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Soil physical attributes and sugarcane biomass production under soil management and straw removal

Atributos físicos do solo e produção de biomassa sob manejo do solo e remoção da palha na cana-de-açúcar

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PhD thesis presented to the School of Agricultural Engineering of the University of Campinas as part of the requirements to obtain the title of Ph.D. in Agricultural Engineering in the area of Agricultural Machinery.

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Resumo

O setor da cana-de-açúcar está constantemente em busca de manejo agrícola, economicamente viável, que contribuam para a sustentabilidade da produção do sistema canavieiro. A aplicação de diferentes práticas de manejo tem a capacidade de alterar as propriedades físicas do solo e, consequentemente, o desenvolvimento do sistema radicular e a produtividade da cana-de-açúcar. Dessa forma, o objetivo deste estudo foi avaliar ao longo prazo as alterações impostas pelo preparo do solo, o controle tráfego e a remoção de palha nas propriedades físicas do solo, e a produção de biomassa de cana-de-açúcar. Para um melhor entendimento das alterações impostas pelos diferentes manejos, o trabalho foi dividido em três objetivos específicos: i) Avaliar as mudanças físicas do solo no plantio convencional (PC) e no plantio direto (PD) por quatro anos; ii) Avaliar os efeitos do plantio direto (PDT) e com e sem tráfego de máquinas (PDST) nas propriedades físicas do solo e desenvolvimento radicular da cana-de-açúcar; e iii) Avaliar o efeito de remoção da palha (sem remoção-SR; moderada remoção -MR e remoção total-TR) nas propriedades físicas do solo e sistema radicular da cana-de-açúcar. Assim, foram realizados dois experimentos em campos de cana-de-açúcar nos municípios de Quirinópolis-GO (solo argiloso) e Quatá-SP (solo franco-arenoso). As amostras de solo indeformadas foram coletadas durante quatro safras (2014 até 2017) nas posições da linha e entrelinha em três profundidades (0-0,10, 0,10-0,20, 0,20-0,40 m) para determinar a densidade solo (DS), resistência do solo à penetração (RP), macroporosidade do solo (MaP) e microporosidade (MiP). A biomassa de colmos e raízes de cana-de-açúcar foram avaliadas durante a colheita de cada ciclo de cultivo. Os resultados mostraram que o PD pode ser utilizado como estratégia de manejo do solo, uma vez que o manejo do CT aliviou a compactação do solo apenas no ciclo da cana-planta e após o preparo do solo apresentou a mesma qualidade física do solo ao longo do tempo. O sulco de plantio em ambos os sistemas foi suficiente para promover as condições físicas do solo necessárias para o desenvolvimento da planta. Na entrelinha da cultura ocorreu a alteração dos atributos físicos do solo, ocasionando a compactação do solo pelo efeito sucessivo do tráfego de máquinas. Por outro lado, avaliando PDST ao longo do tempo observou-se que, principalmente na entrelinha, ocorre a preservação da estrutura do solo e, consequentemente, reduzindo a área compactada. Este efeito promoveu o aumento da produção de raízes, influenciando o crescimento no sentido da entrelinha, permitindo maior exploração do perfil do solo e recursos disponíveis. Desse modo, promover a redução tráfego em uma área maior a adoção da PD na cana-de-açúcar. Outro destaque desta pesquisa foi que a remoção da palha promoveu diferentes efeitos em relação ao tipo de solo. A TR nos dois locais reduziu a qualidade física do solo, afetando negativamente o crescimento radicular e, consequentemente, diminuindo a produtividade da cana-de-açúcar. No entanto, em solos argilosos, a RM e NR apresentaram o mesmo comportamento na estrutura do solo e na produção de biomassa, mostrando que no curto prazo é possível promover a MR para cogeração de energia. Em solos arenosos, deve-se adotar a NR para preservar a qualidade física do solo e promover melhores condições para o desenvolvimento radicular e obter um aumento no rendimento das culturas.

Palavras-chave: Preparo convencional, plantio direto, redução do tráfego, atributos do solo, *Saccharum spp*, raízes, resíduo da cana-de-açúcar.

Abstract

The sugarcane industry is constantly in search to better crop and soil management practices which contribute to the sustainability of sugarcane system. The application of different management practices provides changes on soil physical properties and hence the root system development and sugarcane yield. Thus, the aim of this study was to assess the changes in long-term imposed by soil tillage system, traffic control and straw removal on soil physical properties and sugarcane biomass production. This study was divided into three specific aims: i) evaluate the soil physical properties changes in conventional tillage (CT) and no-tillage (NT) for four years; ii) evaluate the no-tillage (NTT) and no-tillage without machinery traffic (NTWT) effects on soil physical properties and root growth of sugarcane; and iii) evaluate the straw removal levels effects (no removal-NR; moderate removal-MR and total removal-TR) on the soil structural quality and sugarcane root system. Thereby, two experiments were carried out on sugarcane fields in Quirinopolis-GO (clayey soil) and Quatá-SP (sandy loam soil). Undisturbed soil samples were collected representing the row and inter-row positions at 0-0.10, 0.10-0.20 and 0.20-0.40 m depth over four crop cycles (from 2014 to 2017) to determine of the bulk density (BD), soil resistance to penetration (SRP), macroporosity (MaP) and microporosity (MiP). Sugarcane stalks and roots biomass were evaluated during the harvest of each crop cycle. The results suggest that NT can be used as a soil management practice, once the CT management alleviated soil compaction only in the plant cane cycle and after the soil tillage presented the same soil physical quality over time. The planting furrow in both systems promote the soil physical conditions necessary for plant development. At the inter-row occurred soil physical degradation due to soil compaction. On the other hand, under NTWT was observed mainly in the inter-row, soil structure preservation occurs, improving soil physical quality and reducing the soil compaction. This effect promoted root development the inter-row, allowing greater soil profile exploitation and available resources. Thus, less traffic on the field will enable the NT adoption for sugarcane production. Our results also suggest that straw removal effects on soil physical quality in soil texture dependent. The TR on both sites, promoted a soil physical quality reduction, negatively affecting root growth and reducing the sugarcane yield. However, in clayey soils, MR and NR did not affected soil structure and biomass production, in a such way that MR is a sustainable practice for energy cogeneration. In sandy loam soils, NR to preserve the soil physical quality and promote root development.

Keywords: conventional tillage, no-tillage, traffic control, soil attributes, *Saccharum spp*, roots, sugarcane residues

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1.0 GENERAL INTRODUCTION

The sugarcane crop has high social and economic importance due to the versatility in food production and bioenergy (i.e., ethanol and electricity) (Bordonal et al., 2018; Carvalho et al., 2017). Thus, Brazil plays an important role in the global economy as the world's largest sugarcane producer, with approximately 640 million tons in of 8.73 million hectares and average yield of 73 Mg ha^{-1} (Conab, 2018). Despite this scenario, the demand for crops' products will increase in coming years, driven by national and international carbon emission reduction targets (Castillo et al., 2017) and demand for clean energy (Carvalho et al.,2017).

In this context, Brazil has characteristics that can help meet this demand, as it has adequate expansion areas, a favorable climate, as well as development in agricultural technologies (de Souza et al., 2012), such as new sugarcane varieties, increased harvest mechanization, irrigation systems and better use of by-products of sugarcane production (Santini et al., 2011). Among these factors, agricultural mechanization played an important role, changing the sugarcane system production with the implementation of the green harvest to replace burned sugarcane.

The system adoption has reduced the negative impacts on human and environmental health (Carvalho et al.,2017) and has aroused interest in the crop residues for energy cogeneration. The green harvest consists the sugarcane removal, leaving from 8 to 20 Mg ha^{-1} year^{-1} of straw on the soil surface (Carvalho et al., 2013; Franco et al., 2013; Menandro et al., 2017) producing a soil cover composed of the dry leaves and green leaves (Aquino et al., 2015; Franco et al., 2013). This material deposited on the soil influences the sugarcane biomass production (Aquino et al., 2017; Lisboa et al., 2018) and roots (Aquino et al., 2015). Thus, research has shown that high straw rates in the soil, especially in low-temperature regions, negatively affect the plant sprouting (Lisboa et al., 2018; Sordi and Manechini, 2013). On the other hand, the maintenance promotes a stalks production increase (Aquino et al., 2017; Aquino and de Conti Medina, 2014).

The straw maintenance brings physical, chemical and biological benefits to the soil, as it favors the soil conservation process (Franco et al., 2013) being the main source input carbon (C) in soil (Bordonal et al., 2018b; Cerri et al., 2011; Galdos et al., 2009; Segnini et al., 2013) impacting the soil structure (Tormena et al., 2017), dissipating the wheeled machine impact (Braida et al., 2006; Vischi Filho et al., 2015) reducing compaction and improving biological activity (Castioni et al., 2018), in addition to promoting greater soil water retention, maintaining soil moisture (Corrêa et al., 2017) and nutrient availability (Landell et al., 2013; Marin et al., 2014).

However, this material has aroused the industrial interest for its usefulness, both for electricity generating, and for the second-generation ethanol production (Landell et al., 2013; Segnini et al., 2013). It represents 1/3 of the crop energy potential (Leal et al., 2013) and non-use of this material could feature loss to the energy matrix (Santos et al., 2012). However, the straw removal practice is recent and there is few information on the straw dynamics in the field, the soil quality impact, and sugarcane biomass production.

The mechanized harvest promoted plant residue maintenance and their multiple benefits. On the other hand, intensified the traffic of heavy machinery has raising the soil compaction , and consequently, the degradation of soil structure (Cherubin et al., 2016; Souza et al., 2014). The high levels compaction promote loss of essential functions of the structure (Tavares Filho et al., 2012), manifested by increased bulk density and penetration resistance (Barbosa et al., 2018; Cavalieri et al., 2011; Tavares Filho et al., 2012), which, in turn, causes a reduction in pore space (Braunack and McGarry, 2006; Cavalieri et al., 2009), which reduces water infiltration rate (Rossetti and Centurion, 2013), hydraulic conductivity (Cherubin et al., 2016), and the soil gas diffusion (Silva Junior et al., 2010).

This soil structure degradation restricts the root growth (Kaiser et al., 2009; Singh et al., 2012) resulting in lost yield (Souza et al., 2014). To alleviate soil compaction in sugarcane fields, conventional tillage have been used as tillage practice for reform sugarcane productions fields. This management consists of intense soil mobilization through subsoiling and plowing operations associated with the use of heavy disc harrows which can reach up to 0.40 m depth. However, the adoption of this management can deteriorate soil physical quality (Castro et al., 2013). Thus to mitigate the problems arising from conventional tillage, some researches has shown the no-tillage system can be effective for that (Arruda et al., 2016; Barbosa et al., 2018; Cury et al., 2014).

Unlike conventional tillage, the no-tillage (PD) directs the operation only in the planting furrow, reducing the soil impact in 70% in sandy loam and clayey soil (Barbosa et al., 2018). According Barbosa et al. (2018) the no-tillage management is enough to promote the soil physical conditions and favor root development, and consequently crop yield. However, despite the NT benefits for annual crops, it is not commonly adopted in the sugarcane due crop cycle, mechanization process from planting to harvesting, and high soil compaction levels. Thus, it is believed that the implementation of this conservation system will be feasible only with machine traffic reduction.

In this context, reduced or controlled traffic appears as alternatives to mitigate the effects caused by intense mechanization, reducing soil compaction levels (McPhee et al., 2015; Roque et al., 2010; Souza et al., 2014). This management practice can be performed using autopilot on the machines (de Souza et al., 2012), by adjusting the gauge of implements and agricultural machinery (Kingwell and Fuchsbichler, 2011) with the crop spacing (Braunack and McGarry, 2006) or by using the autopilot associated with crop spacing (Esteban et al., 2019). The combined adoption of these techniques promote a favorable environment for root development and crop (Braunack and McGarry, 2006; Roque et al., 2010), because it creates permanently traffic areas in the field, which reduces compaction, preserving a greater soil area for plant exploitation (Esteban et al., 2019).

The root system presents direct relationships with the soil physical conditions (Barbosa et al., 2018; Cury et al., 2014; Souza et al., 2015, 2014), and it development in the soil profile influences crop yield (Carvalho et al., 2013; Smith et al., 2005), as well as it is fundamental for the growth of the plant ratoons, because it plays a key role in water and nutrient absorption (Aquino et al., 2015; Chopart et al., 2010). Sugarcane root system is concentrated 60-90% on the soil surface up to 0.40 m (Baquero et al., 2012; Cury et al., 2014; Otto et al., 2011; Rossi Neto et al., 2018) and 60 to 70% in the crop row and the remainder distributed in the inter-row at the 0.20 m layer (Barbosa et al., 2018).

Poor root development in inter-rows is due to soil compaction caused by successive passes imposed by machines (Barbosa et al., 2018; Esteban et al., 2019). Note that the root system will differentiate their distribution in accordance with the environmental conditions and the soil management adopted and influence the sugarcane stalk development. However, there are few studies on the sugarcane root system behavior related to conservation systems, control traffic, and straw removal. In addition to this, it is necessary to quantify how much straw is required in the field, aiming to provide the best relation in the sugarcane stalk and radicular biomass and consequently the productive system sustainability.

1.1 Hypothesis

This study was carried out to test the following hypotheses:

i) The conventional soil tillage at sugarcane planting reduces soil compaction but does not provides on better soil physical quality and higher sugarcane yield over the crop cycle. Its NT system is an alternative tillage system to improve the sustainability of sugarcane production.

ii) The NT system and controlled traffic promote better soil physical attributes than conventional NT, ensuring greater exploration of the root system in the soil profile.

iii) straw removal induces soil physical degradation, impairing root development and, consequently, reducing stalks yield over time.

1.2 Objective

1.2.1 Overall objective

To quantity the changes imposed by soil tillage, traffic and straw removal in the soil physical attributes and the sugarcane biomass production.

1.2.2 Specific objectives

i) Evaluate the soil physical properties changes associated with conventional and no-tillage over time (Chapter 2);

ii) Evaluate the soil physical quality and the sugarcane root system at the no-tillage with and without wheel traffic over time (Chapter 3);

iii) Evaluate the straw removal effect on soil physical quality and the sugarcane biomass production (i.e., stalks and roots) in the medium term (Chapter 4).

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2. SOIL PHYSICAL QUALITY ASSOCIATED WITH TILLAGE PRACTICES DURING SUGARCANE PLANTING IN SOUTH-CENTRAL BRAZIL

Submitted on Soil & Tillage Research

Abstract

Soil tillage operations had been carried out during the sugarcane planting to improve soil's capacity to perform its physical functions, thus providing proper conditions for sugarcane growth. Long-term field experiments were designed to assess the implications of tillage operations performed during sugarcane planting on soil physical quality and the associated effects on sugarcane yields under two soil types (clayey and sandy loam soils) in south-central Brazil. In 2013, the following treatments were delineated: (i) conventional tillage (CT) involving operations of subsoiling and harrowing, and the opening of planting furrow to a 0.40 m depth; and ii) no-tillage (NT) soil was not disturbed and only planting furrow was opened for sugarcane planting. Undisturbed soil samples were collected representing the row and inter-row positions at 0-0.10, 0.10-0.20 and 0.20-0.40 m depth over four crop cycles for the determination of bulk density (BD), soil resistance to penetration (SRP), macroporosity (MaP) and microporosity (MiP). Additionally, sugarcane yields were measured annually using an instrumented truck equipped with load cells. The CT management showed a reduction of soil compaction only in the plant cane cycle but showed similar patterns compared with NT over four crop cycles, indicating degradation of soil physical quality caused by the intensive traffic of machines in sugarcane fields. The opening of planting furrow in both tillage systems reduced soil physical limitations for values lower than those considered critical for crop development in the row position. The changes in soil physical attributes were observed mostly in the inter-row position, and diferences between tillage systems were evident only in the early two crop cycles. For clayey soil, the soil compaction was evident at 0-0.10 m depth from plant cane to 3rd ratoon, with increased BD of 24 and 16% for CT and NT, respectively. Similarly, SRP increased by 63% for CT and 55% for NT. In sandy loam soil, SRP was modified over time with a increase of 165 and 206% for CT and NT at 0-0.40 m depth, respectively. The data show that MaP decreased for values < 0.10 $m^3\ m^{-3}$ after four years for both soils and tillage systems. Regardless of soil type, tillage management did not show differences in sugarcane yields over the assessed period. Our findings support the conclusion that CT had similar soil physical degradation to NT. The latter could be a management target for handling sugarcane with minimal soil turnover, and consequently, mitigating the negative implications on sugarcane production.

Keywords: No-tillage; soil compaction; *Saccharumspp.*

2.1 Introduction

Sugarcane (*Saccharum* spp. L.) is globally highlighted as one of the most sustainable crops for biofuel production (Bordonal et al., 2018a), once sugarcane-derived ethanol has a potential to reduce 85% of greenhouse gas (GHG) emissions by replacing fossil fuels (Börjesson, 2009). Brazil is the world's leading sugarcane producer (*i.e.*, 659 million tons in the 2017/2018 harvest) with a cultivated area of 8.7 million hectares (Conab, 2018).

In the last 15 years, the Brazilian sugarcane area has increased by 33% but crop yield is well-below of its potential, keeping stagnated in 72 Mg ha^{-1} (Bordonal et al., 2018a). The stagnation of crop yield overlaps with the gradual adoption of mechanized harvest (i.e., green harvesting system) in replacement of manual harvesting with burning. Accordingly, the intensification of uncontrolled traffic of heavy machinery in sugarcane fields increased drastically the compressive forces applied on the soil surface, thus exceeding their load capacity and inevitably causing compaction and degradation of soil structural quality (Souza et al., 2014; Cherubin et al., 2016).

High levels of compaction can impact soil attributes, processes and functions (Tavares Filho et al., 2012; Cherubin et al., 2016), increasing bulk density (Cavalieri et al., 2011) and soil resistance to penetration (Tavares Filho et al., 2012), which consequently reduce soil porosity (Braunack & Mcgarry, 2006; Cavalieri et al., 2009), water infiltration rate (Rossetti & Centurion, 2013) and hydraulic conductivity (Cherubin et al., 2016), and diffusion of gases in the soil (Silva Junior et al., 2010). By critical soil physical functions, root growth is negatively affected (Moraes et al., 2018) and leads to significant yield losses (Souza et al., 2014).

Historically, soil tillage is used before sugarcane planting to reduce soil compaction. Conventional tillage (CT) involves subsoiling and plowing operations associated with the use of heavy harrow for elimination of ratoons, causing severe soil disturbance down to 0.40 m depth. This intensive tillage results in oxidation of organic matter (Galdos et al., 2009; Silva-Olaya et al., 2013), reducing soil aggregate stability, soil pore space (Pires et al., 2017) and soil resilience. Therefore, tillage may make soils more susceptible to recompaction by the successive traffic of machines (Cherubin et al., 2016), especially in carbon-poor soils with high moisture content under heavy traffic (Bonetti et al., 2017; Lima et al., 2017). Therefore, several studies indicate that soil tillage benefits are little persistent in sugarcane fields, disappearing in the short time (Nunes et al., 2014; Cherubin et al., 2016).

The adoption of reduced tillage or no-tillage (NT) system is a conservationist strategy to preserve soil physical quality (Palm et al., 2014; Pires et al., 2017; Blanco-Canqui and Ruis, 2018), once soil disturbance is concentrated only in the planting furrow and most part of soil surface remains covered with crop residues. Furthermore, these agricultural systems sustain greater nutrient cycling and C sequestration (Luo et al., 2010; Segnini et al., 2013; Palm et al., 2014), thermal regulation (i.e., soil moisture) (Crittenden et al., 2015), soil biological activity (Busari et al., 2015), protect soil against erosion (Salem et al., 2015; Zotarelli et al., 2012) and, when judiciously managed, NT might promote yield gains in mid- and long-term, particulartly in tropical soils (Pittelkow et al., 2015).

Although NT benefits are widely recognized in annual crops, the adoption in sugarcane fields remains challenging, especially because sugarcane is semi-perenial crop with a high degree of soil compaction induced by intensive traffic of heavy machinery throughout the crop cycle. However, two of the three principles of the NT system are already adopted in sugarcane fields, including cover crop and straw maintenance in the soil during the renovation period (Bordonal et al., 2018a).

Considering the soil disturbance promoted by tillage operations and the subsequent machinery traffic along the sugarcane crop cycle, we hypothesized that the use of CT during the sugarcane planting reduces soil compaction but does not reflect on better soil physical quality and higher sugarcane yield over the crop cycle, thus justifying NT system as an alternative management to further improve the sustainability of sugarcane production in Brazil. To test this hypothesis, the objective of this study was to assess the four-year effects of the NT and CT systems on soil physical propeties and sugarcane yield in two contrasting locations (clayey and sandy loam soils) within the south-central region of Brazil.

2.2 Materials and methods

2.2.1 Description of the study sites

The study was carried out in two sites located in Quirinópolis, Goiás state and Quatá, São Paulo state. These locations were chosen to represent contrasting edaphoclimatic conditions in the main hotspots of sugarcane expansion within the central-southern Brazil, region that accounts for 92% of national sugarcane production (Conab, 2018).

The experimental area in each site was set up within commercial farms under sugarcane plantation. In the site 1 (clayey soil), the area has been cultivated with pastures before converting into sugarcane in 2006, and the establishment of the experimental area occurred in 2012. The site 2 (sandy loam soil) has a history of 28 years under sugarcane cultivation and has been managed under green mechanized harvest since 2010. The description of location, climate and soil type as well as the characterization of soil chemical and physical attributes is presented in Table 1. The daily data of temperature (maximum and minimum) and rainfall were collected monthly from the meteorological station installed close to the experimental plots and the climatological water balance was computed for both locations according to the methodology proposed by Thornthwaite & Mather (1955) (Fig. 1).

Table 1. Characterization of the experimental sites (Quirinópolis-GO and Quatá-SP) during the establishment in October 2012: geographic coordinates, altitude, precipitation, mean annual temperature, climate type, soil classification, soil physical attributes.

Sites description	Site 1	Site 2
Location	Quirinópolis-GO	Quatá-SP
Geographic coordinates	18º32'S - 50º26'W	22º14'S - 50º42'W
Elevation (m)	460	541
Mean annual rainfall (mm)	1520	1254
Mean annual temperature (°C)	22.5	20.8
Climate type*	Humid with moderate water deficiency in the winter (B1wA'a')	Dry to a sub-humid with moderate hydric excess in the summer (C1wA'a')
Soil type (USDA-Soil taxonomy)†	Rhodic Eutrudox	Arenic Kandiudult
Soil texture	Clayey soil	Sandy loam soil
Chemical attributes (0.0–0.40 m)[a]		
pH $CaCl_2$	5.6	4.8
SOM (g dm^{-3})	46	12
P (mg dm^{-3})	8	15
K ($mmol_c$ dm^{-3})	3.7	0.4
Ca ($mmol_c$ dm^{-3})	38	12
Mg ($mmol_c$ dm^{-3})	11	3.6
CEC ($mmol_c$ dm^{-3})	75	32
BS (%)	71	48
Physical attributes[b]		
Clay/silt/sand content (g kg^{-1})		
0.0-0.10 m	547/186/267	87/60/853
0.10-0.20 m	561/190/249	108/60/832
0.20-0.40 m	580/195/225	142/57/801
Soil bulk density (Mg m^{-3})		
0.0-0.10 m	1.37	1.76
0.10-0.20 m	1.29	1.77
0.20-0.40 m	1.23	1.76

*According to Thornthwaite and Mather (1995);
† Soil survey according to the USDA – Soil Taxonomy (Soil Survey Staff, 2014);
[a] Soil chemical analysis according to Raji et al. (2001). SOM, soil organic matter; CEC, cation exchange capacity; BS, base saturation.
[b]Soil physical attributes were performed according to Blake and Hartge

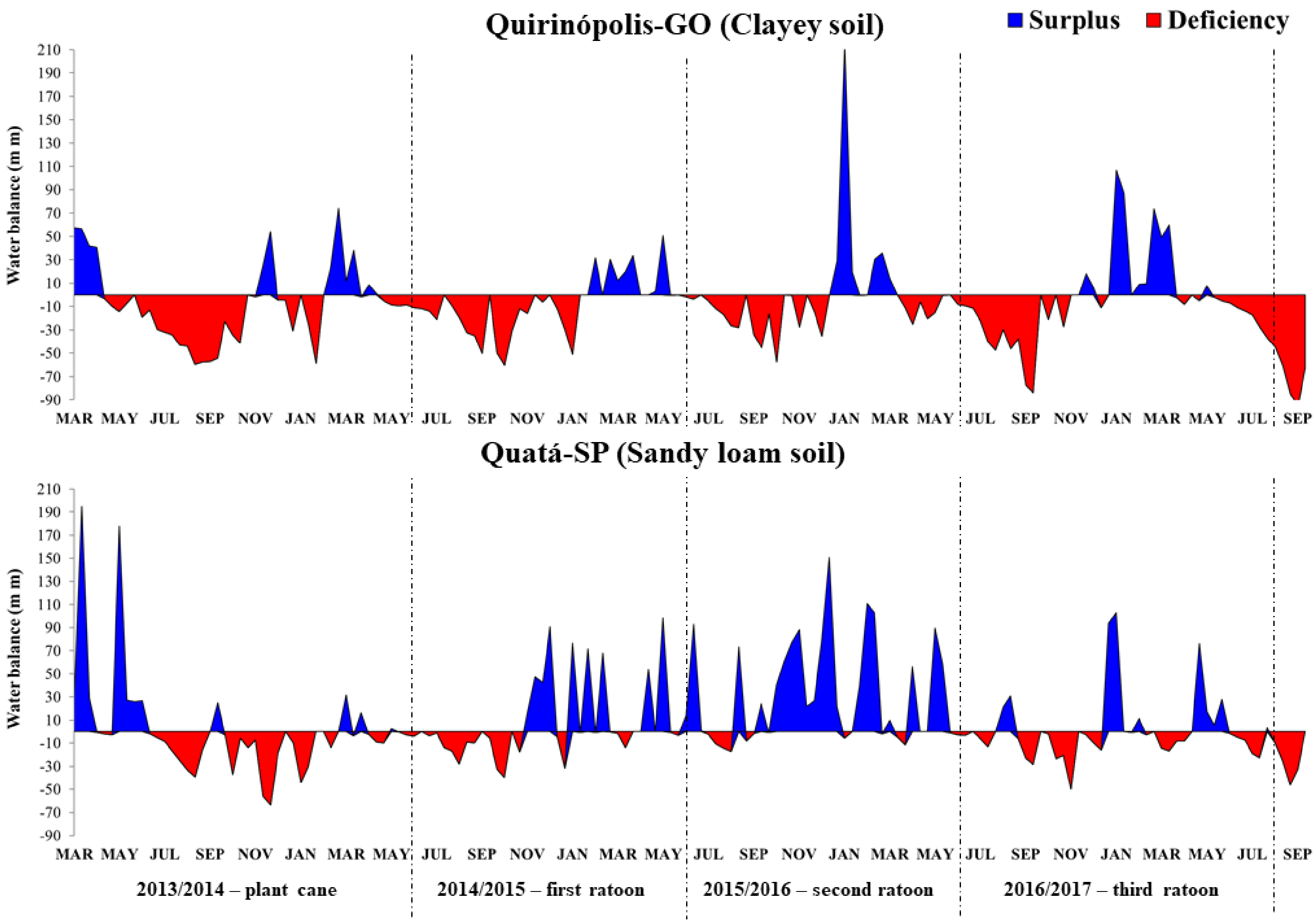

Figure 1. Monthly water balance accounted for the two locations during the sugarcane cycle

2.2.2 Experimental design and treatments

In October 2012, during the renovation of sugarcane field under fifth ratoon cycle of mechanized harvest, after desiccation with herbicides and applications of lime (2 Mg ha^{-1}) and gypsum (1 Mg ha^{-1}), the experimental fields were sown with *Crotalaria spectabilis* as a cover crop using a cereal planter at a rate of 25 kg ha^{-1} of seeds. In March/April 2013, the *C. spectabilis* was chemically desiccated with a mix of herbicides (5 L ha^{-1} of glyphosate, 1.2 L ha^{-1} of 2.4-D and 0.5 L ha^{-1} of triomax). When desiccation occurred, biomass production and nitrogen (N) content of *C. spectabilis* totaled 8.1 Mg ha^{-1} (192 kg ha^{-1} of N) in Quirinópolis-GO, and 6.5 Mg ha^{-1} (169 kg ha^{-1} of N) in Quatá-SP.

Thereafter, a randomized block design experiment with four replications was set up in each site. Each plot (*i.e*., 10 m long by 15 m wide) comprised 10 sugarcane rows at 1.5 m spacing. The treatments were established as follows: i) Conventional Tillage (CT), was carried out by a subsoiling with a subsoiler of 5-rows at 0.40 m depth spaced 0.5 m, a light hydraulic harrowing using a harrow of 36 disks at 0.20 m and next the opening of planting furrows at 0.30 m depth; ii) No-Tillage (NT), was characterized by a single operation of planting furrow opened at a 0.30 m soil depth over the cover crop biomass using a 2-row planter with spacing of 1.5 m. The practices were executed using a 4x4 tractor of 220cv CASE and more information about soil tillage systems are detailed in the Figure 2.

In the planting furrow base, fertilizers were applied at a rate of 40 kg N ha^{-1}, 125 kg P_2O_5 ha^{-1} and 125 kg K_2O ha^{-1}. In both sites, sugarcane was planted manually using 15-20 buds per meter with the variety RB96 6928, which presents adequate sprouting and high tillering and is classified as exhibiting an early to medium maturation cycle. After 60 days of the sugarcane harvest in each cycle, was applied above the straw layer and 0.10 m away from crop row, the following sources: ammonium nitrate (32% N, rate of 120 kg N ha^{-1}) and potassium chloride (60% K_2O; 120 kg K_2O ha^{-1}). The control of pests, diseases and weed was conducted similarly in all treatments according to management practices of each sugarcane mill. The mechanized sugarcane harvesting was done with harvester (CASE) with treadmill wheels of 0.4 m wide, track width of 1.50 m, and mass of 18.50 Mg. The harvested sugarcane was transported in wagons with capacity to transport 10 Mg of sugarcane, pulled by a 4x4 tractor of 220cv CASE with mass of 13.4 Mg.

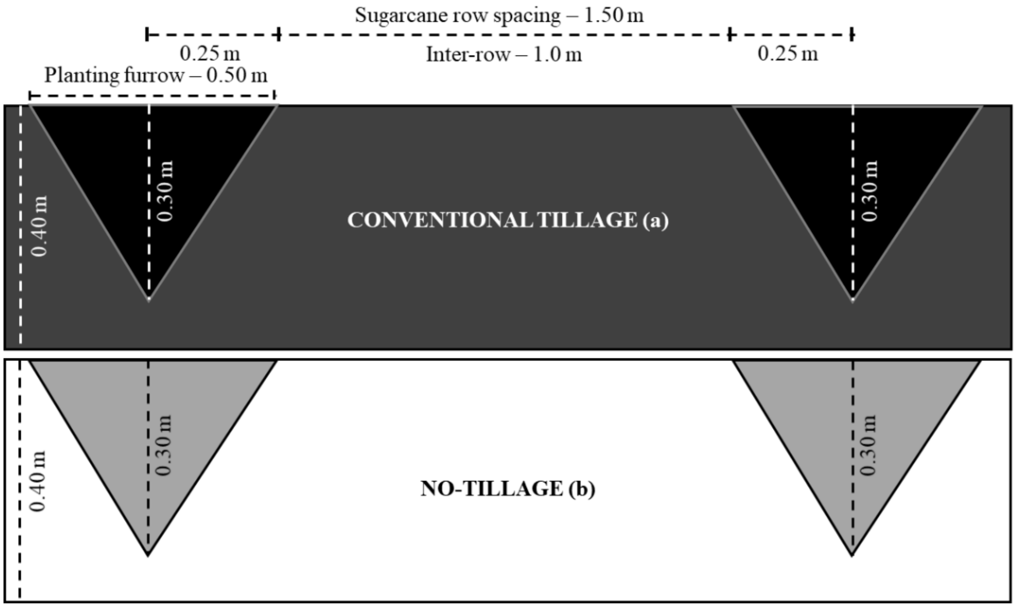

Figure 2. Description of conventional tillage-CT and reduced tillage-RT characteristics adopted in the field experiment. ■ - dark gray color represents soil disturbed during soil tillage practices; ■ - black represents soil disturbed by soil tillage practices plus planting furrow opening; ■ - light gray represents soil disturbed only by planting furrow opening and □ - white is soil undisturbed.

2.2.3 Sampling and soil physical measurements

Soil sampling was carried out over the four crop cycles (2014, 2015, 2016 and 2017) after the harvesting. Undisturbed soil samples were collected using metal ring (0.05 m in diameter and 0.05 m in height) in trenches opened crosswise the cultivation row, from the center to the middle of the row. Each trench had a dimension of 0.40 x 0.90 x 0.30; and thenceforth, samples were collected in the plant row itself, and from between the plant rows (i.e., to a 0.75 m gap from one plant row to the next) (Fig. 3). Samples were collected at three soil depths (0-0.10, 0.10-0.20 and 0.20-0.40 m), with a total of 48 samples per year within each experimental site (*i.e.*, 2 treatments x 4 repetitions x 2 sampling positions x 3 depths).

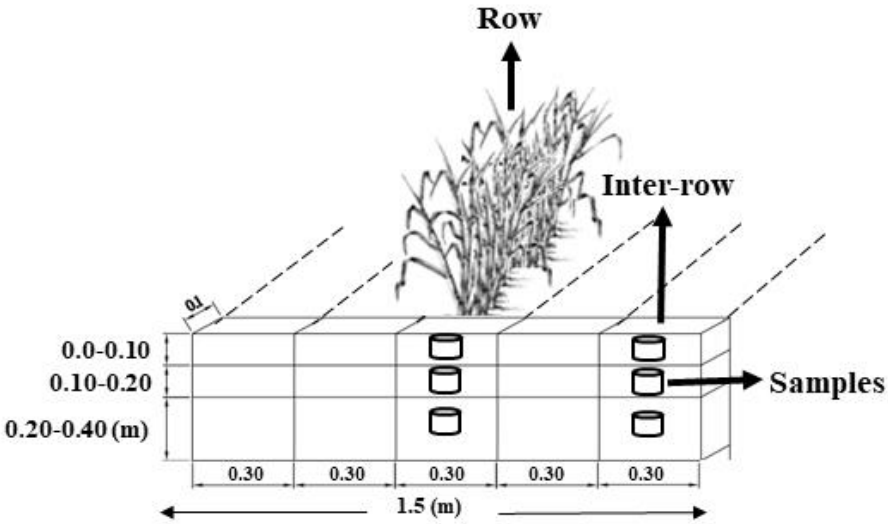

Figure 3. Description of the undisturbed samples collection points

In the laboratory, the undisturbed soil samples were saturated gradually with water by capillarity action and weighed. After total saturation, the soil microporosity (MiP, m^3 m^{-3}) was estimated using the tension table as the soil water potential (Ψ) of −6 kPa (Teixeira et al., 2017), to quantify the diameter pores of $0.002<Ø<0.05$ mm (Klein and Libardi, 2002). The macroporosity (MaP, m^3 m^{-3}) was determined through the difference between microporosity and total porosity, to assess the diameter of pores >0.005 mm. The total porosity (TP, m^3 m^{-3}) was estimated according to following equation: TP = 1 (BD/PD). Soil particle density (PD, Mg m^{-3}) was determined using a gas pycnometer and bulk density (BD, Mg m^{-3}) was calculated by dividing the soil dry mass obtained a 105 ºC for 48h by the volume of the cylinder (Teixeira et al., 2017).

Soil resistance to penetration (SRP, MPa) was obtained after determining the MiP, with the moisture of the balanced sample -6 kPa. The equipment used was an electronic penetrometer with a 4-mm tip and a constant penetration speed of 10 mm s^{-1}. Measures were obtained from the center of undisturbed soil samples. Measures from the upper (0.01 m) and lower portions (0.01 m) were excluded from all samples, following the procedures described in Imhoff et al. (2010) and Otto et al. (2011).

2.2.4 Sugarcane stalk yields

Sugarcane stalk yield was quantified over four years during harvesting, which took place between June and July in 2014 (plant cane), 2015 (1st ratoon), 2016 (2nd ratoon) and 2017 (3rd ratoon) in Quirinópolis-GO and Quatá-SP. Each plot was mechanically harvested, and the stalk yield was computed for the four central rows through an instrumented truck equipped with a loading cell (used exclusively for experiments) (Fig. 4).

Figure 4. Instrumented truck equipped with a loading cell (A); Loading cell control panel (B).

2.2.5 Data analysis

The response variables were analyzed using linear mixed model adjusted in software R 3.3.3 with the lmer function of package lme4 (Bates et al., 2015), allowing us to handle correlated data such as repeated measures. Replicates were considered random effects and soil tillage management and harvest years were considered fixed effects. Treatments and their interactions were considered different when $p \leq 0.05$. The means reported were least square means and were compared using the packet difflsmeans lmerTest (Lenth, 2016). All analyzes were done in R Core Team (2017).

In order to improve the interpretation of results, we summarized comparing the soil physical changes induced by the main variation factors (tillage systems; soil sampling positions; crop cycle). First of all, was calculated the average values of BD, SPR, MaP, MiP, and TP for 0.0-40 m. After, each indicator was normalized ranging from 0 (worse) to 1 (best soil physical quality). For that, each indicator was linearly ranked in ascending or descending order depending on whether a higher value was considered “good” or “bad” in terms of soil physical quality. Bulk density and SRP followed the scoring curve “less is better”, which 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. For indicators MaP, MiP and TP followed the scoring curve “more is better”, which each observation was divided by the highest observed value such that the highest observed value received the score 1. The results were presented in radar graphics that allows easy and intuitive interpretation.

2.3 Results

2.3.1 Bulk density (BD) and soil resistance to penetration (SRP)

In general, BD and SRP increased over the crop cycles in the 0-0.40 m layer, mostly in the inter-row position in the clayey soil (Fig. 5) and in both positions in the sandy loam soil (Fig. 6). The effects of NT and CT resulted in smaller patterns of changes for BD after the 2nd ratoon but different and variable changes for SRP. Significant differences induced by tillage practices were more evident in the inter-row position during the plant cane cycle, thus indicating higher BD and SRP under NT plots. After the 2nd crop cycle, CT and NT showed similar patterns for BD and SRP.

For clayey soil, the changes of soil compaction indicators were most evident in the 0-0.10 m depth of the inter-row, in which BD increased from plant cane to 3rd ratoon by 24% (from 1.19 to 1.57 Mg m^{-3}) and 16% (from 1.33 to 1.58 Mg m^{-3}) for CT and NT, respectively. SRP also increased by 63% for CT (from 0.68 to 1.85 MPa) and 55% (from 1.25 to 2.77 MPa) for NT. In the inter-row position, NT presented higher BD in relation to CT only in the plant cane cycle, while SRP values were higher during the plant cane, 1st and 3rd ratoon (Fig. 5b). On the other hand, BD and SRP in the row position reduced at the 0.10-0.20 m and 0.20-0.40 m depths during the same crop periods (Figs. 5c,e), indicating that BD was reduced by 9 and 11% and SRP by 41 and 27% for the CT and NT plots, respectively.

Sandy loam soil was significantly altered by the effects of tillage practices, crop cycles and sampled positions (Fig. 6). Over four years, increased BD and SRP values were observed for all positions (row and inter-row) and soil depths. Although BD showed small changes over the years, the SRP was most modified by tillage practices in the long-term. CT and NT modified BD in the 0-0.40 m layer with increase of 13% and 9% in the inter-row, respectively, and of 7% for both treatments in the row position.

Considering the effects of CT and NT on SRP in a sandy loam soil, the results show that surface layers were affected by NT at both soil positions during the plant cane and 3rd ratoon (Fig. 6), and this pattern was evident only in the 0-0.40 m layer of the inter-row position (Fig. 6b,d,h). From the period between plant cane to the 3rd ratoon, SRP increased by 165% (from 0.95 to 2.53 MPa) and 206% (from 1.05 to 3.21 MPa) for CT and NT, respectively (Fig. 6h). The adoption of NT tended to increase SRP by 27% in the 0-0.40m (0.68 MPa) in relation to CT in the inter-row position of the 3rd ratoon.

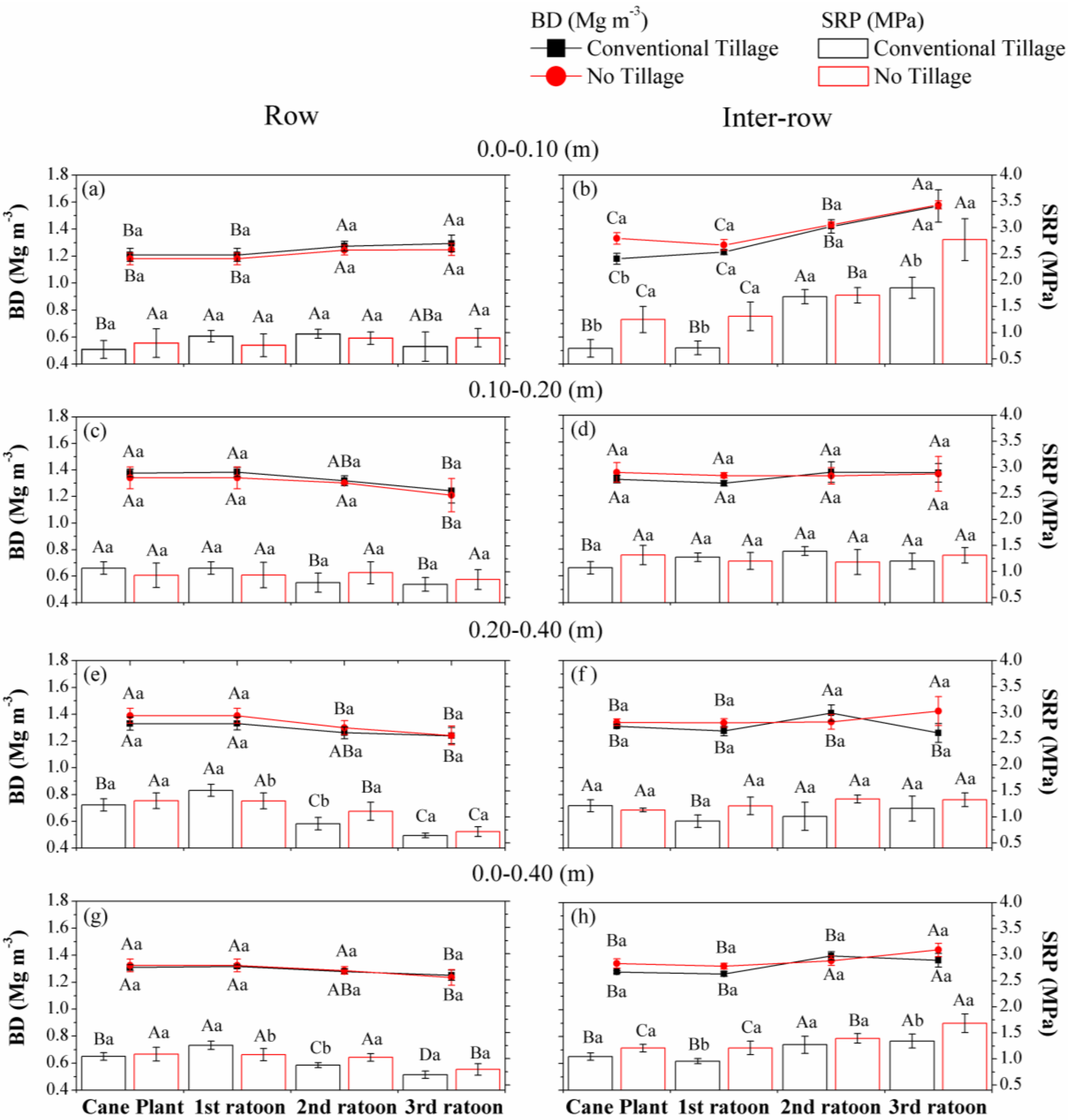

Figure 5. Changes in bulk density (BD, Mg m^{-3}) and soil resistance to penetration (SRP, MPa) in the row and inter-row positions associated with different tillage management in a clayey soil: conventional tillage (CT) and no-tillage (NT) in the 0.0-0.10, 0.10-0.20 and 0.20-0.40 m depths during the sugarcane crop cycle. Different capital letters indicate significant difference over the crop cycles for the same tillage management, while different lowercase letters indicate significant difference between the tillage systems within each crop cycle by least square means with lmerTest (p <0 05). Bars indicate the standard deviation (n = 4).

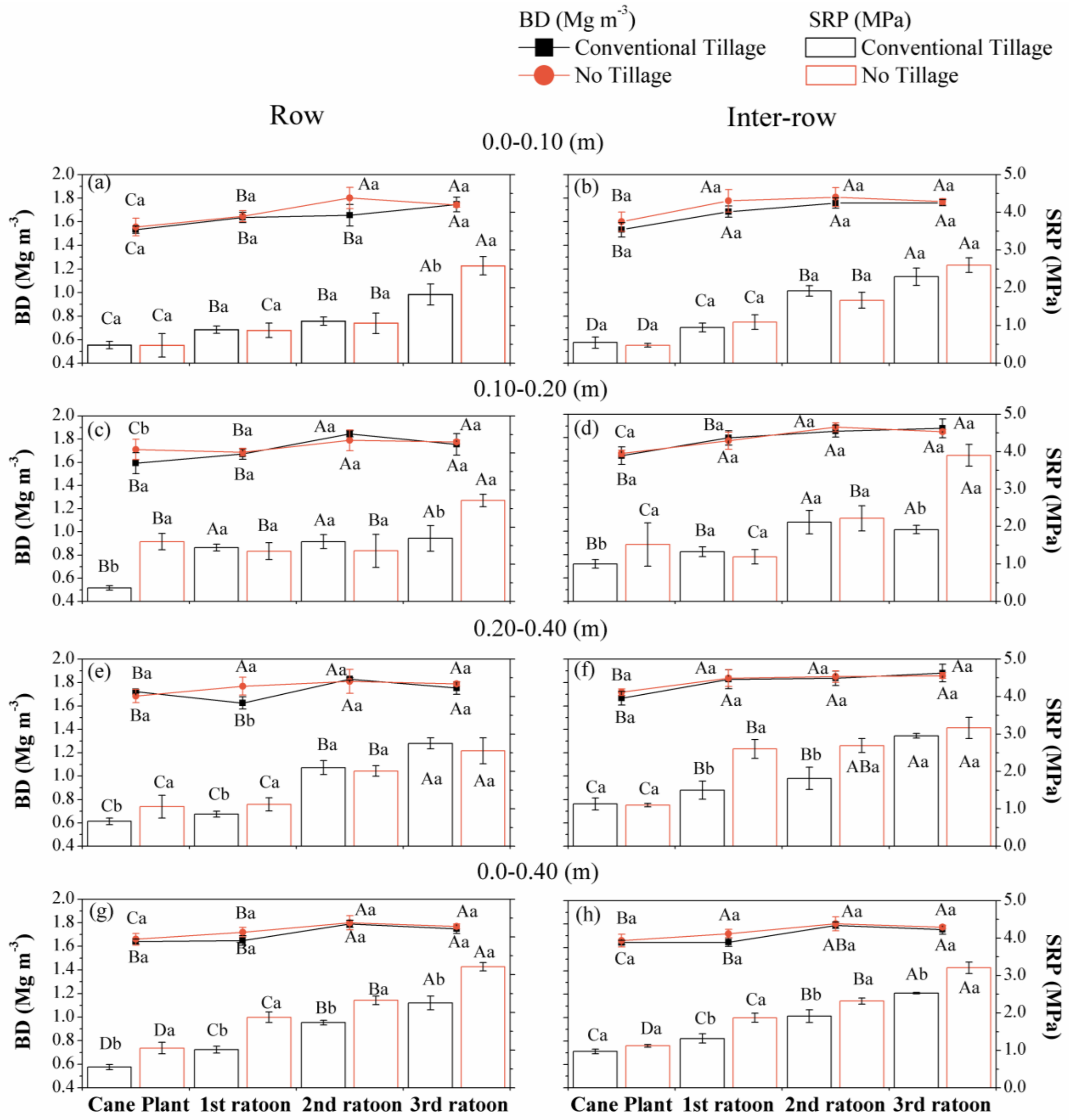

Figure 6. Changes in bulk density (BD, Mg m^{-3}) and soil resistance to penetration (SRP, MPa) in the row and inter-row positions associated with different tillage management in a sandy loam soil: conventional tillage (CT) and no-tillage (NT) in the 0.0-0.10, 0.10-0.20 and 0.20-0.40 m depths during the sugarcane crop cycle. Different capital letters indicate significant difference over the crop cycles for the same tillage management, while different lowercase letters indicate significant difference between the tillage systems within each crop cycle by least square means with lmerTest (p <0 05). Bars indicate the standard deviation (n = 4).

2.3.2 Soil porosity

The variation of soil porosity showed similar pattern for both soil types. The MaP values were more sensitive to effects of tillage, crop cycles and sampling positions (row and inter-row) than MiP values (Fig. 7 and 8). Effects of tillage systems on soil porosity were consistently detected during the plant cane in both soil positions, in which CT promoted MaP increases compared to NT in the 0-0.40 m. Over a four-year cycle, CT and NT had barely affected MaP and MiP for both soils, mainly in the inter-row position. In general, MaP increased in the row while in the inter-row position was reduced for both soil tillage and in long-time.

The adoption of NT in a clayey soil increased MaP in the row position, while CT remained with constant values of MaP over the cycles. In this position, MaP reached values up to 0.10 m^3 m^{-3} in the 3rd ratoon (Fig. 7a,c,e,g). In contrast, CT presented higher pore volumes at the plant cane, but its beneficial effects did not remain during the crop cycle. While CT showed reductions of 53% (from 0.16 to 0.07 m^3 m^{-3}) at 0.40 m depth, NT exhibited similar pores volume over the assessed period (Fig. 7h). However, the magnitude of changes in pores volume ocurred mostly in the inter-row position (0-0.10m), in which CT and NT showed reductions of 82% (from 0.18 to 0.03 m^3 m^{-3}) and 89% (from 0.08 to 0.01 m^3 m^{-3}) from the plant cane to the 3rd ratoon, respectively (Fig. 7b).

In sandy loam soil, the changes in soil porosity followed the same responses to those observed for clayey soil during the plant cane cycle, but with lower magnitude (Fig. 8b, h). For instance, MaP in the inter-row for CT reduced by 39% (from 0.18 to 0.11 m^3 m^{-3}) in the 0.40 m and for NT showed constant values over the years, reaching up to 0.13 m^3 m^{-3} in the fourth year while in the CT remained at 0.10 m^3 m^{-3} (Fig. 8h). Contrary to the clayey soil in the 0-0.10 m, CT showed slight reductions of 26% (from 0.21 to 0.15 m^3 m^{-3}), while NT remained constant over four years (Fig. 8b). Importantly, MaP in the row position under NT (0.19 m^3 m^{-3}) was 36% higher than CT (0.14 m^3 m^{-3}) in the 0.10-0.20 m depth, and 12% higher for the entire soil profile (0.40 m) (Fig. 8c,g).

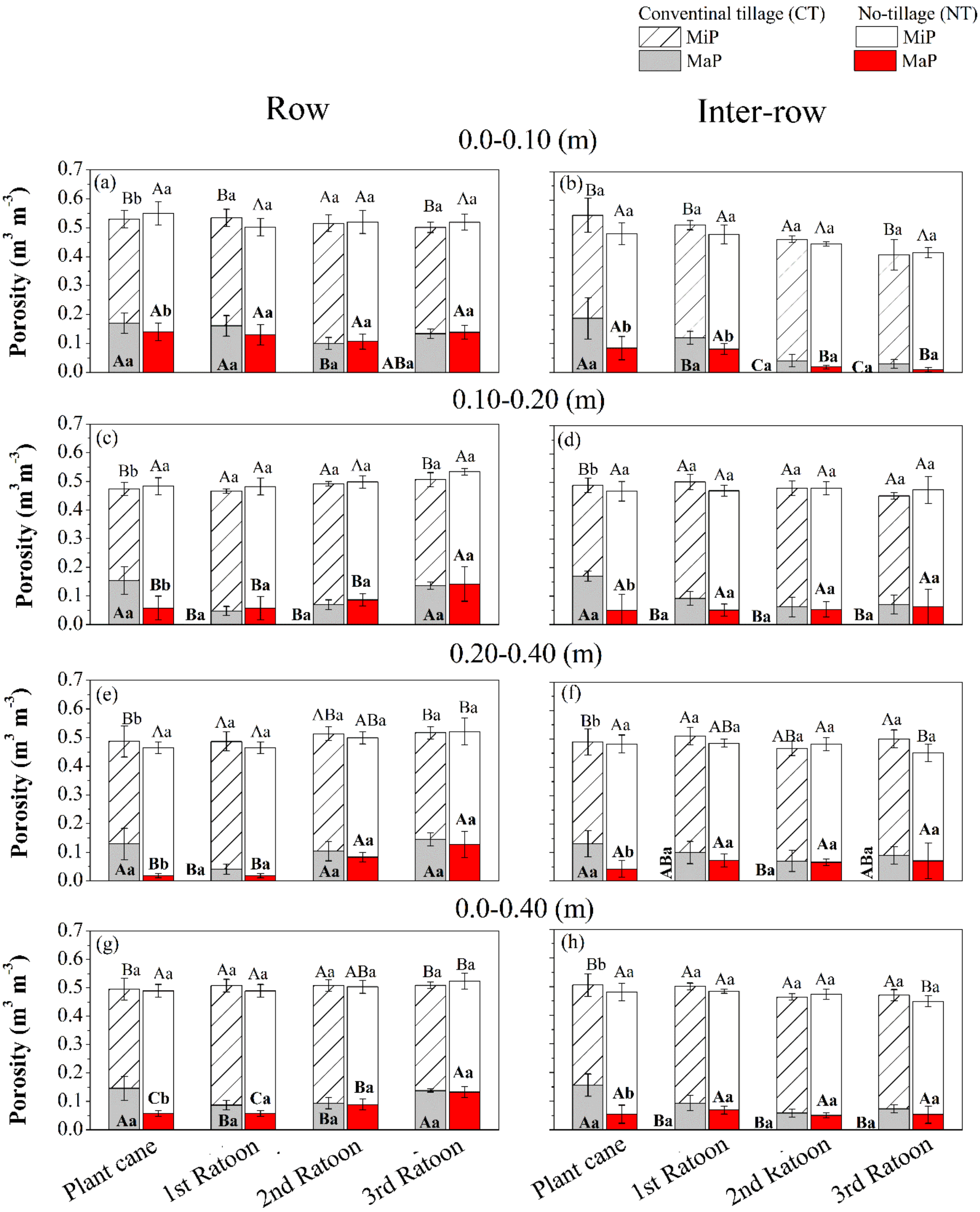

Figure 7. Changes in soil macroporosity (MaP, m^3 m^{-3}) and microporosity (MiP, m^3 m^{-3}) in the row and inter-row positions associated with different tillage management in a clayey soil: conventional tillage (CT) and no-tillage (NT) in the 0.0-0.10, 0.10-0.20 and 0.20-0.40 m depths during the sugarcane crop cycle. Different capital letters indicate significant difference over the crop cycles for the same tillage management, while different lowercase letters indicate significant difference between the tillage systems within each crop cycle by least square means with lmerTest (p <0 05). Bars indicate the standard deviation (n = 4).

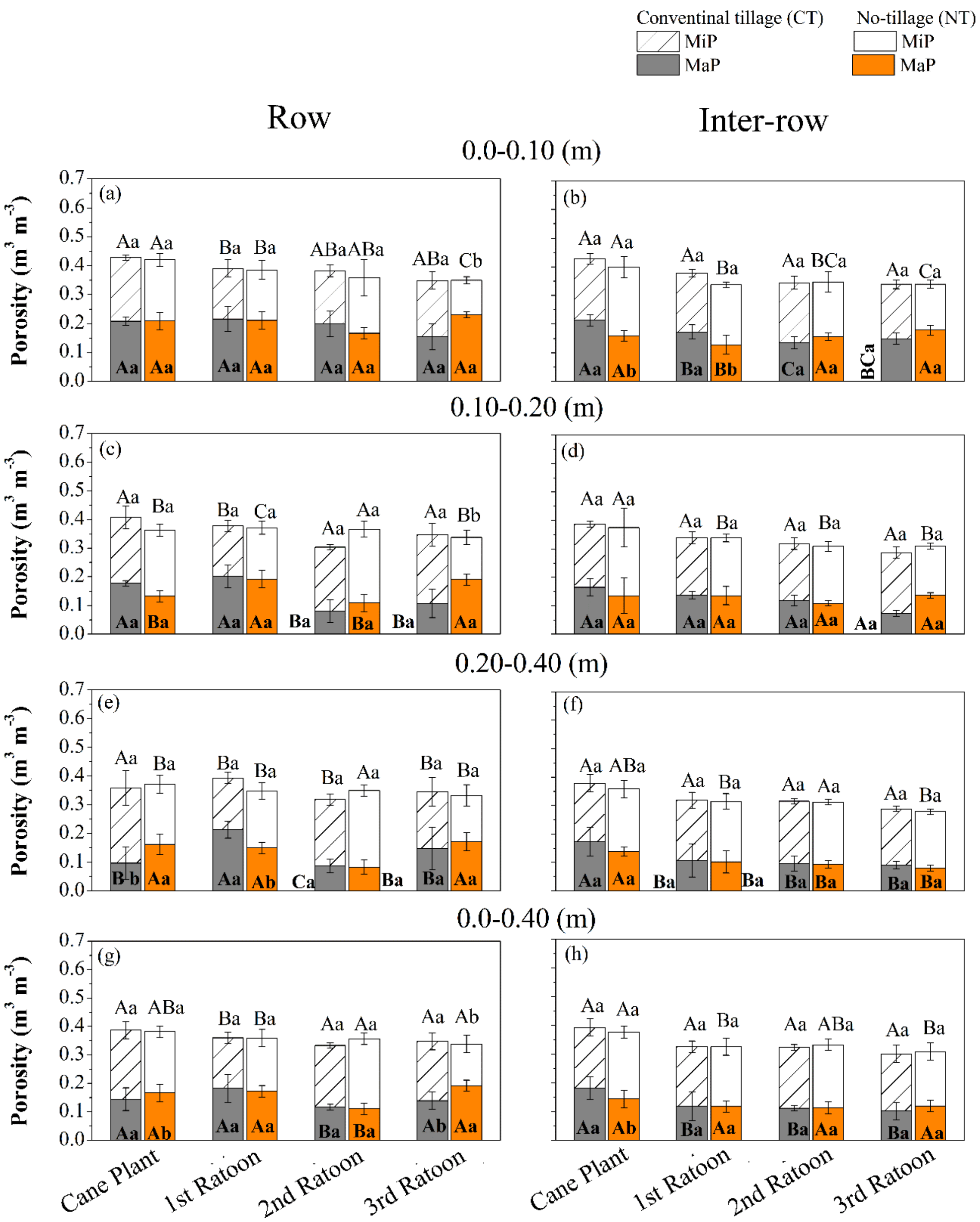

Figure 8. Changes in soil macroporosity (MaP, m^3 m^{-3}) and microporosity (MiP, m^3 m^{-3}) in the row and inter-row positions associated with different tillage management in a sandy loam soil: conventional tillage (CT) and no-tillage (NT) in the 0.0-0.10, 0.10-0.20 and 0.20-0.40 m depths during the sugarcane crop cycle. Different capital letters indicate significant difference over the crop cycles for the same tillage management, while different lowercase letters indicate significant difference between the tillage systems within each crop cycle by least square means with lmerTest (p <0 05). Bars indicate the standard deviation (n = 4).

2.3.3 Sugarcane yield

In general, sugarcane yield (Mg ha^{-1}) showed a slight increase up to 1st ratoon, thus declining during the later crop cycle regardless of the soil tillage systems for both soil types (Table 2). Soil types had different responses to tillage systems along the crop cycle but showed similar results only in specific periods. For example, CT showed higher yields relative to NT during the plant cane sandy loam soil, thus resulting in an increment of 11 Mg ha^{-1} (16%). Overall, sugarcane yield in clayey soil reduced by 12% from the 1st to the 3rd ratoon for CT and 20% for NT in the same period. In the sandy soil, yield reduction of 58% was observed for both tillage systems from the the 1st to the 3rd ratoon. Considering the four-year cumulative yields, there was no difference between CT and NT management for both soil types (sandy loam and clayey).

Table 2. Stalk yield of sugarcane (Mg ha^{-1}) as a function of conventional tillage (CT) and no-tillage (NT) during the harvest of plant cane until the 3rd ratoon in clayey and sandy soil.

	Stalk yield (Mg ha^{-1})				
	Plant cane	1st ratoon	2nd ratoon	3rd ratoon	Cumulative
Clayey soil					
CT	156 Ba	175 Aa	145 Ba	159 Ba	634 a
NT	168 Aa	176 Aa	131 Ba	140 Ba	616 a
Net gain/loss (CT-NT)	-12	-1	14	19	18
Sandy loam soil					
CT	69 Ca	87 Aa	76 Ba	36 Da	268 a
NT	58 Cb	96 Aa	81 Ba	41 Da	275 a
Net gain/loss (CT-NT)	11	-9	-5	-5	-7

Mean values are average of four replicates. Different capital letters in the same line indicate significant difference over the sugarcane cycles for the same management system, while different lowercase letters in the same column indicate significant difference among the tillage management systems in the same crop cycle by least square means with lmertest ($p < 0.05$).

2.4. Discussion

2.4.1 Tillage effects on soil physical quality

The CT management performed during the sugarcane planting attenuated soil compaction by reducing BD and SRP values due to subsoiling and harrowing operations. The effects of CT also increased soil MaP compared to NT (Fig. 9a,d) and were significant only in the plant cane cycle. Intensive soil tillage when sugarcane areas are replanted alleviate compacted layers of the soil, increasing MaP and consequently reducing BD (Dal Ferro et al., 2014; Jabro et al., 2016; Sithole et al., 2016) and SRP (Marasca et al., 2016; Cherubin et al., 2016). However, in the subsequent ratoon cycles, the absence of soil disturbance and the cumulative effects of intensive machine traffic promoted soil compaction (Arruda et al., 2016; Bangita and Rao, 2012; Torres et al., 2015; Vasconcelos et al., 2014) with increases of BD and SPR and a decrease of MaP, thereby resulting in similar soil physical conditions for CT and NT management systems (Fig. 9b,e). Due to the similar soil physical quality observed between CT and NT systems, the results of four-year experiment raise questions regarding the feasibility of CT in sugarcane fields (Fig. 9a,d). Our findings corroborated with Camilotti et al. (2005) and Sá et al. (2016) which reported no difference regarding several soil management effects (*i.e.;* chiseling, harrowing, subsoiling, moldboard and minimum tillage) on soil physical attributes and sugarcane yield after two and three years of management.

Our long-term experiments revealed that NT can be a viable alternative for conservationist management of sugarcane fields under the maintenance of crop residues in the soil surface. The straw maintenance practice preserves soil physical quality (Castioni et al., 2018) because it reduces the contact pressure of the wheels on the soil (Vischi Filho et al., 2015) and promotes the dissipation of applied loads (Braida et al., 2006; Reichert et al., 2016), attenuating the increase of BD e SPR (Reichert et al., 2016; Satiro et al., 2017) and reduction of soil porosity (Gao et al., 2017) during the crop cycles. In addition, the input of soil organic C by sugarcane residue mulching in soil for several years (Carvalho et al., 2017) and the presence of macrofauna (Castioni et al., 2018) contributes to aggregates formation (Lehmann et al., 2017), which are essential to improve soil physical quality in the long-term.

A recent study conducted by Moraes et al. (2017) showed that NT can promote greater soil structural quality over time, basically explained by two main mechanisms related to the age-hardening phenomenon: i) the increase in the number of connections between aggregates and ii) promoting more strong connections between aggregates, thus making the soil structure more stable with greater cohesion and internal friction interna. According to the authors, the long-term NT demonstrated greater resistance to additional compaction because of higher soil load support capacity for the same bulk density related to age-hardening phenomena, which increased the number and strength of bonds among soil particles and led to higher soil cohesion.

Our results showed a negative impact of machinery traffic with an increase of BD e SPR in surface layers in both sites and in subsoil in the sandy loam soil. The effects of load transmission are not uniform along the soil profile (Lipiec et al., 2006). In the sandy loam soil, the poor structural stability related to the high proportion of sand (Dal Ferro et al., 2014) and low organic matter content (Bordonal et al., 2018b) facilitate the transmission of loads imposed by the wheels on the soil surface to deeper layers (Usaborisut and Sukcharoenvipharat, 2011; Afzalinia and Zabihi, 2014).

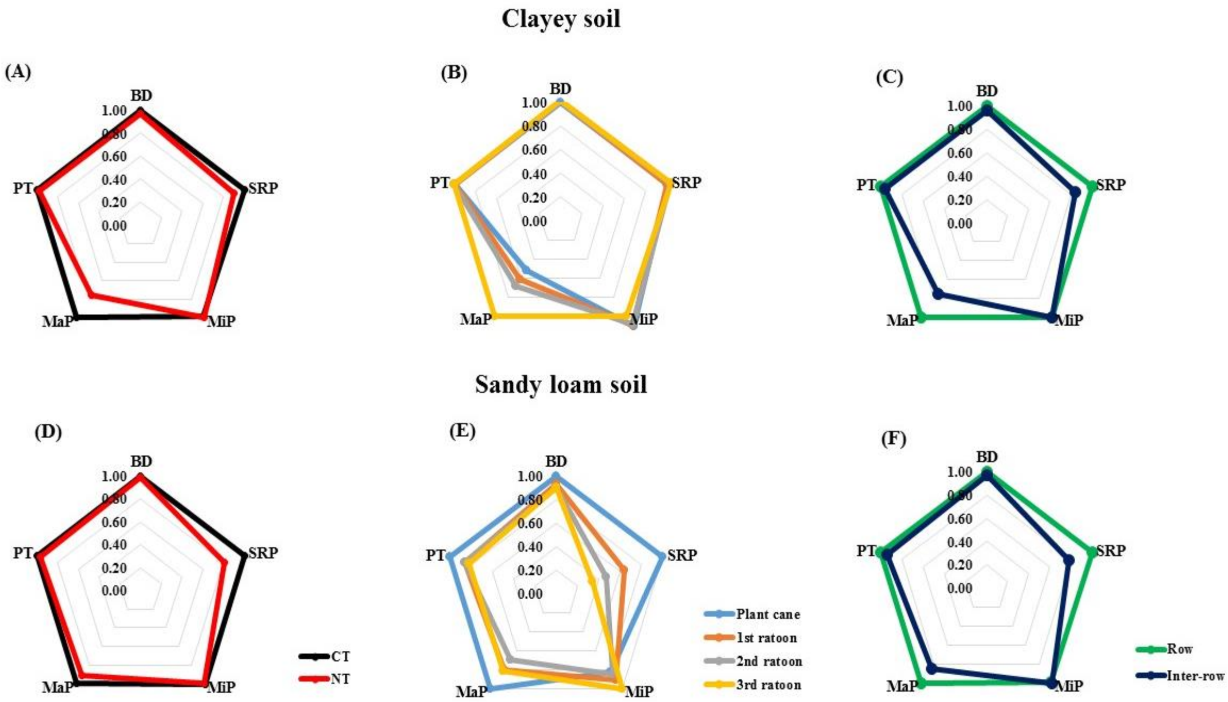

Figure 9. Overall scores of the soil dataset indicators for the 0.0–0.40 cm layer in the sugarcane areas. Wherein: (a; d) are relative comparisons for tillage practices (conventional tillage-CT and no-tillage-NT); (b; e) for crop cycles; and (c; f) for the assessed positions effects.

2.4.2 Tillage effects on soil physical attributes in row and inter-row positions

Soil compaction induced by the intense and uncontrolled traffic in sugarcane fields, especially during harvesting, reduces the soil physical quality not only in the inter-row position (traffic zones) but also in crop row. Heavy traffic on crop row can damage the sugarcane ratoon and cause soil compaction, negatively affecting the crop sprouting and yield in subsequent ratoons and consequently reduces the longevity of sugarcane field. The four-year effects of sugarcane cultivation presented herein showed that, regardless of the tillage management and soil type, the increase of BD and SPR and decrease of MaP were more pronounced in the inter-row positions, with cumulative degradation of soil physical structure over the cycles (Fig. 9c,f), corroborating with results reported in previous studies (Roque et al., 2010; Marasca et al., 2015; Souza et al., 2015). However, the same changes occurred in inter-row were observed on crop row in sandy loam soil, which indicates that some traffic may have occurred in this position in addition to the natural rearrangement of soil particle, thus worsening the physical and mechanical condition of soil for proper root growth.

To interpretate soil physical changes, several studies have tried to identify the critical limit of compaction for different soil types and its influence on the crop development. However, soil interactions with plant and climate conditions over the time are complex and almost unpredictable. Therefore, there is no consensus about the exact critical values for each soil attribute in each specific soil-crop-climate condition. According to the literature, the critical limit of BD and SPR is variable in relation to soil texture (Barbosa et al., 2018; Keller and Håkansson, 2010), soil moisture (Moraes et al., 2014) and tillage system (Moraes et al., 2017, 2014). In a recent study, Barbosa et al. (2018) identified critical values using samples at -6 kPa water potential in soils of sand and clay texture of 1.70 Mg m^{-3} and 1.50 MPa, and 1.25 Mg m^{-3} and 2.50 MPa for BD and SPR, respectively. Our study showed SPR values higher than 2 MPa, which refers above than those considered critical by the literature for the inter-row position. However, we must be cautious with these values, since critical values may change according to soil tillage systems (Moraes et al., 2014; 2017). In general, NT might will have higher SRP values than CT in the same soil density and moisture since this effect occurs due to the high number of particulate soil bonds associated with the organic matter content over time, and even with high SPR values, this system promotes good conditions of root growth in the spaces between aggregates (Moraes et al., 2014; 2017).

In the inter-row position, MaP reduced over time to values lower than 0.10 m^3 m^{-3}, which has been consolidated in the literature as the critical limit for root development (Torres et al., 2016). In contrast, the critical limit obtained at row position in this study were lower than those established in the literature, showing that the crop row presents a favorable environment to plant development for both CT and NT managements. Corroborating the results reported by Barbosa et al. (2018) and Cury et al. (2014), the planting furrow alleviates soil compaction and provides favorable physical conditions for root growth. In clayey soil, the data showed that the planting furrow results in better soil physical conditions in to the root system during crop cycles. The death and decomposition of the roots increase the soil organic matter content (Carvalho et al., 2013), which in turn results in aggregation of lower density organic particles to soil mineral particles that promotes the formation of interconnecting channels biopores, thus facilitating the penetration and development of the root system (Arruda et al., 2016; Souza et al., 2015).

As machinery traffic occurs differently in the row and inter-row positions, recent studies have shown that 60 to 90% of sugarcane root system is concentrated in the soil profile of 0.40 m (Otto et al., 2011; Baquero et al., 2012; Cury et al., 2014; Barbosa et al., 2018; Rossi Neto et al., 2018), where 60 to 70% in the 0-0.20 m depth is grouped in the crop row and the remaninder is distributed in the inter-row (Barbosa et al., 2018). Restriction of the root development in the inter-row positions may be attributed to the physical limitations of the soil caused by the traffic of machines (Souza et al., 2015, 2012; Barbosa et al., 2018). Considering the sugarcane root distribution in the soil profile and the results found herein about the similarity of soil physical quality between tillage systems after four years, some doubts may arise regarding the feasibility of the CT, since this management promotes soil mobilization with high costs during planting period and significant risk of imparing the soil physical quality by compaction and/or erosion.

Based on the results, NT was viable alternative for conservationist management, once this management promotes only 13% of soil mobilization (*i.e.*; only in the row with planting furrow) and preserves 70% of the area (Barbosa et al., 2018). The results indicate the need for future studies to fully understand the NT effects associated with traffic control strategy to improve the performance of NT system in the sugarcane crop, once the adoption of this additional management decreases the intensity of traffic in the area (Gasso et al., 2013) and reduces soil compaction compared to CT (Roque et al., 2010; Baquero et al., 2012; Souza et al., 2014; McPhee et al., 2015). In this way, this ensures that traffic is maintained at the same position during subsequent cycles, providing favorable conditions for root growth and crop development (Braunack and McGarry, 2006; Roque et al., 2010).

2.4.3 Impacts of soil tillage on sugarcane yield

Sugarcane yield decreased over the crop cycles at both sites. This reduction in biomass production can be associated with some factors such as: i) the reduction of vigor and the high energy consuption caused by regrowth of the plant, as well as the increase in the number of failures due to the pull-off of sugarcane ratoons by harvesters (Lisboa et al., 2018; Silva Junior et al., 2013); ii) and the intense traffic of machines that enhances soil compaction levels throughout the crop cycle, reaching high values of BD and SRP and reduction of MaP, which in turn impairs the development of root system (Cherubin et al., 2016, Barbosa et al., 2018). Other factors that may have had a direct influence on the crop development were soil and climatic conditions of the sites, which may have contributed to higher yields observed in the clayey soil (Rossi Neto et al., 2018). For example, even without significant differences among tillage practices in the later sugarcane cycles, the magnitude of increment in yield promoted by CT treatment in the clayey soil was greater in comparison to NT (Table 2). This pattern could be attributed to the intrinsic characteristics of clayey soils in retaining more nutrients and water in addition to better physical conditions promoted by this management during the early crop cycles, which may have favored crop growth. This effect was not observed in the sandy soil, characterized by a smaller capacity to retain water and nutrients. It suggests that NT was more promising to sustain slightly superior yields than CT likely because NT may have provided a better maintenance of water supply to sugarcane growth during the dry seasons observed over the crop cycle (Fig. 1) (Grego et al., 2011).

The absence of significant differences in sugarcane yields between CT and NT may be attributed to the specific planting management adopted in this crop, because the planting furrow makes uniform both treatments by reducing soil compaction to a 0.4 m depth (Barbosa et al., 2018). Our results corroborate with other studies evaluating NT in comparison with CT system that also detected little or no difference in sugarcane yields over sugarcane cycle (Cury et al., 2014; Deus et al., 2015). The similarity of crop yield between soil tillage systems a strong argument to convince farmers to adopt NT system in Brazilian sugarcane fields.

The dataset obtained herein provide a broader understanding of the positive externality of adopting NT in sugarcane fields by considering the reduction of fuel consumption during sugarcane planting. As reported by some studies, the planting operations associated with harvest and transportation of sugarcane to the mill can represent 32% GHG emission factor in sugarcane plantations and NT use can provide emissions reduction of 22.7% (Bordonal et al., 2013) and could save US$ 17 ha^{-1} yr^{-1} (or US$ 0.22 per ton of sugarcane) in comparison to CT (Chagas et al., 2016). In this context, previous perspectives regarding the NT reinforce that this can be a competitive management for the GHG mitigation of diesel-derived and to reduce the production costs (Bordonal et al., 2012), helping Brazilian ethanol production to become more competitive.

2.5 Conclusion

Based on this 4-yr experiment, CT management showed a reduction of soil compaction only in the plant cane cycle and presented the same characteristics as NT throughout the crop cycles, supporting the hypothesis that the adoption of CT during the sugarcane planting does not result in better soil physical quality nor in increases of sugarcane yield. The soil physical degradation caused by compaction due to the intensive traffic of machines reduces sugarcane yield over the crop cycles. The highest impacts of soil tillage systems were observed in the inter-row positions, while the opening of planting furrow alleviated physical limitations for root growth. Best management practices that reduce the adverse effects of intensive mechanization, including NT associated with traffic control are imperative to promote better soil physical quality and prevent damages on the plants. Although our study showed promising data of soil physical quality and crop yield, suggesting that NT may be an effective alternative for sustainable management of sugarcane fields, additional studies are also of paramount importance to confirm these benefits in soil chemical and biological attributes. Integrated approaches that include soil quality (physical, chemical and biological), plant growth and yield data are encouraged to assess the agronomic feasibility of NT systems in sugarcane fields in Brazil.

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3. TRAFFIC ABSENCE IN SUGARCANE NO-TILLAGE SYSTEM PROMOTES ROOTS DEVELOPMENT AND LONG-TERM RECOVERY OF SOIL PHYSICAL QUALITY

Submitted on Soil & tillage Research

Abstract

Traffic reduction can be a management strategy to attenuate adverse effects of soil compaction associated to no-tillage system in sugarcane field**s**. Long-term field experiments (4 yrs) on clayey and sandy loam soils were conducted to assess the impacts of wheel traffic on soil physical quality and sugarcane root growth under no-tillage management system in south-central Brazil. In 2013, the following treatments were delineated: i) no-tillage (NTT), where planting furrows at a 0.30 m soil depth were opened directly in the cover crop biomass, disturbing approximately 30% of soil surface; ii) no-tillage without traffic (NTWT), where the same operations were performed after a four-year absence of machinery traffic. Undisturbed soil samples during four crop seasons (2014, 2015, 2016 and 2017) were collected from rows and inter-rows at three soil depth layers (0-0.10, 0.10-0.20, 0.20-0.40 m) for determination of bulk density (BD), soil resistance to penetration (SRP), macroporosity (MaP), and microporosity (MiP). Evaluation of sugarcane root biomass was conducted during each sugarcane crop cycle harvesting. High impacts in inter-row zones under intensive traffic were observed, but no impacts were identified in no-wheel traffic plots, indicating that traffic absence should be considered in practices for long-term preservation of sandy and loamy soils. Lowest BD and SRP values as well as highest MaP were found under traffic absence plots, where sugarcane bed zones had been established. This management favored better root production, showing high root growth in the soil profile, mainly in inter-row positions. Thus, our findings suggest that traffic reduction associated with specific zones intended for plant growth is a feasible management for enhancing soil physical quality and root development in no-tillage farming system for sugarcane crop fields in Brazil.

Keywords: Soil tillage, control traffic, soil physical attribute, soil compaction

3.1 Introduction

Brazil is the world's largest sugarcane producer (616 million tons of stalks) with a yield of 31 million tons of sugar and 32 billion L of ethanol (Conab, 2019). The sugarcane planted area in 2018/2019 covered 8.63 million hectares, with an average yield of 73 Mg ha^{-1} (Conab, 2019). Sugarcane yield has experienced a downward trend in recent years (Bordonal et al., 2018), seemingly coinciding with the adoption of mechanized sugarcane harvesting system (Rossi Neto et al., 2018). The green harvesting system, currently adopted in Brazil, uses mechanization in all stages of cultivation (tillage, planting, treatments, cropping and harvesting) and may imply a number of adverse production related effects, such as low yield, high operational costs and soil compaction increases (Souza et al., 2014).

Soil compaction reduces macroporosity, leading to high bulk density and soil resistance to root penetration (Barbosa et al., 2018), thus hindering root growth and plant yield (Santos et al., 2018). Currently, in Brazil, conventional tillage is adopted to alleviate soil compaction in sugarcane replanting period since it promotes immediate benefits by intense soil mobilization. However, some studies have questioned the effectiveness of conventional tillage in improves soil physical attributes in medium- and long-term (Barbosa et al., 2018; Cury et al., 2014; Segnini et al., 2013). Conventional tillage system breaks soil aggregates, making them more susceptible to compaction under machinery traffic in subsequent years. Conversely, no-tillage (NT) management in the long-term improves soil structure, ensuring a better physical quality (Reichert et al., 2016).

Studies suggest that the adoption of conservationist systems such as NT, which requires the minimum soil revolving associated with straw retention and crop rotation, brings several benefits to soil quality, especially carbon (C) accumulation in soil profile (Bordonal et al., 2018; Segnini et al., 2013) in addition to improving soil biological activities (Moraes et al., 2017). However, sugarcane production is a highly mechanized activity, and machine-induced soil compaction can render the benefits associated with NT system. Therefore, it is necessary to define wheel traffic zones in the field in order to preserve larger areas of soil for root exploration. Several studies have described those direct relations between soil physical attributes and sugarcane root development in soil profile (Barbosa et al., 2018; Cury et al., 2014; Souza et al., 2015, 2014) as having an influence on crop yield (Carvalho et al., 2013).

In this context, the establishment of areas under permanent machinery traffic and seedbeds destined for plant growth represents an essential management strategy to make

NT feasible in sugarcane areas. This management strategy is adopted as an alternative to reduce the proportion of compacted areas (Baquero et al., 2012; McPhee et al., 2015; Roque et al., 2010; Souza et al., 2014), either by using autopilot (Souza et al., 2012), by increasing machine wheel axels (Kingwell and Fuchsbichler, 2011) and/or by unification between crop row and wheel spacing (Braunack and McGarry, 2006; Roque et al., 2010). These interventions guarantee that traffic activities are maintained in specific areas throughout the crop cycles, physically differentiating the traffic area from the planting area, thus enabling the development of the crop root system.

This study focuses on the hypothesis that the adoption of NT system associated with the creation of permanent areas to machine traffic throughout the cycles (*i.e.,* four years) will promote the recovery of soil structure on the area intended for plant growth, reducing the limiting physical conditions to root growth in soil profile. Thus, the objective of this study was to evaluate the changes of soil physical attributes (i.e., density, porosity and soil resistance to penetration) and of sugarcane root development under NT, with and without traffic control in clayey and sandy loam soils in south-central Brazil.

3.2 Materials and methods

3.2.1 Description of the study sites

The study was carried out in two sites located in Quirinópolis, Goiás state (Site 1) and Quatá, São Paulo state (Site 2). These locations were strategically chosen to represent contrasting edaphoclimatic conditions in the main hotspots of sugarcane expansion and the largest sugarcane-producing region within the central-southern Brazil. The description of location, climate, soil type and physical attributes is shown in Table 3. Rainfall data were collected on a daily basis by a meteorological station installed close to the experimental plots, and the climatological water balance was computed according to the methodology proposed by Thornthwaite & Mather (1955) (Figure 10).

Table 3. Characterization of the experimental site (Quirinópolis-GO and Quatá-SP) during its setting in October 2012: geographic coordinates, altitude, precipitation, mean annual temperature, climate type, soil classification, soil physical attributes.

Sites description	Site 1	Site 2
Location	Quirinópolis-GO	Quatá-SP
Geographic coordinates	18º32'S - 50º26'W	22º14'S - 50º42'W
Elevation (m)	460	541
Mean annual rainfall (mm)	1520	1254
Mean annual temperature (°C)	22.5	20.8
Climate type*	Humid with moderate water deficiency in the winter (B1wA'a')	Dry to a sub-humid with moderate hydric excess in the summer (C1wA'a')
Soil type (USDA-Soil taxonomy)†	Rhodic Eutrudox	Arenic Kandiudult
Soil texture	Clayey soil	Sandy loam soil
Chemical attributes (0.0–0.40 m)[a]		
pH $CaCl_2$	5.6	4.8
SOM (g dm^{-3})	46	12
P (mg dm^{-3})	8	15
K ($mmol_c$ dm^{-3})	3.7	0.4
Ca ($mmol_c$ dm^{-3})	38	12
Mg ($mmol_c$ dm^{-3})	11	3.6
CEC ($mmol_c$ dm^{-3})	75	32
BS (%)	71	48
Physical attributes[b]		
Clay/silt/sand content (g kg^{-1})		
0.0-0.10 m	547/186/267	87/60/853
0.10-0.20 m	561/190/249	108/60/832
0.20-0.40 m	580/195/225	142/57/801
Soil bulk density (Mg m^{-3})		
0.0-0.10 m	1.37	1.76
0.10-0.20 m	1.29	1.77
0.20-0.40 m	1.23	1.76

*According to Thornthwaite and Mather (1995);
† Soil survey according to the USDA – Soil Taxonomy (Soil Survey Staff, 2014);
[a] Soil chemical analysis according to Raji et al. (2001). SOM, soil organic matter; CEC, cation exchange capacity; BS, base saturation.
[b]Soil physical attributes were performed according to Blake and Hartge

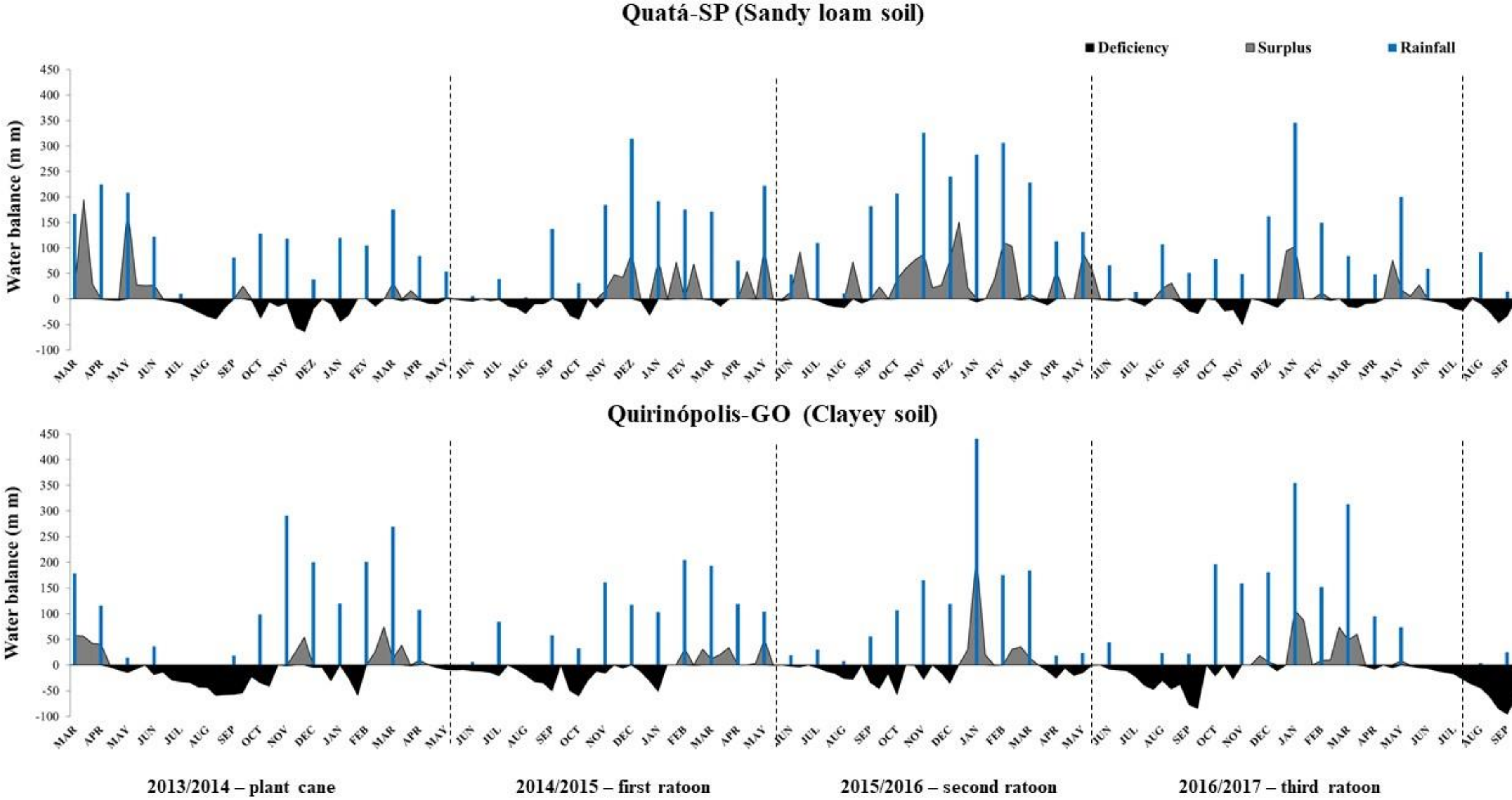

Figure 10. Monthly water balance accounted for the two locations during the sugarcane cycle.

3.2.2 Experimental design and treatments

In October 2012, during the sugarcane crop renovation in the fifth ratoon cycle of mechanized harvesting, desiccation and application of soil correctives (*i.e.*, lime and gypsum), followed by sowing with *Crotalaria spectabilis* as a cover crop, and desiccation performed in March/April 2013. Thereafter, the crop cover was chemically desiccated and the treatments in each site were set up in a randomized block design with four replications. Each plot was 10-m long by 15-m wide, comprised of 10 sugarcane rows with 1.5 m spacing.

The treatments were established as follows: i) no-tillage with regular traffic (NTT); ii) no-tillage without traffic (NTWT). The no-tillage was characterized by a single operation of planting furrow opened at a 0.30 m soil depth over the cover crop biomass to sugarcane planting using a 2-row planter with spacing of 1.5 m. The practices were executed using a 4x4 tractor of 220cv CASE and more information about soil tillage systems are detailed in the Figure 2. The difference between the treatments was associated only with the machinery traffic in sugarcane areas. In NTT the machinery traffic occurred conventionally (in each 1.5 m) and all operations were mechanically performed. Conversely, for NTWT treatment all field operations were performed manually without machinery traffic. This last treatment was established aiming to evaluate the creation seedbeds and areas under permanent traffic, simulating the use of machinery (harvesters, transloaders and other equipment) with long distance between axis.

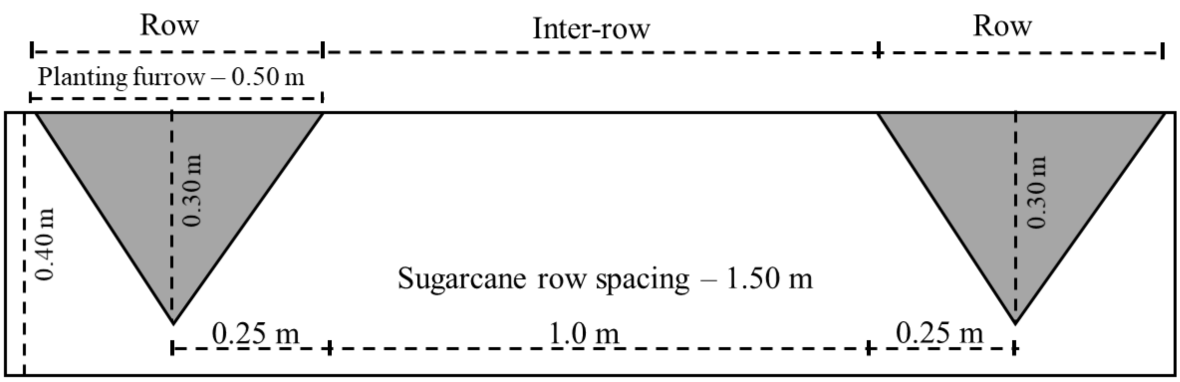

Figure 11. Opening furrow layout for sugarcane planting under no-tillage system; ■ - light gray represents soil disturbed only by planting furrow opening and □ - white is soil undisturbed.

The planting occurred throughout the use planting furrows at a 0.30 m soil depth opened directly on the cover crop biomass, disturbing approximately 30% of soil surface. In both sites, sugarcane was planted manually using 15-20 buds per meter with the variety RB96 6928 sugarcane variety. In the planting furrow base, fertilizers were applied at a rate of 40 kg N ha^{-1}, 125 kg P_2O_5 ha^{-1} and 125 kg K_2O ha^{-1}, which presents adequate sprouting and high tillering and is classified as exhibiting an early to medium maturation cycle. After 60 days of the sugarcane harvest in each cycle, was applied above the straw layer and 0.10 m away from crop row, the following sources: ammonium nitrate (32% N, rate of 120 kg N ha^{-1}) and potassium chloride (60% K_2O; 120 kg K_2O ha^{-1}). The control of pests, diseases and weed was conducted similarly in all treatments according to management practices of each sugarcane mill. The mechanized sugarcane harvesting was done in the NTT with harvester (CASE) with treadmill wheels of 0.4 m wide, track width of 1.50 m, and mass of 18.50 Mg. The harvested sugarcane was transported in wagons with capacity to transport 10 Mg of sugarcane, pulled by a 4x4 tractor of 220cv CASE with mass of 13.4 Mg.

3.2.3 Sampling and soil physical measurements

Soil sampling was done over four crop cycles: 2014, 2015, 2016 and 2017 after harvesting. Undisturbed soil samples were collected using a metal ring (0.05 m diameter and 0.05 m height) at three soil depths (0-0.10, 0.10-0.20 and 0.20-0.40 m), representing plant row and inter-row positions. In each site, 48 samples were collected per year (*i.e.*, 2 treatments x 4 repetitions x 2 sampling positions x 3 depths). Over the whole study, 384 samples were collected (*i.e.*, 48 samples x 2 sites x 4 years).

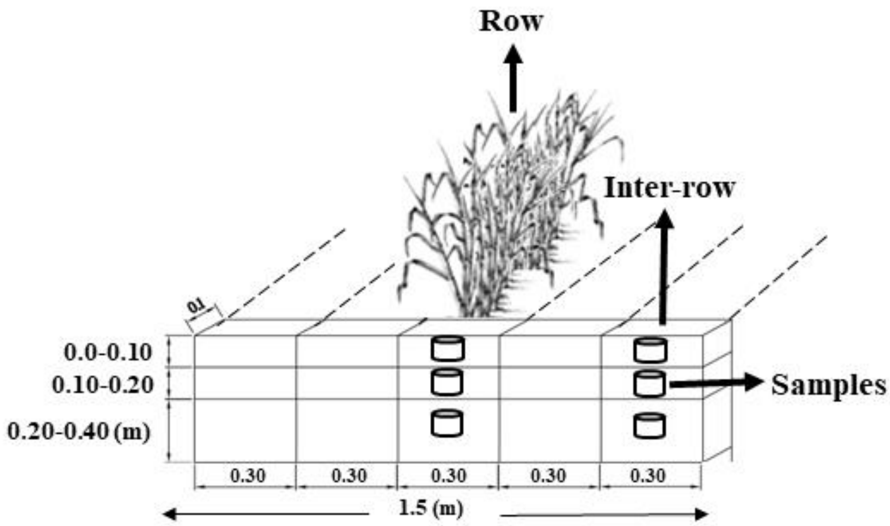

Figure 12. Description of the undisturbed samples collection points.

In the laboratory, each undisturbed soil sample was saturated gradually with water by capillary action and weighed. The samples were used for determination of the following soil physical indicators: i) microporosity (MiP) at the soil water potential of -6kPa (Ψ = -0.006); ii) macroporosity (MaP) was determined by the difference between MiP and total porosity; iii) bulk density (BD) was calculated by dividing the soil dry mass obtained at 105 ºC for 48h by the volume of the cylinder, and iv) soil resistance to penetration (SRP) was obtained after determining the MiP with moisture of the balanced sample -6 kPa, following procedures as described in Barbosa *et al.* (2018).

3.2.4 Sugarcane root system

Sugarcane root sampling was carried out over the 2014, 2015 and 2016 crop cycles before harvesting in a dry season (June). The methodology, as described in Otto *et al.* (2009), used a 1.2 m long probe with a 0.055 m internal diameter. Root samples were collected at 0-0.10, 0.10-0.20, 0.20-0.40, 0.40-0.60 and 0.60-1.0 m depth. Soil samples, including roots, were packed in plastic bags and transported to the laboratory where they were washed in running water through a sieve (1 mm mesh size). Separated root samples were dried in a forced circulation oven at 65 °C for 72 h. After weighing, the amount of dry root biomass (Mg ha^{-1}) was calculated according to the methodology as described in Otto et al. (2009).

3.2.5 Data analysis

Response variables were analyzed using linear mixed model adjusted in software R 3.3.3 with the lmer function of package lme4 (Bates *et al.*, 2015), allowing us to handle correlated data such as repeated measures. Replicates were considered random effects. Traffic management and harvest years were considered fixed effects. Treatments and their interactions were considered different when $p \leq 0.05$**.** The means reported were least square means and were compared using the packet *difflsmeanslmerTest* (Lenth, 2016). All analyzes were performed in (R Core Team, 2017).

3.3 Results

3.3.1 Soil physical attributes

In both sites, NTT treatment caused an increase in both BD and SRP as compared to NTWT over four cycles, with higher values mainly in inter-rows (Table 4). In clayey soil under NTT, increased BD was observed in the superficial layer (0-0.10 m) such that mean values in inter-rows were 7% higher (from 1.33 to 1.43 Mg m^{-3}) and 20% (from 1.32 to 1.58 Mg m^{-3}), as compared to NTWT in the 2nd and 3rd ratoons, respectively. Similarly, in the same cycles (*i.e.*, 2nd and 3rd ratoons) the SRP increased by 36% (from 1.26 to 1.71 MPa) and 122% (from 1.25 to 2.77 MPa) under NTT, which is a substantial difference as compared to NTWT. In the 0.20-0.40 m layer, an average SRP increase of 25% was observed in machine trafficked areas (from 1.07 to 1.34MPa) as compared to NTWT in the 2nd and 3rd ratoons, respectively.

In both evaluated positions (row and inter-row) the impacts on BD and SRP were more pronounced in sandy loam soil. In NTT at 0-0.10 m layer, it was observed in the row had an average BD increase of 11% in the 1st ratoon, and of 8% in the 2nd and 3rd ratoons as compared to NTWT, respectively (Table 4). Likewise, the BD under NTT was 1.77 Mg m^{-3}, significantly different at 3rd ratoon under NTWT in inter-row position. Throughout the cycles, the BD under NTT showed an average increase of 12% and 10% in the 0.0-0.10 m layer in row and inter-row, respectively. In the same site, the SRP under NTT was significantly higher than under NTWT, mainly in the 3rd ratoon at crop row and inter-row position, reaching values >2 MPa in all soil layers (Table 4). During the cycles (i.e., from plant cane to 3rd ratoon) in the row position the SRP showed a 5-fold increase at 0-0.10 m layer. Still, in row position, it was verified an increase of 116% and of 140% in the 0.10-0.20 and 0.20-0.40 m layers. Similarly, response was observed in the inter-row during the cycle, wherein the NTT, reaching 2.60, 3.90 and 3.16 MPa in the 0-0.10, 0.10-0.20 and 0.20-0.40 m layers.

Regarding the 0-0.40 m profile, the NTT treatment promoted high soil impact, verified by the greater BD and SRP in both types of soils after four years (Figure 13). On the other hand, in NTWT the most significant effects were observed in the 3rd ratoon, with lower BD and SRP values than NTT. In clayey soil, the treatment NTWT system reduced BD in the inter-row by 7% (from 1.40 to 1.30 Mg m^{-3}) as compared to the 3rd ratoon under NTT (Figure 13d). Overall, the SRP was more sensitive to soil alterations in both areas, positions and during cycles. So, in clayey soil, the SRP under NTWT in the row position was reduced by 16% and 35% in the 2nd and 3rd ratoons, respectively, as compared to NTT (Figure 13d). In sandy loam soil, were observed SRP differences in both positions. Thereby, in the row position, the NTWT presented values of 1.04 and 1.09 MPa, substantially lower than NTT in the 2nd and 3rd ratoons, respectively (Figure 13a). Similarly, the SRP under NTWT on inter-row was 21%, 40% and 53% lower under NTT in the 1st, 2nd, and 3rd ratoons (Figure 13b).

Table 4. Changes in bulk density (BD, Mg m^{-3}) and soil resistance to penetration (SRP, MPa) in the row and inter-row zones in a clayey and sandy loam soil managed under no tillage with machinery traffic (NTT) and without machinery traffic (NTWT) during sugarcane crop cycle.

	Treatments	0.0-0.10 (m) CP	1st	2nd	3rd	0.10-0.20 (m) CP	1st	2nd	3rd	0.20-0.40 (m) CP	1st	2nd	3rd
								BD (Mg m^{-3})					
Sandy loam soil	**Row**												
	NTT	1.55 Ab	1.65 Ab	1.80 Aa	1.74 Aa	1.71 Aab	1.69 Ab	1.79 Aa	1.78 Aab	1.69 Ab	1.77 Aab	1.81 Aa	1.79 Aa
	NTWT	1.55 Aa	1.48 Ba	1.66 Ba	1.61 Ba	1.71 Aab	1.72 Aab	1.79 Aa	1.66 Bb	1.69 Ba	1.64 Bb	1.82 Aa	1.78 Aa
	Inter-row												
	NTT	1.60 Ab	1.78 Aa	1.81 Aa	1.77 Aa	1.67 Ac	1.77 Ab	1.89 Aa	1.85 Aa	1.72 Ab	1.84 Aa	1.85 Aa	1.81 Aa
	NTWT	1.60 Ab	1.82 Aa	1.74 Ab	1.59 Bb	1.67 Ab	1.83 Aa	1.83 Aa	1.81 Aa	1.72 Ab	1.78 Ab	1.85 Aa	1.88 Aa
								SRP (MPa)					
	Row												
	NTT	0.48 Ac	0.87 Ab	1.06 Ab	2.58 Aa	1.26 Ab	1.35 Ab	0.97 Ac	2.72 Aa	1.06 Ac	1.12 Ac	2.01 Ab	2.55 Aa
	NTWT	0.48 Aa	0.77 Aa	0.94 Aa	0.72 Ba	0.91 Ab	1.36 Aa	1.05 Aa	0.85 Bb	1.06 Aa	1.32 Aa	1.08 Ba	1.39 Ba
	Inter-row												
	NTT	0.48Ac	1.60 Ab	1.67 Ab	2.60 Aa	1.52 Ac	1.19 Bc	2.22 Ab	3.90 Aa	1.10 Ac	2.60 Ab	2.69 Ab	3.16 Aa
	NTWT	0.48 Ac	1.65 Aa	0.92 Bb	0.83 Bc	1.80 Ab	1.94 Aa	1.69 Bc	1.41 Bc	1.30 Ab	1.37 Bb	1.48 Bb	1.93 Ba
								BD (Mg m^{-3})					
Clayey soil	**Row**												
	NTT	1.18 Aa	1.25 Aa	1.24 Aa	1.25 Aa	1.34 Aa	1.34 Aa	1.30 Aa	1.26 Aa	1.39 Aa	1.39 Aa	1.30 Ab	1.24 Ab
	NTWT	1.28 Aa	1.28 Aa	1.30 Aa	1.21 Aa	1.33 Aa	1.33 Aa	1.32 Aa	1.16 Bb	1.31 Ba	1.31 Ba	1.35 Aa	1.23 Ab
	Inter-row												
	NT	1.33 Ac	1.28 Ac	1.43 Ab	1.58 Aa	1.37 Aa	1.35 Aa	1.35 Aa	1.34 Aa	1.34 Aba	1.34 Ab	1.34 Ab	1.42 Aa
	NTWT	1.33 Aa	1.33 Aa	1.33 Ba	1.32 Ba	1.37 Aa	1.37 Aa	1.35 Aa	1.28 Aa	1.34 Aa	1.34 Aa	1.31 Aa	1.30 Ba
								SRP (MPa)					
	Row												
	NTT	0.80 Aa	0.76 Aa	0.90 Aa	0.90 Aa	0.93 Aa	0.94 Aa	0.98 Aa	0.85 Aa	1.43 Aa	1.43 Aa	1.16 Aa	0.72 Ab
	NTWT	1.00 Aa	0.87 Aa	0.71 Aab	0.50 Bb	1.21 Aa	1.21 Aa	1.13 Aa	0.67 Ab	1.40 Aa	1.40 Aa	1.20 Aa	0.67 Ab
	Inter-row												
	NTT	1.25 Ac	1.20 Ac	1.71 Ab	2.77 Aa	1.31 Aa	1.18 Aa	1.18 Aa	1.31 Aa	1.13 Ab	1.24 Aab	1.34 Aa	1.33 Aa
	NTWT	1.33 Aa	1.25 Aa	1.26 Ba	1.25 Ba	1.31 Aa	1.31 Aa	1.29 Aa	0.98 Ab	1.13 Aa	1.13 Aa	1.07 Ba	1.06 Ba

Cane plant – CP; First ratoon -1st; Second ratoon – 2nd; Third ratoon 3rd; Different capital letters indicate significant difference between wheel traffic and without wheel traffic crop cycle, while different lowercase letters indicate significant difference over the crop cycles for the same tillage management by least square means with lmerTest (p <0 05).

During cycles, in the clayey soil, the SRP reduced at row position to 0.80 and 0.62 MPa, from plant cane to the 3rd ratoon under NTT and NTWT, respectively (Figure 13c). In the same cycles and site, the NTT increased by 39% in the inter-row positions (Figure 13d). Similar pattern was observed in sandy loam soil, with SRP increase more intense during the cycles, ~3-fold in the row and inter-row under NTT, reaching values of 2.60 and 3.21 MPa in the 3rd ratoon (Figure 13a). In the same way, although with lower intensity, there was a 43% increase (from 1.05 to 1.50 MPa) under NTWT (Figure 13b).

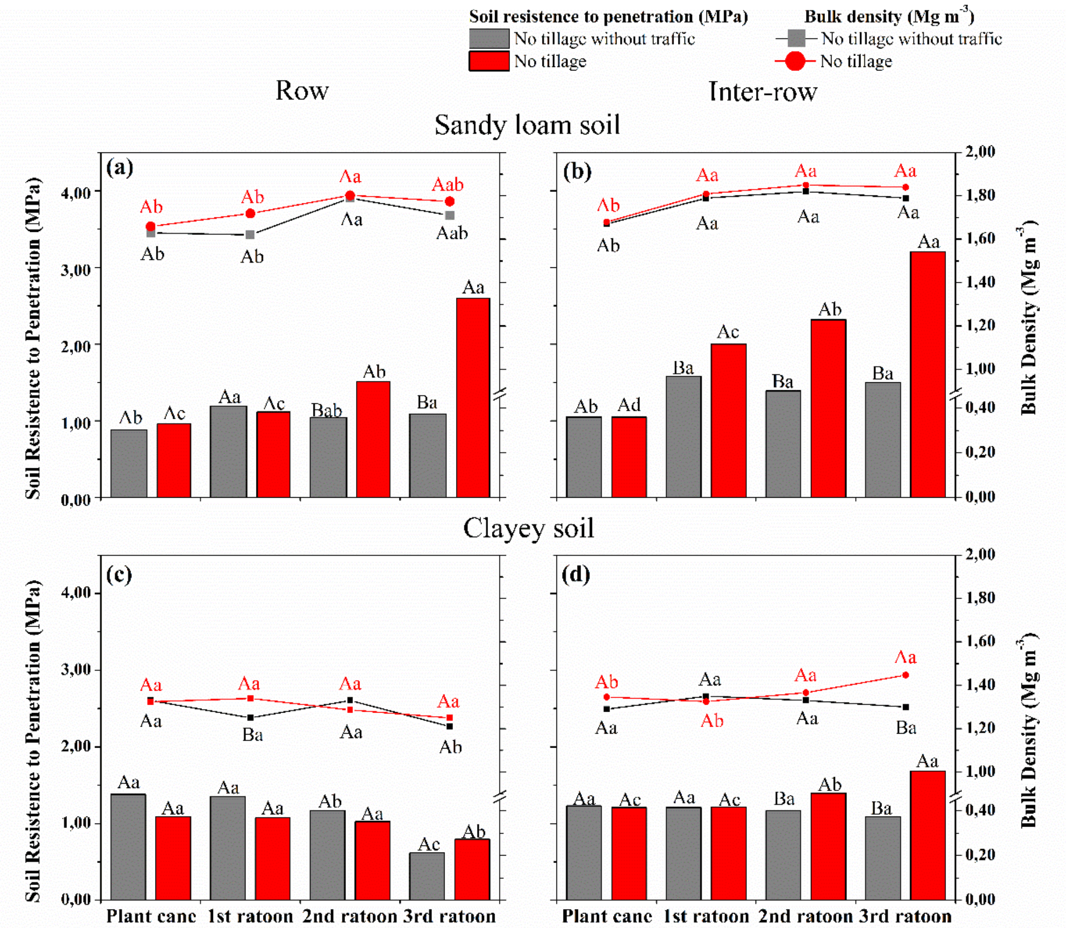

Figure 13. Average soil resistance to penetration (MPa) and bulk density (Mg m^{-3}) values at a 0-0.40 m depth at row and inter-row in a sandy loam and clayey soil managed under no tillage with machinery traffic (NT) and without machinery traffic (NTWT) during sugarcane crop cycle. Different capital letters indicate significant difference between wheel traffic and without wheel traffic in each crop cycle, while different lowercase letters indicate significant difference over the crop cycles for the same tillage management by least square means with lmerTest (p <0 05).

After four years under NT and NTWT treatments, the soil porosity was affected in both sites (Table 5). In general, substantial MaP and MiP differences observed between treatments were site-specific, occurring mainly in the 3rd ratoon. Likewise, in the clayey soil at inter-row, increase in MaP value was observed in the 3rd ratoon under NTWT in all soil layers as compared to NTT, showing values > 0.10 m^3 m^{-3} in all soil layers. On the other hand, reduced MiP was observed in both positions (row and inter-row) from NTWT in three evaluated layers (Table 5). MaP responses in sandy loam soil were similar to clayey soil, showing an increase under NTWT. Thus, the MaP in the crop row under NTWT was 24% and 64% higher than NTT in 1st ratoon, at the 0-0.10 and 0.20-0.40 m layers, respectively (Table 5). In the inter-row, NTWT presented a substantial increase in MaP as compared to NTT, reaching values of 0.26 m^3 m^{-3} in the superficial layer (0-0.10 m). Differences in MiP were observed only between treatments in the 0-0.10 m layer.

MaP values in the 0.40 m layer within the row positions presented the same pattern under NT and NTWT, increasing over the cycles in both evaluated soils (Figure 14). In both sites, specific differences between treatments were observed in both positions. In clayey soil, NTWT showed increase in MaP value in row (from 0.05 to 0.10 m^3 m^{-3}) and inter-row position (from 0.06 to 0.13 m^3 m^{-3}) as compared to the 1st and 3rd ratoon, respectively (Figure 14c, d). The same was observed in the sandy loam soil with a MaP increase of 35% and 33% in row and inter-row positions, respectively (Figure 14a, b).

Table 5. Changes in macroporosity (MaP, m^3 m^{-3}) and microporosity (MiP, m^3 m^{-3}) within the row and inter-row zones in a clayey and a sandy soil managed under no tillage with machinery traffic (NTT) and without machinery traffic (NTWT) during sugarcane crop cycle.

	Treatments	0.0-0.10 (m)				0.10-0.20 (m)				0.20-0.40 (m)			
		CP	1st	2nd	3rd	CP	1st	2nd	3rd	CP	1st	2nd	3rd
						MaP (m^3 m^{-3})							
Sandy loam soil	**Row**												
	NTT	0.20 Aa	0.21 Ba	0.14 Ab	0.23 Aa	0.13 Ab	0.19 Aa	0.08 Ac	0.19 Aa	0.16 Aa	0.14 Ba	0.06 Ab	0.17 Aa
	NTWT	0.20 Ac	0.26 Aa	0.13 Ab	0.25 Aa	0.13 Ab	0.19 Aa	0.09 Ac	0.21 Aa	0.16 Ab	0.23 Aa	0.07 Ac	0.16 Ab
	Inter-row												
	NT	0.16 Aa	0.14 Ab	0.13Abc	0.08 Bc	0.13 Aa	0.14 Aa	0.10 Aa	0.14 Aa	0.14 Aa	0.10 Aa	0.07 Ab	0.12 Aa
	NTWT	0.14 Ab	0.14 Ab	0.15 Ab	0.21 Aa	0.13 Aa	0.13 Aa	0.09 Ab	0.15 Aa	0.14 Aa	0.13 Aa	0.07 Ab	0.14 Aa
						MiP (m^3 m^{-3})							
	Row												
	NTT	0.20 Aa	0.17 Aa	0.19 Ba	0.12 Ba	0.23 Aa	0.18 Ab	0.26 Aa	0.15 Ab	0.21 Ab	0.20 Aab	0.27 Aa	0.16 Ab
	NTWT	0.20 Ab	0.19 Ab	0.25 Aa	0.15 Ac	0.26 Aa	0.17 Ab	0.24 Aa	0.17 Ab	0.21 Aa	0.16 Ab	0.26 Aa	0.18 Aab
	Inter-row												
	NT	0.24 Aa	0.21Aab	0.19 Bb	0.12 Ab	0.24 Aa	0.20 Aab	0.20 Aab	0.17 Ab	0.22 Aab	0.21 Ab	0.24 Aa	0.18 Ac
	NTWT	0.24Aab	0.21 Ab	0.26 Aa	0.17 Ac	0.24 Aa	0.18 Ab	0.20 Aa	0.17 Ab	0.22 Ab	0.21 Ab	0.25 Aa	0.16 Ac
						MaP (m^3 m^{-3})							
Clayey soil	**Row**												
	NTT	0.14 Aa	0.11 Aa	0.11 Aa	0.14 Aa	0.06 Ab	0.06 Ab	0.09 Aab	0.12 Ba	0.02 Ab	0.02 Bb	0.08 Aa	0.13 Aa
	NTWT	0.14Aab	0.11 Ab	0.15Aab	0.19 Aa	0.06 Ab	0.08 Ab	0.09 Ab	0.18 Aa	0.02 Ab	0.11 Aa	0.07 Aa	0.11 Aa
	Inter-row												
	NTT	0.08 Aa	0.08 Aa	0.02 Ab	0.01 Bb	0.05Aa	0.05 Aa	0.05 Aa	0.07 Ba	0.04 Aa	0.07 Aa	0.07 Aa	0.07 Ba
	NTWT	0.07 Ab	0.07 Ab	0.08 Ab	0.15 Aa	0.05 Ab	0.05 Ab	0.07 Ab	0.14 Aa	0.04 Ab	0.04 Ab	0.09 Ab	0.12 Aa
						MiP (m^3 m^{-3})							
	Row												
	NTT	0.41 Aa	0.41 Aa	0.41 Aa	0.38 Aa	0.43 Aa	0.43 Aa	0.41 Aab	0.39 Ab	0.45 Aa	0.45 Aa	0.42 Aab	0.39 Ab
	NTWT	0.42 Aa	0.39 Aa	0.39 Aa	0.35 Ab	0.44 Aa	0.40 Aab	0.41 Aab	0.37 Ab	0.43 Aa	0.39 Aa	0.41 Aa	0.42 Aa
	Inter-row												
	NTT	0.40 Aa	0.41 Aa	0.43 Aa	0.41 Aa	0.42 Aa	0.43 Aa	0.43 Aa	0.41 Aa	0.44 Aa	0.41 Aa	0.42 Aa	0.38 Ab
	NTWT	0.40 Ab	0.40 Ab	0.43 Aa	0.34 Ac	0.42 Aa	0.42 Aa	0.41 Aa	0.37 Ab	0.44 Aa	0.44 Aa	0.41 Ab	0.38 Ab

Cane plant – CP; First ratoon -1st; Second ratoon – 2nd; Third ratoon 3rd; Different capital letters indicate significant difference between wheel traffic and without wheel traffic crop cycle, while different lowercase letters indicate significant difference over the crop cycles for the same tillage management by least square means with lmerTest (p <0 05).

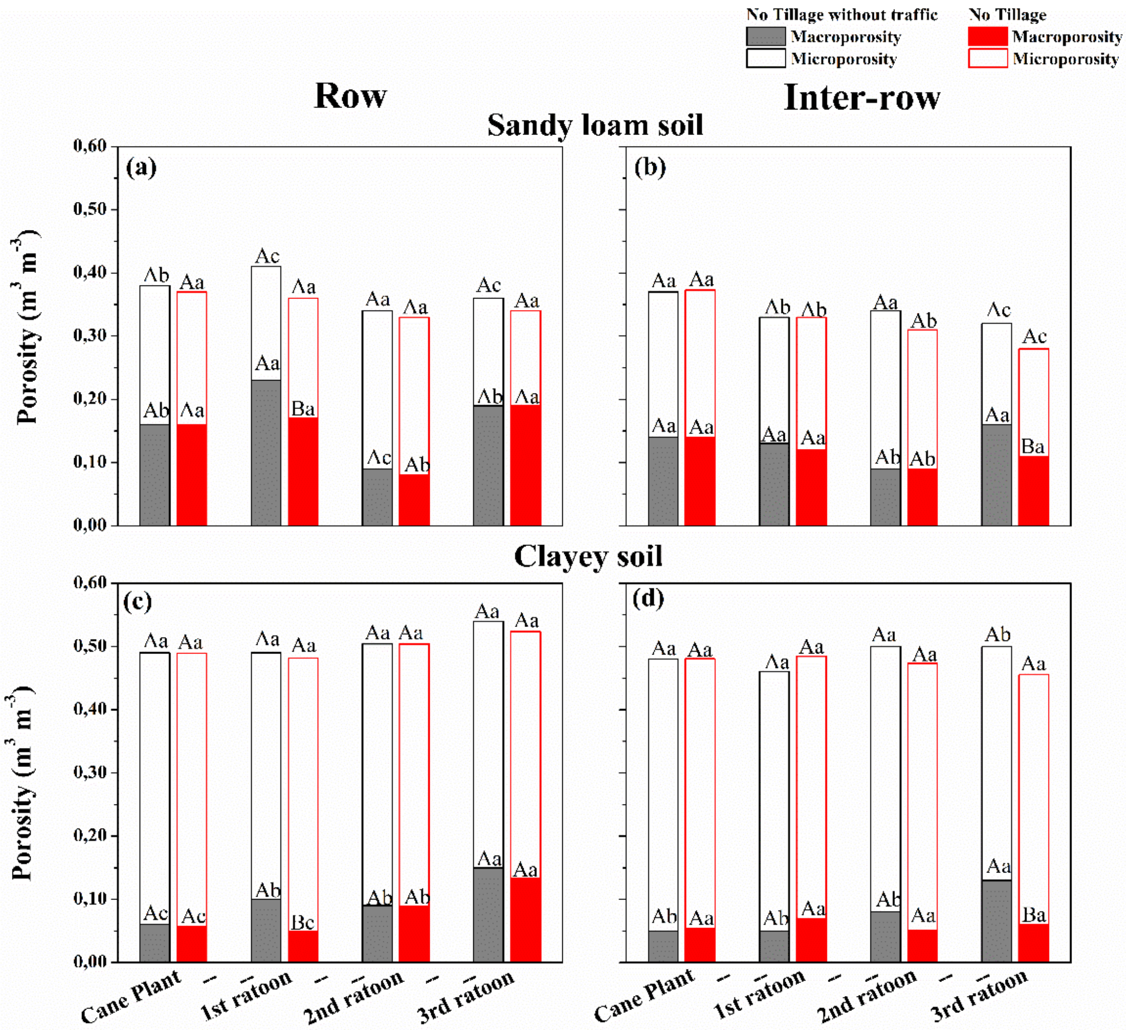

Figure 14. Average values macroporosity (MaP, m^3 m^{-3}) and microporosity (MiP, m^3 m^{-3}) at 0-0.40 m depth in the row and inter-row in a sandy loam and clayey soil managed under no tillage with machinery traffic (NT) and without machinery traffic (NTWT) during sugarcane crop cycle. Different capital letters indicate significant difference between wheel traffic and without wheel traffic in each crop cycle, while different lowercase letters indicate significant difference over the crop cycles for the same tillage management by least square means with lmerTest (p <0 05).

3.3.2 Roots dry biomass

Root biomass data indicate that the NTWT system promoted increases of 120 and 58 kg ha^{-1} in root biomass in the 0-0.10 and 0.20-0.40 m layers as compared to NTT during the 2nd ratoon, respectively (Table 6). In the same cycle, NTWT showed an increase in root biomass of 22% (246 kg ha^{-1}) at a 1 m depth layer, reaching 1337 kg ha^{-1}. In sandy loam soil, the difference occurred only in the 0.60-1.0 m layer, with ~2-fold more root biomass under NTWT in the 1st and 2nd ratoons, respectively.

In clayey and sandy loam soils, root biomass decreased throughout the evaluated cycles, especially in 0.40 m soil depth (Table 6). The clayey soil under NTT management presented an average reduction of 190, 206 and 150 kg ha^{-1} from plant cane to the 2nd ratoon in 0-0.10, 0.10-0.20 and 0.20-0.40 m layers, respectively. Similar pattern was observed under NTWT management, with a root biomass reduction of 192 kg ha^{-1} in the 1st ratoon at 0-0.10 m layer. In the 0.10-0.20 and 0.20-0.40 m layers, the decrease in root biomass under NTWT was 219 and 92 kg ha^{-1}, respectively, from plant cane to the 2nd ratoon.

Considering the 1 m soil profile, the root biomass production in clayey soil reduced 733 kg ha^{-1} in the 1st ratoon, reaching 1045 kg ha^{-1} under both managements. In the 2nd ratoon, there was a reduction in root biomass of 39% and 25% under NTT and NTWT, respectively (Figure 15). In sandy loam soil, the root biomass reduction from plant cane to 2nd ratoon was of 492 and 575 kg ha^{-1} under NTT and NTWT, respectively (Figure 16). The distribution of root system under NTWT revealed in both soil types better production and distribution of roots (Figures 15 and 16). In general, roots concentrated around 40 to 60% on the crop row, in particular at a 0.40 m depth. However, were observed roots increase in NTWT, advancing to the inter-row position throughout the evaluated cycles. On the other hand, the NTT response shown a decrease in root system in the inter-row, with greater intensity in clayey soil.

Table 6. Sugarcane roots dry biomass (kg ha^{-1}) for no-tillage (NTT) with traffic and no-tillage without traffic (NTWT) during de cycles (plant cane, first ratoon-1st and second ratoon-2nd) in clayey and sandy loam soil.

Site	Treat.	Crop cycle	Depth (m)				
			0-0.10	**0.10-0.20**	**0.20-0.40**	**0.40-0.60**	**0.60-1.0**
			Sugarcane roots dry biomass (kg ha^{-1})				
Sandy loam	**NTT**	**Plant cane***	833 a	634 Aa	266 Aa	160 Aa	323 Aa
		1st ratoon	469 Ab	400 Aa	374 Aa	207 Aa	138 Bb
		2nd ratoon	629 Ab	491 Aa	297 Aa	182 Aa	125 Bb
	NTWT	**Plant cane***	833 a	634 Aa	266 Aa	160 Aa	323 Aa
		1st ratoon	469 Ab	285 Bb	271 Ab	267 Aa	334 Aa
		2nd ratoon	370 Aa	410 Ab	390 Ab	191 Aa	280 Aa
Clayey	**NTT**	**Plant cane***	480 a	459 Aa	402 Aa	206 Aa	232 Aa
		1st ratoon	242 Ab	253 Ab	258 Ab	130 Aa	162 Aa
		2nd ratoon	290 Bb	243 Ab	252 Bb	153 Aa	153 Aa
	NTWT	**Plant cane***	480 a	459 Aa	402 Aa	206 Aa	232 Aa
		1st ratoon	288 Ab	194 Bb	208 Ab	176 Aa	177 Aa
		2nd ratoon	410 Aa	240 Ab	310 Ab	171 Aa	206 Aa

Different capital letters indicate significant differences in no-tillage (NTT) with traffic and no-tillage without traffic (NTWT) in each crop cycle, while different lower-case letters indicate significant differences between crops over the crop cycle with or without traffic by least square means with lmerTest (p <0 05). * The plant cane values are the same for both treatments, after the plant cane harvest, differentiation occurred in NTT and NTWT.

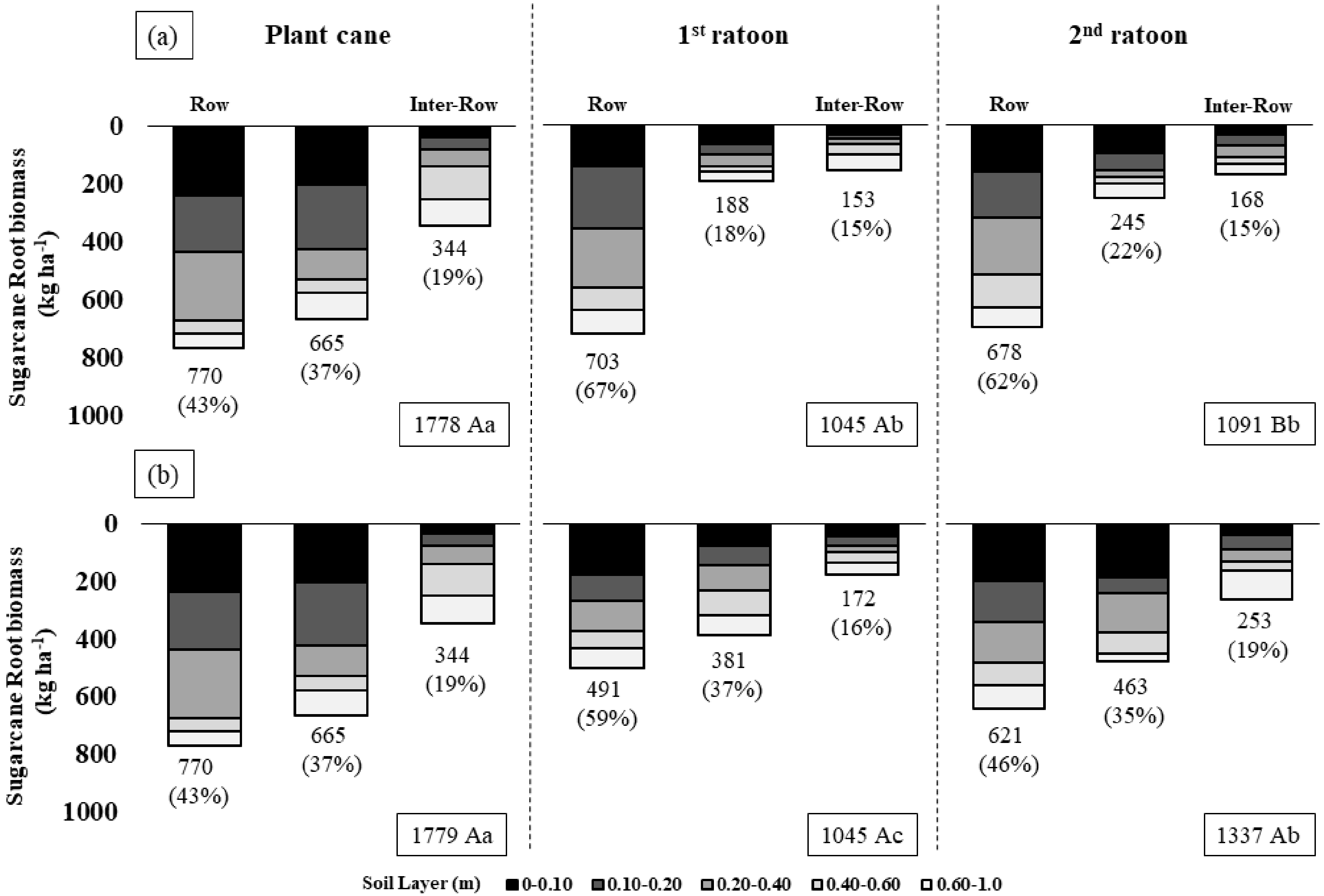

Figure 15. Sugarcane roots biomass (kg ha^{-1}) distribution under no-tillage (NTT, a) with traffic and no-tillage without traffic (NTWT, b) during cycles (plant cane, 1st and 2nd ratoons) in clayey soil. Values of roots total biomass in the soil profile at 1m are found inside the box.

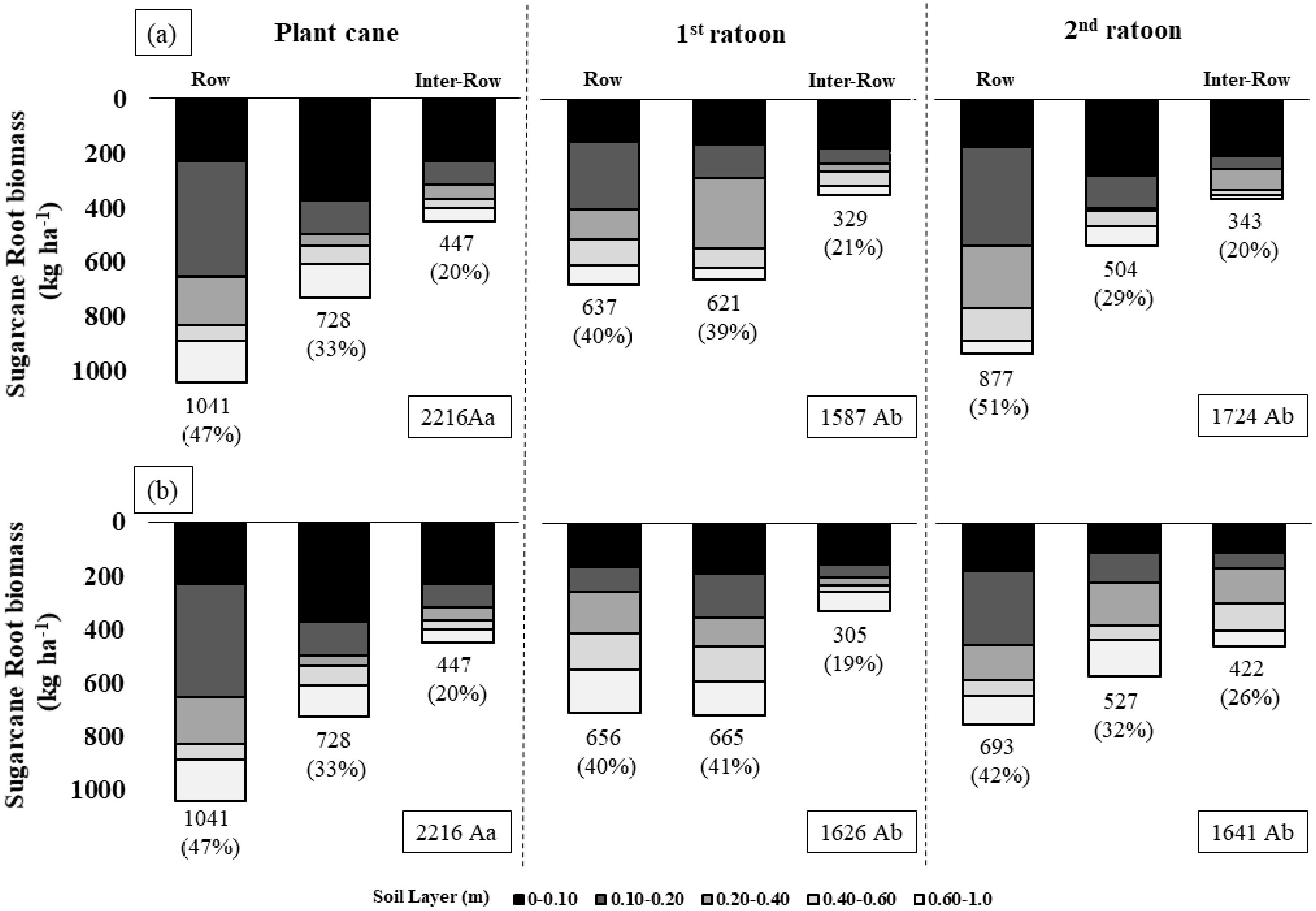

Figure 16. Sugarcane roots biomass distribution (kg ha-1) under no-tillage (NTT, a) with traffic and no-tillage without traffic (NTWT, b) during cycles (plant cane, 1st and 2nd ratoons) in sandy loam soil. Values of roots total biomass in the soil profile at 1m are found inside the box.

3.3.3 Relationship among soil management, physical indicators and limiting conditions for roots growth

The correlation between soil physical indicators and soil management demonstrated that the NTT, particularly in sandy loam soil, shows a tendency of clustering in zones considered as intermediate and restrictive to root development (Figure 17). Thus, the traffic impacts on sandy loam soil promoted a 50% clustering of data (BD x SRP) in limiting zones to root growth (Figure 17a). Similar response was demonstrated by 25% and 38% clustering of MaP, verified in the limiting zone and moderately limiting zone, respectively (Figure 17b). In contrast, at the same site was observed in the NTWT treatment 58% (BD x SRP) and 28% (BD x MaP) of data clustered in non- and moderately limiting zones (Figure 17a, b).

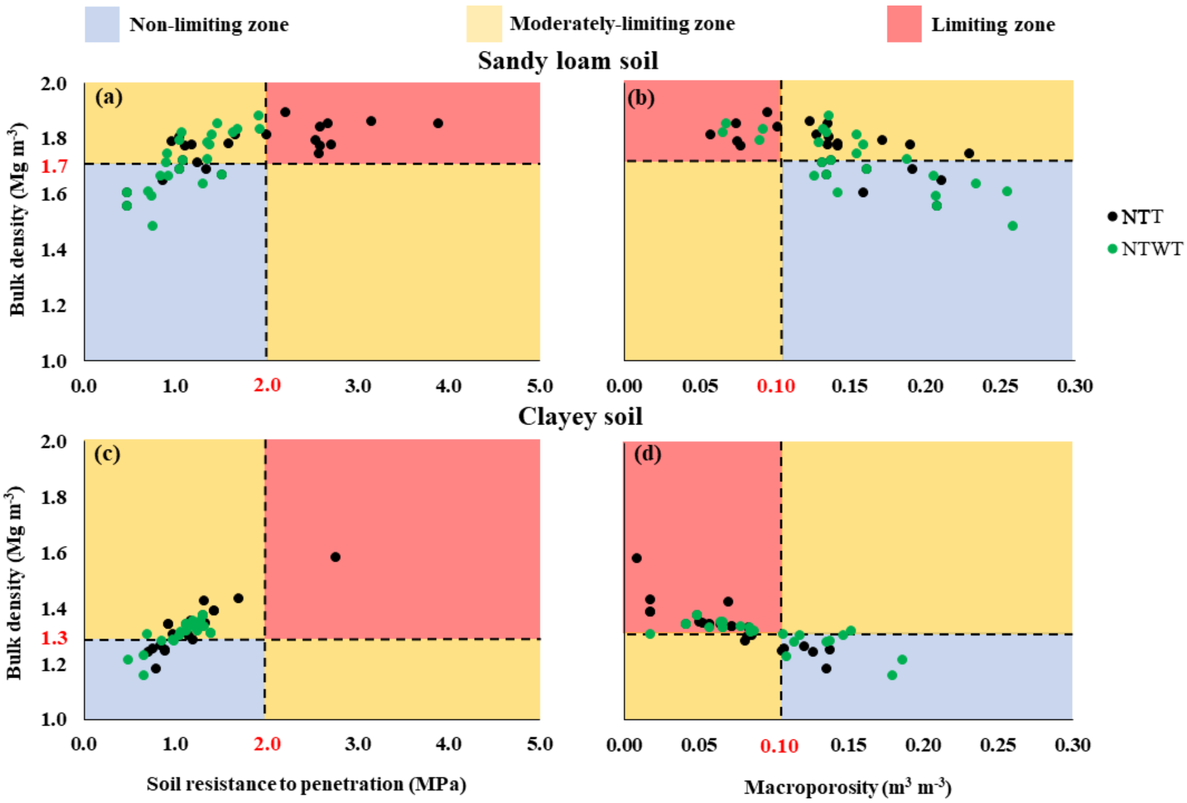

Figure 17. Correlation of bulk density (BD, Mg m^{-3}) with soil resistance to penetration (SRP, MPa) and macroporosity (MaP, m^3 m^{-3}). Black lines indicate the limit of zones (i.e.; non-restrictive, intermediate and restrictive). Red lines indicate BD and SRP values as the critical limit to roots growth as described by Barbosa et al. (2018). For air diffusion a 0.10 m^3 m^{-3} limit was considered. Number of observations (n) = 24 for each treatment.

Clayey soil showed lower concentration of data in limiting zones. It was observed that 42% of NTT data concentrated on the moderately limiting zone with a tendency to advance to limiting zones (Figure 17c). On the other hand, most of NTWT data concentrated between intermediate and non-limiting zones. In the same way, changes on BD and SRP induced an alteration in pore volume, as demonstrated by 75% of MaP data obtained in the limiting zone of root growth under NTWT treatment (Figure 17d).

3.4 Discussion

3.4.1 Impact of machinery traffic on soil physical attributes in the row and inter-row positions

Soil compaction induced by agricultural mechanization is a contentious issue in sugarcane cultivation, motivating discussions in search of alternatives to attenuate the intense and disorderly traffic of machines. In this study, the absence of machinery traffic showed potential to recovery soil physical conditions. In this regard, several studies have indicated the efficiency of reducing traffic for soil structure preservation in sugarcane cultivation areas (Baquero et al., 2012; Esteban et al., 2019; Roque et al., 2010; Sousa et al., 2017; Souza et al., 2015). Thus, lower traffic could be adopted in combination with other different approaches, such as the control of wheel crossings by using autopilot and machinery wheel axle adjustments especially during sugarcane harvesting (Garside et al., 2009; Rossi Neto et al., 2018), in addition to proper resizing of space between plants, or by a combination of all those actions (Esteban et al., 2019).

Soil physical conditions were similar under NTT and NTWT in the row position, enabling adequate soil physical conditions for plant development with low BD and SRP values and increased MaP, thus corroborating the findings of Souza *et al.* (2015) and Barbosa *et al.* (2018). One of the factors accounting for better soil physical conditions in crop row positions was the opening of furrows for sugarcane planting, which disturb around 13% of the soil until 0.40 m (Barbosa et al., 2018). In addition, successive cycles of sugarcane growth and decomposition of root system in row positions are beneficial to soil structure since roots can develop through the points of weakness between aggregates (Braunack and McGarry, 2006), improving aggregation and contributing to the continuity and formation of biopores over time (Reichert et al., 2016; Souza et al., 2015). It is important to highlight that although the trampling in crop row position is relevant problem in sugarcane fields, in these experiments areas this practice was avoided.

On the other hand, increased BD and SRP, with consequent reduction in MaP, was observed in NTT in both sites in the inter-row position. These alterations are indications of soil degradation in sugarcane fields undergoing successively heavy machinery traffic (Braunack et al., 2006; Esteban et al., 2019; Sousa et al., 2017) especially during harvest period (Cavalcanti et al., 2019). Thereby, the most widely used model of sugarcane production in Brazil with 1.5 m spacing promoted repeated traffic in 70% of planted area, especially during harvesting, when track overlapping in inter-rows (due to the need of harvesting one row at a time) causes soil compaction. Thus, every five years the conventional tillage system is practiced under intensive soil management (*i.e.*, subsoiling and plowing operations) to reduce compaction. Therefore, the creation of permanent wheel traffic lanes and the consequent establishment of areas for plant growth (seedbeds) is important to promote better soil conditions for sugarcane production. Recently, in Brazil, practices such as the use of GPS, traffic control, plant spacing adjustment (*i.e.*, planting double and triple line) and adequacy of wheelbase machinery have been adopted to reduce the wheel traffic in sugarcane fields to promote a better soil structure for plant growth.

With this same approach, this study proposed the setting up of seedbeds, which role is to substantially minimize soil compaction and, consequently, reduce wheel traffic. In this study, the absence of machinery traffic for four years, the improved soil physical conditions, showing reduced BD and SRP, and increased MaP. Our findings indicated that the absence of traffic along sugarcane cycle can recovery soil physical quality without the need for tillage practices during sugarcane replanting period. These results are in line with Souza *et al*. (2015) and Esteban *et al*. (2019), reinforcing the importance of reducing machinery traffic by directing it to specific zones, which will provide the conditions to enhance soil physical quality and, consequently, enable the sugarcane root system to growth.

In the long term, the traffic absence associated to NT promoted the natural recovery of soil structure, enhancing better soil physical conditions mainly in the inter-row positions. These results support the findings of McHugh *et al.* (2009), which demonstrated that permanent seedbeds promote soil recovery in association with traffic control and no-tillage management practices. This combination can ensure increasingly benefits for more sustainable productive systems (Luhaib et al., 2017; Tullberg et al., 2007), especially for sugarcane cultivation, as demonstrated in our research.

In addition to our findings, other studies indicated that the reduction of soil tillage practices, combined with straw maintenance provide substantial increase in soil carbon accumulation (Bordonal et al., 2018; Segnini et al., 2013). The increase in soil C stocks will, in turn, affect soil restructuring through the age-hardening phenomenon, which involves the rearrangement and binding of soil particles to form new pores (Moraes et al., 2019, 2017). This, in the long-term, will promote the soil structure recovery (equilibrium) (Reichert et al., 2016) and create better conditions for the root system to develop and “explore” the soil profile. In this context, it is fundamental to distinguish the area intended for wheel traffic from the plant growth area (Braunack and McGarry, 2006; Roque et al., 2010). Other associated benefits associated with the adoption NTWT can be the reduction of fuel consumption and the energy demanded for machinery (Marasca et al., 2015). Higher efficiency in wheel traction in inter-rows positions (soil-wheel) (Roque et al., 2010) was also observed, since tracks are now directed to the same site (McPhee et al., 2015). In addition to these factors, crop longevity in sugarcane areas with traffic control has increased, aggregating several other benefits such as a 43% reduction in greenhouse gas emissions (Chagas et al., 2016). Thus, the use of NT, combined with the strategy of reducing traffic, prevents and minimizes the effects of compaction, preserving soil structure in the long-term, and contributing to increasing productivity and sustainability of sugarcane production.

3.4.2 Traffic machinery effects on sugarcane root system

Machinery traffic compromises soil physical quality even in conservation systems. Our results showed that after four years, the NTWT system presented a better soil physical quality and a reduction in compaction levels, especially in the inter-row positions, which substantially improved root development in the soil profile (Figure 15 and 16). Data show that roots concentrated on soil surface within the crop row. Studies on sugarcane root system soil profile showed that, on average, 60% to 90% of roots concentrate in layers up to 0.40 m depth (Baquero et al., 2012; Barbosa et al., 2018; Otto et al., 2011), and are distributed from 60% to 70% in the crop row, and the remaining in the inter-rows up to a 0.20 m depth (Barbosa et al., 2018).

Roots concentrate in the row position especially because of planting furrows for sugarcane planting promote suitable conditions for root growth (Barbosa *et al*., 2018; Esteban *et al*., 2019). In addition, during sugarcane planting the nutrients are applied in the bottom planting furrow which induce higher root concentration in that position (Carvalho et al., 2017). On the other hand, the low root development inter-row results from the natural physiology of the sugarcane crop and from the soil physical limitations caused by machinery with continuous and disorder traffic overlapping (Barbosa et al., 2018; Souza et al., 2015, 2012), generating a history of compaction over time (Esteban *et al.*, 2019) which directly influences root development (Barbosa et al., 2018; Otto et al., 2011; Souza et al., 2014).

According to the literature, limitations in sugarcane root system development occur under critical BD and SRP values, which are close to 1.70 Mg m^{-3} and 1.50 MPa, and to 1.25 Mg m^{-3} and 2.50 MPa in sandy loam and clayey soil, respectively (Barbosa et al., 2018). MaP lower than 0.10 m^3 m^{-3} (Reichert et al., 2009; Torres et al., 2016) are also considered limiting values. Thereby, sugarcane fields with intense traffic control reach critical limiting zones in the soil, preventing roots from growing (Figure 17), and reinforcing the need for intensive soil tillage every five years, and in shorter periods of time in sandy soils.

On the other hand, by adopting both seedbeds and traffic reduction on the fields, a natural recovery of soil occurs over time since no limiting factors will be present to hamper the root development in rows and inter-rows in no trafficked areas. The adoption of this management increases soil physical quality benefiting greater exploitation of the soil profile by roots and longevity of sugarcane fields. Higher soil profile exploitation by the root system also favors greater water and nutrient uptake, improving the plant productivity (Rossi Neto *et al.*, 2018) which is, according to the authors, fundamental particularly for plants in sandy soils as they have low water retention capacity.

Sugarcane root responses indicate that the reduction of machinery traffic over time foster the improvement of soil physical quality for root development, being a feasible management alternative to increase soil productivity, mainly in sandy loam soils. Therefore, this research points to a new view of sugarcane management since larger planting areas must be protected from machinery traffic, especially during harvesting. In order to achieve the benefits of this practice, a conservation system such as NT should be adopted in conjunction with a machinery traffic configuration (*i.e.*, wheel axis adjustment, autopilot, and spacing) and the alternatives already in place, which should physically distinguish seedbeds from areas exclusively intended for machinery traffic. Over time, these measures will promote the soil restructuring, ensuring a better physical quality of soil for root development and, consequently, for the production of stalks.

3.5 Conclusions

The reduction of machinery traffic associated with no-tillage system over four years promoted the structural recovery of the soil physical quality, without the need for conventional tillage practices during sugarcane replanting period. Thus, the soil physical improvement attenuates the levels of soil compaction, increasing the exploration areas for root system development. Therefore, the findings of this study strongly state the importance of establishing specific zones for plant growth and wheel traffic zones for improvement of soil physical quality. However, further researches on the development of specific zones for both plant development and new machinery structures, especially designed to reduce the wheel traffic impacts on soil, are crucial to ensure the sustainability of soil physical attributes and, consequently the sustainability of sugarcane production.

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4. STRAW REMOVAL EFFECTS ON SOIL PHYSICAL QUALITY AND BIOMASS GROWTH IN SUGARCANE FIELDS

Abstract

Soil physical quality and crop biomass response to sugarcane straw removal management remain important aspects of research to achieve a sustainable increase in straw-derived bioenergy production in Brazil. The objective of this study was to assess the impact of different straw removal rates on soil physical attributes and sugarcane biomass production during three-year period in Brazil. In 2014, a field experiment at clayey and sandy loam soils was established with three straw removal treatments: total removal (TR), moderate removal (MR) and no removal (NR). The soil physical attributes: bulk density (BD), macroporosity (MaP), microporosity (MiP) and resistance to penetration (SRP), and the dry biomass (Mg ha^{-1}) of sugarcane roots and stalks were evaluated annually. Generally, BD was affected at 0-0.10 m depth with an increase during the cycles in a smaller magnitude as the rates of straw removal was reduced (MR and NR). The SRP was high in the 3rd ratoon in both soils where all straw was removed (i.e., TR) reaching values >2.6 MPa at 0-0.10 m depth and in clayey soil during the 1st ratoon with values >1.5 MPa at 0.20-0.40 m. The root biomass decreased with the straw removal rates in the following order: TR>MR>NR. The clayey soil showed higher root biomass than sandy loam soil. The difference in stalk yield was also observed in the clayey soil along the cycles, when the 3rd ratoon had the followed sequence: NR>MR>TR with values of 159, 135 and 121 Mg ha^{-1}, respectively. The significant reduction of sugarcane biomass production was directly related to the decrease in soil physical quality under moderate or total removal rates of straw, proving to be prejudicial for sugarcane production.

Keywords Crop residue management; · Root biomass; · *Saccharum* spp.; · Bulk density; · Soil resistance to penetration; · Soil porosity.

4.1 Introduction

Brazil stands out as the biggest producer and exporter of sugarcane derivatives worldwide (Bordonal et al., 2018a). Thus, a significant increase in bioenergy production is expected in the upcoming years driven by national and international targets to attend the reduction of greenhouse gas (GHG) emissions ("The Paris Agreement – UNFCCC" n.d.) and growing clean energy demand (Carvalho et al., 2017).

The adoption of green harvesting system was the management technique that implicated modifications throughout the sugarcane production system, which has minimized adverse impacts on human and environmental health (Carvalho et al., 2017) and stimulated interest in using crop residues as feedstock for energy and/or cellulosic ethanol production. In the green mechanized harvest system, large amount of straw (10 a 20 Mg ha^{-1} ano^{-1}) is deposited on the soil surface (Carvalho et al., 2013; Franco et al., 2013; Menandro et al., 2017), representing an energy potential by 1/3 of the sugarcane crop (Leal et al., 2013).

Recent studies have revealed tradeoffs associated with indiscriminate removal of sugarcane straw on soil functioning (Cherubin et al., 2018), especially related to the reduction of soil physical quality (Castioni et al., 2018; Lisboa et al., 2019; Satiro et al., 2017). High straw removal rates can reduce soil organic carbon (SOC) stocks (Bordonal et al., 2018b; Satiro et al., 2017) and biological activity (Castioni et al., 2018; Lisboa et al., 2019), damaging water retention and thermal regulation (Corrêa et al., 2017), aggregation and resistance to compaction (Castioni et al., 2018), and consequently increasing the susceptibility of soil loss by erosion (Carvalho et al., 2017). Equally, removal of large amounts of straw also has direct and indirect influences on sugarcane root system growth (Aquino et al., 2015) and stalk biomass production (Aquino et al., 2017; Lisboa et al., 2018). Thus, the straw removal can affect the sugarcane root development mainly during periods of water deficit (Aquino et al., 2015), since the low water availability promotes the decay of root system, and consequently prevents its development under severe conditions (Laclau and Laclau, 2009). According to Aquino et al. (2015), the removal of straw by 25% or more has influence on root development in the soil. Hence, the root system reduction caused by high rates of straw removal may negatively affect the sugarcane productivity response (Carvalho et al., 2013; Smith et al., 2005).

The maintenance of large amounts of straw on the soil can retard sugarcane growth (Lisboa et al., 2018) especially in colder regions. On the other hand, it can promote increased stalk production (Aquino et al., 2017; Aquino and de Conti Medina, 2014) especially in areas under high water deficit. However, the straw amount indicated as sufficient to maintain the crop yield can be site-specific and vary according to soil type and weather conditions. Nevertheless, studies investigating the impacts of sugarcane straw removal on soil physical quality associated with root system and stalks yield production are still scarce. Thus, our study was based on the following hypothesis: straw removal induces soil physical degradation, which impairs the development of sugarcane root biomass and, consequently, reduces stalks yield over time. Therefore, two experiments were conducted in different soil and climatic conditions during three crop cycles (3 yrs.) aiming to: i) evaluate the straw removal effect on soil physical quality indicators and sugarcane biomass development (i.e., stalk and root production); and ii) verify the response and persistence of straw removal effects over time.

4.2 Material and methods

4.2.1. Description of the study areas

The field experiments were conducted in contrasting edaphoclimatic conditions in the central-southern Brazil at two sites: 1) Quirinópolis, Goiás-GO state (18º32'S - 50º26'W, 541 m of altitude) in a Rhodic Eutrudox (clayey soil); 2) Quatá, São Paulo-SP state (22º14'S - 50º42'W, 560 m of altitude) in a Arenic Kandiudult (sandy loam soil), according to soil classification of USA Soil Taxonomy (Soil Survey Staff, 2014). The climate (Köppen classification) of the experiments were classified as follows: For site 1 and 2 the climate classification is tropical zone, dry winter (Aw), with a mean annual temperature of 24.4° and mean annual rainfall of 1400 mm. The characterization of soil physical and chemical attributes (i.e., texture and bulk density) was performed before the installation of field experiments in October 2012 and more details can be found in Table 7. The rainfall was collected monthly from a meteorological station installed within distance to the experimental plots and the climatological water balance was computed according to the methodology proposed by Thornthwaite & Mather (1955) (Fig. 13).

Table 7. Soil physical attributes characterization of the experimental sites (Quirinópolis-GO and Quatá-SP) during the installation period

Sites description	Site 1	Site 2
Location	Quirinópolis-GO	Quatá-SP
Geographic coordinates	18º32'S - 50º26'W	22º14'S - 50º42'W
Elevation (m)	460	541
Mean annual rainfall (mm)	1520	1254
Mean annual temperature (°C)	22.5	20.8
Climate type*	Humid with moderate water deficiency in the winter (B1wA'a')	Dry to a sub-humid with moderate hydric excess in the summer (C1wA'a')
Soil type (USDA-Soil taxonomy)†	Rhodic Eutrudox	Arenic Kandiudult
Soil texture	Clayey soil	Sandy loam soil
Chemical attributes (0.0–0.40 m)[a]		
pH $CaCl_2$	5.6	4.8
SOM (g dm^{-3})	46	12
P (mg dm^{-3})	8	15
K ($mmol_c$ dm^{-3})	3.7	0.4
Ca ($mmol_c$ dm^{-3})	38	12
Mg ($mmol_c$ dm^{-3})	11	3.6
CEC ($mmol_c$ dm^{-3})	75	32
BS (%)	71	48
Physical attributes[b]		
Clay/silt/sand content (g kg^{-1})		
0.0-0.10 m	547/186/267	87/60/853
0.10-0.20 m	561/190/249	108/60/832
0.20-0.40 m	580/195/225	142/57/801
0.40-0.60 m	599/175/226	144/73/783
0.60-1.0 m	592/171/234	159/78/763
Soil bulk density (Mg m^{-3})		
0.0-0.10 m	1.37	1.76
0.10-0.20 m	1.29	1.77
0.20-0.40 m	1.23	1.76
0.40-0.60 m	1.20	1.68
0.60-1.0 m	1.19	1.67

* According to Thornthwaite and Mather (1995);
† Soil survey according to the USDA – Soil Taxonomy (Soil Survey Staff, 2014);
[a] Soil chemical analysis according to Raji et al. (2001). SOM, soil organic matter; CEC, cation exchange capacity; BS, base saturation.
[b]Soil physical attributes were performed according to Blake and Hartge

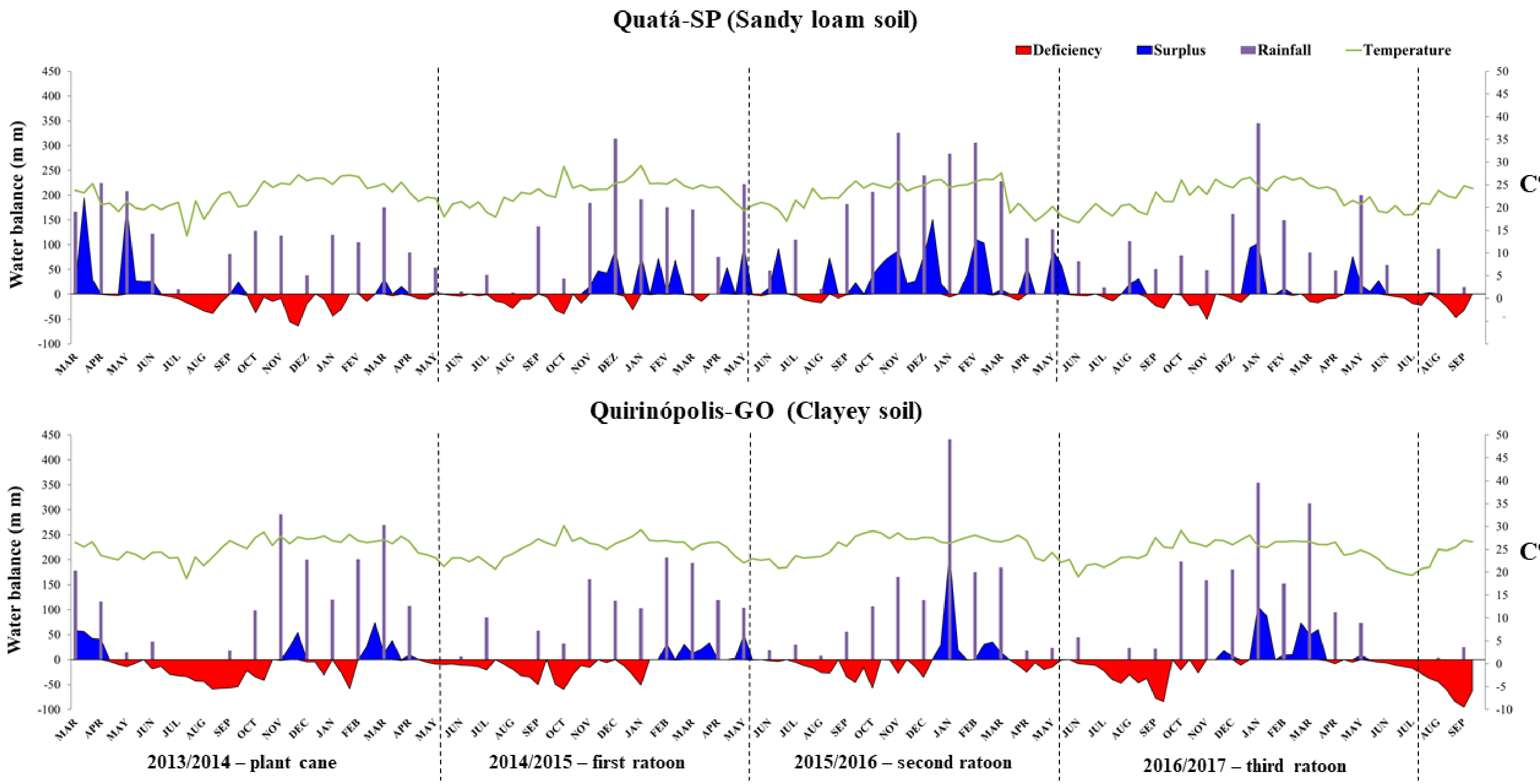

Figure 18. Monthly water balance accounted for the two locations during the sugarcane cycle.

4.2.2. Experimental design and treatments

The treatments were set up in a randomized block design with four replications. Each plot (*i.e*., 10 m long by 15 m wide) was comprised of 10 sugarcane rows at 1.5 m spacing. The soil management used was conventional tillage carried out by a subsoiling with a subsoiler of 5-rows at 0.40 m depth spaced 0.5 m, a light hydraulic harrowing using a harrow of 36 disks at 0.20 m and, after was done the opening of planting furrows at 0.30 m depth over the cover crop biomass using a 2-row planter with spacing of 1.5 m. The practices were executed using a 4x4 tractor of 220cv CASE. In the planting furrow base, fertilizers were applied at a rate of 40 kg N ha^{-1}, 125 kg P_2O_5 ha^{-1} and 125 kg K_2O ha^{-1}. In both sites, sugarcane was planted manually using 15-20 buds per meter with the variety RB96 6928, which presents adequate sprouting and high tillering and is classified as exhibiting an early to medium maturation cycle.

After the plant cane harvest (i.e., 2014), the amounts of straw produced at each site were collected though a square (0.25 m^2) at six random points per area to determine the total biomass input. All straws (e.g., green tops and dry leaves) were collected and weighed, and a sensor was used to quantify the moisture content for dry basis determination. The straw removal treatments were established as follows: i) total removal (TR), all straws were manually removed from soil surface; ii) moderate removal (MR), plots were divided into two symmetrical parts and 50% of its biomass was removed and the other part was uniformly distributed on soil surface; and iii) no removal (NR), all the straw deposited by mechanical harvesting was left on soil surface. These proceedings were repeated for the three following ratoons. The total dry matter (Mg ha^{-1}) produced during each harvest and the equivalent amount of straw left in each treatment are presented in Table 8. In both sites, sugarcane was planted manually using 15-20 buds per meter with the RB96 6928 variety, which presents adequate sprouting, high tillering and is classified as exhibiting an early to medium maturation cycle.

The mechanized sugarcane harvesting was done with harvester (CASE) with treadmill wheels of 0.4 m wide, track width of 1.50 m, and mass of 18.50 Mg. The harvested sugarcane was transported in wagons with capacity to transport 10 Mg of sugarcane, pulled by a 4x4 tractor of 220cv CASE with mass of 13.4 Mg. After 60 days of the sugarcane harvest in each cycle, was applied above the straw layer and 0.10 m away from crop row, the following sources: ammonium nitrate (32% N, rate of 120 kg N ha^{-1}) and potassium chloride (60% K_2O; 120 kg K_2O ha^{-1}). The control of pests, diseases and weed was conducted similarly in all treatments according to management practices of each sugarcane mill.

Table 8. Total dry matter (Mg ha^{-1}) considered for the assessed no removal (NR), moderate removal (MR) and total removal (TR) in the sandy loam and clayey soil, following the harvest of plant cane and two ratoons

Crop cycles	Clayey soil			Sandy loam soil		
	TR	MR	NR	TR	MR	NR
	Straw removal (Mg ha^{-1})					
Plant cane	16.5	8.3	0.0	9.2	4.3	0.0
1st ratoon	17.2	8.6	0.0	12.6	6.3	0.0
2nd ratoon	17.2	8.6	0.0	7.5	3.8	0.0

4.2.3. Sampling and soil physical measurements

Soil sampling was carried out over the first, second and third ratoon cycles (2015, 2016 and 2017 years). Undisturbed soil samples were collected using metal ring (0.05 m in diameter and 0.05 m in height) in trenches (0.30 x 0.30 x 0.40 m) in the row and inter-row positions (spacing of 1.5 m) in soil depths of 0-0.10, 0.10-0.20 and 0.20-0.40 m. In the laboratory, the undisturbed samples were saturated gradually with water by capillary. After saturation, the samples were used to determine the soil microporosity (MiP, m^3 m^{-3}) using a tension table at the soil water potential of -6kPa (Ψ=-0.006). The macroporosity (MaP, m^3 m^{-3}) was computed by the difference between MiP and total porosity The total porosity (TP, m^3 m^{-3}) was estimated according to following equation: TP = 1 (BD/PD). The data of mass water was multiplied by BD to convert into volumetric water. The Bulk density (BD, Mg m^{-3}) was calculated by dividing the soil dry mass obtained at 105 ºC for 48-h by the volume of the cylinder. The soil resistance to penetration (SRP, MPa) was obtained after determining the MiP with the moisture of the balanced sample -6 kPa using the electronic penetrometer (MARCONI®). The upper and lower SRP measures (10 mm) of all samples were excluded following the procedures of Imhoff et al (2010) and Otto et al (2011).

4.2.4 Root biomass sampling

Root biomass sampling was set out over the first and second crop cycles (2015 and 2016 years) before sugarcane harvest in the dry season (June). The root samples were collected using the probe 1.2 m long with an internal diameter of 0.055 m following the methodology described by Otto et al. (2009) in the depth layers of 0-0.10, 0.10-0.20, 0.20-0.40, 0.40-0.60 and 0.60-1.0 m. The soil samples with roots were conditioned in plastic bags and transported to the laboratory where they were washed in running water and separated through sieve (1mm mesh size). Then, the root samples were then oven dried at 65 °C for 72-h to determine the dry root matter. After weighing, the amount of dry root biomass (kg ha^{-1}) was calculated according to the methodology described by Otto et al. (2009).

4.2.5 Statistical analysis

The response variables were analyzed using linear mixed model adjusted in software R 3.3.3 with the lmer function of package lme4 (Bates et al., 2015), allowing us to handle correlated data such as repeated measures. Replicates were considered random effects and straw removal and harvest years were considered fixed effects. Treatments and their interactions were considered different when $p \leq 0.05$. The means reported were least square means and were compared using the packet difflsmeans lmerTest (Lenth, 2016). A principal component analysis (PCA) was conducted to reveal multiple relationships between soil quality indicators and biomass production in straw removal rates and cycles. All analyzes were done in (R Core Team, 2017).

4.3 Results

4.3.1. Soil physical indicators

The straw removal affected significantly bulk density (BD) in both soils. Increasing values of BD were found under moderate removal (MR) and total removal (TR) treatments in the sandy loam soil during the 1st ratoon in the surface layer (Fig. 19b), and similarly in the clayey soil in three soil layers. For example, in the 0-0.10 m layer, the TR and MR treatments presented BD of 1.29 e 1.32 Mg m^{-3} in the 1st ratoon, and in the 3rd ratoon of 1.37 and 1.42 Mg m^{-3}, showing higher values in relation to no-removal (NR) (Fig. 19a), respectively. The same treatments response occurred in the 0.10-0.20 and 0.20-0.40 m layers in 3rd and 2nd ratoon cycles (Fig. 19c, e).

An evident BD increase was observed over the cycles in both sites and it was less impacted by low rates of straw removal. In sandy loam soil, there was an average increase of 3 and 5% from the 1st to 3rd ratoon under TR treatment, reaching values of 1.83 Mg m^{-3} and 1.86 Mg m^{-3} in the 0.10-0.20 and 0.20-0.40 m layers, respectively (Fig. 19d, f). The same occurred in the clayey soil with intensity effect of straw quantities on BD in the superficial layer, increasing ~ 7% under all straw removal rates from the 1st to 3rd ratoon (Fig. 19a). In the 0.10-0.20 and 0.20-0.40 m layers, high BD values occurred only under TR treatment (Fig. 19c, e).

In general, SRP showed differences between the straw removal rates over the cycles and soil layers (Table 9). In clayey soil, the SRP differences under TR reached values by 2.7 and 1.5 MPa in the 0-0.10 and 0.20-0.40 m layers at 3rd ratoon, which were higher than MR and NR treatments, respectively. Likewise, SRP values were 2.6, 2.3 and 2.0 MPa for TR, MR e

NR treatments in the sandy loam soil in 0-0.10 m layer at 3rd ratoon, respectively. (Table 9). The SRP increased over time in both sites. In clayey soil, the TR showed SRP two times (2x) superior than NR at 1st e 3rd ratoon. (from 1.1 to 0.9 MPa) in the upper layer (0-0.10 m). Similarly, in sandy loam soil, the SRP increased following the order TR>MR>NR from 1st to 3rd ratoon, reaching values > 2 MPa at the 0-0.10, 0.10-0.20 e 0.20-0.40 m layers. (Table 9).

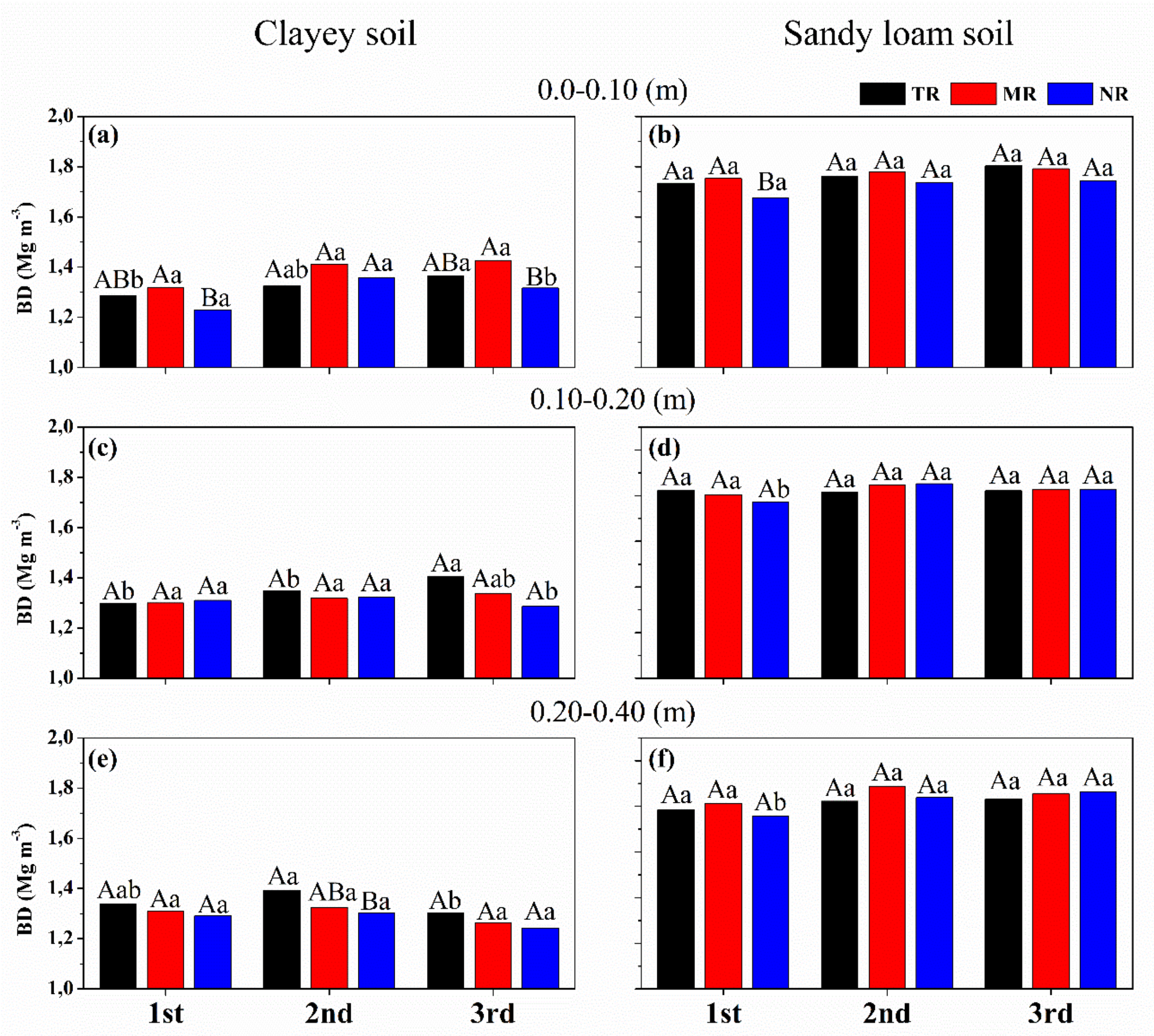

Figure 19. Changes in bulk density (BD, Mg m^{-3}) under different straw removal: total removal (TR), moderate removal (MR) and no removal (NR) in the 0- 0.10, 0.10 - 0.20 and 0.20 - 0.40 m depths in the sandy loam and clayey soil during the sugarcane crop cycles (First ratoon -1st; Second ratoon – 2nd; Third ratoon 3rd). Different capital letters indicate significant differences between the straw removal rates within each crop cycle, while different lowercase letters indicate significant difference over the crop cycles for the same straw removal rate by least square means with lmerTest (p <0 05).

Table 9. Changes of soil resistance to penetration (SRP, MPa) in different straw removal rates (total removal-TR; moderate removal-MR and no-removal-NR) in the clayey and sandy loam soil during the sugarcane crop cycles.

Soil depth (m)	Crop cycles	Clayey soil			Sandy loam soil		
		TR	MR	NR	TR	MR	NR
0-0.10	1st	1.2 Ab	1.2 Aa	0.7 Aa	1.6 Ab	1.2 Ab	1.1 Ab
	2nd	1.4 Ab	1.5 Aa	1.3 Aa	1.7 Ab	1.9 Aa	1.7 Aa
	3rd	2.7 Aa	1.5 Ba	1.4 Ba	2.6 Aa	2.3 ABa	2.0 Ba
0.10-0.20	1st	1.4 Aa	1.2 Aa	1.3 Aa	1.7 Ab	1.9 Ab	1.5 Ab
	2nd	1.2 Aa	1.2 Aa	1.3 Aa	1.6 Ab	2.1 Ab	2.1 Aab
	3rd	1.3 Aa	1.2 Aa	1.1 Aa	3.0 Aa	3.0 Aa	2.5 Aa
0.20-0.40	1st	1.5 Aa	1.1 Bab	1.0 Ba	1.7 Ab	2.1 Aab	2.9 Aa
	2nd	1.3 Aab	1.2 Aa	1.1 Aa	2.0 Aa	2.3 Aa	1.8 Aa
	3rd	1.2 Ab	0.9 Ab	0.9 Aa	2.9 Aa	2.9 Aa	2.2 Aa

First ratoon -1st; Second ratoon – 2nd; Third ratoon 3rd; Different capital letters indicate significant difference between the straw removal rates within each crop cycle, while different lowercase letters indicate significant difference over the crop cycles for the same straw removal rate by least square means with lmerTest (p <0 05).

The MaP changes were evident in the clayey soil with reduction throughout crop cycles, soil depths and increased rates of straw removal, reaching values of 0.05 m^3 m^{-3} (Table 10). Equally, a reduction in MaP in the sandy loam soil occurred under MR in the 1st and 3rd in the surface layer (0-0.10 m) and the 1st and 2nd ratoon in the subsurface layer (0.20-0.40 m) (Table 10). The MiP showed reduction with the adoption of TR and MR treatments during 3rd ratoon at the 0-0.10 and 0.20-0.40 m layers in the clayey soil. In the sandy loam soil, MiP showed differences only in the 2nd ratoon at 0.20-0.40m layer, with high values under lower straw removal rates.

Over the cycles in clayey soil, MaP showed a high decrease during the 2nd ratoon along the soil layers, reaching values < 0.10 m^3 m^{-3} in all straw removal treatments (TR, MR and NR) (Table 10). However, MaP increased in the 3rd ratoon mainly under MR and NR rates. In the same soil, MiP decreased under TR in the 0.20-0.40 m layer, and under MR in the 0-0.10 e 0.20-0.40 m layers. In sandy loam soil, the reduction of MiP occurred over cycles in all evaluated layers, especially in the TR treatment.

Table 10. Changes macroporosity (MaP, m^3 m^{-3}) and microporosity (MiP, m^3 m^{-3}) under different straw removal (total removal-TR; moderate removal-MR and no-removal-NR) in a clayey and sandy loam soil during the sugarcane crop cycles.

Soil depth (m)	Crop cycle	MaP			MiP		
		TR	MR	NR	TR	MR	NR
				Clayey soil			
	1st	0.10 Aa	0.10 Aa	0.12 Aa	0.40 Aa	0.42 Aa	0.39 Aa
0-0.10	**2nd**	0.04 Ab	0.03 Ab	0.05 Ab	0.43 Aa	0.45 Aa	0.42 Aa
	3rd	0.05 Bb	0.11 Aa	0.12 Aa	0.43 Aa	0.31 Bb	0.42 Aa
	1st	0.09 Aa	0.09 Aa	0.09 Aa	0.41 Aab	0.41 Aa	0.41 Aa
0.10-0.20	**2nd**	0.05 Bb	0.09 Aa	0.09 Aa	0.42 Aa	0.40 Aa	0.42 Aa
	3rd	0.09 Aa	0.10 Aa	0.12 Aa	0.37 Ab	0.34 Ab	0.38 Aa
	1st	0.06 Bb	0.10 Ab	0.08 ABb	0.42 Aa	0.39 Aa	0.43 Aa
0.20-0.40	**2nd**	0.06 Bb	0.07 ABb	0.10 Ab	0.41 Aa	0.42 Aa	0.40 Aa
	3rd	0.21 Aa	0.17 Ba	0.17 Ba	0.30 Cb	0.32 Bb	0.38 Aa
				Sandy loam soil			
	1st	0.15 ABa	0.14 Ba	0.17 Aa	0.21 Aa	0.19 Aa	0.20 Aa
0-0.10	**2nd**	0.13 Aa	0.12 Aa	0.15 Aa	0.21 Aa	0.22 Aa	0.21 Aa
	3rd	0.16 ABa	0.12 Aa	0.18 Aa	0.17 Ab	0.19 Aa	0.17 Ab
	1st	0.12 Aa	0.13 Aa	0.14 Aa	0.21 Aa	0.20 Aa	0.20 Aa
0.10-0.20	**2nd**	0.10 Aa	0.11 Aa	0.12 Aa	0.22 Aa	0.20 Aa	0.21 Aa
	3rd	0.15 Aa	0.12 Aa	0.12 Aa	0.16 Ab	0.19 Aa	0.20 Aa
	1st	0.15 Aa	0.12 Ba	0.13 Ba	0.20 Ab	0.20 Aab	0.22 Aa
0.20-0.40	**2nd**	0.09 ABb	0.07 Bb	0.10 Aa	0.25 Ba	0.23 ABa	0.22 Aa
	3rd	0.12 Aa	0.11 Aa	0.14 Aa	0.18 Ab	0.20 Ab	0.18 Ab

First ratoon -1st; Second ratoon – 2nd; Third ratoon -3rd; Different capital letters indicate significant difference between the straw removal rates within each crop cycle, while different lowercase letters indicate significant difference over the crop cycles for the same straw removal rate by least square means (p <0 05).

4.3.2. Sugarcane biomass production

Significant differences in roots biomass (RB) between straw removal rates were found in specific crop cycles and soil profile. Overall, RB decreased with straw removal listed in the order: TR>MR>NR. RB reduction was observed in clayey soil in subsoil (0.20-0.40, 0.40-0.60 e 0.60-1.0 m) under TR and MR rates in the 1st and 2nd ratoon. (Table 5). Regarding the sandy loam soil, differences occurred under NR with high RB values than TR and MR in 1st ratoon at 0.60-1.0 m layer, and 2nd ratoon in the 0-0.10 and 0.20-0.40 m layers.

Table 11. Sugarcane root dry biomass (kg ha^{-1}) under different straw removal rates (total removal-TR; moderate removal-MR and no-removal-NR) during the crop cycles (first ratoon -1st; second ratoon – 2nd) in the clayey and sandy loam soils.

Cycle		**Clayey soil**			**Sandy loam soil**		
		TR	**MR**	**NR**	**TR**	**MR**	**NR**
	Soil layers (m)	**Sugarcane root dry biomass (kg ha^{-1})**					
1st ratoon	0-0.10	305 Ab	320 Aa	404 Ab	395 Aa	496 Aa	541 Aa
	0.10-0.20	233 Aa	311 Aa	252 Ab	329 Aa	363 Aa	442 Aa
	0.20-0.40	143 Ab	159 Ab	200 Ab	277 Aa	250 Ab	390 Aa
	0.40-0.60	78 Bb	172 Ab	152 Ab	141 Aa	175 Aa	304 Aa
	0.60-1.0	93 Bb	192 Ab	265 Ab	328 Ba	256 Ba	522 Aa
2nd ratoon	0-0.10	495 Aa	469 Aa	574 Aa	218 Bb	364 Ba	545 Aa
	0.10-0.20	301 Aa	242 Aa	426 Aa	242 Aa	307 Aa	353 Aa
	0.20-0.40	474 Ba	304 Ca	687 Aa	180 Ba	427 Aa	315 ABa
	0.40-0.60	452 Ba	362 Ca	619 Aa	265 Aa	266 Aa	325 Aa
	0.60-1.0	583 Ba	541 Ba	1219 Aa	271 Aa	247 Aa	206 Ab

Different capital letters indicate significant difference between the straw removal rates within each crop cycle, while different lowercase letters indicate significant difference over the crop cycles for the same straw removal rate by least square means (p <0 05).

Roots system production was different during the cycles. Clayey soil showed increased RB from 1st to 2nd ratoon, and the inverse was observed in the sandy loam soil. In both cycles and sites, an RB accumulation of 50 to 80% was recorded in the superficial layers up to 0.40 m, especially at the row position for all straw removal rates. Likewise, it was verified that the root system distribution in the soil profile was higher according to the sequence NR> MR> TR, mainly in the clayey soil during the 2nd ratoon.

The NR treatment showed greater RB production in all crop cycles. The magnitude of differences between straw removal treatments was noticeable among the sites as observed in the soil profile (i.e., 1 m depth) (Fig. 20). In clayey soil, the RB was 49% (421 kg ha^{-1}) superior under NR than TR treatment in 1st ratoon. In addition, the same soil showed RB increase of 52% (1199 kg ha^{-1}) and 83% (1586 de kg ha^{-1}) under NR in relation to TR and MR in 2nd ratoon, respectively. Similarly, in sandy loam soil RB increased by 50% (730 kg ha^{-1}) and 43% (659 kg ha^{-1}) under NR at 1st ratoon relative to MR and TR, in the order given. In the same site, RB under NR was 1.5 higher than TR in the 2nd ratoon.

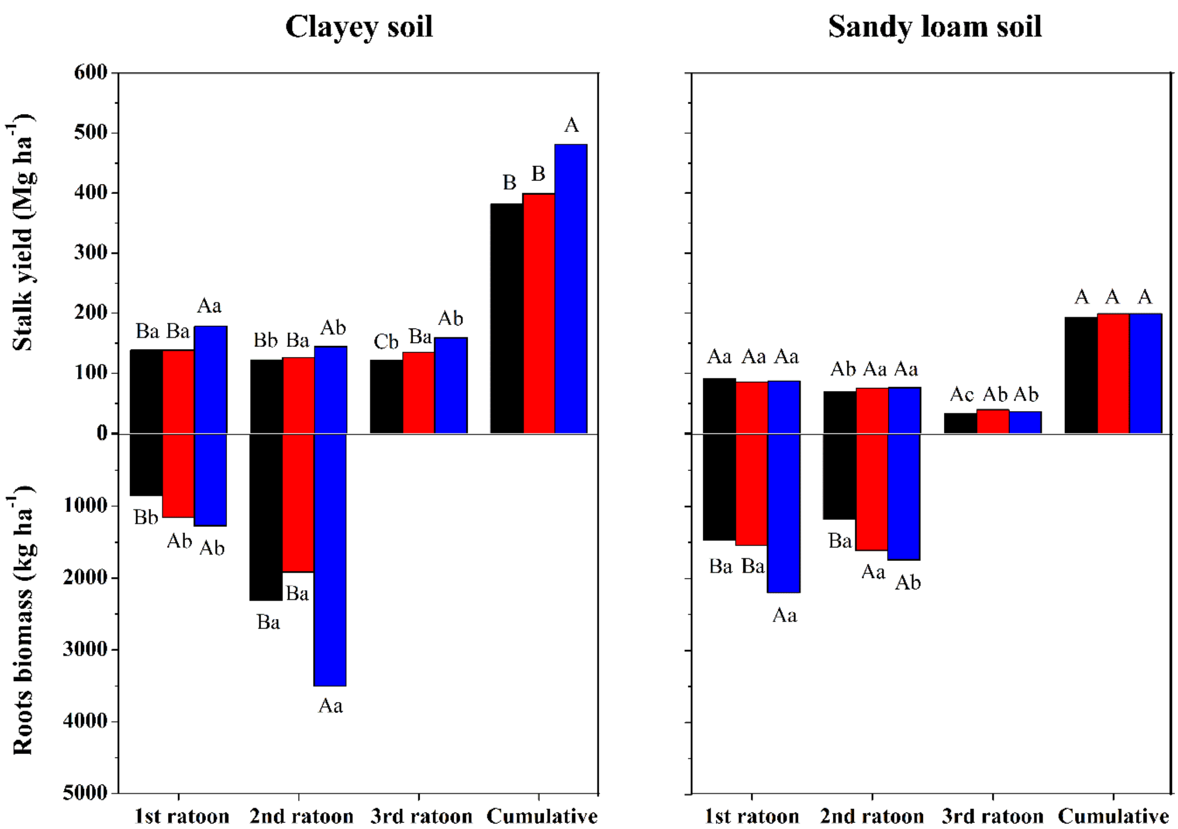

Figure 20. Sugarcane stalk yield (Mg ha^{-1}) and Root biomass (kg ha^{-1}) under different straw removal (total removal-TR; moderate removal-MR and no-removal-NR) during the crop cycles (First ratoon -1st; Second ratoon – 2nd; Third ratoon 3rd) in the clayey and sandy loam soils. Different capital letters indicate significant difference between the straw removal rates within each crop cycle, while different lowercase letters indicate significant difference over the crop cycles for the same straw removal rate by least square means with lmerTest (p <0 05).

The sugarcane stalks yield (Mg ha^{-1}) decreased with the increasing straw removal rates in the clayey soil (Table 12). In this site, NR treatment was higher compared with MR and TR, reaching yields of 178 and 144 Mg ha^{-1} in the 1st and 2nd ratoons, respectively. In the 3rd ratoon, there were differences for all straw removal rates in the sequence NR> MR> TR, reaching yields of 159, 135 and 121 Mg ha^{-1}, according to the order listed. In sandy loam soil, no differences in sugarcane yield was found in relation to straw removal rates. In the short-time, the sugarcane yield decreased under NR and TR in both sites (Table 12). Therefore, the yield reduction in clayey soil occurred from 1st to 3rd by 12% (17 Mg ha^{-1}) and 11% (19 Mg ha^{-1}) for TR and NR treatments, respectively. At same period in the sandy soil, the yield decreased 64% (58 Mg ha^{-1}), 57% (49 Mg ha^{-1}), and 59% (51 Mg ha^{-1}) in the TR, MR and NR, as seen in sequence.

4.3.3 Relationship between soil physical indicators and sugarcane biomass in function of straw removal rates

The principal components analysis (PC) showed multiple relations between soil physical attributes and biomass sugarcane under the straw removal rates and crop cycles in different soil texture conditions at 0.0-0.40 m layer. (Fig 21). The two PCs explained 76% of the data variance in the clayey soil, being 39.03% and 36.73% for PC1 and PC2, respectively. Equally, in sandy loam soil, the two PCs explained 86% of the data variance, whose PC1 explained 46.48% and PC2 39.68%. The PC response was different in relation to soil types with strong correlated variables.

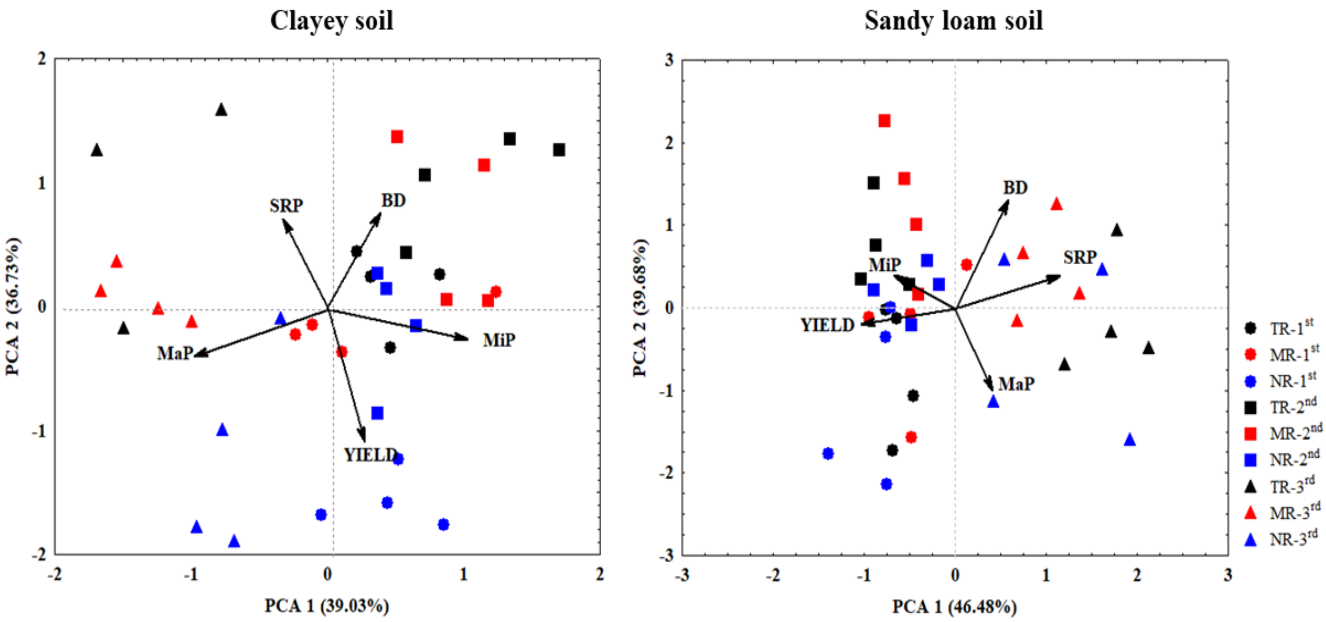

Figure 21. Principle component analysis (PCA) projection of the attributes evaluated for the principal component 1 (x-axis) and 2 (y axis) and loadings of the samples (n=12) categorized by straw removal rates no-removal (NR, blue); moderate removal (MR, red) and total removal (TR, black) and the cycles first ratoon (circle, 1st), second ratoon (square, 2nd) and three ratoon (triangle, 3rd). Soil resistance to penetration (SRP), bulk density (BD), macroporosity (MaP), microporosity (MiP) and yield.

For each type of soil, the evaluative attributes showed different patterns in PC1 and 2. In the clayey soil was retained the attributes MaP and MiP in PC1, and the attributes BD, SRP and Yield in PC2. According to the signs of the loads, the soil MaP was opposite to MiP. In PC2, productivity inversion was associated with BD and SRP; thus, the higher density and resistance to penetration and, lower yield in the clayey soil. In the sandy loam soil, attributes retained in PC 1 were SRP, MiP and Yield, and in PC2 were BD and MaP. Therefore, in this area, the increase of SRP promoted the reduction of MiP and Yield, and it also was verified that an increase in BD promoted the MaP reduction. Due to the PCs relationships, these can be defined as the time effect on soil compaction and the straw removal on soil quality.

Although the biplot plot (Fig. 21) showed that the straw removal effect occurs, it is less significant than time effect. According to the evaluated cycles in the clayey soil, the dispersions indicated different agglomerations by sight, in which were identified in the 1st and 2nd ratoons. Similar characteristics presented themselves when compared to the 3rd ratoon, accordingly these cycles showed higher BD and MiP values. The 3rd ratoon has the characteristic of high values of SRP and MaP. By observing the straw removal effect on soil quality, the NR dispersion was focused on Yield, on the other hand, MR and TR were in the direction to soil compaction attributes, showing higher BD and SRP. In the sandy soil, there were well defined agglomerations in relation to the evaluated cycles, in which the 1st ratoon related to yield, 2nd ratoon with MiP, and 3rd ratoon with BD, SRP, and MaP parameters. In this site, observing the straw removal effect, the dispersion of MR and TR inclined to higher BD and SRP.

4.4. Discussion

4.4.1 Straw removal effects on soil physical indicators

The removal of sugarcane straw promoted negative changes on soil physical indicators and were found to be related to soil quality degradation. This can be observed by our results under TR treatment, which corroborates with other findings under sugarcane fields (Castioni et al., 2018) and corn fields in the USA (Tormena et al., 2017). On the other hand, MR and NR treatments promoted lower BD and SRP values and greater MAP on both sites. This could be associated with positive effects that the presence of straw on soil surface can promote, such as: i) protection against raindrops impact, which reduces soil susceptibility to erosion (Blanco-Canqui and Lal, 2009; Johnson et al., 2016); ii) protection and resilience of the soil structure by organic matter input (Six et al., 2002); and iii) reduction of pressure in the soil imposed by agricultural wheel traffic (Braida et al., 2006; Vischi Filho et al., 2015).

Results showed clear changes in the surface layer and along the crop cycle, mainly in the 3rd ratoon with high values of BD and SRP and low of MaP, which indicates that these soil attributes were highly responsive to soil compaction, as also observed by Castioni et al. (2018). However, the intensity of straw removal effects on soil physical attributes varied according to soil texture, being in agreement with results observed by Satiro et al. (2017).

Given the physical indicators, SRP was the physical attribute more sensitive to temporal changes along the sugarcane cycles and straw management. This indicator is directly correlated with soil moisture and root development. Thus, higher SRP was found under straw removal (i.e., MR and TR) and along sugarcane cycles (i.e., from 1st to 3rd ratoon), showing values > 1.5 and 2.5 MPa, which is considered critical by Barbosa et al. (2018) for root growth in sandy loam and clayey soils, respectively. In our SRP analyzes, the water equilibrium of soil samples was made in the laboratory considering -6 kPa to remove the main effect of the straw in holding soil moisture. The results demonstrated that where there was more straw better conditions were maintained for roots growth by preserving the soil structure.

The soil physical degradation observed over time was a relevant finding in this study, with remarkable changes induced by MR and TR treatments. The intense traffic of machines in all crop cycles promotes the overlap of the wheels impact, causing soil compaction (Arruda et al., 2016; Torres et al., 2015). Furthermore, the effect of straw mulching is likely to protect soil structure from wheel traffic impact, making the soil less vulnerable to physical degradation and consequently softening the changes over crop subsequent cycles. The changes on soil physical indicators were more evident during 1st to 2nd ratoon and decreased with time (from 2nd to 3rd ratoon) due to the compaction process as observed in this research. In addition, during sugarcane harvesting time of each cycle the straw left on the soil did not reflect the initial conditions of straw coverage in the NR and MR treatments, once about 70% of the biomass residues are decomposed in one year (Dietrich et al., 2017; Fortes et al., 2012; Robertson and Thorburn, 2007; Yamaguchi et al., 2017). Thus, at the time of greatest machine impact, the remaining straw in the NR and MR treatments of our study were 6 and 3 Mg ha^{-1} in the clayey soil, and 3.5 and 2 Mg ha^{-1} in the sandy loam soil, which are values below 7 Mg ha^{-1} suggested by Carvalho et al., (2017) as ideal for maintaining soil ecosystem functions. In this context, the necessity of straw permanence is reinforced to guarantee the soil physical quality through protecting against the raindrops effects and machine traffic (Cherubin et al., 2018). Additionally, these better conditions will favor the increase of SOC (Bordonal et al., 2018b; Carvalho et al., 2017), soil aggregation, macrofauna (Castioni et al., 2018) and ensure greater soil structure for the crop root system and biomass production in the long-term.

4.4.2 Changes on sugarcane biomass and its relationship with soil physical indicators in areas managed with straw removal

The production of sugarcane biomass is influenced by environmental conditions (i.e., water, temperature and soil) and the straw retained on sugarcane fields have important functions in maintaining soil moisture for root biomass development, mainly in dry periods. In this study, the evaluation of the root system was conducted in the dry season to capture the effect of water stress period and the results revealed a reduction of the root system with the straw removal. Under water deficit conditions, the reduction of the root system is expected to occur; and under stress conditions may even interrupt its development, which results in roots mortality (Laclau and Laclau, 2009). Aquino et al. (2015) verified that the total removal and low maintenance (0 e 5 Mg ha^{-1}) of straw in the sugarcane crop resulted in lower root production during dry season in clayey soil in the state of Paraná - Brazil.

Nevertheless, the NR promoted ideal conditions for roots growth and distribution, which reflected in an advantage of greater exploration of root system in the soil profile (Fig. 2), corroborating to Aquino et al. (2015). These researchers found that the straw removal of 50% or less (i.e., NR and MR in our study) provided higher root biomass, which seems to have greater maintenance of soil moisture. As noted by Castioni et al. (2018), the soil moisture decreases with the straw removal, and according to Farias et al. (2010), the water availability influences roots exploration in the soil, and as the soil water content increases the root concentration also rises. In the sugarcane crop, studies on soil root development show that 60 to 90% of the root biomass are concentrated on the surface layers to 0.40 m (Barbosa et al., 2018; Cury et al., 2014; Otto et al., 2011; Rossi Neto et al., 2018), with the highest concentration in the crop row position (Barbosa et al., 2018). Thus, it was possible to verify reduction of roots from the inter-row to row position in all the treatments and, consequently lower production of the root biomass in the soil profile, mainly in the TR and MR treatments in both sugarcane cycles and soils.

The root system development have a direct influence on the biomass production of sugarcane (Carvalho et al., 2013; Rossi Neto et al., 2018; Smith et al., 2005). As observed in this research, higher production of root biomass reflected in higher stalk yield. However, the biomass production (i.e. stalk and roots) is directly balanced by climate and soil conditions, presenting different responses for the same variety (Rossi Neto et al., 2018).

The results demonstrated that NR treatment in the clayey soil provided an increase of 22% (40 Mg ha^{-1}) and 14% (20 Mg ha^{-1}) in the stalks biomass compared to MR and TR in the 1^{st} and 2^{nd} ratoon, respectively. In the same soil, the straw removal effect was evident in the 3rd ratoon with a reduction of 15% (24 Mg ha^{-1}) and 24% (38 Mg ha^{-1}) of the stalks biomass in MR and TR treatments. This can be explained by the permanence of crop residue that facilitated the root growth into the soil during periods of drought, which resulted in higher sugarcane yield. On the other hand, there was no yield response among straw removal rates in short-term in the sandy loam soil. This is believed that this occurred because of the high rate of water infiltration and loss by evapotranspiration in this type of soil (Corrêa et al., 2017), along with the low fertility condition that did not favor the crop development. In addition, even under the most favorable environment with higher amount of straw (NR treatment) it was also not sufficient to promote the necessary conditions for sugarcane yield increase. Thus, under environments with these characteristics it is not advisable to remove the straw, because even if there was no increase of yield in the short-term, the straw remaining in the soil in the long-term together with conservationist tillage management can preserve and improve soil structure with organic matter and nutrients supply.

According to the literature, other studies found that straw removal induces reduction of sugarcane yield. Aquino et al. (2018, 2017) showed that maintaining 50% (10 Mg ha^{-1}) of the straw is sufficient to increase the sugarcane yield by 47%, and another 50% can be removed for bioenergy production. Lisboa et al. (2018) found that 4-9 Mg ha^{-1} of straw left on the soil is adequate to maintain the crop productivity. Oliveira et al. (2016) verified that to increase cane yield it is necessary to maintain 9.5 Mg ha^{-1} and 4.7 Mg ha^{-1} of straw in the first (1st ratoon) and second cycle (2^{nd} ratoon), respectively.

The integrated analysis of soil quality indicators (0-0.40 m) and sugarcane biomass production showed significant modifications by the straw management over time. Overall, there was a direct relationship among the degradation of soil physical quality and reduced cane yield with the increasing straw removal rates (MR and TR) along the cycles and both soil types. Lisboa et al. (2019) also observed a strong correlation among soil physical quality and cane yield under straw removal in different soil types. According to these authors, prioritizing the monitoring of soil physical attributes is important to ensure sustainable sugarcane production. Thus, the NR (clayey ~ 17 Mg ha^{-1} yr^{-1} and sandy loam soil ~ 9.7 Mg ha^{-1} yr^{-1}) would be the appropriate management to preserve soil physical quality and improve yield in the short and long-time under sandy soil texture.

The impact of straw management on the reduction of soil physical quality and cane yield was more evident in sandy loam than in clayey soil, especially when the straw was removed (MR and TR) from the field. Clayey soils are more resilient to physical changes since the higher cohesive forces between the soil particles and the interaction with SOC (Bonetti et al., 2017) ensures better structural stability (Braga et al., 2005). On the other hand, the major changes in sandy soil can be attributed to low structural stability (Dal Ferro et al., 2014), the less SOC stocks (Bordonal et al., 2018b) and the weak interaction between the soil particles with organic compounds (Braida et al., 2010). Thereby, the long-term input of crop residues will promote formation of soil aggregates, ensuring greater soil stability and a favorable environment for the root system with water and nutrients (Reichert et al., 2016).

4.5. Conclusions

In the short-term, MR (moderate removal) and TR (total removal) treatments promoted soil physical degradation in relation to NR (no-removal), which supported our hypothesis. NR improved soil physical quality in both sites, promoting better values of soil physical indicators. The biomass production of cane stalks and roots was negatively influenced by the MR and TR treatments. Furthermore, NR promoted increased biomass of stalks and roots in clayey soil. Overall, the results demonstrated that MR and TR in the short-term on both sites promoted a reduction of soil physical quality, impacting the sugarcane biomass production, in which was more evident in the sandy loam than clayey soil.

This research demonstrated that it is not feasible to remove straw in the short-term, especially in sandy soil areas. On the other hand, in areas of clayey soils the study verified the possibility adopting MR of sugarcane straw. However, more long-term researches are needed to understand the straw removal effects on the soil physical quality and sugarcane biomass production. Another important point is to promote research associated with no-tillage and traffic control to enable the straw removal practice without reducing soil physical quality. Thus, the sector has to support decisions that will contribute to the increase of sustainable bioenergy production in Brazil.

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5. FINAL REMARKS

Currently sugarcane sector had experienced a reduction in crop yields influenced by factors such as the high impacts mechanized operations from the planting until biomass harvesting. However, these impacts can be intensified according to crop cycles, maintenance of residues, machinery traffic, soil texture and management. Thus, the aim of this study was to evaluate the changes imposed by soil tillage, traffic reduction and straw removal in the soil physical attributes and sugarcane biomass production in the long-term.

Thereby, we verified that no-tillage (NT) can be an alternative in the sugarcane crop in view of the need for conservationist management to replace conventional tillage (CT) stated in the first chapter. This was verified by the short effect of the CT system on the maintenance of soil physical conditions after soil tillage, which after one cycle reached the same response in the inter-row with high bulk density (BD) and soil resistance to penetration (SRP) values, and low macroporosity (MaP), previously presented as a consequence of wheel traffic in NT. The opening furrow for sugarcane planting was also a factor that ensured NT in the sugarcane crop, which was enough to promote the crop development in both CT and NT systems (Barbosa et al., 2019). In addition, it reduced soil structure disturbance and promoted the constant maintenance of plant residues.

In both NT and CT systems, there was no difference in sugarcane stalk production. Nevertheless, high machine traffic is still the greatest obstacle to implement these systems in the crop. Thus, it is believed that to make the NT system feasible, it needs plausible practices to reduce machinery traffic in the fields. So, in the second chapter, we verified that the efficiency of NT in sugarcane can be increased when associated with the reduction of agricultural machinery traffic. The results showed that, in the absence of wheel traffic, the soil promoted a natural recovery over time, reducing compaction levels in relation to current practices that promote high soil disruption. In this way, the practice of reducing wheel traffic contributed to reduce of BD and SRP, increase MaP and creating a seedbed without trampling for the crop, which favored root development and as consequence can potentialize biomass production increase.

In this context, there is also interest of using the sugarcane straw for bioenergy production that has raised the question of what would be the impact of straw removal on soil physical quality and development of stalk and crop roots. Therefore, in the third chapter, we observed that the moderate removal (MR) and total removal (TR) of straw during three years promoted reduction of soil physical quality in relation to no-removal treatment (NR). Similarly, MR and

TR presented negative influence on the production of sugarcane stalks and roots biomass. These changes have different responses which were more evident in sandy soil over crop cycles.

Overall, the results of this study analyzed the performance of management practices aimed to preserve soil quality, and to increase sugarcane yield. Therefore, to achieve the sugarcane production efficiency, some steps need to be considered as i) soil conservation with no-tillage system; ii) practices that physically differs the plant region from the wheel traffic region, and iii) straw maintenance on the soil to improve soil physical quality. Thereby, the association of these practices may enable straw removal management without promoting soil degradation and reduced yield. Nevertheless, long-term studies involving all these practices are fundamental for understanding the holistic soil and plant effects to develop new management practices aimed at sugarcane sustainable production.

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