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SCARIFICATION IN NO-TILLAGE: SOIL PHYSICS AND PLANT DEVELOPMENT

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ABSTRACT - No-tillage is conservationist soil management for agricultural production and it is based on soil cover by crop residues and restricted mobilization to the sowing line. However, its structure can be affected by the excessive compaction resulting from the traffic of machines. The objective of this study was to evaluate soil physical properties and crop performance in no-tillage with and without scarification, combined with different successions of plant species, in a Humic Cambisol. For this, the species of black oat, wheat and forage turnip were cultivated in winter, and later, corn and beans in summer. Soil samples were collected at the beginning and at the end of the experimental period, while evaluations of plant yield were carried out in the final stage of development. Soil scarification reduces relative density (RD) and soil resistance to penetration (RP) after preparation of soil, with effect restricted to the surface layer. Such effects persist for one year, however RD and RP increase over time, regardless of soil management. RP is more sensitive for evaluation of soil compaction and correlates positively with RD, with exponential adjustment. The aerial biomass of black oat, wheat and forage turnip was not affected by soil scarification, and crop yield of beans and corn showed to be more related to the previous cultivation than the scarification in no-tillage.
Keywords: compaction, crop yield, soil management.

ESCARIFICAÇÃO EM SEMEADURA DIRETA: FÍSICA DO SOLO E DESENVOLVIMENTO DE PLANTAS

RESUMO - A semeadura direta é considerada manejo conservacionista de solo para produção agrícola e fundamenta-se na cobertura do solo por restos culturais e na mobilização restrita à linha de semeadura. Por outro lado, a estrutura do solo pode ser afetada negativamente pela compactação excessiva resultante do tráfego de máquinas. O estudo objetivou avaliar atributos físicos de um Cambissolo Húmico e o desempenho de culturas na presença e ausência de uma escarificação em semeadura direta associada a diferentes sucessões de espécies vegetais. Para isso, conduziram-se os cultivos de aveia preta, trigo e nabo forrageiro no inverno e posteriormente de milho e feijão no verão. Amostras de solo foram coletadas no início e no fim do período experimental, enquanto as avaliações de produção vegetal foram realizadas ao final do desenvolvimento das plantas. A escarificação do solo reduz a densidade relativa (DR) e a resistência do solo à penetração (RP) logo após o preparo, com efeito restrito à camada superficial. Tais efeitos persistem por período de um ano, no entanto DR e RP aumentam ao longo do tempo, independente do manejo do solo. A RP é indicador mais sensível para avaliação da compactação do solo e correlaciona-se positivamente com a DR, com ajuste do tipo exponencial. A biomassa de parte aérea dos cultivos de aveia preta, trigo e nabo forrageiro não foi afetada pela escarificação do solo e a produção vegetal de feijão e milho demonstrou estar mais relacionada com o cultivo antecedente do que a escarificação em semeadura direta.
Palavras-chave: compactação, produção vegetal, manejo do solo.

INTRODUCTION

Soil management comprises agricultural operations that aim to favor plant development through changes in the physical, chemical, and biological attributes of the soil. No-tillage (NT) is considered a conservationist soil management system, as it preserves cultural residues on the surface, increases the content of organic matter and reduces water erosion (BERTOL et al., 2000). However, the reduced mobilization of the soil restrict to sowing line and the intense traffic of machines tend to increase the density and the mechanical resistance of the soil to surface penetration (CAMARA and KLEIN, 2005a, 2005b).

The occurrence of soil compaction in NT, depending on its degree, decreases the crop yield (MAHL et al., 2008). Thus, soil scarification becomes a management alternative to correct this limitation, characterizing the minimum tillage. The scarification operation has positive effects in the soil (COLET et al., 2009), since it mechanically breaks the compacted surface layer and the preparation is less intense than that with a plow and harrow, called conventional tillage (ARAÚJO et al., 2004). Thus, the minimum tillage damages the soil structure in a lesser degree, maintaining greater aggregate stability, roughness, surface coverage and water

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infiltration in the soil, which favors the general conditions for plant development (CAMARA and KLEIN, 2005a). In an area of NT with signs of compaction, scarification reduced the density and the soil resistance to root penetration and increased the yield of corn grains and the dry mass of aerial part of oats, in comparison to the absence of preparation (KLEIN, 2011).

One of the questions about soil scarification is the duration of its positive effects on the soil surface physical characteristics. In this regard, Drescher et al. (2011) established that the effects of scarification in NT are ephemeral in mitigating soil compaction. In a very clayey Latosol, the effects lasted for nine months, and, therefore, did not improve the physical conditions of the soil (NICOLOSO et al., 2008). In another study, water infiltration in the soil increased, however, this increase persisted for only one year (TAVARES FILHO et al., 2006).

Cultivation systems that include crop rotation and abundant root system species, capable of breaking compacted layers, are alternatives to mechanical soil decompression. The use of plants with this potential increases the persistence of good physical conditions induced to the soil by the mechanical scarification operation (NICOLOSO et al., 2008).

Soil resistance to penetration (RP) is used to define levels from which the soil is compacted and requires corrective measures (BEUTLER et al., 2005). It represents the physical impediment that the soil offers to something that moves through it, such as a growing root or a cultivation tool and results from forces arising from compaction (PEDROTTI et al., 2001). The RP value of 2.0 MPa is considered a critical limit, after which there are severe restrictions to the root development of cultivated plants (TAYLOR et al., 1966; LAL, 1999). This critical value may vary according to the type of soil and species cultivated (MORAES et al., 2014).

The relative density (RD) is another parameter of physical soil quality, obtained by the ratio between the bulk density of soil evaluated in the field and the maximum bulk density of soil estimated in the laboratory by the Proctor Normal test (KLEIN, 2006). RD values close to 0.90 (from 0.88 to 0.91) or higher, are considered critical, as they restrict root development and can affect the performance of the aerial part of plants (CARTER, 1990; LIPIEC et al., 1991; KLEIN, 2006).

For this study, the hypothesis was established that the scarification of the soil in no-tillage positively affects the plant development and the physical attributes of a Humic Cambisol for a minimum period of one year. Thus, the objective was to evaluate the relative density, the soil resistance to penetration and the performance of cultures in the presence and absence of scarification in no-tillage combined with different successions of plant species.

MATERIAL AND METHODS

Characteristics of the experimental area

The research was carried out in the south of Brazil (27º47' S, 50°19' W and 937 m altitude) on a silty clay Humic Cambisol (Cambissolo Húmico alumínico léptico), with granulometry in the 0-0.2 m layer of 0.421, 0.437 and 0.142 kg kg^{-1} of clay, silt and sand, respectively. The climate of the site, according to criteria established by the Köppen classification, is *Cfb* type (subtropical humid, rainy and with cool summers), with an average annual rainfall of 1,533 mm (SCHICK et al., 2014).

The experimental area, originally covered by a native field, has been cultivated in the past 22 years with different managements and plants of annual cycle. In May 2011, 6 Mg ha^{-1} of dolomitic limestone was incorporated into the soil, using a scarifier and harrow, aiming to raise the pH to 6.0. From this moment on, the area was conducted by no-tillage (NT). In May 2015, the tractor wheels ran over the entire surface, in a soil condition with moisture above the friable consistency, intensifying the compaction processes to predispose the soil to the desired conditions for the beginning of this research.

Treatments and conduction of the research

The treatments were formed by the combination of two soil managements, three winter crops and two summer crops, in a sub-subdivided plots scheme in a randomized block design with three replications. The tested managements were no-tillage (NT) and no-tillage submitted to a soil mechanical scarification (NTS), in plots with dimensions of 6 x 10 m. Then, sowing of the species black oat - BO (*Avena strigosa*), wheat - WT (*Triticum aestivum*) and forage turnip - FT (*Raphanus sativus*) was done separately, for winter cultivation, composing the subplots with dimensions of 2 x 10 m. Subsequently in the summer the subplots were divided and cultivated one half with corn - CO (*Zea mays*) and the other half with black beans - BB (*Phaseolus vulgaris*), forming the sub-subplots with dimensions of 2 x 5 m.

For the implementation of the research, in June 2015, a scarification operation was carried out in the plots that received this treatment. The scarifier contained two lines of mismatched rods, the front one consisting of seven rods and the rear one consisting of six rods, with a distance of 0.5 m between them. With this, the scarification resulted in furrows 0.25 m apart from each other, with a 0.25 m depth.

The sowing of the winter crops occurred in July 2015, using 80 and 20 kg ha^{-1} of BO and FT seeds, respectively. For the treatments with WT, 330 seeds m^{-2} were used. In December 2015, after the end of the winter crop cycle, CO and BB crops were implanted with 0.5 m row spacing and density of 80,000 and 300,000 plants ha^{-1}, respectively.

Collections and determinations

The collection of soil samples for physical determinations was carried out in two moments, the first after the soil scarification and before the sowing of winter crops, in June 2015, and the second in May 2016, at the end of the summer crop cycle. In the cultivation line, small trenches were opened to collect samples with preserved structure in 141.3 cm^3 volumetric rings, in the 0-0.05; 0.05-0.1; 0.1-0.2; and 0.2-0.3 m layers.

The measurement of the soil mechanical resistance to penetration (RP) was determined in laboratory, in the soil samples collected in the volumetric rings, after they had been passed through the sand tension table at the equilibrium tension of 10 kPa, equivalent to the field capacity. For this, a bench-type penetrometer of the static type (MA 933 MARCONI®) was used, with a metal rod formed by a cone with an angle of 30° and diameter of 4 mm, with insertion speed of 30 mm min^{-1}. The relative density (RD) was calculated by the relation between the bulk density of soil obtained in the volumetric rings and the maximum bulk density of soil determined by the Proctor Normal test, following the standard NBR-7182 (ABNT, 1986) in a Soiltest model CN-4230 device.

Vegetable production was determined by the dry mass yield of aerial part (DMY) in all crops and by the grain yield (GY) of the summer crops. The BO, TR and FT DMY were obtained at the moment when the cultures reached full bloom. The collection area was delimited by a 0.4 x 0.6 m frame, cutting the plant material close to the ground. In the CO and BB cultures, two linear meters were collected from the three central rows, totaling 3 m^2. In the CO, the ears were separated from the aerial part and threshed manually, while in the BB all the collected material was dried in an oven and subsequently manual separation was performed to determine the DMY and GY. The samples were dried in an oven at 60°C and the grain moisture was standardized at 12%.

The data were subjected to analysis of variance and the means, when they differed, compared by the Tukey test, at 5% probability of error ($p < 0.05$). For the physical attributes of the soil, statistical analysis was performed individually by soil layer. The Sisvar 5.6 statistical program was used (FERREIRA, 2014).

RESULTS AND DISCUSSION

Soil compaction assay

The maximum bulk density of soil (BDmax) obtained in the Proctor Normal test was 1.38 and 1.47 kg dm^{-3} respectively for the 0-0.05 and 0.05-0.3 m layers, while the critical water content for maximum soil compaction (CWC) was 0.268 and 0.255 kg kg^{-1}, respectively. BDmax and CWC did not vary between layers from 0.05 to 0.3 m, so an equation was adjusted to represent the interval between these layers (Figure 1).

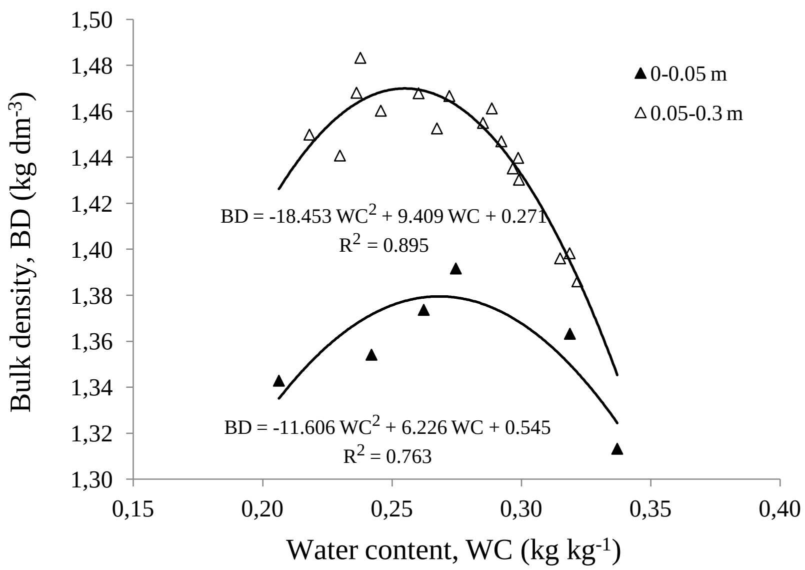

FIGURE 1 - Soil compaction curves obtained by the Proctor Normal test with second degree polynomial equation adjustment to determine the maximum bulk density of soil and the critical water content for maximum soil compaction.

In the 0-0.05 m layer the BDmax was 6.1% lower and the CWC 5.1% higher in relation to the 0.05-0.3 m layer. This is explained by the higher content of organic matter on the soil surface. The organic constituents have lower specific density than the soil minerals and condition better structural quality, which reduces BDmax. The increase in CWC is attributed to the high water retention capacity of the organic matter, requiring a greater volume of water to reduce the cohesion and internal friction between the particles and allow the plastic deformation of the soil (LUCIANO et al., 2012). The results are in agreement with Marcolin and Klein (2011) who evaluated soils with different textures. These authors obtained a negative linear correlation between the BDmax and the soil organic matter. This behavior partly explains the reason for greater soil compaction in the subsurface of areas managed under NT, due to the gradient of organic matter in the profile, with a marked reduction in the first centimeters below the surface.

The knowledge of the CWC is essential to plan the control of machine traffic in agricultural areas, aiming to avoid entering the area when the water content is close to the CWC value. The CWC indicates the optimum condition for the water to lubricate the soil particles, making them slide among themselves and accommodate themselves in a more compact arrangement, thereby increasing the bulk density of soil (WEIRICH NETO et al., 2002). Knowledge of the BDmax, on the other hand, is essential for calculating the relative density of soil (RD).

Relative density of soil

In the initial phase of the research, the relative density of soil (RD) was influenced by the preparation in the superficial layer (Figure 2A). The NTS treatment caused a 10% reduction in the RD value compared to the NT in the 0-0.05 m layer. This result is in accordance with a study by Ferreras et al. (2001), in a silty loam soil, where a reduction of 13% of the RD was observed, provided by the scarification in NT in the 0-0.06 m layer, with no effect in the layer below.

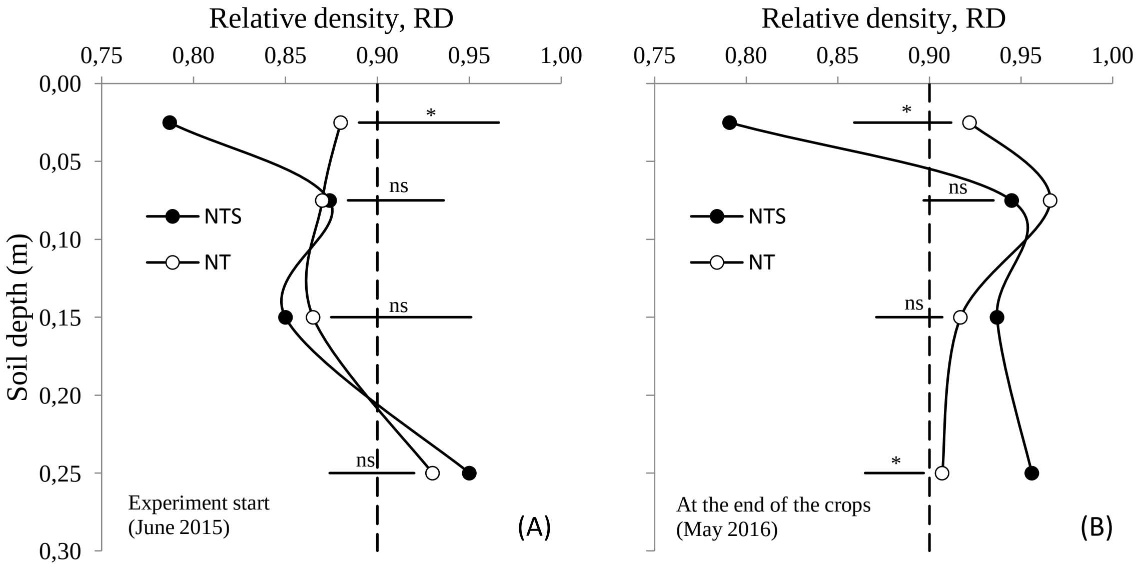

FIGURE 2 - Relative density of soil (RD) in the initial period of the experiment (A) and at the end of the crops (B), in the management of no-tillage scarified (NTS) and no-tillage (NT), in different soil layers. The horizontal bars represent the minimum significant difference by the Tukey test ($p < 0.05$). *Significant effect and ^{ns} not significant by Tukey ($p < 0.05$). The dashed line represents the critical RD limit of 0.90 (CARTER, 1990; LIPIEC et al., 1991; KLEIN, 2006).

In the present study, the RD values were within the non-restrictive range to a depth of 0.2 m, although in the 0-0.05 m layer in the NT treatment the RD was very close to the critical value of 0.90 (CARTER, 1990; LIPIEC et al., 1991; KLEIN, 2006), indicating compaction where the largest root mass of the plants is usually concentrated. In the 0.2-0.3 m layer, the RD values were above 0.90 for both managements, demonstrating that there was no effect of the scarifying rods to mitigate soil compaction in depth (Figure 2A).

In the evaluation carried out at the end of the crops, the RD was influenced by the soil scarification (Figure 2B), not being affected by the winter and summer plant species and by the interactions between soil management and crops. In the 0-0.05 m layer, the NTS treatment presented RD similar to the one at the beginning of the research and statistically inferior to the NT. However, between the 0.05 to 0.2 m layers, the NTS values increased substantially, exceeding the critical limit of 0.90. In NT, the values increased from the surface layer up to a depth of 0.2 m, exceeding the limiting value. In the 0.2-0.3 m layer, both managements showed high values, however the RD was higher in the NTS.

The results indicate that although the scarification had mobilized the soil, in the course of the twelve months between the mechanical preparation and the evaluation, the soil reconsolidated, which was also verified by De Maria et al. (1999). On the other hand, in the superficial layer, the physical conditions induced by scarification were maintained, possibly due to the action of the plant roots capable of developing in the pores created by the preparation (NICOLOSO et al., 2008).

The highest RD values occurred in the 0.05-0.1 m layer, being 0.945 and 0.966 respectively for NTS and NT (Figure 2B). The differentiated behavior between soil layers is attributed to the existence of a higher content of organic matter, biological activity (roots of plants and edaphic fauna) and intensity of the wetting and drying cycles of the soil in the superficial layer. In contrast, the subsurface layer is more subject to the load applied by machine traffic and, in it, the wetting and drying cycles are short and do not reduce the density of soil (DRESCHER et al., 2011).

Soil resistance to penetration

Soil resistance to penetration (RP) at the beginning of the research was affected by treatments in the

0-0.05 m layer, with values of 0.52 and 0.99 MPa respectively for NTS and NT (Figure 3A) This means greater efficiency of scarification in reduction of the mechanical resistance of the soil on the surface. A similar result was obtained by Camara and Klein (2005b), but with no effect from the depth of 0.025 m on in a very clayey Latosol.

In both treatments there was an increase in the RP in depth in the soil (Figure 3A), but, in general, the values were less than 2.0 MPa. Above this value there is a severe limitation for the root development of cultivated plants (TAYLOR et al., 1966; LAL, 1999).

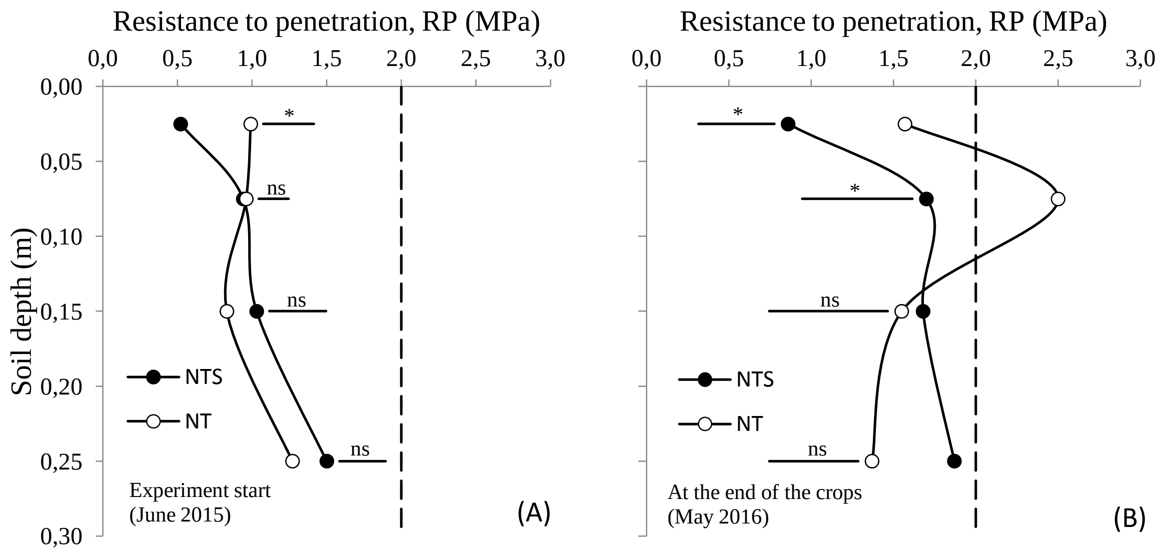

FIGURE 3 - Soil resistance to penetration (RP) evaluated with moisture content at a tension of 10 kPa in the initial period of the experiment (A) and at the end of the crops (B), in the management of no-tillage scarified (NTS) and no-tillage (NT), in different soil layers. The horizontal bars represent the minimum significant difference by the Tukey test ($p < 0.05$). *Significant effect and ^{ns} not significant by Tukey ($p < 0.05$). The dashed line represents the critical RP limit of 2.0 MPa (TAYLOR et al., 1966; LAL, 1999).

In the evaluation at the end of the crops, the RP was influenced by scarification, with no effect of the winter and summer plant species and of the interactions between soil management and crops. The RP in NTS remained below the considered critical value (2.0 MPa) in all layers of soil (Figure 3B), although its values increased by an average of 53% compared to the beginning of the research. In this treatment, the lowest RP was observed in the 0-0.05 m (0.86 MPa) layer, while in the other layers it varied between 1.70 and 1.87 MPa.

In NT, the RP also increased compared to the initial research period, however in the 0.05-0.1 m layer the value was 2.5 MPa (Figure 3B), exceeding the critical limit. Streck et al. (2004) observed a maximum RP value in NT between 0.06 and 0.14 m in depth, similar to what was found by this research. The reasons that justified higher RD values in the 0.05-0.1 m layer can be used to explain the higher RP values in this layer.

When comparing the managements, the RP in the NTS was lower in the layers of 0-0.05 and 0.05-0.1 m compared to the NT, which demonstrates the persistence of the positive effect of the scarifier rods in the upper layers after twelve months of preparation. However, in the 0.2-0.3 m layer, the RP value was close to the critical in the NTS, with no statistical difference between managements. Araújo et al. (2004) observed a higher RP value in NTS in the 0.15-0.3 m layer and attributed this behavior to the compression caused by the scarifier in the lower layer. Abreu et al. (2004) observed, in NT, a higher RP at a depth of 0.075 m, while in scarified soil the maximum RP occurred at a greater depth.

By relating the RP values as a function of the RD, using data from treatments (management and crops) and soil layers, a positive exponential correlation was obtained (Figure 4), with significant adjustment ($p < 0.01$). In this case, 48.8% of the RP variation was explained by the RD. Through the equation, the critical RP value of 2.0 MPa occurred in the RD of 0.948. The exponential relationship demonstrates that small increases in RD cause large increases in RP, which makes RP more sensitive than RD to assess soil compaction. This result is in line with work carried out by Streck et al. (2004), who found that RP was the soil physical attribute that best evidenced the effect of compaction in NT.

Dry mass yield of aerial part of winter crops

The dry mass yield of aerial part (DMY) of winter crops was influenced by the interaction between soil management and plant species (Figure 5). The black oats (BO) resulted in greater biomass production capacity, being 43 and 130% higher than wheat (WT) and forage turnip (FT), respectively, in the average of the managements. Within each management, in NTS, BO was statistically higher than other cultures, while in NT it was higher than FT. In evaluations carried out in southern Brazil, Wolschick et al. (2016) observed higher DMY of black oat compared to forage turnip, being 9.91 and 4.26 Mg ha^{-1}, respectively, while Barbosa et al. (2012) obtained 3.6 Mg ha^{-1} of wheat. The importance of high plant biomass in winter crops is related to the adequate coverage of the soil by its cultural residues in no-tillage. The minimum mass considered must be 6 Mg ha^{-1} (ALVARENGA et al., 2001), which, in this case, was achieved by BO in both managements and by WT in NT.

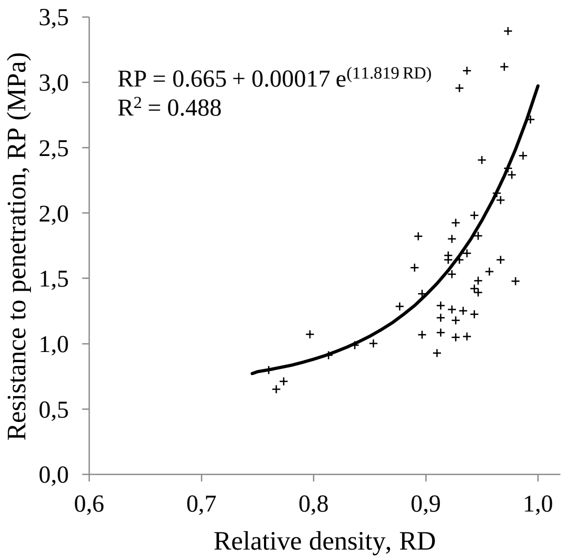

FIGURE 4 - Relationship between soil resistance to penetration (RP) and relative density of soil (RD).

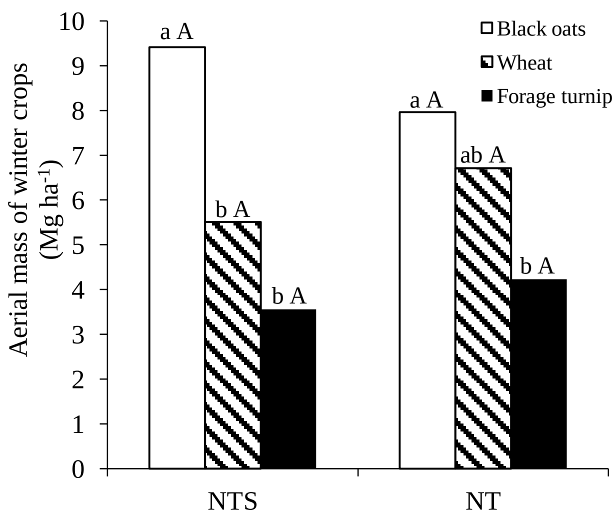

FIGURE 5 - Dry mass yield of aerial part of winter crops in the management of no-tillage scarified (NTS) and no-tillage (NT). Means followed by the same lowercase letter (culture comparison in each management) or uppercase letter (management comparison in each culture) do not differ by the Tukey test ($p < 0.05$).

When comparing the managements within each winter crop, there was no significant effect of the presence or absence of soil scarification under no-tillage for DMY (Figure 5). Thus, the reduction of RD and RP of the 0-0.05 m surface layer provided by the preparation did not result in positive changes for the plant production of winter species. The results are in agreement with Nicoloso et al. (2008), who did not observe the effect of scarification on the DMY of winter crops, including oats and forage turnip, in a very clayey Latosol. Debiasi (2008) obtained a negative response from the scarification in the DMY of the species mentioned above, being 25 and 33% inferior, respectively, in relation to the no-tillage, in a sandy clay loam Argisol.

Dry mass of aerial part and grain yield of summer crops

The DMY of summer crops varied depending on soil management and the previous plant species (Figure 6). The black bean crop (BB) obtained a higher response in production when in succession to the cultivation of BO for both managements and also after WT in NT (Figure 6A). When comparing the managements, soil preparation with a scarifier did not influence the DMY of BB cultivated after BO and FT, but it reduced the DMY by 23% in succession to the WT. In regards to biomass for soil cover, the BB showed low production, regardless of management and previous crop, ranging from 1.68 to 2.69 Mg ha^{-1}.

In the corn crop (CO), the previous plant species influenced DMY in the NT management, being found after FT production 66 and 80% higher than after BO and WT, respectively (Figure 6B). When comparing the effect of management, the DMY had the opposite behavior between NTS and NT due to the previous culture. After BO and WT, DMY was 27 and 29% higher in NTS compared to NT, respectively, while after FT it was 60% higher in NT than in NTS. Probably in NTS the turning of the soil provided by the scarifying rods favored the decomposition of BO and WT residues and, consequently, the supply of nutrients for the corn crop. Vegetable residues of grasses have a higher carbon/nitrogen ratio (C/N) compared to FT (GIACOMINI et al., 2003), with this, the absence of mechanical soil preparation in NT made degradation of grass residues difficult and also the release of nutrients for the corn crop, which resulted in lower DMY. On the other hand, due to the fact that the FT has a lower C/N ratio and is easy to decompose, the scarification acted negatively by rapidly degrading its biomass and releasing nutrients in the soil too early, resulting in better performance after NT.

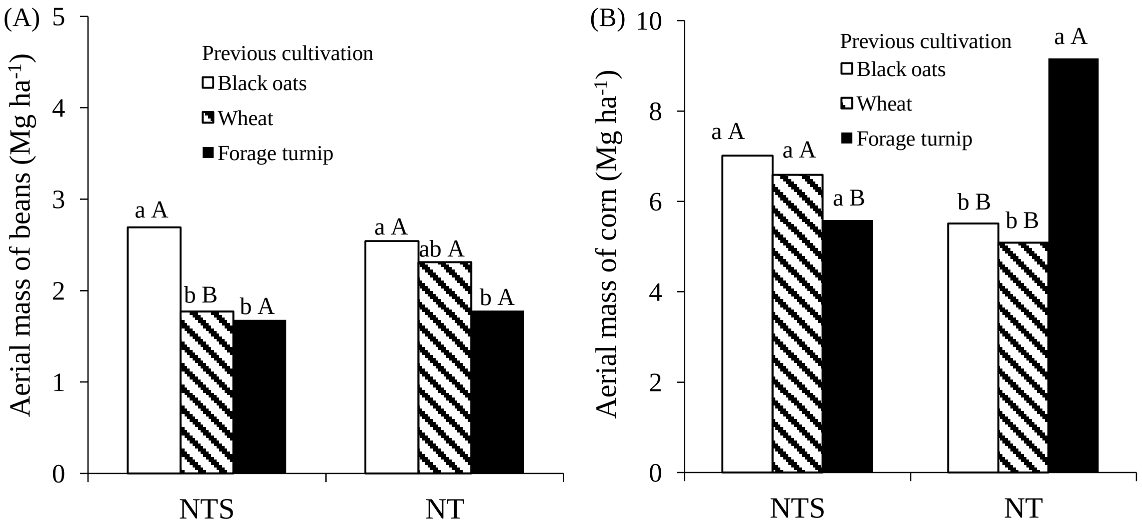

FIGURE 6 - Dry mass yield of aerial part of beans (A) and corn (B) after different winter crops in the management of no-tillage scarified (NTS) and no-tillage (NT). Means followed by the same lowercase letter (comparative of previous cultivation in each management) or upper case (comparative of management in each previous cultivation) do not differ by the Tukey test ($p < 0.05$).

The grain yield (GY) of BB varied between 1.02 and 1.94 Mg ha^{-1}. It was not significantly influenced by soil scarification, but responded positively to the cultivation of BO in the different managements and of WT in NT (Figure 7A). This result is in agreement with the records of Derpsch et al. (1985), who stated that a legume in succession to a non-leguminous species is favored, since the first is less dependent on nitrogen mineralization. The yield after FT was significantly lower, corresponding to 53% of that obtained after BO, in the average of the managements.

The results obtained are in agreement with Collares et al. (2006) and Collares et al. (2008), respectively, in a loamy sand Argisol and a clayey Latosol, who found that scarification reduced soil compaction and favored the root development of beans, but did not affect the GY compared to continuous no-tillage.

In CO cultivation, GY was not significantly influenced by soil management and previous crops, ranging from 9.30 to 11.79 Mg ha^{-1} (Figure 7B). In absolute values, the highest GY was observed in NT after FT. This is similar to what happened with the DMY of CO and is justified in the same way. The absence of the effect of scarification in NT on the corn yield was found by Mahl et al. (2008) and Nunes et al. (2014), both in Nitisol. On the other hand, Debiasi et al. (2010) observed a reduction in GY by scarification in a sandy clay loam Argisol, while Secco et al. (2009) found an increase in yield in clayey Latosol.

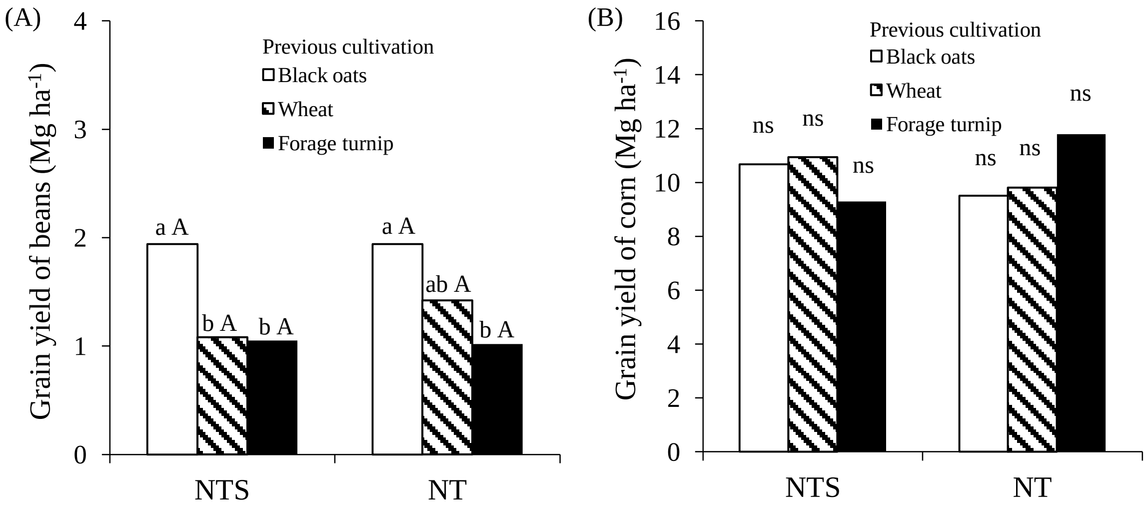

FIGURE 7 - Grain yield (GY) of beans (A) and corn (B) after different winter crops in the management of no-tillage scarified (NTS) and no-tillage (NT). Means followed by the same lowercase letter (comparative of previous cultivation in each management) or upper case (comparative of management in each previous cultivation) do not differ by the Tukey test ($p < 0.05$).

In general, although scarification has positively affected the physical attributes of the topsoil, it has not been able to promote greater plant development in the Humic Cambisol. Future research should take into account sequences of plant species that can attenuate soil compaction under no-tillage and that the scarification response varies according to the type of soil.

CONCLUSIONS

The soil scarification in no-tillage reduces the relative density (RD) and the soil resistance to penetration (RP) soon after the preparation, with effect restricted to the superficial layer. Such effects persist for a period of one year, however RD and RP increase over time, regardless of soil management.

The RP is the most sensitive indicator for assessing soil compaction and correlates positively with RD, with adjustment of the exponential type.

The aerial part biomass of the black oat, wheat and turnip crops was not affected by the soil scarification and the crop yield of beans and corn showed to be more related to the previous cultivation than to the scarification in no-tillage.

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