.87 A a
0.40-0.60	10.12 A a	11.22 A a
[2]CV (%)	Soiltillage = 16.22	Depht = 18.12

[1]**Means followed by different uppercase letters on the column indicate differences among depths and means followed by different lowercase letters on the row indicate differences between the soil tillage systems according to Tukey's test (p ≤ 0.05).**
[2]**Coefficient of variation.**

as porous, resulting from the accumulation of microaggregates on the OxisolBw horizon, and occupied a greater area in the profiles under CT (Figure 3), showing that tillage caused less alterations in the soil than DLST. Under CT, the NAM structure occurred at an average depth of 0.50 m, compared to 0.70 m under DLST.

In contrast to the structures found under CT, the profiles under DLST exhibited large volumes of soil with the L structure (~0.00-0.65 m), highly porous because of the disaggregation caused by farming implements (Figure 2). This higher degree of soil disaggregation under DLST can reduce levels of organic matter (Signor et al. 2014) and impair water retention and aggregate stability, excessively exposing the soil to the corrosive effects of rainfall (Garbiate et al. 2011, Oliveira et al. 2014).

A volume of compact soil with low visible porosity, represented by CΔ (~0.00-0.60 m) was also observed in DSLT profiles (Figure 2), occupying the larger altered areas in the profiles (Figure 3). This structure could be the result of the load and/or pressure exerted by machinery wheels, which compact the aggregates and fine disaggregated soil when passing over the land. Under the traffic control system, wheel track compaction is intensified as traffic is concentrated along permanent tracks (Souza et al. 2015).

In agricultural soils, the pressure exerted by machinery and implements has been highlighted as the main cause of compaction (Souza et al. 2015, Cherubin et al. 2016a). Some factors related to agricultural machinery, such as high axle load, narrow tires and high pressure tire inflation, increase to soil compaction (Souza et al. 2012b, 2015).

Despite the implementation of traffic control using GPS and assisted steering (automatic pilot) to enhance the precision of the operations and reduce machine transit over cropped areas, under DLST the machinery did pass over the sugarcane cultivation strip in two profiles (Figures 2b and 2c), causing CμΔ, CΔμ and CΔ to appear in the profiles. This was due to the deviation of the wheels from the planned travel path, possibly because the vehicle was being driven at higher than recommended speed and/or a failure in machine control (for instance, adjustment of the tractor-trailer wheel gauge, contributing to the concentration of traffic along the wheel tracks) (Souza et al. 2012b). The presence of these structures can have serious consequences for plant growth and development, since the CμΔ and CΔμ structures can develop into the compact CΔ structure with zero visible porosity. According to Souza et al. (2015) and Cherubin et al. (2016b), compaction

has been considered one of the main factors influencing sugarcane yield.

The morphological and structural modifications observed in DSLT can result in an increase in the superficial run off and, consequently, in erosion (Garbiate et al. 2011, Oliveira et al. 2014). Soil loss by rainfall erosion is a consistent factor in this region, not just in agricultural areas but also in urban areas, showing how fragile sandstone soils can be.

Alterations in microbiological parameters

The alterations observed in the soil structure caused changes in CMB and NMB, with significantly higher levels obtained in the FΔμmtgt structure under CT (Figures 5 and 6) and in the 0.00-0.20 m layer under CT (Table II and III). Although CT also involves tilling the soil, the morphostructural changes caused by this practice do not lead to pulverization of the soil, a phenomenon observed under DLST (Figure 2). The medium and large clods formed under CT were actually responsible for protecting the microorganisms living inside them. However, the presence of these clods does not mean that the CT system provided adequate conditions for the microorganisms, nor that it is the best option for working the soil, since tillage affects the percolation of water and the flow of heat due to changes in roughness and aeration, affecting not only the biomass but also microbial communities (Souza et al. 2012a, Silvia et al. 2014).

A number of studies have shown that the no-till system (NT) boosts the formation and stabilization of macroaggregates, which combined with a permanent covering, provides an environment with a greater quantity of available organic matter and moisture retention, as well as weaker fluctuations in temperature and water (Souza et al. 2012a, Silvia et al. 2014). All these factors result in improved structural quality of the soil, protecting microorganism habitats, and bring higher levels of microbial biomass to the system (Silvia et al. 2014).

Soil microbial biomass (SMB) is concentrated mainly inside macroaggregates, where the organic matter is protected from oxidation, thereby creating an ideal chemical and physical habitat for microorganisms in the soil (Evangelista et al. 2013, Oliveira et al. 2014, Paredes Junior et al. 2014). Greater disturbance of the soil impairs the formation and stabilization of macroaggregates, and leads to falling levels of SMB, as observed in the profiles under DLST.

In agricultural systems, SMB plays a fundamental role in fertility and plant nutrition thanks to its capacity to immobilize significant quantities of nutrients, reducing exchangeable levels of nutrients in the soil, which cuts losses through leaching and/or denitrification (Souza et al. 2012a). Furthermore, the nutrients in the microbial cells are released five times faster than those obtained from the decomposition of plant residues (Paul & Clark 1996).

DLST also promoted changes in NMB content, in the profile structures (Figure 6) as well as in depth (Table III). The higher levels of NMB can be ascribed to the higher rate of N mineralization, which, under CT, remains bonded to organic compounds protected inside the clods. The standard deviation in the culture profile structures was greater in NMB (Figure 6) than in CMB (Figure 5), possibly indicating differences in the environmental conditions like the ones the microbiota was submitted to such as alterations in the organicmatter, moist, pH and/or the genetic population structure and its functionality, a similar situation also reported by Babujia et al. (2010). The results show that DLST can lead to N exhaustion in the soil, which can impair crop yield and longevity, reducing the number of harvests or cuts between restorations (Vitti et al. 2007).

According to Souza et al. (2012a) and Mariano et al. (2016), in systems with higher soil disturbance, nitrogen is released soon after soil tillage due to the breakup of aggregates, intensifying microbial activity and nitrogen compound mineralization, and reducing NMB. However, nitrogen compound mineralization occurs at a steadier rate in systems in which there is lower disturbance of the soil, such as no-till (Babujia et al. 2010, Silva et al. 2014).

Lower levels of CMB and NMB in other structures and at a different depth are an indicator of soil fragility, especially in intensively worked sandstone soils, and this is caused by the restriction on the accumulation of organic matter and the high rate of plant residue decomposition favored by the region's climatic conditions.

The highest levels of BR and qCO_2 (Figures 7 and 8) were found in the L structure under DLST, showing that pulverization of the soil is a decisive factor in the metabolic stress imposed on the microbial population. In our study, the L structure under DLST exhibited a higher rate of CO_2 emission, since when the aggregates are broken up, some of the carbon previously sequestered is exposed to microbial action, rendering it more susceptible to mineralization (Moitinho et al. 2013). However, it is desirable for this process to occur slowly, reducing losses in the soil, as observed in relatively undisturbed environments (Babujia et al. 2010, Bini et al. 2014). Higher levels of BR can bring about changes in the chemical and physical properties of the soil, such as cation exchange capacity and aggregation, which can lead to nutrient losses (Evangelista et al. 2013, Oliveira et al. 2014, Paredes Junior et al. 2014).

The presence of the L structure also accelerated the decomposition of organic waste, resulting in an increased rate of qCO_2 and higher losses of carbon per unit CMB caused by the respiration process, indicating that the soil is stressed or disturbed (Islam & Weil 2000). According to Evangelista et al. (2013) and Bardgett & Saggar (1994), high qCO_2 values are indicative of ecosystems suffering stress or disturbance, pointing to low efficiency in the immobilization and mineralization of nutrients by the microorganisms in the soil.

The results obtained in this study show that cropping systems that rely heavily on excessive mechanization can severely impair the sustainability of the soil, especially poorly structured soils. In this respect, DLST can impair the quality and functionality of the soil, especially fragile soils like the one in this study. The mechanical action of the implement caused soil pulverization, eliminating the stability of aggregates in the soil, which is already poor due to its sandy texture and low levels of organic matter. Furthermore, this morphostructural alteration is reflected in changes to the biomass and microbial activity in the soil, indicating that the microorganisms are suffering metabolic stress. Note that DLST causes the most severe soil disturbances soil and impaired parameters than CT, but CT also brings about changes and adversely affects soil attributes.

CONCLUSIONS

The results confirm the hypothesis put forward in this study that DLST can severely impair the structural quality of the soil, affecting the microbiota. Adopting this practice adversely affects the sustainability and functionality of sugarcane cropping, inducing a total disaggregation of the soil and aggravating soil losses through erosion. Furthermore, DLST reduces SMB and mainly affecting NMB. Finally, DLST imposes metabolic stresses on the

microbial population, augmenting CO_2 emissions into the atmosphere.

Although CT also involves tilling the soil, the soil structures were less disaggregated and compact compared to the structures observed under DLST. The results for CT show higher levels of soil microbial biomass and lower metabolic rates indicating less stress on the microbiota. Even though the structures found under CT were better than those found under DLST in terms of parameters, this does not mean that it is capable of enhancing soil quality.

The adoption of cropping systems that disturb the soil less, such as no-till, with countless benefits already proved in the production of grains, could be a viable alternative for cropping sugarcane, especially since disturbing the soil less has proved to be fundamental to improving soil quality under tropical conditions.

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