# Soil physical change and sugarcane stalk yield induced by cover crop and soil tillage

**Article** · January 2022

DOI: 10.36783/18069657rbcs20210123



**7 authors**, including:

Camila Viana Vieira
University of Campinas
40 PUBLICATIONS 151 CITATIONS


Zigomar Menezes Souza
University of Campinas
219 PUBLICATIONS 3,497 CITATIONS


Maurício Roberto Cherubin
University of São Paulo
161 PUBLICATIONS 2,283 CITATIONS


Lenon Henrique Lovera
53 PUBLICATIONS 145 CITATIONS

Revista Brasileira de Ciência do Solo

**Division - Soil Processes and Properties** | Commission - Soil Physics

# Soil physical change and sugarcane stalk yield induced by cover crop and soil tillage

**Camila Viana Vieira Farhate[(1,2)*], Zigomar Menezes de Souza[(2)], Maurício Roberto Cherubin[(3)], Lenon Henrique Lovera[(2)], Ingrid Nehmi de Oliveira[(2)], Wellingthon da Silva Guimarães Júnnyor[(4)] and Newton La Scala Junior[(1)]**

[(1)] Universidade Estadual Paulista, Faculdade de Ciências Agrárias e Veterinárias, Jaboticabal, São Paulo, Brasil.
[(2)] Universidade Estadual de Campinas, Faculdade de Engenharia Agrícola, Campinas, São Paulo, Brasil.
[(3)] Universidade de São Paulo, Escola Superior de Agricultura "Luiz de Queiroz", Piracicaba, São Paulo, Brasil.
[(4)] Universidade Estadual de Mato Grosso do Sul, Unidade Universitária de Cassilândia, Mato Grosso do Sul, Brasil.

*** Corresponding author:**
E-mail: camilavianav@hotmail.com

**Received:** August 24, 2021

**Approved:** October 25, 2021

**How to cite:** Farhate CVV, Souza ZM, Cherubim MR, Lovera LH, Oliveira IN, Guimarães Júnnyor WS, La Scala Jr. N. Soil physical change and sugarcane stalk yield induced by cover crop and soil tillage. Rev Bras Cienc Solo. 2022;46:e0210123.
https://doi.org/10.36783/18069657rbcs20210123

**Editors:** José Miguel Reichert and João Tavares Filho.



**ABSTRACT:** Conventional tillage and intensive machinery traffic are the major causes of physical soil degradation in sugarcane fields. This study evaluates the impact of adopting conservation management practices during sugarcane planting on soil physical properties and stalk yield of sugarcane in the municipality of Ibitinga, state of São Paulo, Brazil. The experimental design (split-block) included four cover crops and three soil tillage systems, with three repetitions. For comparison purposes, a control treatment was also included (without cover crop and under conventional tillage). Sampling for soil physical analysis was performed in three layers that coincide with soil horizons A (0.00-0.20 m), AB (0.20-0.30 m), and Bt (0.30-0.70 m), during cane-plant and first sugarcane ratoon cycles. The results showed that cultivation of sunn hemp associated with deep subsoiling induced high stalk yield of sugarcane in both production cycles, cane plant (116 Mg ha$^{-1}$) and first ratoon (114 Mg ha$^{-1}$), with a net gain of 11 and 9 Mg ha$^{-1}$ compared with the control treatment, respectively. However, these results were not sufficient to induce significant differences in sugarcane yield. Nonetheless, the use of sunn hemp and millet, associated with subsoiling (at 0.40 or 0.70 m depth) during sugarcane planting, are promising management strategies to sustain better soil's physical quality when compared to traditional management, conventional soil tillage without cover crops and/or cash crop, as peanuts, that increase the risks of soil compaction and physical degradation.

**Keywords:** soil compaction, sunn hemp, millet, no-tillage system, subsoiling.

## INTRODUCTION

Brazil is the largest sugarcane producer, accounting for 41 % of global production in 2017 (FAO, 2019). Sugarcane covers more than 10 million hectares in Brazil, resulting in 29 million tons of sugar and 33 billion ethanol liters (Conab, 2019a). Most of Brazilian sugarcane is produced in the mid-southern region (90 %), where the cultivated area increased 40 % in the past 15 years (Conab, 2019b), mainly over low-productivity pasturelands (Dias et al., 2016; Oliveira et al., 2019). Since early 2000, mechanized green harvesting system has been gradually adopted, reaching 98 % of current sugarcane areas in mid-southern Brazil (Conab, 2019a).

Sugarcane is traditionally cultivated under conventional tillage (using plowing and harrowing) in Brazil, involving intense disaggregation on soil in the layer of 0.00-0.40 m, which leads to substantial soil carbon losses (Silva-Olaya et al., 2013; Bordonal et al., 2017; Weiler et al., 2019), changes in soil temperature and water status (Awe et al., 2015a,b) degradation of soil structure, and in a last level, limits the production of food, fiber and fuel (Bordonal et al., 2018). Despite all the efforts in adopting mechanized sustainable harvest systems, soil physical degradation induced by intensive machine traffic is one of the leading causes that limit sugarcane yields (Filoso et al., 2015; Souza et al., 2015; Cherubin et al., 2016; White and Johnson, 2018; Esteban et al., 2019; Guimarães Júnnyor et al., 2019a) and threats the sustainability of the production system (Filoso et al., 2015; Bordonal et al., 2018).

Mechanical management practices, such as plowing and subsoiling, are commonly used by farmers to instantly alleviate soil compaction (Hoorman et al., 2011) in the first 0.30-0.40 m depth. More recently, Scarpare et al. (2019) also used a deeper subsoiling to break the compact layer at 0.70-0.80 m depth to improve soil physical properties related to sugarcane rooting, preventing yield reduction in intensive water stress conditions. However, although this system has potentially improved soil physical properties for rooting, there was no increase sugarcane yield in a condition of mild water stress.

Deep subsoiling temporarily benefits soil physical quality (Hoorman et al., 2011), but this tillage has high cost (Chamen et al., 2015). Furthermore, soil disturbance induced by tillage accelerates microbial respiration and soil C losses to the atmosphere as $CO_2$ (Teixeira et al., 2011; Silva-Olaya et al., 2013; Farhate et al., 2019; Tenelli et al., 2019). Therefore, the impacts of mechanical soil tillage before sugarcane planting still need to be further investigated to establish more sustainable and viable management practices. As an alternative to conventional management, conservation management is being carried out, studying the effects of plant roots, mainly legumes (e.g., sunn hemp) for the biological decompaction of the soil.

Conservation practices, such as no-tillage or minimal tillage systems, characterized by the absence or minimal soil mobilization associated with crop residue retention and crop rotation (i.e., mainly with cover crops), are promising strategies to mitigate soil degradation in sugarcane field (Tenelli et al., 2019; Farhate et al., 2020), as widely reported in grain crops (Palm et al., 2014; Blanco-Canqui and Ruis, 2018). More recently, cover crops have been shown as a good option for C inputs in the soil (Poeplau et al., 2015), enhancing soil aggregation and structure (Nascente et al., 2015; Reeves, 2018), reducing erosion, thus providing a favorable environment for the plant growth (Blanco-Canqui et al., 2015; Alvarez et al., 2017).

Several studies highlight the importance of monitoring physical quality throughout the sugarcane cultivation cycle, either by a general index of soil's physical quality (Cherubin et al., 2016; Vischi Filho et al., 2017; Farhate et al., 2020) or by individual changes in physical properties (Castioni et al., 2018; Barbosa et al., 2019; Awe et al., 2020). The bulk density, porosity, and soil resistance to penetration are physical properties sensitive to changes induced by management practices and have been often used to characterize the soil compaction in agricultural areas (Nawaz et al., 2013; Vischi Filho et al., 2017). Furthermore, the bulk density can indirectly reflect aeration, strength, and ability to store and transmit water inside the soil (Reynolds et al., 2009). Regarding pore-size distributions, the macroporosity, e.g., is related (albeit indirectly) to the soil's ability to quickly drain excess water and facilitate root proliferation (Reynolds et al., 2009). Besides being used as a compaction measurement, soil resistance to penetration is also an indicator of the root penetration and root growth capabilities (Nawaz et al., 2013). Soil structure regulates water retention and infiltration, gaseous exchanges, soil organic matter and nutrient dynamics, root penetration, and susceptibility to erosion, becoming another important indicator of soil physical quality (Rabot et al., 2018). Examples of poor physical quality are when soils exhibit one or more of the following symptoms: poor water infiltration, runoff of water from the surface, hard-setting, poor aeration, poor rootability and poor workability. In contrast, good soil physical quality occurs when soils exhibit the opposite or the absence of the conditions listed above (Dexter, 2004).

In this context, the following question remains: the adoption of crop rotation, including cover crops before sugarcane cultivation, could attenuate the negative impacts of soil tillage or even enhance soil physical quality? We hypothesized that cover crop cultivation coupled with conservation tillage practices before sugarcane planting is an efficient management strategy to attenuate soil physical degradation and increase stalk yield of sugarcane, compared to the traditional system (i.e., bare soil and conventional tillage). To test this hypothesis, a field study was carried out to evaluate the effects of cover crop systems and soil tillage practices before sugarcane planting on soil's physical quality and stalk yield of sugarcane.

## MATERIALS AND METHODS

### Study area

The study was conducted in an experimental area located at the Santa Fé sugarcane mill (municipality of Ibitinga, São Paulo, Brazil) (21° 50' 6.03" S, 48° 52' 30.00" W, 455 m a.s.l.) (Figure 1). Regional climate is classified as tropical wet and dry (Aw) according to the Köppen climate classification system (Alvares et al., 2013), with cold and dry winter and hot and rainy summer. Region's average annual rainfall is 1,260 mm, and the relative average air temperature is 23 °C (Cepagri, 2018).

The soil was classified as Ultisols [Udults] (USDA, 2014) and as *Argissolo Vermelho Distrófico típico* according to the Brazilian Soil Classification System (Santos et al., 2018), with sandy loam texture for the 0.00-0.20 m layer and sandy clay loam for the deeper layers (Farhate et al., 2020). The land use capacity class was classified as Class IIIe (Lepsch et al., 2015).

The study area had been cultivated with pasture (*Brachiaria sp.*) for about 11 years. In 2014, a physical soil characterization was performed before converting the area from pasture to a sugarcane field. Soil characterization can be observed in table 1. At the time of conversion, soil acidity was neutralized by liming, 2.0 Mg ha$^{-1}$ of dolomitic limestone (effective neutralizing power = 85 %) incorporated by heavy (0.00-0.40 m) and light (0.20 m) harrowing.

In December 2014, three cover crops (sunn hemp, sorghum and millet) and one cash crop (peanut) were sown. Sunn hemp (*Crotalaria juncea*) and sorghum (*Sorghum bicolor L.*) were sown with a no-tillage seeder using 25 and 10 kg ha$^{-1}$ of seeds, respectively. Peanut (*Arachis hypogaea L.*) was sown with a four-row seeder using 110 kg ha$^{-1}$ of seeds. In contrast, the seeding of millet (*Pennisetum glaucum L.*) occurred manually, in rows using a manual furrower and 18 kg ha$^{-1}$ of seeds.

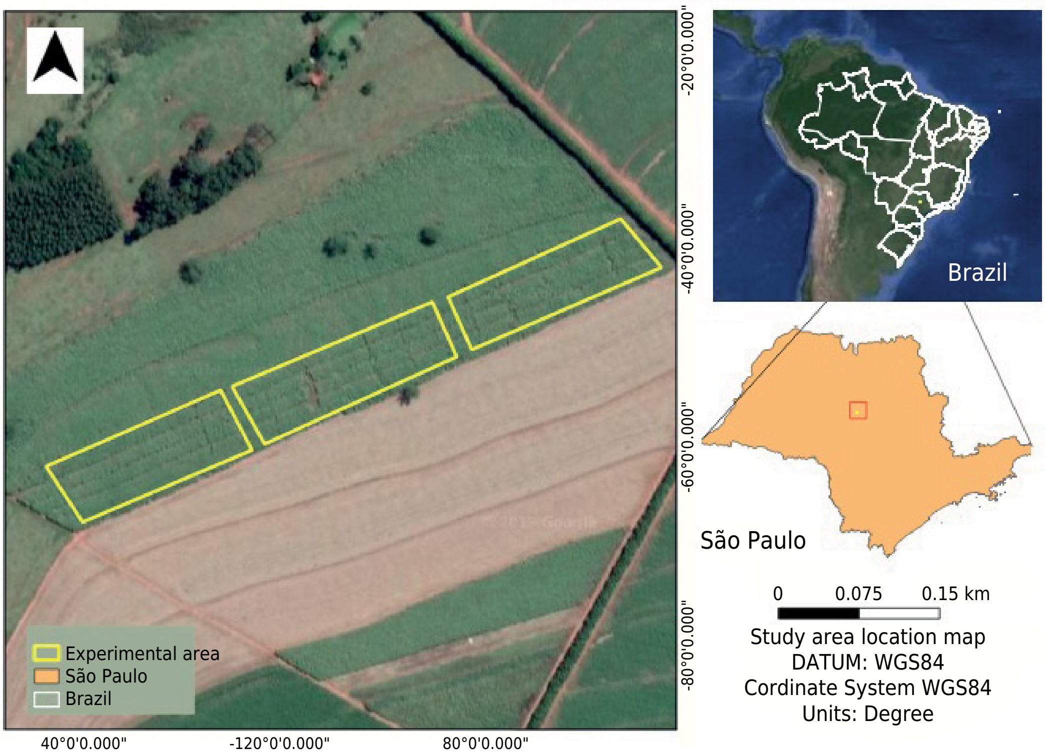


**Figure 1.** Location of the experimental area in the municipality of Ibitinga, São Paulo State, in Brazil.

**Table 1.** Mean ± standard deviation for particle-size fractions, physical and chemical properties of the experimental area, and soil texture classification

| Soil properties | Layers | | | |
|---|---|---|---|---|
| | 0.00-0.10 m | 0.10-0.20 m | 0.20-0.30 m | 0.30-0.70 m |
| Sand (g kg$^{-1}$) | 736 ± 17 | 694 ± 28 | 631 ± 28 | 571 ± 59 |
| Silt (g kg$^{-1}$) | 97 ± 2 | 111 ± 2 | 102 ± 6 | 107 ± 9 |
| Clay (g kg$^{-1}$) | 169 ± 14 | 195 ± 18 | 267 ± 17 | 322 ± 58 |
| Bulk density (Mg m$^{-3}$) | 1.55 ± 0.05 | 1.61 ± 0.02 | 1.66 ± 0.08 | 1.51 ± 0.01 |
| Particle density (Mg m$^{-3}$) | 2.67 ± 0.04 | 2.69 ± 0.03 | 2.71 ± 0.07 | 2.70 ± 0.01 |
| Macroporosity (m$^3$ m$^{-3}$) | 0.11 ± 0.07 | 0.14 ± 0.05 | 0.11 ± 0.04 | 0.10 ± 0.01 |
| Microporosity (m$^3$ m$^{-3}$) | 0.30 ± 0.05 | 0.27 ± 0.02 | 0.27 ± 0.05 | 0.33 ± 0.01 |
| Mean weight-diameter (mm) | 1.94 ± 0.19 | 1.83 ± 0.28 | 1.28 ± 0.23 | 0.67 ± 0.06 |
| Soil resistance to penetration (MPa) | 1.01 ± 0.26 | 1.59 ± 0.59 | 1.60 ± 0.36 | 1.79 ± 0.63 |
| Total carbon content (g kg$^{-1}$) | 8.83 ± 0.12 | 6.38 ± 0.36 | 5.42 ± 0.71 | 4.66 ± 0.29 |

During flowering, cover crops were sampled (two square meters per plot) by cutting plants close to the soil surface to quantify biomass production. The samples were oven-dried at 65 °C for 72 h and then weighted. Biomass production averaged 5, 10, 11 and 21 Mg ha$^{-1}$ (dry mass) for peanut, sunn hemp, millet, and sorghum, respectively. After sampling, plants of sunn hemp, millet and sorghum were managed (desiccation) applying the dose of 200 L ha$^{-1}$ of syrup made with 6 L ha$^{-1}$ of glyphosate, plus 70 mL ha$^{-1}$ of Aurora, and 1 L ha$^{-1}$ of mineral oil. The plants were mechanically harvested for the peanut crop with a Sweere Double Master V peanut harvester pulled by a Massey Fergusson model 7140 tractor, with a power rating of 104 kW.

Planting of sugarcane occurred mechanically in April 2015 with the CTC 4 variety of sugarcane. On this occasion, fertilization for plantation occurred with the application of

300 kg ha$^{-1}$ of N-P-K fertilizer (10-51-00). In plots without cover crops (control), the soil tillage was carried out using two light-disk harrowings. In addition, another three soil tillage practices were carried out: (i) no-tillage (NT); (ii) minimum tillage with subsoiling to 0.40 m depth (MT); and (iii) minimum tillage with deep subsoiling to 0.70 m depth (MT/DS). For the first, no soil tillage was carried out before sugarcane plating. For (ii) and (iii), the operations were carried out using a five-shank subsoiler at different operating depths. The chronological order of events that occurred in the study area is shown in figure 2.

## Experimental design and treatments

Experimental design was in split-block, with three replications, in which four species of cover crops (*e.g.*, sunn hemp, millet, sorghum and peanut) were planted in one direction and the three tillage systems [*e.g.*, no-tillage (NT); minimum tillage (MT); and minimum tillage with deep subsoiling (MT/DS)], were performed in the opposite direction adopted for cover crops. In addition, a control treatment was left without cover crop (bare soil) and under conventional tillage (CT). Each plot had six rows of sugarcane, with a spacing of 1.5 and 30 m in length, totaling an area of 300 m$^2$ per plot.

## Cover crops analysis

When the cover crops reached the point of maximum flowering, we performed a plant sampling to analyze dry mass production (DM) in an area of two square meters per plot, in which the plants were cut near the soil. Subsequently, the samples were dried at 65 °C for 72 h, weighed, and the results were expressed in Mg ha$^{-1}$.

For the analysis of the nutrients accumulated by the cover crops, samples of aboveground biomass were ground, and the contents of P, K, Ca and Mg were determined according to Malavolta et al. (1997). The carbon was determined by combustion using the LECO TruSpec CN Analyzer (LECO®).

## Soil sampling and laboratory analyses

Soil samplings were carried out before harvesting the plant-cane production cycle (harvest 2015/16) and just after harvesting the first ratoon cycle (harvest 2016/17). The samples were collected in the inter-row down to 0.70 m depth, subdivided into the 0.00-0.05, 0.05-0.10, 0.10-0.20, 0.20-0.30 and 0.30-0.70 m layers. Subsequently, to improve the interpretation of the results, the results were grouped according to the soil horizons, that is, A (0.00-0.20 m), AB (0.20-0.30 m), and Bt (0.30-0.70 m).

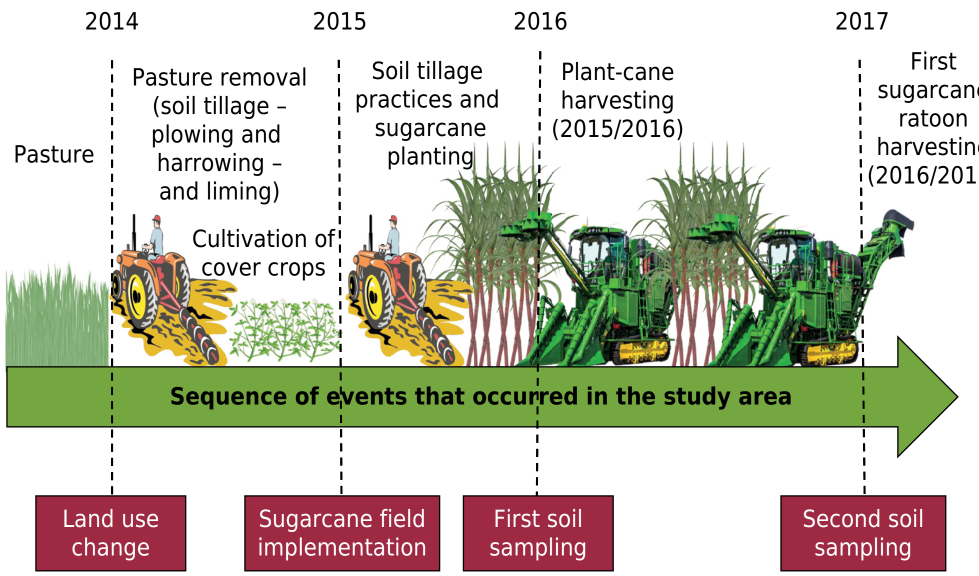


**Figure 2.** Timeline and main management practices adopted in the study area.

Soil particle-size analysis was performed as established by Camargo et al. (2009). Soil particle density (Mg $m^{-3}$), bulk density (Mg $m^{-3}$) (BD), macro ($m^3$ $m^{-3}$) (MaP) and microporosity ($m^3$ $m^{-3}$) (MiP) were determined according to the methodologies described by Teixeira et al. (2017). Particle density was determined using a 50 mL pycnometer, and BD was calculated by the ratio between the soil dry mass at 105 °C and the total volume of the soil sample. The MiP (pores with diameter between 0.05 and 0.0002 mm) was determined by the volume of water retained in the undisturbed soil samples subjected to matric potentials of -6 kPa in the suction table (Dane and Hopmans, 2002), MaP (pores with a diameter greater than 0.05 mm) was calculated by the difference between total porosity and MiP, and total porosity ($m^3$ $m^{-3}$) was calculated by an indirect method, as shown in equation 1:

$$TP = 1 - \left(\frac{BD}{Pd}\right) \qquad \text{Eq. 1}$$

in which: TP is the total porosity; BD is the bulk density; and Pd is the particle density.

Maximum bulk density (kg $dm^{-3}$) (BD max) was estimated by a pedotransfer equation (Equation 2) as described by Marcolin and Klein (2011) and, from the relationship between BD and BD máx, the degree of compactness (DC) was obtained (%) by equation 3.

$$BD\ max = 2.03133855 - (0.00320878 \times SOM) - (0.00076508 \times clay) \qquad \text{Eq. 2}$$

$$DC = \left(\frac{BD}{BD\ max}\right) \times 100 \qquad \text{Eq. 3}$$

in which: BD max is the maximum bulk density; SOM is the soil organic matter; DC is the degree of compactness; and BD is the bulk density.

Mean weight-diameter (MWD) of soil aggregates (mm) was determined using the wet-sieving method as proposed by Kemper and Chepil (1965), in which 20 g of aggregates that passed through the 6.35 mm sieve were retained in the 2.00 mm sieve and were used for this analysis. The aggregates were pre-moistened by capillarity for 10 min and then transferred to a set of five sieves with a mesh diameter of 2.00, 1.00, 0.50, 0.25 and 0.125 mm and subjected to vertical agitation in water for 30 min. After that, soil retained in each sieve was oven-dried at 105 °C for 24 h. The following aggregate size classes were obtained: 4.48 mm (6.35-2.00 mm), 1.50 mm (2.00-1.00 mm), 0.75 mm (1.00-0.50 mm), 0.38 mm (0.50-0.25 mm), 0,19 (0.25-0.125 mm) and 0.06 mm (> 0.125). Equation 4 was used to calculate the MWD:

$$MWD = \sum_{i=1}^{n} (xi \times wi) \qquad \text{Eq. 4}$$

in which: xi is the average diameter of the classes (mm) and wi is the fraction of each class regarding the total.

Soil resistance to penetration (SRP) measurements are highly dependent on soil water content, and this relationship can induce errors in the interpretation of the soil compaction state between different treatments. Therefore, SRP was determined in the laboratory under controlled soil water content conditions aiming to reduce those effects. For this, the undisturbed samples were placed under the tension table and equilibrate at a tension of 0.006 MPa following the methodology described by Teixeira et al. (2017). This allowed the measure of SRP of all samples were carried out in the same matric potential. The SRP was determined using the equipment MA model 933 electronic penetrometer (MARCONI®) with a 4 mm tip and a constant penetration speed of 10 mm $s^{-1}$, according to the procedures performed by Tormena et al. (1999). Three replicated penetrations were realized for each soil sample. The measurements obtained from the upper (1.0 cm) and lower portions (1.0 cm) were excluded, and only the middle three centimeters of the samples were used. The average soil water content during the SRP measurements in the plant cane cycle was 0.16 $m^3$ $m^{-3}$ and was 0.19 $m^3$ $m^{-3}$ in the first ratoon cane cycle.

Soil total carbon (C) content was determined according to the methodology proposed by Nelson and Sommers (1996). First, the soil samples were air-dried and sieved at 2 mm. From each sample, 20 g was ground and sieved at 100 mesh (150 μm), then C was determined using the LECO TruSpec CN Analyzer (LECO®).

### Statistical analysis

The Dunnett test determined differences among treatment groups (cover crops and tillage) and the control at the 0.05 level of significance, implemented in the Minitab 19 software.

Radar graphs were elaborated to obtain a better interpretation of the results. The average values of the soil physical properties were normalized into a unitless scale ranging from 0 (worse) to 1 (best soil physical quality). Linear scoring techniques were used to transform the values of each property. Firstly, the soil physical properties were ranked in ascending or descending order depending on whether a higher value was considered "good" or "bad" in terms of its physical quality. Bulk density and SRP followed the "less is better" scoring curve, where the lowest observed value (in the numerator) was divided by each observation (in the denominator) such that the lowest observed value received the score 1. The indicators MaP, MiP and MWD followed the "more is better" scoring curve, in which each observation was divided by the highest observed value such that the highest observed value received the score 1. More information on linear transformation can be obtained from Andrews et al. (2002).

## RESULTS

### Nutrient accumulation in different cover crops

Sorghum was the cover crop that produced the largest amount of dry matter (DM) (21 Mg $ha^{-1}$), with a C:N ratio of 28. Sunn hemp and millet presented intermediate DM production (11 and 10 Mg $ha^{-1}$, respectively). However, with distinct C:N ratio values, corresponding to 13 and 48, respectively. Peanut was the cover crop that resulted in the lowest DM production (5 Mg $ha^{-1}$), associated with a C:N ratio of 15 (Table 2).

Sorghum was by far the cover crop with the highest potential for C input to the soil, with an average content of 10 Mg $ha^{-1}$, followed by sunn hemp (5 Mg $ha^{-1}$), millet (4.5 Mg $ha^{-1}$) and peanut (2 Mg $ha^{-1}$). The sorghum and sunn hemp were the cover crops that reached the largest N, K and Ca contents, in which they were accumulated 350 kg $ha^{-1}$ of N, 319 kg $ha^{-1}$ of K and 95 kg $ha^{-1}$ of Ca by sorghum. While sunn hemp accumulated 413 kg $ha^{-1}$ of N, 259 kg $ha^{-1}$ of K and 109 kg $ha^{-1}$ of Ca. Sorghum also had higher accumulations of P (40 kg $ha^{-1}$) and Mg (85 kg $ha^{-1}$) (Table 2).

**Table 2.** Dry matter production, C:N ratio, accumulation of carbon, nitrogen and macronutrients in vegetable residues of cover crops

| Cover crop | DM | C:N | C | N | P | K | Ca | Mg |
|---|---|---|---|---|---|---|---|---|
| | Mg $ha^{-1}$ | | Mg $ha^{-1}$ | kg $ha^{-1}$ | | | | |
| Peanut | 5 c | 15 bc | 2 d | 140 b | 9 d | 114 b | 62 b | 31 b |
| Sunn hemp | 11 b | 13 c | 5 b | 413 a | 31 b | 259 a | 109 a | 34 b |
| Millet | 10 b | 48 a | 4.5 c | 97 b | 21 c | 131 b | 30 c | 22 b |
| Sorghum | 21 a | 28 b | 10 a | 350 a | 40 a | 319 a | 95 a | 85 a |

Mean values are average of three replicates. DM: dry matter; C: carbon; N: nitrogen; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium. Mean values followed by the same letter in the column do not differ among themselves according to Tukey's test ($p<0.05$).

## Soils physical properties

On horizon A, during the plant cane cycle, the use of sunn hemp with MT (BD = 1.54 kg $dm^{-3}$) and MT/DS (BD = 1.56 kg $dm^{-3}$) and, during the first ratoon cane cycle, the management systems with sunn hemp and NT (BD = 1.68 kg $dm^{-3}$) and MT (BD = 1.72 kg $dm^{-3}$), induced values of BD significantly lower ($p<0.05$) than the control treatment (plant cane - BD = 1.69 kg $dm^{-3}$; first ratoon cane - BD = 1.82 kg $dm^{-3}$) (Figure 3). On the other hand, in the AB horizon, the use of cover crops with greater root exploration capacity, such as millet and sorghum, combined with soil tillage systems MT and MT/DS, reduced significantly ($p<0.05$) the BD regarding the control treatment. In-depth, at the Bt horizon, the management systems did not induce significant changes ($p<0.05$) regarding the conventional system (control) for the cultivation cycle of the plant cane. However, after the machine traffic and harvest operations, the treatments that used peanuts and NT (BD = 1.77 kg $dm^{-3}$) and MT/DS (BD = 1.76 kg $dm^{-3}$) presented BD significantly higher ($p<0.05$) than the control treatment (BD = 1.60 kg $dm^{-3}$) (Figure 3).

In general, there was an average increase of 10 % in the BD values in the horizon A, between the production cycles of cane plant and first ratoon cane, reflecting the effect of two sequential harvests (Figure 3). These results are also supported by the DC (degree of compactness) shown in table 2. We observed that for horizon A, only the control treatment

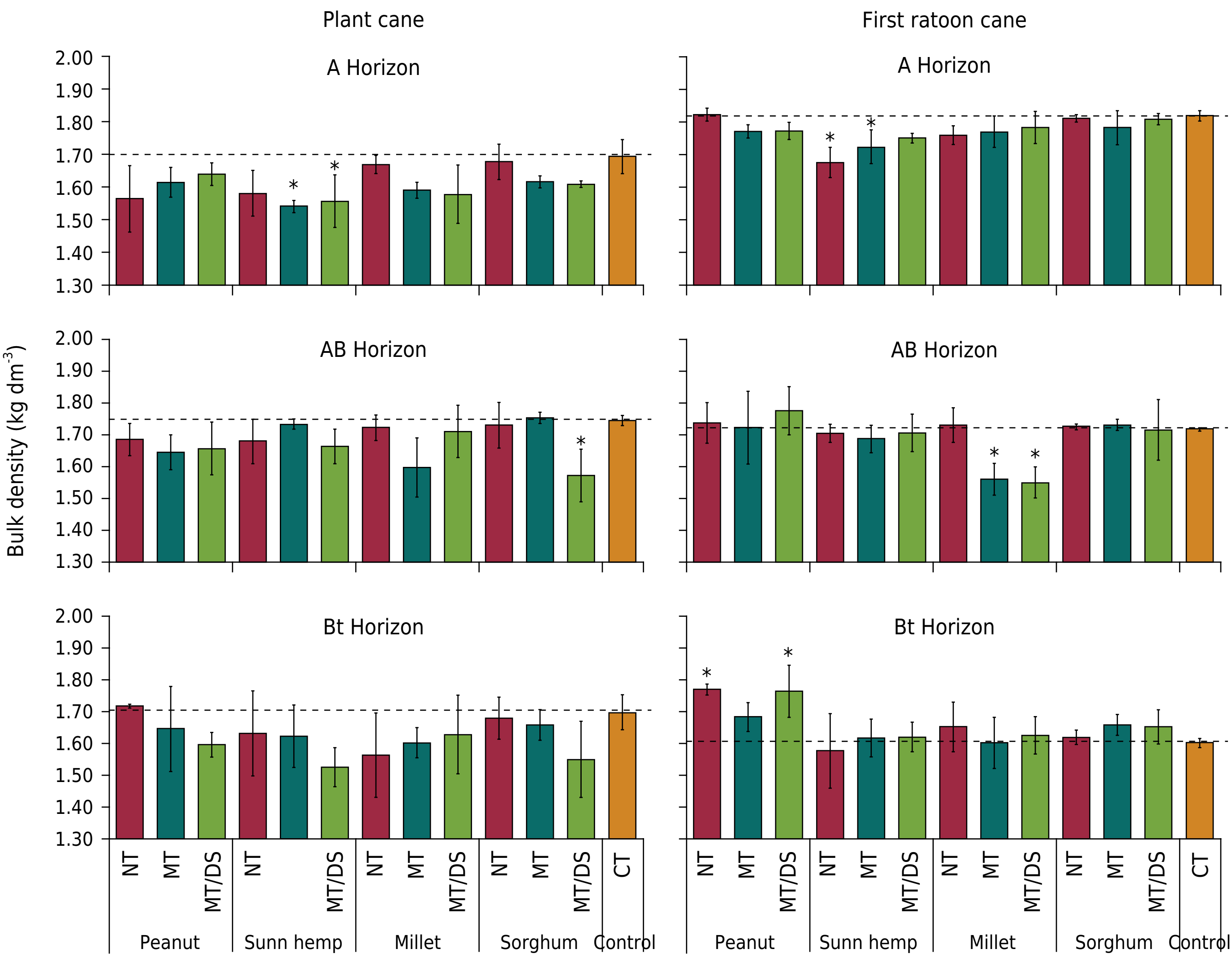


**Figure 3.** Bulk density (kg $dm^{-3}$) in an area of sugarcane expansion using different cover crops and soil tillage systems. NT: no-tillage; MT: minimum tillage; MT/DS: minimum tillage with deep subsoiling; Control: sugarcane grown without the introduction of cover crops and with conventional tillage. * Significant by Dunnett's test at 5 % probability when compared to control treatment. Horizontal dashed line indicates the value obtained by the control treatment. Bars indicate the standard deviation (N = 3).

indicated soil compaction (DC >90 %) during the production cycle of plant cane. However, between the production cycles of cane plant and first ratoon, all treatments presented soil compaction, except for treatment sunn hemp with NT, that besides to not showing compaction, it also provided a significantly lower ($p<0.05$) DC than the control treatment. In addition, we note the high levels of soil compaction in the Bt horizon, achieved by the treatments that combined peanuts with NT and MT/DS (101 and 100 %, respectively). This result contributed to these treatments to present compaction significantly higher ($p<0.05$) than the control treatment (Table 3).

In general, during the plant cane cycle, the treatments showed a high amount of MaP (Figure 4). However, between the plant cane and first ratoon cycles, we observed a negative effect of the machine traffic during the sugarcane harvest, where there was a considerable reduction in MaP, the order of 69, 58 and 50 % for A, AB and Bt horizons, respectively. However, even in restrictive conditions, we observed that some treatments, during the first ratoon cane cycle, showed MaP values significantly higher ($p<0.05$) than the control treatment (0.05 $m^3\ m^{-3}$), such as peanut with MT/DS (0.08 $m^3\ m^{-3}$), sunn hemp with MT/DS (0.07 $m^3\ m^{-3}$), in A horizon and sunn hemp with MT/DS (0.11 $m^3\ m^{-3}$) in Bt horizon.

Machine traffic between the plant cane and first ratoon cane cycles also induced an increase in MiP, with values on average 25, 27 and 13 % higher for the A, AB and Bt horizons, respectively (Figure 4). Furthermore, for horizon A, during the first ratoon cane cycle, the use of sunn hemp with NT (0.33 $m^3 m^{-3}$) and MT (0.32 $m^3\ m^{-3}$) provided values significantly higher ($p<0.05$) than the control treatment (0.29 $m^3\ m^{-3}$).

**Table 3.** Degree of compactness (DC) according to different cover crops and soil tillage systems

| Cover crops | Plant cane | | | First ratoon cane | | |
|---|---|---|---|---|---|---|
| | Soil tillage | | | | | |
| | NT | MT | MT/DS | NT | MT | MT/DS |
| | Degree of compactness | | | | | |
| | % | | | | | |
| | Horizon A | | | | | |
| Peanut | 84 ± 5.56 | 87 ± 2.39 | 88 ± 1.87 | **98 ± 0.93** | **95 ± 1.51** | **95 ± 1.20** |
| Sunn hemp | 85 ± 3.76 | 83 ± 0.88* | 84 ± 4.31 | 90 ± 2.76* | **93 ± 2.85*** | **95 ± 0.82** |
| Millet | 90 ± 1.55 | 85 ± 1.26 | 85 ± 4.82 | **94 ± 1.90** | **95 ± 2.58** | **96 ± 2.59** |
| Sorghum | 90 ± 2.70 | 86 ± 1.11 | 86 ± 0.40 | **97 ± 0.71** | **96 ± 2.71** | **98 ± 1.05** |
| Control | | **91 ± 2.79** | | | **98 ± 0.60** | |
| | Horizon AB | | | | | |
| Peanut | **94 ± 2.75** | **91 ± 2.87** | **91 ± 4.64** | **97 ± 3.72** | **96 ± 6.59** | **99 ± 4.11** |
| Sunn hemp | **93 ± 3.85** | **96 ± 0.93** | **92 ± 3.02** | **95 ± 1.50** | **94 ± 2.17** | **95 ± 3.27** |
| Millet | **95 ± 2.14** | 89 ± 5.20* | **95 ± 4.59** | **96 ± 2.93** | **91 ± 5.64** | 87 ± 3.06 |
| Sorghum | **95 ± 3.89** | **97 ± 0.98** | 87 ± 4.64* | **96 ± 0.44** | **96 ± 1.07** | **95 ± 5.53** |
| Control | | **97 ± 0.79** | | | **96 ± 0.16** | |
| | Horizon Bt | | | | | |
| Peanut | **97 ± 0.31** | **93 ± 7.53** | **91 ± 2.10** | **101 ± 1.04*** | **96 ± 2.93** | **100 ± 4.42*** |
| Sunn hemp | **92 ± 7.59** | **92 ± 5.66** | 86 ± 3.47 | 90 ± 6.58 | **91 ± 3.34** | **92 ± 2.69** |
| Millet | 89 ± 7.49 | **91 ± 2.66** | **92 ± 7.06** | **94 ± 4.36** | **91 ± 4.57** | **92 ± 3.37** |
| Sorghum | **95 ± 3.76** | **94 ± 2.58** | 88 ± 6.81 | **92 ± 1.27** | **94 ± 2.04** | **94 ± 2.98** |
| Control | | **96 ± 2.85** | | | **91 ± 0.77** | |

NT: no-tillage; MT: minimum tillage; MT/DS: minimum tillage with deep subsoiling; Control: sugarcane grown without the introduction of cover crops and with conventional tillage. Mean values are the average of three replicates. * Significant by Dunnett's test ($p<0.05$) when compared to control treatment. Bold values indicate soil compacted and very compacted, according to Klein (2014).

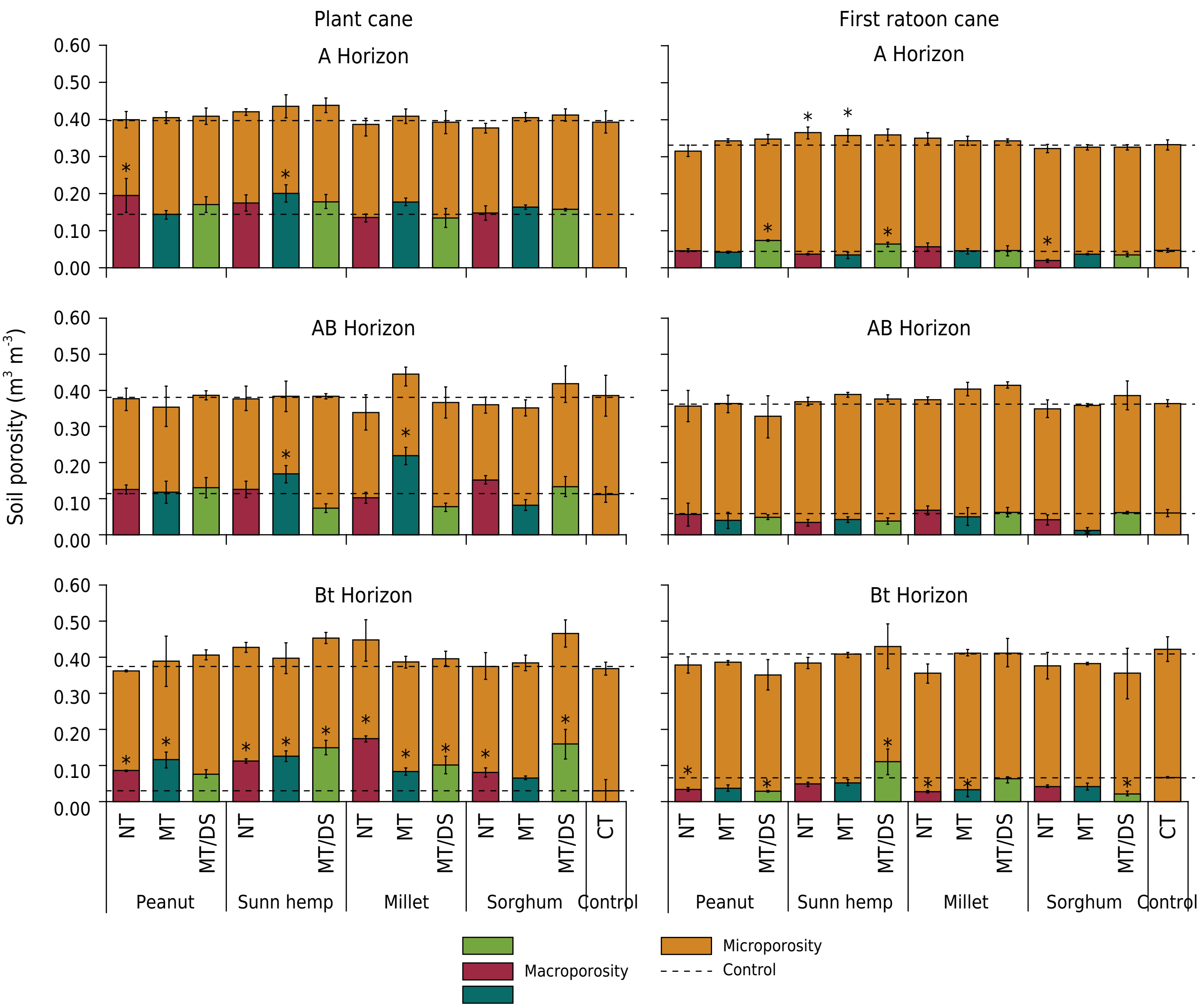


**Figure 4.** Macro and microporosity ($m^3$ $m^{-3}$) in an area of sugarcane expansion using different cover crops and soil tillage systems. NT: no-tillage; MT: minimum tillage; MT/DS: minimum tillage with deep subsoiling; Control: sugarcane grown without the introduction of cover crops and with conventional tillage. * Significant by Dunnett's test at 5 % probability when compared to control treatment. Horizontal dashed line indicates the value obtained by the control treatment. Bars indicate the standard deviation (N = 3).

Regarding the Soil Resistance to Penetretion (SRP), in general, there was also an increase in this property between the plant cane and first ratoon cane cycles, mainly in the top layer (Table 4). On horizon A, during the cane plant cycle, regardless of the cover crop, the use of MT and MT/DS reduced significantly ($p<0.05$) the SRP compared to control treatment. After the harvest of the first ratoon cane cycle, the use of peanuts and sunn hemp with NT (1.82 and 1.15 MPa, respectively), sunn hemp with MT (1.72 MPa), and peanuts and millet with MT/DS (1.29 and 1.73 MPa, respectively), showed values significantly lower ($p<0.05$) of SRP when compared to the control treatment. For the AB horizon, during the plant cane cycle, the use of peanuts and sorghum, both with MT/DS, presented significantly lower ($p<0.05$) SRP than the control treatment and, during the first ratoon cane cycle, the treatments with NT using peanut, millet, and sorghum, peanut with MT, and peanut, sunn hemp, and millet with MT/DS stood out. Considering the Bt horizon, we observed that some combinations of cover crops and soil tillage systems were harmful to root penetration. This was caused since they induced higher SRP values than the control treatment, such as the combination of peanuts with NT (2.24 MPa) during the cane plant cycle and, millet and sorghum with NT (2.54 and 2.34 MPa, respectively) and MT/DS (1.98 and 2.25 MPa, respectively), during the first ratoon cane cycle.

**Table 4.** Soil resistance to penetration according to different cover crops and soil tillage systems

| Cover crops | Plant cane | | | First ratoon cane | | |
|---|---|---|---|---|---|---|
| | Soil tillage | | | | | |
| | NT | MT | MT/DS | NT | MT | MT/DS |
| | Soil resistance to penetration | | | | | |
| | MPa | | | | | |
| | A Horizon | | | | | |
| Peanut | 1.13 ± 0.02 | 0.88 ± 0.05* | 0.57 ± 0.04* | 1.82 ± 0.14* | 2.35 ± 0.16 | 1.29 ± 0.09* |
| Sunn hemp | 0.80 ± 0.08* | 0.62 ± 0.07* | 0.66 ± 0.13* | 1.15 ± 0.11* | 1.72 ± 0.15* | 2.11 ± 0.13 |
| Millet | 1.78 ± 0.07* | 0.67 ± 0.04* | 0.97 ± 0.10* | 1.86 ± 0.15 | 1.98 ± 0.15 | 1.73 ± 0.71* |
| Sorghum | 1.11 ± 0.12 | 0.81 ± 0.12* | 0.69 ± 0.03* | 1.86 ± 0.26 | 2.11 ± 0.22 | 3.36 ± 0.43* |
| Control | | 1.16 ± 0.01 | | | 2.36 ± 0.19 | |
| | AB Horizon | | | | | |
| Peanut | 1.93 ± 0.31 | 1.23 ± 0.20 | 0.88 ± 0.21* | 1.32 ± 0.06* | 1.03 ± 0.07* | 0.83 ± 0.08* |
| Sunn hemp | 1.52 ± 0.29 | 2.14 ± 0.14 | 1.48 ± 0.46 | 1.39 ± 0.22 | 1.50 ± 0.08 | 0.89 ± 0.13* |
| Millet | 1.88 ± 0.05 | 1.46 ± 0.29 | 1.28 ± 0.16 | 1.31 ± 0.10* | 1.56 ± 0.32 | 0.82 ± 0.17* |
| Sorghum | 1.64 ± 0.14 | 1.55 ± 0.26 | 0.62 ± 0.03* | 1.20 ± 0.50* | 1.72 ± 0.26 | 1.71 ± 0.39 |
| Control | | 1.59 ± 0.09 | | | 1.93 ± 0.06 | |
| | Bt Horizon | | | | | |
| Peanut | 2.24 ± 0.25* | 1.83 ± 0.15 | 1.20 ± 0.05* | 1.24 ± 0.12 | 1.22 ± 0.29 | 1.04 ± 0.18 |
| Sunn hemp | 1.47 ± 0.34 | 0.78 ± 0.12* | 1.26 ± 0.01 | 1.10 ± 0.25 | 1.39 ± 0.35 | 0.64 ± 0.10 |
| Millet | 1.54 ± 0.01 | 1.16 ± 0.09* | 1.42 ± 0.27 | 2.54 ± 0.55* | 0.89 ± 0.09 | 1.98 ± 0.39* |
| Sorghum | 1.74 ± 0.11 | 1.64 ± 0.32 | 1.28 ± 0.15 | 2.34 ± 0.39* | 1.17 ± 0.37 | 2.25 ± 0.53* |
| Control | | 1.69 ± 0.24 | | | 0.89 ± 0.15 | |

NT: no-tillage; MT: minimum tillage; MT/DS: minimum tillage with deep subsoiling; Control: sugarcane grown without the introduction of cover crops and with conventional tillage. Mean values are the average of three replicates. * Significant by Dunnett's test (p<0.05) when compared to control treatment. Mean ± standard deviation.

Regarding the mean weight-diameter (MWD) of aggregates, in general, in the top layer (horizons A and AB), during the plant cane cycle, the treatments induced greater aggregation compared with the control treatment (Figure 5). Furthermore, regardless of soil tillage system, we observed in horizon A that millet increased significantly (p<0.05) the MWD of the aggregates regarding the control. However, at the horizon Bt, there was a reduction of MWD regarding the control treatment, in which only the treatment using peanuts and NT was equal to this (Figure 5). We also observed, during the first ratoon cane cycle, that the use of millet with NT on horizon A (0.86 mm), millet with MT/DS on horizon B (0.78 mm), and peanut with MT (0.99 mm) resulted in MWD of the aggregates significantly larger (p<0.05) than the control.

There was, in general, an increase in soil total carbon content between the plant cane and the first ratoon cane cycle (Table 5). It also should be noted that during the plant cane cycle, soil C increments were observed only in the top layer (A horizon), in which the treatments using sunn hemp with NT and millet with NT and MT/DS presented the higher C contents. In contrast, significant differences (p<0.05) occurred in deeper layers (AB horizon) in the first ratoon, in which millet associated with MT (8.62 g $kg^{-1}$) presented a higher soil C content than the control (5.31 g $kg^{-1}$).

Thus, the conventional system (without cover crop combined with conventional tillage) induced higher values of BD and SRP, and low values of MaP and MWD. It also contributed to reducing soil physical quality in all horizons, except for the Bt horizon during the plant cane cycle, in which higher values of MiP, SRP and MWD were evidenced for this treatment (Figures 6 and 7).

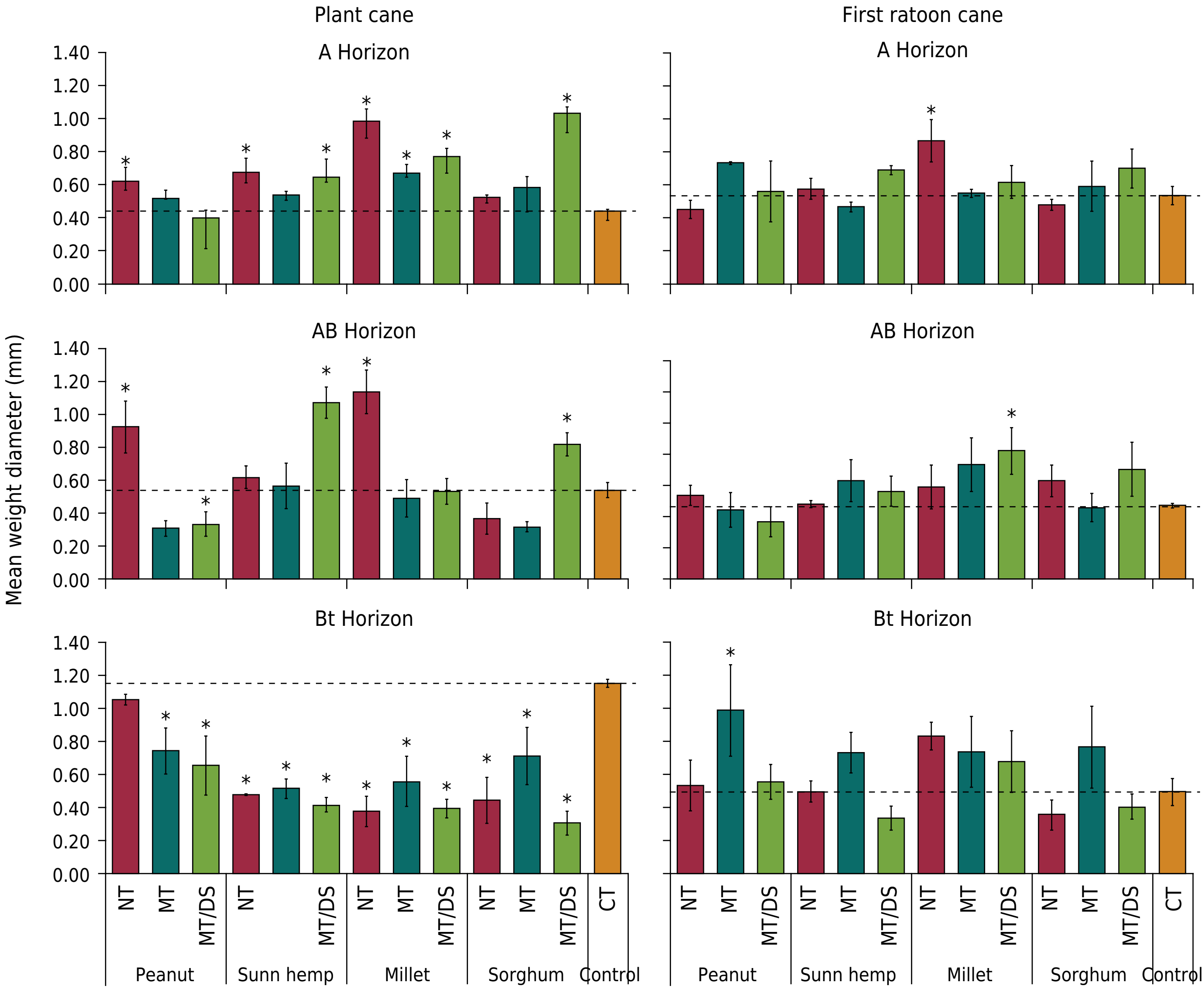


**Figure 5.** Mean weight-diameter of soil aggregates (mm) in an area of sugarcane expansion using different cover crops and soil tillage systems. NT: no-tillage; MT: minimum tillage; MT/DS: minimum tillage with deep subsoiling; Control: sugarcane grown without the introduction of cover crops and with conventional tillage. * Significant by Dunnett's test at 5 % probability when compared to control treatment. Horizontal dashed line indicates the value obtained by the control treatment. Bars indicate the standard deviation (N = 3).

The use of sunn hemp before the cultivation of sugarcane was associated with higher values of MaP, MiP and SRP, and low values of BD. Alternatively, millet use induced an improvement in the BD, MaP, MiP and MWD of the soil aggregates. Furthermore, during the first ratoon cane cycle, we noticed a reduction in physical quality in all horizons and treatments, evidenced by low MaP (Figure 6). About the soil tillage system, MT and MT/DS use reduced the SRP and increased the MaP and MWD providing greater physical quality (Figure 7).

### Stalk yield of sugarcane

Regardless of the production cycle, there were no significant differences in the sugarcane yield between the management systems (cover crops + soil tillage) and the conventional system (control) by Dunnett's test ($p<0.05$) (Table 6). However, during the cane plant cycle, sorghum and MT/DS increased sugarcane yield by 15 Mg $ha^{-1}$ regarding the conventional system. We also observed a decrease in the stalk yield of sugarcane for all treatments between the plant cane and first ratoon cane cycles. This decrease was more easily observed for the sorghum and MT/DS treatments, which presented an average sugarcane yield 10 % lower. On the other hand, higher sugarcane yields were observed

**Table 5.** Soil total carbon content according to different cover crops and soil tillage systems

| Cover crops | Plant cane | | | First ratoon cane | | |
|---|---|---|---|---|---|---|
| | Soil tillage | | | | | |
| | NT | MT | MT/DS | NT | MT | MT/DS |
| | Soil total carbon | | | | | |
| | g kg$^{-1}$ | | | | | |
| | Horizon A | | | | | |
| Peanut | 5.25 ± 0.53 | 5.02 ± 0.18 | 4.53 ± 0.48 | 5.88 ± 1.02 | 6.70 ± 1.37 | 6.37 ± 1.26 |
| Sunn hemp | 5.25 ± 0.12* | 5.87 ± 0.56 | 5.27 ± 0.19 | 6.85 ± 1.30 | 5.60 ± 0.59 | 7.68 ± 1.01 |
| Millet | 6.84 ± 0.26* | 5.13 ± 0.55 | 5.79 ± 0.95* | 6.23 ± 0.22 | 6.34 ± 0.57 | 6.89 ± 0.48 |
| Sorghum | 4.13 ± 0.96 | 3.71 ± 0.52 | 5.39 ± 0.55 | 6.20 ± 1.07 | 5.79 ± 0.62 | 7.40 ± 0.55 |
| Control | | 4.49 ± 0.10 | | | 6.26 ± 1.29 | |
| | Horizon AB | | | | | |
| Peanut | 4.82 ± 0.58 | 3.53 ± 0.71* | 4.63 ± 0.69 | 5.42 ± 0.51 | 4.34 ± 1.02 | 4.80 ± 0.48 |
| Sunn hemp | 4.42 ± 0.44 | 5.18 ± 0.65 | 4.64 ± 0.16 | 5.69 ± 1.11 | 5.06 ± 1.09 | 5.18 ± 0.29 |
| Millet | 4.22 ± 0.37 | 4.60 ± 0.03 | 4.83 ± 0.14 | 4.72 ± 0.22 | 8.62 ± 1.09* | 5.64 ± 0.20 |
| Sorghum | 3.32 ± 0.23* | 2.13 ± 0.01* | 4.51 ± 0.37 | 4.53 ± 0.67 | 4.64 ± 1.40 | 6.32 ± 0.94 |
| Control | | 5.06 ± 0.33 | | | 5.31 ± 0.99 | |
| | Horizon Bt | | | | | |
| Peanut | 3.90 ± 0.31 | 1.94 ± 0.34* | 5.51 ± 1.03 | 4.80 ± 0.11 | 4.72 ± 1.25 | 4.22 ± 0.75 |
| Sunn hemp | 3.79 ± 0.24 | 3.66 ± 0.27 | 2.77 ± 0.00* | 4.71 ± 0.26 | 4.89 ± 0.58 | 4.27 ± 0.58 |
| Millet | 3.83 ± 0.22 | 3.80 ± 0.00 | 4.21 ± 0.04 | 5.36 ± 0.42 | 5.61 ± 0.07 | 4.93 ± 0.01 |
| Sorghum | 3.14 ± 0.86* | 3.83 ± 0.52 | 3.32 ± 0.07* | 4.71 ± 0.26 | 4.89 ± 0.58 | 4.27 ± 0.58 |
| Control | | 4.64 ± 0.79 | | | 4.98 ± 0.26 | |

NT: no-tillage; MT: minimum tillage; MT/DS: minimum tillage with deep subsoiling; Control: sugarcane grown without the introduction of cover crops and with conventional tillage. Mean values are the average of three replicates. * Significant by Dunnett's test ($p<0.05$) when compared to control treatment. Mean ± standard deviation.

under sunn hemp and MT/DS treatment in both cane plant cycle (116 Mg ha$^{-1}$) and first sugarcane ratoon cycle (114 Mg ha$^{-1}$), with a net gain of 11 and 9 Mg ha$^{-1}$ regarding the control treatment, respectively.

## DISCUSSION

### Effect of cover crops and soil tillage

Our results reveal that the adoption of sunn hemp before planting of the sugarcane field induced higher porosity (MaP and MiP) associated with lower bulk density (BD) values (Figures 3, 4 and 6). These results are possibly a consequence of the high exploration of the sunn hemp root system that can grow even in compacted soil layers, contributing to the formation of biopores and improving soil physical conditions. For instance, Foloni et al. (2006) observed a high root length density of sunn hemp even at high compaction levels. The authors highlight that as soil compaction increases, this cover crop can develop a large number of lateral roots, which are thinner and capable of penetrating pores of reduced diameter in the soil, which justifies its potential to improve the quality of soil physical properties. This statement is in accordance with Calonego et al. (2017), who evaluated the effects of cover crops on soil physical properties and observed an increase in macroporosity by sunn hemp up to 0.20 m depth.

On the other hand, the use of grasses, such as millet, improved soil aggregation conditions. For the plant cane cycle, in A horizon, we observed that regardless of the soil tillage system, the millet increased significantly the MWD of the aggregates regarding the

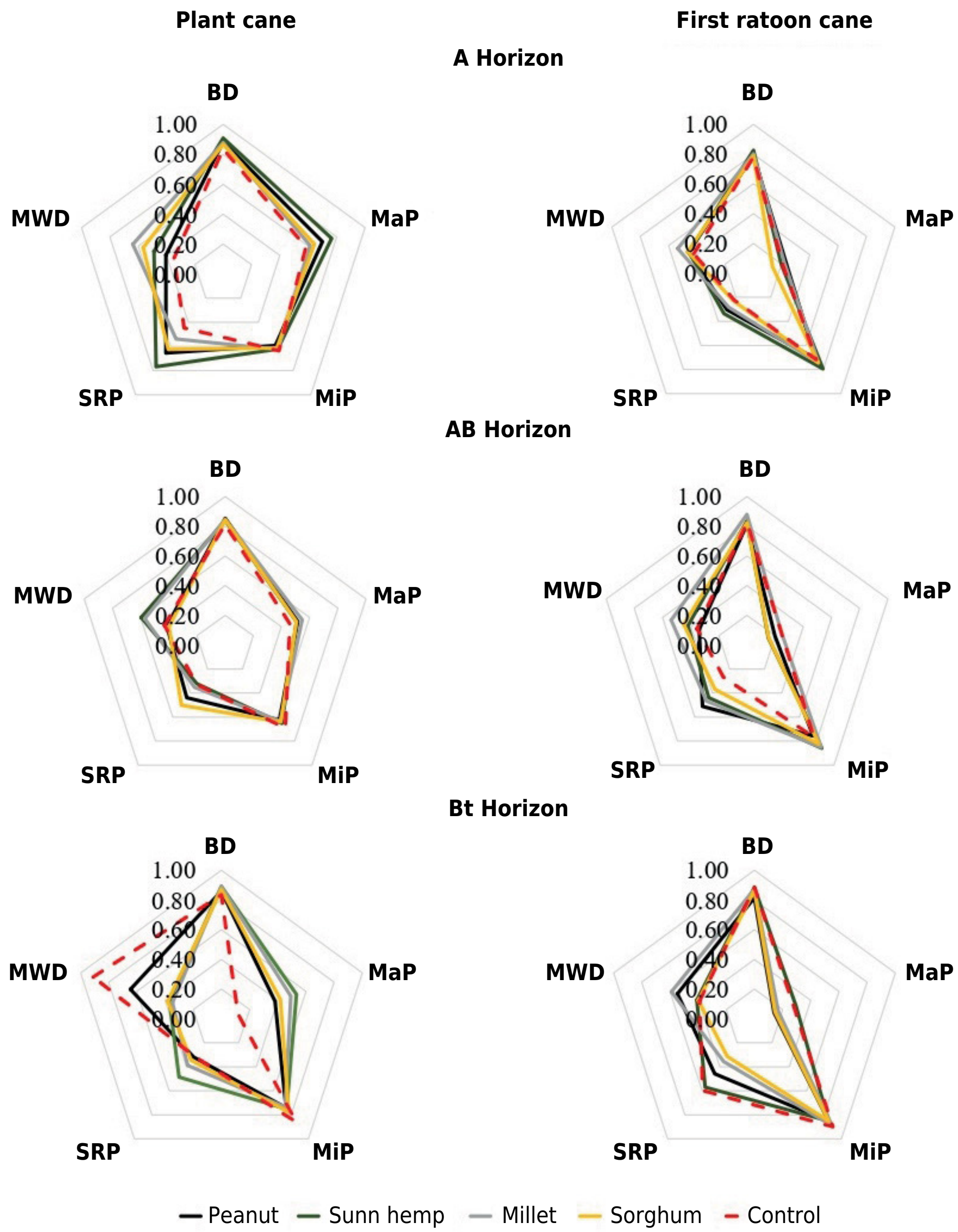


**Figure 6.** Contribution of each physical quality indicator to the different cover crops used before sugarcane planting. Control: sugarcane grown without the introduction of cover crops and with conventional tillage. BD: bulk density; MaP: macroporosity; MiP: microporosity; SRP: soil resistance to penetration; MWD: mean weight-diameter.

control. Similar results were reported by Oliveira et al. (2019), who found that the use of millet and sunn hemp before sugarcane cultivation improved the soil structural quality. Although millet is also considered a cover crop capable of breaking up compacted layers, it differs from sunn hemp in that it has a vigorous and abundant root system (Scaléa, 1998). This suggests that these characteristics contributed to this cover plant to stand out in relation to the others in terms of soil aggregation. In agreement, the effect of the organic substances provided by the roots (e.g., root residues and exudates) acting in the stabilization of soil aggregates is reported by Six et al. (2004).

Peanut as cover crop increased soil compaction, mainly when peanut cultivation is associated with NT and MT/DS (i.e., increased BD and DC, and reduced MaP). The peanut harvest process involves high soil disturbance as a result of the belowground growth of

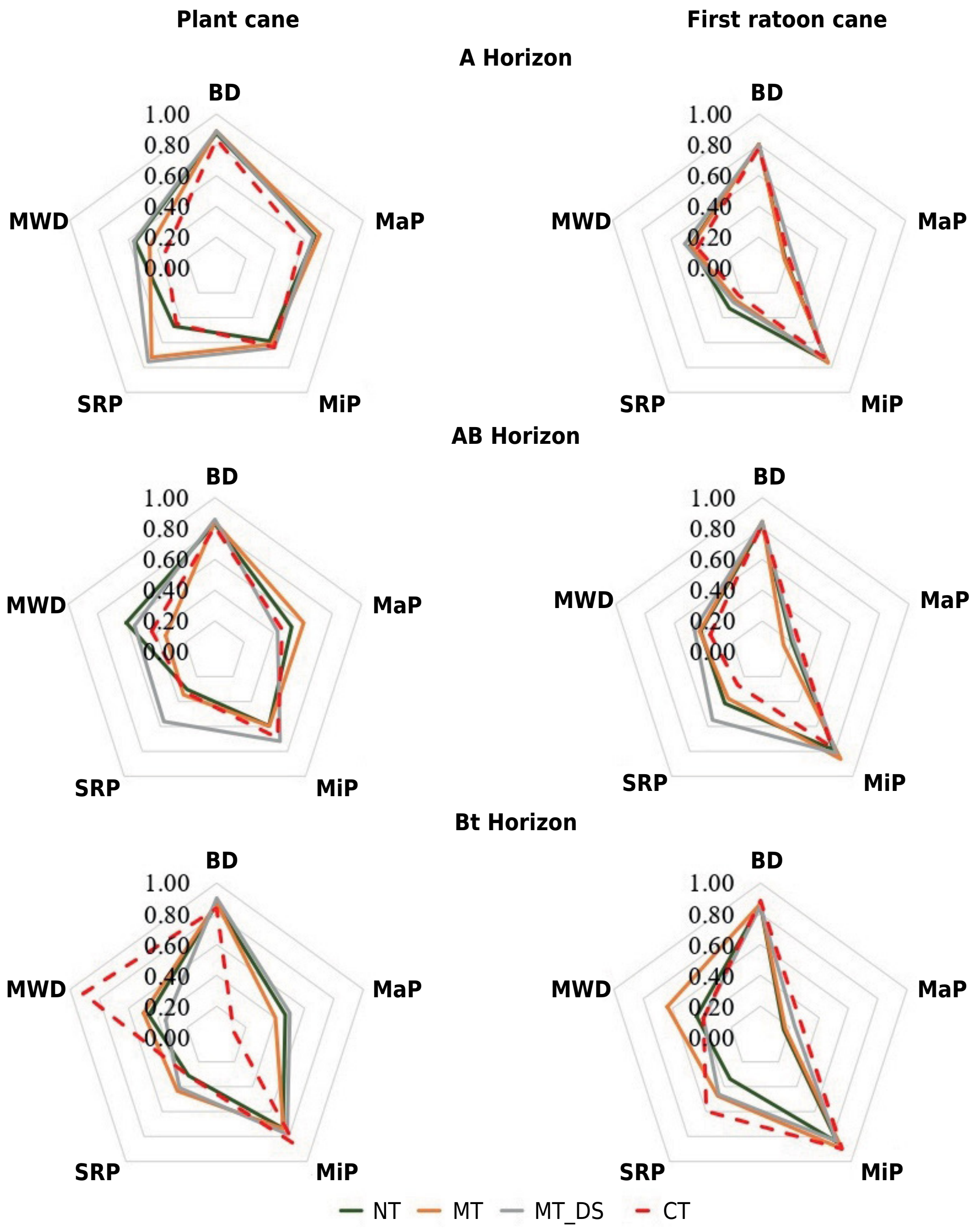


**Figure 7.** Contribution of each physical quality indicator to the different tillage systems used before sugarcane planting. NT: no-tillage; MT: minimum tillage; MT/DS: minimum tillage with deep subsoiling; Control: sugarcane grown without introduction of cover crops and with conventional tillage. BD: bulk density; MaP: macroporosity; MiP: microporosity; SRP: soil resistance to penetration; MWD: mean weight-diameter.

pods. In medium- and large-scale crops, harvesting is mechanized and uses a piece of equipment (e.g., plant lifter) that penetrates the soil to a depth of approximately 0.05 m below the pods. Then, peanut plants are carried to the top of the running machine and fall on a device that groups them on the soil surface. After drying the pods in the field, another stage of the harvest takes place, which consists of gathering and Shaking the plants with a piece of equipment named picker-beater, which separates the pods of the plant (Santos et al., 2009). According to Guimarães Júnnyor et al. (2019), high risks of severe soil compaction were found for the peanut harvesting, due to the peanut harvester promoting the grubbing of the plants, and thus intensively disaggregates the soil surface, the traffic of this machine caused subsoil compaction until 0.30 m depth. Soil compaction induced by peanut harvester is associated with the high load carried by the wheels of its single axle, which applies compressive stress that exceeds soil bearing

**Table 6.** Stalk yield of sugarcane (Mg ha$^{-1}$) in an area of sugarcane expansion using different cover crops and soil tillage systems

| Cover crops | Soil tillage systems | Plant cane | | First ratoon cane | |
|---|---|---|---|---|---|
| | | Stalk yield | Net gain/loss | Stalk yield | Net gain/loss |
| | | Mg ha$^{-1}$ | | Mg ha$^{-1}$ | |
| Peanut | NT | 106 ± 15.81 | -1 | 102 ± 11.24 | 2 |
| | MT | 110 ± 22.23 | -6 | 99 ± 15.32 | 6 |
| | MT/DS | 104 ± 9.98 | 1 | 102 ± 13.31 | 3 |
| Sunn hemp | NT | 117 ± 22.39 | -12 | 104 ± 1.70 | 1 |
| | MT | 102 ± 5.16 | 2 | 99 ± 4.69 | 5 |
| | MT/DS | 116 ± 2.44 | -11 | 114 ± 12.12 | -9 |
| Millet | NT | 113 ± 4.31 | -8 | 106 ± 2.47 | -1 |
| | MT | 100 ± 8.81 | 5 | 99 ± 5.30 | 6 |
| | MT/DS | 110 ± 19.42 | -6 | 103 ± 11.58 | 2 |
| Sorghum | NT | 101 ± 7.47 | 4 | 97 ± 15.76 | 8 |
| | MT | 109 ± 4.73 | -4 | 108 ± 11.89 | -3 |
| | MT/DS | 119 ± 18.53 | -15 | 108 ± 7.42 | -3 |
| Control | CT | 105 ± 1.83 | - | 104 ± 2.39 | - |

NT: no-tillage; MT: minimum tillage; MT/DS: minimum tillage with deep subsoiling; Control CT: sugarcane grown without the introduction of cover crops and with conventional tillage. Mean values are the average of three replicates. Mean ± standard error.

capacity causing compaction in the soil profile. Because of soil degradation induced by peanuts as a cover crop, there is a reduction in soil water contents and the least limiting water range (LLWR) (Oliveira et al., 2019). In this case, some combinations between cover crops and tillage systems are not relevant since they are not aligned with the soil conservation principles.

Despite the different management systems induce changes in the soil physical properties in our study, these modifications were not enough to generate significant differences in the stalk yield of sugarcane. Similar results were recently reported by Awe et al. (2020) in southern Brazil. Despite that, the authors recommended tillage systems that promote higher soil quality for sugarcane production. Likely, soil health promotion by conservation tillage can bring benefits to crop yield on a long-term basis, as reported by Ambrosano et al. (2011). These authors showed that sunn hemp cultivation as a cover crop before sugarcane planting did not affect sugarcane yield in the short-term, but there was an increase of 30 % on average of five harvestings compared to the control, without cover crops. In addition, sunn hemp provided the best cost-benefit ratio to be used in the sugarcane renovation, standing out regarding the production of dry mass and accumulating nutrients, especially nitrogen.

Cultivation of sorghum and sunn hemp, both with MT/DS, presented an expressive net gain in the stalk yield of sugarcane compared to the control treatment. Blanco-Canqui et al. (2012) reported that under favorable climatic conditions, cover crops with high biomass production and nitrogen fixation could provide faster and greater effects on productivity and soil properties than cover crops with low biomass production. Higher sugarcane yield induced by sorghum cultivation under MT/DS in the plant cane cycle can be attributed to factors such as high dry mass production and high sorghum potential for nutrient cyclings, such as nitrogen, phosphorus, potassium, calcium and magnesium. However, it should be noted that after the mechanized harvesting of sugarcane, there was a reduction in the soil physical quality in plots previously cropped with sorghum, leading to a significant reduction in stalk yield of the first sugarcane ratoon cycle. This result is in line with Guimarães Júnnyor et al. (2019) and Oliveira et al. (2019), who found that the cultivation systems as sorghum with deep subsoiling present high risks of severe degradation to the soil structure from harvesting of the sugarcane.

Use of cover crops in sugarcane areas, however, has some specific characteristics. Since sugarcane is a semi-perennial crop, its cultivation occurs for five to six cycles in the area. After that period, the sugarcane fields are ‘reformed’ or replanted (Lisboa et al., 2011). Therefore, the cover crops are grown in the area only every 5-6 years, for approximately three months. Therefore, it is fundamental to associate some conservation tillage strategy to prolong the persistence of benefits induced by cover crop cultivation on soil health. Nevertheless, although the no-tillage system is a consolidated and widely accepted practice among Brazilian farmers, it is still little used in sugarcane cultivation (Cury et al., 2014; Barbosa et al., 2019). The main barriers for no-tillage adoption in the sugarcane sector are associated with soil compaction induced by planting operation (Arruda et al., 2016; Bordonal et al., 2018) and the large size of the planting furrow, which disturbs about 30 % of the soil surface (0.00-0.30 m) (Tenelli et al., 2019), which makes it challenging to adopt no-tillage in its totality (Bordonal et al., 2018).

Some agricultural practices have shown promise to overcome the obstacles of using the no-tillage in sugarcane areas. For instance, Esteban et al. (2019) results indicated that controlled traffic with double-row spacing improvements soil physical properties due to induce smaller traffic area and, consequently, smaller compacted area. Another important practice is related to the use of no-tillage of pre-sprouted seedlings, once the seedling transplant occurs in planting furrows smaller than the conventional, guaranteeing the principle of minimal soil disturbance. Santos Júnior et al. (2015) point out that the no-tillage can be perform in two sequential phases. In the first phase, the soil compaction and acidity are corrected in-depth and only in the second phase, the principle of minimum soil disturbance finally is reached. However, although there are good expectations about using controlled traffic, spacing row combined or alternating and pre-sprouted seedlings to perform the no-tillage in sugarcane areas, there is still no pre-established standard to guide the producers. Soon, more scientific studies are needed, especially for the long term, to understand and establish this dynamic.

Deep subsoiling reduced soil SRP and increased MaP in relation to other tillage systems, evidencing to be one more option of conservation management for sugarcane management. These results agree with Oliveira et al. (2019), who observed beneficial effects on soil quality with the use of minimum tillage (MT and MT/DS), in which occurred highest LLWR in both cane plant and first ratoon for these treatments. However, Santos Júnior et al. (2015) argue that the costs of subsoiling as single operation (minimum tillage) must be evaluated carefully because in this case, there is no economy in machinery and fuel as in no-tillage and the subsoiling tends to be a high-cost practice. This way, we also emphasize the need for future long-term studies to confirm the efficiency of deep subsoiling and the respective costs involved in this management system.

Conventional tillage reduced the physical quality across all soil horizons, except for the Bt horizon during the plant cane cycle, which presented higher values of MiP and MWD. However, this result may be related to the formation of “plow pans” immediately below the plow layers typically reported in the subsoil of an area with conventional tillage (Cavalcanti et al., 2019). In a study performed by Guimarães Júnnyor et al. (2019) on the prediction of soil stresses and compaction in sugarcane cultivation systems with and without cover crops, the authors observed that only the treatment with conventional tillage did not present compaction risk during mechanized sugarcane harvesting, due to the high initial compaction.

### Effect of sugarcane harvesting

During the renovation of the sugarcane field, biological and mechanical management practices have been used to minimize problems related to soil compaction and physical degradation, including the cultivation of cover crops associated or not with plowing/subsoiling operations. However, we observed that independent of the cover crops or soil tillage, the particle rearrangement and soil reconsolidation due to alternate wetting and drying cycles, associated with machinery traffic during the sugarcane harvesting, caused to an increase in BD and DC, and reduction of MaP and MiP, indicating soil compaction. The machine traffic is one of the major causes of soil compaction, in which the stress imposed by the passage of machines causes damage to the soil's pores (Chamen et al., 2015). This damage leads to high SRP, BD, volumetric contents of water and field capacity, as well as reduction of total porosity, soil aeration, water infiltration rate, and saturated hydraulic conductivity (Nawaz et al., 2013), which can reduce the penetration of roots into the soil and crop yield (Whiteand Johnson, 2018; Esteban et al., 2019).

Our measurements showed a reduction in MaP of about 69, 58 and 50 % for A, AB and Bt horizons, respectively, after the machine traffic and harvest operations. Similar results were observed by Barbosa et al. (2019) between the cycle of plant cane and 3rd ratoon, in which the magnitude of changes in pores volume were on the order of 82 and 89 % to conventional tillage and no-tillage, respectively. Results obtained by Esteban et al. (2019) also indicate reduced MaP below the minimum level suitable to soil aeration after machine traffic in an area of sugarcane without controlled traffic.

Soil bulk density was close to 1.64 kg $dm^{-3}$ to plant cane and 1.71 kg $dm^{-3}$ to first ratoon cane, suggesting soil compaction between the production cycles. This effect is also evidenced by the DC property, in first ratoon cane all treatments presented soil compaction, except for sunn hemp with NT. This result agreed with that from Cherubin et al. (2016), who verified that sugarcane fields in central-southern Brazil presented critical soil compaction that consequently contributed to decreasing of soil pore space and soil aeration. Vischi Filho et al. (2015) also observed compaction due to the cumulative effect of machine traffic on the soil over the sugarcane cultivation cycles.

Due to soil tillage and harvesting operations, problems related to soil disaggregation and compaction are usually inherent to sugarcane plantations (Filoso et al., 2015; Bordonal et al., 2018). Vischi Filho et al. (2015), Silva et al. (2016) and Guimarães Júnnyor et al. (2019) point out that the traffic-loaded trailers during sugarcane harvesting induce a high risk of soil compaction. However, this is not the only cause of soil compaction in areas of sugarcane. Operations performed before the sugarcane harvesting, such as harvesting the peanut (cash crop) and planting the sugarcane seedlings, significantly increase the risk of causing severe soil compaction (Guimarães Júnnyor et al., 2019). Although there is a continuous increase in organic carbon in the topsoil with the number of ratoon sugarcane harvests, resulting in better soil physical condition in the soil surface, the degree of compaction may increase due to the frequency of traffic caused by the increase in the number of harvests, becoming compaction more severe close to the sugarcane renovation (Cavalcanti et al., 2019).

### Best management practices for sugarcane planting

Although cover crops and less intensive soil tillage systems improve the soil physical quality compared to conventional tillage, these practices are only partially effective. To properly control the soil degradation in a sugarcane area, it is necessary to simultaneously employ other management practices to minimize the soil physical degradation, thus providing a less restrictive environment for the growth of plants. Therefore, to reduce tillage and the number of cover crops, we suggest complementary management practices to maintain and improve the soil's physical functions in sugarcane fields.

Recent studies have shown the relevance of straw for maintaining the soil's physical quality, indicating that the judicious adoption of straw management is necessary, keeping at least 7 Mg $ha^{-1}$ of straw on the soil surface, when the industry has the interest of use part of straw for bioenergy production (Awe et al., 2015a,b; Carvalho et al., 2017; Satiro et al., 2017; Vischi Filho et al., 2017; Castioni et al., 2018; 2019; Silva et al., 2019). Management of machine traffic in sugarcane fields is also relevant. A combined set of strategies reduces trafficked zones in the field or even attenuates machinery traffic effects on the soil physical properties. Integrated management to control soil physical degradation in areas of intense sugarcane production include complementary practices, such as traffic control (Souza et al., 2015; Esteban et al., 2019), traffic in soil drier than friable condition (Klein 2014; Cherubin et al., 2016), distribution and spacing of the crop in the area (Esteban et al., 2019), adjusting the machine loads to the soil load-bearing capacity, and increasing the number of axles of the trailers without increasing the load capacity (Guimarães Júnnyor et al., 2019).

## CONCLUSIONS

Our hypothesis has been partially confirmed since cover crop and conservation tillage were efficient to attenuate soil physical degradation; however, these practices were not enough to increase the stalk yield of sugarcane. Therefore, our result suggests that sugarcane yield is determined by a complex group of properties and not exclusively by soil physical condition.

Although the treatments in our study did not induce substantial differences in the stalk yield of sugarcane, the use of cover crops, such as sunn hemp and millet, associated with subsoiling (at 0.40 or 0.70 m depth) during sugarcane planting, are promising management strategies to sustain better soil's physical quality when compared to traditional management, conventional soil tillage without cover crops and/or cash crop, as peanuts, that increase the risks of soil compaction and physical degradation.

Continuous improvement in soil physical properties, year by year, provided by the use of more sustainable management systems in sugarcane cultivations, can generate benefits in the soil quality. However, subsoiling benefits tend not to be persistent over time. Thus, we encourage long-term studies to assess the permanence of these results.

## ACKNOWLEDGMENTS

The authors thank the Santa Fé Mill for providing the study area and Itallo Dirceu Costa Silva for making the location map of the experimental area. This study was supported by the financial support of the National Council for Scientific and Technological Development (CNPq - Brazil) (grant No. 870371/1997-5), the Fundação Agrisus (grant No. 1439/15 and 2662/19), and the São Paulo Research Foundation (FAPESP) (grant No. 2018/09845-7 and 2018/14958-5).

## AUTHOR CONTRIBUTIONS

**Conceptualization:** Camila Viana Vieira Farhate (equal), Maurício Roberto Cherubin (equal), Newton La Scala Junior (equal), Wellingthon da Silva Guimarães Júnnyor (equal) and Zigomar Menezes de Souza (equal).

**Data curation:** Camila Viana Vieira Farhate (lead).

**Formal analysis:** Camila Viana Vieira Farhate (lead).

**Funding acquisition:** Camila Viana Vieira Farhate (equal) and Zigomar Menezes de Souza (equal).

**Investigation:** Camila Viana Vieira Farhate (equal), Ingrid Nehmi de Oliveira (equal), Lenon Henrique Lovera (equal) and Wellingthon da Silva Guimarães Júnnyor (equal).

**Methodology:** Camila Viana Vieira Farhate (equal), Ingrid Nehmi de Oliveira (equal), Lenon Henrique Lovera (equal), Maurício Roberto Cherubin (equal) and Zigomar Menezes de Souza (equal).

**Project administration:** Camila Viana Vieira Farhate (equal), Ingrid Nehmi de Oliveira (equal), Lenon Henrique Lovera (equal) and Wellingthon da Silva Guimarães Júnnyor (equal).

**Supervision:** Newton La Scala Junior (equal) and Zigomar Menezes de Souza (equal).

**Validation:** Newton La Scala Junior (lead).

**Visualization:** Newton La Scala Junior (lead).

**Writing – review & editing:** Camila Viana Vieira Farhate (equal), Maurício Roberto Cherubin (equal), Newton La Scala Junior (equal) and Zigomar Menezes de Souza (equal).

## REFERENCES

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G. Köppen's climate classification map for Brazil. Meteorol Z. 2013;22:711-28. https://doi.org/10.1127/0941-2948/2013/0507

Alvarez R, Steinbach HS, Paepe JL. Cover crop effects on soils and subsequent crops in the pampas: A meta-analysis. Soil Till Res. 2017;170:53-65. https://doi.org/10.1016/j.still.2017.03.005

Ambrosano EJ, Cantarella H, Ambrosano GMB, Schammas EA, Dias FLF, Rossi F, Trivelin PCO, Muraoka T, Sachs RCC, Azcón R. Produtividade da cana-de-açúcar após o cultivo de leguminosas. Bragantia. 2011;70:810-8. https://doi.org/10.1590/S0006-87052011000400012

Andrews SS, Karlen DL, Mitchell JP. A comparison of soil quality indexing methods for vegetable production systems in Northern California. Agr Ecosyst Environ. 2002;90:25-45. https://doi.org/10.1016/S0167-8809(01)00174-8

Arruda EM, Almeida RF, Domingues LAS, Silva Junior AC, Moraes ER, Barros LR, Sousa JLO, Lana RMQ. Soil porosity and density in sugarcane cultivation under different tillage systems. Afr J Agric Res. 2016;11:2689-96. https://doi.org/10.5897/AJAR2015.10608

Awe GO, Reichert JM, Fontanela E. Sugarcane production in the subtropics: Seasonal changes in soil properties and crop yield in no-tillage, inverting and minimum tillage. Soil Till Res. 2020;196:104447. https://doi.org/10.1016/j.still.2019.104447

Awe GO, Reichert JM, Timm LC, Wendroth OO. Temporal processes of soil water status in a sugarcane field under residue management. Plant Soil. 2015a;387:395–411. https://doi.org/10.1007/s11104-014-2304-5

Awe GO, Reichert JM, Wendroth OO. Temporal variability and covariance structures of soil temperature in a sugarcane field under different management practices in southern Brazil. Soil Till Res. 2015b;150:93–106. https://doi.org/10.1016/j.still.2015.01.013

Barbosa LC, Magalhães PSG, Bordonal RO, Cherubin MR, Castioni GAF, Tenelli S, Franco HCJ, Carvalho JLN. Soil physical quality associated with tillage practices during sugarcane planting in south-central Brazil. Soil Till Res. 2019;195:104383. https://doi.org/10.1016/j.still.2019.104383

Blanco-Canqui H, Claassen MM, Presley DR. Summer cover crops fix nitrogen, increase crop yield, and improve soil-crop relationships. Agron J. 2012;104:137-47. https://doi.org/10.2134/agronj2011.0240

Blanco-Canqui H, Ruis SJ. No-tillage and soil physical environment. Geoderma. 2018;326:164-200. https://doi.org/10.1016/j.geoderma.2018.03.011

Blanco-Canqui H, Shaver TM, Lindquist JL, Shapiro CA, Elmore RW. Cover crops and ecosystem services: Insights from studies in temperate soils. Agron J. 2015;107:2449-74. https://doi.org/10.2134/agronj15.0086

Bordonal RO, Carvalho JLN, Lal R, Figueiredo EB, Oliveira BG, La Scala Júnior N. Sustainability of sugarcane production in Brazil. A review. Agron Sustain Dev. 2018;38:13. https://doi.org/10.1007/s13593-018-0490-x

Bordonal RO, Lal R, Ronquim CC, Figueiredo EBF, Carvalho JLN, Maldonado Júnior W, Milori DMBP, La Scala Júnior N. Changes in quantity and quality of soil carbon due to the land-use conversion to sugarcane (Saccharum officinarum) plantation in southern Brazil. Agr Ecosyst Environ. 2017;240:54-65. https://doi.org/10.1016/j.agee.2017.02.016

Calonego JC, Raphael JPA, Rigon JPG, Oliveira Neto L, Rosolem CA. Soil compaction management and soybean yields with cover crops under no-till and occasional chiseling. Eur J Agron. 2017;85:31-7. https://doi.org/10.1016/j.eja.2017.02.001

Camargo OA, Moniz AC, Jorge JA, Valadares JMAS. Métodos de análise química, mineralógica e física de solos do Instituto Agronômico de Campinas. Rev Atual. Campinas: Instituto Agronômico; 2009. (Boletim técnico, 106).

Carvalho JLN, Hudiburg TW, Franco HCJ, Lucia EH. Contribution of above and belowground bioenergy crop residues to soil carbon. Glob Change Biol. 2017;9:1333-43. https://doi.org/10.1111/gcbb.12411

Castioni GA, Cherubin MR, Menandro LMS, Sanches GM, Bordonal RO, Barbosa LC, Franco HCJ, Carvalho JLN. Soil physical quality response to sugarcane straw removal in Brazil: A multi-approach assessment. Soil Till Res. 2018;184:301-9. https://doi.org/10.1016/j.still.2018.08.007

Castioni GAF, Cherubin MR, Bordonal RO, Barbosa LC, Menandro LMS, Carvalho JLN. Straw removal affects soil physical quality and sugarcane yield in Brazil. BioEnerg Res. 2019;12:789-800. https://doi.org/10.1007/s12155-019-10000-1

Cavalcanti RQ, Rolim MM, Lima RR, Tavares UE, Pedrosa EMR, Gomes IF. Soil physical and mechanical attributes in response to successive harvests under sugarcane cultivation in Northeastern Brazil. Soil Till Res. 2019;189:140-7. https://doi.org/10.1016/j.still.2019.01.006

Centro de Pesquisas Meteorológicas e Climáticas aplicadas a Agricultura – Cepagri. Clima dos Municípios Paulistas. Campinas: Cepagri; 2018 [cited 2018 May 17]. Available from: http://www.cpa.unicamp.br/outras-informacoes/clima_muni_374.html.

Chamen WCT, Moxey AP, Torres W, Balana B, Hallett PD. Mitigating arable soil compaction: A review and analysis of available cost and benefit data. Soil Till Res. 2015;146:10-25. https://doi.org/10.1016/j.still.2014.09.011

Cherubin MR, Karlen DL, Franco ALC, Tormena CAT, Cerri CEP, Davies CA, Cerri CE. Soil physical quality response to sugarcane expansion in Brazil. Geoderma. 2016;267:156-68. https://doi.org/10.1016/j.geoderma.2016.01.004

Companhia Nacional de Abastecimento - Conab. Acompanhamento da Safra Brasileira: de cana-de-açúcar - Safra 2019/20. Brasília, DF: Conab; 2019a.

Companhia Nacional de Abastecimento - Conab. Série histórica das safras [cited 2019b Nov 13]. Brasília: Conab; 2019b. Available from: https://www.conab.gov.br/info-agro/safras/serie-historica-das-safras.

Cury TN, De Maria IC, Bolonhezi D. Biomassa radicular da cultura de cana-de-açúcar em sistema convencional e plantio direto com e sem calcário. Rev Bras Cienc Solo. 2014;38:1929-38. https://doi.org/10.1590/S0100-06832014000600027

Dane JH, Hopmans JW. Water retention and storage. In: Dane JH, Topp GC, editors. Methods of soil analysis: Part 4 - Physical methods. Madison: Soil Science Society of America; 2002. p. 721-38.

Dexter AR. Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma. 2004;120:201-14. https://doi.org/10.1016/j.geoderma.2003.09.004

Dias LCP, Pimenta FM, Santos AB, Costa MH, Ladle RJ. Patterns of land use, extensification, and intensification of Brazilian agriculture. Glob Change Biol. 2016;22:2887-903. https://doi.org/10.1111/gcb.13314

Esteban DA, Souza ZM, Tormena CA, Lovera LH, Lima ES, Oliveira IN, Ribeiro NP. Soil compaction, root system and productivity of sugarcane under different row spacing and controlled traffic at harvest. Soil Till Res. 2019;187:60-71. https://doi.org/10.1016/j.still.2018.11.015

Farhate CVV, Souza ZM, Cherubin MR, Lovera LH, Oliveira IN, Carneiro MP, La Scala Junior N. Abiotic soil health indicators that respond to sustainable management practices in sugarcane cultivation. Sustainability. 2020;12:9407. https://doi.org/10.3390/su12229407

Farhate CVV, Souza ZM, La Scala Júnior N, Sousa ACM, Santos APG, Carvalho JLN. Soil tillage and cover crop on soil $CO_2$ emissions from sugarcane fields. Soil Use Manag. 2019;35:273-82. https://doi.org/10.1111/sum.12479

Filoso S, Carmo JB, Mardegan SF, Lins SRM, Gomes TF, Martinelli AA. Reassessing the environmental impacts of sugarcane ethanol production in Brazil to help meet sustainability goals. Renew Sust Energ Rev. 2015;52:1847-56. https://doi.org/10.1016/j.rser.2015.08.012

Foloni JSS, Lima SL, Büll LT. Crescimento aéreo e radicular da soja e de plantas de cobertura em camadas compactadas de solo. Rev Bras Cienc Solo. 2006;30:49-57. https://doi.org/10.1590/S0100-06832006000100006

Food and Agriculture Organization - FAO. Corporate statistical database. Rome: Food and Agriculture Organization of the United Nations; 2019 [cited 2019 Nov 13]. Available from: http://www.fao.org/faostat/en/#data.

Guimarães Júnnyor WS, Diserens E, De Maria IC, Araujo-Junior CF, Farhate CVV, Souza ZMS. Prediction of soil stresses and compaction due to agricultural machines in sugarcane cultivation systems with and without crop rotation. Sci Total Environ. 2019;681:424-34. https://doi.org/10.1016/j.scitotenv.2019.05.009

Hoorman JJ, Sá JCM, Reeder R. The biology of soil compaction. Science. 2011;68:49-57.

Kemper WD, Chepil WS. Size distribution of aggregates. In: Black CA, editor. Methods of soil analysis: Part 1 - Physical and mineralogical properties. Madison: American Society Agronomy; 1965. p. 499-510.

Klein VA. Física do solo. 3. ed. Pelotas: Editora da Universidade Federal de Pelotas; 2014.

Lepsch IF, Espindola CR, Vischi Filho OJ, Hernani LC, Siqueira DS. Manual para levantamento utilitário e classificação de terras no sistema de capacidade de uso. Viçosa, MG: Sociedade Brasileira de Ciência do Solo; 2015.

Lisboa CC, Butterbach-Bahl K, Mauder M, Kiese R. Bioethanol production from sugarcane and emissions of greenhouse gases - known and unknowns. Glob Change Biol. 2011;3:277-92. https://doi.org/10.1111/j.1757-1707.2011.01095.x

Malavolta E, Vitti GC, Oliveira SA. Avaliação do estado nutricional das plantas: princípios e aplicações. 2. ed. Piracicaba: Potafos; 1997.

Marcolin CD, Klein V. Determinação da densidade relativa do solo por uma função de pedotransferência para a densidade do solo máxima. Acta Sci. 2011;33:349-54. https://doi.org/10.4025/actasciagron.v33i2.6120

Nascente AS, Li Y, Crusciol CAC. Soil aggregation, organic carbon concentration, and soil bulk density as affected by cover crop species in a no-tillage system. Rev Bras Cienc Solo. 2015;39:871-9. https://doi.org/10.1590/01000683rbcs20140388

Nawaz MF, Bourrié G, Trolard F. Soil compaction impact and modelling. A review. Agron Sustain Dev. 2013;33:291-309. https://doi.org/10.1007/s13593-011-0071-8

Nelson DW, Sommers LE. Total carbon, organic carbon, and organic matter. In: Black CA, editors. Methods of soil analysis: Part 1 - Physical and mineralogical properties. Madison: American Society Agronomy; 1965. p. 961-1010.

Oliveira IN, Souza ZM, Lovera LH, Farhate CVV, Lima ES, Esteban DAA, Fracarolli JA. Least limiting water range as influenced by tillage and cover crop. Agric Water Manag. 2019;225:105777. https://doi.org/10.1016/j.agwat.2019.105777

Palm C, Blanco-Canqui H, Clerck F, Gatere L, Grace P. Conservation agriculture and ecosystem services: An overview. Agr Ecosyst Environ. 2014;187:87-105. https://doi.org/10.1016/j.agee.2013.10.010

Poeplau C, Kätterer T, Bolinder MA, Börjesson G, Berti A, Lugato E. Low stabilization of aboveground crop residue carbon in sandy soils of Swedish long-term experiments. Geoderma. 2015;237-238:246-55. https://doi.org/10.1016/j.geoderma.2014.09.010

Rabot E, Wiesmeier M, SchlüteraH S, Vogel J. Soil structure as an indicator of soil functions: A review. Geoderma. 2018;314:122-37. https://doi.org/10.1016/j.geoderma.2017.11.009

Reeves DW. Cover crops and rotations. In: Hatfield JL, editor. Crops residue management. Boca Raton: CRC Press; 2018. p. 125-72.

Reynolds WD, Drury CF, Tan CS, Fox CA, Yang XM. Use of indicators and pore volume-function characteristics to quantify soil physical quality. Geoderma. 2009;152:252-63. https://doi.org/10.1016/j.geoderma.2009.06.009

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbreras JF, Coelho MR, Almeida JA, Araújo Filho JC, Oliveira JB, Cunha TJF. Sistema brasileiro de classificação de solos. 5. ed. rev. ampl. Brasília, DF: Embrapa; 2018.

Santos Júnior JDG, Sá MAC, Oliveira CM, Franz CAB, Rein TA, Souza DMG. Sistema de plantio direto de cana-de-açúcar no Cerrado. Planaltina: Embrapa; 2015. (Circular técnica, 30).

Santos RC, Freire RMM, Moraes T, Suassuna F. Amendoim: O produtor pergunta, a Embrapa responde. Brasília, DF: Embrapa Informação Tecnológica; 2009.

Satiro LS, Cherubin MR, Safanelli JL, Lisboa IP, Rocha Júnior PR, Cerri CEP, Cerri CC. Sugarcane straw removal effects on Ultisols and Oxisols in south-central Brazil. Geoderma Reg. 2017;11:86-95. https://doi.org/10.1016/j.geodrs.2017.10.005

Scaléa MJ. Perguntas & Respostas sobre o plantio direto. Piracicaba: Informações Agronômicas; 1998.

Scarpare FV, Van Lier QJ, Camargo L, Pires RCM, Ruiz-Corrêa ST, Bezerra AHF, Gava GJC, Dias CTS. Tillage effects on soil physical condition and root growth associated with sugarcane water availability. Soil Till Res. 2019;187:110-8. https://doi.org/10.1016/j.still.2018.12.005

Silva AGB, Lisboa IP, Cherubin MR, Cerri CEP. How much sugarcane straw is needed for covering the soil? BioEnerg Res. 2019;12:858-64. https://doi.org/10.1007/s12155-019-10008-7

Silva RBD, Iori P, Souza ZMD, Pereira DDMG, Vischi Filho OJ, Silva FADM. Contact pressures and the impact of farm equipment on Latosol with the presence and absence of sugarcane straw. Cienc Agrotec. 2016;40:265-78. https://doi.org/10.1590/1413-70542016403001716

Silva-Olaya AM, Cerri CEP, La Scala Júnior N, Dias CTS, Cerri CC. Carbon dioxide emissions under different soil tillage systems in mechanically harvested sugar cane. Environ Res Lett. 2013;8:015014. https://doi.org/10.1088/1748-9326/8/1/015014

Six J, Bossuyt H, Degryze S, Denef K. A history of research on the link between micro aggregates, soil biota and soil organic matter dynamics. Soil Till Res. 2004;79:7-31. https://doi.org/10.1016/j.still.2004.03.008

Soil Survey Staff. Keys to soil taxonomy. 12th ed. Washington, DC: United States Department of Agriculture, Natural Resources Conservation Service; 2014.

Souza GS, Souza ZM, Cooper M, Tormena CA. Controlled traffic and soil physical quality of an Oxisol under sugarcane cultivation. Sci Agric. 2015;72:270-7. https://doi.org/10.1590/0103-9016-2014-0078

Teixeira LG, Fukuda A, Panosso AR, Lopes A, La Scala Júnior N. Soil $CO_2$ emission as related to incorporation of sugarcane crop residues and aggregate breaking after rotary tiller. Sci Agric. 2011;31:1075-84. https://doi.org/10.1590/S0100-69162011000600005

Teixeira PC, Donagemma GK, Fontana A, Teixeira WG. Manual de métodos de análise de solo. 3. ed. rev e ampl. Brasília, DF: Embrapa; 2017.

Tenelli S, Bordonal RO, Barbosa LC, Carvalho JLN. Can reduced tillage sustain sugarcane yield and soil carbon if straw is removed? BioEnerg Res. 2019;12:764-77. https://doi.org/10.1007/s12155-019-09996-3

Tormena CA, Silva AP, Libardi PL. Soil physical quality of a Brazilian Oxisol under two tillage systems using the least limiting water range approach. Soil Till Res. 1999;52:223-32. https://doi.org/10.1016/S0167-1987(99)00086-0

Vischi Filho OJ, Souza ZM, Silva RB, Lima CC, Pereira DMG, Lima ME, Sousa ACM, Souza GS. Capacidade de suporte de carga de Latossolo Vermelho cultivado com cana-de-açúcar e efeitos da mecanização no solo. Pesq Agropec Bras. 2015;50:322-32. https://doi.org/10.1590/S0100-204X2015000400008

Vischi Filho OJ, Souza ZM, Souza GS, Silva RB, Torres JLR, Lima ME, Tavares RLM. Physical attributes and limiting water range as soil quality indicators after mechanical harvesting of sugarcane. Aust J Crop Sci. 2017;11:169-76. https://doi.org/10.21475/ajcs.17.11.02.p215

Weiler DA, Moro VJ, Awe GO, Oliveira DMS, Cerri CEP, Reichert JM, Giacomini SJ. Carbon balance in sugarcane areas under different tillage systems. BioEnerg Res. 2019;12:778-88. https://doi.org/10.1007%2Fs12155-019-10002-z

White P, Johnson R. Improving soil management in sugarcane cultivation. In: Rott P, editors. Achieving sustainable cultivation of sugarcane. London: Burleigh Dodds Science Publishing; 2018. p. 97-109.