SOIL PENETRATION RESISTANCE IN A RHODIC EUTRUDOX AFFECTED BY MACHINERY TRAFFIC AND SOIL WATER CONTENT

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ABSTRACT: Soil compaction caused by machinery traffic reduces crop yields. This study aimed to evaluate the effects of intensive traffic, and the soil water content, on the soil penetration resistance (PR) of a Rhodic Eutrudox (Distroferric Red Latosol, Brazilian Classification), managed under no-tillage (NT). The experiment consisted of six treatments: NT with recent chiseling, NT without additional compaction, and NT with additional compaction by 4, 8, 10 and 20 passes of a harvester with a weight of 100 kN (70 kN on the front axle). Undisturbed soil samples were collected at 5.5-10.5 cm and 13.5-18.5 cm depth to quantify the soil bulk density (BD). The PR was assessed in four periods, using an impact penetrometer, inserted in the soil to a depth of 46 cm. The effect of traffic intensities on the PR was small when this variable was assessed with the soil in the plastic consistency. Differences in PR among treatments increased as the soil water content decreased. The increase in the values of PR and BD was higher in the first passes, but the increase in the number of traffics resulted in deeper soil compaction. The machinery traffic effects on PR are better characterized in the friable soil consistency.

KEYWORDS: soil layers with mechanical impedance, no-tillage, soil compaction, soil consistency, soil profile.

RESISTÊNCIA DO SOLO À PENETRAÇÃO EM LATOSSOLO INFLUENCIADA PELO TRÁFEGO AGRÍCOLA E O CONTEÚDO DE ÁGUA DO SOLO

RESUMO: A compactação do solo causada pelo tráfego de máquinas reduz a produtividade das culturas. O objetivo deste trabalho foi avaliar os efeitos do tráfego intensivo e do conteúdo de água do solo na resistência à penetração (PR) de um Latossolo Vermelho distroférrico, muito argiloso, manejado em sistema plantio direto (NT). O experimento foi composto por seis tratamentos: NT escarificado; NT sem compactação adicional; e NT com compactação adicional pelo tráfego de uma colhedora com massa de 100 kN (70 kN no eixo dianteiro) por 4; 8; 10 e 20 passadas. A densidade do solo (BD) foi determinada utilizando amostras indeformadas, coletadas nas camadas de 5,5-10,5 cm e 13,5-18,5 cm. A RP foi determinada em quatro épocas, utilizando um penetrômetro de impacto, inserido no solo até a profundidade de 46 cm. O efeito das intensidades de tráfego no NT sobre a PR foi pequeno quando esta variável foi avaliada com o solo na consistência plástica. As diferenças na PR entre os tratamentos aumentaram à medida que o conteúdo de água no momento da avaliação diminuiu. O aumento nos valores de PR e BD foi maior nas primeiras passadas, mas o incremento do número de tráfegos aumentou a profundidade de compactação do solo. O aumento da PR proporcionado pelo tráfego de máquinas é mais bem caracterizado quando determinado com o solo na consistência friável.

PALAVRAS-CHAVE: camadas de solo com impedimento mecânico, sistema plantio direto, compactação do solo, consistência do solo, perfil do solo.

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INTRODUCTION

The continuous traffic of heavy machinery on agricultural areas has led to soil structure degradation and crop yields reduction (ROQUE et al., 2011; BOTTA et al., 2010). The identification of the magnitude and depth of the soil compaction by traffic is important to scale the agricultural machinery weight, or indicate adequate management practices to increase the soil bearing capacity. However, few studies relating soil compaction to agricultural machinery traffic intensities have been carried out under Brazilian conditions (BERGAMIN et al., 2010).

Soil structure changes caused by inadequate soil management, animal trampling or machinery traffic have been evaluated applying several soil physical attributes. Soil bulk density (BD), pore size distribution and soil penetration resistance (PR) have been widely used as indicators of soil compaction. PR describes the mechanical resistance provided by the soil against something moving through it, e.g., roots or a tillage tool, showing high correlations with BD (CONTE et al., 2008; ROBOREDO et al., 2010; BENGOUGH et al., 2011; WHALLEY et al., 2007). VEIGA et al. (2007) found that PR is more sensitive to detect differences in the soil compaction level among soil management systems compared to determinations based on mass/volume ratios, being the physical property that best shows the machinery traffic effects on the soil structure (STRECK et al., 2004). The main factor controlling the crop growth is the soil water content, which determines the water availability to plants, aeration, temperature and PR (LETEY, 1985). These properties are also affected by BD and pore size distribution (COLLARES et al., 2011). According to the same authors, the PR is the main factor that influences the plant root growth. However, the definition of a critical PR value to root growth is difficult taking into account that crops respond differently to PR (REICHERT et al., 2007).

PR values increase exponentially as the soil water content decreases and the BD increases (VAZ et al., 2011). The rate of PR reduction with the increase in the soil water content is greater with higher BD values (TORRES & SARAIVA, 1999). Therefore, compacted soil layers may not be detected if PR is assessed under high soil water contents (VAZ et al., 2011). Moreover, PR depends on other attributes such as the soil type (SILVA et al., 2009), organic matter content (TAVARES FILHO et al., 2012), soil texture (VAZ et al., 2011), soil compressibility (SILVA et al., 2002) and the metal-soil friction (DEXTER et al., 2007; SUN et al., 2012).

Several types of cone penetrometers can be utilized to evaluate PR, and the choice should be based on the soil compaction level. Manual static penetrometers provide field-level measurements of PR up to 5 MPa (ASABE, 2010). Conversely, dynamic (impact) penetrometers enable PR measurements ranging from zero to 20 MPa (VAZ et al., 2011). Additionally, the main advantages of using impact cone penetrometers are the low cost and the capacity to work in soils with stones and/or high resistance (low water content and high clay levels).

The objective of this study was to evaluate the effects of intensive traffic, and the soil water content, on the soil penetration resistance of a Rhodic Eutrudox, managed under no-tillage.

MATERIALS AND METHODS

The study was carried out at the experimental station of Embrapa Soja, located at an altitude of 620 m, in Londrina (23° 11' S, 51° 11' W), state of Paraná, southern Brazil. The trial was established on an Oxisol (Latossolo Vermelho Distroférrico, Brazilian classification; Rhodic Eutrudox, USA classification) managed under NT since 1996, with 731 g clay kg^{-1} soil, 146 g silt kg^{-1} soil, 123 g sand kg^{-1} soil, 18.50 g organic carbon kg^{-1}, and particle density of 2.96 Mg m^{-3} at 0-20 cm depth. The average slope of the experimental area is 0.03 m m^{-1}.

The experiment had a randomized block design with sampling in the plots and two replications. The treatments consisted of six compaction levels on 2,5 m wide and 20 m long plots: NT with recent chiseling (NTCh), NT without chiseling and without additional compaction (NT), and NT with additional compaction by harvester traffic in 4 different intensities, represented by four

(NTC4), 8 (NTC8), 10 (NTC10) and 20 (NTC20) passes over the same track. The additional compaction was carried out on 08.16.2010 (month, day, year) by means of a self-propelled grain harvester (weight of 66 kN) equipped with grain header (weight of 12 kN) and with the grain tank filled (wheat , weight of 22 kN), presenting a total weight of 100 kN (70 kN on the front axle). The harvester were equipped with single front tires, 18.4-30 R1, diagonals, inflated to pressure of 180 kPa; and rear tires 9.00-16 F2 10PR, diagonals, inflated to a pressure of 410 kPa. The ground pressure of the front tires was estimated in 230 kPa, using a simple procedure proposed by O'SULLIVAN et al. (1999). Following this methodology, the soil-tire contact area was estimated from tire width and diameter, inflation pressure and load, using an empirical model developed for a rigid surface. The soil gravimetric water content (GWC) during the harvester traffic was equivalent to the field capacity (0.34 kg kg^{-1}). The chiseling was performed seven days before the 1st PR evaluation, when the soil was in the friable consistency (GWC of 0.28 kg kg^{-1}), by means of a chisel plow equipped with five shanks spaced 35 cm each other, and working at an average depth of 30 cm, followed by a disking with a light disc harrow operating at 8 cm depth.

On 08/23/2010, the experiment was sprinkler-irrigated with 100 mm of water in order to uniform and increase the GWC up to the field capacity. The PR evaluations were carried out at four periods (2, 4, 11 and 23 days after irrigation), in layers of 2 cm to a depth of 46 cm using an impact penetrometer (IAA model/Planalsucar-Stolf) (STOLF, 1991) equipped with a 130 mm^2 base area, 30° stainless circular cone (ASABE, 2010). In each plot, the PR readings were performed at eight points spaced by 15 cm on a perpendicular line to the direction of the harvester or chisel plow pass, totalling 96 points per evaluation period. Two soil samples were collected in each plot and evaluation period at 0-10 cm and 10-20 cm depth to quantify the GWC (EMBRAPA, 1997).

Two days after the 4th PR evaluation, four trenches per treatment were opened and undisturbed soil samples were collected at depths of 5.5-10.5 and 13.5 to 18.5 cm using cores with an inner diameter of 5 cm and a height of 5 cm. 6 cores were horizontally inserted into the wall of each trench and layer by means of a hydraulic jack, totalling 288 samples. The undisturbed soil samples were used to determine BD according to EMBRAPA (1997).

Statistical analyses were performed using the SAS LEARNING EDITION 8.0 (2002). The results of BD, GWC and PR were subjected to variance analysis (F test, p <0.05). The BD was analysed following a 6x2 factorial arrangement (compaction levels x depth). For GWC and PR, the statistical analysis was performed separately for each depth, following a 6x4 factorial arrangement (compaction levels x evaluation periods). Means were compared through the t test, equivalent to Fisher's least significant difference test (LSD test) (p <0.05). The BD values were related to the traffic intensity by means of regression analysis (F test, p <0.05).

RESULTS AND DISCUSSION

As expected, chiseling and traffic provided significant changes in soil structure, as evidenced by the BD values (Table 1). The lower BD values in both depths (5.5-10.5 and 13.5-18.5 cm) were obtained in the NTCh, demonstrating that chiseling is an effective practice to break compacted soil layers. Chiseling has been recommended to reduce the soil compaction level (KLEIN et al., 2009), increasing the optimal water range to plant growth by reducing the soil water content in which the PR reaches the critical values for root growth (CALONEGO & ROSOLEM, 2011), as well as the number of days in which the soil moisture is adequate to plant growth (KAISER et al., 2009). Furthermore, chiseling has been found to increase the soil hydraulic conductivity and water infiltration rate (VIEIRA & KLEIN, 2007). However, even one traffic with a light tractor after the chiseling can reduce drastically the effect of previous tillage on PR (VEIGA et al., 2007) leading to the soil recompaction in the short-term.

The BD increased exponentially with the increase of the harvester traffic intensity in both soil layers (Table 1 and Figure 1), but the effects were greater at 5.5-10.5 cm depth. BERGAMIN et al. (2010) also showed higher increases in the BD values due to the traffic of a tractor weighting 50kN

in the topsoil (10 cm). The differences in the soil bearing capacity between the soil layers were likely small since the BD values were not influenced by the sampling depth (Table 1 and Figure 1). In addition, GWC values were also similar for both layers, since the traffic was performed in the field capacity. Thus, the greater BD values at 5.5-10.5 cm depth can be ascribed to the dissipation of the stress applied by the harvester wheels to the soil surface with increasing depth, which is explained mathematically by the Boussinesq equation (ALAKUKKU et al., 2003).

The greater changes in the soil compaction level were caused by the first harvester traffics, but increases in the BD were identified in both depths up to 20 passes (Table 1 and Figure 1). Higher increments in the soil compaction level during the first traffics of agricultural machinery were also observed by BERGAMIN et al. (2010). TOLON-BECERRA et al. (2010) reported that subsoil compaction depended on the axle load and the number of tractor passes. Interestingly, the average BD for NTC20 at 5.5-10.5 depth was 1.50 Mg m^{-3}, which is similar to the maximum BD estimated by the Proctor test for this soil (1.53 Mg m^{-3}) (TORRES & SARAIVA, 1999).

TABLE 1. Descriptive statistics for the soil bulk density of a Rhodic Eutrudox under six compaction levels at 5.5-10.5 cm and 13.5-18.5 cm depth.

Treatment[a]	Mini-mum	Maxi-mum	Mean	Medium	Mode	Standard deviation	Variation Coefficient
	---------------------------------- Mg m^{-3} ----------------------------------						-- % --
	-- 5.5-10.5 cm --						
NTCh	0.95	1.28	1.10Ea*	1.11	1.04	0.073	6.67
NT	1.16	1.32	1.25Da	1.25	1.25	0.044	3.50
NTC4	1.28	1.46	1.36Ca	1.36	1.36	0.038	2.84
NTC8	1.38	1.47	1.43Ba	1.44	1.47	0.030	2.11
NTC10	1.36	1.52	1.45Ba	1.46	1.46	0.040	2.86
NTC20	1.43	1.53	1.50Aa	1.50	1.52	0.030	2.01
	-- 13.5-18.5 cm --						
NTCh	0.98	1.23	1.10Ea	1.11	1.15	0.069	6.32
NT	1.16	1.32	1.25Da	1.26	1.27	0.043	3.42
NTC4	1.28	1.43	1.34Cb	1.33	1.33	0.036	2.69
NTC8	1.29	1.42	1.36BCb	1.36	1.35	0.026	1.93
NTC10	1.26	1.47	1.38Bb	1.38	1.44	0.058	4.18
NTC20	1.34	1.49	1.42Ab	1.42	1.43	0.048	3.42

[a]No-tillage chiseled (NTCh); No-tillage without additional soil compaction (NT); No-tillage with additional compaction by 4 (NTC4), 8 (NTC8), 10 (NTC10) and 20 (NTC20) passes of a harvester.* Means followed by the same capital letter in the same layer and lowercase in layers of the same treatment did not differ among them by the LSD test at the 5% level of error probability.
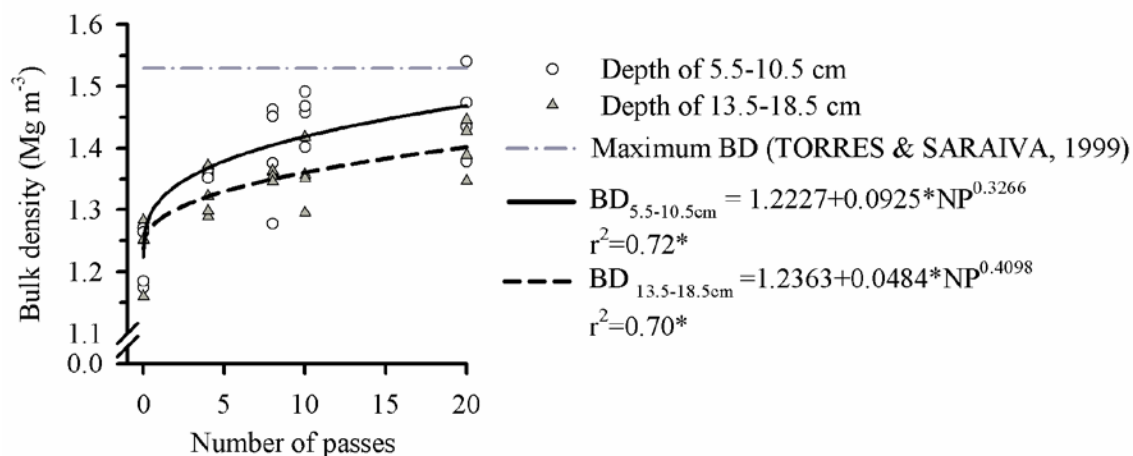

FIGURE 1. Soil bulk density (BD) at 5.5-10.5 cm and 13.5-18.5 cm depth as affected by the number of harvester passes on a Rhodic Eutrudox. *equations statistically significant (F test, p < 0.05).

For GWC at the moment of PR assessment, the interaction between compaction levels and evaluation periods was not significant ($p < 0.05$), in both layers. The GWC decreased from the 1st to the 4th assessment period, and this reduction was higher at 0-10 cm depth (Table 2). The compaction levels also influenced the GWC. The largest GWC at 0-10 cm depth were obtained in the NTCh and NT, whereas the lowest values were observed for the treatments with additional compaction. A similar behaviour was found at 10-20 cm depth; however, the NTC4 and NTC8 did not differ from the NTCh and NT. Moreover, the NTCh and NT resulted in higher GWC than the NTC10 and NTC20 in both layers.

The PR readings at different times and the absence of rainfall and irrigation during the evaluation period provided a wide variation in the GWC values (Table 2), enabling the PR assessment under different soil consistencies. For this soil, liquid, friability, and contraction limits were estimated at 0.45, 0.29 e 0.25 kg kg^{-1}, respectively (TORRES & SARAIVA, 1999). Therefore, the PR was determined with the soil in the plastic (1st and 2nd evaluations), friable (3rd evaluation) and dry condition (4th evaluation).

The interaction between compaction levels and evaluation periods for the PR was significant in all depths ($p < 0.05$). In general, the PR increased with the decrease in the GWC from the 1st to the 4th evaluation, and this increase was higher for the trafficked treatments in the topsoil (0-15 cm depth) (Figure 2). The increase in the GWC reduces the internal friction and cohesive forces between the soil particles and aggregates leading to PR reduction (ASSIS et al., 2009; ROS et al., 2011). Moreover, the water acts as a lubricant, reducing the friction between the soil and the steel cone (CHANCELLOR, 1994). The PR values were significantly lower in the NTCh in comparison with other treatments at 0-30 cm depth regardless the evaluation time (Figure 2). Below 30 cm depth, the PR in NTCh was similar to NT, revealing that the soil disturbance by chisel shanks were limited to the 0-30 cm depth.

TABLE 2. Gravimetric soil water content as affected by evaluation times and compaction levels in a Rhodic Eutrudox.

Treatments[a]	Assessment Periods				Means
	First 25/08	Second 27/08	Third 03/09	Fourth 15/09	
-- kg kg^{-1} --					
--- 0-10 cm ---					
NTCh	0.34	0.32	0.29	0.25	0.30a
NT	0.33	0.32	0.27	0.24	0.29ab
NTC4	0.32	0.31	0.24	0.22	0.28bc
NTC8	0.32	0.30	0.25	0.23	0.28bc
NTC10	0.32	0.30	0.27	0.22	0.27c
NTC20	0.32	0.30	0.28	0.23	0.27c
Means	0.33A*	0.31B	0.26C	0.23D	
CV (%)	2.10	3.23	7.67	4.29	
--- 10-20 cm ---					
NTCh	0.35	0.33	0.31	0.28	0.32a
NT	0.34	0.33	0.31	0.28	0.32a
NTC4	0.33	0.33	0.29	0.27	0.31ab
NTC8	0.33	0.33	0.30	0.27	0.31ab
NTC10	0.33	0.33	0.29	0.25	0.29b
NTC20	0.33	0.33	0.29	0.26	0.30b
Means	0.33A	0.33A	0.29B	0.27C	
CV(%)	2.19	3.04	4.78	2.96	

[a]No-tillage chiseled (NTCh); No-tillage without additional soil compaction (NT); No-tillage with additional compaction by 4 (NTC4), 8 (NTC8), 10 (NTC10) and 20 (NTC20) passes of a harvester. *At each depth, means followed by the same letter, capital in the line, and lowercase in the column, do not differ among them by the LSD test, at the level of 5% of error probability.

The traffic effects on the PR depended on the evaluation time and the number of passes (Figure 2). Trafficked treatments, even at higher intensities (NTC10 and NTC20), increased the PR in relation to the control without traffic (NT) only up to 12 cm depth in the 1st evaluation (Figure 2a), which was performed with the soil in the plastic consistency. In the 2nd evaluation (Figure 2b), the NTC4 resulted in higher PR than NT up to 10-12 cm depth, resembling the 1st assessment (Figure 2a). However, the increase in the number of passes (NTC8, NTC10 and NTC20) increased the PR in relation to NT up to 18 cm depth (Figure 2b), indicating that the reduction in GWC observed from the 1st to the 2nd evaluation resulted in a greater sensitivity of the PR to soil compaction caused by the harvester traffic. In general, considering the soil layers affected by the harvester traffic, the higher the number of passes, the higher the PR values in the 1st (Figure 2a) and 2nd (Figure 2b) evaluations.
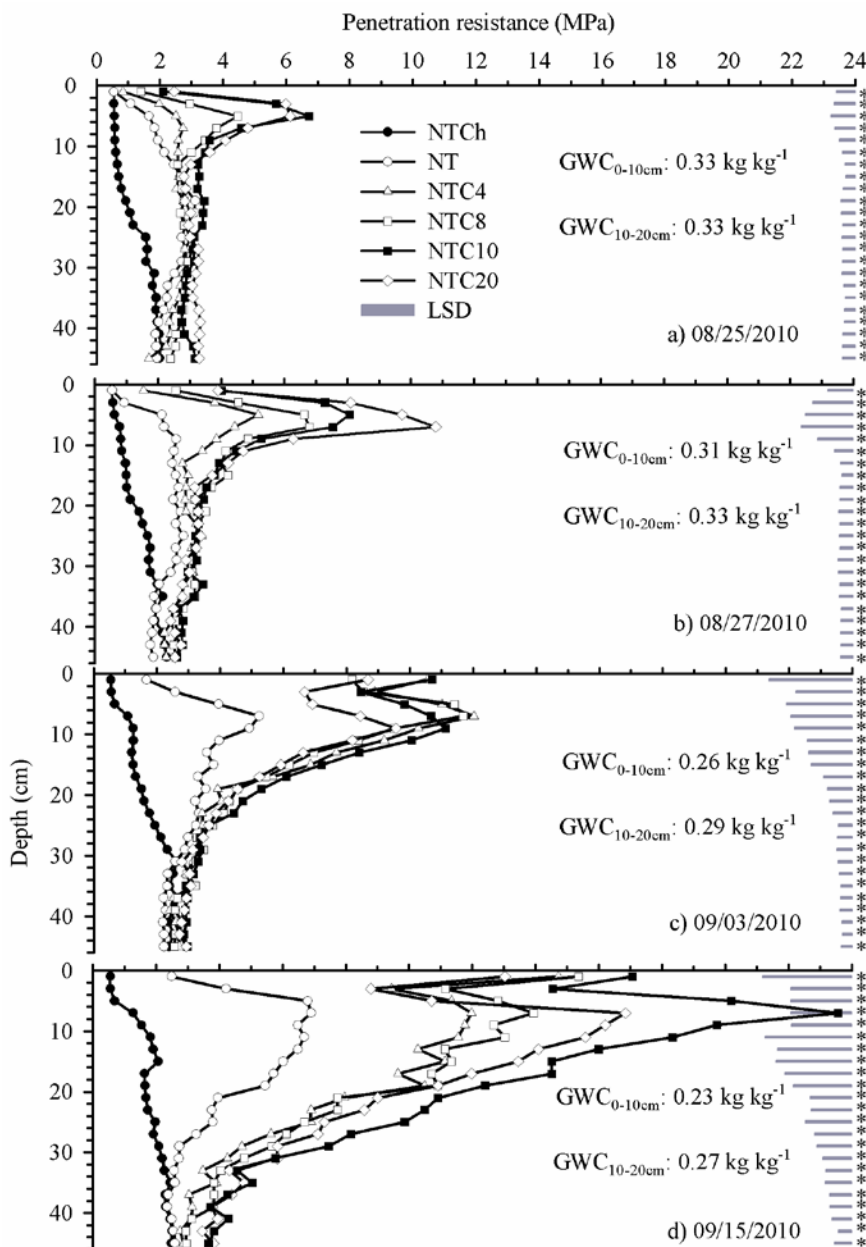

FIGURE 2. Penetration resistance of a Rhodic Eutrudox by layers of 2 cm, at 0-46 cm depth, measured at 2 (a), 4 (b), 11 (c) and 15 (d) days after the irrigation, under six soil compaction levels [No-tillage chiseled (NTCh); No-tillage without additional soil compaction (NT); No-tillage with additional soil compaction by 4 (NTC4), 8 (NTC8), 10 (NTC10) and 20 (NTC20) harvester passes].* Horizontal lines indicate the least significant difference (LSD test, $p<0.05$), and compare the means of treatments at each layer.

In the 3rd (Figure 2c) and 4th (Figure 2d) PR evaluations, the depth of soil compaction by the harvester traffic increased compared to the previous evaluations (Figures 2a and 2b) for all trafficked treatments. When the soil was in the friable consistency (3rd evaluation), the NTC4 resulted in greater PR than the NT up to 16-18 cm depth, whereas the NTC8, NTC10, and NTC20 increased the PR in comparison to the NT up to 22 cm (Figure 2c). In the 4th evaluation (dry soil), the PR was higher in the NTC4 and NTC8 relative to NT up to 40 cm depth, but NTC10 and NTC20 increased the PR at least up to 46 cm depth (Figure 2d). Additionally, the PR differences between the trafficked treatments and the control (NT) in the 3rd and 4th evaluations were higher comparatively to the assessments conducted under higher GWC.

As previously observed for the 1st and 2nd evaluations, the PR also increased with the increment in the number of harvester passes in the 3rd and 4th assessments. Interestingly, the PR in NTC20 was equal or lower than in the other trafficked treatments in the last two evaluations (Figures 2c and 2d), even with the NTC20 showing higher BD values (Table 1). The high soil strength observed in the NTC20 under low soil water content led to the formation of vertical cracks below the cone during its displacement in the soil. These cracks facilitate the cone movement through the soil, reducing the PR to inconsistent values taking into account the high compaction level of the NTC20. MULQUEEN et al. (1977), and TO & KAY (2005) reported reductions in the PR values due to small vertical cracks resulting from cone displacement through soils with high BD and low water content.

In general, the PR data (Figure 2) showed that the increase in the number of passes of a harvester with 70 kN on the front axle resulted in the stress transmission to deeper soil layers. Similarly, SCHÄFFER et al. (2007) found that the stresses measured at 32 cm depth in the track centre increased from 80 kPa in the 1st traffic to 120 kPa in the 7th traffic of a grain harvester with a ground pressure of 120 kPa and weight of 34 kN. The increasing depth of soil compaction with the increase in the tractor passes was also reported by TOLON-BECERRA et al. (2010), even using a tractor with a low axle load. Besides the passes number, the vertical stress distribution beneath wheels depends on the axle load and the ground pressure (LAMANDÉ & SCHØNNING, 2011a), as well as soil characteristics such as the water content (LAMANDÉ & SCHØNNING, 2011b) and structure (HAMZA & ANDERSON, 2005).

The reduction in the GWC increased the PR sensitivity to detect soil compaction due to the harvester traffic (Figure 2), agreeing with the results reported by ASSIS et al. (2009). This result can be attributed to a higher increase in PR with the BD increase as the soil dries (MULQUEEN et al., 1977; TORRES & SARAIVA, 1999; VAZ et al., 2011). As the soil becomes drier, compression under and around the probe becomes more important and the PR is very dependent on soil cohesion and BD (MULQUEEN et al., 1977). Under high GWC, these authors compare the soil with viscous materials, where the resisting force on a body moving through the material depends on the viscosity and not on the density. Furthermore, the reduction in the friction between the soil and the cone, resultant from the "lubricant action" of the water (CHANCELLOR, 1994), becomes more important as the soil compaction level increases.

Considering the PR sensitivity to soil compaction level, the dry soil condition (GWC lower than the soil contraction limit) would be the best option to PR evaluation. However, below a particular soil water potential, the PR values tend to decrease with the reduction in the GWC due to the decrease in the effective stress and the formation of cracks beneath the penetrometer cone (MULQUEEN et al., 1977; TO & KAY, 2005), leading to the misinterpretation of PR values, as observed in this study (Figure 2d). Additionally, the soil strength is higher under lower GWC, making the PR evaluation difficult especially in compacted areas. Furthermore, when assessed in a dry soil condition, high PR values may reflect a high restriction to root growth by low soil water availability rather than a critical soil compaction level to root growth, as observed in the NT at 5-20 cm depth (Figure 2d). For this treatment and soil layer, the BD was less than 1.33 Mg m^{-3} (Table 1), considered the critical BD threshold to plant growth (TORRES & SARAIVA, 1999). In spite of this, the PR was much higher than 3.5 MPa when evaluated under the dry soil condition (Figure 2d),

value pointed out by TORRES & SARAIVA (1999) as the critical PR threshold to root growth. Thus, as previously indicated by TORRES & SARAIVA (1999) and ASSIS et al. (2009), the best soil water content to assess PR is the correspondent to the friable consistency, since this condition favours the detection of the traffic effects on the soil compaction level, and also enables an easy and precise determination of PR.

CONCLUSIONS

The soil penetration resistance increases with the number of traffics mainly after the first machinery passes.

The increase of soil penetration resistance in depth is determined by number of traffics.

The sensitivity of the soil penetration resistance decreases with the increase in the soil water content.

The machinery traffic effects on soil penetration resistance are better characterized in the friable soil consistency.

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