academicJournals

Vol. 12(13), pp. 1067-1073, 30 March, 2017
DOI: 10.5897/AJAR2016.12027
Article Number: 401C0C363443
ISSN 1991-637X

http://www.academicjournals.org/AJAR

African Journal of Agricultural Research

Full Length Research Paper

Effect of seed-furrow openers on soybean root growth in compacted Oxisol

Alcir José Modolo[1*], Gabrielli Fiorentin Dedordi[1], Thiago de Oliveira Vargas[1], Rivanildo Dallacort[2], Murilo Mesquita Baesso[3], José Ricardo da Rocha Campos[1], Robson Gonçalves Trentin[1], Gilberto Santos Andrade[1] and Emerson Trogello[4]

[1]Programa de Pós-graduação em Agronomia, Universidade Tecnológica Federal do Paraná - PPGAG/UTFPR, Via do Conhecimento, km 01, Pato Branco – PR, 85503-390, Brasil.

[2]Programa de Pós-graduação em Ambiente e Sistemas de Produção Agrícola, Universidade do Estado de Mato Grosso – PPGASP/UNEMAT, Rodovia MT - 358, Km 07, Tangará da Serra - MT, 78300-000, Brasil.

[3]Departamento de Engenharia Biossistemas, Universidade de São Paulo - FZEA/USP, Av. Duque de Caxias Norte, 225, Pirassununga – SP, 13635-900, Brasil.

[4]Curso de Agronomia, Instituto Federal Goiano. – IFGoiano, BR-153, km 633, Morrinhos - GO, 75.650-000, Brasil.

Received 1 December, 2016; Accepted 16 February, 2017

This study aimed to evaluate the effects of seed-furrow openers and soil compaction on parameters such as sowing quality and root growth of soybean. The experiment was conducted using a randomized blocks experimental design with split plots, with the plots arranged by compaction level (1.16, 1.20, 1.22 and 1.26 Mg m^{-3}) and the subplots by type of furrow opener (double disk and shank type). Root growth was assessed at three depths (0.00-0.10; 0.10-0.20 and 0.20-0.30 m) in the sowing line and interrow. The sowing quality data means were compared using the Tukey test ($p \leq 0.05$), while the root growth data means were compared using the LSD test ($p \leq 0.05$). Penetration resistance increased with increasing soil compaction to a depth of 0.20 m. The sowing depth and mobilized soil area were not affected by soil compaction levels. The type of furrow opening mechanism only influenced the sowing depth, with greater depth achieved using the double disc. Neither the seed-furrow openers nor the level of soil compaction significantly influenced soybean root growth when evaluated in the sowing line. The type of furrow opening mechanism did not influence any of the evaluated parameters. Soil compaction altered soybean root growth in the interrow, but did not impede rooting. Regardless of the assessment depth in the interrow, there was a reduction in root volume, length, surface area and diameter with increased soil density.

Key words: No-tillage, seeder, soil density, sowing depth, penetrometer resistance.

INTRODUCTION

The growing expansion of the area planted with soybean and the aggregation of technologies for cultivation mean that it is the most important crop for Brazilian agribusiness. Much of the crop is sown using a no-tillage system, which involves restricting soil disturbance to the line of the planting furrow (Palma et al., 2010). This system also features intense traffic of machinery and implements and has caused soil compaction in regions with varying soil and climatic characteristics (Freddi et al., 2007). Studies developed by *Embrapa Soja* shows that about 45% of agricultural areas in Paraná with clayey soil that are cultivated with soya/corn, present a degree of compaction in the 0.10-0.20 m layer, which is restrictive to root development and to the development of the aerial part of the plant (Franchini et al., 2011).

The root growth of crops in compacted soils is commonly related to the density and mechanical resistance to penetration of the soil, which mainly depends on its textural class (Reinert et al., 2008) and soil moisture (Valicheski et al., 2012). Secco et al. (2009), studying Oxisols managed as no-tillage systems, found that soil density values of 1.62 and 1.54 Mg m^{-3}, respectively, did not cause decreases in soybean yield. However, Ferreras et al. (2001) observed a 47% decrease in soybean yield when using no-tillage cultivation as compared to the same scarified soil. This difference was attributed to reduced root development as a result of the increased mechanical resistance, with induced branching of adventitious surface roots making them less efficient at absorbing nutrients and water.

The use of shank type furrow openers during the sowing operation has been used as an alternative to break up the compacted surface layer in regions with clay soils. However, the use of the shank has become commonplace even in areas without high levels of soil compaction resulting in problems such as excessive soil mobilization, encouragement of erosion and increased weed growth in the sowing row (Reis et al., 2006), as well as increased fuel consumption (Santos et al., 2008) and resulting in increases to production costs.

In order to measure the effects of soil compaction on crop root systems, various methods can be utilized, however, the majority of these methods are time consuming and laborious, besides being imprecise and demanding a great deal of manpower, which makes evaluation difficult (Benjamin et al., 2004). The most accurate method for acquiring data on root volume, surface area, diameter and length is through the digital processing of images with washed roots, where the data is obtained using specific software, specially developed for this purpose.

In this context, the objective was to evaluate the effects of furrow opening mechanisms and soil compaction levels on the parameters of sowing quality and root growth of soybean.

MATERIALS AND METHODS

The experiment was conducted in the Pato Branco region, Paraná (Figure 1), in Typic Hapludox (Soil Survey Staff, 2014) with a very clayey texture and with the following chemical characteristics in the 0.0-0.20 m depth layer prior to the experiment: pH $_{(CaCl)}$ = 4.85; OM $_{(Walkley\text{-}Black)}$ = 49.09 g dm^{-3}; P $_{(Mehlich\ I)}$ = 10.59 mg dm^{-3}; K $_{(Mehlich\ I)}$ = 0.19 $cmol_c$ dm^{-3}; Ca^{2+} $_{(1\ M\ KCl)}$ = 4.44 $cmol_c$ dm^{-3}; Mg^{2+} $_{(1\ M\ KCl)}$ = 1.40 $cmol_c$ dm^{-3}; Al^{3+} $_{(1\ M\ KCl)}$ = 0.06 $cmol_c$ dm^{-3}; H+Al = 5.29 $cmol_c$ dm^{-3}; Sum of the Bases (SB = 5.96 $cmol_c$ dm^{-3}); cation exchange capacity (CEC= 11.25 $cmol_c$ dm^{-3}); base saturation (V= 52.91%).

The climate is defined as humid subtropical Cfa according to the Köppen climate classification. The coordinates of the location are 26°16'36"S 52°41'20"W with an average altitude of 750 m. The treatments consisted of the lagged double disc and shank type furrow openers of a seeder fertilizer and four induced levels of soil compaction, obtained by tractor traffic across the plot, so that the tires compacted parallel areas. The number of times the tractor passed across the plot varied according to the treatment, as follows: Level 0- no additional compaction; Level 1- additional compaction by means of two passes; Level 2- additional compaction by means of four passes and Level 3- additional compaction by means of six passes, corresponding to soil densities of 1.16, 1.20, 1.22 and 1.26 Mg m^{-3}, respectively.

The tractor used to apply the different levels of soil compaction was a New Holland®, TL75E 4x2 TDA (Front Wheel Drive Assist) with maximum permitted ballast (4630 kg), Standard 12.4 x 24 front tires and 18.4 x 30 back tires and a mounted sprayer (250 kg), filled with 600 L of water, providing a total mass of 5480 kg. The compaction process was performed in November 2013, with soil moisture at 38.1%.

The experiment was arranged across split plots in which the plots were formed by the four compaction levels and the subplots by the two types of furrow openers, with a randomized blocks design consisting of eight treatments and four replications, resulting in a total of 32 experimental units each with an area of 75 m^2 (3.75 x 20 m).

The soybean cultivar, Don Mario 5.8i® (BMX Apollo RR) was used with a stand density of 300,000 plants ha^{-1}, sowed on 12 December 2013. The furrow openers used for deposition of fertilizer were the shank type with tips of 17.76 mm width, attack angle of 20° and height of 0.45 m and double disc type with 381 mm (15") diameter discs, depending upon the treatment. In-furrow fertilization of 390 kg ha^{-1} was provided with a 02-20-18 formulation.

To evaluate the penetration resistance of the soil, a Falker® penetrometer was used, model PLG1020, with a ferrule (cone) of 1.0 cm^2 area, with ten random measurement points in each experimental unit. During the assessment soil moisture was at 37.7%.

The depth of seed deposition was determined in the three central sowing lines of each experimental unit, assessing the depth of 10 seeds per row. To assess the mobilized soil area, a wooden profilometer was used, with vertical graded rulers arranged transversely to the sowing row at 0.02 m intervals. The measurements were taken in the three central sowing lines, with two repetitions per line, obtaining the natural and final surface profiles of the furrow. Assessments of root growth were obtained using the washed roots method with samples collected from the crop at the reproductive growth stage R3 (beginning of pod formation). Roots were collected in the field following the trenches methodology proposed by Jorge and Silva (2010), with trenches opened across the sowing lines.

The methodologies proposed by Micucci and Taboada (2006) and Gao et al. (2010) were adapted to facilitate sample collection and involved adjusting a wooden lattice with dimensions of 1.00 x 0.5 m, subdivided with a white string grid into 0.10 x 0.10 m squares along the wall of each trench. Soil cores of 209.13 cm^3

*Corresponding author. E-mail: alcir@utfpr.edu.br. Tel: 55 46 3220-2536.

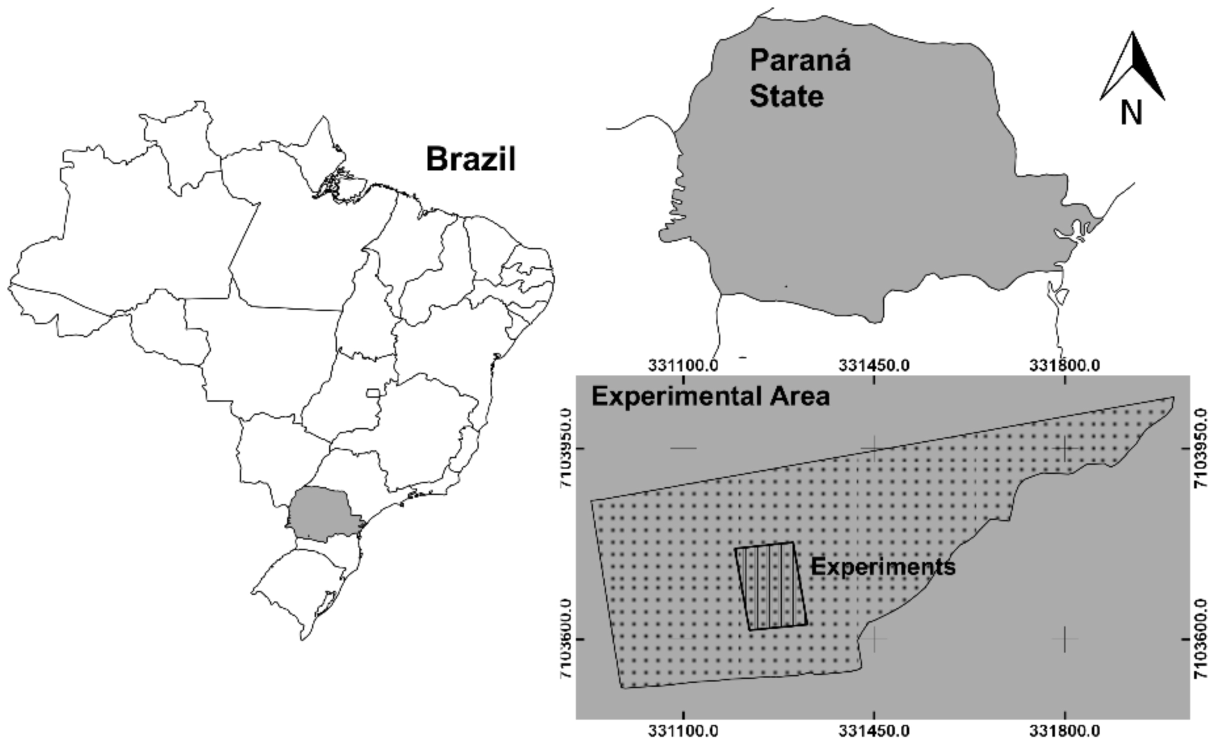

Figure 1. Geographical location of the study area.

were then collected for root sampling in each subdivision at depths of 0.0-0.10; 0.10-0.20 and 0.20-0.30 m. Fifteen samples were collected per experimental unit, of which six samples were from two sowing rows and nine samples from three interrows.

The roots were separated and cleaned with the aid of a set of sieves with 4.75, 2.00 and 1.00 mm meshes, respectively. Once separated, the roots were scanned using an optical scanner with a minimum resolution of 200 dpi. To perform the scan, the roots were displayed with water on a transparent glass plate equal in size to the scanner screen in order to avoid shading and overlay at the time of scanning.

The scanned images were processed using SAFIRA software (Jorge and Rodrigues, 2008), which generated data for the volume (mm^3), surface area (mm^2), weighted mean diameter (mm) and total length (mm) of the roots. These results represent the average crop root population corresponding to each collection point.

Data were evaluated for analysis of variance using the F test. The sowing quality data means were compared using the Tukey test ($p \leq 0.05$), while root growth data means were compared using the Fisher test (LSD, $p \leq 0.05$). The analyses were performed using the statistical analysis system, SAEG version 9.1 (Funarbe, 2007).

RESULTS AND DISCUSSION

The highest soil penetration resistance (PR) values were observed in the treatment with the greatest number of tractor passes, down to a depth of about 0.20 m, followed by the treatments with four and two passes, respectively (Figure 2). At the depth of 0.20 to 0.40 m, similar behavior was observed between the treatments, which demonstrated that the effects of soil compaction tend to be concentrated in the top 0.20 m. This behavior, with higher PR in the surface layer of the soil is a feature of no-tillage farming, whereby the cumulative effect of stress generated by machinery and implement traffic is dissipated across the surface layers (Bonini et al., 2008).

Many soil compaction problems are related to machine traffic and the type of tires used on the machines. Most tires are diagonally banded, which prevents the tire from molding to the soil and following the irregularities of the terrain. This reduces the tire-soil contact area and consequently increases the pressure on the soil surface (Silva et al., 2000).

Soil compaction causes various consequences and limitations and may compromise the growth and functionality of the root systems of some crops when PR values are greater than 2.0 MPa (Lipiec et al., 2012; Valicheski et al., 2012). Based on studies conducted in the field, some authors reported that 2.0 MPa may result in a reduction in soybean root growth (De Maria et al., 1999). In this study, only the treatment involving six passes of the tractor presented PR values that could be limiting to root growth.

Sowing depth was between 0.04 and 0.05 m (Figure 3), generally suitable for soybean. If the seeds are deposited at greater depths, the seedlings have to grow through a thick layer of soil after germination before reaching the surface, taking longer to emerge.

With respect to the furrow opening mechanisms, it was observed that sowing depths were greater with the

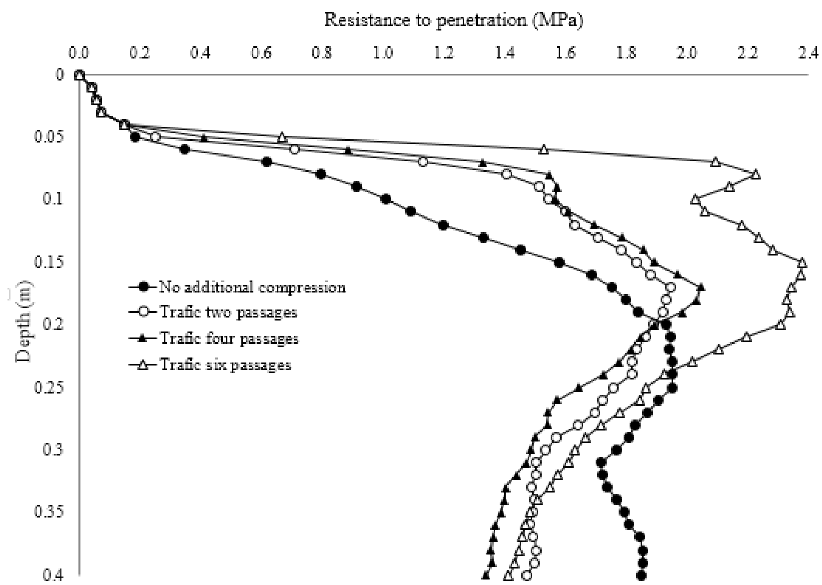

Figure 2. Mechanical resistance of the soil to penetration (MPa) as a result of the number of passes with the tractor.

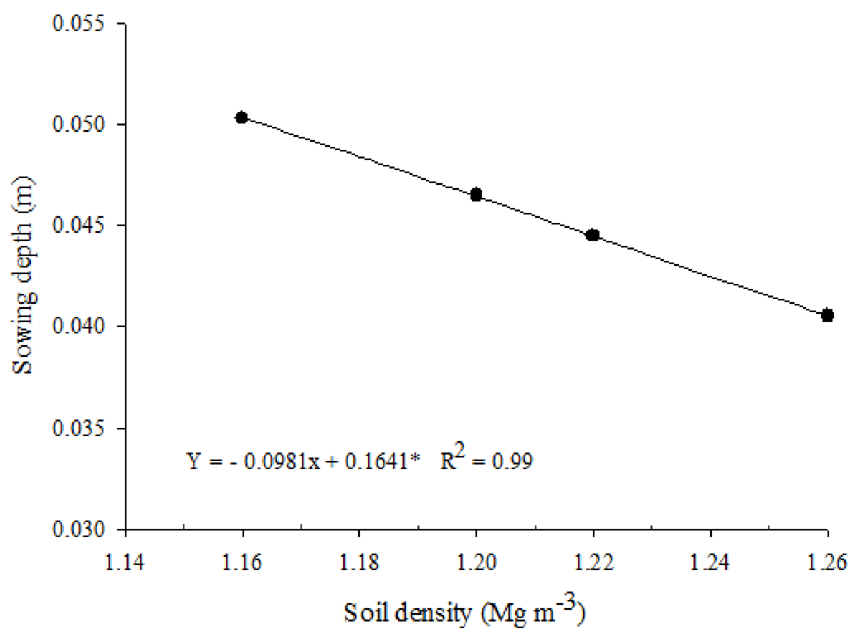

Figure 3. Soybean sowing depth (m) as a result of soil density.

double disc than with the shank type (Table 1). The planting line was composed of a set of articulated rods and compression springs inclined to the vertical with the function of displacing the shank tine backwards when it encounters an obstacle (stone, wood or compacted soil), which offers greater resistance than the tension of the safety spring (Mialhe, 2012). This caused the shank type to work at a shallower depth than the disc, thereby reducing sowing depth.

Table 1. Soybean sowing depth (m) as a result of seed drill mechanisms.

Openers	Sowing depht (m)
Disc	0.047^{a}
Shank	0.044^{b}

Means followed by differing lowercase letters in the column differ (P≤0.05) according to the Tukey test.

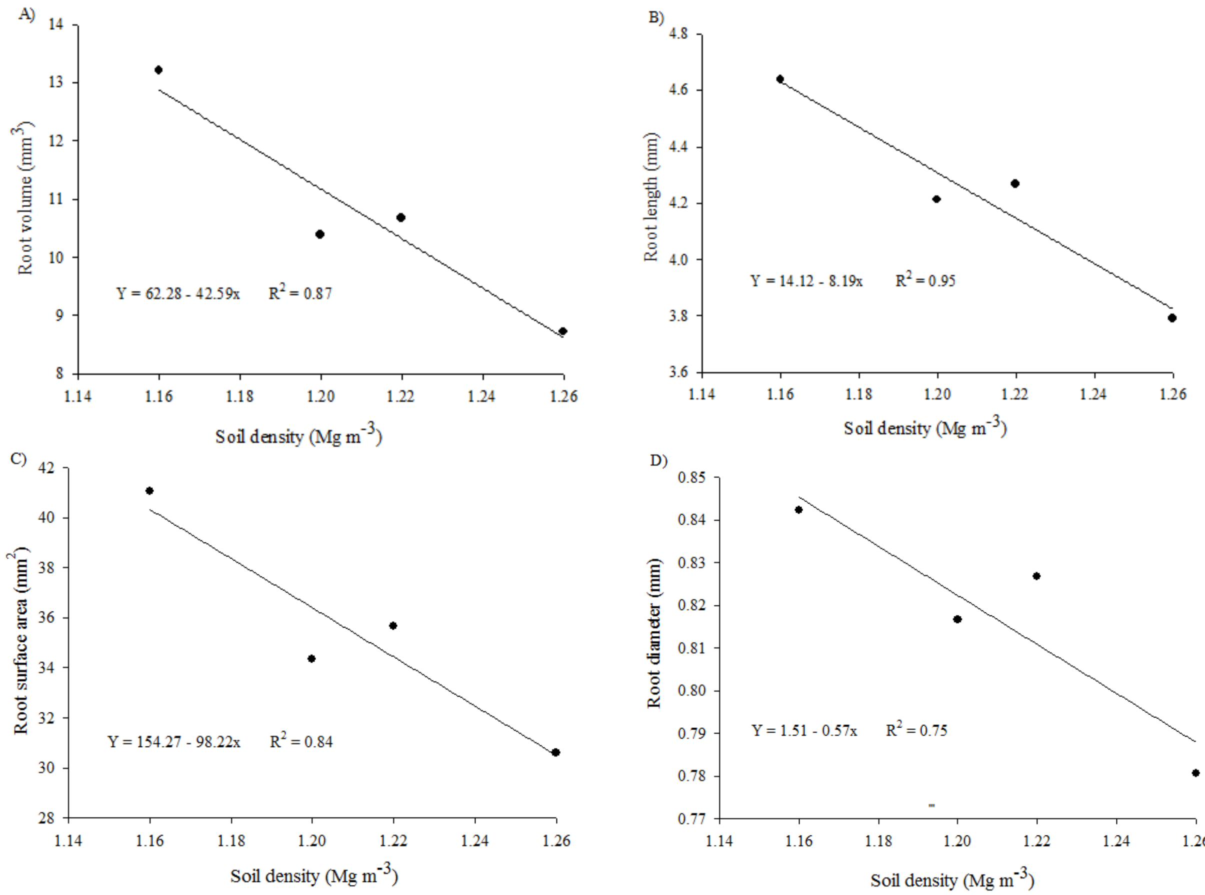

Figure 4. Soybean root growth in the interrows: A) root volume (mm^3) at a depth of 0.20-0.30 m, B) root length (mm) at a depth of 0.10-0.20 m, C) root surface area (mm^2) at a depth of 0.20-0.30 m, D) root diameter (mm) at a depth of 0.20-0.30 m as a result of soil density.

Soil density and the type of furrow opening mechanism had no significant effect on the mobilized soil area. The mean value was 51.18 cm^2. Mion et al. (2009) evaluated the draught power required by five models of furrow opener and also found no significant differences between the disc and shank type furrow openers in relation to the mobilized soil area. However, Modolo et al. (2013) described a 42% increase in the soil area mobilized by the sowing furrow of the furrow opener with the shank mechanism in relation to the double disc. According to the authors, this was attributable to the greater depth at which the shank tine works and it's characteristic of breaking up layers of denser soil while the double disk furrow opener mechanism aims to open the sowing furrow with minimal soil mobilization.

There were no significant differences in root volume as a result of furrow opener type or compaction level for measurements taken within the sowing row, with mean values of 21.20; 20.42 and 15.97 mm^3 at depths of 0.0-0.10, 0.10-0.20 and 0.20-0.30 m, respectively. These results may be related to good plant growth as a result of good tillage by the furrow openers in the planting rows and the ample rainfall (430 mm) recorded in the period from December 2013 to February 2014, which included the peak growth of the soybean root system. Under field conditions, root system behavior is greatly influenced by spatial and temporal variations in water and soil compaction and therefore soil resistance (White and Kirkegaard, 2010; Bengough et al., 2011). Freddi et al. (2007) also observed no effects from soil compaction when evaluating the root growth of corn under favorable rainfall conditions.

The only significant effect observed in the interrows was at the depth of 0.20 to 0.30 m (Figure 4A), with a linear reduction in root volume as the soil density increases. The depths of 0.00-0.10 and 0.10-0.20 m showed mean values of 16.69 and 15.24 mm^3, respectively. As surface soil compaction has more significant effects down to the 0.20 m depth layer, the roots that reach this depth or go deeper tend to find fewer physical constraints; thus, presenting significantly greater differences between root volumes as compared to the surface layers. This is in agreement with Croser et al. (2000), who found that after the roots pass through the impeding layers, they return to growth patterns similar to sites without such hindrance.

Differences in root length were only significant at the 0.10-0.20 m depth level in the interrows (Figure 4B), with a linear reduction as the density of the soil increases. Atkinson et al. (2009) showed that root growth was higher in moderately compacted soil, possibly due to higher levels of water retention and better contact between the roots and the soil.

The depths of 0.0-0.10; 0.10-0.20 and 0.20-0.30 m showed no significant differences within the sowing line, with means of 4.05; 4.21 and 4.07 mm², respectively and means of 4.37 and 4.52 mm² at the depths of 0.0-0.10 and 0.20-0.30 m in the interrows. This reduced root growth in compacted soils is due to the reduced cell elongation rate as a result of a reduction in the meristem cell division rate (White and Kirkegaard, 2010; Lipiec et al., 2012).

Observing the root development of five species in compacted and uncompacted soil, Lipiec et al. (2012) noted changes in root structure, which indicates that roots with circular and flattened profiles grow through the circular pores and cracks that are present in the soil, respectively. This result may be associated with the possibility of roots having found pores in the surface layer and thereby succeeding in developing below the obstructing layer.

Evaluating the effect of soil compaction on root growth and anatomy in five cereals, Lipiec et al. (2012) observed reduced root length and changes in the root anatomy in seedlings with seven days of development. Root length was 50% lower in barley and 79% lower in triticale in compacted soil as compared to uncompacted soil.

At the depths of 0.0-0.10, 0.10-0.20 and 0.20-0.30 m within the sowing line, there were no significant differences in terms of root surface area, averaging 57.43; 54.82 and 45.18 mm², respectively. Means of 49.9 and 45.02 mm² were obtained at the depths of 0.0-0.10 and 0.10-0.20 m in the interrows. Only at the depth of 0.20-0.30 m in the interrows were significant differences observed (Figure 4C), with a linear reduction in root surface area as soil density increases. Tracy et al. (2012) showed that a certain level of soil compaction can be beneficial to root growth, given that soil-root contact increases, which is limited when the soil presents as loose, resulting in lower length and surface area, this being an alternative explanation for the absence of significant differences in the data when assessed in the sowing line.

Another factor that influences root growth and the surface area of the roots is soil moisture. Silva et al. (2000) observed that in conditions of high soil humidity, differences in penetration resistance between compacted and uncompacted soil are generally small. However, when soils become dry, the compacted layers cause damage and restrict root development.

Significant differences in root diameter were also only observed at the depth of 0.20 to 0.30 m in the interrows (Figure 4D). The absence of significant differences in the rest of the root growth data may follow the reasoning of Croser et al. (2000), who describe that an increase in root cell diameter tends to increase the root diameter, which may help them to develop in a compacted soil. It is also known that as a result of the expansion and contraction of the soil, more resistant aggregates and inter-aggregate pores are formed, even in compacted soil, which allows root expansion as well as reduce the susceptibility of the soil to deformation (Lipiec et al., 2012).

The means recorded for root diameter at depths of 0.0-0.10, 0.10-0.20 and 0.20-0.30 m were 0.92; 0.94 and 0.87 mm, respectively in the sowing row and 0.89 and 0.88 mm in the interrows at the depths of 0.0-0.10 and 0.10-0.20 m. Studies by Beutler and Centurion (2004) in Red Latosol subject to soil compaction with soil bulk density of 1.19 to 1.81 Mg m^{-3}, described no significant changes in soybean root diameter to the depth of 0.15 m.

The morphological and anatomical plasticity of cereal roots is clearly demonstrated by Lipiec et al. (2012), resulting in cell deformation in order to adapt to the soil conditions. Bengough et al. (2011) reported that roots are capable of locating cracks and channels in the soil and thus are able to penetrate into more structured subsoil.

For most of the root system parameters analyzed, significant differences were only observed at the depth of 0.20-0.30 m, indicating a direct relationship between root volume, surface area and diameter. However, according to Lipiec et al. (2012), there is still little information available regarding the effect of changes to the structure of the pores on root development. According to them, most of the research on root development and anatomy has been performed using soil samples prepared by static compaction, without considering the effects of machinery traffic in the field on the structure of the pores.

Conclusions

Penetration resistance increased with increasing soil compaction to a depth of 0.20 m. The sowing depth and mobilized soil area were not affected by soil compaction levels. The type of furrow opening mechanism only influenced the sowing depth, with greater depth achieved using the double disc. Neither, the seed-furrow openers nor the level of soil compaction significantly influenced soybean root growth when evaluated in the sowing line.

The type of furrow opening mechanism did not influence any of the evaluated parameters. Soil compaction altered soybean root growth in the interrow, but did not impede rooting. Regardless of the assessment depth in the interrow, there was a reduction in root volume, length, surface area and diameter with increased soil density.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENTS

The authors thank the CNPq (Research Productivity), and the Araucaria Foundation for the financial support.

REFERENCES

Atkinson BS, Sparkes DL, Mooney SJ (2009) Effect of seedbed cultivation and soil macrostructure on the establishment of winter wheat (*Triticum aestivum*). Soil Till. Res. 103:291-301.

Bengough AG, Mckenzie BM, Hallett PD, Valentine TA (2011). Root elongation, water stress, and mechanical impedance: a review of limiting stresses and beneficial root tip traits. J. Exp. Bot. 62:59-68.

Benjamin JG, Nielsen DC (2004). A method to separate plant roots from soil and analyze root surface área. Plant Soil, 267:225-234.

Beutler NA, Centurion JF (2004). Matéria seca e altura das plantas de soja e arroz em função do grau de compactação e do teor de água de dois Latossolos. Eng. Agríc. 24:142-149.

Bonini AK, Filho AG, Secco D, Souza RF, Tavares C (2008). Atributos físicos e requerimento de potência de uma semeadora-adubadora em um Latossolo sob estados de compactação. Eng. Agríc. 28:136-144.

Croser C, Bengough AG, Pritchardb J (2000). The effect of mechanical impedance on root growth in pea (*Pisum satium*). II. Cell expansion and wall rheology during recovery. Physiol. Plant. 109:150-159.

De Maria IC, Castro OM, Dias HS (1999). Atributos físicos do solo e crescimento radicular de soja em Latossolo Roxo sob diferentes métodos de preparo do solo. Rev. Bras. Cienc. Solo 23:703-709.

Ferreras LA, Battista JJ de, Ausilio A, Pecorari C (2001). Parámetros físicos del suelo en condiciones no perturbadas y bajo laboreo. Pesq. Agropec. Bras. 36:161-170.

Franchini JC, Costa JM, Debiasi H, Torres E (2011). Importância da rotação de culturas para a produção agrícola sustentável no Paraná. Londrina: Embrapa Soja, 52 p. (Embrapa Soja. Documentos, 327).

Freddi OS da, Centurion JF, Beutler AN, Aratani RG, Leonel CL (2007). Compactação do solo no crescimento radicular e produtividade da cultura do milho. Rev. Bras. Cienc. Solo. 31:627-636.

FUNARBE (Fundação Arthur Bernardes) (2007). SAEG Sistema para Análise Estatística. Versão 9.1, UFV, Viçosa.

Gao Y, Duan A, Qiu X, Liu Z, Sun J, Zhang J, Wang H (2010). Distribution of roots and root length density in a maize/soybean strip intercropping system. Agric. Water Manage. 98:199-212.

Jorge LAC, Rodrigues AFO (2008). Safira: sistema de análise de fibras e raízes. São Carlos: Embrapa Instrumentação Agropecuária, 21p. (Embrapa Instrumentação Agropecuária. Boletim de pesquisa e desenvolvimento, 24).

Jorge LA de C, Silva DJ da CB (2010). SAFIRA: Manual de utilização. Embrapa Instrumentação, São Carlos 29 p.

Lipiec J, Horn R, Pietrusiewicz J, Siczek A (2012). Effects of soil compaction on root elongation and anatomy of different cereal plant species. Soil. Till. Res. 121:74-81.

Mialhe LG (2012). Máquinas agrícolas para plantio. Editora Millennium, 1ª ed, 2012, 648 p.

Micucci FG, Taboada MA (2006). Soil physical properties and soybean (*Glycine max*, Merrill) root abundance in conventionally- and zero-tilled soils in the humid Pampas of Argentina. Soil. Till. Res. 86:152-162.

Mion RL, Benez SH, Viliotti CA, Moreira JB, Salvador N (2009). Análise tridimensional de esforços em elementos rompedores de semeadoras de plantio direto. Ciênc. Rural. 39:1414-1419.

Modolo AJ, Franchin MF, Trogello E, Adami PF, Scarsi M, Carnieletto R (2013). Semeadura de milho com dois mecanismos sulcadores sob diferentes intensidades de pastejo. Eng. Agríc. 33:1200-1209.

Palma MAS, Volpato CES, Barbosa JÁ, Spagnolo RT, Barros MM de, Vilas Boas L do A (2010). Efeito da profundidade de trabalho das hastes sulcadoras de uma semeadora-adubadora na patinagem, na força de tração e no consumo de combustível de um trator agrícola. Ciênc. Agrotec. 34:1320-1326.

Reinert DJ, Albuquerque JÁ, Reichert JM, Aita C, Andrada MMC (2008). Limites críticos de densidade do solo para o crescimento de raízes de plantas de cobertura em Argissolo Vermelho. Rev. Bras. Cienc. Solo 32:1805-1816.

Reis EF dos, Schaefer CEGR, Fernandes HC, Naime JM, Araújo EF (2006). Densidade do solo no ambiente solo-semente e velocidade de emergência em sistema de semeadura de milho. Rev. Bras. Cienc. Solo 30:777-786.

Santos AP, Volpato CES, Tourino MCC (2008). Desempenho de três semeadoras-adubadoras de plantio direto para a cultura do milho. Ciênc. Agrotec. 32:540-546.

Secco D, Reinert DJ, Reichert JM, Sia VR da (2009). Atributos físicos e rendimento de grãos de trigo, soja e milho em dois Latossolos compactados e escarificados. Ciênc. Rural 39:58-64.

Silva VR, Reinert DJ, Reichert JM (2000). Densidade do solo, atributos químicos e sistema radicular do milho afetados pelo pastejo e manejo do solo. Rev. Bras. Cienc. Solo 24:191-199.

Soil Survey Staff (2014). Keys to soil taxonomy. 12th edition U.S. Department of Agriculture. Natural Resources Conservation Service, Washington, D.C. 372 p.

Tracy SR, Black CR, Roberts JA, McNeill A, Davidson R, Tester M, Samec M, Korošak D, Sturrock C, Mooney SJ (2012). Quantifying the effect of soil compaction on three varieties of wheat (*Triticum aestivum* L.) using X-ray Micro Computed Tomography (CT). Plant Soil. 353:195-208.

Valicheski RR, Grossklaus F, Stürmer SLK, Tramontin AL, Baade ESAS (2012). Desenvolvimento de plantas e cobertura e produtividade da soja conforme atributos físicos em solo compactado. Rev. Bras. Eng. Agríc. Ambient. 16:969-977.

White RG, Kirkegaard JA (2010). The distribution and abundance of wheat roots in a dense, structured subsoil-implications for water uptake. Plant Cell Environ. 33:133-148.