



Effects of the soil compaction on root growth of cover crops in the western Amazon

Efeitos da compactação do solo no crescimento radicular de plantas de cobertura na Amazônia Ocidental

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The intensification of agriculture has increased the traffic of heavy machines, which can cause soil compaction, becoming a limiting factor for plant growth and development. The aim of this work was to evaluate the effects of machine traffic on soil physical attributes, root growth and dry mass production of legumes and grasses cultivated as cover. The experiment was carried in Rolim de Moura (RO). The experimental design was randomized blocks, in a split-plot scheme, with three replications. The treatments in the plots consisted of four induced soil compaction states: 0, 1, 4, 7 passes of an agricultural tractor, and in the subplots four cover crops species: *Crotalaria*, *Stylosanthes*, Millet and *Palisadegrass*. After two days of intense rainfall, compaction was carried out by passing the wheelsets of a New Holland-TL85E agricultural tractor, with 88hp of power, 4x2 TDA, standard tires 7.5x16 and 18.4x34, with blowing pressure of 110 kPa and 124 kPa, with a total mass of 3.16 Mg. Density, microporosity, macroporosity and total porosity were evaluated, surface area, root length and diameter and dry mass were also evaluated. During the period of full flowering of each crop, trenches were opened in each subplot for root evaluation and deformed soil and shoot dry mass samples were collected for evaluation. Significant discrepancies were observed for the physical attributes evaluated, surface area, length and root diameter of grasses in relation to legumes. After a tractor pass, there is an increase in soil density, and reductions in macroporosity and total porosity.

Keywords: machine traffic, soil bulk density, soil physical quality.

A intensificação da agricultura tem aumentado o tráfego de máquinas pesadas, que podem causar compactação do solo, tornando-se um fator limitante para o crescimento e desenvolvimento das plantas. O objetivo deste trabalho foi avaliar os efeitos do tráfego de máquinas sobre os atributos físicos do solo, crescimento radicular e produção de massa seca de hortaliças e gramíneas. O experimento foi realizado em Rolim de Moura (RO). O delineamento experimental foi de blocos casualizados, em esquema de parcelas subdivididas, com três repetições. Os tratamentos nas parcelas consistiram em quatro estados de compactação induzida do solo: 0, 1, 4, 7 voltas do trator, e nas subparcelas quatro espécies de plantas de cobertura: *Crotalaria*, *Stylosanthes*, Milheto e *Braquiaria*. Após dois dias de chuva intensa, foi realizada a compactação do solo passando os rodados de um trator agrícola New Holland-TL85E, com 88cv de potência, 4x2 TDA, pneus padrão 7,5x16 e 18,4x34, com pressão de sopro de 110 kPa e 124 kPa, com massa de 3,16 Mg. Foram avaliadas densidade, microporosidade, macroporosidade e porosidade total, área superficial, comprimento e diâmetro de raiz e massa seca. Durante o período de plena floração de cada cultura, foram abertas trincheiras em cada subparcela para avaliação das raízes e amostras de solo e parte aérea deformadas foram coletadas para avaliação da massa seca. Foram observadas discrepâncias significativas para os atributos físicos avaliados, área superficial, comprimento e diâmetro de raiz das gramíneas em relação às hortaliças. Depois do tráfego do trato, isso aumentou a densidade do solo ocasionando redução na macroporosidade e na porosidade total.

Palavras-chave: tráfego de máquinas, densidade do solo, qualidade física do solo.

1. INTRODUCTION

In the Amazon region, the constant interference of anthropological action has caused countless changes in the processes that control the sustainability of its ecosystem. Sánchez (2006) [1] reports that the environmental impact causes the loss or deterioration of environmental quality, the reduction of the natural conditions of an environment. Deforestation and the implantation of cultivation areas cause disturbances in the physical properties of the soil, where agricultural practices carried out in a disorderly manner, associated with intense rainfall, which normally occur in this region, constitute factors responsible for the degradation of the structure and the formation of compacted layers [2].

Among the types of soils, Latosolos have excellent physical properties, however the compaction caused by incorrect management, such as intensive traffic of agricultural machines, causes changes in their physical attributes [3]. Compaction is mentioned as the main cause of physical degradation of soils due to the reduction of its pore space [4], resulting mainly from the traffic of machines in soil preparation, seeding, cultural treatments and harvesting operations [5].

The alteration caused by compaction in the physical attributes of the soil reflects on the growth and production of plants, causing a reduction in productivity [6]. For Bergamin et al. (2010) [7], machines traffic alters the physical quality of the soil, which increases with the intensity of machine passes, affecting plant growth and development, decreasing productivity over the years and increasing production costs. For Shah et al. (2017) [8], as a result of compaction, there is a structural change in the soil due to the reorganization of particles and its aggregates, increases the density and resistance of the soil to penetration and reduces macroporosity, inhibits the plant root development. This plant response is more easily observed when there is irregular rainfall during the growing season. The improvement of practices and the development of techniques that seek to combat soil degradation is necessary for its conservation.

Biological descompaction using plants that have a root system capable of growing in layers of compacted soil provide the formation of stable biopores, improving the physical environment [9]. Studies such as Severiano et al. (2010) [10], found beneficial effects of different types of cover and its residues left on the soil, in its chemical and physical attributes and in crop yield.

Due to the considerable difficulty in evaluating the soil compaction caused by agricultural machinery traffic in the field and also the use of soil cover species that can provide biological descompaction, few studies have been carried out. However, it is necessary to know the compaction states that reduce the growth of the plant root system, aiming at the efficient and sustainable use of the soil, [7], in addition to developing soil management practices with crops that can minimize the adverse effects of compaction.

The processes involving the management of plant cover subjected to environmental variations, specifically soil compaction, should be further studied, especially its effects and its relationship with its root system. The selection of appropriate soil management and crops rotation practices depends on monitoring the effect these practices have on soil density, root growth and crops yield. In this way, the evaluation and monitoring of the soil mechanical impediment layers to root development become important tools to characterize the evolution of agricultural systems, and also to serve as an indispensable subsidy to be used in the planning and direction of the practices of crops employed within an agricultural property [5].

Given this problem, the objective of this work was to evaluate the physical attributes of a dystrophic Red-Yellow Latosol with different compaction states induced by agricultural machine traffic, root development and shoot dry mass production of legumes and grasses species and to identify cover species that improve the physical quality of the soil through the development of its root system, reducing the negative effects of compaction.

2. MATERIAL AND METHODS

The experiment was installed in a dystrophic Red-Yellow Latosol at the Experimental Farm of the Rolim de Moura Campus (RO) of the Fundação Universidade Federal de Rondônia – UNIR, at an average altitude of 277 m, located at 11° 34' 58.52" S and 61° 46' 14.45" W.

The climate, according to Koppen is Am, this climate has lot rains during half of the ground, with a well-defined dry season, minimum temperature of 24 °C, maximum of 32 °C and average of 28 °C, average annual precipitation of 2,250 mm, with high relative humidity in the rainy season, oscillating in around 85% [11].

The experimental design was in randomized blocks, in a split-plot scheme, with three repetitions. In the plots (4 x 20 m) four induced soil compaction states were allocated: (C1) 0, (C2) 1, (C3) 4 and (C4) 7 passes of an agricultural tractor, respectively. In the subplots (4 x 5 m), four ground cover crops were evaluated, being two legumes: (E1) *Crotalaria* (*Crotalaria juncea*, L.), (E2) *Stylosanthes* cv. campo-grande (*Stylosanthes capitata* x *Stylosanthes macrocephala*) and two of grasses: (E3) Millet (*Pennisetum glaucum*) and (E4) Palisadegrass (*Brachiaria brizantha* cv. Marandu).

Soil preparation was carried out three months before sowing, correction was made with dolomitic limestone, PRNT 62%, to raise the base saturation to 60% and limestone incorporation occurred through two harrowing (Drag harrow Baldan GR, 14 26" disc), one with a plow harrow and the other with a leveling harrow. After ninety days, mechanical soil preparation was performed again with two plow harrows, and phosphating was carried out with the application of 90 kg of P₂O₅, in the form of triple superphosphate, which was incorporated with a pass through a leveling harrow.

After the mechanical preparation of the soil and the practice of phosphating, the induction of soil compaction was carried out, which occurred on February 2nd, 2015, two days after intense rainfall (soil close to field capacity) through the passage of wheelsets of an agricultural tractor (NH-TL85E, 88hp, 4x2 TDA, standard tires 7.5x16 and 18.4x34, with inflation pressure of 110 kPa and 124 kPa, respectively) with a total mass of 3.16 Mg, covering the entire surface of the plot so that the tires compressed areas parallel to each other. The number of times the tractor traveled varied according to the treatment, and the traffic was superimposed on the previous one so that the entire area of each plot was trafficked with an equal number of times.

Seeding of ground cover crops was carried out manually on February 4th, 2015, in density indicated for each species, being for *Crotalaria*, 30 kg/ha, *Stylosanthes*-campo-grande, 3 kg/ha, Millet, 25 kg/ha, *Brachiaria*, 6 kg/ha. Furrows spaced by 0.25 m and approximately two centimeters in depth were made using a small narrow hoe (mattock) to not eliminate the possible negative effects of compaction.

Soil samples with preserved structure were collected using 100 cm³ metal cylinders, collected between the rows of crops, when the plants were in full bloom. A trench was opened in each subplot, and samples were collected in three soil layers: 0–0.05, 0.05–0.1 and 0.1–0.2 m. For each subplot and depth, two subsamples were collected, totaling 288 samples with preserved structure. The samples with preserved structure were used for determinations of macroporosity, microporosity, total porosity and soil density. In the laboratory, after preparing the samples with preserved structure, they were saturated by gradually raising a layer of water until reaching about 2/3 of the height of the metal cylinder and the procedure for obtaining microporosity was performed using the table method voltage, applying a potential of -0.006 MPa, as described in Embrapa (1997) [12]. After stabilization at this potential, the samples were removed from the tension table, weighed and taken to a drying oven at 105–110 °C for 48 hours to determine the soil density by the volumetric ring method. Total and macro porosity were obtained as proposed in Embrapa (1997) [12].

The root system determinations were performed at the same time as the collection of deformed soil samples to avoid root system alterations and minimize experimental errors. These were the days: April 18th, 2015 for Millet, May 16th, 2015 for the *Crotalaria*, June 2nd, 2015 for the *Stylosanthes* and June 16th, 2015 for the *Brachiaria*. In each plot, a trench transversal to two rows of cultivation was opened, where the vertical wall of the trench was 3 cm from a plant of each row chosen so that it represented the set of plants in the experimental unit, with its roots

exposed. After the exposure of the roots, the profile was divided into layers of 0.5 x 0.05 m, with the help of a mesh placed in full contact with the soil, with a length of 0.5 m (two cultivation lines) and depth 0.2 m. Then, profile photographs were taken with a digital camera (12.1 megapixels). This image was segmented using the thresholding technique. Subsequently, the roots were processed and analyzed at depths of 0–0.05, 0.05–0.1 and 0.1–0.2 m, about the length, surface and root diameter, using the software Safira v1.1 [13].

To determine the phytomass production by the cover plants, all the aerial part of the plants was randomly collected in full bloom in an area of 0.5 m² (0.5 x 1.0 m). After collection, the material was placed in a drying oven at 65 °C until constant weight to determine the dry mass of the aerial part. The results were extrapolated to one hectare and presented in kg ha⁻¹.

The data obtained in the experiment were analyzed using analysis of variation and, when significant, the Tukey test at 5% was applied to compare averages. To this end, the computer application ASSISTAT [14] was used.

3. RESULTS AND DISCUSSION

There were differences between treatments for the physical attributes of the soil only up to 0.1 m in depth, except for the microporosity that was not altered in any studied soil layer. Macroporosity, total porosity and soil density were influenced by both tractor passes and cover crops in the 0–0.05 and 0.05–0.1 m layers, showing significant interactions between crops and number of passes. In the 0.1–0.2 m layer there were no differences between the physical attributes evaluated in any of the treatments, corroborating the work by Bergamin et al. (2010) [7]. Soil pore space plays an important role in root growth along with other soil physical attributes, highlights [15].

From the lowest to the highest compaction level (C1 to C4), there is an increase in the soil density value, while macroporosity and total porosity are reduced. It is noteworthy that compaction promotes less growth and fewer roots, in addition to being concentrated in the surface layer of the soil, as seen in several studies, as in Bergamin et al. (2010) [7], Castagnara et al. (2013) [16] and Mazurana et al. (2013) [17].

In the 0 to 5 cm layer (Table 1) treatment C1 (conventional prepare, without tractor passes), *Crotalaria* presented the lowest soil density, and the highest macroporosity and total porosity. *Brachiaria* showed an opposite effect to *Crotalaria*, and Millet and *Stylosanthes* did not differ statistically.

In treatment C2 (Table 1), Millet and *Brachiaria* showed no difference between them, presenting the best results for the soil attributes, with the lowest density, highest macroporosity and total porosity. *Stylosanthes*, on the other hand, did not show significant improvements, presenting the highest density with no statistical difference from *Crotalaria*. Crops that have fasciculate roots and smaller diameter provide less density for the soil in relation to legumes. Soil compaction reduces the number of large pores, similar in size and diameter, to plant roots and, therefore, the roots cannot penetrate into pores with diameters smaller than itself. Fine roots (fascicular root system) can penetrate compacted soils more easily than thick ones (pivoting), which was also verified in studies carried out by Reichert et al. (2007) [5]. However, fasciculated roots reach more superficial layers, while pivoting roots reach deeper layers, also being reaffirmed by Silva et al. (2014) [18].

The effects that occurred in treatments C1 and C2 (Table 1) are attributed to the development of the root system of the species and its ability to overcome compaction and providing an improvement in soil aggregates, changing its attributes. Hu et al. (2018) [19] emphasized that the soil aeration porosity plays an important role in root growth. However, in this layer of 0–0.05 m, in C3 and C4 (Table 1) there was no statistical difference between the treatments for the evaluated attributes.

Table 1: Density, macroporosity and total porosity of the soil under different cover crops and number of tractor passes in the 0 to 5 cm layer.

Passes ⁽¹⁾	<i>Brachiaria</i>	<i>Millet</i>	<i>Stylosanthes</i>	<i>Crotalaria</i>
 Bulk density (Mg m ⁻³)			
C1	1.24 bA	1.18 cAB	1.18 bAB	1.14 bB
C2	1.29 abB	1.30 bB	1.39 aA	1.36 aAB
C3	1.37 aA	1.40 aA	1.39 aA	1.37 aA
C4	1.37 aA	1.42 aA	1.40 aA	1.37 aA
CV%-a (Passes) = 4.25				
CV%-b (Crops) = 2.33				
..... Macroporosity (m ⁻³ m ⁻³)				
C1	0.17 aB	0.21 aA	0.19 aAB	0.22 aA
C2	0.13 aA	0.11 bAB	0.09 bB	0.10 bAB
C3	0.07 bA	0.07 bA	0.09 bA	0.09 bA
C4	0.07 bA	0.06 bA	0.07 bA	0.08 bA
CV%-a (Passes) = 32.16				
CV%-b (Crops) = 15.30				
..... Total Porosity (m ⁻³ m ⁻³)				
C1	0.52 aB	0.58 aA	0.54 aAB	0.58 aA
C2	0.51 aA	0.48 bAB	0.45 bB	0.46 bB
C3	0.44 bA	0.44 bA	0.45 bA	0.45 bA
C4	0.45 bA	0.44 bA	0.45 bA	0.45 bA
CV%-a (Passes) = 6.48				
CV%-b (Crops) = 4.48				

⁽¹⁾ 0 – conventional planting without additional compaction; 1, 4 and 7 – correspond to conventional planting with additional compaction by tractor traffic of 3.16 Mg (88 hp) in one, four and seven passes, respectively. Averages followed by equal capital letters in rows and equal lowercase letters in columns do not differ by Tukey's test at the 5% level.

For the second layer evaluated 0.05–0.1 m (Table 2), a similar result to that of the first layer was observed for *Brachiaria* in treatment C1, therefore the other cultures did not differ in this treatment. In C2, *Brachiaria* and *Stylosanthes* did not show statistical differences, presenting lower density values, higher macroporosity and total soil porosity, and the largest root diameter was observed for the *Stylosanthes* in this treatment.

In the state of compaction C3 and C4, *Brachiaria* and *Crotalaria* showed no difference for density, macroporosity and total porosity of the soil, and *Millet* and *Stylosanthes* did not stand out in relation to the improvement in the evaluated attributes.

The level of compaction may have interfered with the root distribution in the soil profile and consequently with the soil density, where grasses have a fasciculated root resulting in their bigger growth in the superficial layers, providing an improvement in the physical structure of the soil. In contrast, legumes plants have a pivoting root system, producing fewer adventitious roots, in turn with bigger penetration power in the deep layers. According to Nicoloso et al. (2008) [20] the use of cover plants with a pivoting root system present the capability to grow in compacted layers, form stable biopores and improve the physical attributes of the soil.

Table 2: Density, macroporosity and total porosity of the soil under different cover crops and number of tractor passes in the 5 to 10 cm layer.

Passes ⁽¹⁾	<i>Brachiaria</i>	Millet	<i>Stylosanthes</i>	<i>Crotalaria</i>
 Bulk Density (Mg m ⁻³)			
C1	1.29 bA	1.20 cB	1.20 cB	1.18 bB
C2	1.30 bC	1.34 bB	1.28 bC	1.39 aA
C3	1.38 aB	1.41 aAB	1.42 aA	1.39 aB
C4	1.42 aA	1.41 aA	1.42 aA	1.39 aA
CV%-a (Passes) = 1.61				
CV%-b (Crops) = 1.11				
..... Macroporosity (m ⁻³ m ⁻³)				
C1	0.12 aB	0.14 aA	0.14 aA	0.16 aA
C2	0.11 aAB	0.09 bBC	0.11 bA	0.07 bC
C3	0.07 bA	0.06 cAB	0.05 cB	0.07 bAB
C4	0.05 bA	0.05 cA	0.05 cA	0.06 bA
CV%-a (Passes) = 14.77				
CV%-b (Crops) = 9.11				
..... Total Porosity (m ⁻³ m ⁻³)				
C1	0.50 aB	0.53 aA	0.52 aAB	0.53 aA
C2	0.50 aA	0.48 bA	0.49 aA	0.44 bB
C3	0.45 bA	0.45 cA	0.44 bA	0.44 bA
C4	0.44 bA	0.45 cA	0.44 bA	0.45 bA
CV%-a (Passes) = 3.11				
CV%-b (Crops) = 2.89				

⁽¹⁾ 0 – conventional planting without additional compaction; 1, 4 and 7 – correspond to conventional planting with additional compaction by tractor traffic of 3.16 Mg (88 hp) in one, four and seven passes, respectively. Averages followed by equal capital letters in rows and equal lowercase letters in columns do not differ by Tukey's test at the 5% level.

Cover crops subjected to induced compaction states underwent changes in root growth (Table 3), there was a gradual decrease in root growth as the level of compaction in the soil increased to the 0–10 cm layer. Corroborating with Sivarajan et al. (2018) [21] who observed the corn crop, where both soil density and root surface were negatively influenced by different states of compaction.

The root surface area results (Table 3) showed a significant interaction between treatments in the studied layers, except in the 0.1–0.2 m layer, where significant differences occur only between crops, not being influenced by the traffic level of the tractor. Calonego et al. (2011) [22], found that sorghum was influenced by compaction in the 0.15–0.3 m layer, in a Red Argisol with two compaction levels and with density values of 1.1 and 1.6 kg dm⁻³.

Brachiaria stood out in the superficial layers 0.05–0.1 m, presenting bigger root surface area than the other cultures, however Millet showed no statistical difference in the C4 treatment in the 0.05–0.1 m layer (Table 3). In the 0.05–0.1 m layer, only the *Stylosanthes* crop showed no changes in the root surface area as a function of compaction level (Table 3). For the other crops, a reduction in the root surface area was observed with the increase of the soil compaction states, this effect being more pronounced for the *Brachiaria* crop, except that it was superior to the other crops. The results obtained for *Crotalaria* and *Stylosanthes* (Table 3) corroborate those obtained by Valadão et al. (2015) [23] who found a reduction in the root surface area of the soybean crop in the 0.05–0.1 m layer under four levels of induced compaction (0, 2, 4 and 8 passes of a 5.0 Mg agricultural tractor) in a typical dystrophic Red-Yellow Latosol.

Among the crops, *Brachiaria* suffered the biggest reduction in root surface area under states of induced compaction in the topsoil (Table 3), causing reductions of 29.1%, 47% and 50% according to the increased level of compaction C2, C3, C4, respectively. Bergamin et al. (2010) [7], obtained reductions in the root surface of the corn crop in the 0–0.2 m layer when compaction states were increased (0, 1, 2, 4 and 6 passes of a 5.0 Mg agricultural tractor) in one

Dystroferric Red Latosol cultivated under no-tillage system. However, these results differed from those found by Calonego et al. (2011) [22] in which compaction did not influence the root dry matter of *Brachiaria* in the 0–0.15 m layer. In the 0.1–0.2 m layer, the crops did not show significant interaction between treatments, and the tractor traffic did not influence the root surface area, but there were differences between crops, with *Brachiaria* being the crop that obtained the highest root surface area values (Table 3).

Table 3: Root surface area of cover crops at different depths and number of tractor passes.

Passes ⁽¹⁾	Root surface area (m ² m ⁻²)			
	<i>Brachiaria</i>	<i>Crotalaria</i>	<i>Stylosanthes</i>	Millet
..... 0 – 5 cm				
C1	0.6586 aA	0.1612 aC	0.1463 aC	0.2597 aB
C2	0.4670 bA	0.1487 abBC	0.1104 abC	0.1983 abB
C3	0.3487 cA	0.0951 abB	0.0671 abB	0.1135 bB
C4	0.3301 cA	0.0694 bB	0.0591 bB	0.1143 bB
CV%-a (Passes) = 18.49				
CV%-b (Crops) = 18.36				
..... 5 – 10 cm				
C1	0.2246 aA	0.1033 aBC	0.0644 aC	0.1332 aB
C2	0.1633 bA	0.0818 abB	0.0508 aB	0.0904 abB
C3	0.0976 cA	0.0479 abAB	0.0344 aB	0.0522 bAB
C4	0.0647 cA	0.0317 bA	0.0325 aA	0.0505 bA
CV%-a (Passes) = 27.18				
CV%-b (Crops) = 32.91				
..... 10 – 20 cm				
C1	0.0473 aA	0.0100 aB	0.0172 aB	0.0172 aB
C2	0.0467 aA	0.0074 aB	0.0156 aB	0.0180 aB
C3	0.0445 aA	0.0088 aB	0.0197 aB	0.0162 aB
C4	0.0421 aA	0.0095 aB	0.0179 aB	0.0147 aB
CV%-a (Passes) = 42.05				
CV%-b (Crops) = 38.45				

⁽¹⁾ 0 – conventional planting without additional compaction; 1, 4 and 7 – correspond to conventional planting with additional compaction by tractor traffic of 3.16 Mg (88 hp) in one, four and seven passes, respectively. Averages followed by equal capital letters in rows and equal lowercase letters in columns do not differ by Tukey's test at the 5% level.

There was a decrease in root length according to the depth studied and the increase in the level of compaction. When analyzing the root length of cover crops in different compaction states, were observed significant interactions only in the 0–0.1 m layer, where tractor traffic negatively influenced the root length of the crops (Table 4). *Crotalaria* and *Stylosanthes* showed no difference in root length with increasing levels of compaction in the 0–0.05 m layers, so *Brachiaria* and Millet showed better results (Table 4).

For the 0.05–0.1 m layer, *Brachiaria* stood out from the others, followed by *Crotalaria*, which was not different from Millet. In the 0.1–0.2 m layer, there was no difference in root length for any of the compaction levels studied. *Brachiaria* stood out with the longest length, followed by *Stylosanthes*, which presented better results than *Crotalaria* and Millet. In turn, Millet was indifferent to *Crotalaria*.

Table 4: Root length of cover crops at different depths and number of tractor passes.

Passes ⁽¹⁾	Root Length (m m ⁻²)			
	<i>Brachiaria</i>	<i>Crotalaria</i>	<i>Stylosanthes</i>	Millet
..... 0 – 5 cm				
C1	263.87 aA	65.07 aC	41.24 aC	115.24 aB
C2	185.51 bA	54.58 aBC	36.84 aC	87.50 abB
C3	132.19 cA	41.31 aB	19.00 aB	56.83 bB
C4	103.46 cA	39.40 aB	18.15 aB	55.79 bAB
CV%-a (Passes) = 21.29				
CV%-b (Crops) = 25.84				
..... 5 – 10 cm				
C1	101.54 aA	47.62 aB	27.44 aC	43.31 aB
C2	53.04 bA	42.81 abB	22.21 abC	33.73 aB
C3	36.42 cA	34.91 bA	15.54 bB	18.64 bB
C4	32.84 cA	23.65 cAB	14.84 bB	18.60 bB
CV%-a (Passes) = 15,78				
CV%-b (Crops) = 12,50				
..... 10 – 20 cm				
C1	22.019 aA	4.99 aC	8.76 aB	5.15 aBC
C2	19.32 aA	2.12 aC	6.53 aB	6.05 aBC
C3	18.61 aA	6.56 aC	7.22 aB	5.47 aBC
C4	23.86 aA	4.04 aC	10.25 aB	4.84 aBC
CV%-a (Passes) = 32.01				
CV%-b (Crops) = 33.63				

⁽¹⁾ 0 – conventional planting without additional compaction; 1, 4 and 7 – correspond to conventional planting with additional compaction by tractor traffic of 3.16 Mg (88 hp) in one, four and seven passes, respectively. Averages followed by equal capital letters in rows and equal lowercase letters in columns do not differ by Tukey's test at the 5% level.

Foloni et al. (2006) studying green manures and the soybean cultivation observed that, regardless of the soil compaction level in a layer less than 0.15 m, the soil compaction state did not inhibit the root growth of the crops. Differing from data from Calonego et al. (2011) [22], in which *Brachiaria*, labe labe and sorghum were not influenced by compaction in the upper layer (0–0.15 m).

For the root length of the covering species in the surface layer, the best results were obtained with *Brachiaria*, although in the C4 treatment the millet was statistically equal. No less different, the results in the 0.05–0.1 m layer show that *Brachiaria* was not superior to *Crotalaria* in treatments C3 and C4 (Table 4).

For the average root diameter, significant interactions were observed up to the 0–0.1 m layer (Table 5), in the 0.1–0.2 m layer there was no difference between treatments, only between cultures. Considering that the studied grasses had their root average diameter decreased with the increase in the level of compaction, whereas the legumes plants showed the opposite effect, having their diameter increased with the level of compaction of the treatment.

Stylosanthes was superior in root diameter in all studied soil layers. *Brachiaria* and Millet did not change significantly in root diameter with increasing compaction level in the 0.05–0.1 m and 0.1–0.2 m layers. When analyzing the root growth of corn and soybean under the influence of compaction, Afzalnia and Zabihi (2014) [24] obtained similar results, showing that compaction provided an increase in the average root diameter.

Table 5: Average root diameter of cover crops at different depths and number of tractor passes.

Passes ⁽¹⁾	Average root diameter (mm)			
	<i>Brachiaria</i>	<i>Crotalaria</i>	<i>Stylosanthes</i>	Millet
..... 0 – 5 cm				
C1	0.57 aA	0.5067 bB	0.5800 bA	0.5767 aA
C2	0.567 bB	0.5533 aB	0.5900 bA	0.5633 abB
C3	0.5333 bB	0.5467 aB	0.7533 aA	0.5500 bcB
C4	0.5267 bB	0.5467 aB	0.7467 aA	0.5400 cB
CV%-a (Passes) = 1.48				
CV%-b (Crops) = 1.65				
..... 5 – 10 cm				
C1	0.5567 aA	0.5267 bB	0.5533 cAB	0.5367 aAB
C2	0.5500 aAB	0.5433 abB	0.5767 cA	0.5433 aB
C3	0.5333 aBC	0.5600 aB	0.6300 bA	0.5233 aC
C4	0.5333 aC	0.5700 aB	0.6733 aA	0.5233 aC
CV%-a (Passes) = 1,69				
CV%-b (Crops) = 2,37				
..... 10 – 20 cm				
C1	0.5667 aB	0.5000 aB	0.5600 aA	0.5267 aB
C2	0.5467 aB	0.4967 aB	0.6067 aA	0.5400 aB
C3	0.5500 aB	0.5467 aB	0.6067 aA	0.5433 aB
C4	0.5500 aB	0.5400 aB	0.6100 aA	0.5400 aB
CV%-a (Passes) = 7.51				
CV%-b (Crops) = 6.16				

⁽¹⁾ 0 – conventional planting without additional compaction; 1, 4 and 7 – correspond to conventional planting with additional compaction by tractor traffic of 3.16 Mg (88 hp) in one, four and seven passes, respectively. Averages followed by equal capital letters in rows and equal lowercase letters in columns do not differ by Tukey's test at the 5% level.

The results obtained by *Crotalaria* and *Stylosanthes* (pivoting root systems) were opposite to those of *Brachiaria* and Millet (fascicular root systems), having its root diameters altered by the level of compaction. Bergamin et al. (2010) [7] analyzing the average diameter of the corn crop (fascicular root system), obtained similar results, where with the increase in soil compaction there was a reduction in the average diameter of the crop roots.

For shoot dry mass, a significant interaction was observed between cover crops, however Millet, *Stylosanthes* and *Crotalaria* were not influenced by soil compaction levels. *Brachiaria* was the species with the highest dry mass production in all treatments, however without statistical difference from *Crotalaria* in treatment C4 (Table 6).

Similar results were found by Andrade et al. (2008) [25] evaluating the effect of cover crops on the physical quality of a dystrophic Red Latosol under no-tillage in the 0–0.1 m layer, where legumes species (*Stylosanthes* and *Crotalaria*) produced the smallest amounts of dry matter, being the higher for *Brachiaria* and Mombasa, which the results show the importance of grasses in soil aggregation, that have high dry matter production.

Crotalaria was the second crop with the highest production of dry mass. Millet and *Stylosanthes* do not differ from each other, and were the ones that produced less dry mass in all treatments. *Crotalaria*, *Stylosanthes* and Millet were presented as compaction tolerant crops, with no decrease as the soil compaction increased (Table 6).

Table 6: Shoot dry mass of cover crops exposed to different states of soil compaction.

Passes ⁽¹⁾	Shoot Dry Mass			
	<i>Brachiaria</i>	Millet	<i>Stylosanthes</i>	<i>Crotalaria</i>
 (Mg m ⁻³)			
C1	17589.86 aA	9226.66 aC	9166.73 aC	14770.00 aB
C2	17503.13 aA	9291.13 aC	9073.86 aC	14535.66 aB
C3	17102.33 aA	9258.65 aC	8790.66 aC	14627.13 aB
C4	3849.46 bA	9338.20 aB	8945.20 aB	14686.80 aA
CV%-a (Passes) = 6.79				
CV%-b (Crops) = 6.75				

⁽¹⁾ 0 – conventional planting without additional compaction; 1, 4 and 7 – correspond to conventional planting with additional compaction by tractor traffic of 3.16 Mg (88 hp) in one, four and seven passes, respectively. Averages followed by equal capital letters in rows and equal lowercase letters in columns do not differ by Tukey's test at the 5% level.

As the results obtained in this work, we can say that *Brachiaria* has an aggressive root system, standing out in its root development to the point of compromising the production of the aerial part, when comparing the treatments C1 with C4, it presented a decrease of 21,26% in dry mass production (Table 6).

4. CONCLUSIONS

Brachiaria showed a bigger root surface area and root length than *Crotalaria*, Millet and *Stylosanthes*, regardless of the induced compaction states in up to seven tractor passes, to the point of compromising its aerial mass production.

The *Stylosanthes* presented a bigger average root diameter, therefore species with a pivoting root system had its diameter increased with the level of soil compaction, while for crops with a fasciculated root system, it was reduced.

Brachiaria was superior in its development, where the results achieved showed its ability to develop in compacted environments, changing the physical attributes of the soil, producing a bigger amount of dry mass, and contributing to the deposition of cementing material.

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