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Scientific Article
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Soil compaction in areas of maize used for silage with the application of wastewater[1]

Compactação do solo em áreas de milho para silagem com aplicação de água residuária

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ABSTRACT - The mechanical resistance of the soil to penetration (RP) was evaluated over two consecutive years in areas where off-season maize is produced for silage. Removal of the aerial part of the maize during the ensiling process leaves the soil exposed and subject to compaction, which may compromise a no-till system (NTS). The aim of this study therefore, was to monitor the RP of a soil under plant cover associated with the application of wastewater from pig farming (WPF) in areas of maize ensiling under NTS. The study was conducted in Matelândia, in the State of Paraná, employing seven management systems: soybean/silage/oats and turnip (SSOT); soybean/oats and turnip (SOT); soybean/silage/scarification + oats and turnip (SSSOT); soybean/silage and brachiaria (SSB); soybean/silage/oats (SSO); soybean and silage (SS) and soybean and maize (SM), repeated over two consecutive years. In the treatments that included WPF, 100 m^3 ha^{-1} yr^{-1} were applied, split into two equal doses: one on the maize and the other on the cover crops. The experimental design was of randomised complete blocks (RCB), with four replications per treatment, and four samples per replication. The system with no cover crops had a higher RP; the 0.10 to 0.15 m layer of soil had the highest RP; whereas the application of WPF at a dose of 100 m^3 ha^{-1} $yr^{-}1$ decreased the RP.

Key words: Mechanical resistance of the soil to penetration. Crop rotation. Systems of soil management.

RESUMO - Durante dois anos consecutivos, a resistência mecânica do solo à penetração (RP) foi avaliada em áreas de produção de milho segunda safra para silagem. A retirada da parte aérea do milho no processo de silagem deixa o solo exposto, sujeito à compactação, o que pode comprometer o sistema plantio direto (SPD). Neste contexto, este trabalho teve por objetivo monitorar a RP sob cultivo de plantas de cobertura, associadas à aplicação de água residuária de suinocultura (ARS), em áreas de silagem de milho sob SPD. O trabalho foi desenvolvido em Matelândia, Paraná com sete sistemas de manejo: soja/silagem/aveia e nabo (SSAN); soja/aveia e nabo (SAN); soja/silagem/escarifição + aveia e nabo (SSEAN); soja/silagem e braquiária (SSB); soja/silagem/aveia (SSA); soja e silagem (SS) e soja e milho (SM), repetidos por dois anos consecutivos. Nos tratamentos com ARS foram aplicados 100 m^3 ha^{-1} ano^{-1}, divididos em duas doses iguais: uma sobre o milho e outra nas plantas de cobertura. O delineamento experimental foi em blocos casualizados (DBC), com quatro repetições por tratamento, com quatro amostras por repetição. O sistema sem utilização de plantas de cobertura apresentou maior RP; a camada do solo com maior RP foi a de 0,10 a 0,15 m; a aplicação de ARS, na dose de 100 m^3 ha^{-1} ano^{-1} diminuiu a RP do solo.

Palavras-chave: Resistência mecânica do solo à penetração. Rotação de culturas. Sistemas de manejo de solo.

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INTRODUCTION

The use of silage is an efficient solution for periods of low fodder production, providing good-quality bulk, which is widely used in ruminant diets. Maize is one of the best plants for silage, due to its good dry-matter production per hectare and its high nutritional value (POSSENTI *et al*., 2005).

Systems such as this, which includes intensive farming, require the use of forages with high productivity and good-quality biomass, as they employ intense machine traffic, which can cause soil compaction (CARRARA *et al*., 2007). In addition, inappropriate agricultural practices can adversely affect the quality of the soil, contributing to erosion and degradation (LÓPEZ-GARRIDO *et al*., 2014).

Compaction negatively alters several of the soil properties, such as root penetration capacity and water and nutrient availability to the plants, restricting the rate of photosynthesis and shoot growth, and consequently, crop yield (DRESCHER *et al*., 2012), especially in areas used for silage production. According to the same authors, by using a penetrometer it is possible to identify layers of higher RP and thereby infer the presence or lack of soil compaction, the degree of compaction and the depth of the compacted layer in the soil profile. With this information, the most suitable technology for decompaction can be chosen.

RP values critical to crop development vary according to the plant species and soil characteristics, such as for example, granulometric composition and structure. An RP value of 2.0 MPa has been widely quoted by several authors as critical for the growth of such plants as soybean and maize under different management systems (BOTTA *et al*., 2006; FUENTES-LLANILLO; GUIMARÃES; TAVARES FILHO, 2013; MAZURANA *et al*., 2013). Tormena *et al*. (2007) used 3.5 MPa as the maximum RP value in soil under a no-till system, based on the argument of the presence of continuous and effective biopores that result from this management system; whereas Chen *et al*. (2005) used 1.8 MPa as the agronomic limit for plant root development.

To set up the NTS, it is important to establish crops that produce plant mass in adequate quantities to provide ground cover. This becomes a problem in warmer regions with water restrictions due to the difficulty of establishing such crops and their accelerated process of decomposition (CRUZ *et al*., 2009).

The agricultural use of WPF has already been studied and documented by several authors (CERETTA *et al*., 2010; MENEGHETTI *et al*., 2012; PRIOR *et al*., 2009). For the most part, results indicate that this waste allows the cycling of nutrients and organic matter (OM).

Based on the above, the aim of this study was to evaluate the mechanical resistance of the soil to penetration, coupled with cultivating cover crops using wastewater from pig farming, in areas under a no-till system, used for whole maize plant silage.

MATERIAL AND METHODS

The study was conducted on 50 ha of agricultural land in Matelândia, in western Paraná, at latitude 25º20’ S and longitude 53º59’ W, an average altitude of 360 m and a slope of 6.8%. The soil is a Eutrophic Red Latosol (EMBRAPA, 2013), with 585 g kg^{-1} clay, 175 g kg^{-1} silt, and 240 g kg^{-1} sand. Mean precipitation and temperature for the two years of the experiment were 1922 mm and 22.8 °C respectively (SIMEPAR, 2015).

Prior to introducing the NTS, the area had consisted of degraded pasture. When setting up the NTS, the necessary soil correction was carried out based on chemical analysis. For the last twelve years, the area has been under NTS, with soybean planted in the summer, and maize alternating with black oats in the winter.

The management systems used in the experiment consisted of soybean during the summer and maize used for whole plant silage during the winter, and, after harvesting the silage and maize for grain (Table 1), an intercrop of cover plants, with and without the application of WPF and scarification.

The experimental design was of randomised complete blocks (RCB), with four replications per treatment, collected at four points per replication, giving 56 experimental plots of 14 m^2 each.

In the treatments that included WPF, 100 m^3 ha^{-1} yr^{-1} were applied, divided into two equal doses, one for the maize and the other for the cover crops. The WPF used was available on the farm. The distance from the collection point to the site of application was 800 m. The WPF was placed in an anaerobic lagoon, covered by a waterproof sheet and, after spending 120 days in the lagoon, used on the crops. An applicator drawn by agricultural tractor was used to apply the WPF directly to the experimental plots.

The RP was determined to a depth of 0.4 m, using a Falker Solo Track automated soil compaction meter equipped with a number 2 shaft. The equipment recorded the RP values every 0.01 m; these were stored in the internal memory and then transferred to a computer for processing. The measurements were taken at four random points in each experimental plot, with the mean

Table 1 - Management systems used in the experiment

Management system	Summer	Winter	Scarification	Cover crops
T1 (SSOT)	Soybean	Maize for silage	No	Oats and turnip
T2 (SOT)	Soybean	Fallow	No	Oats and turnip
T3 (SSSOT)	Soybean	Maize for silage	Yes	Oats and turnip
T4 (SSB)	Soybean	Maize for silage	No	Brachiaria
T5 (SSO)	Soybean	Maize for silage	No	Oats
T6 (SS)	Soybean	Maize for silage	No	No
T7 (SM)	Soybean	Maize for grain	No	No

value of these points representing one replication for each treatment. Four analyses were made: at the end of September before sowing the soybean and in February, after the harvest, in both the 2013/2014 and 2014/201 agricultural years.

The soybean was planted after the cover-crops, which were desiccated twenty days before sowing the soybean using a non-selective, systemic, post-emergent glyphosate herbicide *(N-(phosphonomethyl)glycine)*, at a dose of 4.0 L ha^{-1}. The Nidera 5909 RG cultivar was used in both years, at a population density of 320,000 plants ha^{-1}, or 16 plants m^{-1}, and distributed using an eight-row NTS seeder at a spacing of 0.50 m. A base dressing of 350 kg ha^{-1} NPK formulation 0-20-18 was incorporated by furrower to a depth of 0.12 m. Herbicides and insecticides were applied as recommended for the crop. The data were submitted to analysis of variance, and the mean values were compared by Scott-Knott test at a level of 5%.

RESULTS AND DISCUSSION

The accumulated rainfall and the mean monthly maximum and minimum temperatures from February 2013 to February 2015 are shown in Figure 1. Rainfall was recorded each month, with low values occurring only during February and July of 2013 and July of 2014; however, plant development was not impaired and no irrigation was necessary.

The summary of the analysis of variance for the mechanical resistance to penetration (MPa) in the four evaluations (Table 2) showed a significant difference in the three factors under study (eight depths, with and without WPF and seven management systems). A double and triple interaction between the factors can also be seen. Only the interaction between depth and WPF showed no significant difference at a level of 5%, except in the evaluation made during September 2014.

In the first evaluation, carried out in September 2013 (Figure 2), a lower RP was found under the system including soybean, silage and scarification with oats and turnip (SSSOT) for the 0 to 0.2 m layer, than in the other treatments, both with and without the application of WPF. This result had been expected due to soil turning, which was carried out to a depth of 0.25 m. Gao *et al.* (2016) also found that for a system including soil turning, the RP was lower in the surface layer. Afzalinia and Zabihi (2014) found that bulk density and RP increased under NTS in relation to conventional tillage due to the lack of soil turning. However, studies show that turning decreases the RP during a certain period only. Botta *et al.* (2006), when evaluating scarification in the Pampas Region of Argentina, found soil re-compaction after two years.

The greatest RP levels for the remaining treatments under NTS were found in the layer down to 0.2 m. The same was found by Cunha, Cascão and Reis (2009), where the most influential layer was from 0 to 0.2 m, showing the effects of disaggregation caused by soil preparation. The systems with no mechanical interference showed similar behaviour in the soil profile. Down to the 0.05 m layer, the RP was less than 2.0 MPa. This value has been widely adopted by authors as critical for the growth of plants under different management systems (BOTTA *et al*., 2006; CUNHA; CASCÃO; REIS, 2009; FUENTES-LLANILLO; GUIMARÃES; TAVARES FILHO, 2013; MAZURANA *et al*., 2013).

However, Tormena *et al*. (2007) used 3.5 MPa as the maximum RP value in a soil under no-tillage, based on the argument of the presence of continuous and effective biopores that result from this management system. There is still uncertainty concerning these RP values, especially as different plants respond differently to these critical values, and although this evaluation is more sensitive in identifying compacted layers, it does not consider the bioporosity of the soil, which is so important for root growth in compacted soils (REICHERT; SUZUKI; REINERT, 2007).

Table 2 - Summary of the analysis of variance of the mechanical resistance to penetration (MPa) in the four evaluations

Source of variation	September 2013				February 2014			
	DF	SS	MS	F	DF	SS	MS	F
Depth	7	55.56	7.94	0.00**	7	55.36	7.91	0.00**
WPF	1	1.01	1.01	0.00**	1	0.34	0.34	0.01*
Management	6	28.03	0.05	0.00**	6	6.44	1.07	0.00**
Depth*WPF	7	0.31	0.45	0.66^{ns}	7	0.20	0.03	0.80^{ns}
Depth*Management	42	19.08	2.19	0.00**	42	14.93	0.36	0.00**
WPF*Management	6	13.15	0.10	0.00**	6	4.70	0.78	0.00**
Depth*WPF*Management	42	4.49	0.06	0.00**	42	4.23	0.10	0.00**
CV (%)	13.24				13.54			
Overall Mean (Mpa)	1.91				1.71			
	September 2014				February 2015			
	DF	SS	MS	F	DF	SS	MS	F
Depth	7	45.50	6.50	0.00**	7	44.81	6.40	0.00**
WPF	1	6.09	6.09	0.00**	1	0.26	0.26	0.04*
Management	6	16.13	2.69	0.00**	6	11.45	1.91	0.00**
Depth*WPF	7	1.57	0.22	0.00**	7	0.34	0.05	0.57^{ns}
Depth*Management	42	14.70	0.35	0.00**	42	15.10	0.36	0.00**
WPF*Management	6	9.83	1.64	0.00**	6	1.25	0.21	0.00**
Depth*WPF*Management	42	4.70	0.11	0.00**	42	3.92	0.09	0.01*
CV (%)	14.21				13.56			
Overall Mean (Mpa)	1.79				1.78			

Notes: Considering the F-test, ^{ns} not significant at 5% probability; ** significant at 1%; * significant at 5%

Without WPF (Figure 2a), higher values for soil RP were seen in the 0.05 to 0.2 m layer, with an average of 2.5 MPa between the management systems, except for SSSOT. From 0.2 to 0.4 m the systems displayed similar behaviour, with the RP stabilising at under 2.0 MPa; except for SS (soybean and silage), in which the RP was higher, with only spontaneous plants and little increase in the roots, showing the importance of cover crops in protecting and forming biopores in the soil profile at the deeper layers.

With the application of WPF (Figure 2b), in the 0.05 to 0.2 m layer, higher RP values (over 2.5 MPa) were seen between management systems, except in the SSSOT and the soybean, silage and oats (SSO). In the 0.2 to 0.4 m layer, the systems showed similar behaviour, with values under 2.0 MPa, demonstrating that the machine traffic did not change the RP at this depth. These results reinforce those obtained by Cunha, Cascão and Reis (2009), highlighting that the effect of tractor traffic was mainly concentrated in the 0 to 0.2 m surface layer.

According to the values for water content, all the evaluations were carried out near field capacity (Figures 2, 3, 4 and 5), as recommended by Reichert, Suzuki and Reinert (2007). RP is dependent on the water content when determined in the field, and increases exponentially with its reduction (CONTE *et al*., 2011). Values over 2.0 MPa, even under conditions of high humidity, may be unfavourable to plants (STRECK *et al*., 2004).

In the evaluation of February 2014 (Figure 3), the same effect was seen as in the previous evaluation (Figure 2), i.e. the SSSOT system had an RP of less than 2.0 Mpa. In the 0.05 to 0.2 m profile, without the application of WPF (Figure 3a), the management systems under NTS had a RP value between 2.0 and 2.5 MPa; results that confirm those of Kumar *et al*. (2012), who found that the RP can reach up to 2.2 MPa in the 0 to 0.2 m layer under NTS.

Mean RP values before the soybean (Figure 2a) were higher than after the crop was harvested (Figure 3a). The same happened in the second year (Figure 4a and 5a). This was due to the intense machine traffic needed

Figure 1 - Accumulated rainfall (mm) and mean maximum and minimum temperatures from February 2013 to February 2015. Data obtained from the SIMEPAR weather station (2015)

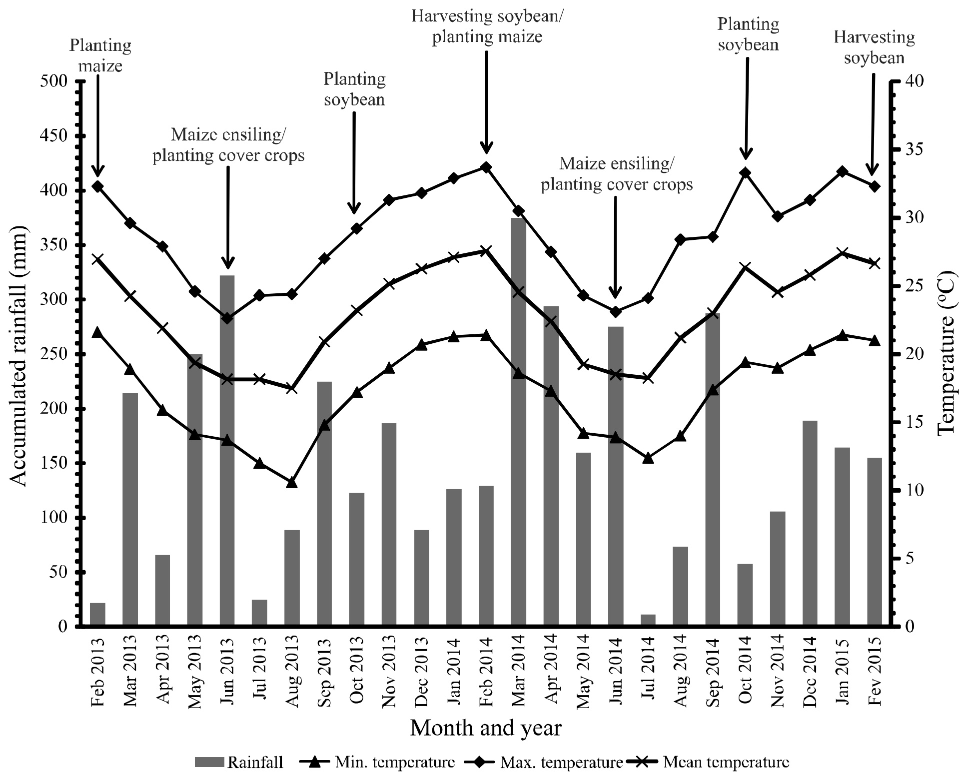


Figure 2 - Mechanical resistance to penetration (MPa) obtained in the first evaluation of the experimental area in September 2013 after the management of cover crops, without the application of WPF (a) and with the application of WPF (b)

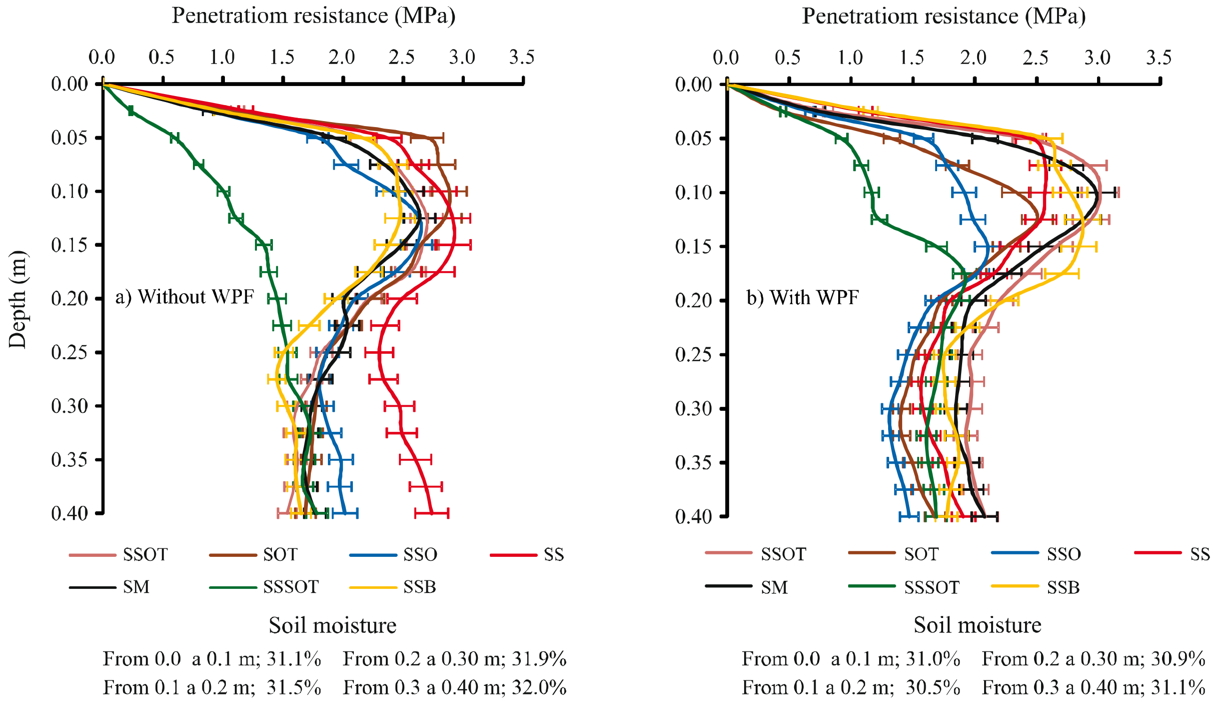
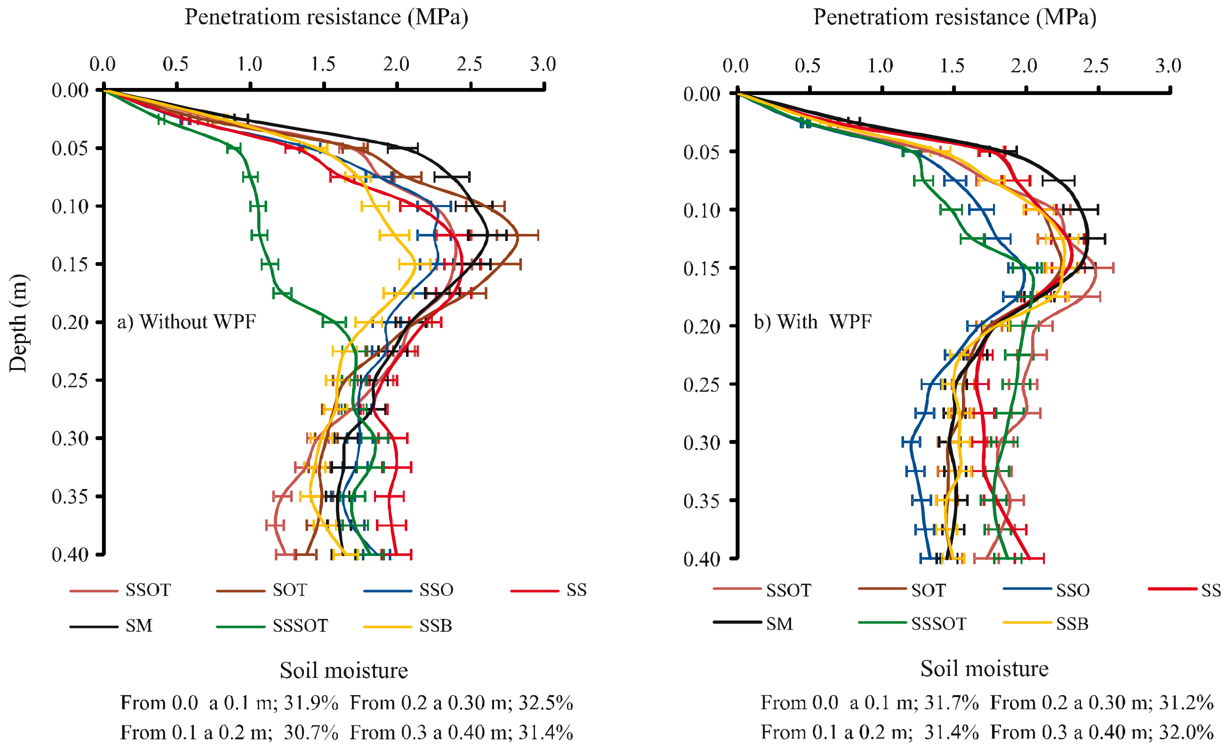


Figure 3 - Mechanical resistance to penetration (MPa) obtained after the soybean harvest in the second evaluation of the experimental area in February 2014, without the application of WPF (a) and with the application of WPF (b)



to harvest the maize for whole plant silage, and to the aggressive root system of the soybean crop.

With the application of WPF (Figure 3b), higher RP values can be seen in the 0.05 to 0.2 m layer, of over 2.0 MPa between management systems, except for the SSSOT and SSO. Similar results were found by Streck *et al*. (2004), who saw maximum RP values at depths of 0.06 to 0.14 m for the treatments. In the 0.2 to 0.4 m layer, the systems were similar, with the RP stabilising at under 2.0 MPa.

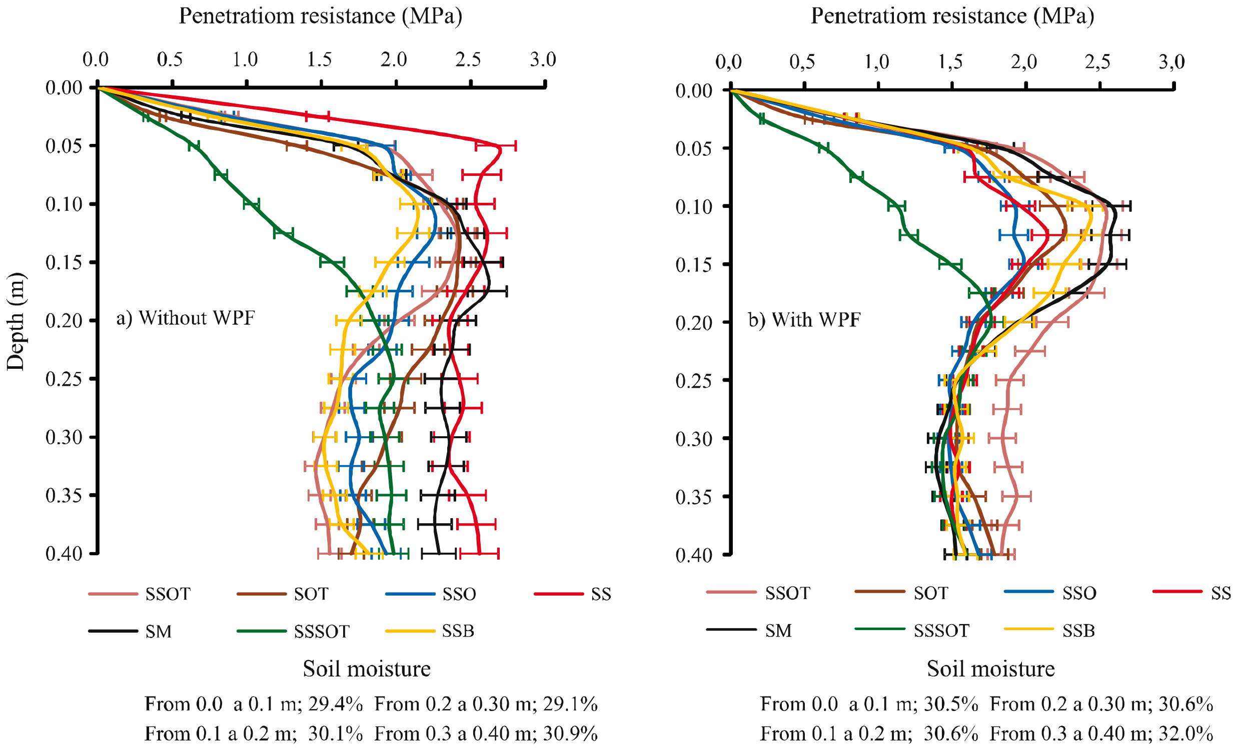
Figure 4 shows RP values in September 2014 after the management of cover crops, without the application of WPF (a) and with application of WPF (b). The same effect can be seen as in the previous evaluations, with the SSSOT system displaying lower RP values of from 0 to 0.05 m, with the same characteristics as in the first two evaluations. However, in Figure 4a, from 0.05 to 0.1 m the SS system had a higher RP. This value shows that the lack of ground cover, as well as the smaller biopore volume under NTS, resulted in a higher RP value in the surface layer, which also occurred in the last evaluation in February 2015 (Figures 5a and 5b), and was statistically superior to the other treatments at 1% probability.

The system of soybean silage (SS) was the only system to leave the ground without cover crops after the completion of whole plant ensiling, with only spontaneous plants remaining. In areas under NTS, keeping the plant cover and the use of cover crops is fundamental to maintaining the physical quality of the soil, especially in the surface layer, which displays low density and high total porosity due to the higher concentration of roots and organic matter (REICHERT; SUZUKI; REINERT, 2007) from the remains of the main crop and/or from the cover crops planted for this purpose.

Because in areas intended for silage production the whole plant is ensiled, leaving only the roots and a small part of the stem, the soil is more susceptible to compaction. However, under the systems that included cover crops, after the maize was harvested for silage, the RP remained at similar levels to the soybean, oat and turnip (SOT) and soybean and maize (SM) systems, which were not subjected to the ensiling process.

The values seen in the management systems from the evaluation carried out in February 2015 (Figure 5), showed a significant difference at a level of 1%. The SSSOT system had a lower RP value in the 0.05 to 0.20 m layer (Figures 5a and 5b), which was the depth

Figure 4 - Mechanical resistance to penetration (MPa) obtained in the third evaluation of the experimental area in September 2014 after the management of cover crops, without the application of WPF (a) and with the application of WPF (b)



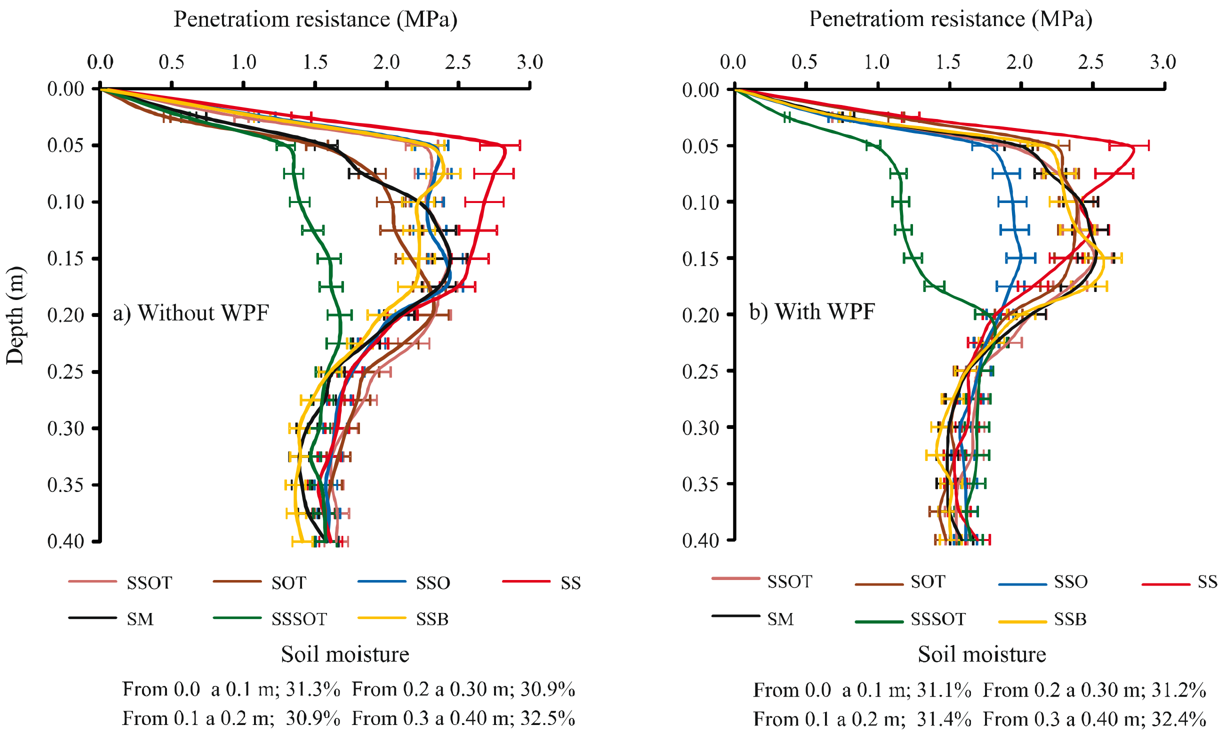
that had the greatest effect on the evaluations. This demonstrates the efficiency of scarification in reducing the RP. These results agree with those of Cunha, Cascão and Reis (2009), who found the same effect of a reduction in RP with the use of a scarifier in preparing the soil. In the 0.2 to 0.4 m layer, no system showed any significant difference in either evaluation, with an RP below 2.0 MPa both with and without WPF.

With no WPF (Figure 5a), a significant difference can be seen between the management systems and the depth of 0.10 to 0.15 m, which is statistically superior to the other layers under evaluation. According to Reichert, Suzuki and Reinert (2007), compaction in agricultural areas and pastures usually occurs to a maximum depth of 0.2 m. The highest RP (over 2.5 MPa) was found in the SS system, which was significant at a level of 1% compared to the other systems under evaluation. This result was due to the absence of ground cover under NTS, highlighting the importance of cover crops, which provide necessary protection, avoid the surface compaction caused by machine traffic and reduce bulk density.

Similar results were found in the management systems with WPF (Figure 5b). The SS system showed an RP over 2.5 MPa, but only from 0.05 to 0.1 m. Under this management system, surface soil compaction was caused by the lack of ground cover. Such RP values under the SS system may compromise crop productivity. According to Beutler *et al*. (2006), soybean productivity decreases at RP values of >2.24 MPa, and maize productivity at RP values of >1.65 MPa, restricting shoot growth and crop productivity (FREDDI *et al*., 2007). Similar results were found by Rossetti and Centurion (2013), who stated that plant height, stalk diameter, height of the first ear insertion and maize productivity showed a decreasing linear relationship for increases in the RP. There is still no consensus among researchers. For Betioli Júnior *et al*. (2012), under NTS, the bioporosity resulting from less mechanical movement of the soil may offer alternatives for root growth, compensating for the higher resistance of the soil matrix; because of this, the critical resistance limit of 2.0 MPa can be increased.

The systems that presented values below 2.0 MPa at a depth of 0.10 to 0.15 m, were SSO and SSSOT (Figure 5b). Among the management systems under NTS only, with no mechanical interference of the soil, it can be seen that SSO appears in all the evaluations which include the application of WPF (Figures 2b, 3b, 4b and 5c), with RP

Figure 5 - Mechanical resistance to penetration (MPa) obtained in the fourth evaluation of the experimental area in February 2015 after the soybean harvest, without the application of WPF (a) and with the application of WPF (b)



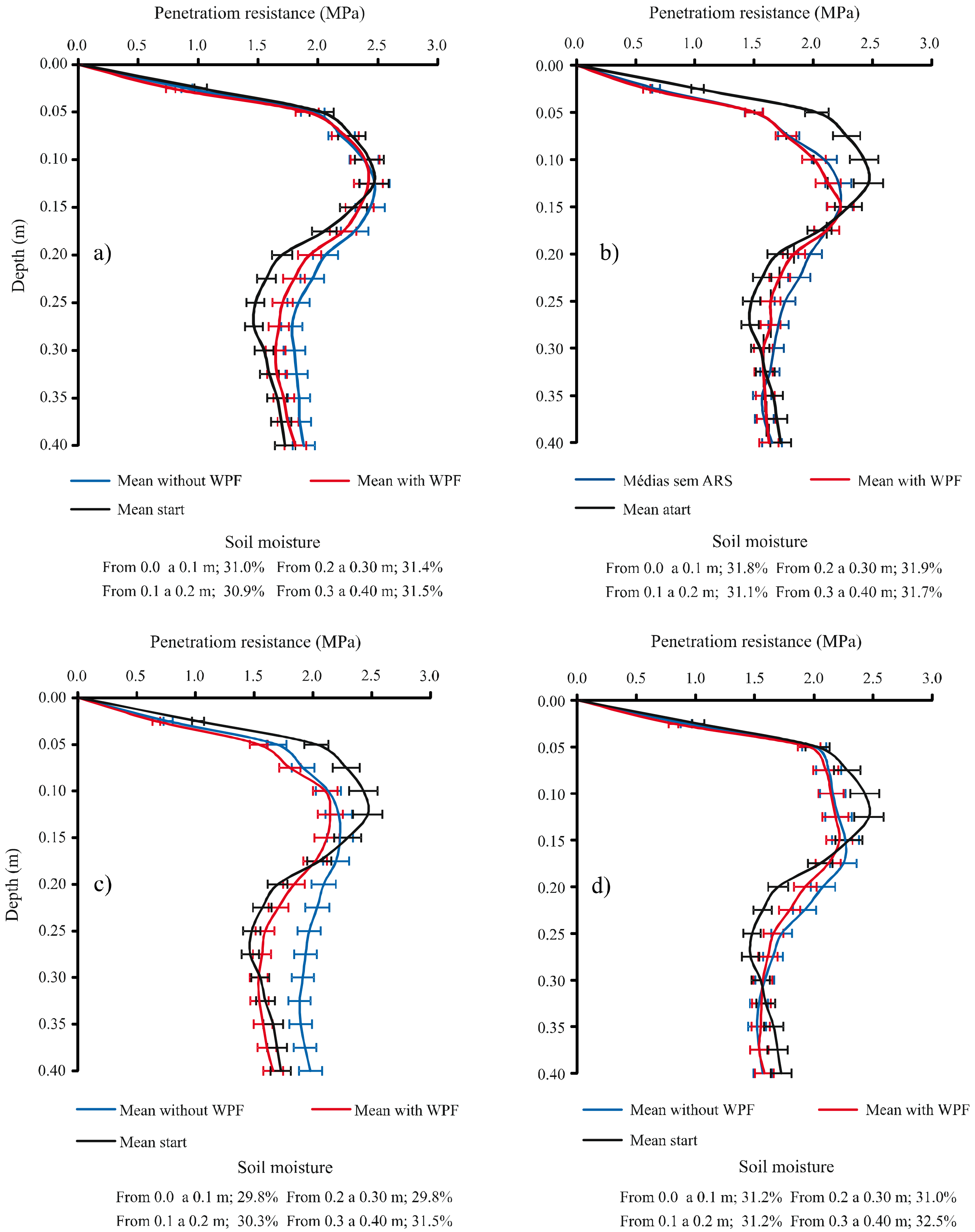
values below 2.0 MPa in the 0.10 to 0.15 m layer. This layer, under the other management systems, had the highest RP values. The application of WPF under the SSO system, which used black oats as ground cover, reduced the RP in the 0.10 to 0.15 m layer, and was statistically lower than the other management systems under NTS. This is probably due to the response of the black oats to the application of WPF, with greater shoot and root-system development, the creation of biopores and an increase in soil aeration, thereby reducing the RP, especially at this depth.

Valicheski *et al*. (2012) studied the effect of compaction on the physical properties of the soil and the development of cover crops (forage turnip and black oats). They found that the high resistance of the soil to penetration, mainly at the more intense levels of traffic, restricted root development in the forage turnip that, because it is a plant with a tuberous root system, exploited a smaller volume of soil, thereby absorbing a smaller amount of nutrients and showing less shoot development. According to the same authors, black oats, due to its fasciculated root system (which allowed the roots to develop in small cracks), exploited a larger volume of soil, resulting in greater shoot development.

The mean RP values under the management systems with and without WPF are shown in Figure 6, together with the values collected before the start of the experiment. In each of the collections, the mean values were greater in the 0.10 to 0.15 m layer, which may impair crop development. These values agree with those of Mazurana *et al*. (2013), who found that the traffic conditions imposed on the soil by the tractor in an area of oats + vetch, increased the RP to a depth of 0.15 m.

The behaviour of the RP in the first evaluation (Figure 6a) was similar to that at the start of the experiment to a depth of 0.2 m. This did not occur from 0.2 to 0.3 m, where the mean values both with and without WPF were higher than the data obtained prior to the experiment, with a mean RP of 2.0 MPa. There was a significant difference between the mean values of the treatments with and without WPF in the first evaluation (Figure 6a). The same was seen in the other evaluations (Figures 6b, 6c and 6d). The application of WPF resulted in a significant difference in RP in the 0 to 0.4 m profile, which disagreed with Oliveira, Lima and Verburg (2015) and Costa *et al*. (2011), who found no alteration in the physical attributes of the soil due to the application of WPF.

Figure 6 - Mean values for mechanical resistance to penetration (Mpa), with WPF and without WPF, and the initial value characterising the experimental area, obtained in the first evaluation (a), second evaluation (b), third evaluation (c) and fourth evaluation (d)



According to Arruda *et al.* (2010), applying WPF at doses of 50 and 100 m^3 ha^{-1} in relation to the control with no fertiliser, did not alter the physical attributes of the soil after four years, showing that the agricultural use of WPF preserves the physical quality of the soil.

In each of the evaluations (Figures 6a, 6b, 6c and 6d), there was a significant difference seen at the depth of 0.10 to 0.15 m.

There was no variation between mean values with and without WPF for any of the evaluations (Figures 6a, 6b, 6c and 6d), compared to initial values before the start of the experiment. This shows that under NTS there is no effect on RP in production areas of whole plant silage if the management is suitable and includes cover crops.

These results demonstrate that in areas already established under NTS, the effect of compaction caused by intense machine traffic can be controlled and still preserve the physical quality of the soil. Ralisch *et al*. (2008) found that for 14 consecutive years, in systems under NTS in areas of pasture with no soil turning, the RP approached the values for native forest, showing that in areas of established NTS the effect is minimised.

The continuous use of cover crops under SPD, and monitoring the physical conditions of the soil over time, are fundamental for the evaluation and development of management systems. Biological action in reducing the effects of compaction by the use of cover crops and crop rotation may have a beneficial effect in the medium- and long-term, where this effect is not detectable by the routine evaluation of such physical properties of the soil as the RP (REICHERT; SUZUKI; REINERT, 2007).

Before carrying out scarification of the area, there must be a real need for the operation. In most cases, simply planting cover crops, or changes in the type of management, are sufficient to recover the physical quality of the soil. A well-managed NTS is the best way of reducing soil loss through surface runoff, protecting the soil from the direct action of raindrops, and preventing the water from evaporating.

When scarification is carried out, in addition to increasing costs, especially of fuel, a part of the benefits from NTS is lost. In agricultural areas, NTS is not established during the early years, but only over time (4 to 5 years) and, depending on the type of management, the physical properties of the soil can be maintained in conditions that do not impede root development in such crops as soybean or maize.

CONCLUSIONS

1. The application of wastewater from pig farming decreased the mechanical resistance of the soil to penetration; the system of soybean, silage and scarification with oats and turnip had the lowest RP; and at the depth of 0.2 to 0.4 m, all the treatments under evaluation displayed similar behaviour, with no signs of compaction;
2. The greatest mechanical resistance of the soil to penetration was in the 0.10 to 0.15 m layer and under the system with no cover crops (SS);
3. The study led to the conclusion that the management system under NTS including black oats associated with the use of wastewater from pig farming is the most suitable for reducing the RP in production areas of whole plant silage.

REFERENCES

AFZALINIA, S.; ZABIHI, J. Soil compaction variation during corn growing season under conservation tillage. **Soil and Tillage Research**, v. 137, p. 1-6, Apr. 2014.

ARRUDA, C. A. O. *et al.* Aplicação de dejeto suíno e estrutura de um Latossolo Vermelho sob semeadura direta. **Ciência e Agrotecnologia**, v. 34, p. 804-809, 2010.

BETIOLI JÚNIOR, E. *et al*. Intervalo hídrico ótimo e grau de compactação de um Latossolo Vermelho após 30 anos sob plantio direto. **Revista Brasileira de Ciência do Solo**, v. 36, n. 3, p. 971-982, 2012.

BEUTLER, A. N. *et al.* Efeito da compactação na produtividade de cultivares de soja em Latossolo Vermelho. **Revista Brasileira de Ciência do Solo**, v. 30, p. 787-794, 2006.

BOTTA, G. F. *et al.* Deep tillage and traffic effects on subsoil compaction and sunflower (Helianthus annus L.) yields. **Soil and Tillage Research**, v. 91, n. 1/2, p. 164-17, Dec. 2006.

CARRARA, M. *et al*. Mapping of penetrometer resistance in relation to tractor traffic using multivariate geostatistics. **Geoderma**, v. 142, n. 3/4, p. 294-307, Dec. 2007.

CERETTA, C. A. *et al*. Frações de fósforo no solo após sucessivas aplicações de dejetos de suínos em plantio direto. **Pesquisa Agropecuária Brasileira**, v. 45, n. 6, p. 593-602, 2010.

CHEN, Y. *et al*. Short-term tillage effects on soil cone index and plant development in a poorly drained, heavy clay soil. **Soil and Tillage Research**, v. 82, n. 2, p. 161-171, June 2005.

CONTE, O. *et al*. Evolução de atributos físicos de solo em sistema de integração lavoura - pecuária. **Pesquisa Agropecuária Brasileira**, v. 46, n. 10, p. 1301-1309, 2011.

COSTA, M. S. S. M. *et al.* Atributos físicos do solo e produtividade do milho sob sistemas de manejo e adubações. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 15, n. 8, p. 810-815, 2011.

CRUZ, S. C. S. *et al.* Consórcio de milho e Brachiaria decumbens em diferentes preparos de solo. **Acta Scientiarum. Agronomy**, v. 31, n. 4, p. 633-639, 2009.

CUNHA, J. P. A. R.; CASCÃO, V. N.; REIS, E. F. Compactação causada pelo tráfego de trator em diferentes manejos de solo. **Acta Scientiarum. Agronomy**, v. 31, n. 3, p. 371-375, 2009.

DRESCHER, M. S. *et al.* Resistência à penetração e rendimento da soja após intervenção mecânica em latossolo vermelho sob plantio direto. **Revista Brasileira de Ciência do Solo**, v. 36, n. 6 p. 1836-1844, 2012.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA. **Sistema brasileiro de classificação de solos**. Rio de Janeiro: Embrapa Solos, 2013. 353 p.

FREDDI, O. S. *et al*. Compactação do solo e intervalo hídrico ótimo no crescimento e na produtividade da cultura do milho. **Bragantia**, v. 66, n. 3, p. 477-486, 2007.

FUENTES-LLANILLO, R.; GUIMARÃES, M. F.; TAVARES FILHO, J. Morfologia e propriedades físicas de solo segundo sistemas de manejo em culturas anuais. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 17, n. 5, p. 524-530, 2013.

GAO, W. *et al*. A simple model to predict soil penetrometer resistance as a function of density, drying and depth in the field. **Soil and Tillage Research**. v. 155, p. 190-198, Jan. 2016.

KUMAR, A. *et al*. Soil cone index in relation to soil texture, moisture content, and bulk density for no-tillage and conventional tillage. **Agricultural Engineering International: The CIGR Journal**, v. 14, n. 1, p. 26-37, 2012.

LÓPEZ-GARRIDO, R. *et al.* Reduced tillage as an alternative to no-tillage under Mediterranean conditions: a case study. **Soil and Tillage Research**, v. 140, p. 40-47, Jul. 2014.

MAZURANA, M. *et al*. Propriedades físicas do solo e crescimento de raízes de milho em um Argissolo vermelho sob tráfego controlado de máquinas. **Revista Brasileira de Ciência do Solo**, v. 37, n. 5, p. 1185-1195, 2013.

MENEGHETTI, A. M. *et al.* Mineral composition and growth of baby corn under swine wastewater combined with chemical fertilization. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 16, n. 11, p. 1198-1205, 2012.

OLIVEIRA, D. M. S.; LIMA, R. P.; VERBURG, E. E. J. Qualidade física do solo sob diferentes sistemas de manejo e aplicação de dejeto líquido suíno. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 19, n. 3, p. 280-285, 2015.

POSSENTI, R. A. *et al*. Parâmetros bromatológicos e fermentativos das silagens de milho e girassol. **Ciência Rural**, v. 35, n. 5, p. 1185-1189, 2005.

PRIOR, M. *et al*. Acúmulo e percolação de fósforo no solo devido à aplicação de água residuária de suinocultura na cultura do milho (*Zea mays L.)*. **Pesquisa Aplicada & Agrotecnologia**, v. 2, n. 1, p. 89-96, 2009.

RALISCH, R. *et al.* Resistência à penetração de um Latossolo Vermelho Amarelo do Cerrado sob diferentes sistemas de manejo. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 12, n. 4, p. 381-384, 2008.

REICHERT, J. M.; SUZUKI, L. E. A. S.; REINERT, D. J. Compactação do solo em sistemas agropecuários e florestais: identificação, efeitos, limites críticos e mitigação. *In:* CERETTA, C. A.; SILVA, L. S.; REICHERT, J. M. (Ed.) **Tópicos em ciência do solo**. 5. ed. Viçosa, MG: SBCS, 2007. p. 49-134.

ROSSETTI, K. V.; CENTURION, J. F. Sistemas de manejo e atributos físico-hídricos de um Latossolo Vermelho cultivado com milho. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 17, n. 5, p. 472-479, 2013.

SIMEPAR. Sistema Meteorológico do Paraná. 2015.

STRECK, C. A. *et al.* Modificações em propriedades físicas com a compactação do solo causada pelo tráfego induzido de um trator em plantio direto. **Ciência Rural**, v. 34, n. 3, p. 755-760, 2004.

TORMENA, C. A *et al*. Variação temporal do intervalo hídrico ótimo de um Latossolo Vermelho Distroférrico sob sistemas de plantio direto. **Revista Brasileira de Ciência do Solo**, v. 31, p. 211-219, 2007.

VALICHESKI, R. R. *et al.* Desenvolvimento de plantas de cobertura e produtividade da soja conforme atributos físicos em solo compactado. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 16, n. 9, p. 969-977, 2012.