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Soil Compaction Curve of an Oxisol under Sugarcane Planted after In-Row Deep Tillage

SOIL COMPACTION CURVE OF AN OXISOL UNDER SUGARCANE PLANTED AFTER IN-ROW DEEP TILLAGE

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ABSTRACT

Soil tillage that maintains the productivity of sugarcane plantations, providing an area for the root development and without traffic on crop rows, has given rise to new technologies in rural areas. The purpose of this study was to evaluate the soil physical properties in two sugarcane plantations, one of which was prepared with deep tilling and the other with conventional tillage. The experiment was conducted in Lençóis Paulista, São Paulo State. Soil penetration resistance and relative density were analyzed. The cone index was lower in deep-tilled soil without traffic in all layers, than in deep-tilled soil with traffic and in conventional tillage. In both tillage treatments, the relative density values were acceptable in the 0.00-0.15 m soil layer, but considered detrimental for sugarcane development in the 0.15-0.30 and 0.30-0.45 m layers.

Keywords: soil management, soil tillage, subsoiler, traffic control system, *Saccharum spp.*

RESUMO: *COMPACTAÇÃO DO SOLO EM UM LATOSSOLO VERMELHO CULTIVADO COM CANA-DE-AÇÚCAR UTILIZANDO EQUIPAMENTO DE PREPARO PROFUNDO E CANTEIRIZADO DO SOLO*

Um preparo de solo que seja capaz de manter a produtividade dos canaviais, proporcionado a cultura área de desenvolvimento radicular e sem tráfego em cima da cana-de-açúcar, tem impulsionado novas tecnologias no meio rural. Este trabalho objetivou avaliar o comportamento dos atributos físicos do solo em duas áreas de cultivo de cana-de-açúcar sendo uma delas manejada com equipamento de preparo profundo canteirizado e a outra, pelo método de preparo convencional. O experimento foi realizado em Lençóis Paulista, São Paulo. Os atributos analisados do solo foram a resistência à penetração e a densidade relativa. O Índice de Cone do Solo (ICS) apresentou valores menores no Preparo Profundo Canteirizado sem tráfego (PPC sem tráfego) para todas as camadas em comparação ao Preparo Profundo Canteirizado com tráfego (PPC com tráfego) e ao Preparo Convencional (PC). Para ambos os tratamentos, a Densidade Relativa do Solo (DRS) apresentou valores aceitáveis para a camada de 0,00-0,15 m; nas camadas de 0,15-0,30 e 0,30-0,45 m, foi considerada prejudicial ao desenvolvimento da cultura.

Palavras-chave: manejo do solo, mobilização do solo, subsolagem, enxada rotativa, Saccharum spp.

INTRODUCTION

In the 2013/2014 growing season, an estimated acreage of 8.8 million hectares of sugarcane was harvested, making the State of São Paulo the largest producer, with a 52 % share of the total cane-producing area. In addition, the recovery of degraded cultivated areas in 2014 increased the sugarcane area, compared to the 2013 growing season by 3.8 % (Conab, 2013). Sugarcane is one of the most successful agricultural crops in Brazil, and, due to the high economic returns, interesting for the food industry and as alternative energy source (Andrade et al., 2011).

In recent years, mechanical harvest has induced changes in sugarcane cultivation. Although straw mulch left on the soil can reduce the pressure of machine wheels, successive operations of mechanical harvest and stalk transport, performed by heavy equipment, can cause soil compaction and compromise the productivity in subsequent growing seasons (Otto, 2012).

Sugarcane root system reaches greater depths than other crops, with rhizomes and fasciculate roots, of which 85 % is found to a depth of 0.50 m and 60 % in the 0.20-0.30 m layer, where the crop is most affected by soil compaction (Lima et al., 2013a).

The intensive use of agricultural equipment for all agricultural operations (sowing, crop treatments and harvesting) has increased soil compaction, affecting mainly the area exploited by the plant rhizosphere. The main reason for this phenomenon is the repetition of operations over years (Oliveira et al., 2003).

A possible alternative is to establish soil patches in the sugarcane plantations. In this case, the minimum tillage management includes the tilling of soil patches. This means that the soil is tilled, limed and fertilized only in the rows where sugarcane will be planted. No soil improvement treatments are applied in the inter-rows, reserved for machine traffic. This reduces compaction in the crop rows, caused by the pressure of harvester tires, transshipment vehicles and even by the presence of field workers (Rossetto et al., 2011).

To reduce machine traffic in sugarcane plantations, and to minimize the working stress and increase the efficiency of vehicle operators, in terms of number of working hours and effective nighttime operations, Oliveira and Molin (2011) suggested the installation of autopilot systems. Soil tillage prior to sugarcane planting is crucial for crop longevity, since the soil is only plowed again after the fifth or sixth sugarcane harvest, depending on the variety and/or productivity (Carvalho et al., 2011).

Brazil has one of the world's most extensive agricultural areas with sugarcane and palm trees for ethanol and sugar production in highly mechanized systems, which can modify the soil physical properties and cause compaction (Souza et al., 2012). Soil compaction influences all stages of crop development. Nevertheless, in many areas with low sugarcane yields, the critical values and effects of soil compaction are ignored, while the producers claim not to know the location and intensity of soil compaction (Oliveira Filho et al., 2015).

Soil compaction in sugarcane systems has been attributed mainly to mechanical harvesting in periods of high moisture content in the soil (Pankhurst et al., 2003), resulting in a reduction of the total porosity and consequent increase in bulk density, mainly in the 0.20-0.40 m layer, due to the absence of soil disturbance (Carvalho et al., 2011). Several authors suggested that soil compaction is determined by physical properties such as bulk density, pore-size distribution and aggregate stability in water, or by soil penetration resistance

(Assis and Lanças, 2005). Soil susceptibility to compaction is a function of factors such as moisture content and texture, which influence the soil behavior when subjected to external pressure such as friction and bonding of particles (Macedo et al., 2010).

The purpose of this study was to evaluate soil compaction by the Cone Index and Relative Density methods, managing the soil with in-row deep tillage as well as conventional tillage.

MATERIAL AND METHODS

Experimental setup

The study was conducted in an area of a partner company of the group Zilor, PHD Cana, in Lençóis Paulista, Sao Paulo State (22° 40' S and 48° 53' W). The climate is temperate warm with a dry season from April to August and a rainy season from September to March; January is the wettest month. The soil of the area is classified as *Latossolo Vermelho* (Oxisol), with a medium sandy texture with 16 % sand (Embrapa, 2013).

In both treatments, seedlings were planted at a spacing of 0.90 × 1.50 m, with 2.40 m in-between the wheel tracks. Seedlings of the variety RB 966928 were planted and first cut at the age of 15 months (Figure 1).

The study area was divided in two subareas of 2.5 ha each (500 × 100 m), for the two soil tillage treatments: In-row deep tillage (IRDT) and Conventional Tillage (CT). Each treatment was subdivided into four 100-m long plots in the direction of the crop rows, with a 30 m wide border (Table 1). Both soil tillage treatments were replicated four times, and data collected in 2012 and 2013.

The variety RB 966928 was developed by the sugarcane breeding program of the Federal University of Paraná, has a particularly high sucrose content, when grown in environments with medium to high production potential. In addition, RB 966928 is tolerant to the diseases rust, coal, scald, red stripe, false red stripe, rickets, mosaic, and drill (PMGCA, 2015).

In-row deep tillage equipment

The equipment used for the intensive in-row deep tillage of soil consists of components that allow the performance of five operations or functions at once, which coined the popular name "Penta". The equipment consists of a subsoiler rod, a lime application mechanism, a fertilizer application mechanism with adaptable application depth (0.40 to 0.80 m), a rotary hoe to break the soil crust and a system to raise crop rows (formation of plant beds in rows).

Table 1. Description of both soil tillage systems in an area of *Latossolo Vermelho* (Oxisol)

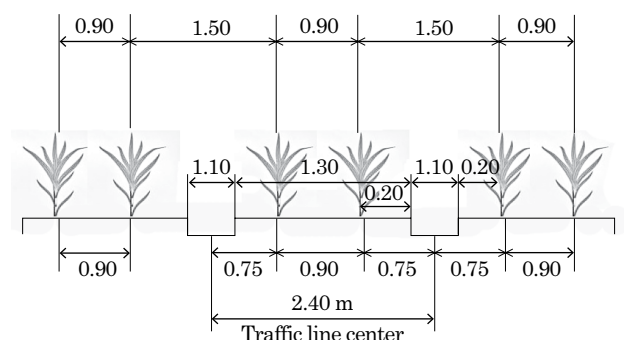| In-row deep tillage (IRDT)	Conventional tillage (CT)
Harrowing	Harrowing
In-row deep tilling	Subsoiling
Lime and gypsum application	Lime and gypsum application
Furrowing	Furrowing
Filter cake application	Filter cake application
Seedling planting	Seedling planting
Furrow covering	Furrow covering

Figure 1. Sugarcane spacing in this experiment in two soil tillage treatments: In-row deep tillage and Conventional Tillage.

The tractor-drawn "Penta" is manufactured by Mafes Equipamentos Agrícolas, with a coupling system on the drawbar of the tractor (total height 3.00 m, total width 3.70 m, width of working bar 1.20 m). The rotary hoe has 16 knives, with a working depth of 0.30-0.40 m, and a central gearbox with a rotation of 540 rpm at the power outlet.

Soil penetration resistance

To measure soil penetration resistance, we used a mobile sampling soil unit UMAS (Unidade Móvel de Amostragem do solo, figure 1), developed at the test center for agricultural machinery and tires NEMPA (Núcleo de Ensaios de Máquinas e Pneus Agrícolas do Departamento de Engenharia Rural), of the College of Agricultural Sciences (FCA/UNESP) in São Paulo State (Lanças and Santos Filho, 1998).

Tillage was performed at a soil moisture content of 0.12 kg kg^{-1} and harvest at 0.10 kg kg^{-1}. Soil tillage operations were performed in areas with a soil friability between 0.12 and 0.14 kg kg^{-1} (Figure 2).

The UMAS can be transported on the road, pulled by cars or pickup trucks, and in the field, by a tractor (Figure 1), using a hydraulic system as power source to drive the two mechanisms: soil auger and penetrometer (Lanças and Santos Filho, 1998). The penetrometer was used to evaluate soil

(a)

(b)

Figure 2. Evaluation after soil tillage (a) and after sugarcane harvest after 15 months (b) with the mobile soil sampling unit.

penetration resistance at certain points. The data were collected by a load cell, model CS 1000, Líder Balanças, fixed to a rod, recording the displacement by a multi-turn potentiometer and penetrometer speed set at 30 mm s^{-1}, according to the standards of ASABE (2012).

The variable soil penetration resistance was evaluated in the form of a curve. In 2012, samples were collected at 15 points, 4 in the wheel tracks alongside the crop rows, and 7 in the crop row. In 2013, only the 7 points in the crop row were sampled, to avoid sugarcane trampling. The curves were assembled with the collected mean values, and the treatments divided into 4 sections, with 4 random locations per section, totaling 16 curves with 15 sampling points per treatment (in-row deep tillage and conventional tillage, with a total of 480 (240 + 240) points, sampled after soil tillage in 2012.

Soil penetration resistance was measured to a depth of 0.45 m, and separated in layers (0.00-0.15, 0.15-0.30 and 0.30-0.45 m). From soil penetration resistance values, the soil cone index was calculated as described by Lanças and Santos Filho (1998).

Relative soil density

Samples for soil density determination to calculate relative soil density were obtained after soil tillage and sugarcane harvest in both treatments. For soil density evaluation, undisturbed soil samples were taken with an auger.

The assessments of in-row deep tillage (IRDT) were divided in two categories: with traffic (traffic with IRDT), where the transshipment truck was driven in the inter-row, and without traffic (IRDT without traffic), resulting in a total of 224 samples. The same was done for conventional tillage (CT) with 112 samples, where the areas with traffic could not be distinguished from those without traffic, with a total of 336 sampling points in 2013.

A total of 24 soil samples were taken per treatment and year (2012 and 2013), 12 from the plant line and 12 from the wheel track, in the 0.00-0.15, 0.15-0.30, and 0.30-0.45 m layers, to determine soil density.

The Relative Soil Density (RSD) was determined by a methodology proposed by Klein (2006):

$$RSD = SD/Dsmax \qquad \text{Eq. 1}$$

where RSD is the relative soil density, SD soil density and Dsmax the maximum soil density obtained by the Normal Proctor test.

By the compaction curve equation generated by the Normal Proctor test, it is mathematically possible to calculate the maximum soil density (Dsmax), as well as the optimum moisture content for compaction at that level of applied energy (Marcolin and Klein, 2011).

The results of the Proctor test and density indicated high compaction. These values of soil density were used to calculate relative density, resulting in an approximate value of 1.87 Mg m^{-3}.

RESULTS AND DISCUSSION

Soil penetration resistance

After soil tillage, in 2012, the values of soil cone index were significantly higher under conventional tillage in the layers 0.15-0.30 and 0.30-0.45 m, compared to in-row deep tillage. However, for the 0.00-0.15 m layer, a significant difference of about 10 % was found and the lowest value of soil penetration resistance was observed in the IRDT treatment (Table 2).

These results agree with those of Dedecek and Gava (2005), who studied the effect of traffic of harvest equipment on eucalyptus yield. They claimed that traffic caused compaction in the 0.0-0.3 m layer in sandy soils, resulting in mean values of soil penetration resistance above 5.0 MPa. Mean values of penetration resistance close to those in this study (4.7 MPa) were also found by Lima et al. (2013b), in a sandy clay soil with loamy texture at a depth of 0.3 m.

The soil cone index was higher in the wheel track after soil tillage, a result already expected due to the use of controlled traffic. The lowest value (1.2 MPa) was found in the deep-tilled crop row and was statistically different from the value of conventionally tilled soil (Table 3).

Analyzing compaction and surface settlement of a *Latossolo Vermelho* (Oxisol) exposed to different traffic levels under field conditions, Couto et al. (2013) confirmed that traffic intensity was the only factor that influenced the analyzed variables, determining the density values and degree of soil compaction.

Increased soil aggregation depends on the soil type and tillage and the use of controlled traffic avoids excessive compaction. The negative effects of tillage on a sandy loam Hapludalf were reduced after 12 months, demonstrating the soil capacity of recovery of structure and aggregation (Prevedello et al., 2014). Agricultural machinery traffic increases soil density by decreasing the mean pore diameter and macroporosity in the wheel track, causing cumulative degradation of soil physical quality over the years of cultivation (Roque et al., 2010).

Transshipment traffic increased the soil cone index to values similar to conventional tillage. This indicates the need to avoid vehicle traffic, which would be possible by installing a traffic control system on transshipment trucks.

After the first cut, in 2013, the soil cone index of IRDT with traffic differed from conventional tillage only in the 0.30-0.45 m layer, and from IRDT without traffic in all layers (Table 4).

Soil cone index was lowest in IRDT with controlled traffic. After 450 days (15 months), the cone index under IRDT had increased 1 MPa, and 2 MPa under conventional tillage (Tables 3 and 4). The cone index values for soil tillage showed that the management zones corresponded to each treatment, reaching the expected mobilization layer. The points 1, 2, 3, 4, and 11 12, 13, and 14 represent the areas of controlled traffic (Figure 3).

Measures of traffic control can improve the soil physical structure and reduce fuel consumption, as a larger area of soil will be uncompacted and less resistant to be broken up by the passing soil tillage equipment. In addition, these measures improve the traction potential of the soil (tire-soil interface), which increases the traction efficiency resulting from machine traffic on firmer soil (wheel tracks) (Roque et al., 2010).

Machine traffic zones are efficient to minimize soil compaction caused by IRDT, due to the low values of soil cone index (Figure 3). A soil cone index value (SCI) of 4.0 MPa is considered critical for sugarcane by Ribeiro (2010), who reported that root development in sugarcane can be restricted at this SCI value.

The diagrams of 2012, based on data from soil sampled under wheel tracks and crop rows, showed lower values of soil penetration resistance (SPR) under IRDT, and clearly indicated the wheel track (Figure 4a).

Under conventional tillage (Figure 5a), the soil cone index of the samples was highest in the 0.30-0.45 m layer, approaching 5 MPa. Root growth is possible in soils with high moisture content and aeration,

Table 2. Soil cone index in treatments: In-row deep tillage (IRDT) and Conventional Tillage (CT), in different layers, after soil tillage

Treatment	Cone index			
	0.0-0.15 m	0.15-0.30 m	0.30-0.45 m	Mean
	MPa			
IRDT	1.3 a	3.9 b	5.7 b	4.0
CT	1.2 a	4.6 a	7.8 a	5.0

Mean with same letters in a column do not differ by the Tukey test (p<0.10). Standard deviation: 3.72; Coefficient of variation: 43 %.

Table 3. Soil cone index in treatments: In-row deep tillage (IRDT) and Conventional Tillage (CT), at different sampling locations, after soil tillage

Treatment	Cone index	
	Wheel track	Crop row
	MPa	
IRDT	6.1 a	1.2 b
CT	5.7 a	3.4 a

Means with same letters in a column do not differ by the Tukey test (p<0.10). Standard deviation: 3.72; Coefficient of variation: 43 %.

Table 4. Soil cone index of treatments in different layers after sugarcane harvest

Treatment	Cone index			
	0.00-0.15 m	0.15-0.30 m	0.30-0.45 m	Mean
	MPa			
In-row deep tillage with traffic	2.4 a	7.3 a	9.8 b	7.0
In-row deep tillage without traffic	1.5 b	3.2 b	3.8 c	3.0
Conventional tillage	2.3 a	7.1 a	10.3 a	7.0

Mean with same letters in a column do not differ by the Tukey test (p<0.10). Standard deviation: 3.56; Coefficient of variation: 33 %.
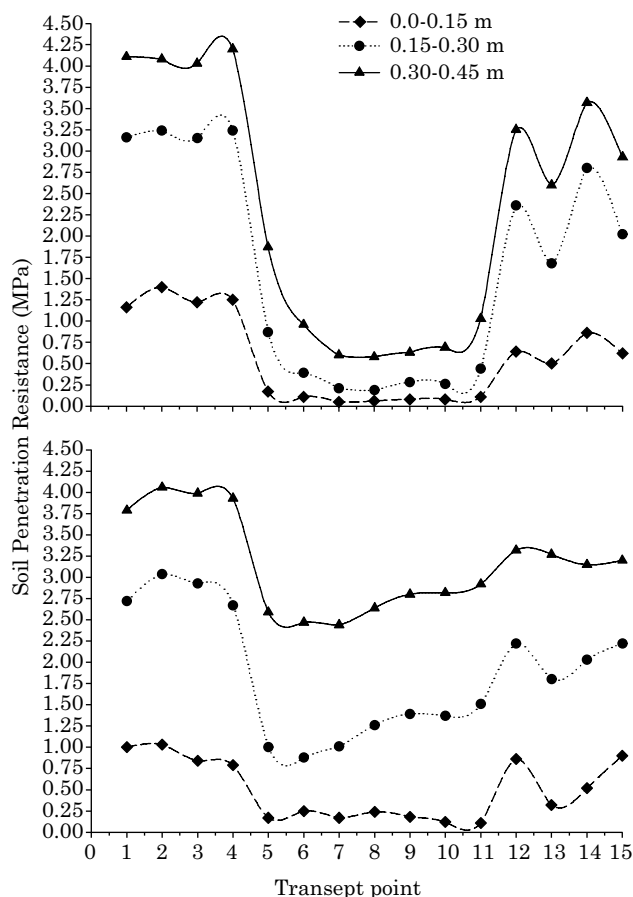
Figure 3. Soil cone index curves for the layers (0.00-0.15, 0.15-0.30 and 0.30-0.45 m), for in-row deep tillage (a) and for conventional tillage (b) in 2012.

Figure 4. Sampling points for data collection of soil penetration resistance in 2012 (a) and in 2013 (b).

even when the soil cone index exceeds 4.0 MPa (Dexter, 1987). For sandy soils with high contents of coarse sand, Sene et al. (1985) considered values of penetration resistance from 6.0 to 7.0 MPa as critical. These authors reported mean SPR values for conventional tillage and IRDT with traffic (Figure 5b) that were considered harmful to corn root development.

The lowest compaction values were observed in IRDT without traffic (Figure 5c). Braunack et al. (2006) found reduced compaction and increased crop productivity of sugarcane in areas with traffic control at sugarcane harvest.

The representation of evaluations in form of a curve was chosen for demonstrating the soil variability and accurately identifying the values in the plant rhizosphere, in the spacing of this study. The sampling points in 2013 are shown in figure 4b.

Relative soil density

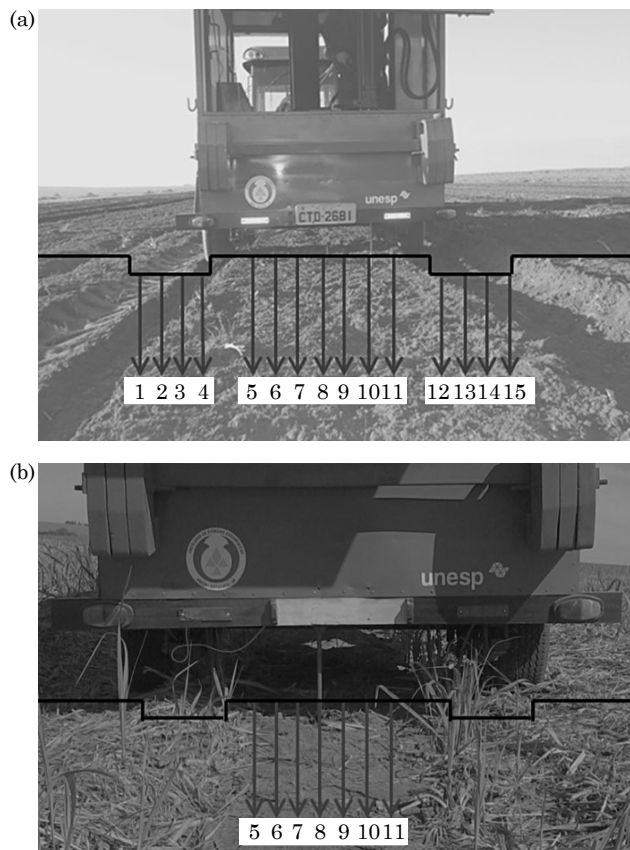For the physical property relative soil density (RSD), there was no statistical difference between treatments (Table 5). In the 0.15-0.30 and 0.30-0.45 m layers, RSD was considered high and may have affected crop productivity negatively.

For all tillage operations (subsoiling in crop row + leveling harrow, plowing with moldboard plow + leveling harrow, subsoiling in total area + leveling harrow, subsoiling in total area, and intermediate harrowing), soil density was maximized when machine traffic occurred under the above moisture conditions (Carvalho et al., 2014).

The low yields in the fourth sugarcane harvest can be explained in part by: after four years of cultivation, soil bulk density was higher than 1.45 Mg m^{-3}, hampering the plant nutrient uptake, and macroporosity was less than 15 %, impeding the development of the root system (Camilotti et al., 2005).

Our data (Table 5) agree with those reported by Lindstron and Voorhees (1994), in that RSD above 0.86 is high and harmful for crop development and below 0.80 may affect productivity. In the 0.30-0.45 m layer, IRDT without traffic differed from the other treatments, due to the absence of traffic in the crop row (Table 5). Over time, the accumulation of crop residues will tend to reduce the soil density, since a reduction in soil density and relative density was observed with increasing organic matter contents,
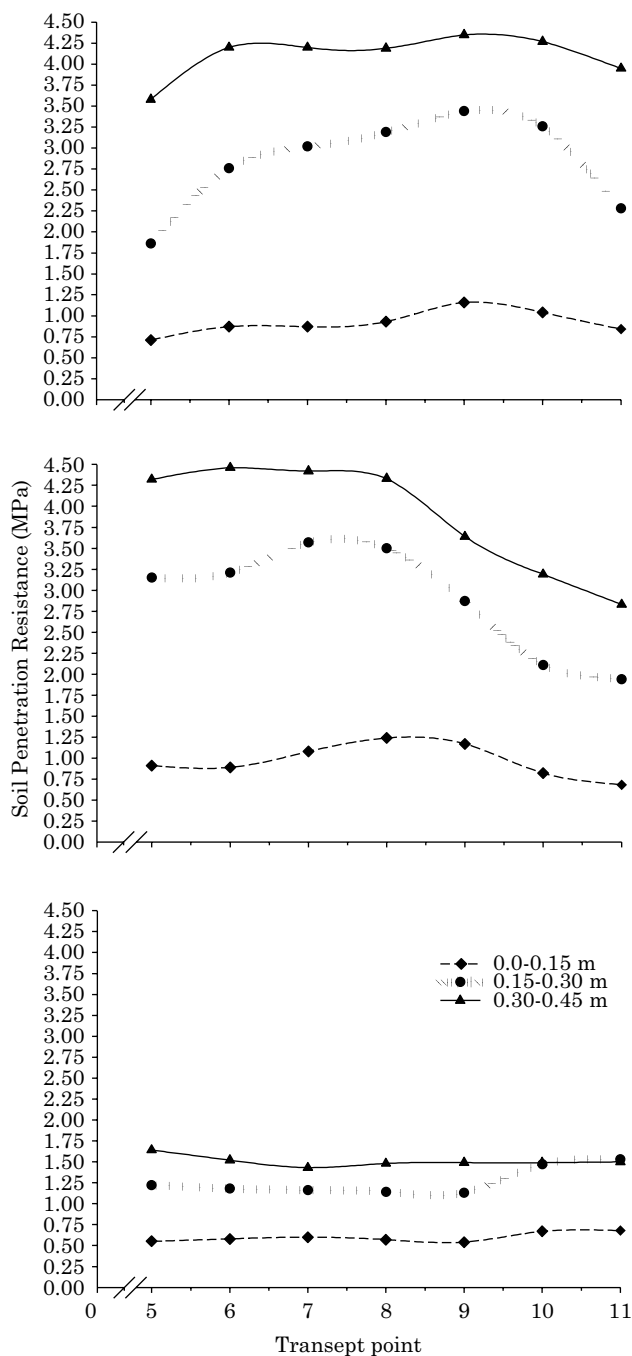
Figure 5. Soil cone index curves in layers (0.00-0.15, 0.15-0.30 and 0.30-0.45 m), under conventional tillage (a), in-row deep tillage with traffic (b), and in-row deep tillage without traffic (c), in 2013.

Table 5. Relative soil density (RSD) in treatments (in-row deep tillage - IRDT, and conventional tillage - CT), in different layers, after soil tillage and after sugarcane harvest

Treatment	Relative soil density		
	0.00-0.15 m	0.15-0.30 m	0.30-0.45 m
	Soil tillage		
In-row deep tillage	0.72 a	0.85 a	0.87 a
Conventional tillage	0.71 a	0.95 a	0.79 a
	Sugarcane harvest		
In-row deep tillage with traffic	0.83 a	0.93 a	0.93 a
In-row deep tillage without traffic	0.75 a	0.88 a	0.88 b
Conventional tillage	0.77 a	0.95 a	0.93 a

For soil tillage: mean with same letters in a column do not differ by the Tukey test (p<0.10). Standard deviation: 0.13; Coefficient of variation: 31 %. For sugarcane harvest: means with same letters in a column do not differ by the Tukey test (p<0.10). Standard deviation: 0.07; Coefficient of variation: 8 %.

study, soil density was higher when the agricultural machine traffic was limited to restricted zones.

CONCLUSIONS

The in-row deep tillage without traffic (IRDT without traffic) had lower soil cone index values in all layers compared to in-row deep tillage with traffic (IRDT with traffic) and to conventional tillage (CT).

For both tillage treatments, the relative soil density (RSD) was acceptable in the 0.00-0.15 m layer, but considered detrimental for crop development in the 0.15-0.30 and 0.30-0.45 m layers.

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with consequent increase in the optimal gravimetric moisture content (Braida et al., 2006).

With a view to the sustainability of sugarcane plantations, organic matter incorporation can influence the soil compaction degree, requiring further research. For the soil managements evaluated in this

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